EMISSION FACTORS OF SEVERAL PARTICLE PROPERTIES FROM CURRENT DIESEL PASSENGER CARS

C. Pastorello, L. Ntziachristos, Z. Samaras

Laboratory of Applied Thermodynamics
Department of Mechanical Engineering
Aristotle University of Thessaloniki

Environmental section
Topics

Create speed-dependent emission factors curves for particle exhaust emission

• effect of vehicle technology improvements on particle emission factors
• effect of decreasing fuel sulphur content on particle emission factors
• statistical validity of the emission factors, conducing analysis of variance
• effect of developing emission factors curves using ARTEMIS sub-cycles

PM mass [g km⁻¹]
PM active surface [cm² km⁻¹]
PM total particle [# km⁻¹]
PM solid particle [# km⁻¹]
Particle size distribution [dN dlogdp⁻¹]
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Property</th>
<th>Size resolution</th>
<th>Temporal resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensation Particle Counter (CPC)</td>
<td>Particle number concentration</td>
<td>One channel &gt;7 nm</td>
<td>1 s (transients)</td>
</tr>
<tr>
<td>Scanning Mobility Particle Sizer (SMPS)</td>
<td>Particle sizing and concentration</td>
<td>64 channels per decade</td>
<td>90 s (steady states)</td>
</tr>
<tr>
<td>Electrical Low Pressure Impactor (ELPI) + thermodenuder (TD)</td>
<td>Solid particle sizing and concentration</td>
<td>First 8 channels with filter stage 7nm-1 µm</td>
<td>1 s (transients)</td>
</tr>
<tr>
<td>Diffusion Charger (DC)</td>
<td>Active surface</td>
<td>One channel 7nm – 1 µm</td>
<td>1 s (transients)</td>
</tr>
</tbody>
</table>
Vehicle sample

Conventional diesel: 5 EURO III, 2 EURO II, 1 “simulated” EURO I

DPF equipped: 5 vehicles

Fuel used

<table>
<thead>
<tr>
<th>Diesel fuels</th>
<th>Sulfur (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2</td>
<td>280</td>
</tr>
<tr>
<td>D3</td>
<td>38</td>
</tr>
<tr>
<td>D4</td>
<td>8</td>
</tr>
<tr>
<td>D5</td>
<td>3</td>
</tr>
</tbody>
</table>
Driving cycles

Standard driving cycles

Real world driving cycles

hot UDC
EUDC
ARTEMIS urban
ARTEMIS road
ARTEMIS motorway
ARTEMIS urban

Cycle time (s)

Vehicle speed (km/h)

Urban dense    Free-flow urban                  Congested, stop      Congested, low speed      Flowing stable
Driving cycles

Standard driving cycles: hot UDC, EUDC

Real world driving cycles: ARTEMIS urban, ARTEMIS road, ARTEMIS motorway

Steady states: 50 kmh⁻¹, 90 kmh⁻¹, 120 kmh⁻¹
Results

1. effect of vehicle technology improvements on particle emission factors

2. effect of decreasing fuel sulphur content on particle emission factors

3. statistical validity of the emission factors, conducting analysis of variance

4. effect of developing emission factors curves using ARTEMIS sub-cycles
1 - Effect of vehicle technologies

Diesel passenger car, <= 2000cc

- Euro II
- Euro III
- Euro III+DPF

PM mass [g/km] vs. Average speed [km/h] graph.
1 - Effect of vehicle technologies

Diesel passenger car, <= 2000cc

Average speed [km/h]

PM active surface [cm²/km]

- Euro II
- Euro III
- Euro III+DPF
- Poli. (EURO II)
- Poli. (EURO III)
- Poli. (EURO III+DPF)
1 - Effect of vehicle technologies

Diesel passenger car, <= 2000cc

Average speed [km/h]

PM total particle [#/km]

- Euro II
- Euro III
- Euro III+DPF
- Poli. (EURO II)
- Poli. (EURO III)
- Poli. (EURO III+DPF)
1 - Effect of vehicle technologies

Diesel passenger car, <= 2000cc

Average speed [km/h]

PM solid particle [#/km]

- Euro II
- Euro III
- Euro III+DPF
- Poli. (EURO II)
- Poli. (EURO III)
- Poli. (EURO III+DPF)
1 - Effect of vehicle technologies

