A Comparison of Two Gasoline and Two Diesel Cars with Varying Emission Control Technologies

DEER 2002, August 25-29

Peter Ahlvik, Ecotraffic ERD³ AB
Acknowledgements

- Olle Hådell and Pär Gustafsson, the Swedish National Road Administration
- Katarina Sandling, K W Bruun Autoimport AB (Swedish Peugeot importer)
- Jean-Claude Momique, PSA, France
- Anders Norén, Svenska Volkswagen (Sweden)
- Klaus-Peter Schindler, Volkswagen, Germany
- John Fairbanks, DOE
Outline of the presentation

- Introduction and background
- Selection of test cars
- Measurement program
- Results, exhaust emissions
- Results, impact on health and environment
- Outlook
- Discussion and summary
What’s new in this study?

- First tests (in Sweden) of unregulated (harmful) emissions components on:
  - Newer diesel cars than MY’93 (e.g. direct injection)
  - Diesel cars with high-pressure injection
  - Ultra-low sulfur diesel fuel (introduced in 1990)

- Complementary driving cycles/temp.: cold start at -7°C, US06, overtaking (70-110 km/h)

- Calculation of impact of exhaust emissions
- Low-cost project (about $ 135 000)
- Inspiration for an open-minded debate (in Swe.)
Diesel and gasoline share of new car sales in Europe, 2001

Share of new car sales (%)

- EU-15
- A
- B
- DK
- F
- FIN
- GER
- GR
- IRE
- IT
- LUX
- NL
- P
- SP
- SE
- UK

Graph showing the percentage of new car sales attributed to gasoline and diesel for various countries in Europe in 2001.
Ecotraffic’s forecast for future energy converters in the EU

- IDI diesel
- CIDI diesel
- SIDI (comb.)
- SIDI otto
- Fully VVT otto (TWC)
- Conv. otto (TWC)
- Fuel cells

Market share, new vehicles (%)

Why are diesel cars so popular in Europe (except in Sweden..)?

**Mercedes E 240 (gasoline)**
- Power: 130 kW
- Torque: 240 Nm
- Acc.: 9.1 s (0-100)
- Speed: 236 km/h
- FC: 10.9 l/100 km
- CO₂: 262 g/km

**Mercedes E 270 CDI (diesel)**
- Power: 130 kW
- Torque: 400 Nm
- Acc.: 9.0 s (0-100)
- Speed: 233 km/h
- FC: 6.5 l/100 km
- CO₂: 172 g/km
Selection of test cars

- Peugeot 307, 80 kW 1,6 liter gasoline (SI-P)
- VW Golf 77, kW 1,6 liter gasoline (SI-G)
- Peugeot 307, 80 kW 2,0 HDi FAP diesel with CR injection and particulate filter (CI-CR/DPF)
- VW Golf, 96 kW 1,9 TDI diesel, high-pressure unit injectors (CI-UI/HP)

Fuels used: Swedish Environmental Class 1 diesel fuel (<10 ppm S) and Swedish Gasoline according to EU 2005 specification (<50 ppm S)
Emission development for VW Golf diesel cars

Source: mot No. 12, May 26, 2001

Emission development for VW Golf diesel cars

Particulate emissions (g/km)

<table>
<thead>
<tr>
<th>Euro 2</th>
<th>Euro 3</th>
<th>Euro 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 hp, Euro 2, MY’93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90 hp, Euro 2, MY’96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>130 hp, Euro 3, MY’01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150 hp, Euro 3, MY’01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 hp, Euro 3, MY’01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 hp, Euro 4, MY’01/02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Potential for 4-V tech

Test car

HC+NOx emissions (g/km)
Certification data for particulate emissions (source: VCA)

Euro IV limit

With particulate filter  Without particulate filter

Particulate emissions (g/km)

In total: 62 vehicles ≤0.025 /km

Particulate emissions (g/km)

With particulate filter
Without particulate filter

0,000  0,005  0,010  0,015  0,020  0,025

1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24
Measurement program
- Driving cycles

- NEDC test at +22°C
- NEDC test at –7°C
- US06 test ("tougher" driving cycle)
- Overtaking, 70 – 110 km/h. “Simulating” overtaking of a truck with maximum acceleration
Measurement program
- Emissions components

- Measurements at the chassis dyno of MTC
- Regulated emissions: CO, HC, NO\textsubscript{X}, part.
- Unregulated gaseous emissions
  - Nitrous oxide (N\textsubscript{2}O), ammonia (NH\textsubscript{3})
  - Aldehydes: formaldehyde and acetaldehyde
  - Light aromatics: benzene
  - Alkenes: ethene, propene, 1,3-butadiene
  - Acrylamide
  - Polycyclic aromatic hydrocarbons (PAH)
- Particle number and size distribution
Emission testing at MTC
Instrument set-up for particle size measurements with ELPI

