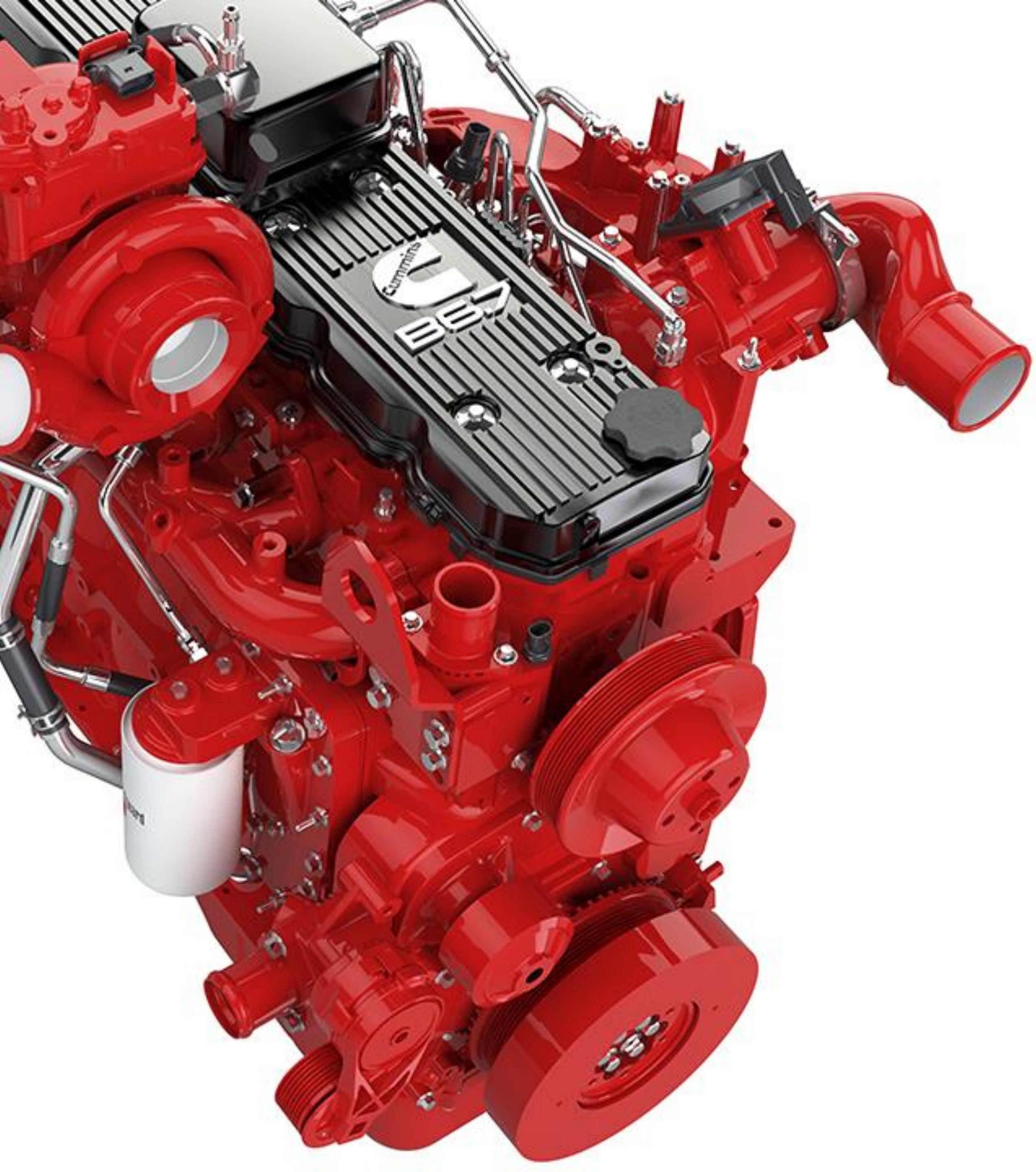


Predicting DPF Soot Loading Using GT-SUITE Soot Model

Apurva Pawar
Saideep Shinde

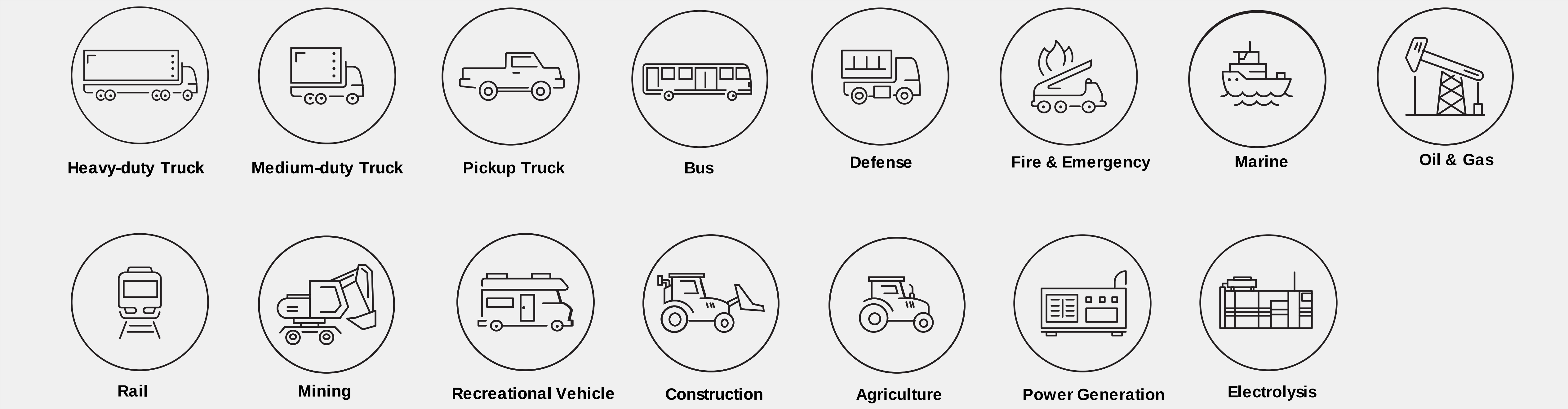
23 January 2023

Public

Introduction

About Cummins:

