UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
NATIONAL VEHICLE AND FUEL EMISSIONS LABORATORY
2565 PLYMOUTH ROAD
ANN ARBOR, MICHIGAN 48105-2498

MEMORANDUM

To: **Docket EPA-HQ-OAR-2022-0829**

From: **Stani Bohac, U.S. EPA-OTAQ-ASD-LDVSEC**

CC: **Michael Olechiw, Director, U.S. EPA-OTAQ-ASD-LDVSEC**

Date: **7/6/2023**

Re: **EPA conference presentations relevant to LMDV rulemaking**

EPA recently made three conference presentations relevant to the criteria pollutant emissions standards proposed by the LMDV rulemaking.

1) Bohac, S. V., "PM Mass-Based Standard for Achieving PM Emissions Commensurate with Model Year 2022 GPF Technology for Light-Duty and Medium-Duty Vehicles," 26th ETH Nanoparticles Conference, Zurich, Switzerland, June 20-22, 2023.
2) Bohac, S. V., "Drive Cycle PM Mass Measurements Capable of Resolving GPF-Level Emissions from Light-Duty and Medium-Duty Vehicles," 33rd CRC Real World Emissions Workshop, San Diego, CA, March 26-29, 2023.
3) Butler, A., Guerra Z., Bohac, S., Geidosch, J., "Effect of Fuel Properties on PM Emissions from 4-Cycle Gasoline Nonroad Engines," 33rd CRC Real World Emissions Workshop, San Diego, CA, March 26-29, 2023.

Slides from the three presentations are attached below.

PM Mass-Based Standard for Achieving PM Emissions Commensurate with Model Year 2022 GPF Technology for Light-Duty and Medium-Duty Vehicles

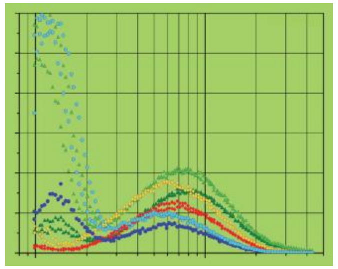
new filter

GPF

no GPF

26th ETH Nanoparticles Conference

June 20-22, 2023 | ETH Zurich



Stanislav V. Bohac

U.S. Environmental Protection Agency

EPA Proposed Rulemaking

April 2023, EPA proposed multipollutant emissions standards (criteria pollutants and GHG)

Light-duty and medium-duty vehicles; GVWR ≤ 14,000 lb (6350 kg)

Applies to MY 2027 – 2032

Performance-based, inter-dependent, synergistic

Public comment period through July 5, 2023, plans for final rule by March 31, 2024

Criteria pollutant fleet phase-in

	GVWR ≤ 6000 lb	**6001 – 8500 lb**		**8501 – 14,000 lb**	
		default*	early**	default*	early**
2027	40%	0%	40%	0%	40%
2028	80%	0%	80%	0%	80%
2029	100%	0%	100%	0%	100%
2030-2032	100%	100%	100%	100%	100%

* Default phase-in provides 4 years lead time as required by CAA

** Incentives for choosing early phase-in (e.g., carry forward $NMOG+NO_x$ credits)

Light-Duty Vehicle Standards (LDV, LDT, MDPV)

NMOG+NOx standards

- 30 → 12 mg/mi fleet average standard, BEVs included (60% reduction)
- Same standard over 4 cycles: 25°C FTP, HFET, US06, SC03
- Eliminates higher bins (no high emitters) and adds lower bins
- -7°C fleet average standard: NMHC → NMOG+NO_x; 300 mg/mi; BEVs not included so fleet average doesn't decline
- New engine start-up standards: PHEV high power starts (cold start US06), early driveaway (in gear at 6 seconds), intermediate soak (10 min, 40 min, 3-12 hr)

PM

0.5 mg/mi (0.3 mg/km) per vehicle standard (cap) for -7°C FTP, 25°C FTP, US06 (from na/3/6 mg/mi)

CO

1.7 g/mi per vehicle standard (cap) for 25°C FTP, HFET, US06, SC03

10.0 g/mi per vehicle standard (cap) for -7°C FTP

HCHO

4 mg/mi per vehicle standard (cap) for 25°C FTP

Elimination of the allowance for the use of commanded enrichment for power or component protection

Medium-Duty Vehicle Standards (Class 2b and Class 3)

NMOG+NOx standards

- 178/247 → 60 mg/mi fleet average standard, BEVs included (66-76% reduction)
- Same standard over 4 cycles: 25°C FTP, HFET, US06, SC03
- Eliminates higher bins (no high emitters) and adds lower bins
- New -7°C fleet average standard: NMOG+NO_x; 300 mg/mi; BEVs not included in fleet average so fleet average doesn't decline

PM

0.5 mg/mi (0.3 mg/km) per vehicle standard (cap) for -7°C FTP, 25°C FTP, US06 (from 8/10 mg/mi in FTP and 10/7 mg/mi in HD-SFTP for class 2b/3)

CO

3.2 g/mi per vehicle standard (cap) for 25°C FTP, HFET, US06, SC03

New 10.0 g/mi per vehicle standard (cap) for -7°C FTP

HCHO

6 mg/mi per vehicle standard (cap) for 25°C FTP

Elimination of the allowance for the use of commanded enrichment for power or component protection

MDV with GCWR > 22,000 lb comply with HD engine-dynamometer-based criteria pollutant standards

PM Standards

EPA 2027+ Proposal	Euro 7 Proposal
Measurement	
PM mass (mg/mi)	Solid PN (#/km)
Includes solid and semi-volatile PM	Excellent sensitivity at low PN
Health benefits quantifiable by PM2.5 epi studies	Addresses nanoparticles with very low mass (toxicology studies)
Test Cycles	
-7°C FTP	WLTC
25°C FTP	RDE normal conditions (0 to 35°C, …)
US06	RDE extended conditions (-10 to 40°C, …)
	RDE budget for <10 km trips
Standards	
0.5 mg/mi for all cycles ~6x10^{11} #/km >23 nm (SAE 2019-01-0314)	6x10^{11} #/km in WLTC and RDE normal conditions, >10 nm
	9.6x10^{11} #/km in RDE extended conditions, >10 nm
	6x10^{12} #/trip budget for <10 km trips, >10 nm
Stringency	
Significant stringency during -7°C cold start (high engine-out PM), high load (passive regen), and enrichment (semi-volatile PM)	More stringent wrt nanoparticles, especially in moving to >10 nm
	Significant stringency during RDE extended conditions: low temperature (-10°C) high speeds (160 km/h), high max ave power <2 km after cold start, and towing

Purpose of PM Test Cycles

-7°C FTP

-7°C important real-world temperature (addresses uncontrolled cold PM in Tier 3)

Differentiates vehicles with GPF-level PM from vehicles with Tier 3 levels of PM

25°C FTP

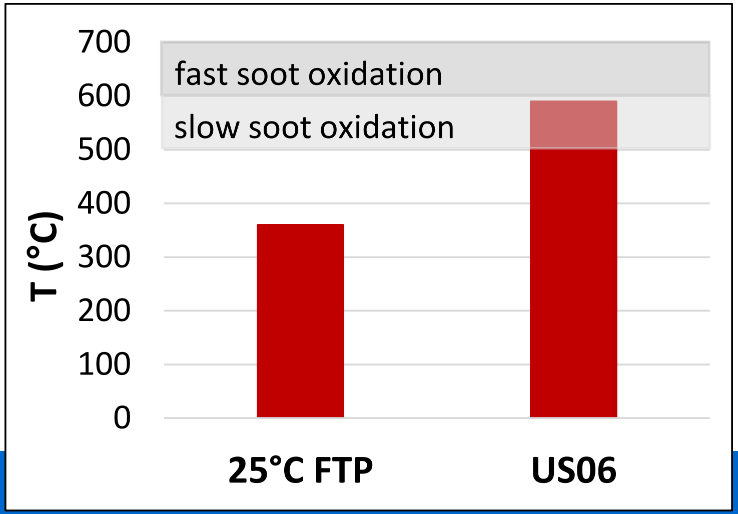
Standards at 25°C and -7°C ensure clean vehicle operation over a range of temps

