DPF Durability

Reggie Zhan
Southwest Research Institute

Cheng Li, Frank Mao
Dow Automotive

DPF R&D and Application Roadmap

DPF Modeling

Performance

- Filtration Efficiency
- Pressure drop performance
- Thermal survivability
  - Normal thermal cycle
  - Thermal shock
- Loading and regeneration
- Catalyst efficiency

Component

Durability

- Thermal aging
- Ash accumulation
- On-vehicle durability

Assembly

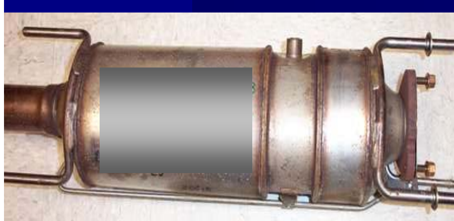
Validation

- Thermal & mechanical
  - "Vibration"
  - "Liquid spray"

System

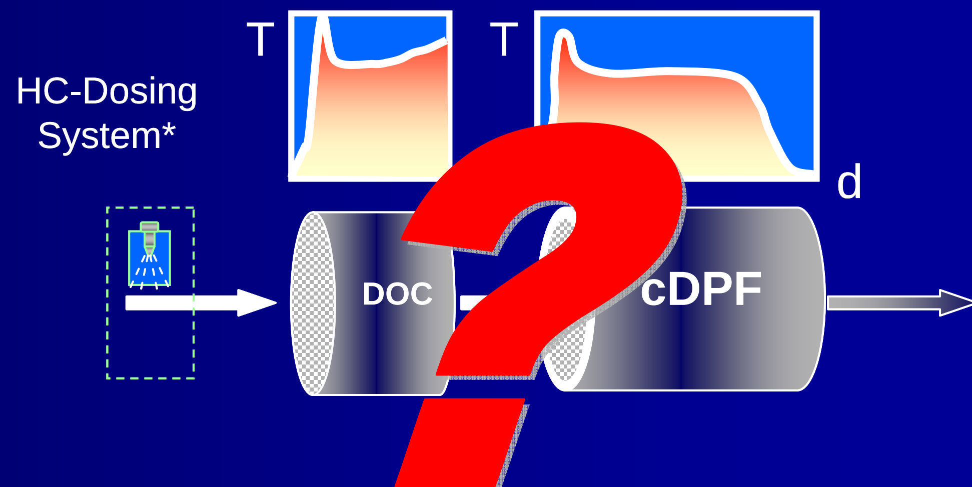
Application

- Control strategy
- Calibration
- OBD



DPF Integration Challenges – can modeling help?

- **How to determine DPF inlet soot rate?**



- **How to predict DPF aging effect?**
  - Thermal aging
  - cDPF poisoning
  - Ash accumulation and effect

DPF Integration Challenge 1(1) – can modeling help?

- **How to predict DPF soot loading level (g/L) to direct active DPF regeneration?**
  - **Build an ideal soot model:**
    - Steady-state 3-D (RPM, Torque, EGR) maps
      - **PM and SOF**
      - NO_x
      - Temperatures (DOC-in and DPF-in)
      - Exhaust Flowrate

      } "Existing (from calibration)"

$$PM_{ss} = f\,(F, T, NOx, RPM, \tau, EGR)$$
$$SOF_{ss} = f\,(F, T, NOx, RPM, \tau, EGR)$$

Engine-out

    - Estimate "transient PM rate" ("Driver variability")

      Most dominating factor! ("Cycle beat" may fail NTE limit)

$$PM_{T} = f\,(F, T, NOx, RPM, \tau, EGR, a/\Delta\tau)$$
$$SOF_{T} = f\,(F, T, NOx, RPM, \tau, EGR, a/\Delta\tau)$$

Engine-out

DPF Integration Challenge 1(2) – can modeling help?

- Establish DOC efficiencies (SOF, NO-to-NO_2)

$$NOx_{DOC} = f\,(F,\ T,\ NOx,\ RPM,\ \tau,\ EGR,\ DOC)$$
$$SOF_{DOC} = f\,(F,\ T,\ NOx,\ RPM,\ \tau,\ EGR,\ \mathbf{DOC})$$
$$PM_{DOC\text{-}out} = PM_{engine\text{-}out} - SOF_{DOC}$$

DOC-out

- Establish DPF soot rate

$$PM_{passive} = f\,(F,\ T,\ RPM,\ \tau,\ EGR,\ DPF,\ NO_2\text{-}NOx/PM)$$
$$PM_{DPF} = PM_{DOC\text{-}out} - PM_{passive}$$

- Integrate for DPF soot accumulation (SS and transient)

$$\Sigma\, PM = \Sigma PM_{ss\text{-}DPF} + \Sigma PM_{\text{T-DPF}}$$

Target: < 1.0g/L error for LD!

DPF Integration Challenge 1(3) – can modeling help?

– Re-calibrate system for NO_2 compliance
  - New regulation on NO_2 in California

– Controls to avoid runaway regenerations, handles incomplete regenerations (*SAE 2006-01-1090*)

– Build control layers for DPF active regenerations
  - **Soot model** (if reliable)
  - Fuel Consumption
  - Mileage
  - DPF pressure-drop (doesn't have good correlation to PM loading in real world)
  - more

Target: < 1.0g/L error for LD!