- Venturi
- Dilution tunnel
- Diluter
- Aerosol 10 lpm
- ELPI
- Sampling filter
- Pump
- PC/laptop
- Data Processing

2002-08-27

Gasoline & diesel
Schematic lay-out of the ELPI instrument

Aerosol

Charger

High Voltage

Insulated Impactor Stages (13)

100 mbar

Pump

A/D & Control Electronics

PC/laptop

Data Processing

ELPI

Electrical Low Pressure Impactor

1 fA = 10^{-15} A

0.000000000000001 A

Multichannel Electrometer Amplifier
Emissions for the gasoline cars in comparison to a Honda ULEV

- CO emissions (g/km): 0.37, 0.24, 0.37, 0.05, 0.046, 0.044
- HC & NOx emissions (g/km): 0.059, 0.05, 0.046, 0.042, 0.046, 0.046
HC emissions in NEDC

<table>
<thead>
<tr>
<th></th>
<th>SI-P</th>
<th>SI-G</th>
<th>CI-CR/DPF</th>
<th>CI-UI/HP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gasoline</strong></td>
<td>0.050</td>
<td>0.084</td>
<td></td>
<td>0.013</td>
</tr>
<tr>
<td><strong>Diesel</strong></td>
<td></td>
<td></td>
<td>0.012</td>
<td>0.027</td>
</tr>
<tr>
<td>Temperature: +22°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature: -7°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
NO\textsubscript{X} emissions in NEDC

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{nox_emissions.png}
\end{figure}

- Gasoline:
  - SI-P: 0.040 (Temperature: +22°C), 0.052 (Temperature: -7°C)
  - SI-G: 0.073, 0.033
  - CI-CR/DPF: 0.61
  - CI-UI/HP: 0.37

- Diesel:
  - 0.55
Benzene emissions in NEDC

Gasoline

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Temperature: +22°C</th>
<th>Temperature: -7°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI-P</td>
<td>0.59</td>
<td>2.31</td>
</tr>
<tr>
<td>SI-G</td>
<td>1.03</td>
<td>6.13</td>
</tr>
</tbody>
</table>

Diesel

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Temperature: +22°C</th>
<th>Temperature: -7°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI-CR/DPF</td>
<td>0.17, 0.25</td>
<td></td>
</tr>
<tr>
<td>CI-UI/HP</td>
<td>0.15, 0.81</td>
<td></td>
</tr>
</tbody>
</table>

Temperature: +22°C

Temperature: -7°C
Emissions of alkenes in NEDC Interpolated to +7°C

Ethene & propene emissions (mg/km)

SI-P: 1.94, 0.23
SI-G: 4.36, 0.41
CI-CR/DPF: 1.54, 0.50
CI-UI/HP: 2.15, 0.50

1,3-butadiene emissions (g/km)

SI-P: 3.00, 0.10
SI-G: 3.01, 0.20
CI-CR/DPF: 1.30, 0.30
CI-UI/HP: 2.15, 0.40

Ethene & propene:
- SI-P: 1.94, 0.23
- SI-G: 4.36, 0.41
- CI-CR/DPF: 1.54, 0.50
- CI-UI/HP: 2.15, 0.50

1,3-butadiene:
- SI-P: 3.00, 0.10
- SI-G: 3.01, 0.20
- CI-CR/DPF: 1.30, 0.30
- CI-UI/HP: 2.15, 0.40

Emissions of alkenes in NEDC Interpolated to +7°C

2002-08-27
PAH emissions i NEDC Interpolated to +7°C

<table>
<thead>
<tr>
<th></th>
<th>Gasoline</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI-P</td>
<td>6,6</td>
<td>9,8</td>
</tr>
<tr>
<td>SI-G</td>
<td>17,9</td>
<td>42,0</td>
</tr>
<tr>
<td>CI-CR/DPF</td>
<td>0,2</td>
<td>0,8</td>
</tr>
<tr>
<td>CI-UI/HP</td>
<td>10,0</td>
<td>14,4</td>
</tr>
</tbody>
</table>

PAH emissions (μg/km)
Other unregulated emissions

- Nitrous oxide (N₂O): in general low levels, however higher for diesel (mix-up?)
- Ammonia (NH₃) in NEDC: gasoline=low, diesel=0. Higher level for gasoline in US06
- Aldehydes: gasoline=0, diesel=0 or at the detection level at +22°C, 3 mg vid -7°C
- Acrylamide: not detectable in the overtaking test, below detection limit in US06 for all cars except in one case (CI-UI/HP), where it was 2 times higher than detection limit
Particulate emissions in NEDC