- A corporation of complementary business segments that design, manufacture, distribute and service a broad portfolio of power solutions.
- Cummins in India is a group of seven legal entities across 200 locations in the country with a combined turnover of ₹17,900 crores in 2021 and employing over 10,000 individuals.



Problem Statement

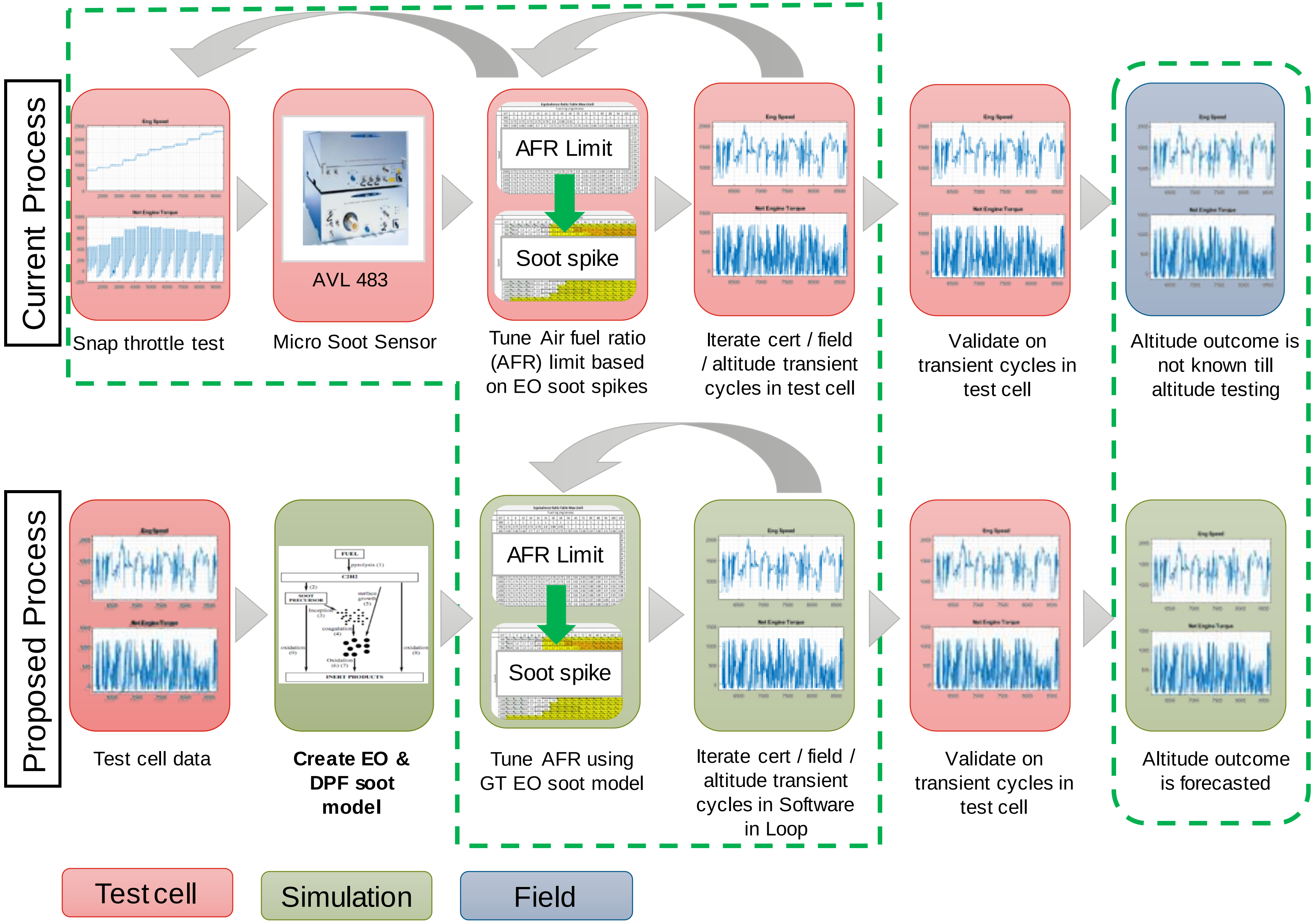
Motivation

- Diesel Particulate Filter (DPF) architecture is added in after-treatment systems to meet BSVI norms
- DPFs require regeneration for continuous operation on vehicles
- Regeneration intervals should maintain good fuel economy, aftertreatment reliability and emissions capability
- DPF soot loading needs to be controlled in all engine operating conditions, to maintain healthy regeneration intervals
- To achieve this, it is critical to simulate net DPF soot loading reliably to design robust systems
- Accurate engine-out soot prediction is building block for simulation of net DPF soot loading

Commercial Impact

- Accurate engine-out soot prediction, enables quick & dependable optimization of engine & after-treatment systems performance with minimal testing
- Predicting off nominal DPF soot loading performance enables Right First-Time calibration at altitude