Challenge 2 – DPF Modeling

- How to incorporate DPF aging into model?
  - **cDPF Thermal Aging** – uncontrolled regeneration may not follow typical TWC thermal aging threshold (Arrhenius Rate Law)
  - **cDPF Poisoning** – lubricant poisoning and ash accumulated may affect DOC light-off and efficiency (e.g., passive regeneration), as well as cDPF efficiency (e.g., BPT)
  - Need a **realistic DF estimate** at different vehicle mileage, with realistic estimate of uncontrolled regenerations and oil consumption.

Presentation Outline

- Why DPF Durability?
- Objectives
- Test Equipments and Procedures
  - On-Engine Test
  - On-Vehicle Test
- Test Results
  - On-Engine Test Results
  - On-Vehicle Test Results
- Summary

Why DPF Durability is Important?

- **DPF Needs to Survive Vehicle Lifetime**
  - For light-duty vehicles (e.g., passenger cars), DPF maintenance may not be considered during the entire vehicle lifetime.
  - For heavy-duty vehicles, the maintenance interval may not be less than 150,000 miles during the 435,000 mileage of vehicle durability (Cost of cleaning)

- **DPF Durability and Survivability**
  - DPF regeneration
  - On-vehicle DPF performance

Questions on DPF Durability Testing

- How to test DPF thermal aging on an engine bench?
- How to perform accelerated ash accumulation on DPF?
- How to perform accelerated DPF durability test on a production vehicle?

Objectives

1. Develop an on-engine DPF aging procedure (LD application)

2. Optimize DPF design based on ash accumulation, and prove design concept on production vehicle

Logic – DPF Thermal Aging Cycle

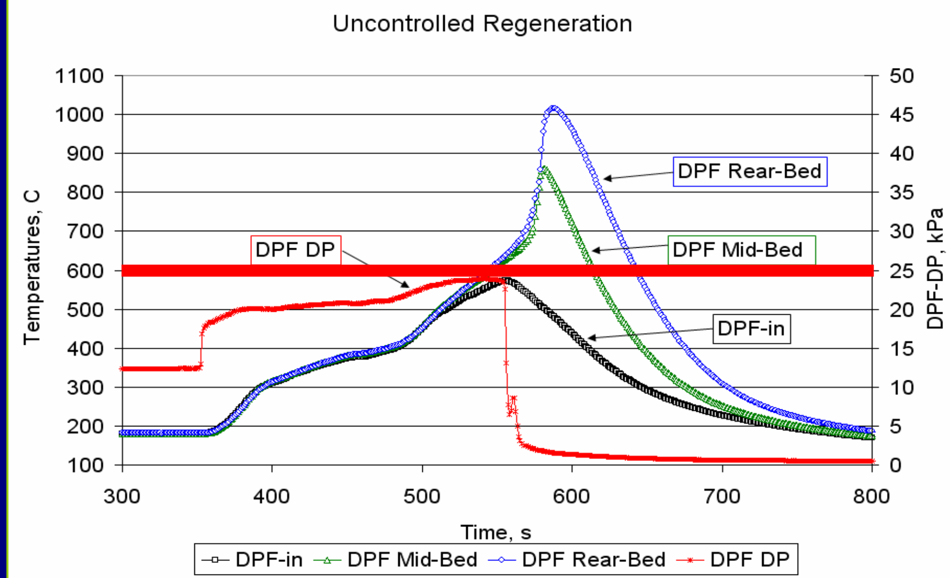
- Soot loading has minimum thermal aging effect
- Controlled DPF regeneration has limited thermal aging effect (<750^{o}C)
  - 150-200 cycles for vehicle lifetime (optimized FE)
- Uncontrolled (runaway) regeneration has the largest impact on DPF thermal aging (850-1300^{o}C)
  - Less than 5% in real-world statistics
  - Ways to avoid runaway regeneration being implemented
- Higher soot loading has added exothermal during regeneration (incomplete regeneration)

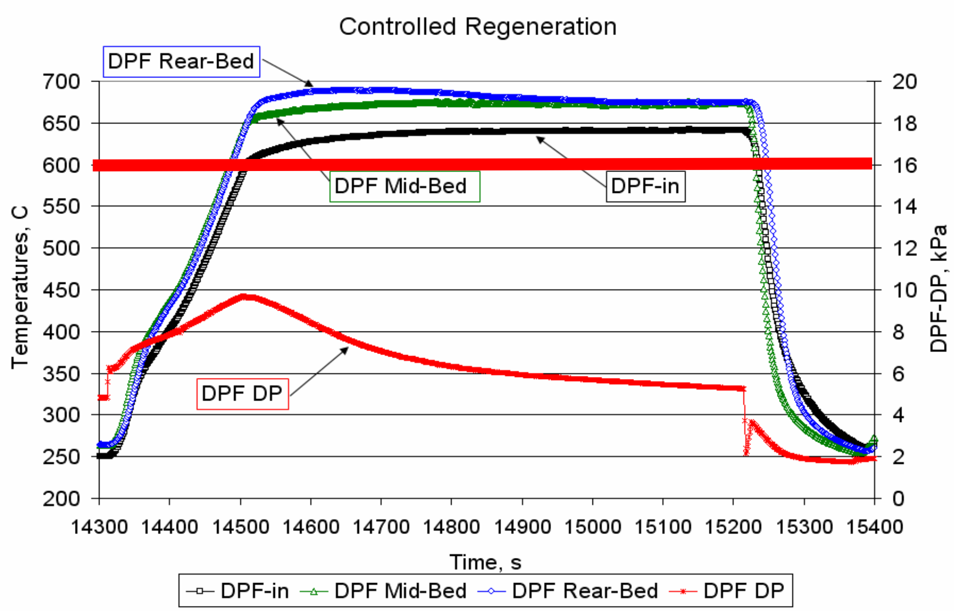
Test Equipments and Procedures (1)
– on-engine test (continued)