US06

High load real-world driving

Ensures good PM control during and immediately after GPF regeneration by inducing on-cycle passive GPF regeneration

Max GPF Inlet Temperature
F150, underfloor GPF



Selected Elements of PM Mass Test Procedures (CFR Part 86, 1065, 1066)

Critical elements

Pure PTFE membrane filters (Part 1065.170)

- Less gas-phase artifact than borosilicate fibers reinforced with woven glass cloth and bonded with PTFE

Static charge removal using an α-emitter (Part 1065.190)

- e.g., five 500 µCi strips of ^{210}Po placed around filter on microbalance

Increase PM signal-to-noise ratio

Use lower half of allowable dilution factor range (7-20) (Part 1066.110)

Increase FFV from 90→140 cm/s (Part 1066.110). Improves signal-to-noise ratio[1,2]

Load 1 filter/test (not 1 filter/phase) (Part 1066.815). Improves signal-to-noise ratio[1,2]

1) Xue, Durbin, Kittelson, et al., 2018, Journal of Aerosol Science, 117, 1-10.
2) CRC E-99

Other important considerations

Temperature, dewpoint, grounding, HEPA-filtered dilution air, filter handling (Part 1065.140/190)

Coarse particle separator (removes >50% of PM10 and <1% of PM1 at sampling conditions) (Part 1065.145)

Robotic auto-handler weighing (Part 1065.190)

Background correction ≤ 5ug or 5% of std (Part 1066.110)