<table>
<thead>
<tr>
<th></th>
<th>Gasoline</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particulate emissions (mg/km)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Temperature: +22°C</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SI-P</td>
<td>0,7</td>
<td></td>
</tr>
<tr>
<td>SI-G</td>
<td>1,3</td>
<td></td>
</tr>
<tr>
<td>CI-CR/DPF</td>
<td>0,3</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature: -7°C</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CI-UI/HP</td>
<td>22,1</td>
<td>32,4</td>
</tr>
</tbody>
</table>

2002-08-27

Gasoline & diesel
Particulate emissions compared to gasoline direct injection cars

Sources: SAE 2000-01-2017
MTC 9704
VTT: EU 2000 gasoline and Finnish reformulated gasoline
MTC: Swedish commercial gasoline

Particulate emissions (mg/km)

<table>
<thead>
<tr>
<th>Source</th>
<th>Gasoline</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTT, EU2000</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>VTT, RFG</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>MTC, Swe gas</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>CI-UI/HP</td>
<td>27</td>
<td></td>
</tr>
</tbody>
</table>
Total number of particles in NEDC

- **Gasoline**
  - SI-P: 9.5E+12
  - SI-G: 8.2E+12
  - CI-CR/DPF: 4.1E+12
  - CI/UI/HP: 6.1E+11

- **Diesel**
  - Temperature: +22°C
    - SI-P: 3.5E+13
    - SI-G: 4.1E+12
    - CI-CR/DPF: 1.9E+11
    - CI/UI/HP: 7.2E+14
  - Temperature: -7°C
    - SI-P: 8.2E+13
    - SI-G: 3.5E+13
    - CI-CR/DPF: 6.1E+11
    - CI/UI/HP: 8.2E+14
Particle size distribution for the Peugeot cars in NEDC at +22°C

Aerodynamic diameter (µm)

Number of part. dN/dlogDp (#/km)

1,0E+08
1,0E+09
1,0E+10
1,0E+11
1,0E+12
1,0E+13
1,0E+14

0,001 0,01 0,1 1 10

SI-P
CI-CR/DPF
Particle size distribution for the VW Golf cars in NEDC at +22°C

Number of particles dN/dlogDp (#/km)

Aerodynamic diameter (μm)

1,0E+15
1,0E+14
1,0E+13
1,0E+12
1,0E+11
1,0E+10
1,0E+09
1,0E+08

0,001 0,01 0,1 1 10

- SI-G
- CI-UI/HP

2002-08-27 Gasoline & diesel
Total number of particles in US06 and during overtaking

<table>
<thead>
<tr>
<th></th>
<th>SI-P</th>
<th>SI-G</th>
<th>CI-CR/DPF</th>
<th>CI-UI/HP (5)</th>
<th>CI-UI/HP (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>4.4E+14</td>
<td>6.3E+13</td>
<td>3.3E+14</td>
<td>2.3E+14</td>
<td>2.2E+14</td>
</tr>
<tr>
<td>Diesel</td>
<td>2.6E+12</td>
<td>2.1E+12</td>
<td>1.4E+10</td>
<td>1.4E+10</td>
<td>1.0E+10</td>
</tr>
</tbody>
</table>

- SI-P: SI-P
- SI-G: SI-G
- CI-CR/DPF: CI-CR/DPF
- CI-UI/HP (5): CI-UI/HP (5)
- CI-UI/HP (6): CI-UI/HP (6)
Total number of particles in real time in US06

Time (s) vs. Total number of particles (#/km)

- SI-P
- SI-G
- CI-CR/DPF
- CI-UI/HP
- US06 (km/h)

2002-08-27 Gasoline & diesel
Particle size distribution for the Peugeot cars in US06

Number of particles dN/dlogDp (#/km)

Aerodynamic diameter (µm)
Particle size distribution for the VW Golf cars in US06

Number of particles dN/dlogDp (#/km)

Aerodynamic diameter (µm)

10^0 to 10^15

SI-G

CI-UI/HP
Ozone formation potential, +14°C

Gasoline & diesel
Local NO$_X$ emissions, $+7^\circ$C

<table>
<thead>
<tr>
<th>Gasoline</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas 93/94</td>
<td>100</td>
</tr>
<tr>
<td>SI-P</td>
<td>15,8</td>
</tr>
<tr>
<td>SI-G</td>
<td>11,8</td>
</tr>
<tr>
<td>Diesel 93/94</td>
<td>192</td>
</tr>
<tr>
<td>CI-CR/DPF</td>
<td>137</td>
</tr>
<tr>
<td>CI-UI/HP</td>
<td>129</td>
</tr>
</tbody>
</table>
Local particulate emissions, +7°C