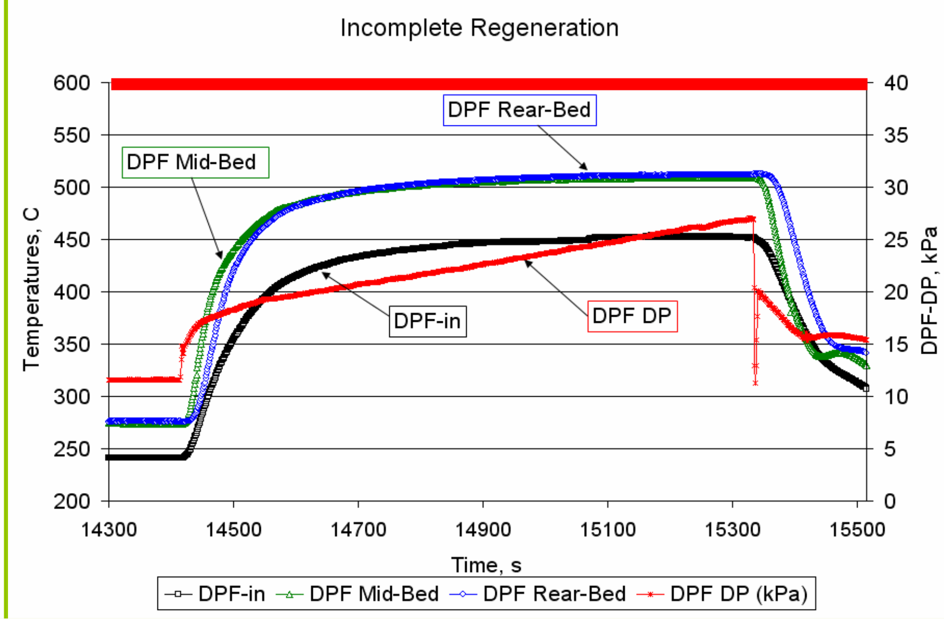
Combination of 100 cycles

- **Controlled regenerations: 80%**
- **Uncontrolled regenerations: 12%**
- **Incomplete regenerations: 8%**

SAE 2007-01-0918







Test Equipments and Procedures (1)
– on-engine test

Engine: MY2002 PSA DW-10
2.0L, common-rail,
waste-gated turbo,
intercooler, EGR

Test DPF: ACM®
Race-track
200 cspi
3.0L
160mm X 125mm X 180mm (long)

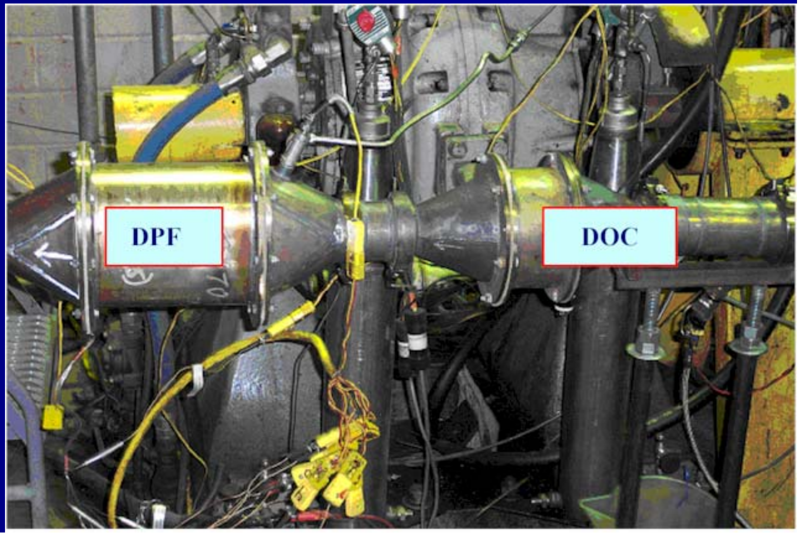
DPF loading: Steady-state

DPF regeneration:
In-exhaust fuel injection to DOC

Filtration eff. Measurement:
Duel partial-flow dilution system

Test fuel: LSD (390ppm S)

No. of cycles: targeted 100



DPF Oil Poisoning and Ash Accumulation

Accelerated Oil Consumption:

