Demonstrating Ultra-Low Diesel Vehicle Emissions

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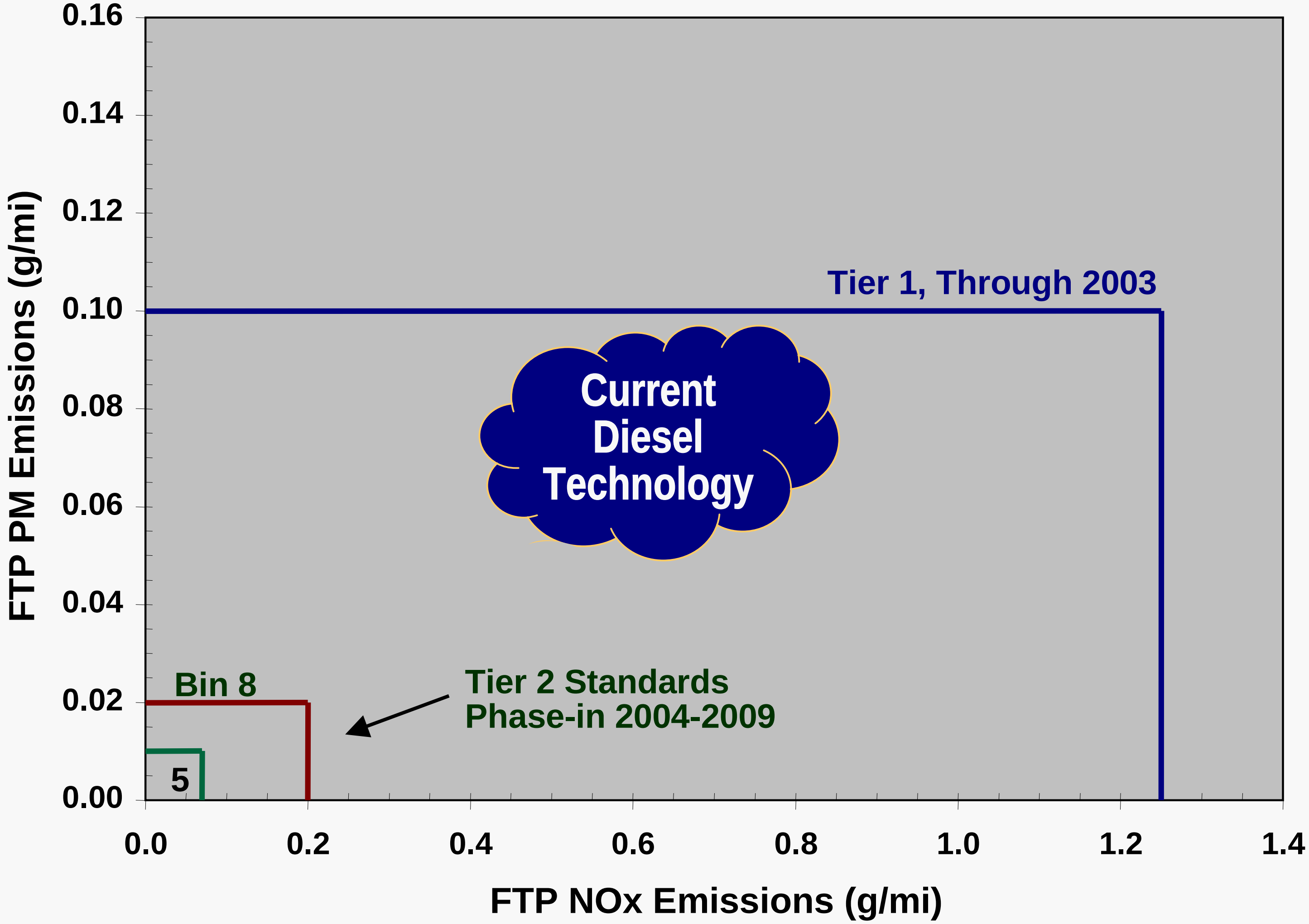
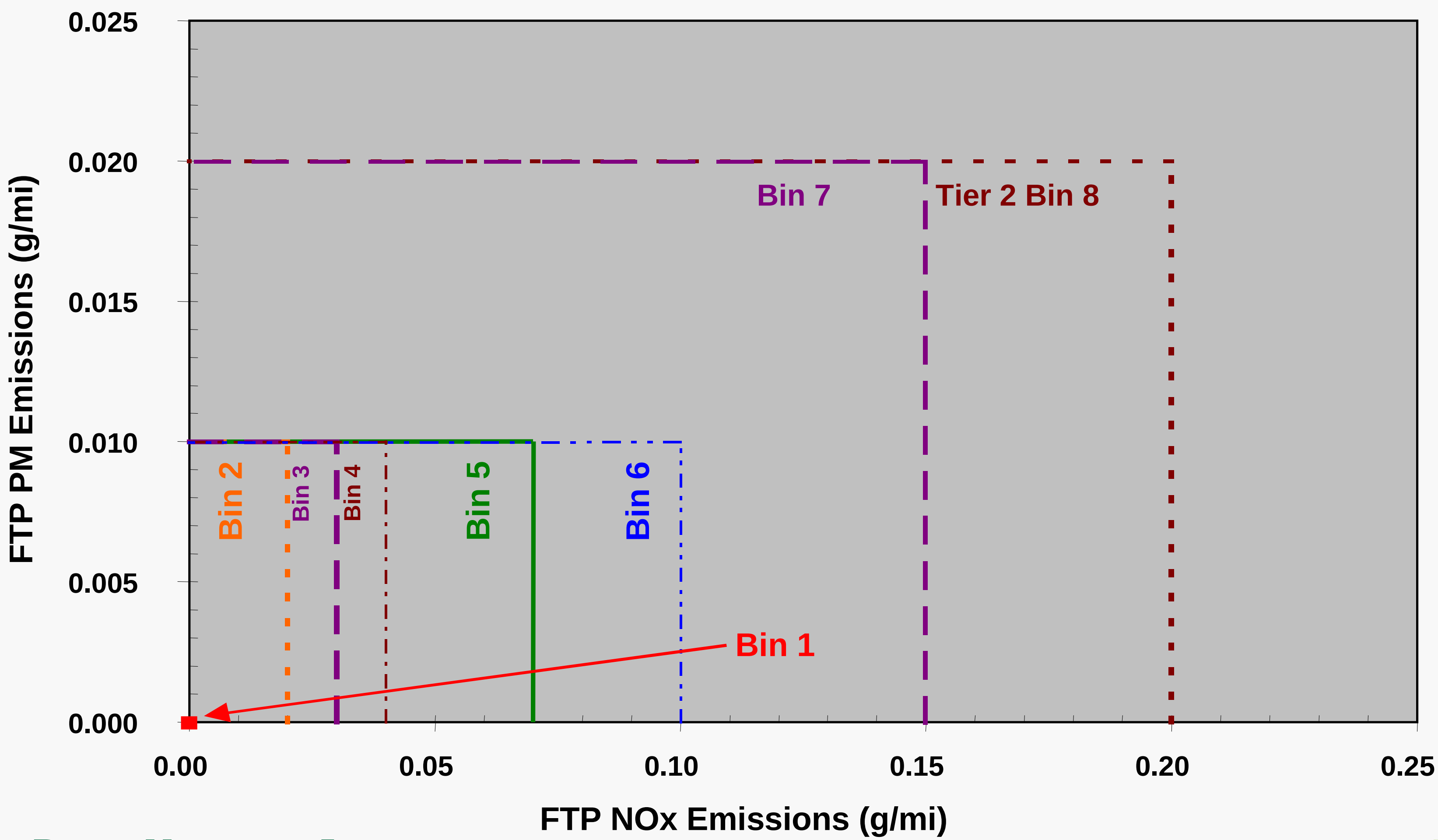
Some groups favor large scale “reintroduction” of diesel engine to U.S. market