Laboratories, Vehicles, GPFs

EPA, Ann Arbor, MI
HTF, CTF, cell 5

ECCC, Ottawa, Canada
cold test facility

Environment Canada

FEV, Auburn Hills, MI
cold test facility

2011 3.5L F150
GPF, no GPF

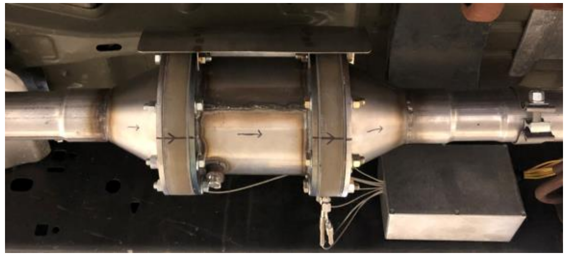
2019 5.0L F150
GPF, no GPF

2021 F150 3.5L HEV
GPF

2021 Corolla 2.0L
no GPF

2022 F250
GPF, no GPF

2019 catalyzed
underfloor

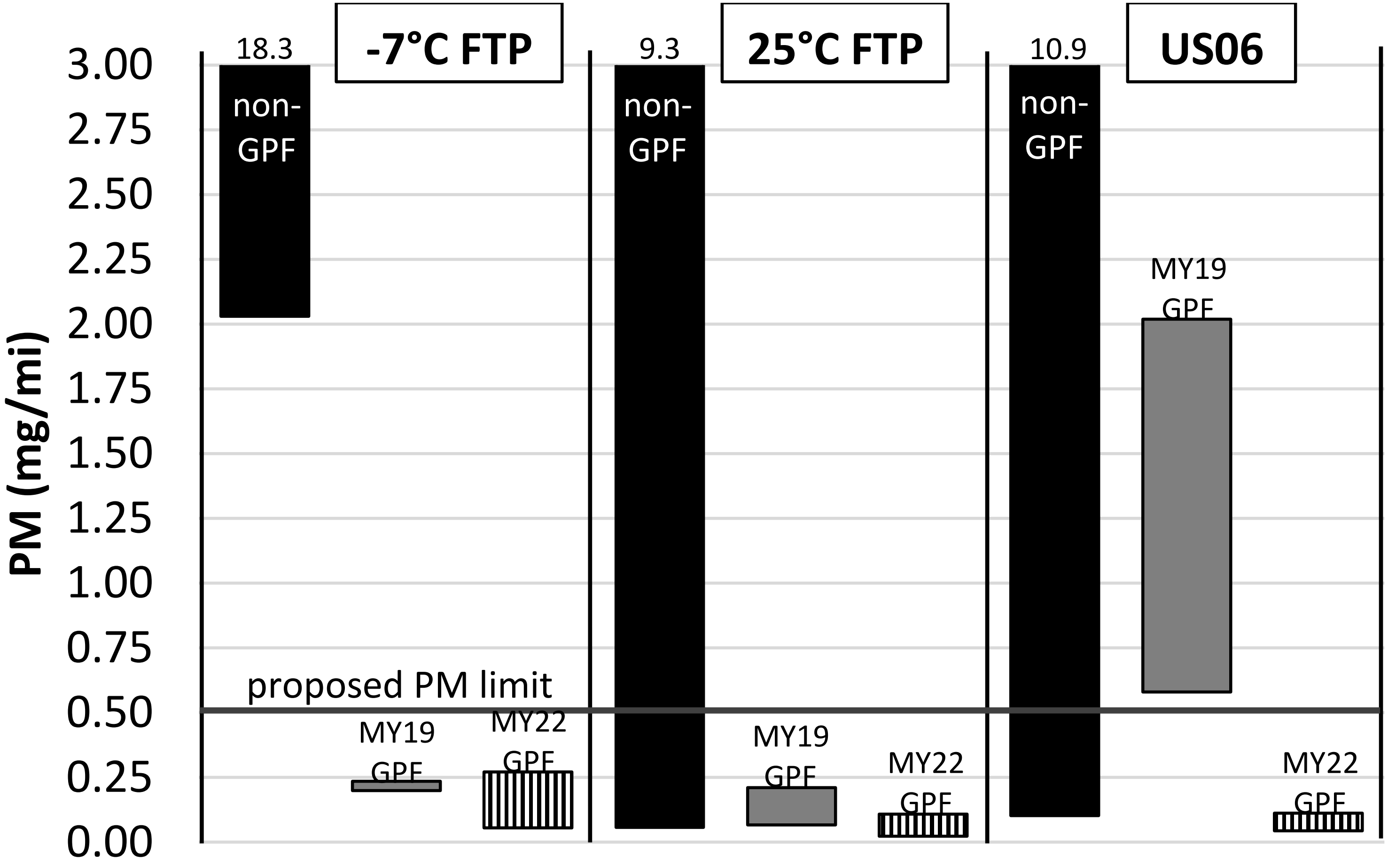


2019 catalyzed
close-coupled

2022 bare
underfloor

2022 bare
underfloor

Overview of PM Data across -7°C FTP, 25°C FTP, US06 Test Cycles

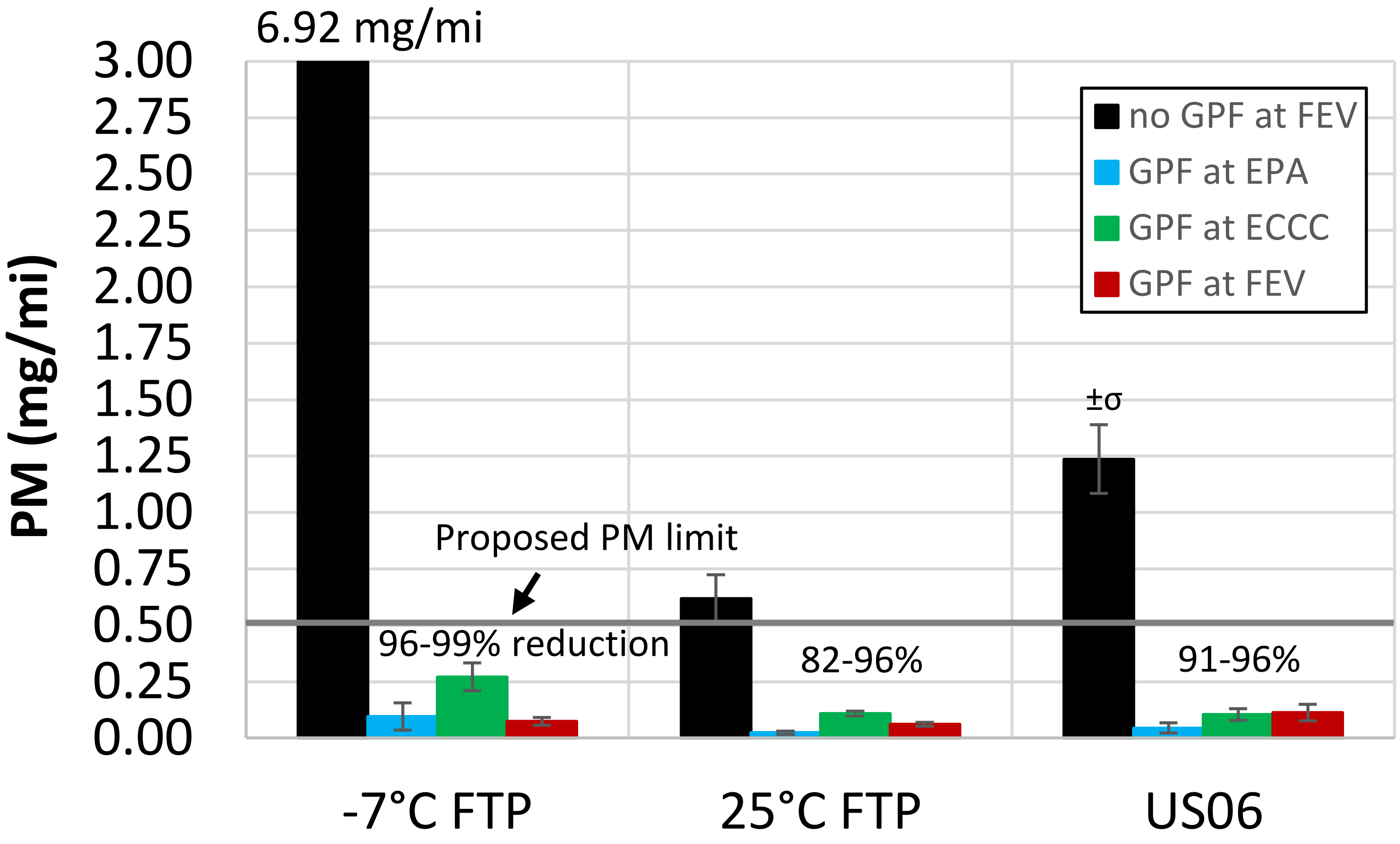


GPF results are conservative because

1) Data not background corrected
2) GPF tests performed with little or no stored soot (unloaded GPF)
3) GPF technology will improve further between now and 2027

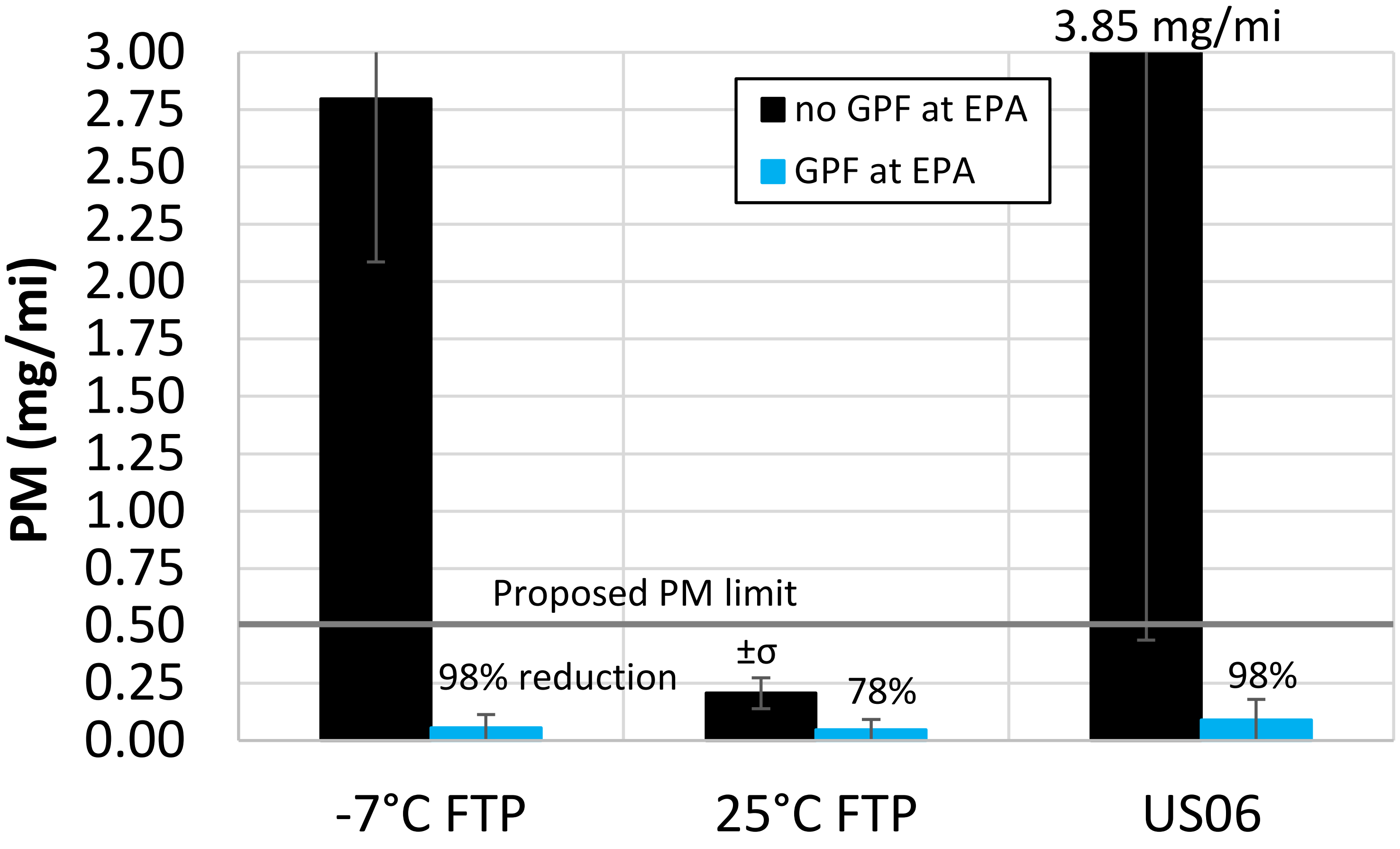
- Large gap between non-GPF and GPF-equipped vehicles in -7°C FTP (high engine-out PM)
- MY2022 GPFs performed significantly better than MY2019 GPFs in US06 (GPF regeneration) and easily meet the proposed 0.5 mg/mi standard

Light-Duty Vehicle (MY2021 F150 HEV) with MY2022 GPF



- ❖ GPF PM measurements shows some lab-to-lab bias exists (also reflected in tunnel blanks), but GPF PM results including lab-to-lab bias and test-to-test variability easily comply with the proposed 0.5 mg/mi standard.

Medium-Duty Vehicle (MY2022 F250) with MY2022 GPFs



- ❖ GPF is equally effective on medium-duty vehicle as on light-duty vehicle.
- ❖ GPF PM results, including test-to-test variability, easily comply with the proposed 0.5 mg/mi standard.

Summary

- Existing Part 86/1065/1066 procedures afford low lab-to-lab bias and low test-to-test variability, and can be used to require PM emissions commensurate with model year 2022 GPF technology

- -7°C FTP differentiates non-GPF and GPF-equipped vehicles.

- MY2022 GPFs demonstrate high filtration across three cycles and three testing organizations and perform significantly better than MY2019 GPFs in the US06.

