New Proposed Light-Duty PM Regulations in the USA: Can it be Controlled and Measured?

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Outline

- EPA Notice of Proposed Rule Making (NPRM) includes STRINGENT particulate matter (PM) emissions relative to current standard for 2027 and beyond
  - PM MASS-based emissions standard. No PN
  - GPF technology can meet the standard
  - E-Fuel with Ultra Low PM index can play a very positive role
  - Current CFR Part 1065/1066 measurement procedures are applicable to demonstrate compliance with the standard

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NPRM PM Emissions Standard (LDV, mg/mi)

Model Year	US EPA				CARB			
	FTP, -7°C	FTP, 25°C	US06, 25°C	Phase In	FTP, -7°C	FTP, 25°C	US06, 25°C	Phase In
2024	N/A	3	6	Tier 3	N/A	3	6	Tier 3
2025	N/A	3	6	Tier 3	N/A	1	6[b]	25%
2026	N/A	3	6	Tier 3	N/A	1	6[b]	50%
2027	0.5[a]	0.5[a]	0.5[a]	40%	0.5[a]	0.5[a]	0.5[a]	40%
2028				80%				80%
2029				100%				100%
2030				100%				100%
2031				100%				100%
2032[c]				100%				100%

[a] Emissions Cap, [b] No Phase in, [c] Fleet Average

- 83% Reduction from current level
- Introducing -7°C for the first time
- Emissions Cap
- More stringent than CARB for 2027+ Model Year

Federal Rule supersedes previous less stringent CARB rule. California moves to 0.5 mg/mile in MY2027

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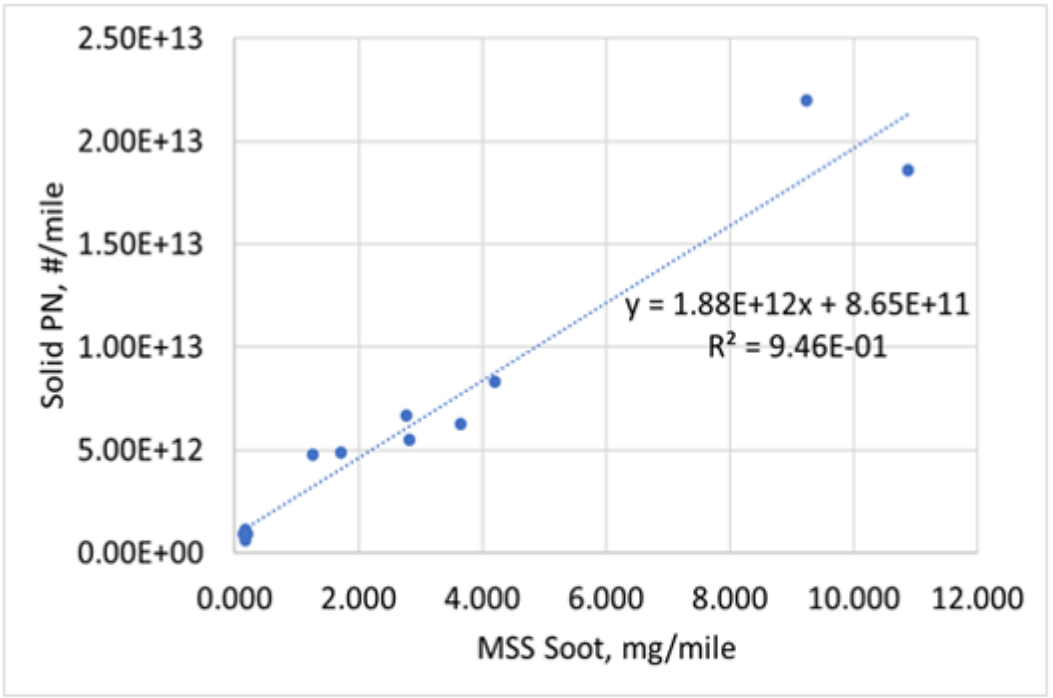
Mass vs. Solid Particle Number