- **PNGV has selected diesel as key to high fuel economy family sedans**
- **Diesels gaining popularity in larger trucks/SUVs**
- **But…..**
  - **Tier 2 regulations require ultra-low emissions, regardless of powerplant, fuel, or vehicle mass**
  - **NOx and PM emissions are generally accepted as potential Achilles' heel of diesel powerplants**
  - **Conventional 3-way catalyst cannot control NOx in lean-burn engine exhaust**
  - **Oxidation catalysts only reduce PM by 30-50%**

EPA’s Tier 2 emissions standards require substantial PM and NOx reductions



By 2009, all vehicles must fit into one of Bins 1-8. Fleet average NOx must be 0.07 g/mi (Bin 5 NOx). Full useful life emissions stds shown



Due to stringent new emissions standards, advanced emissions controls are key to survival of diesel engine

- **Diesel Particulate Filters (C-DPF, CR-DPF)**
- **Selective catalytic reduction (SCR)**
- **Lean NOx catalysts**
- **NOx adsorbers or Lean NOx traps**
- **New exhaust treatment systems may require new or reformulated fuels**

Diesel Vehicle Emission Control Sulfur Effects (DVECSE) Project Objectives

- **Evaluate performance of near-term exhaust emissions control technologies on a modern diesel vehicle over transient drive cycles**
  - **Phase 1: Independent (separate) evaluations of engine-out, OEM catalysts, CDPF, and NOx adsorber (Completed March 2000)**
  - **Phase 2: Combine NOx adsorber and CDPF to evaluate / demonstrate simultaneous reduction of NOx and PM (Underway - interim results available)**
- **Establish potential for these technologies to help CIDI engines meet emission reduction targets**
- **Investigate short-term effects of fuel sulfur on emissions performance**

Mercedes A170 was used as the test vehicle

- 1999 Mercedes A170
  - Curb Weight: 2,400 pounds
  - 5-speed manual transaxle
- 1.7L Turbocharged diesel engine
  - Common rail direct-injection
  - Intercooled, with EGR
  - 4 valves per cylinder
  - 89 Hp (66 kW) @ 4,200 RPM
- No air conditioning system was installed (impacts SC03 results).
- Not certified for sale in U.S.

How is *DVECSE* different from DECSE?

- **DECSE focused primarily on determining the effects of fuel sulfur on emissions control devices.**
  - **Mostly steady-state tests on stationary engine dynamometers**
  - **Largely aimed at heavy-duty applications**
- ***DVECSE* focused on demonstrating the potential effectiveness of these devices**
  - **In transient light-duty *vehicle* applications**
  - **Investigating short term fuel sulfur effects.**

DVECSE used the same fuels and lubricant as the DECSE program

- **Fuels: Phillips Ultra-low Sulfur base fuel (3 ppm sulfur)**
- **30 and 150 PPM fuels used sulfur dopants (Blended by Phillips)**
- **Lubricant: Shell Rotella T 15W-40**

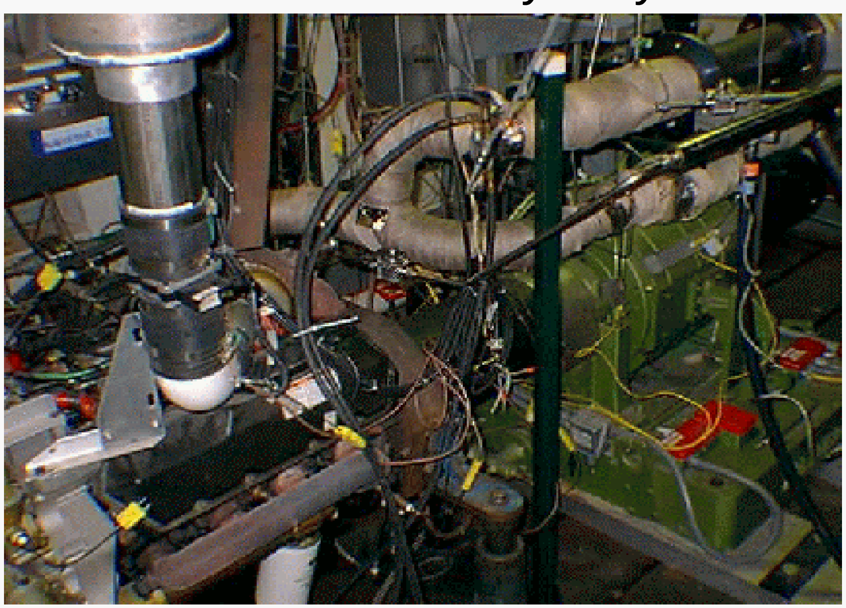
How are heavy-duty engines and standards different from light-duty?

Heavy-duty

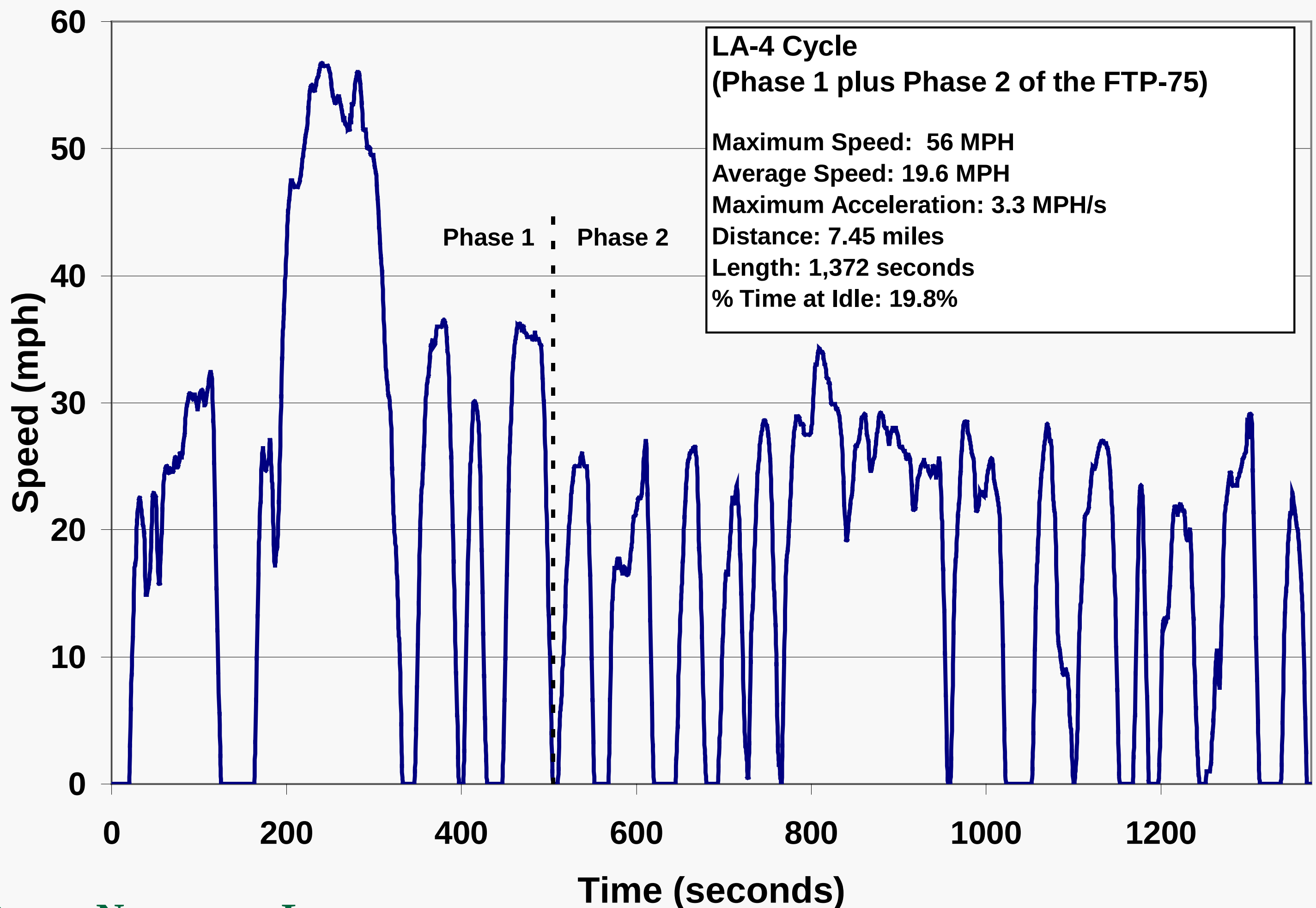
- Transient *engine* certification
- Stationary engine dynamometer
- Emissions reported in *g/hp-hr*
- Historically produce lower brake-specific PM at the expense of NOx
- Acceptable steady-state surrogates (AVL 8-mode, OICA) are publicly available for heavy-duty tests

