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

Srikanth Dabbikar, Darren Ellis & Ian Evans

Caterpillar, United Kingdom

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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

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DPF is a best available technology to limit PM/PN

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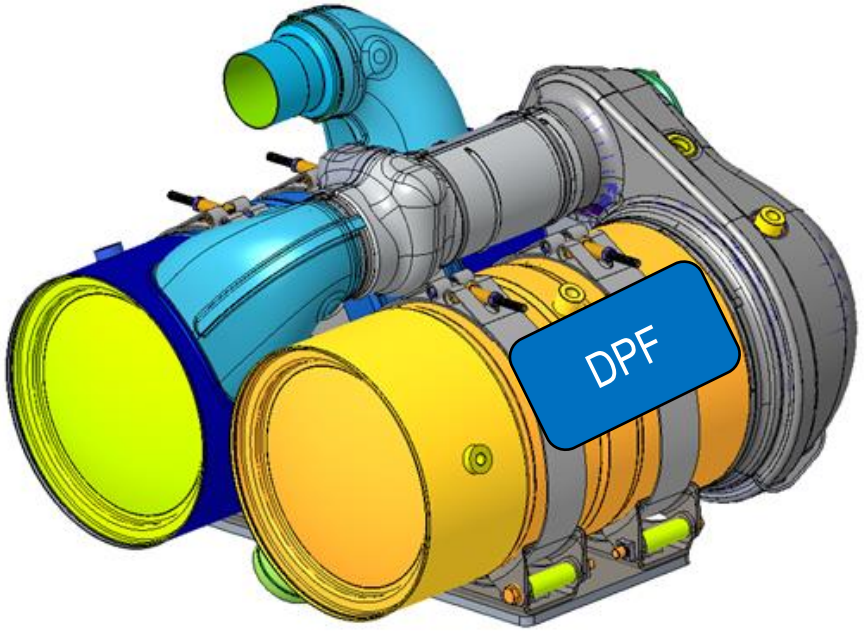

- Stage V legislative limits for non road applications[1]

Power range	Year	CO	HC	NOx	PM	PN
kW		g/kWh				1/kWh
56 ≤ P < 130	2020	5	0.19	0.4	0.015	1E+12
130 ≤ P ≤ 560	2019	3.5	0.19	0.4	0.015	1E+12
P > 560	2019	3.5	0.19	3.5	0.045	-

1.https://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.

2.SAE 2000-01-1016 Fundamental Studies of Diesel Particulate Filters: Transient Loading, Regeneration and Aging
3.SAE 2012-01-0363 Measurement and Prediction of Filtration Efficiency Evolution of Soot Loaded Diesel Particulate Filters
4.SAE 2014-01-1516 An Investigative Study of Sudden Pressure Increase Phenomenon Across the DPF
5.Impact of particle number limitations on engine and exhaust aftertreatment layout ,10th International Exhaust Gas and Particulate Emissions Forum