Solution



- Current process of tuning *EO-soot is testing intensive and iterative
- Altitude testing is required to assess the DPF soot loading at off-nominal conditions

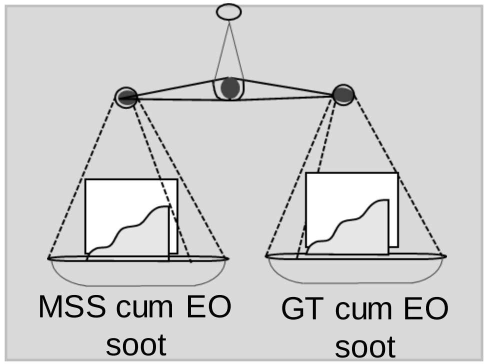
- Can save expensive test cell time
- Can forecast DPF soot loading at altitude before actual field operation
- Can optimize DPF soot loading better, to balance minimum EO soot with best transient response

**EO = Engine Out*

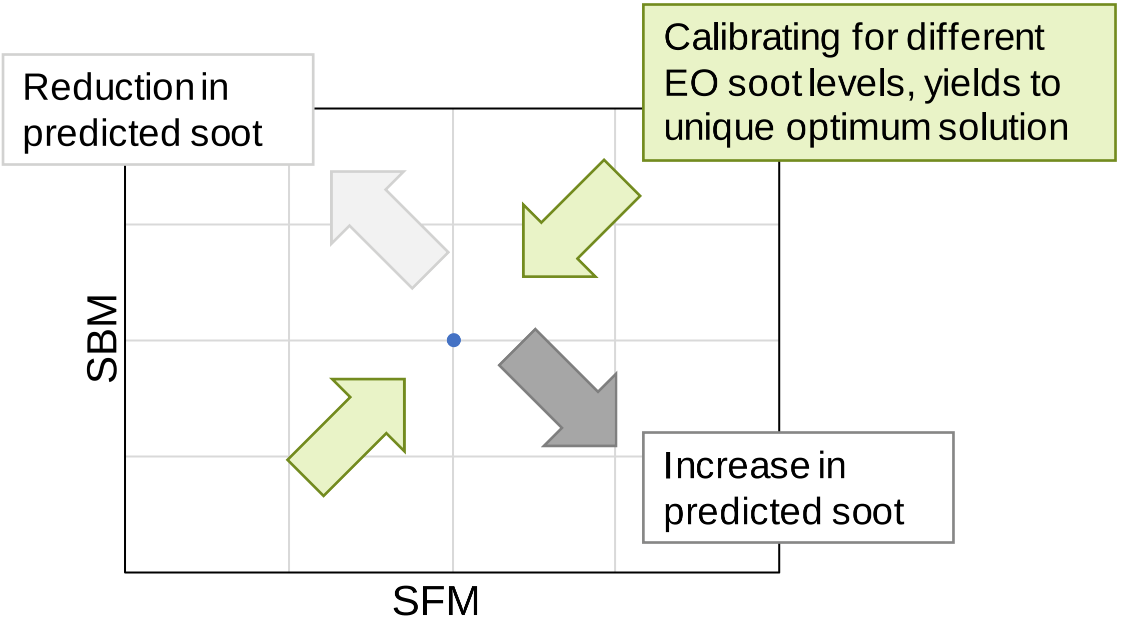
Process for DPF Soot Model

Step 1: Calibrate Engine-Out (EO) Soot Model

1. GT EO soot is calibrated to EO soot measured with Micro Soot Sensor (MSS) from test data



2. GT Hiroyasu soot model is calibrated using 2 multipliers:
   1. Soot Formation Multiplier (***SFM***)
   2. Soot Burn Up Multiplier (***SBM***)

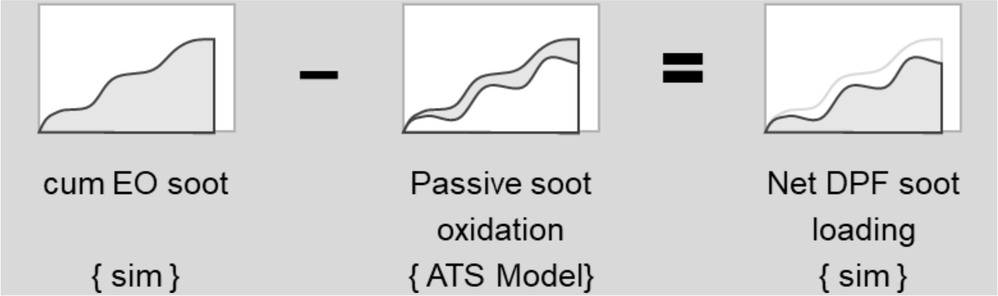


Ref: Hiroyasu, Hiroyuki, Toshikazu Kadota, and A. R. A. I. Masataka. "Development and use of a spray combustion modeling to predict diesel engine efficiency and pollutant emissions: Part 1 combustion modeling." Bulletin of JSME 26.214 (1983): 569-575