Acknowledgements

ECCC (Fadi Araji)

FEV (Henning Kleeberg, Frank Richardson)

Corning (Ameya Joshi, Jason Warkins, Angus Craig): bare GPFs, contracting FEV

Aftertreatment Supplier #2: catalyzed GPFs

EPA (Scott Ludlam, Rachael Balogh, John Needham, Jeff Cieslak, Jim Bryson, Spencer Ames, Joe Bolitho, Martin Marion, Michael Olechiw, Robin Moran)

Drive Cycle PM Mass Measurements Capable of Resolving GPF-Level Emissions from Light-Duty and Medium-Duty Vehicles

33rd CRC Real World Emissions Workshop
March 26-29, 2023 | Long Beach, CA

Stanislav V. Bohac
U.S. Environmental Protection Agency

These slides represent deliberative considerations, not an EPA position or pending action.

Background

European, Chinese and Indian regulations require PM emissions commensurate with Gasoline Particulate Filter (GPF) technology

Particulate Measurement Programme (PMP) offers good sensitivity for GPF-level solid PN measurements

	Euro 6d	China 6b	Bharat 6 Stage 2
Applicability	Pure GDI vehicles	All gasoline vehicles	Pure GDI vehicles
Solid PN standard	6×10^{11} #/km, >23 nm	6×10^{11} #/km, >23 nm	6×10^{11} #/km, >23 nm
Test cycles and dates	WLTC and RDE new type approvals 9/2017 first registration 9/2019	WLTC 2020 WLTC and RDE 2023	MIDC (NEDC) & RDE 4/2023

Background

EPA Tier 3 PM standards for on-road vehicles:

Mass-based

- Include solid and semi-volatile parts of PM
- Health benefits readily quantifiable using $PM_{2.5}$ epidemiological studies

Use different test cycles

- FTP includes ambient soak start (3 mg/mi)
- US06 includes moderate/high power (6 mg/mi)

Less stringent

- Potentially easier to measure PM mass from Tier 3 vehicles than from EU6/CN6/BS6 vehicles ($6x10^{11}$ #/km ~ 0.5 mg/mi)
- Has not led to GPF adoption

Objective

How well can current EPA test procedures and cycles quantify PM mass from GPF-equipped vehicles being sold in markets outside the U.S. today

To examine GPF-level PM mass measurements

using existing U.S chassis dynamometer test cycles (-7°C FTP, 25°C FTP, US06) and existing test procedures (40 CFR Part 1065/1066)

to assess the potential for future PM mass emissions control opportunities.

Test Cycles

-7°C FTP

-7°C important real-world temperature (could address uncontrolled cold PM in Tier 3)

Differentiates vehicles with GPF-level PM from vehicles with Tier 3 levels of PM

25°C FTP

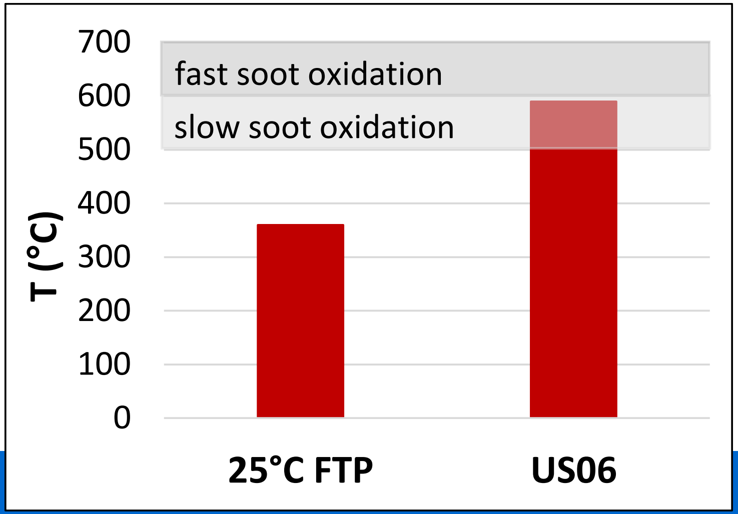
Standards at 25°C and -7°C ensure clean vehicle operation over a range of temps

US06

High load real-world driving

Could ensure good PM control during and immediately after GPF regeneration by inducing on-cycle passive GPF regeneration