Light-duty

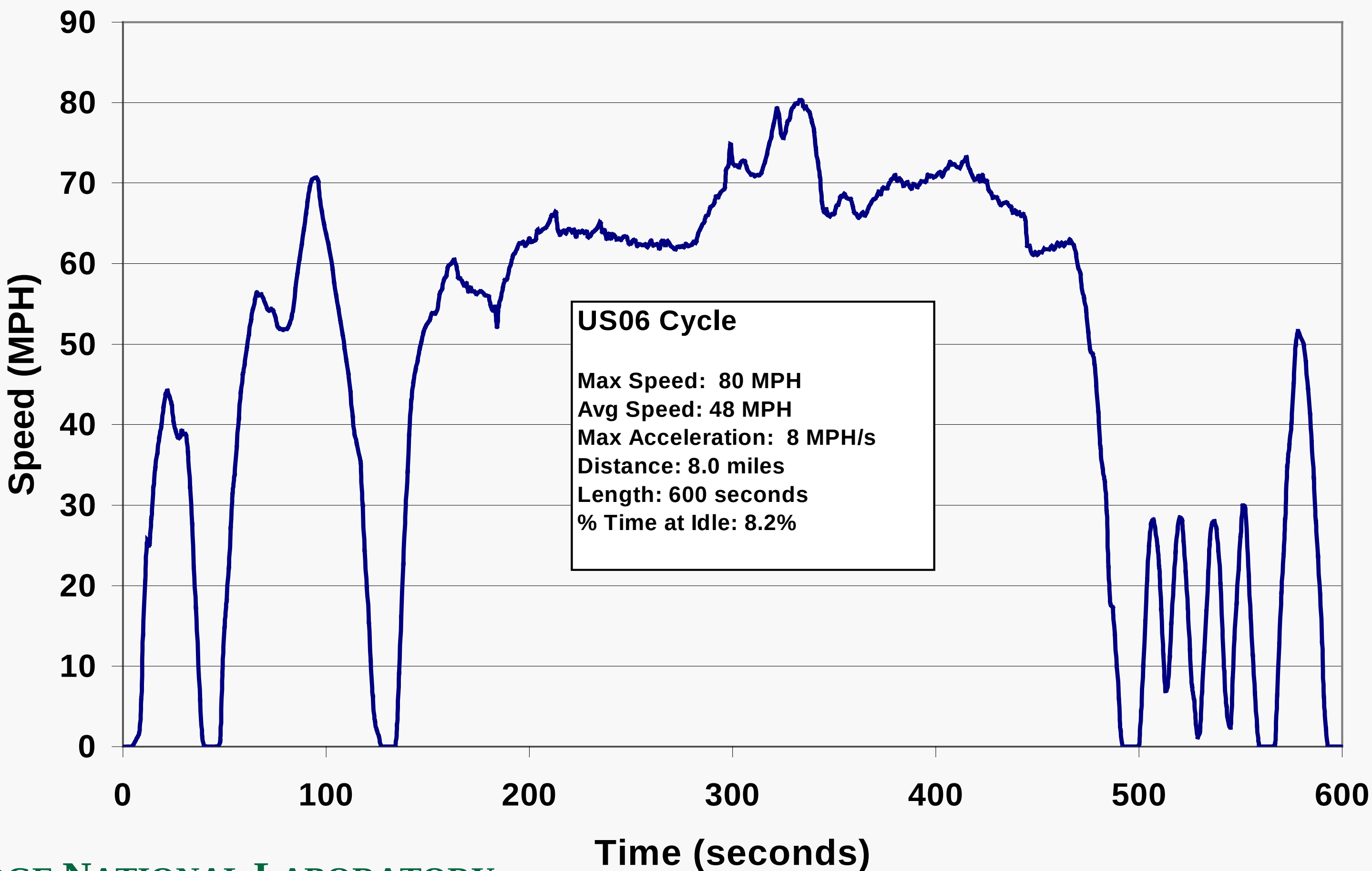
- Transient *vehicle* certification
- Chassis dynamometer
- Emissions reported in *g/mi*
- Historically produce lower brake-specific NOx at expense of PM
- No widely accepted steady-state surrogate



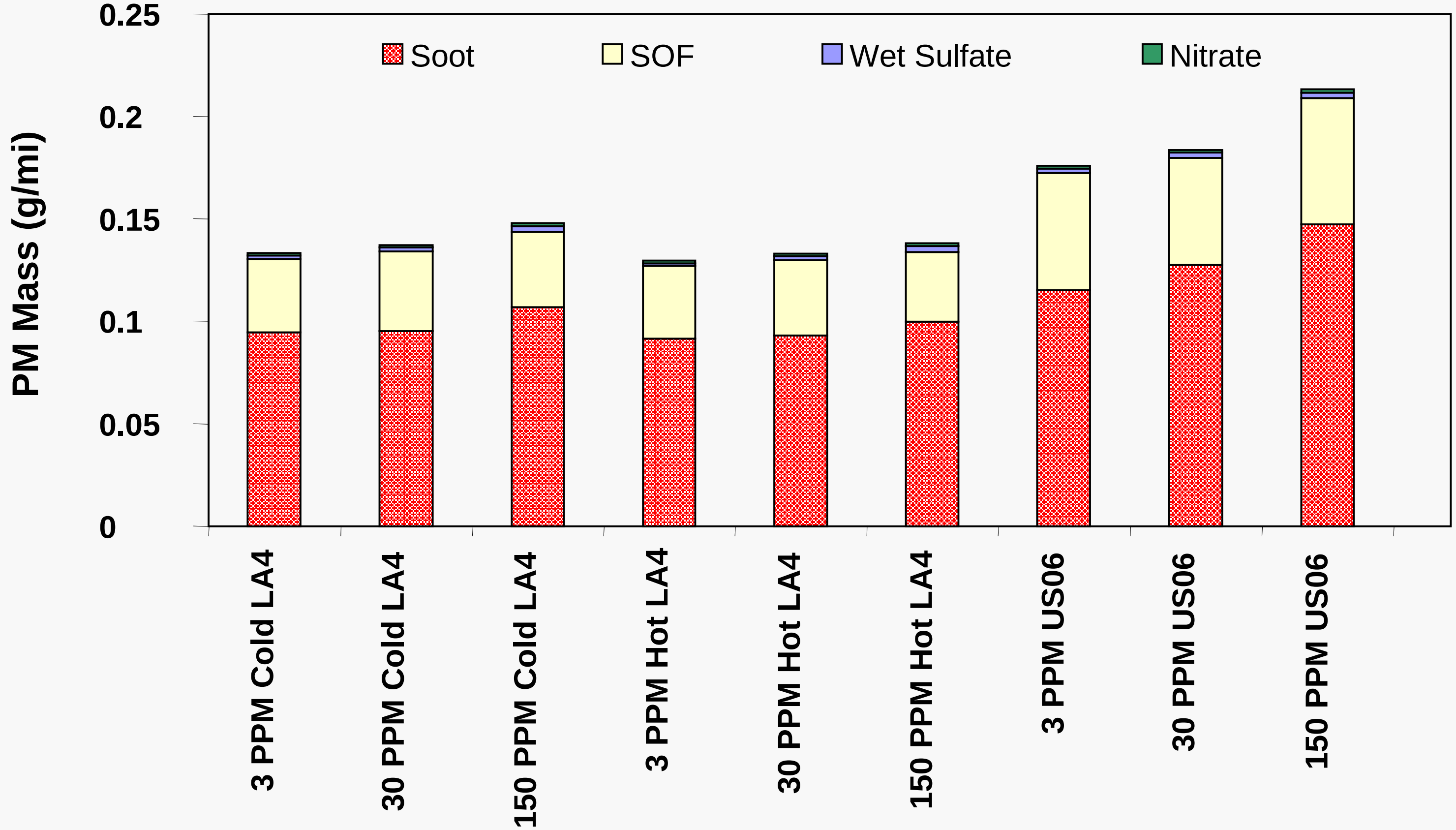
The FTP-75 is currently the standard light-duty drive cycle for emissions regulation in the U.S.