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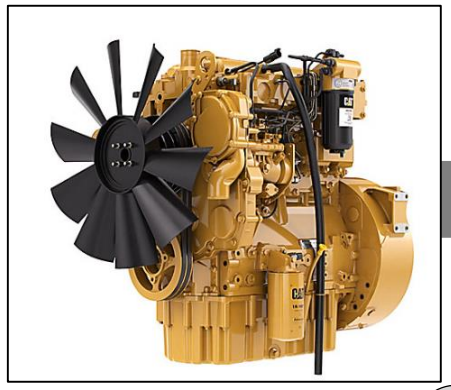
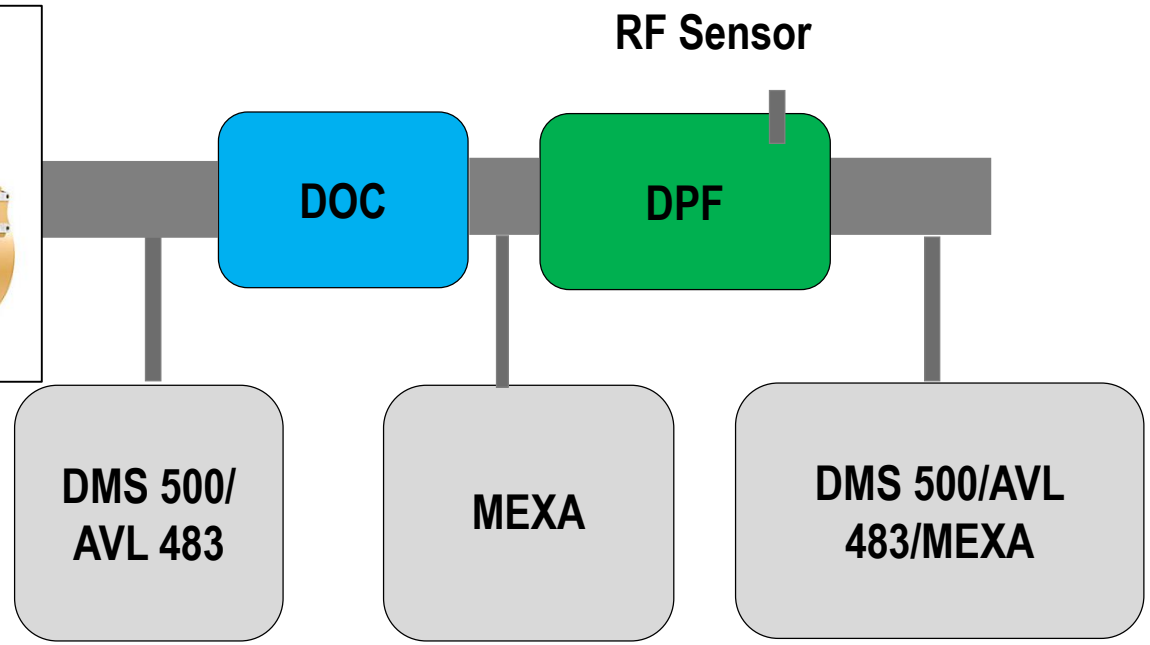
Test Set up and Measurements



CAT Production Intent Stage V Engine



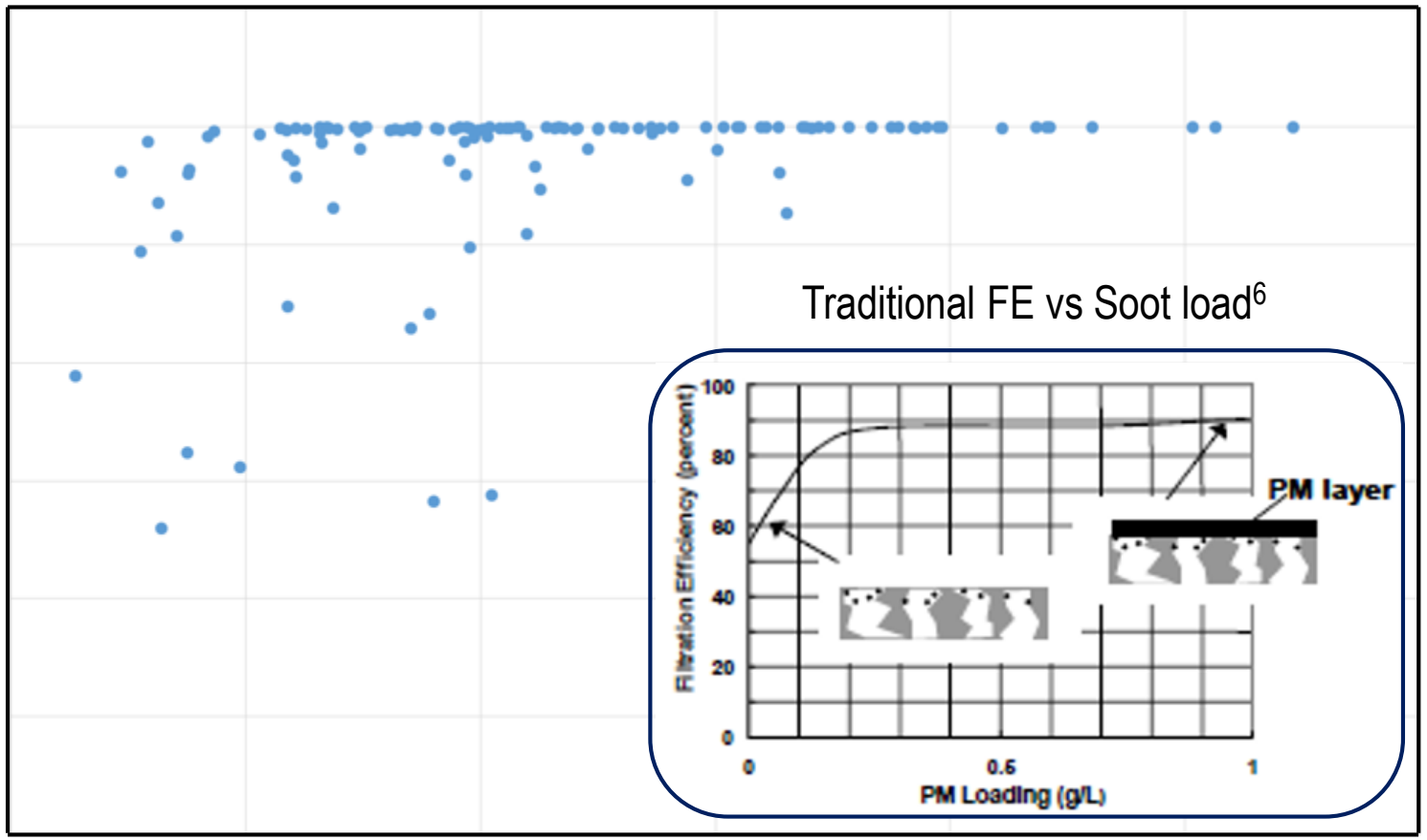
DPF is pre conditioned with different soot loads and tests run with selected engine operating points for each soot loading