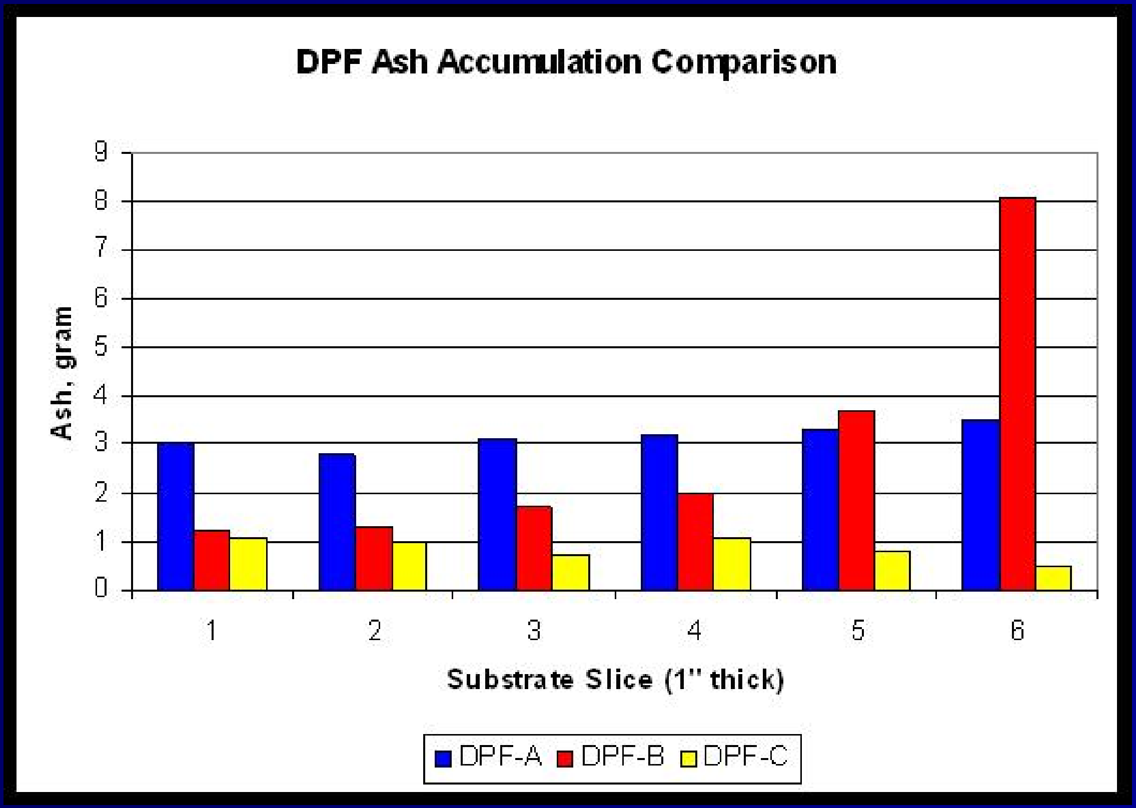
- Oil blend with diesel fuel
- Oil injection to exhaust
- Oil injection to intake
- Increased oil leak through piston ring
- **High ash oil**

Need a realistic ash loading cycle!

SAE 2007-01-0920

DPF Oil Poisoning and Ash Accumulation

Substrate Structure Matters!

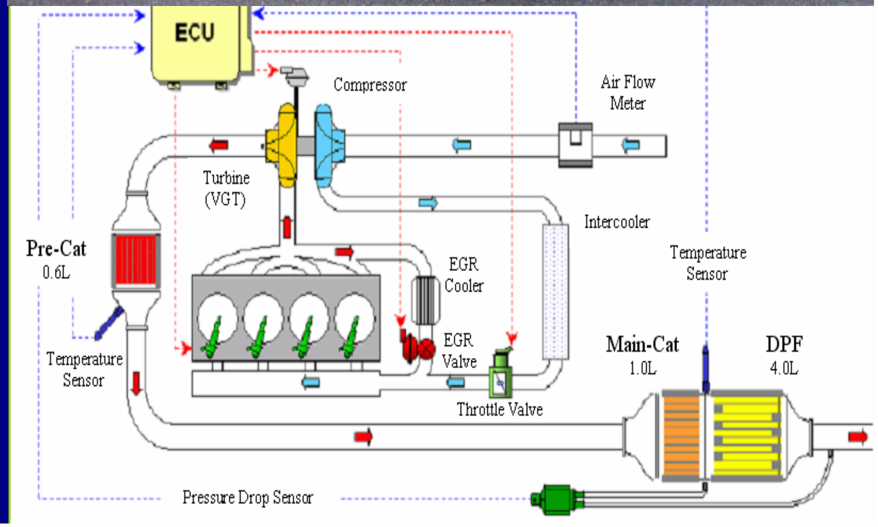


A realistic Ash Accumulation Cycle is critical!

