DIESEL PARTICULATE FILTER (DPF)
PARTICLE NUMBER MODELLING FOR
STAGE V NON ROAD APPLICATIONS

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## Particle Matter/ Particle Number (PM/PN) Emissions (Stage V)

PN is introduced as regulated emission for Stage V non road applications

DPF is a best available technology to limit PM/PN

- Stage V legislative limits for non road applications⁠¹

<table>
<thead>
<tr>
<th>Power range (kW)</th>
<th>Year</th>
<th>CO (g/kWh)</th>
<th>HC</th>
<th>NOx</th>
<th>PM (1/kWh)</th>
<th>PN</th>
</tr>
</thead>
<tbody>
<tr>
<td>56 ≤ P &lt; 130</td>
<td>2020</td>
<td>5</td>
<td>0.19</td>
<td>0.4</td>
<td>0.015</td>
<td>1E+12</td>
</tr>
<tr>
<td>130 ≤ P ≤ 560</td>
<td>2019</td>
<td>3.5</td>
<td>0.19</td>
<td>0.4</td>
<td>0.015</td>
<td>1E+12</td>
</tr>
<tr>
<td>P &gt; 560</td>
<td>2019</td>
<td>3.5</td>
<td>0.19</td>
<td>3.5</td>
<td>0.045</td>
<td>-</td>
</tr>
</tbody>
</table>

¹https://www.dieselnet.com/standards/cycles/nte.php
Challenges: Tail Pipe (TP) Particle Number (PN)

- **Understanding Micro phenomena**\(^2,^3\)
  - Soot cake internal characteristics

- **Rapid fluctuations in Engine Speed and Load**
  - DPF mode of operation history i.e. Regen followed by Loading and Regen
  - Cold start and Warm up \(^4\)

- **NOx Vs Soot constrains**
  - Engine out NOx and Soot have influence on DPF mode of operation i.e. Loading or Regen

- **Higher regen rates**\(^5\)
  - DPF in temperatures >400-450°C leads to Regen thus results into lower filtration efficiency (FE).

- **Legislature protocol**
  - It is mandatory as per the protocol that engine operating points must select randomly for the certification to measure Tail Pipe PN. However, each point has to spend a specific time (minimum of 3mins). Hence, FE can affect with high temps and higher times.

- **TP PN measurement over entire engine operation**
  - It involves significant resources and time to measure TP PN over entire engine operating regime.
**Test Set up and Measurements**

**CAT Production Intent Stage V Engine**

- **DOC**
- **DPF**
- **RF Sensor**

**Partial after treatment system (Without including SCR) is employed to perform this test work**

- **DMS 500/AVL 483**
- **MEXA**
- **DMS 500/AVL 483/MEXA**

**DPF is pre conditioned with different soot loads and tests run with selected engine operating points for each soot loading**

**Engine out mean particle size variation is not significant across engine operating points from DMS data**

**RF sensor is calibrated with respect to DPF in temperatures and soot loadings ranging low to high**

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Test Results: Filtration Efficiency (FE) Vs Soot Load

- Filtration Efficiency typically increases with DPF soot load.
- Observed much more scatter in test data than traditional filtration efficiency vs soot load curve.

Maintaining adequate filtration efficiency requires more than having enough soot in the filter.

It is important to understand DPF soot cake characteristics and DPF operation history to explain this phenomena.

Mathematical modelling can provide a direction to comprehend this test data and provide insights about TP PN over engine operation.