Max GPF Inlet Temperature
F150, underfloor GPF



Laboratories, Vehicles, GPFs

EPA, Ann Arbor
HTF, CTF, cell 5

ECCC, Ottawa
cold test facility

Environment
Canada

FEV, Auburn Hills
cold test facility

2011 3.5L F150
GPF, no GPF

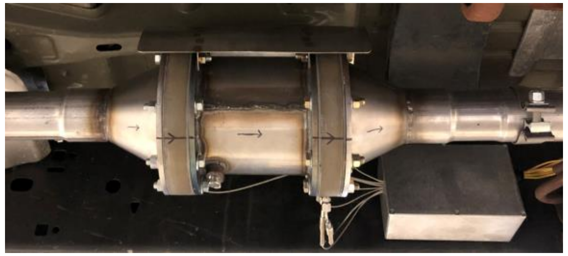
2019 5.0L F150
GPF, no GPF

2021 F150 3.5L HEV
GPF

2021 Corolla 2.0L
no GPF

2022 F250
GPF, no GPF

2019 catalyzed
underfloor

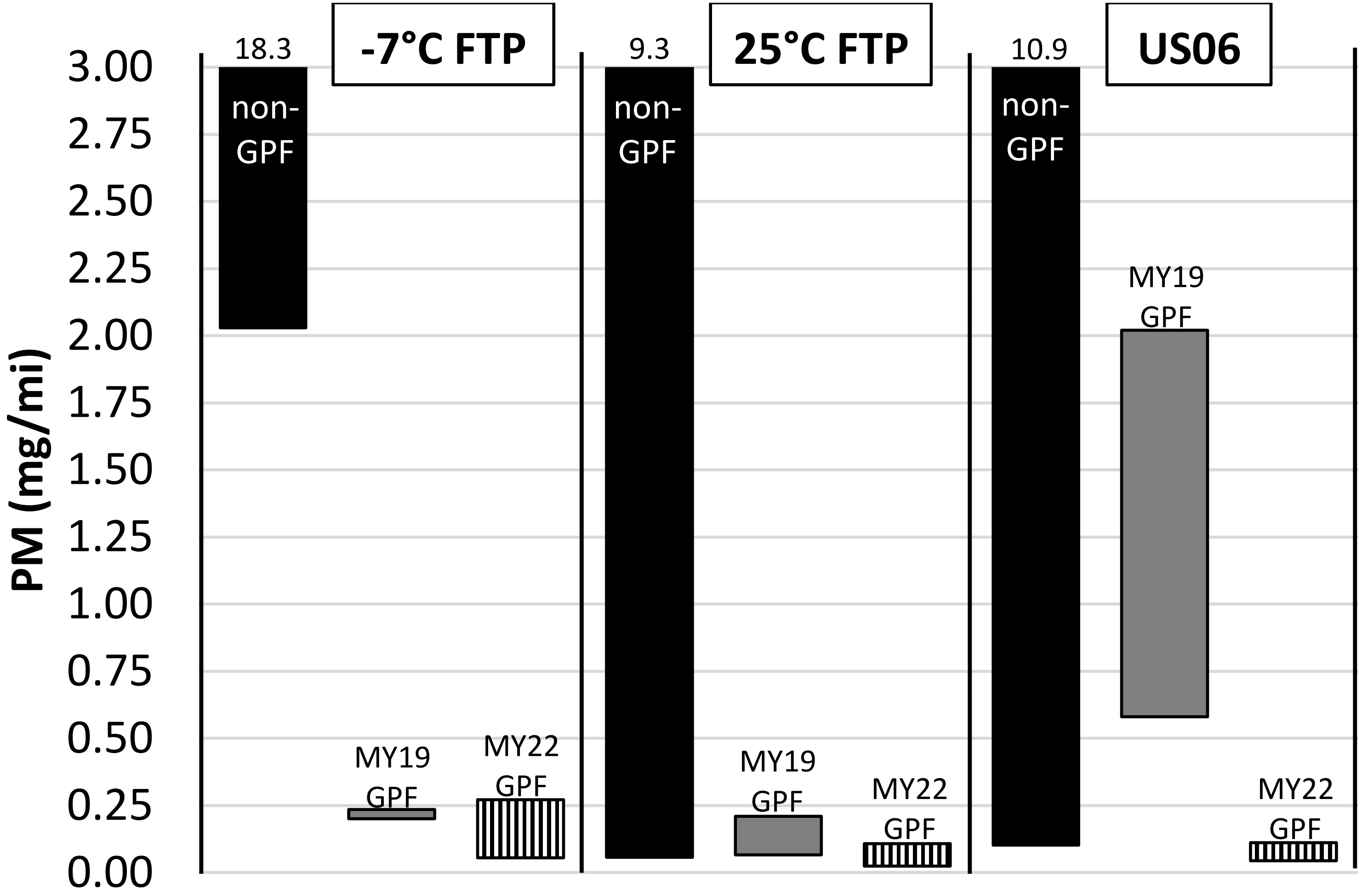


2019 catalyzed
close-coupled

2022 bare
underfloor

2022 bare
underfloor

Overview of PM Data across -7°C FTP, 25°C FTP, US06 Test Cycles

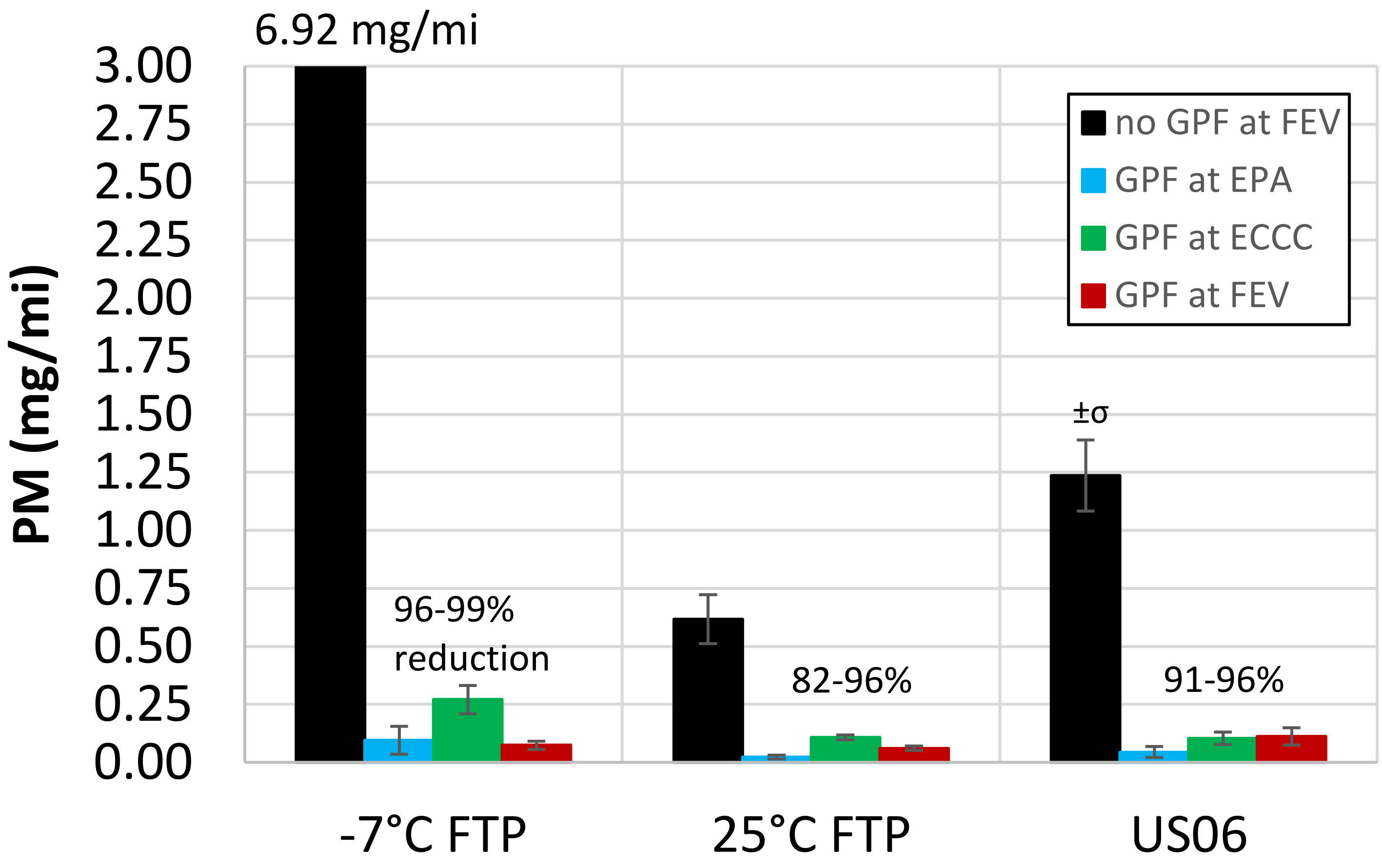


<u>GPF results are conservative because</u>

1) Data not tunnel blank subtracted
2) GPF tests performed with little or no stored soot (unloaded GPF)
3) GPF technology will improve further between now and 2027

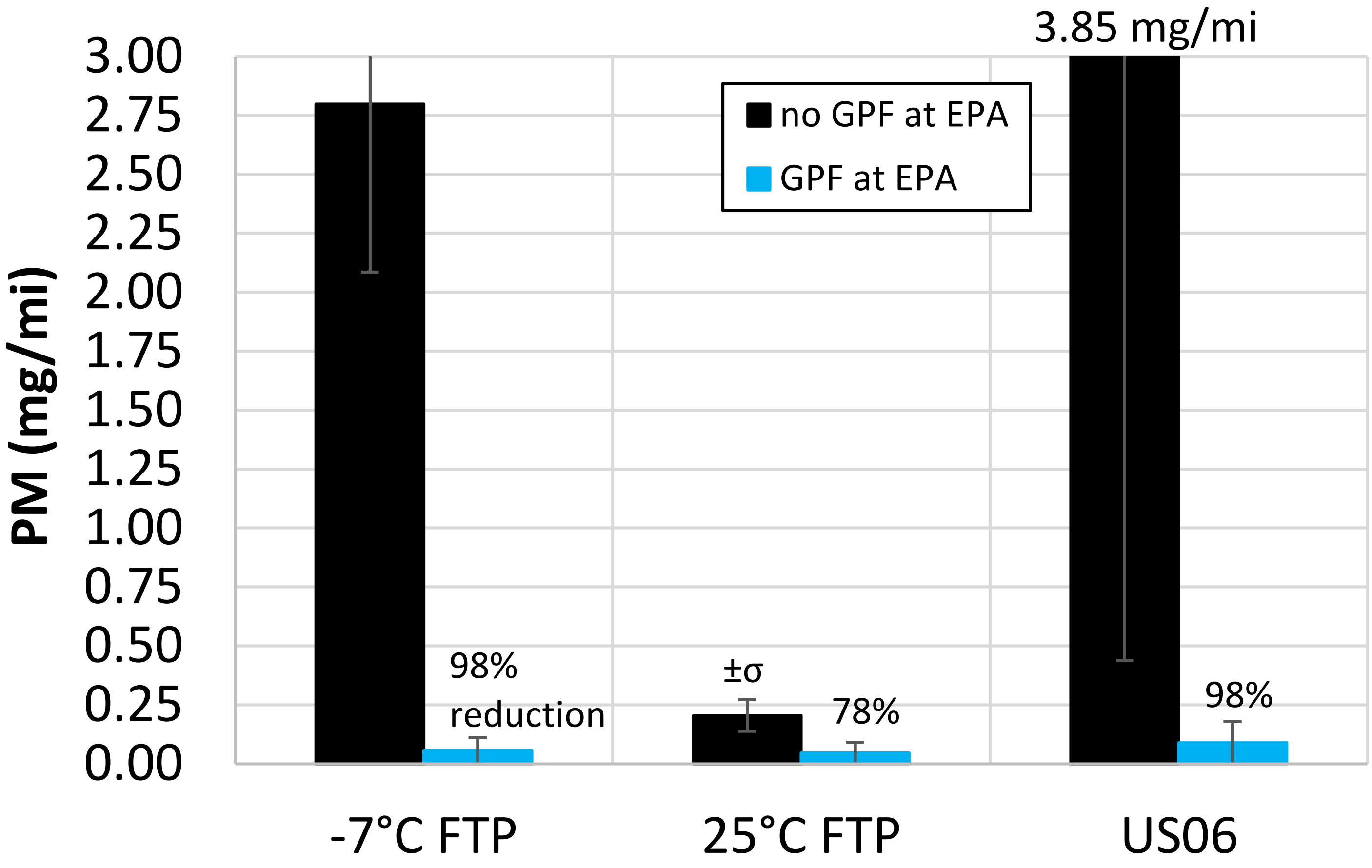
- <u>Large gap</u> between non-GPF and GPF-equipped vehicles in -7°C FTP (high engine-out PM)
- <u>MY2022 GPFs performed significantly better</u> than MY2019 GPFs in US06 (GPF regeneration)