Implication to DPF design and optimization

Test Equipments and Procedures (2)
– on-vehicle test

Test vehicle: **MY2005 European diesel passenger car, Euro 4 certified**



Engine:

- **1.9L CR, EGR, VGT**

Aftertreatment:

- **0.6L pre-Cat (metallic)**
- **1.0L main-Cat (cordierite)**
- **4.0L SiC cDPF**

DPF regeneration control:

- **Stock ECU**

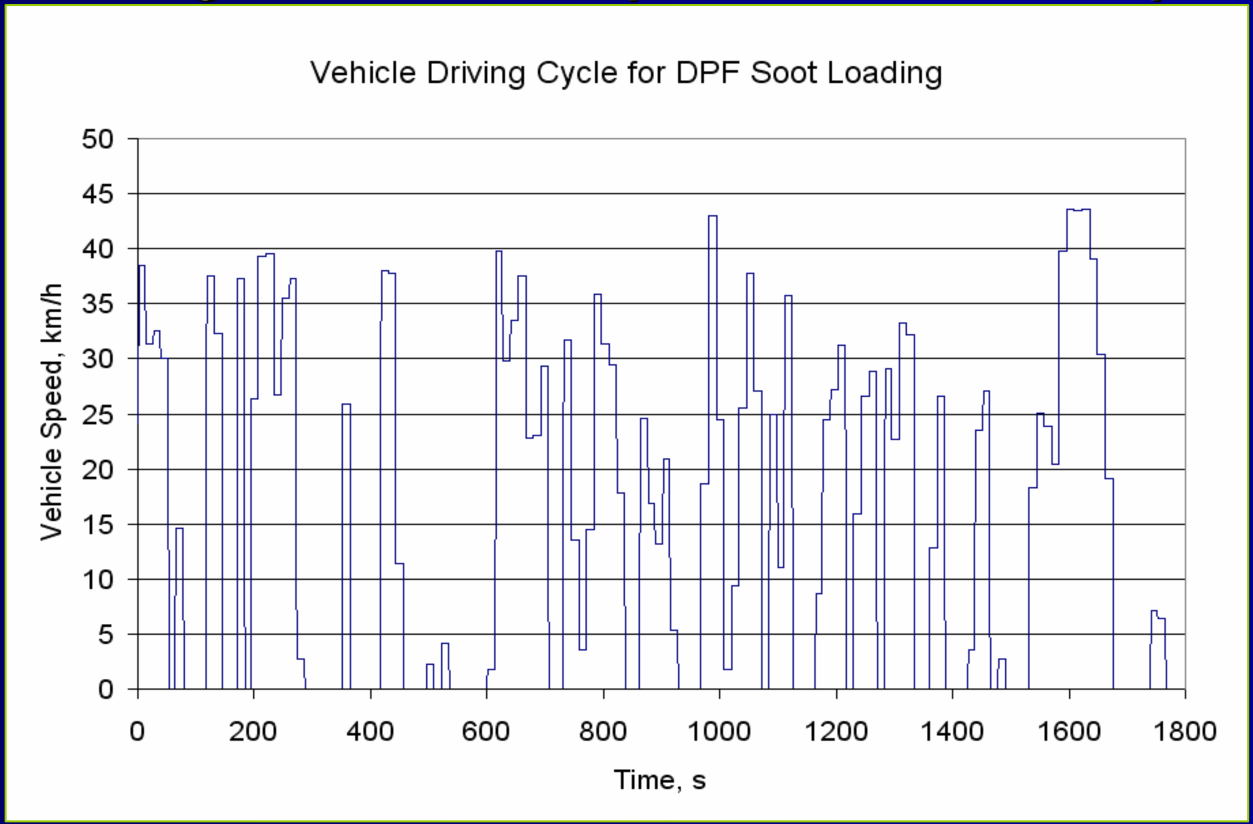
Fuel:

- **LSD (390ppm S)**

Test Equipments and Procedures (2)
– on-vehicle test (Continued)

DPF Loading Target

Over 20 grams total soot (4.0L OEM, 3.0L ACM)



25% DPF volume reduction based on:

(1) Ash accumulation and effect on pressure drop;

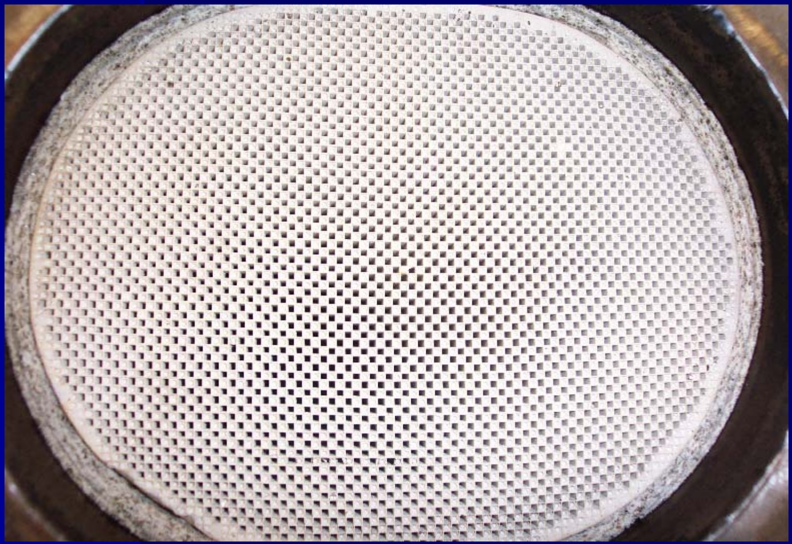
(2) DPF thermal behavior

Presentation Outline

- Introduction
- Objectives
- Test Equipments and Procedures
  - On-Engine Test
  - On-Vehicle Test
- **Test Results**
  - **On-Engine Test Results**
  - **On-Vehicle Test Results**
- Summary