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

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

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

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

6. SAE 2007-01-0921,Filtration Behavior of Diesel Particulate Filters

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

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PN Modelling Layout-I

Boundary Conditions
- Exh. Mass Flow
- EO Temperature
- EO Soot
- EO NOx

Geometric Properties

EO-Engine Out

1D DOC / DPF Model

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

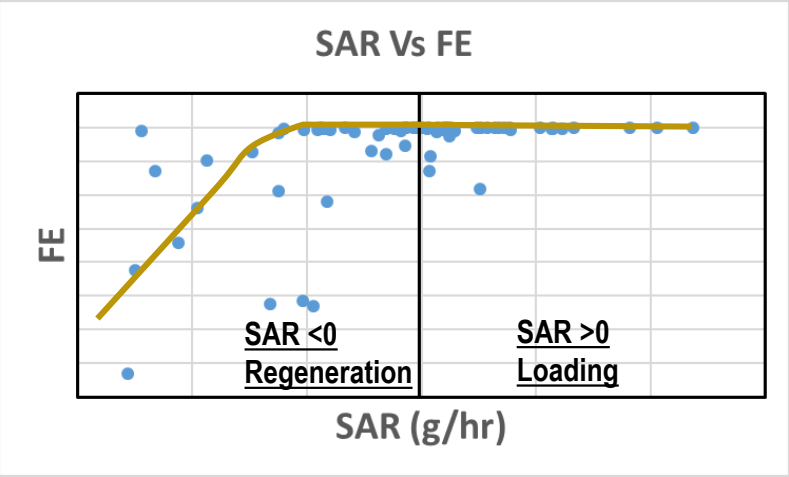
Model is calibrated to predict DPF soot load and DOC/DPF performance for NO oxidation/NO2 reduction

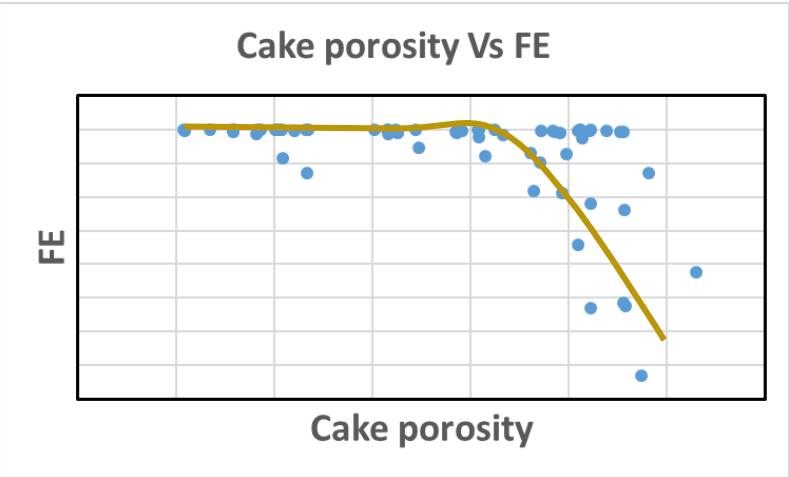
1D DOC/DPF Model is employed to predict soot cake and wall porosity characteristics