- We typically measure ~1.7E12 particles (> 23 nm) per 1 mg of PM mass
  - 0.5 mg/mi = 0.31 mg/km ~ 5.3E11 part./km
- One can argue that the 0.5 mg/mi standard is equivalent to Euro 6 standard of 6E11 part./km
  - **But Euro 7 for particles > 10 nm in diameter will likely be more stringent than the 0.5 mg/mi standard**



Relationship	SEE % of mean	R^2	Slope
Solid PN (#/mile) vs Soot (mg/mile)	28%	0.95	1.88E+12
Solid PN (#/mile) vs PM (mg/mile)	23%	0.95	1.67E+12
Soot (mg/mile) vs PM (mg/mile)	17%	0.97	1.12

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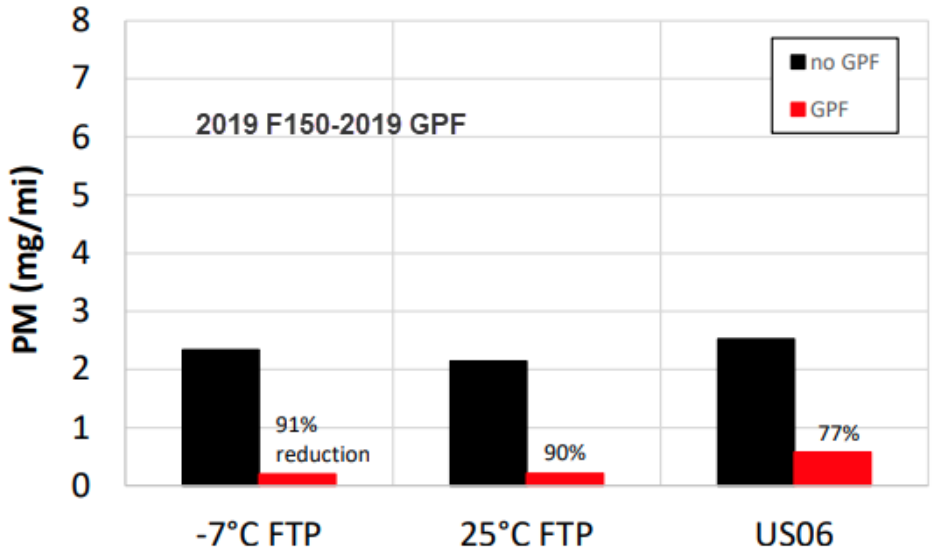
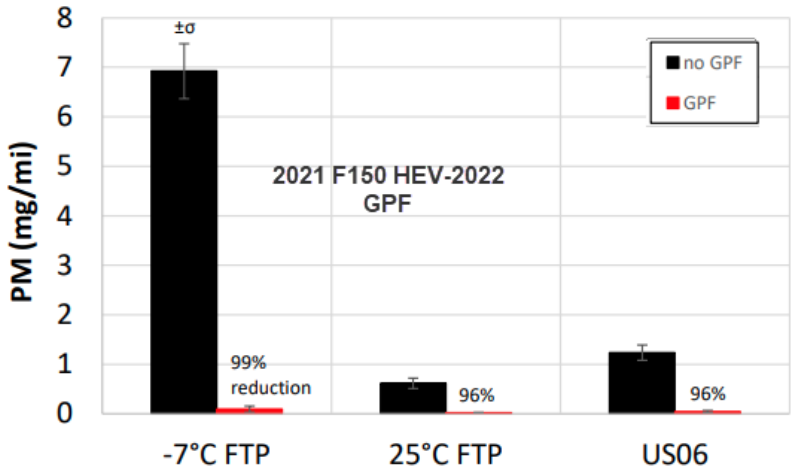
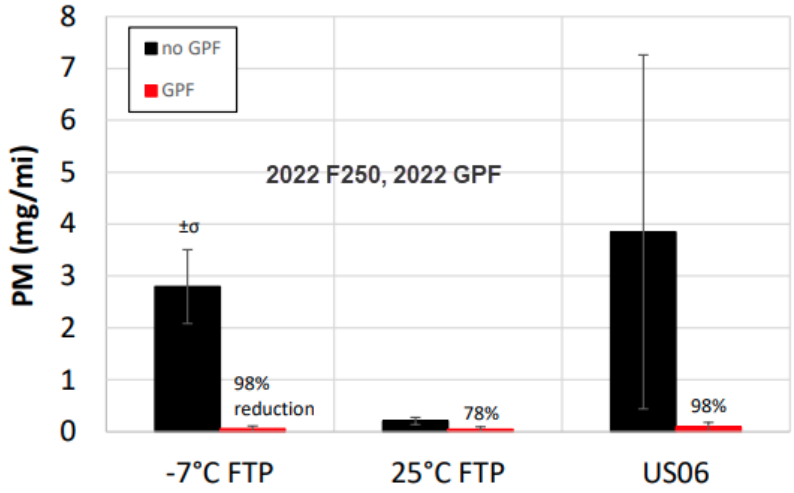
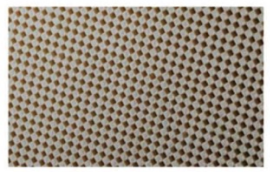
Approaches to Meeting the New PM Standards Gasoline Particle Filter (GPF)