Light-Duty Vehicle (MY2021 F150 HEV) with MY2022 GPF



- GPF PM measurements show lab-to-lab bias exists (also reflected in tunnel blanks), but GPF PM results including lab-to-lab bias and test-to-test variability are an order of magnitude smaller than non-GPF results.
- GPF-level PM is easily resolved from Tier 3 levels of PM using current test procedures.

Medium-Duty Vehicle (MY2022 F250) with MY2022 GPFs



- GPF is equally effective on medium-duty vehicle as on light-duty vehicle.
- GPF PM results including test-to-test variability are an order of magnitude smaller than non-GPF results, making GPF-level PM easily resolved from Tier 3 levels of PM using current test procedures.

Summary

- ❖ MY2022 GPFs demonstrate high filtration across three cycles and three testing organizations and perform significantly better than MY2019 GPFs in the US06.

- ❖ -7°C FTP differentiates non-GPF and GPF-equipped vehicles.

- ❖ -7°C FTP, 25°C FTP, US06 cycles used with existing 1065/1066 procedures afford low lab-to-lab bias and test-to-test variability.

- ❖ Findings are being considered in EPA's assessment of the potential for future PM emission control opportunities.

Acknowledgements

ECCC (Fadi Araji)

FEV (Henning Kleeberg, Frank Richardson)

Corning (Ameya Joshi, Jason Warkins, Angus Craig): bare GPFs, contracting FEV

Aftertreatment Supplier #2: catalyzed GPFs

EPA (Scott Ludlam, Rachael Balogh, John Needham, Jeff Cieslak, Jim Bryson, Spencer Ames, Joe Bolitho, Martin Marion, Robin Moran)

Effect of Fuel Properties on PM Emissions from 4-Cycle Gasoline Nonroad Engines

Aron Butler, Zuimdie Guerra, Stanislav Bohac, Justine Geidosch
US EPA Office of Transportation and Air Quality

CRC Real World Workshop
March 29, 2023

Motivation for This Work

Numerous emission studies have associated high-boiling compounds in gasoline with increased tailpipe PM emissions[1,2]

Market fuel data shows that the high-boiling tail of gasoline contains a high proportion of aromatics[3]

- Heavy aromatics have very high leverage on direct PM emissions[4,5,6,7]
- High-boiling material in gasoline is also expected to contribute to secondary organic aerosol (SOA)[8]

Motivation for This Work

Testing to date has focused on light-duty vehicles, leaving uncertainty about how the impacts might carry over to nonroad

This study examines the emission impacts of replacing heavy aromatics in gasoline with other octane sources on high-sales nonroad engines

Engine Selection

Focused on two 4-stroke equipment types likely to remain in production for several years

- Zero-turn riding lawnmower (presented today)
- Portable generator (data still being reviewed)

Kawasaki FR730V (Manufacturer Specifications)	
Displacement	726 cc (44.3 cu. in.)
Number of Cylinders	2
Maximum Power	24.0 hp (17.9 kW) at 3,600 RPM
Maximum Torque	39.8 ft-lbs (53.9 N·m) at 2,400 RPM

Test Fuel Design

- Fuel A represents a high-PM-Index, high-distillation-endpoint gasoline in the current U.S. market, with an aromatics profile matching accordingly (PMI is defined in reference 7)
- Fuels B, C, and D represent replacement of ~3% of C10+ aromatics in Fuel A with other octane sources (3% light aromatics, 3% alkylate, and 5% ethanol, respectively)
- Other properties were held constant where practical, or allowed to shift in natural ways

Parameter	Unit	Method	Fuel A	Fuel B	Fuel C	Fuel D
Net Heating Value	MJ/kg	D240	41.63	41.56	41.78	40.74
PM Index (PMI)	-	D6730	2.72	1.53	1.50	1.41
Ethanol	vol%	D4815	9.3	9.2	9.2	14.7
AKI	-	D2699/D2700	87.5	87.6	87.4	89.2
DVPE	psi	D5191 (EPA)	9.1	8.9	9.0	9.1
T50	vol%	D86	205	205	200	162
T90			332	316	312	311
Total Aromatics	vol%	D6730	26.8	27.3	24.1	23.2
C10+ Aromatics	vol%	D6730	7.2	4.5	4.4	4.2

Emission Test Procedures

Acquired new engine from national retailer

Performed engine and lube oil break-in sequence using market fuel:

- Initial engine break-in of ~6 hours
- Oil change
- Additional ~6 hours of aging on new oil before emission testing