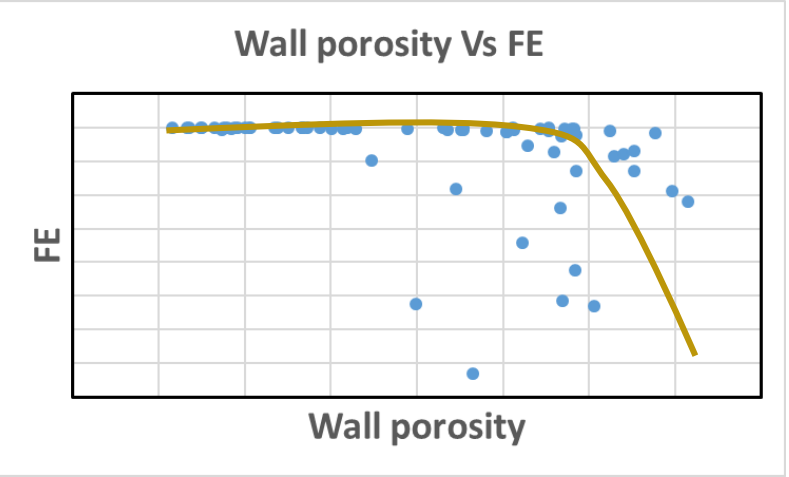
Model predictions are compared with FE from the test data

Model
Input
Output

Model Predictions: Regeneration and Loading







Soot Balance over DPF[7]

$$\frac{d(SL)}{dt} + (SL)(K) - (FE)\left(DPF_{in,Soot}\right)$$

$\frac{d(SL)}{dt} = Soot\ Accumlation\ Rate\ \ (SAR)$
$SL = Soot\ Load$
$K = Passive\ oxidation\ constant$
$FE = Filteration\ Efficency$
$DPF_{in,Soot} = DPF\ In\ Soot$

DPF Operation Modes

$\frac{d(SL)}{dt} > 0\ \ Loading$

$\frac{d(SL)}{dt} < 0\ \ Regeneration$

$\frac{d(SL)}{dt} = 0\ \ Balancing$

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)

PCR-Cake Porosity Change Rate

7.https://www.dieselnet.com/tech/dpf_regen.php

PN Modelling Layout-II

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

PN empirical model

FE=f(Soot Accumulation Rate (SAR), Soot load, Cake porosity change rate (PCR), Cake porosity, Exhaust mass flow, wall porosity)

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

$$TP\ PN = EO\ PN(1 - FE)$$

Here,
TP PN= Tail pipe Particle Number
EO PN= Engine out Particular Number
FE=Filtration efficiency