Diesel passenger car, <= 2000cc, 120 km/h

- Euro II
- Euro III
- Euro III+DPF
Results

1 effect of vehicle technology improvements on particle emission factors

2 effect of decreasing fuel sulphur content on particle emission factors

3 statistical validity of the emission factors, conducting analysis of variance

4 effect of developing emission factors curves using ARTEMIS sub-cycles
2 - Effect of sulphur content of fuel on emission

For high speed cycle and all metrics, the D2 emission level are higher than the other measured fuels Diesel, Euro III+DPF, >=1400 and <=2000 cc.
2 - Effect of sulphur content of fuel on emission

DPF Diesel passenger car, <= 2000cc

Average Speed [km/h]

PM solid particle [#/km]

D2
D3
D4
D5
2 - Effect of sulphur content of fuel on emission

DPF Diesel passenger car, <= 2000cc, 120km/h

- DAF Diesel passenger car, <= 2000cc, 50 km/h
- DAF Diesel, Euro III+DPF, 90 km/h, >=1400 and <=2000 cc
- DAF Diesel, Euro III+DPF, 120 km/h, >=1400 and <=2000 cc
Results

1 effect of vehicle technology improvements on particle emission factors

2 effect of decreasing fuel sulphur content on particle emission factors

3 statistical validity of the emission factors, conducting analysis of variance

4 effect of developing emission factors curve using ARTEMIS sub-cycles
In order to explore whether there are significant effects on emissions using DPF, a parametric analysis of variance was applied to the emission factors, considering three speed ranges:

- $\leq 40$ km/h
- $40-90$ km/h
- $\geq 90$ km/h

Kruskal-Wallis test
Kruskal-Wallis test

- All the measure assembled into a single set of size N.
- All data are rank-ordered from lowest to highest and returned to the sample.
- Mean ranks in each group \((Mg)\) is calculated.
- Mean the mean of the N ranks in all groups combined \((Mn)\) is calculated.
- Between-groups sum of squared deviates is calculated as:
  
  \[
  SSbg(R) = \Sigma [ng(Mg—Mn)^2]
  \]

- Statistic:

  \[
  H = \frac{SSbg(R)}{N(N + 1)} \times 12
  \]
### 3 - analysis of variance

#### PM mass

<table>
<thead>
<tr>
<th></th>
<th>Average speed cycle &lt;40 km/h</th>
<th>Average speed cycle 40-90 km/h</th>
<th>Average speed cycle &gt;90 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chi-Square</td>
<td>22,791</td>
<td>26,539</td>
<td>13,017</td>
</tr>
<tr>
<td>Degree of freedom</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Asymp. Sig.</td>
<td>0,001</td>
<td>0,001</td>
<td>0,005</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Average speed cycle &lt;40 km/h</th>
<th>Average speed cycle 40-90 km/h</th>
<th>Average speed cycle &gt;90 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chi-Square</td>
<td>6,604</td>
<td>3,691</td>
<td>2,136</td>
</tr>
<tr>
<td>Degree of freedom</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Asymp. Sig.</td>
<td>0,037</td>
<td>0,158</td>
<td>0,334</td>
</tr>
</tbody>
</table>
### PM active surface

<table>
<thead>
<tr>
<th></th>
<th>Average speed cycle &lt;40 km/h</th>
<th>Average speed cycle 40-90 km/h</th>
<th>Average speed cycle &gt;90km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chi-Square</td>
<td>28,913</td>
<td>32,443</td>
<td>5,613</td>
</tr>
<tr>
<td>Degree of freedom</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Asymp. Sig.</td>
<td>0.001</td>
<td>0.001</td>
<td>0.132</td>
</tr>
</tbody>
</table>

### PM solid particle number

<table>
<thead>
<tr>
<th></th>
<th>Average speed cycle &lt;40 km/h</th>
<th>Average speed cycle 40-90 km/h</th>
<th>Average speed cycle &gt;90km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chi-Square</td>
<td>33,883</td>
<td>25,941</td>
<td>39,602</td>
</tr>
<tr>
<td>Degree of freedom</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Asymp. Sig.</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Results

1 effect of vehicle technology improvements on particle emission factors

2 effect of decreasing fuel sulphur content on particle emission factors

3 statistical validity of the emission factors, conducting analysis of variance

4 effect of developing emission factors curves using ARTEMIS sub-cycles
ARTEMIS road