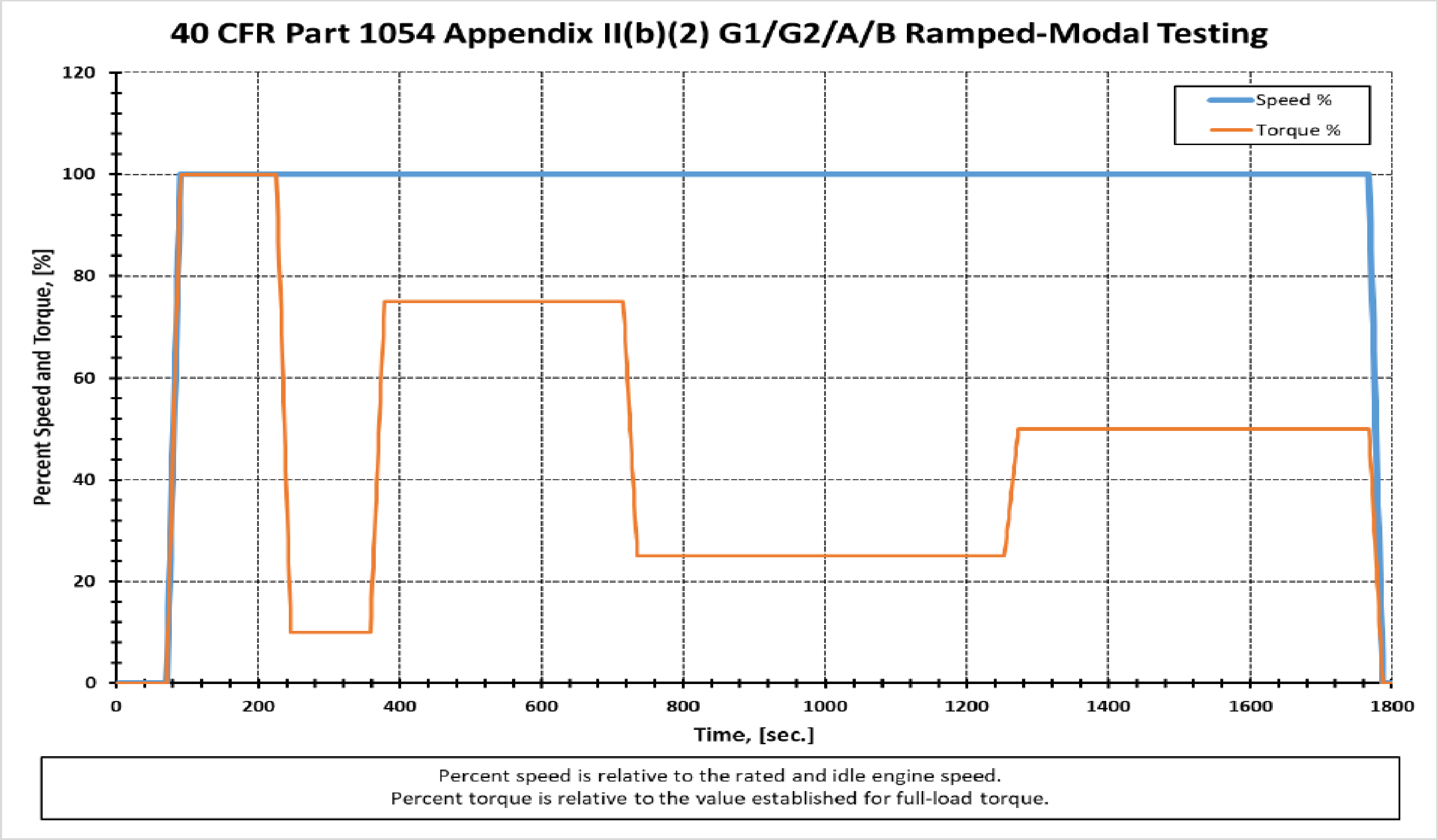
Test fuel sequence A-B-C-A-D

- Fuel A repeatability check at the end of E10 set, followed by Fuel D (E15)

Performed three test replicates of each fuel on each engine measuring

- Gaseous emissions
- $PM_{2.5}$ mass on Teflon filter
- Particle size analysis by EEPS

Emission Test Cycle



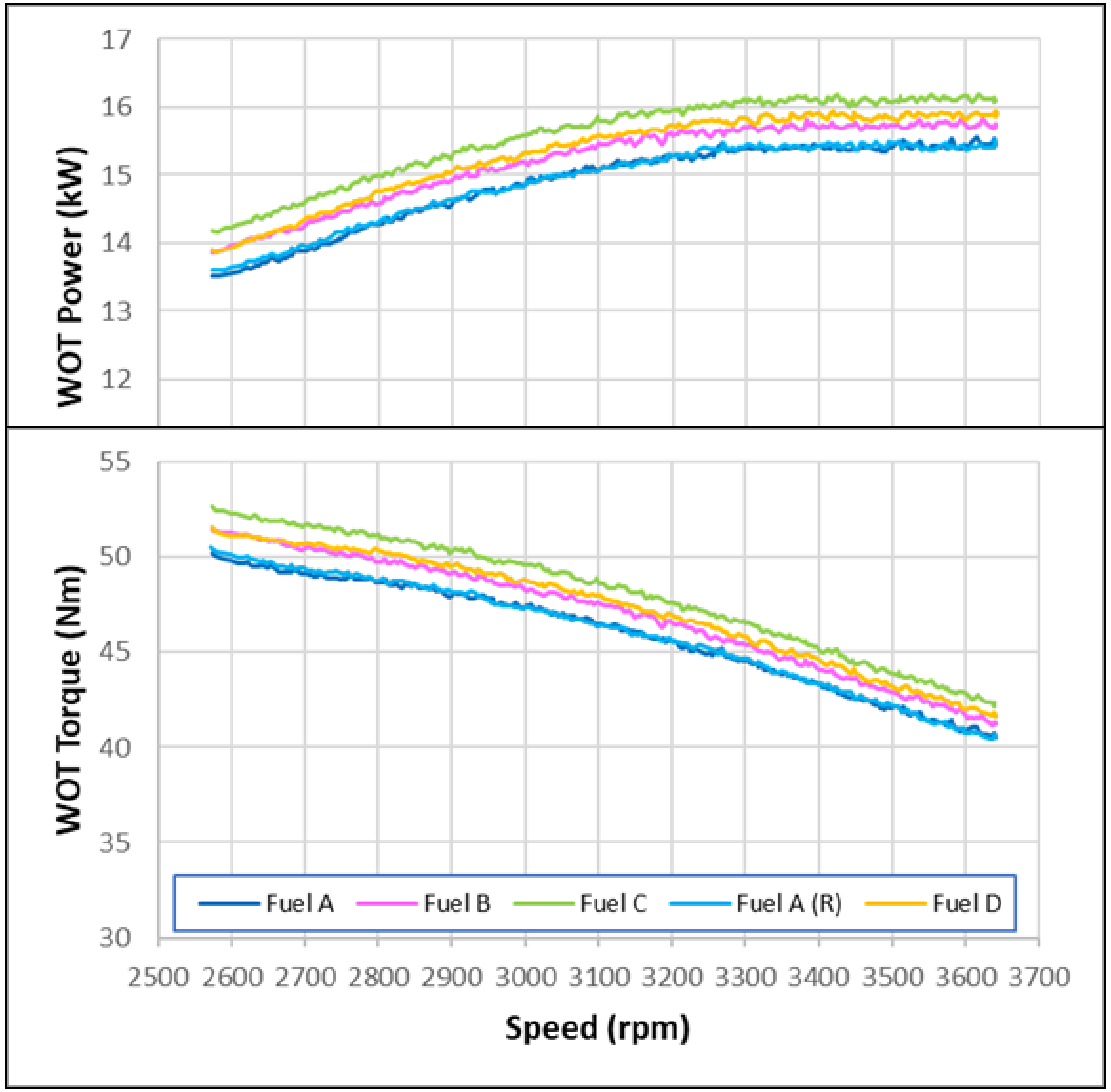
Torque Curve Determination

Part 1054 G1/A procedure

- Wide-open-throttle (WOT) torque curves were determined for each test fuel
- WOT torque values at 3060 rpm were used as 100% test points