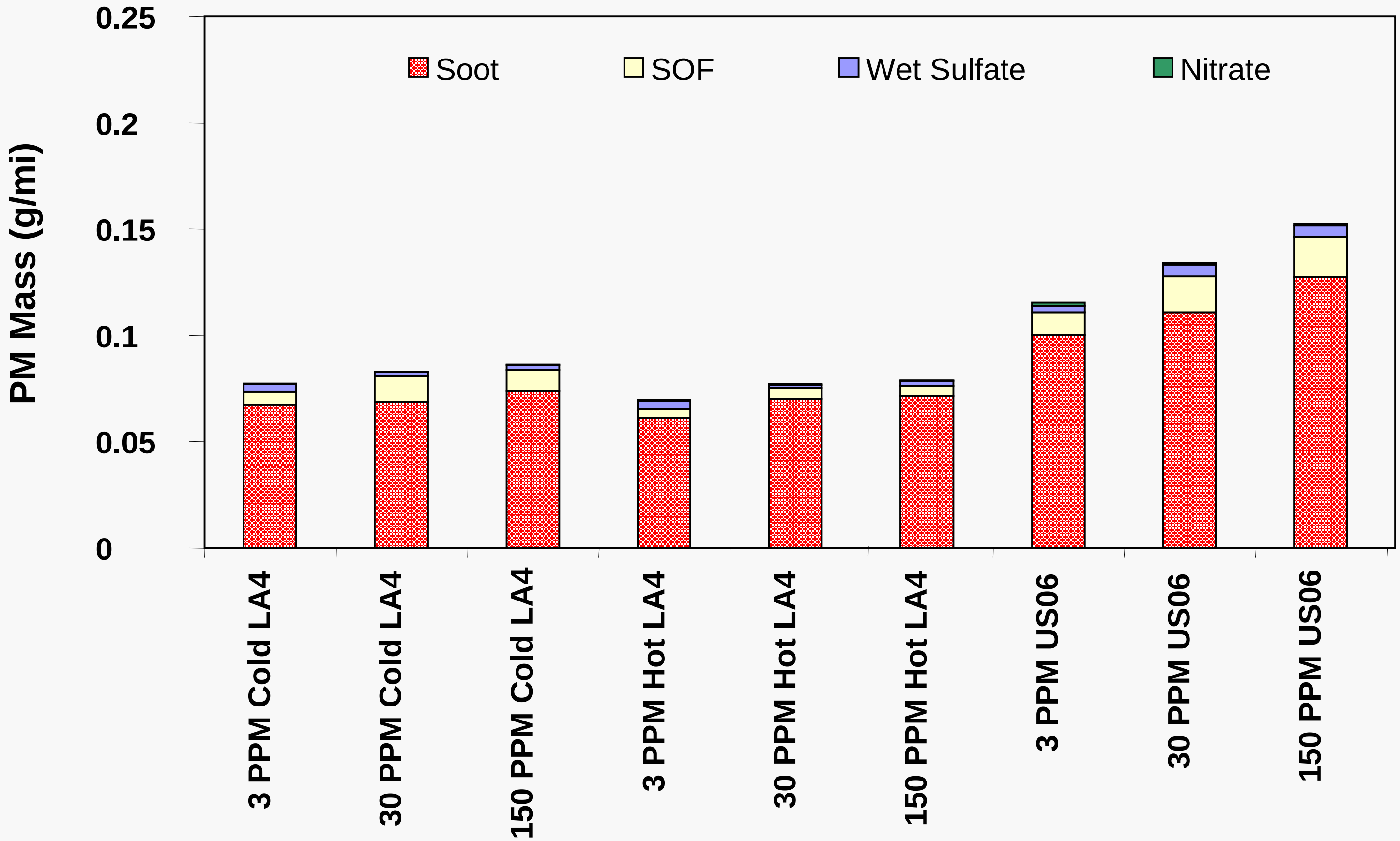
The US06 cycle is a new high-speed, high-load cycle being added to light-duty emissions certification



As expected, engine-out PM emissions contained a significant soluble organic fraction



The OEM catalysts reduced PM emissions by 30-40% (primarily by oxidation of SOF)

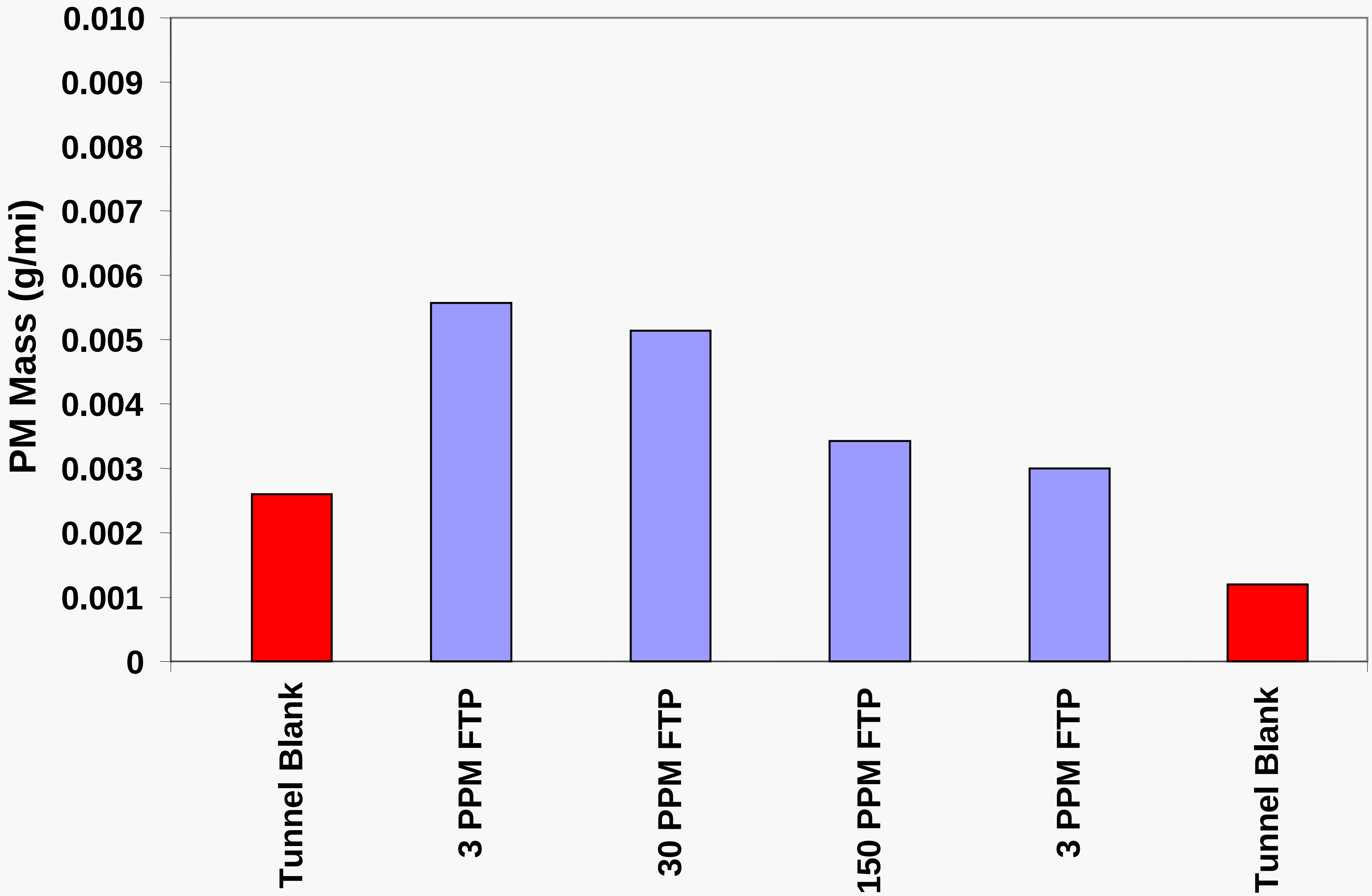


Catalyzed diesel particulate filter (CDPF) was installed in an underfloor location for emissions evaluation