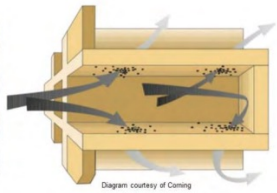






- EPA demonstrated meeting the standard in the Draft Regulatory Impact Analysis (DRIA) using GPFs
- PM emissions reported well below 0.5 mg/mi with new technology GPFs
- GPF was shown to decrease PAHs and off-cycle emissions





GPF Size and Cost Estimate

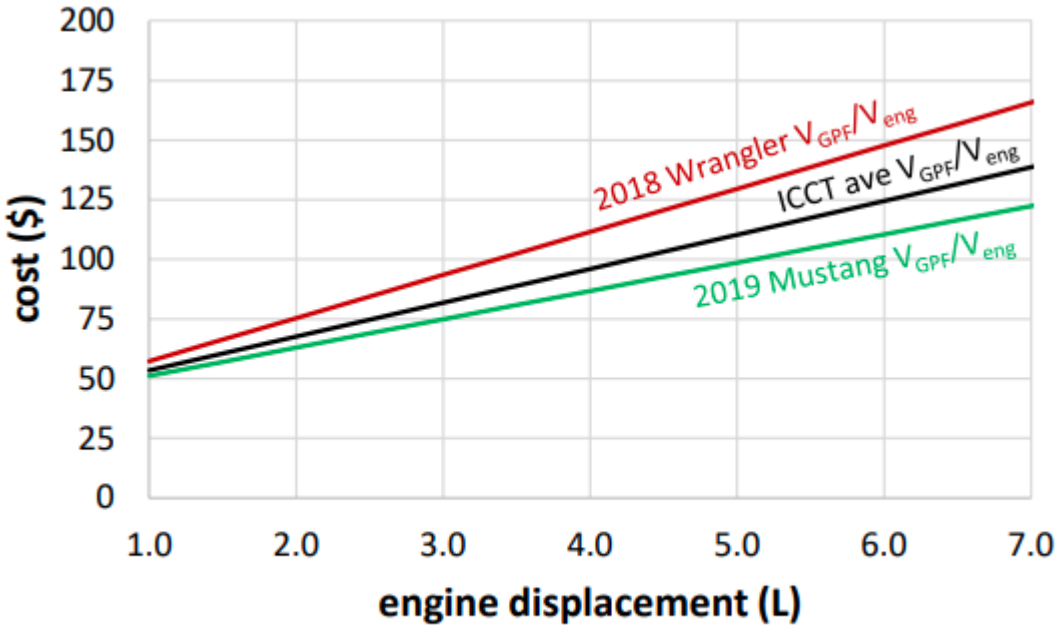


Figure 3-22: GPF cost estimate.