Good curve repeatability between Fuel A sets

- Suggests differences were related to fuel properties

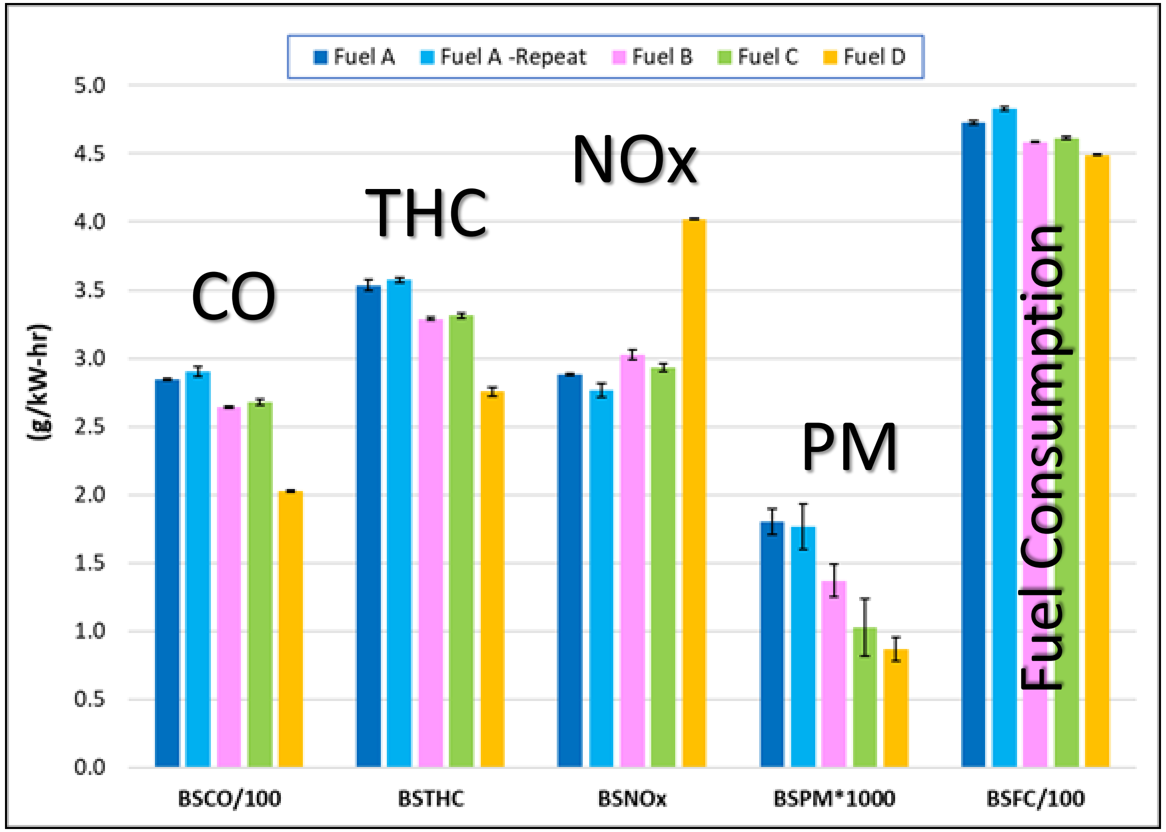


Gaseous & PM Results

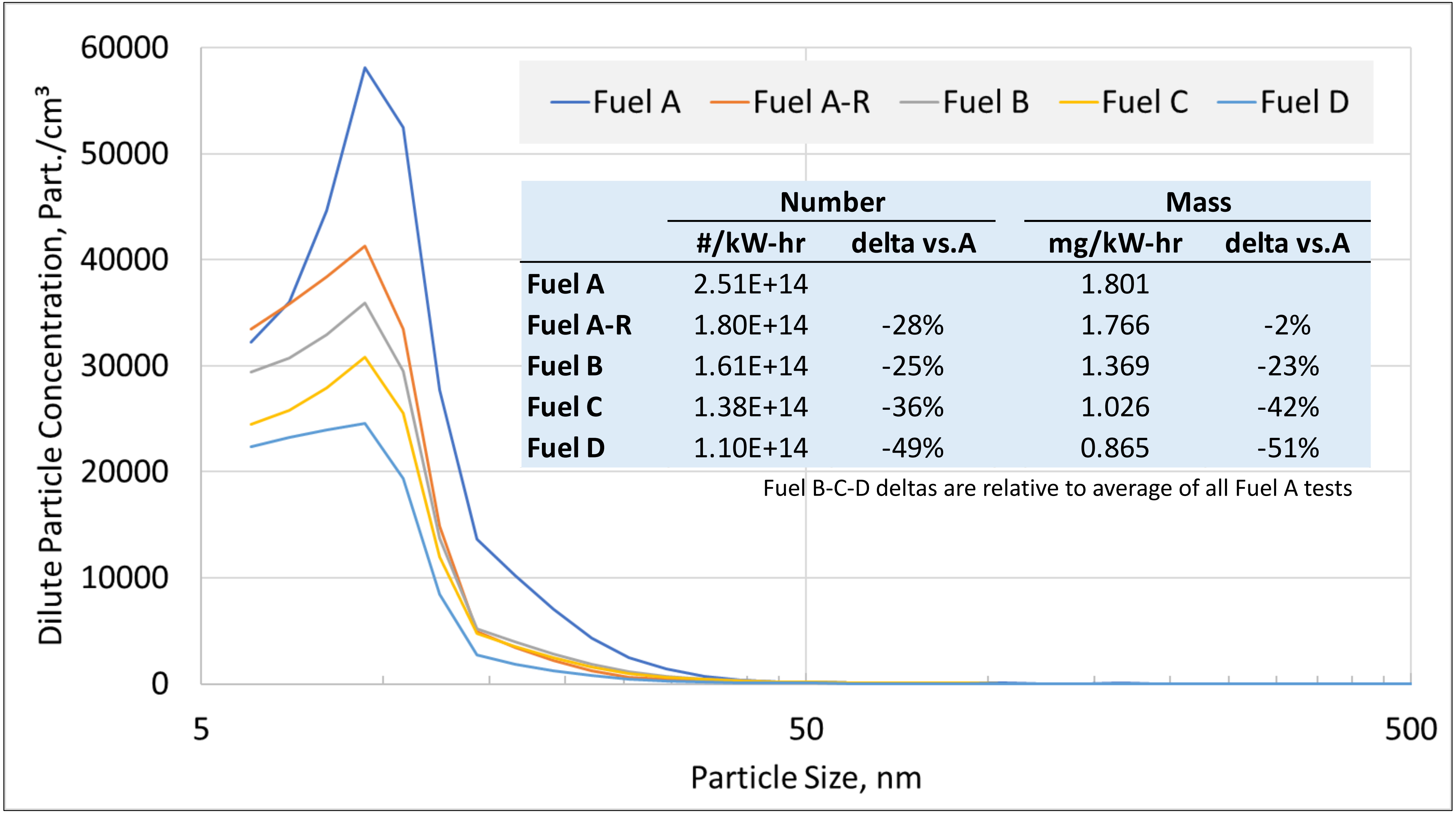
Results indicate:

- High sensitivity of PM to PMI
- Some sensitivity of total hydrocarbons (THC) and CO to PMI
- Fuel D emission impacts are consistent with leaner combustion than the other fuels
  - No air-fuel feedback controls
  - Calculated lambda shift from 0.88 to 0.91 between fuels A-D
- Good repeatability between Fuel A sets

	Fuel A	Fuel B	Fuel C	Fuel D
PM Index	2.7	1.5	1.5	1.4



Particle Size Distribution



	Number		Mass	
	#/kW-hr	delta vs.A	mg/kW-hr	delta vs.A
Fuel A	2.51E+14		1.801	
Fuel A-R	1.80E+14	-28%	1.766	-2%
Fuel B	1.61E+14	-25%	1.369	-23%
Fuel C	1.38E+14	-36%	1.026	-42%
Fuel D	1.10E+14	-49%	0.865	-51%

Fuel B-C-D deltas are relative to average of all Fuel A tests

Summary of Findings

- Commercial lawn and garden engine was tested using ramped-modal certification protocol and four test fuels
- PM emissions showed high sensitivity to fuel PM Index
- Changes in gaseous pollutants and fuel consumption were consistent with more complete combustion at lower PM Index values
    - Significantly higher NOx with E15 blend
- Particle size distribution showed single peak around 10nm, consistent with nucleation mode

References

1. Coordinating Research Council, “Evaluation and Investigation of Fuel Effects on Gaseous and Particulate Emissions on SIDI In-Use Vehicles,” Report No. E-94-2, March 2016.
2. USEPA “Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards: Analysis of Data from EPAct Phase 3 (EPAct/V2/E-89),” April 2013. Document EPA-420-R-13-002.
3. Sobotowski, R., Butler, A., Loftis, K., and Wyborny, L., “A Method of Assessing and Reducing the Impact of Heavy Gasoline Fractions on Particulate Matter Emissions from Light-Duty Vehicles,” SAE Int. J. Fuels Lubr. 15(3):2022, doi:10.4271/04-15-03-0015
4. Chapman E., Winston-Galant M., Geng P., Latigo R., Boehman A., “Alternative Fuel Property Correlations to the Honda Particulate Matter Index (PMI),” SAE Technical Paper 2016-01-2550, 2016.
5. Ben Amara A., Tahtouh T., Ubrich E., Starck L., Moriya H., Iida J., Koji N., “Critical Analysis of PM Index and Other Fuel Indices: Impact of Gasoline Fuel Volatility and Chemical Composition,” SAE Technical Paper 2018-01-1741, 2018.
6. Sobotowski R. A., Butler A. D., Guerra Z., “A Pilot Study of Fuel Impacts on PM Emissions from Light-duty Gasoline Vehicles,” SAE Int. J. Fuels Lubr. 8(1):2015.
7. Aikawa, K., Sakurai K., Jetter J. J., “Development of a Predictive Model for Gasoline Vehicle Particulate Matter Emissions,” SAE Technical Paper 2010-01-2115, 2010.
8. Gentner D.R., et al., “Elucidating secondary organic aerosol from diesel and gasoline vehicles through detailed characterization of organic carbon emissions,” PNAS 109 (2018) 18318-18323.