Process for DPF Soot Model

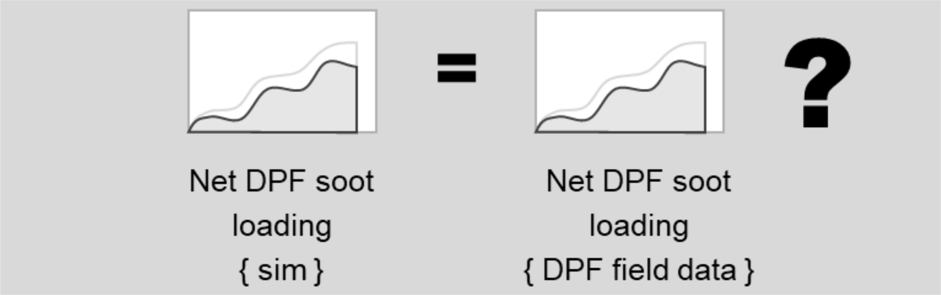
Step 2: Predict Net DPF Soot Loading

- {Cum EO soot} – {Passive soot oxidation} = {Net DPF soot loading}



Step 3: Validate Net DPF Soot Loading Model

- Validate sim net DPF soot loading with field data



**cum = cumulative, EO= Engine Out*

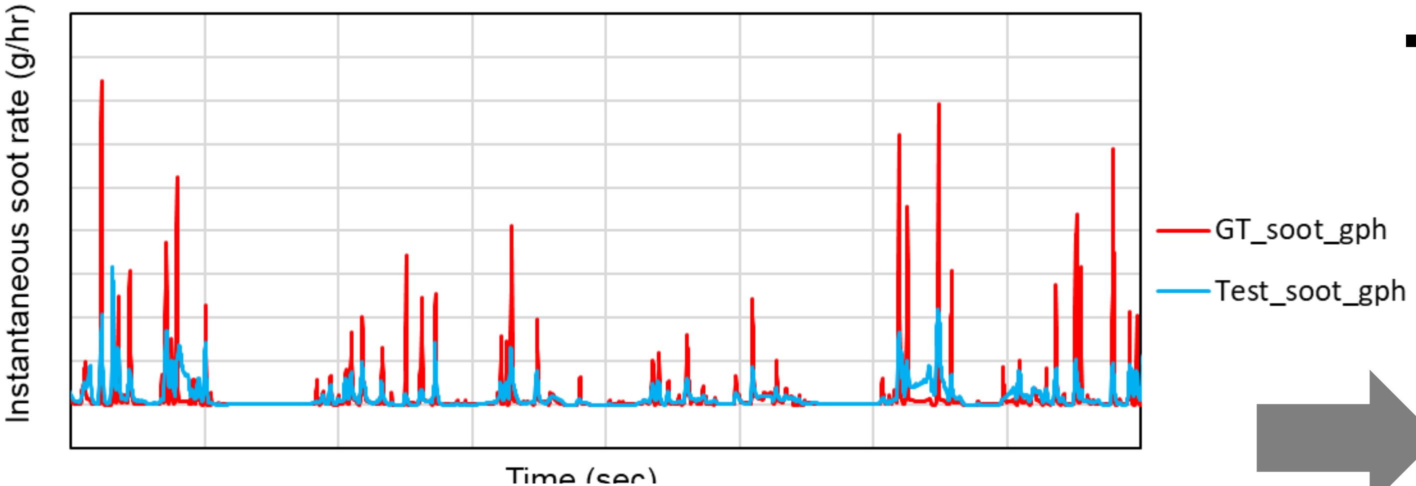
sim= simulation, ATS= After-Treatment System