Traditional FE vs Soot load

Soot load (g) → Filtration Efficiency

6. SAE 2007-01-0921, Filtration Behavior of Diesel Particulate Filters
**Boundary Conditions**
- Exh. Mass Flow
- EO Temperature
- EO Soot
- EO NOx

**Geometric Properties**

**Model**
- Soot loading
- Soot Accumulation Rate
- Cake Porosity
- Cake porosity Rate-of-Change
- Wall porosity

1D DOC / DPF Model

Model is calibrated to predict DPF soot load and DOC/DPF performance for NO oxidation/NO2 reduction

1D DOC/DPF Model is employed to predict soot cake and wall porosity characteristics

Model predictions are compared with FE from the test data

**EO-Engine Out**
Soot Balance over DPF

\[
\frac{d(SL)}{dt} + (SL)(K) - (FE)(DPF_{in,Soot})
\]

- \(d(SL)/dt = \text{Soot Accumulation Rate (SAR)}\)
- \(SL = \text{Soot Load}\)
- \(K = \text{Passive oxidation constant}\)
- \(FE = \text{Filteration Efficiency}\)
- \(DPF_{in,Soot} = \text{DPF In Soot}\)

DPF Operation Modes

- \(d(SL)/dt > 0 \quad \text{Loading}\)
- \(d(SL)/dt < 0 \quad \text{Regeneration}\)
- \(d(SL)/dt = 0 \quad \text{Balancing}\)

Imaginary lines are drawn to show non linear behaviour of FE with SAR, cake and wall porosity.

FE= function(SAR, Exhaust mass flow, PCR, Soot Load, Cake porosity, Wall porosity)

Model Predictions: Regeneration and Loading
**PN Modelling Layout-II**

**Boundary Conditions**
- Exh. Mass Flow
- FE based on PN

**PN empirical model**
\[
FE = f(\text{Soot Accumulation Rate (SAR), Soot load, Cake porosity change rate (PCR), Cake porosity, Exhaust mass flow, wall porosity})
\]

**Input**
- Soot loading
- Soot Accumulation Rate
- Cake Porosity
- Cake porosity Rate-of-Change
- Wall porosity

**Output**
- DPF Filtration Efficiency
- Tailpipe Particle Number Emissions

\[
TP\ PN = EO\ PN (1 - FE)
\]

**Here,**
- TP PN = Tail pipe Particle Number
- EO PN = Engine out Particular Number
- FE = Filtration efficiency
PN Model Predictions (Validation Studies)

Model predictions are correlated with test data. However, it could not predict low TP PN observed during DPF regeneration.
Random Point Selection: TP PN Estimation

- **Legislation Protocol**

  - Pre-Conditioning → RMC
  - Selection of three random points in NTE zone

**CAT Production Intent Stage V Engine is selected for random point generation and PN is predicted over NTE zone.**

*RMC* Ramped Mode Cycle
*NTE* Not To Exceed

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**Engine Speed** → **Engine Torque**

**NTE zone**

First point of NTE out of 3 is circled with red colour outline
Model predictions confirm that all NTE points are within the target. Test studies also confirmed the same behaviour.

<table>
<thead>
<tr>
<th>Probability To pass</th>
<th>PN Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Point</td>
<td>1</td>
</tr>
<tr>
<td>2nd Point</td>
<td>1</td>
</tr>
<tr>
<td>3rd Point</td>
<td>1</td>
</tr>
</tbody>
</table>

Industrial Power Systems Division
Summary

- It is observed from this work that having enough soot load and engine NOx/Soot is not sufficient to maintain high FE to lower TP PN.
- It is found that soot cake porosity, DPF soot load, soot accumulation rate and rate of change in cake porosity are key parameters to affect FE and TP PN.
- Based on these observations, empirical model is developed, and it is found that predictions are well correlated with the test data.
- Model does have certain limitations, specifically it could not predict low TP PN observed during DPF regeneration.
- TP PN is estimated across different engines over NTE zones and found that PN is with in the target.
We Are Ready for Stage V

PROVEN READY
Cat® Industrial Engine product line designed to meet EU Stage V emission standards.

STAGE V IS HERE. YOUR SOLUTIONS ARE READY.
We're prepared with a full line of Stage V solutions, all designed to meet the emission standards. Our experience and our global and regional development capability deliver core engine platforms with modular emissions options. We have everything you need to help keep performance high and cost of ownership low.

Thank you.