DRIA analysis based on ICCT analysis. Engine OEMs may have different views

- Ratio of GPF volume to engine displacement volume was calculated to be 0.55 based on ICCT analysis
- This ratio was reasonable when compared with two European models (Mustang and Wrangler)
- For an engine displacement of 1 liter, the cost can be ~$50, and ~$110 for a 5-liter engine

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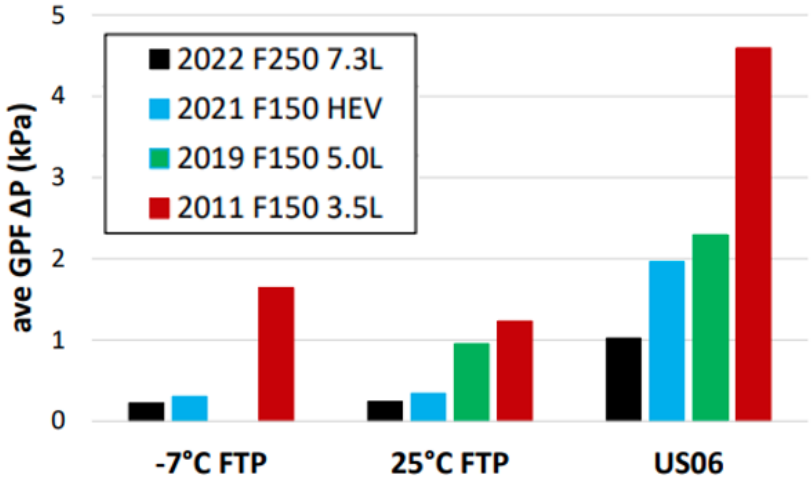
GPF Backpressure & CO_2 Emissions

- Pressure drop is higher with lower $GPF_{vol.}$/$Engine_{disp.Vol.}$
- Highest pressure drop for the US06
- Higher $GPF_{vol.}$ to US06 power leads to lower pressure drop
- Avg. CO_2 increase for all vehicles combined was less than 1%



Test Cycle	CO_2 Increase (%)
-7°C FTP	0.6
25°C FTP	0.0
US06	0.9

	MY2022 F250 7.3L	MY2021 F150 3.5L Powerboost HEV	MY2019 F150 5.0L	MY2011 3.5L Ecoboost
GPF model year	2022	2022	2019	2019
GPF type and location	bare underfloor	bare underfloor	catalyzed close-coupled	catalyzed underfloor
GPF size (L)	6.42 (total for two)	3.21	2.30 (total for two)	1.65
GPF volume / engine displacement (-)	0.88	0.92	0.46	0.47
GPF volume / ave US06 power (L/kW)	0.199	0.115	0.107	0.065
GPF ϕ x L (in)	6.443 x 6 (each)	6.443 x 6	5.2 x 3.3 (each)	5.66 x 4
GPF cell density (cpsi)	200	200	300	300
GPF wall thickness (mil)	8	8	12	12

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GPF OBD Requirement

1. In-use Monitor Performance Ratio (IUMPR) of 0.15 is required using Title 13, Section 1968.2 of California Code of Regulations 2022
2. A monitor is required to detect if PM emissions exceeds 10 mg/mi if GPF is removed
3. A monitor is needed to detect if frequent GPF regeneration causes HC, CO or NO_X to exceed 1.5 times the standard over the FTP
    1. If 3 is satisfied, then a monitor is still needed to trigger if the number of GPF regeneration cycles exceed the manufacturers specified limit
4. Detection of GPF missing, significantly damaged or destroyed
    1. This may be done with a pressure sensor or a particle sensor if available. This will require additional research

If the limit of 10 mg/mi is never exceeded with the removal of GPF, then 3 and 4 will be the only default diagnostics required