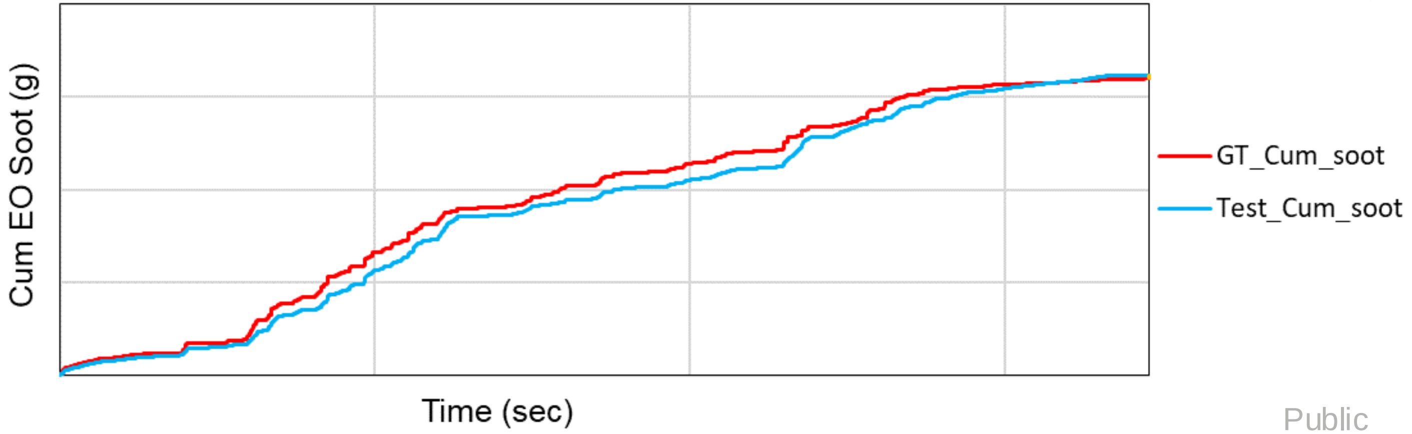
Results for EO Soot Model

Step 1 | Step 2 | Step 3

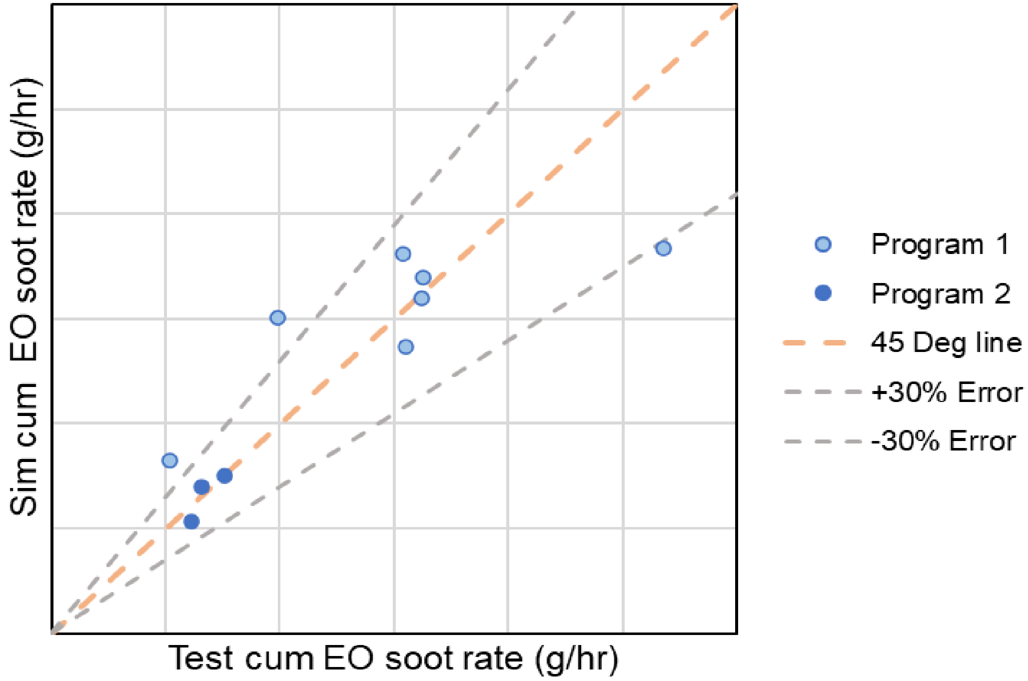
Step 1: Prediction of *EO Soot Model

- GT Hiroyasu soot model prediction for test data





- EO soot for multiple duty cycles on 2 Engine programs



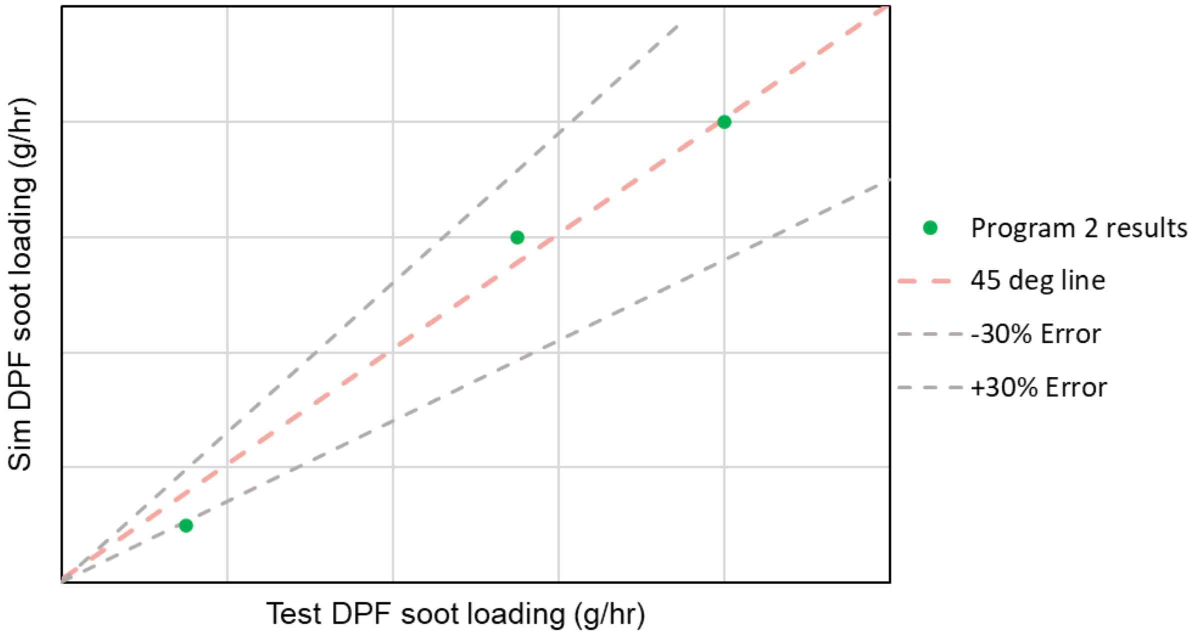
**EO= Engine Out*

Results for DPF Soot Model

Step 1 | Step 2 | Step 3

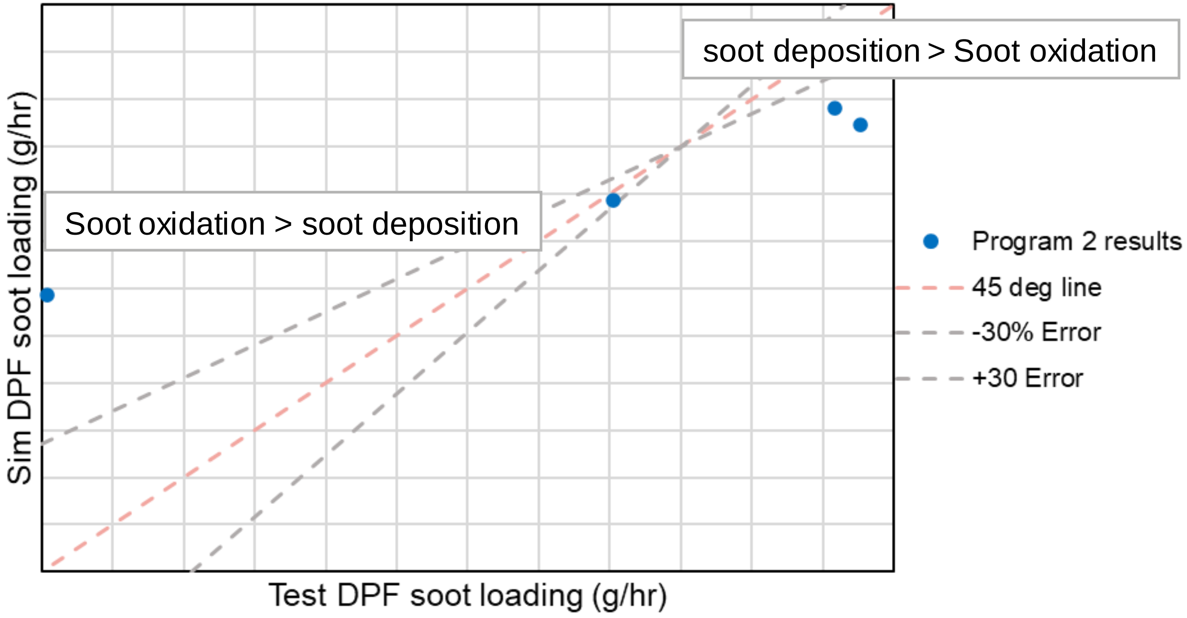
Step 2: Calibration of DPF Soot Model

- Test cell data with (EO soot + DPF soot loading) is used for calibrating DPF soot model



Step 3: Validation of DPF Soot Model

- Field data (with only DPF soot loading) is used for DPF soot model validation
- Model shows ability to capture directional trends



Conclusions & Learnings

- Soot data repeatability should be checked at multiple operating conditions
- GT engine out soot model needs to be calibrated at different levels of engine out soot
- DPF soot loading model needs to be calibrated at different levels of soot loading & oxidation
- GT Hiroyasu soot model can capture engine out soot prediction within 30% error
- DPF soot model shows ability to capture directional trends in DPF soot loading