- **Wall-flow exhaust filter. Catalyzed oxidation of accumulated PM is accomplished passively with exhaust heat**
- **Tailpipe emissions (except PM) were similar to OEM results - PM drastically reduced**
- **No statistically significant fuel economy penalty. Estimates based on flow and pressure data set penalty at less than 3%**
- **Triplicate tests were run per sample filter to increase the PM mass collected for fractionation**

The CDPF reduced PM emissions by more than 95%, to below 0.01 g/mi

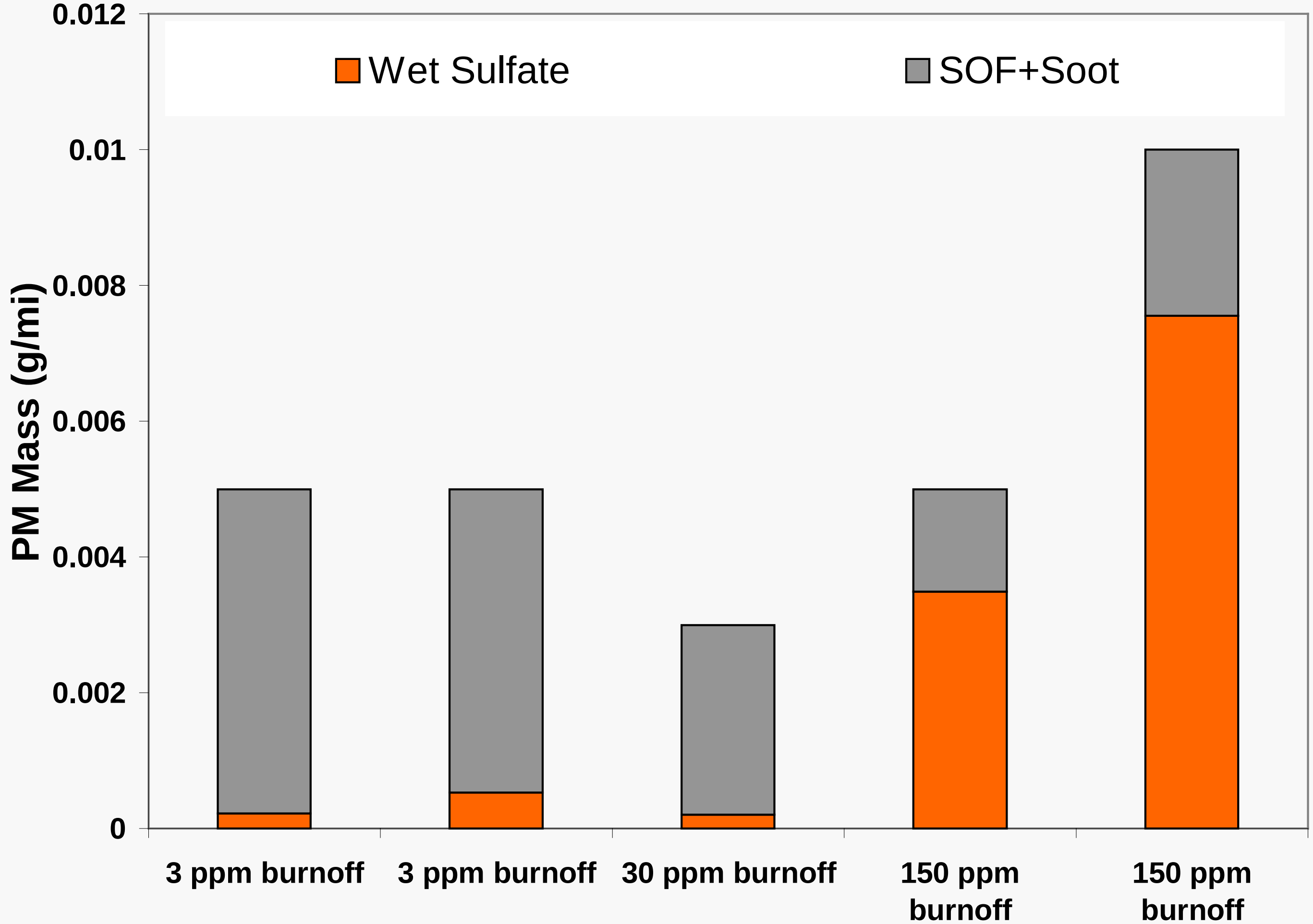
No attempt was made to demonstrate durability of this technology or its emissions reduction potential at full useful life



CDPF was not completely passive in these evaluations. *(Regeneration accomplished by driving at high speeds at road-load)*

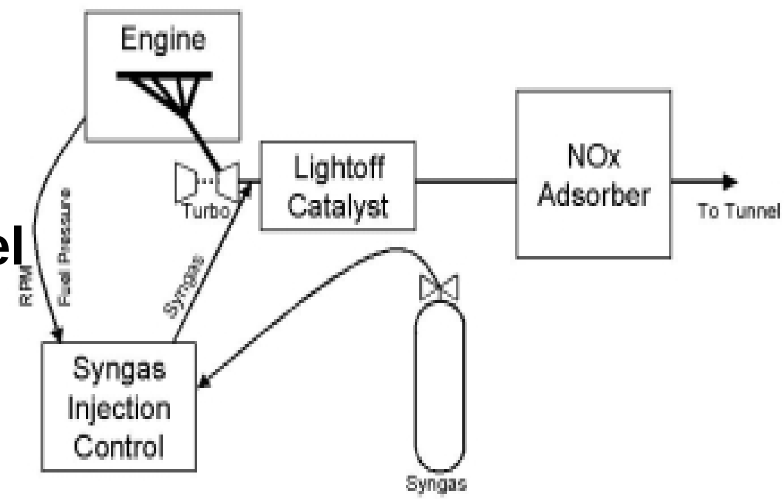
- **Exhaust temps too low for completely passive CDPF operation**
- **Regeneration took approximately 1 hour at about 85 mph. Regeneration also observed at 70 mph, but would have taken longer**
- **Regeneration conducted after approximately 100 miles of test cycles on each fuel (at beginning of fuel switch)**
- **US06 cycle generated temperatures hot enough to partially regenerate the CDPF, but for short periods of time**
- **With more development of the technology, close-coupling, and perhaps engine-control accommodation, complete regeneration may be accomplished during normal driving**

CDPF regeneration (burnoff) also produced very low PM emissions. Sulfate conversion significant only during regeneration on 150-ppm sulfur fuel



NOx adsorber requires periodic rich excursions. Synthesis gas was periodically injected into the exhaust to regenerate / reduce NOx

- **Simulated late-cycle, in-cyl injection**
- **Aftermarket engine controller used to meter the flow of synthesis gas into exhaust system through 4 gaseous fuel injectors.**
  - **Synthesis gas composed of CO, hydrogen, and ethylene.**
  - **Syngas injected upstream of a lightoff catalyst to consume excess exhaust oxygen**