<table>
<thead>
<tr>
<th>Lokal particulate emissions (gas 93/94=100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
</tr>
<tr>
<td>SI-P</td>
</tr>
<tr>
<td>SI-G</td>
</tr>
<tr>
<td>Diesel 93/94</td>
</tr>
<tr>
<td>CI-CR/DPF</td>
</tr>
<tr>
<td>CI-UI/HP</td>
</tr>
</tbody>
</table>

Gasoline: 100
SI-P: 9.7
SI-G: 23.3
Diesel 93/94: 618
CI-CR/DPF: 2.1
CI-UI/HP: 191
Cancer risk index (gas 93/94=100)
URFs by Törnqvist/Ehrenberg

- **Gasoline**
  - Cancer risk index (gas 93/94=100)
  - SI-P: 4.1
  - SI-G: 11

- **Diesel**
  - Cancer risk index (gas 93/94=100)
  - CI-CR/DPF: 71
  - CI-UI/HP: 15

- **Chemicals**
  - PAC
  - Aldehydes
  - Alkeners
  - Benzene
  - Particles

2002-08-27 Gasoline & diesel
Acidification potential
$\text{NO}_X$-equivalents

<table>
<thead>
<tr>
<th>Acidification potential (gas 93/94=100)</th>
<th>Gasoline</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gas 93/94</strong></td>
<td>100</td>
<td>143</td>
</tr>
<tr>
<td>SI-P</td>
<td>48</td>
<td>112</td>
</tr>
<tr>
<td>SI-G</td>
<td>45</td>
<td>106</td>
</tr>
<tr>
<td>Diesel 93/94</td>
<td>143</td>
<td>102</td>
</tr>
<tr>
<td>CI-CR/DPF</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>CI-UI/HP</td>
<td>102</td>
<td></td>
</tr>
</tbody>
</table>

Vehicle and Fuel prod.
Voluntary CO₂ reduction by EU car manufacturers (ACEA)

Average CO₂ emissions for ACEA manufacturers

- ACEA commitment
- Statistics 1995-2000
- Sweden 1995 & 2000

Target 2008: 140
Indicative target 2012: 120

CO₂ emissions (g/km)
Emissions of climate gases
\( \text{CO}_2\)- equivalents

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Fuel prod.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td></td>
</tr>
<tr>
<td>Gas 93/94</td>
<td>100</td>
</tr>
<tr>
<td>SI-P</td>
<td>82,9</td>
</tr>
<tr>
<td>SI-G</td>
<td>81,5</td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td>Diesel 93/94</td>
<td>78,4</td>
</tr>
<tr>
<td>CI-CR/DPF</td>
<td>68,6</td>
</tr>
<tr>
<td>CI-UI/HP</td>
<td>70,0</td>
</tr>
</tbody>
</table>

Climate gases (gas 93/94=100)

- Gasoline: 17.6, 15.9, 15.4
- Diesel: 10.7, 9.1, 9.3
Relative mileage for gasoline and diesel cars with similar performance

Fuel consumption in NEDC
Equal performance: acc., 0-100 km/h

Fuel economy diesel vs. gas (%)

- Relative mileage
- Number of cars


Number of cars (#)

0 40 80 120 160 200

120% 125% 130% 135% 140% 145%
Outlook

- Euro V, EEV (low-emission) not yet decided
- Phase-in of ultra-low sulfur fuel...
- Gasoline fuel econ. must (and will) improve
- Tax harmonization on diesel fuel in EU?
- Activities in Sweden
  - Workshop on diesel emissions this fall
  - Future fuel and vehicle taxation is discussed
  - Additional tests on cars (?)
  - CNG/diesel comparison on transit buses
- Fuels for future diesel engines?
Conclusions 1(2) - Emissions

- CO, HC lower for diesel, NO$_x$ higher
- PM higher for diesel w/o DPF, lower with.
- Ammonia, N$_2$O low for all cars in general
- Aldehydes: “zero” for gasoline, low for diesel
- PAH low for all cars, extremely low with DPF
- Most harmful gaseous emissions. lower for diesel
- Number of particles & size is influenced by the driving pattern (→ new driving cycle?). The particulate filter is very effective (→ advantage for diesel in the future?)
Conclusions 2(2)
- Impact on health and environment

- Ozone formation, fuel consumption, climate gases, energy use are lower for diesel
- Impact related to NO\textsubscript{X} lower for gasoline: local NO\textsubscript{2}, acidification, eutrophication
- Cancer risk: low, in general, but with varying results (PM filter → future advantage for diesel?)
- Gasoline development: low emissions=TWC; low fuel consumption: direct injection (NO\textsubscript{X}, PM?)
- Diesel engine development: fuel consumption, particulate filter, NO\textsubscript{X} catalyst
- Is there a new view on diesel cars (e.g. US EPA)?
This concludes my presentation

✧ Thank you for your attention!

✧ Questions?

✧ More information is available at the Internet at:
  www.vv.se
  www.ecotraffic.se