Future Improvements

- Improve DPF soot model to get accuracy within 30% error
- Validate DPF soot loading model at off nominal field conditions

ROI of Simulation Work

By doing calibration iterations and boundary condition robustness in simulation domain, prospective benefits achievable are:

- Testing time saving of 5-10%
- Testing cost saving of 5-10%
- Improved soot control calibration quality can lead to:
  - Right First-Time calibration
  - Huge reliability cost savings
  - Great customer uptime and satisfaction

Acknowledgements

I am very grateful to all the contributors & would like to take an opportunity to thank my,

- Manager & Mentors for giving an opportunity to work on this project & their continuous guidance for improvement
- Yusuf Poonawala –Technical Advisor, for project guidance & conceptual support
- Pavan Chandras – Technical Specialist, for continuous GT support
- Vivek Tiwari – After-Treatment System Expert & SiL team members for providing all required project help

Q+A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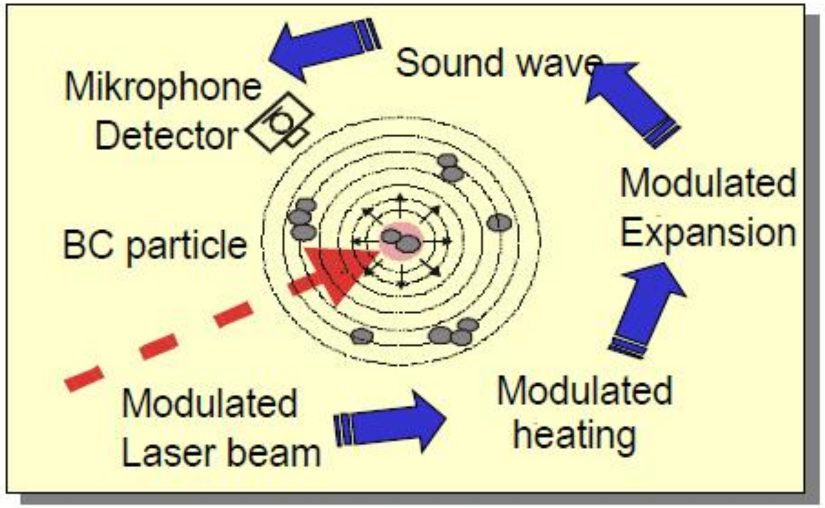
GT Hiroyasu Soot Model