- DPF Filtration Efficiency
- Tailpipe Particle Number Emissions

Model
Input
Output

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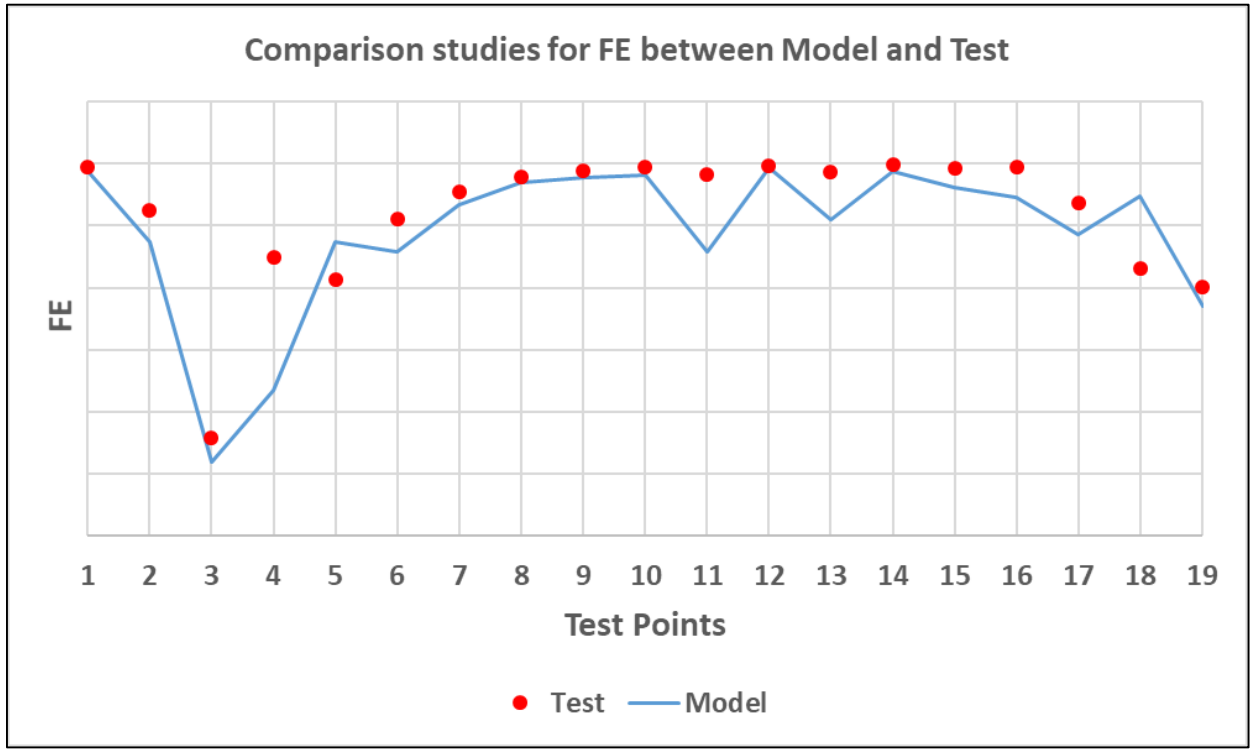
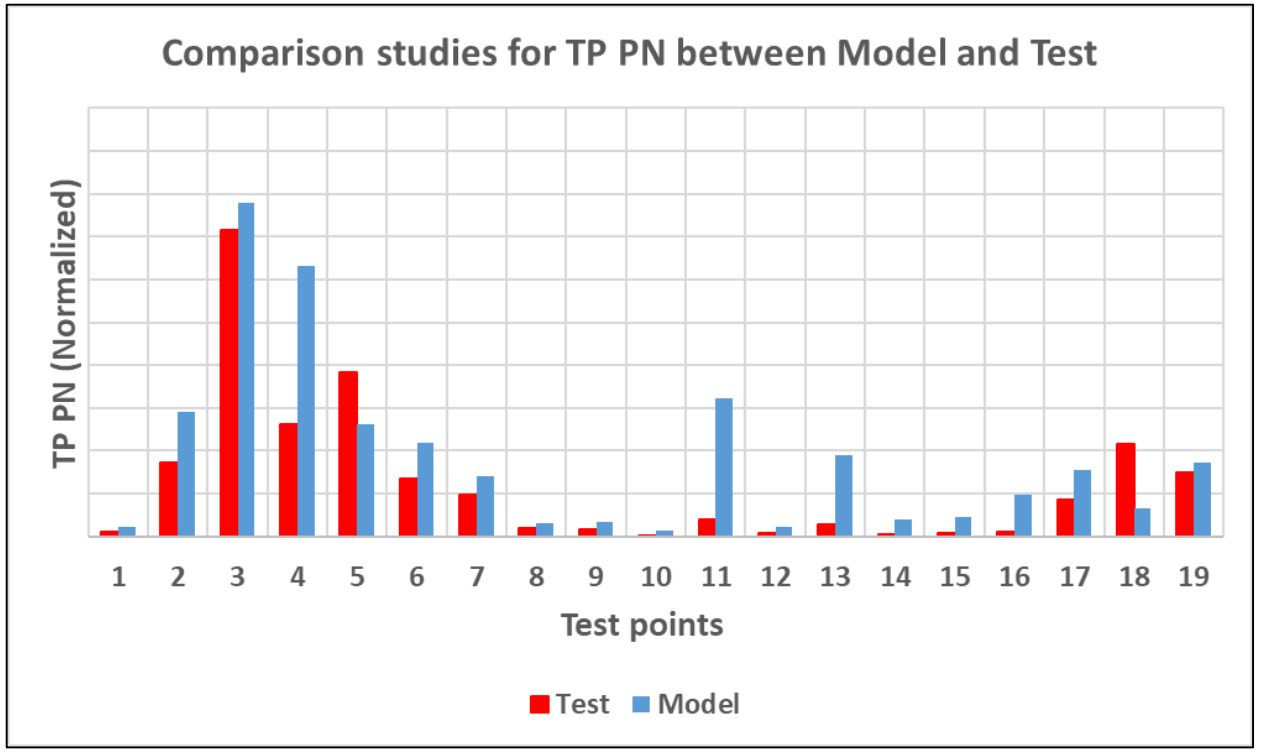
PN Model Predictions (Validation Studies)