On-Engine Test Results

Regeneration Type	No. of Cycles
Controlled	**82**
Incomplete R	**8**
Uncontrolled	**12**
Total	**102**



Filtration Efficiency

Cycle	Fil. Eff., wt. %
23A	**98.4**
24B	**98.9**
28A	**93.5**
29B	**99.9**
30B	**95.1**
35B	**97.1**
46A	**99.0**
46B	**96.5**
90B	**99.0**
101A	**97.9**
101B	**93.5**
102A	**97.8**

Peak DPF Temperature

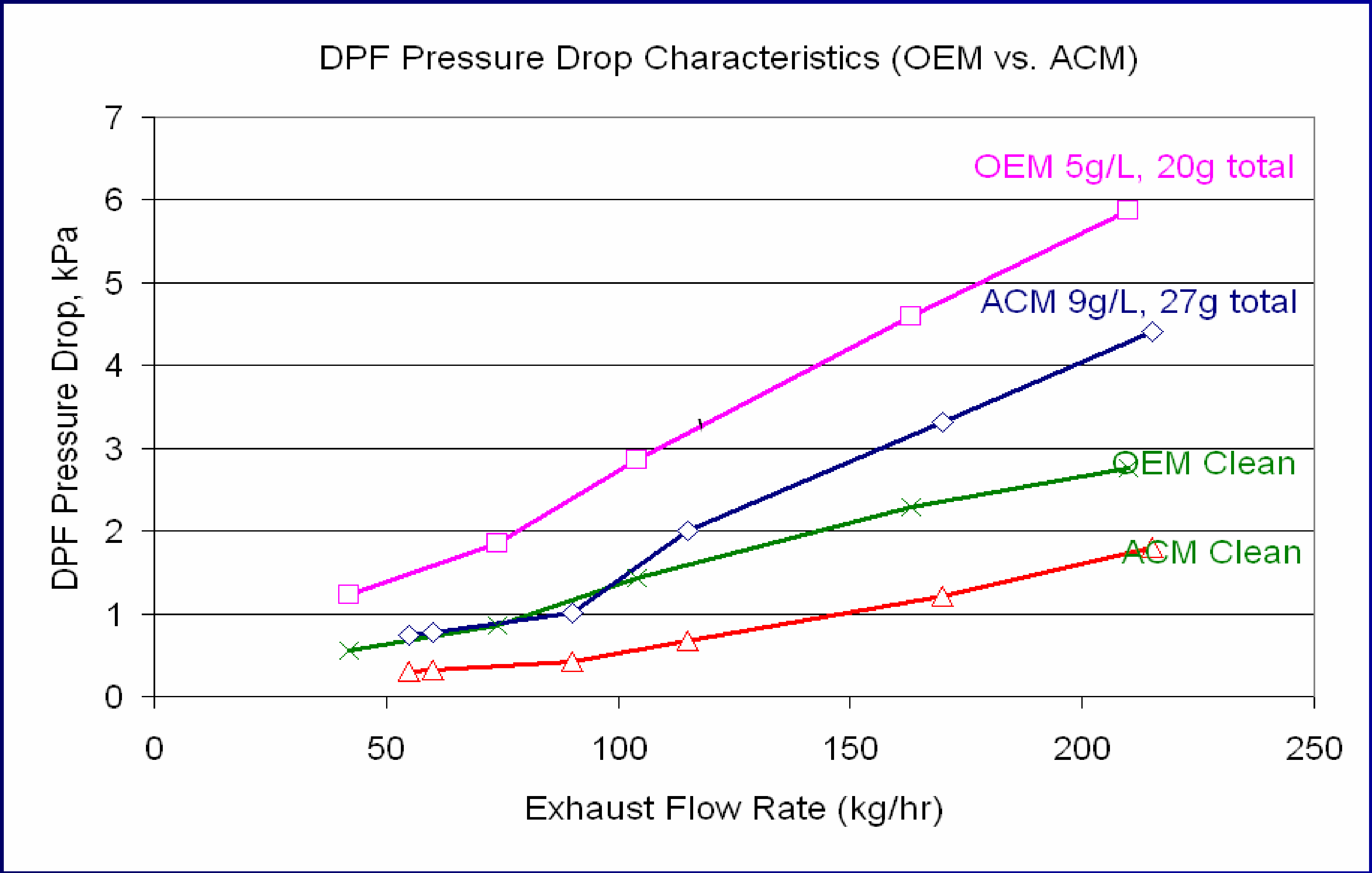
Cycle	Peak Temp, ^{o}C
13	**973**
23	**1075**
24	**1043**
25	**1109**
32	**1001**
33	**968**
34	**1032**
35	**940**
43	**1095**
72	**1052**
85	**1052**
87	**973**

On-Vehicle Test Results

1. Pressure Drop Characteristics
2. Soot Loading Performance
3. Regeneration Performance
4. Accelerated On-Vehicle Durability Performance

On-Vehicle Test Results (1)

Pressure Drop Characteristics – OEM (4.0L) vs. ACM (3.0L)