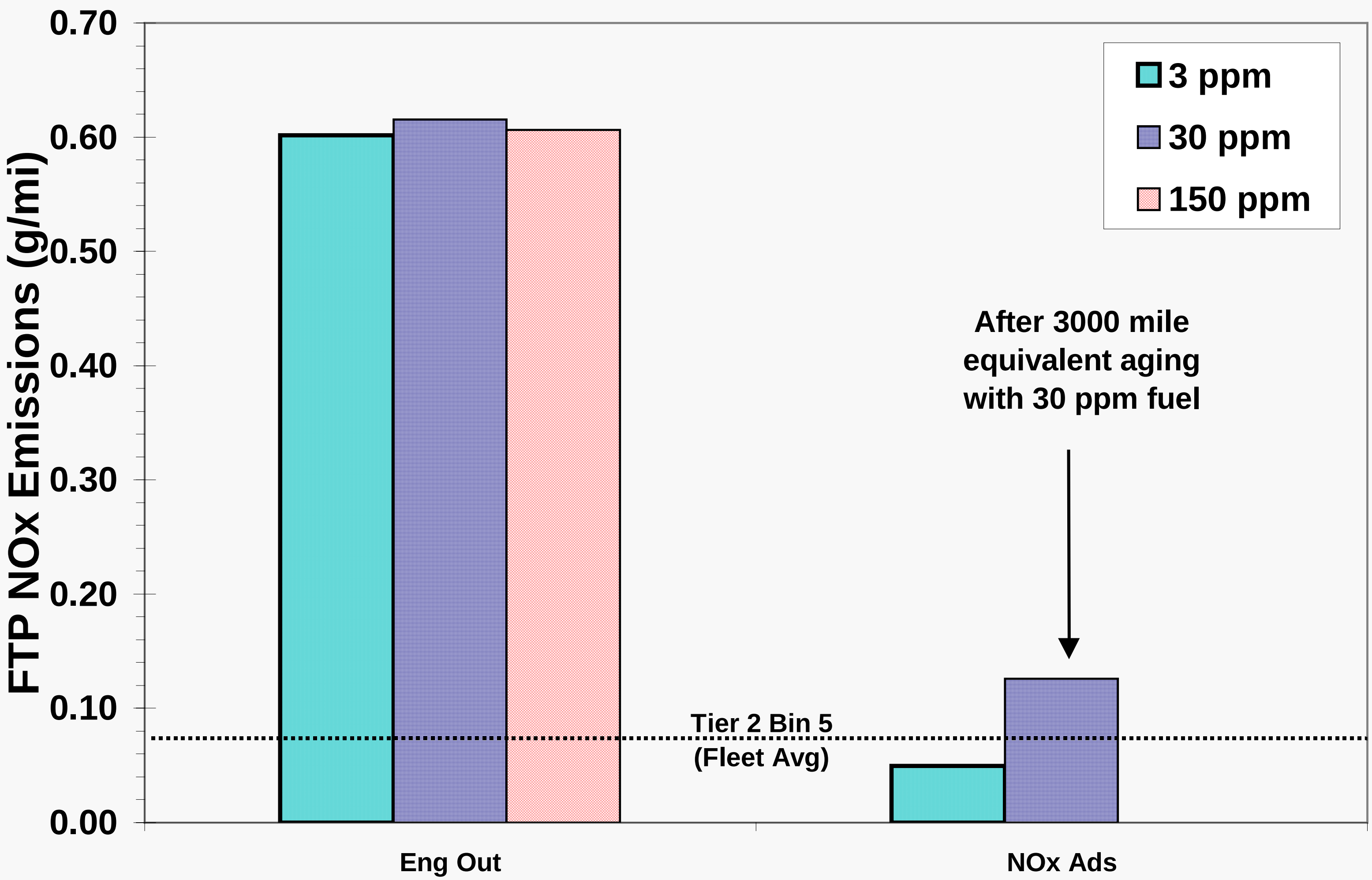


64-66% CO
31-32% H_2
2-5% C_2H_4

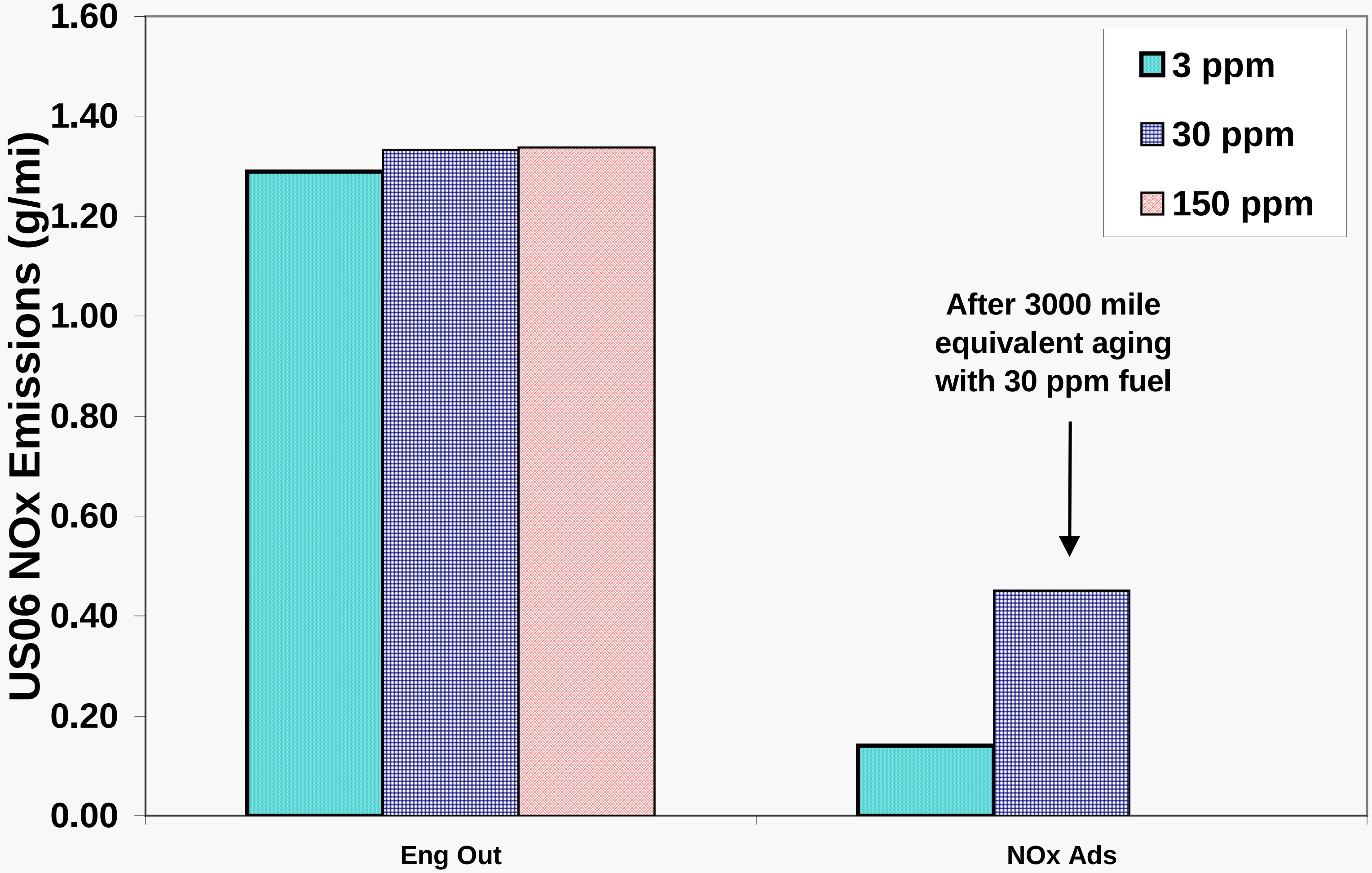
NOx adsorber was installed in an underfloor location, with a close-coupled lightoff catalyst upstream

- **NOx adsorber was evaluated first with 3 ppm fuel**
- **Sulfur loading phase consisted of 600 miles of operation on 150 ppm sulfur DECSE fuel (simulating 3,000 miles with 30 ppm)**
  - **SO_2 measurements during loading phase indicated no significant SO_2 slip**
- **Triplicate 30 ppm evaluations conducted following sulfur loading phase**