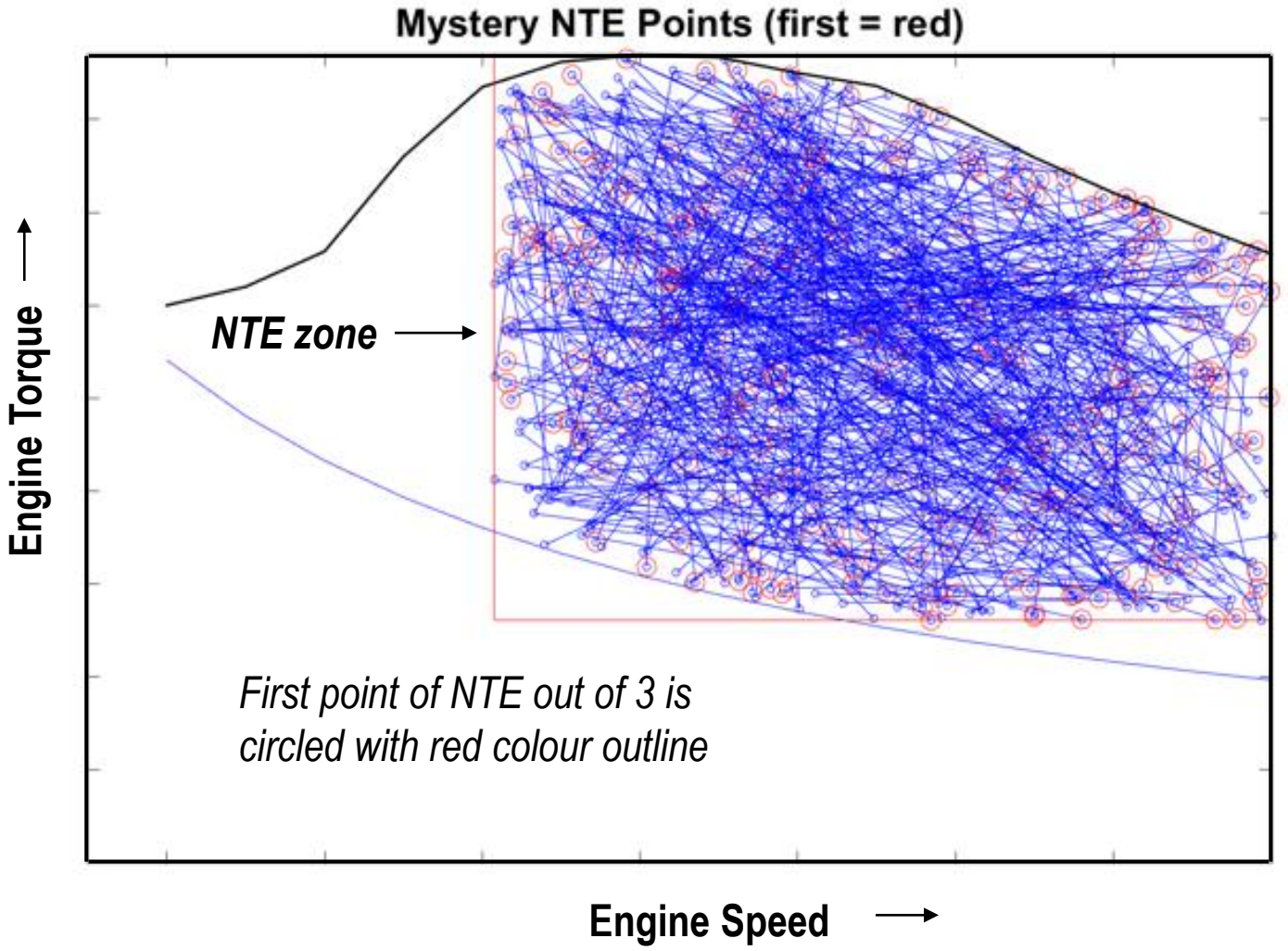


Model predictions are corelated with test data. However, it could not predict low TP PN observed during DPF regeneration.

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