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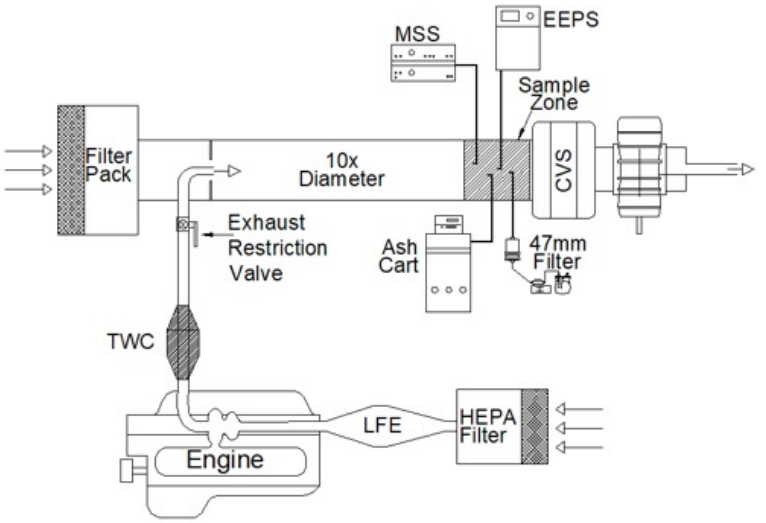
Other Possible Approaches to Reduce PM/PN, WLTC, E-Fuel

- One can get significant reduction in all particle metrics using E-Fuel with ultra low PM Index (PMI)

$$PM\ Index = \sum_{i=1}^{n}\left(\frac{DBE_i + 1}{VP(443K)_i} \times Wt_i\right)$$

	EPA Tier 3 Cert Fuel, PMI 2.4						
Test Name	Soot Mass	SPN23	SPN10	Ash	PM	EEPS	SPN10-SPN23
F1, mg/#/kW-hr	55.71	6.9E+13	1.1E+14	9.9E+12	79.7	2.3E+14	3.9E+13
Stdev, mg/#/kW-hr	4.38	5.9E+12	1.4E+13	7.7E+11	5.3	3.1E+13	
COV, %	0.08	8.6E-02	1.2E-01	7.8E-02	0.1	1.3E-01	
	% Change Relative to EPA Fuel						
	CARB LEV III Cert Fuel, PMI 1.23						
F2	-42.6%	-51.1%	-16.4%	-38.2%	-34.4%	25.1%	44.2%
	E-Fuel with Ultra Low PMI of 0.27						
F3	-95.3%	-86.0%	-84.3%	-87.3%	-91.2%	-74.0%	-81.2%

- 2018 Ford Ecoboost, turbocharger, direct injection engine
- 2.3 L, 310 hp/350 ft.lb torque at 3,000 rpm
- Used in MY 2018 Ford Mustang



Drop-in E-Fuel with Ultra Low PMI can benefit existing fleet by reducing PM/PN emissions and greenhouse gas

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PM Measurement Variability

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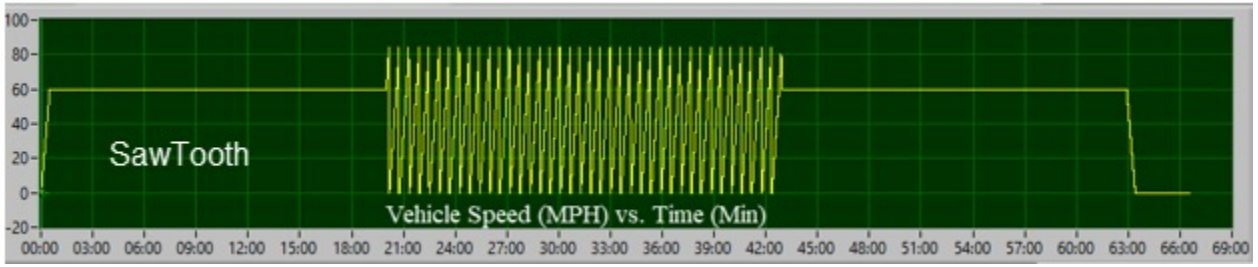
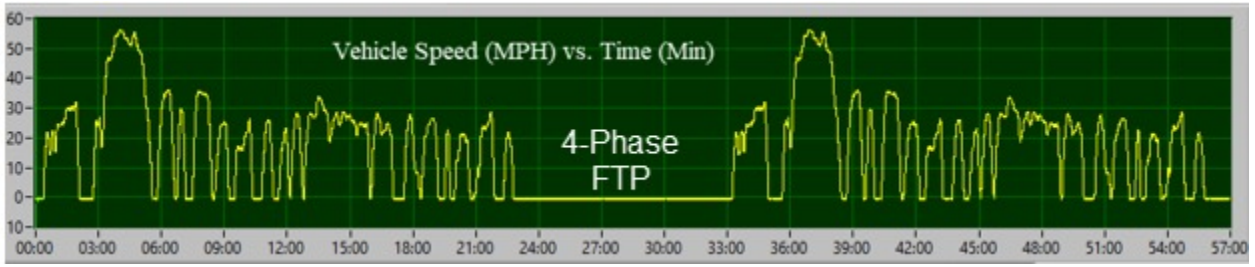
Experimental Setup & Procedures