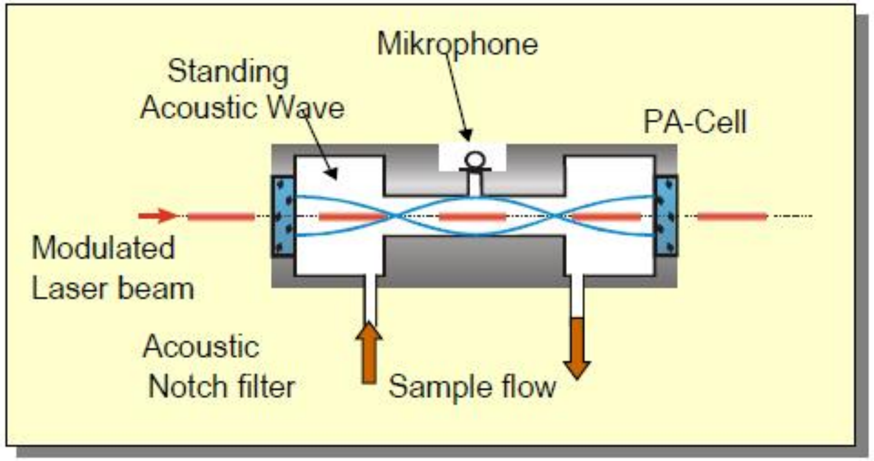
$$\frac{dm_{soot}}{dt} = \frac{dm_{soot}}{dt}\Big|_{\text{form}} - \frac{dm_{soot}}{dt}\Big|_{\text{oxid}}$$

$$\frac{dm_s}{dt}\Big|_{form} = \boldsymbol{A_f}\, mfuel\, p^{0.5} \exp\left(\frac{-Ef}{R\,T}\right)$$

$$\frac{dm_s}{dt}\Big|_{oxid} = \boldsymbol{A}_o\, msoot\, XO_2\, p^{1.8} \exp\left(\frac{-EO}{R\,T}\right)$$

AVL 483 MSS Working Principal

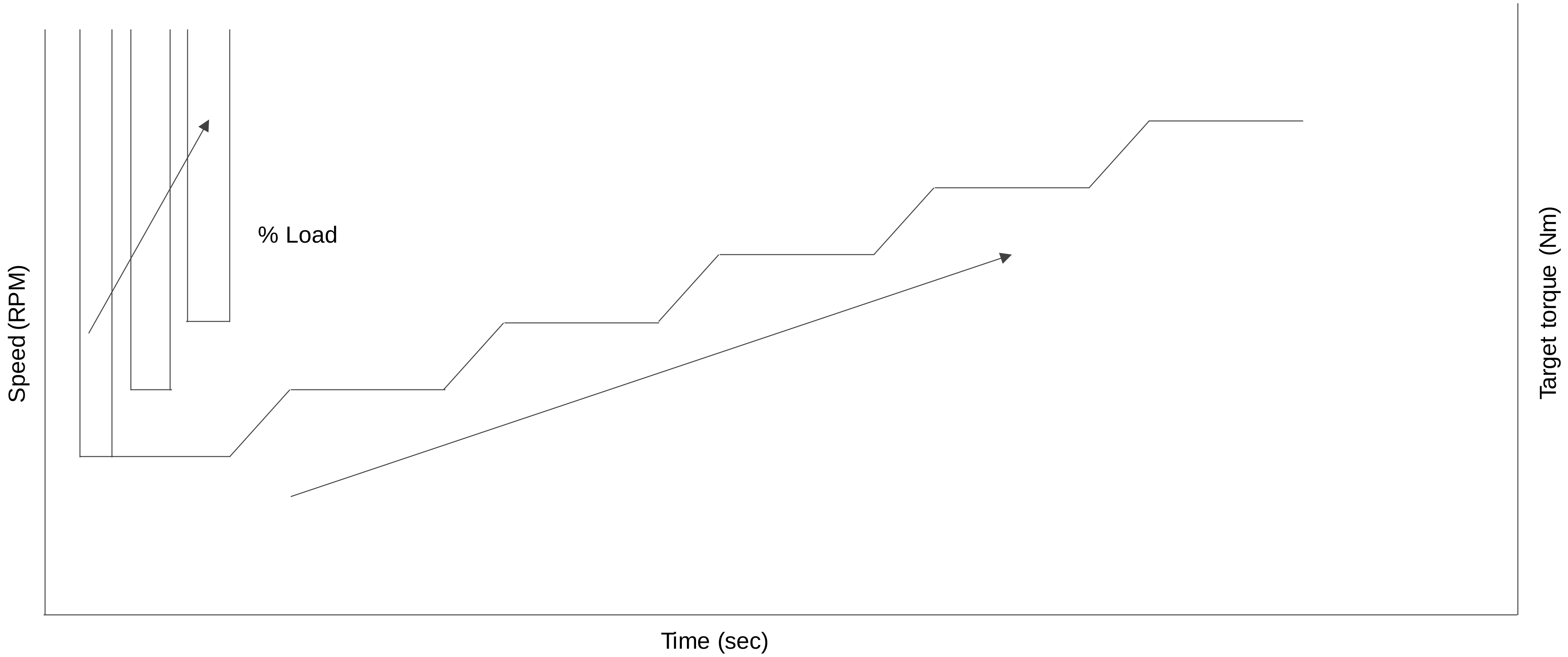




Continued…

- A chopped laser beam (4000 Hz, 50/50 duty cycle) irradiates the particle in the measuring volume
- When the soot particles absorb the radiation, the un-bound, freely movable pie electrons are excited-which is equivalent to an increase of the internal energy of the particle
- When the laser beam is off, the elevated energy equilibrates with the surrounding gas, raising its temperature
- Periodic heating and cooling of a gas causes a periodic pressure wave- a sound wave. This is why this measuring principle is called "photo-acoustic measurement"
- The amplitude of the sound wave is enhanced by using a resonant acoustic cell
- The acoustic wave is detected with sensitive microphones
- The signal is processed with digital electronic "lock-in" technology to discriminate the soot generated sound from ambient acoustic noise.