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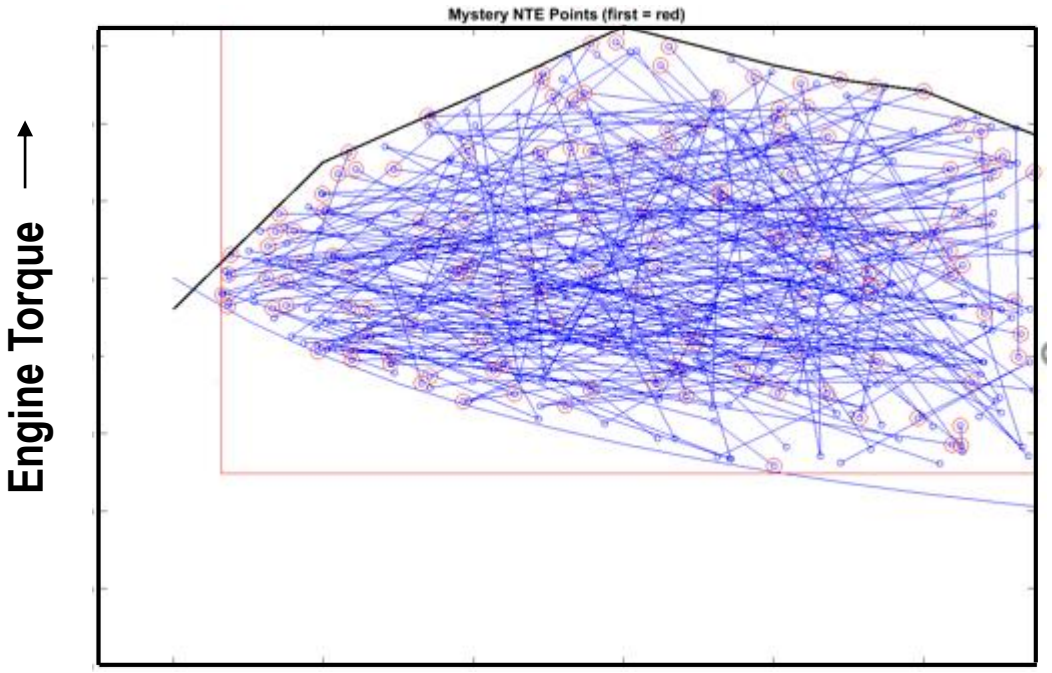
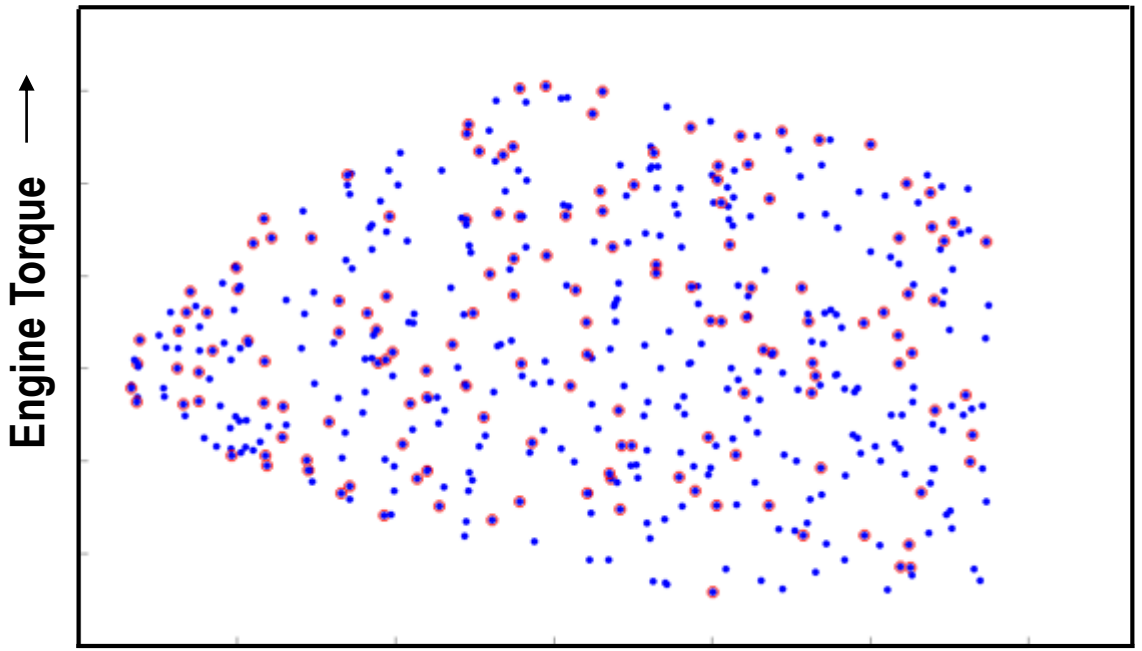
TP PN Predictions – CAT Production Intent Stage V Engine