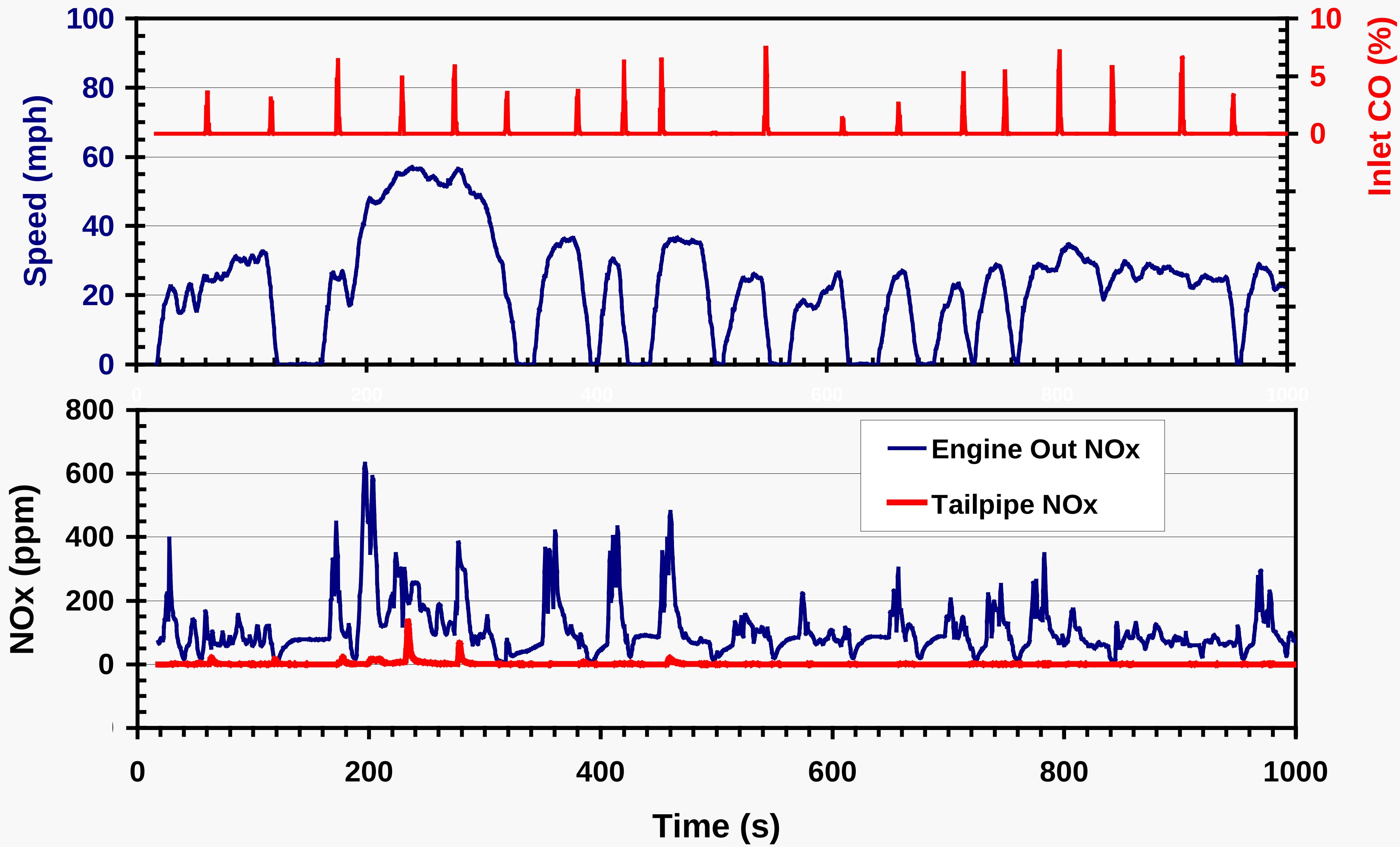
Adsorber provided 92% NOx reduction from the engine-out level on FTP with 3 ppm sulfur fuel. 3,000 miles equivalent with 30 ppm fuel degraded performance to only 80% reduction



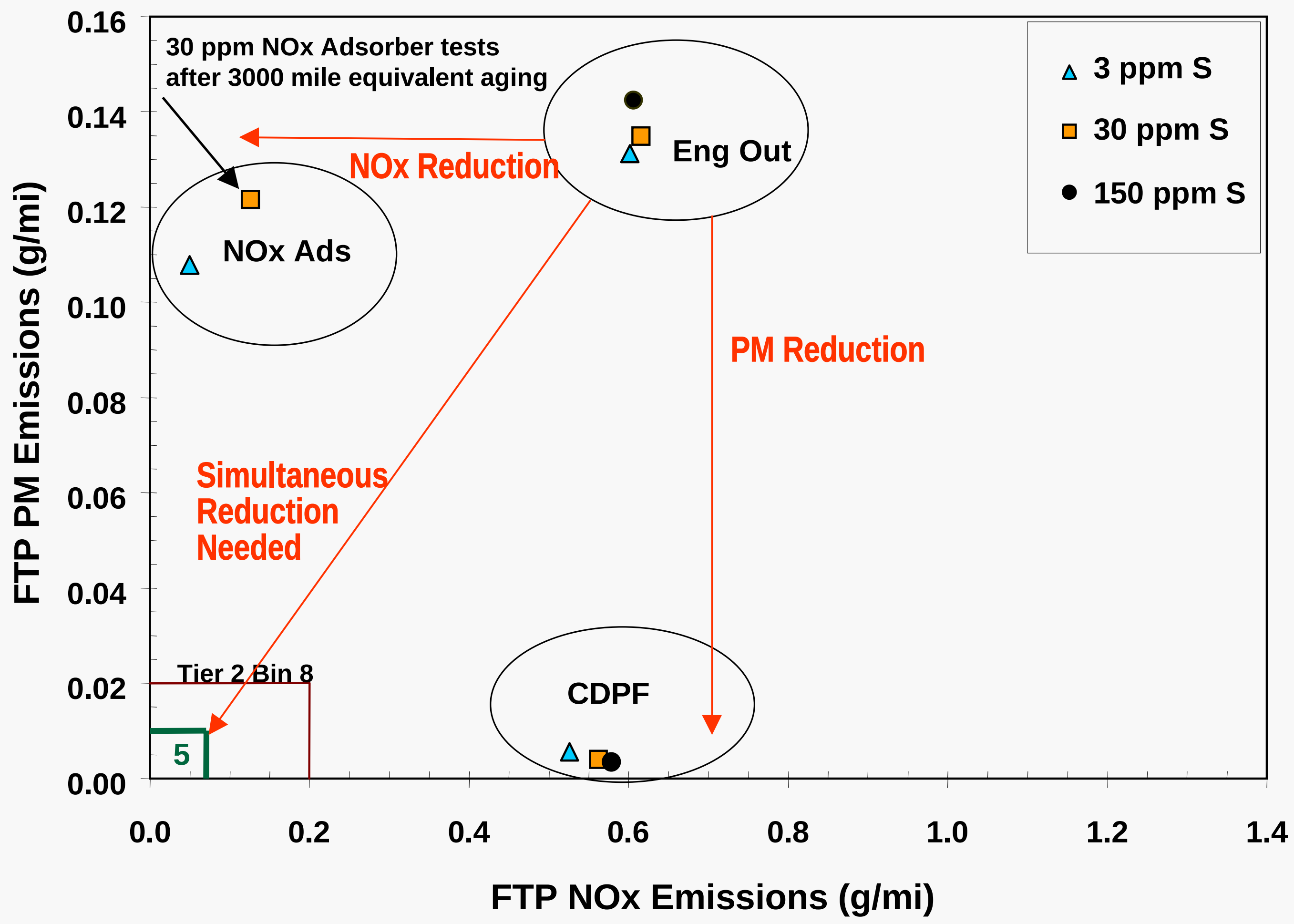
Adsorber provided 89% NOx reduction from the engine out level on US06 cycle with 3 ppm sulfur fuel. 3,000 miles equivalent with 30 ppm fuel degrades performance to only 66% reduction



NOx adsorber was regenerated at nominal 1 minute intervals



Evaluations of individual devices show a path towards meeting Tier 2 emissions standards