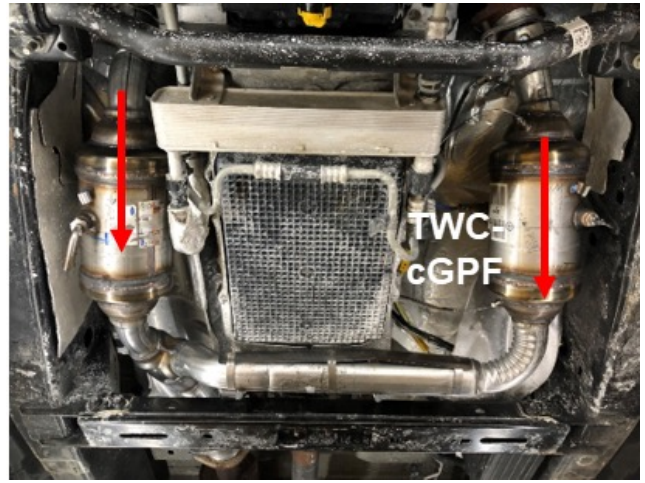


Regeneration Cycle



Cold & Hot Start Cycle (Single Filter)

Prep. US06 + 2-US06 (Single Filter)



- 25°C Ambient Temperature, Filter Face Velocity 120 cm/sec, Measurement PM Filter Collection & MSS
  - 5 Repeats of 4-Phase FTP, Single Filter
  - 5 Repeats of 2-US06, Single Filter
  - Sawtooth Cycle was used for GPF Regeneration

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Results

Analytics	FTP-PM	FTP-MSS	2-US06-PM	2-US06-MSSavg
	mg/mi	mg/mi	mg/mi	mg/mi
Avg	0.111	0.132	0.248	0.138
stdev	0.010	0.003	0.055	0.008
COV	9.3%	2.5%	22.2%	5.6%
Average + 3xStdev at the 99.7% Confidence				
Avg + 3x Stdev	0.142	0.142	0.413	0.161

- Average FTP is 78% below the proposed standard of 0.5 mg/mi
- Average US06 is 50% below the proposed standard of 0.5 mg/mi
- MSS soot mass measurement is showing less variability. It was comparable to filter mass for the FTP and lower for the US06
  - US06 is expected to have more volatile/semivolatile PM
- Data showed that measurements are still well below the standard of 0.5 mg/mi @ 25°C at the 99.7% confidence using three standard deviations

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Summary

- Stringent PM emissions of 0.5 mg/mi have been proposed
- GPF technology was demonstrated to comply with the new PM standard, with a small CO_2 penalty of less than 1% at all temperatures
    - GPF is expected to provide benefit for off-cycle operation, and in reducing PAHs
    - GPF volume to engine displacement ratio is expected to be on the order of 0.55
    - GPF cost ranges from ~$50 for 1-liter engine to ~$110 for a 5-liter engine
- Ultra low PMI E-Fuel is expected to reduce drastically all particle metrics (PM, Soot Mass, SPN23 & SPN10, and total PN). This would benefit existing fleet PM emissions and greenhouse gas
- Work showed that current CFR Part 1065/66 procedures are sufficient to demonstrate that a vehicle can meet the standard at 25°C at the 99.7% confidence interval using three standard deviation

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Acknowledgements

- PM measurement variability effort presented in this work was funded by US EPA. An official publication on these efforts is underway.

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