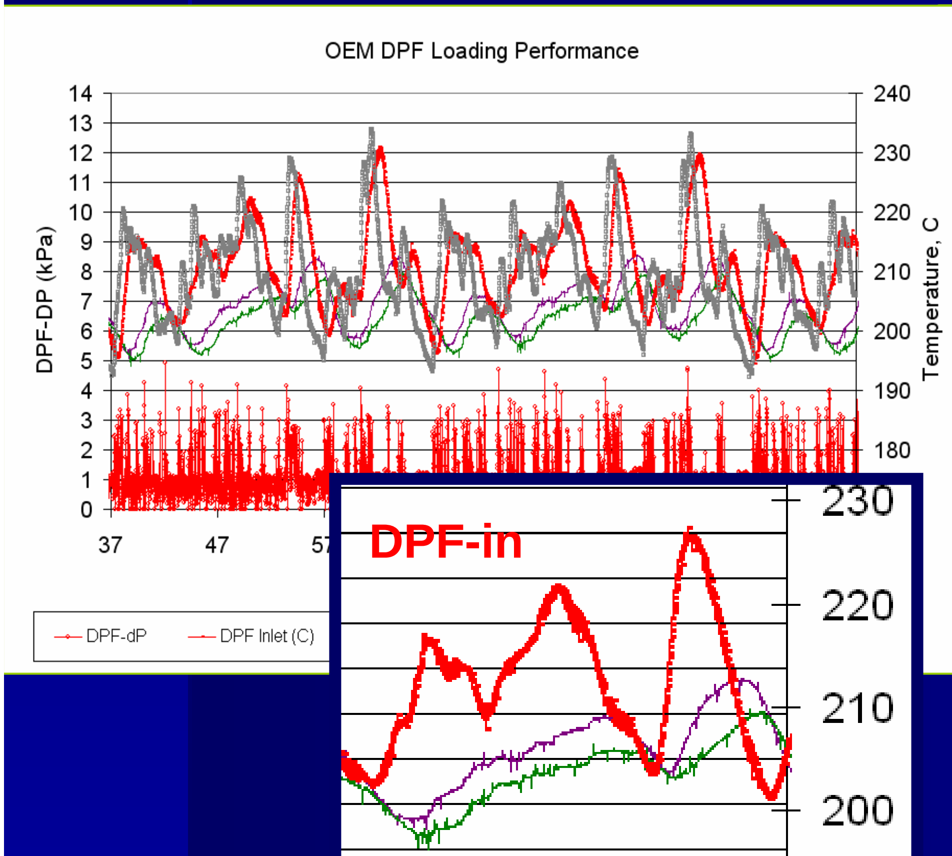


On-Vehicle Test Results (2)

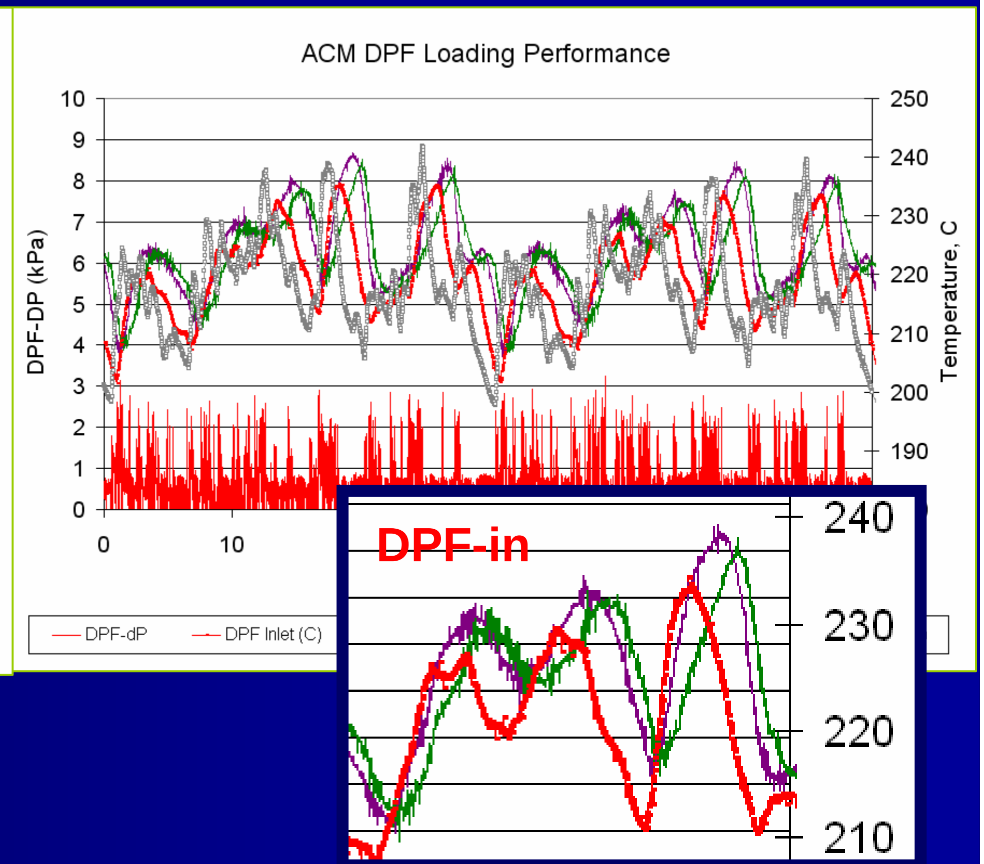
Substrate Thermal Behavior Matters!