NTE Random Points



TP PN Pass/Fail Chart



Model predictions confirms that all NTE points are with in the target. Test studies also confirmed the same behaviour.

Probability To pass	PN Target
1st Point	1
2nd Point	1
3rd Point	1

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.

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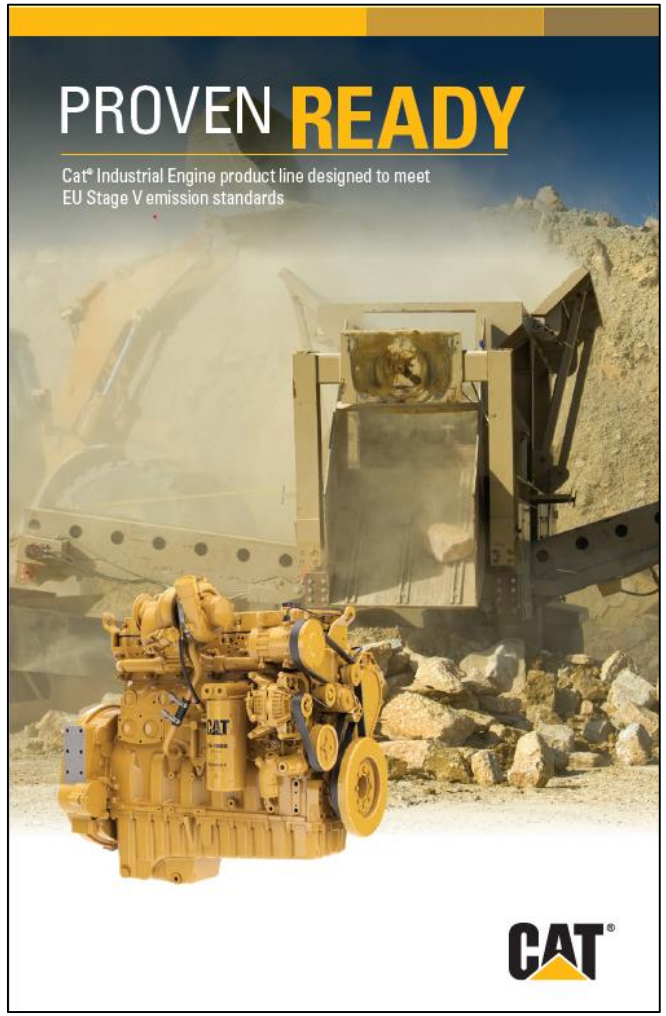
We Are Ready for Stage V



THANK YOU

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