![Graph showing vehicle speed over cycle time with phases labeled: Urban, Unstable phase, More stable, Unstable phase, Highway, More stable, Urban]

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Cycle type</th>
<th>Average speed [km/h]</th>
<th>Duration [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artemis Motorway_1</td>
<td>stable</td>
<td>122,5</td>
<td>272</td>
</tr>
<tr>
<td>Artemis Motorway_2</td>
<td>unstable</td>
<td>103,4</td>
<td>173</td>
</tr>
<tr>
<td>Artemis Motorway 150_3</td>
<td>stable</td>
<td>125,4</td>
<td>182</td>
</tr>
<tr>
<td>Artemis Motorway 150_4</td>
<td>unstable</td>
<td>133,6</td>
<td>109</td>
</tr>
<tr>
<td>Artemis Motorway_3</td>
<td>stable</td>
<td>117,6</td>
<td>182</td>
</tr>
<tr>
<td>Artemis Motorway_4</td>
<td>unstable</td>
<td>119,7</td>
<td>109</td>
</tr>
<tr>
<td>Artemis Road_1</td>
<td>unstable phase</td>
<td>49,9</td>
<td>240</td>
</tr>
<tr>
<td>Artemis Road_2</td>
<td>more stable phase</td>
<td>65,9</td>
<td>171</td>
</tr>
<tr>
<td>Artemis Road_3</td>
<td>unstable phase</td>
<td>43,1</td>
<td>183</td>
</tr>
<tr>
<td>Artemis Road_4</td>
<td>highway</td>
<td>78,6</td>
<td>177</td>
</tr>
<tr>
<td>Artemis Road_5</td>
<td>more stable phase</td>
<td>87,5</td>
<td>91</td>
</tr>
<tr>
<td>Artemis Urban_1</td>
<td>urban dense</td>
<td>15,5</td>
<td>236</td>
</tr>
<tr>
<td>Artemis Urban_2</td>
<td>free flow urban</td>
<td>31,8</td>
<td>198</td>
</tr>
<tr>
<td>Artemis Urban_3</td>
<td>congested, stops</td>
<td>8,7</td>
<td>243</td>
</tr>
<tr>
<td>Artemis Urban_4</td>
<td>congested low speed</td>
<td>11,8</td>
<td>128</td>
</tr>
<tr>
<td>Artemis Urban_5</td>
<td>stable</td>
<td>21,7</td>
<td>116</td>
</tr>
</tbody>
</table>
4 - ARTEMIS sub-cycles

DPF Diesel passenger car, <= 2000cc

Average speed [km/h] vs. PM active surface [cm²/km]

- Euro III+DPF
- Poli. (EURO III+DPF)
- Poli. (EURO III+DPF) - sub-cycle
4 - ARTEMIS sub-cycles

DPF Diesel passenger car, <= 2000cc

- Euro III+DPF
- Poli. (EURO III+DPF)
- Poli. (EURO III+DPF sub-cycle)

Average speed [km/h]

PM total particle [#/km]
4 - ARTEMIS sub-cycles

DPF Diesel passenger car, <= 2000cc

- Euro III+DPF
- Poli. (EURO III+DPF)
- Poli. (EURO III+DPF) subcycle
Conclusions on technology comparison

• EURO II and EURO III are in a narrow range.

• Trap equipped vehicles are associated to a effective reduction of PM emission, for all metrics. Except for high speed cycle.

• Solid particle emission seems to be insensitive to the cycle type. The DPF vehicle has emission level lower than three order of magnitude for all speed ranges.

• Picks of nucleation mode for EURO III and DPF vehicles at high speed condition.

• The Krustal-Wallis test underlines the differences between vehicles technologies, showing that while DPF vehicle differ from the Conventional ones, the older vehicles seems to belong to the same group for most of the metrics.
Conclusions on fuel sulphur content effect

• EURO II and EURO III seem not affect by fuel content.
• Using high sulphur fuel contents increased DPF vehicle emission factors at high speed.
• Influence of higher sulphur content fuel on nucleation mode for DPF vehicle.

Conclusions on sub-cycles

• The emission factors functions obtained using sub-cycles are similar to those calculated using only the composite cycles.