OEM 4.0L

ACM 3.0L



September in Texas

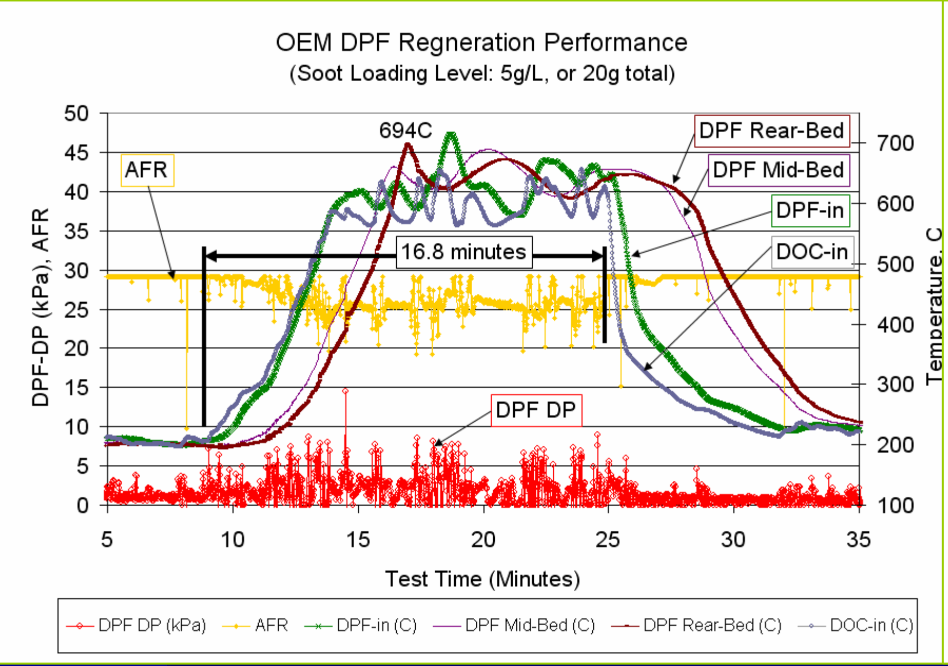


November in Texas

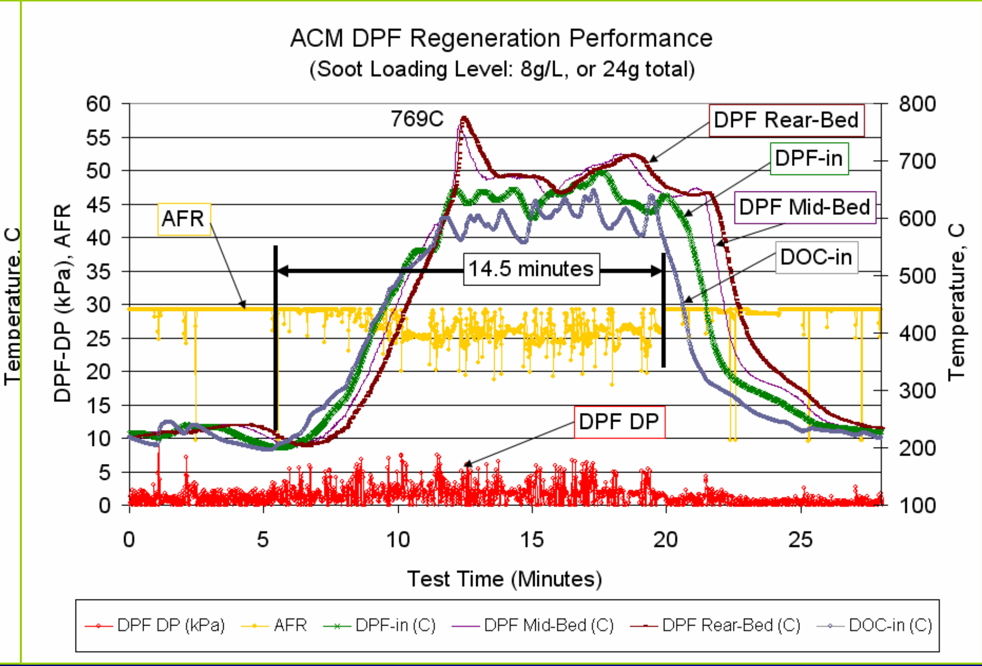
On-Vehicle Test Results (3)

Substrate Thermal Behavior Matters!

SiC 4.0L



ACM 3.0L



Take substrate thermal behavior into account for modeling

Presentation Outline

- Introduction
- Objectives
- Test Equipments and Procedures
  - On-Engine Test
  - On-Vehicle Test
- Test Results
  - On-Engine Test Results
  - On-Vehicle Test Results
- **Summary**

Summary

- A DPF thermal aging cycle is developed
  - 80% controlled
  - 8% incomplete and
  - 12% uncontrolled regenerations
- Ash accumulation may affect DPF design, on-vehicle test showed that by reducing 25% in volume, the ACM DPF had
  - Lower pressure drop
  - Higher filtration efficiency
  - Fast temperature response
- Call for DPF aging modeling, on-engine and on-vehicle durability validation procedures exist