Snap throttle test

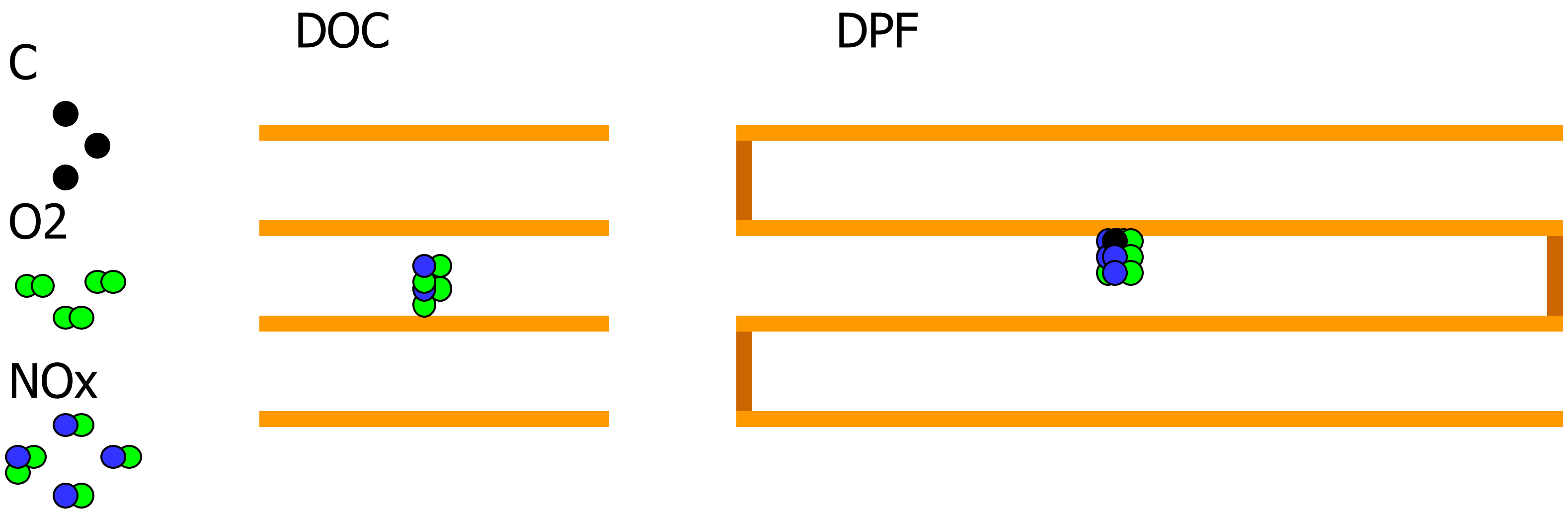


Software in Loop

- Software-in-the-loop (SiL) is a method of simulating all primary subsystems i.e. dyno, engine, aftertreatment, controller, sensors and actuators in a simulation environment in order to quickly and cost-effectively catch bugs and improve the quality of the model.
- SIL testing is conducted in the early stages of the model development process, while the more complex, costlier hardware-in-the-loop (HIL) testing is done in later stages.
- Each new program whether it is related to advanced safety, autonomous driving, user experience or other areas has thousands of specific requirements, and it is not practical to perform manual testing to make sure the model does what it is supposed to do.
- It is prohibitively expensive and time-consuming to physically load model under development into an actual vehicle and test-drive it for the potentially hundreds of thousands of miles needed to make sure the model works in all types of driving conditions, so SiL is preferred in such condition.

Diesel Particulate Filters (DPF)

Passive Regeneration



$$2NO + O_2 \Rightarrow 2NO_2$$

$$C + 2NO_2 \Rightarrow CO_2 + 2NO$$

Temperature Range	220 – 400°C	300 – 500°C	500°C and above
Primary Oxidation Mechanism	NO_2	Catalytic, oxygen radicals	O_2
Regime	"Passive"		"Active"

Slide courtesy of T. Grana

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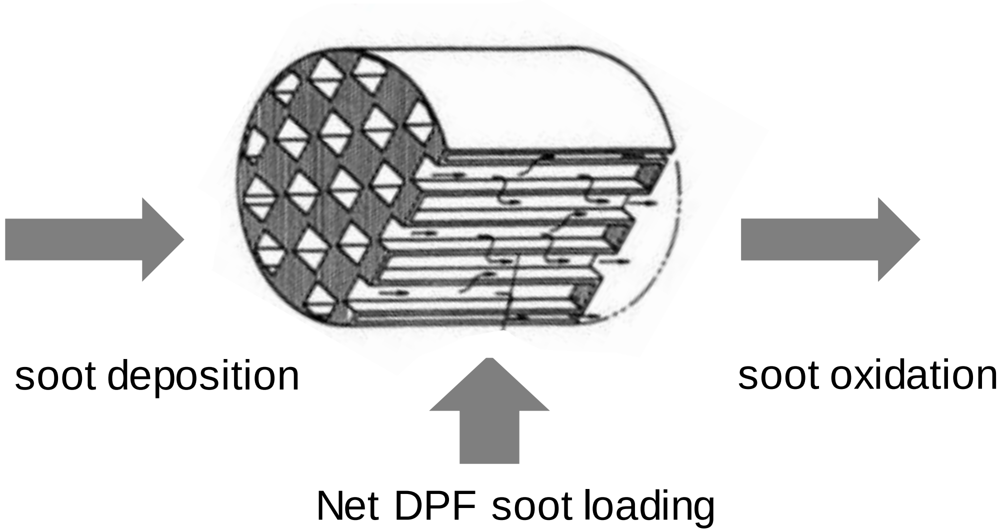
EO soot deposition
soot oxidation
Net DPF soot loading