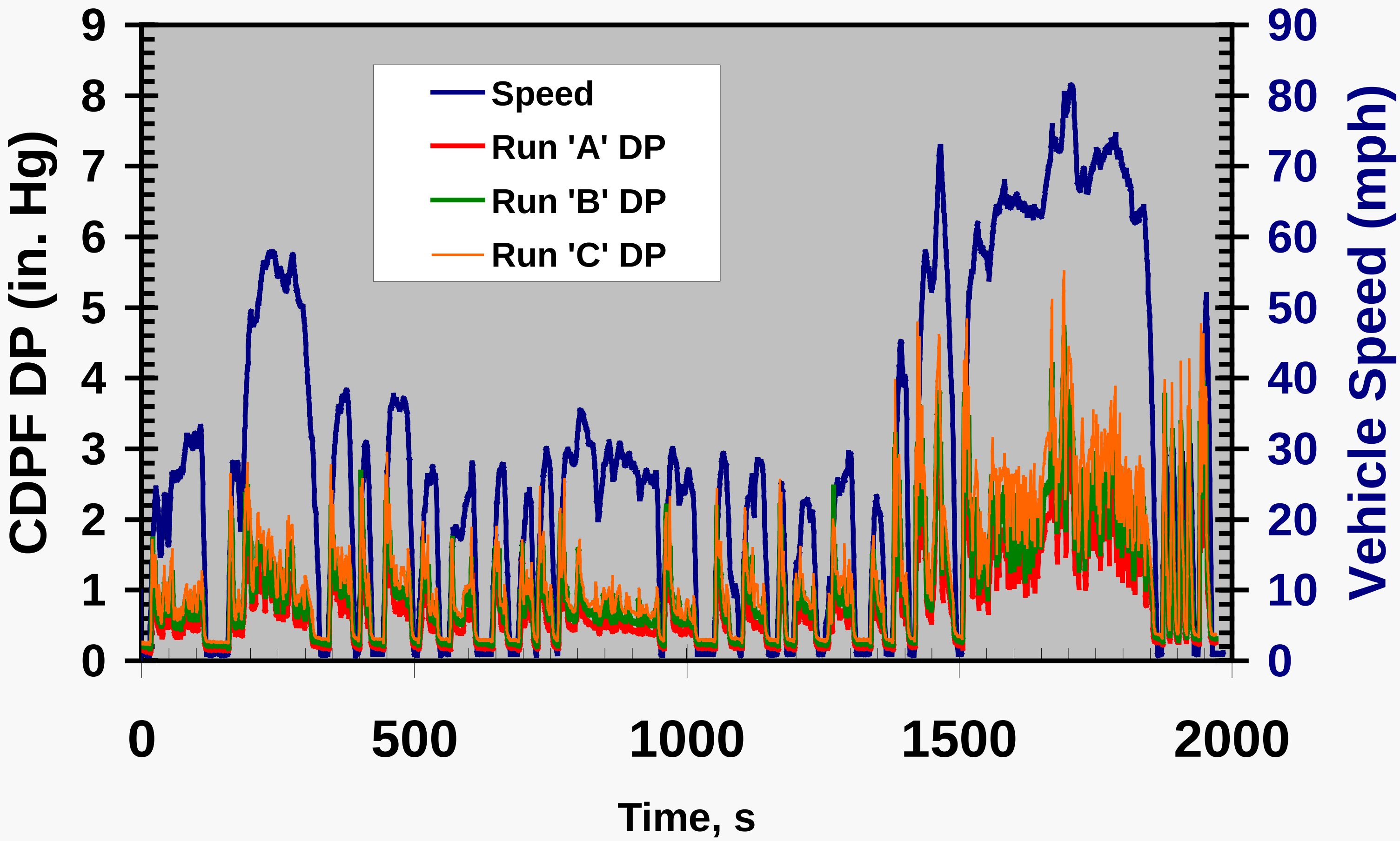


Phase 2 Interim Results: Completed initial system evaluations (CDPF and NOx adsorber together)

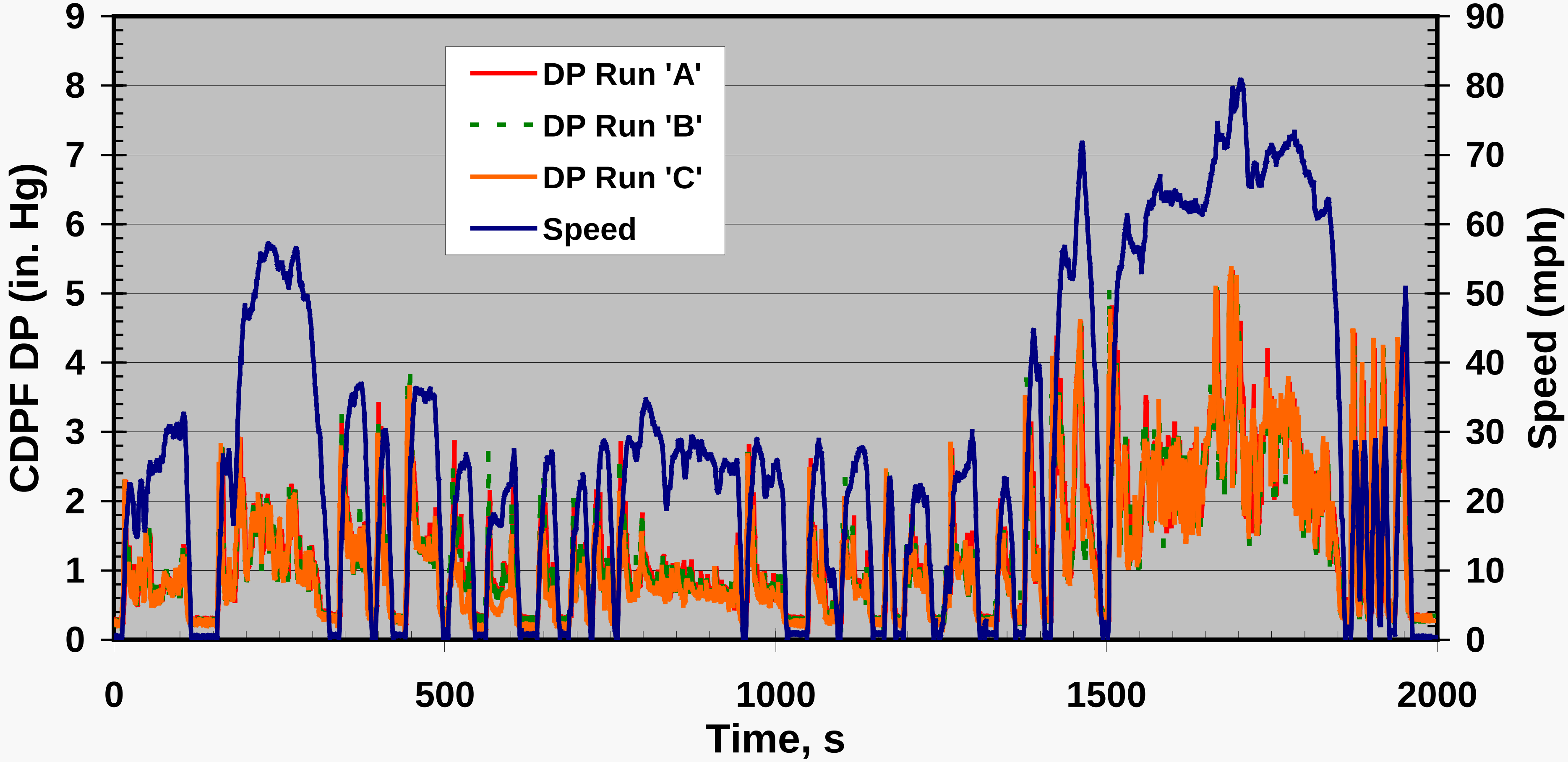
- **CDPF appears to be "inherently passive" when used in conjunction with actively controlled NOx adsorber**
- **Rich excursions (NOx regeneration events) can sacrifice some PM control**
- **Simultaneous diesel NOx and PM control appear achievable, but many challenges remain in optimizing the emissions control system**
  - **Controlling ALL criteria pollutants simultaneously**
  - **Minimizing fuel economy penalty**
  - **Consumer acceptance, durability, etc.**

- **All phase 2 evaluations done with 3 ppm sulfur fuel**

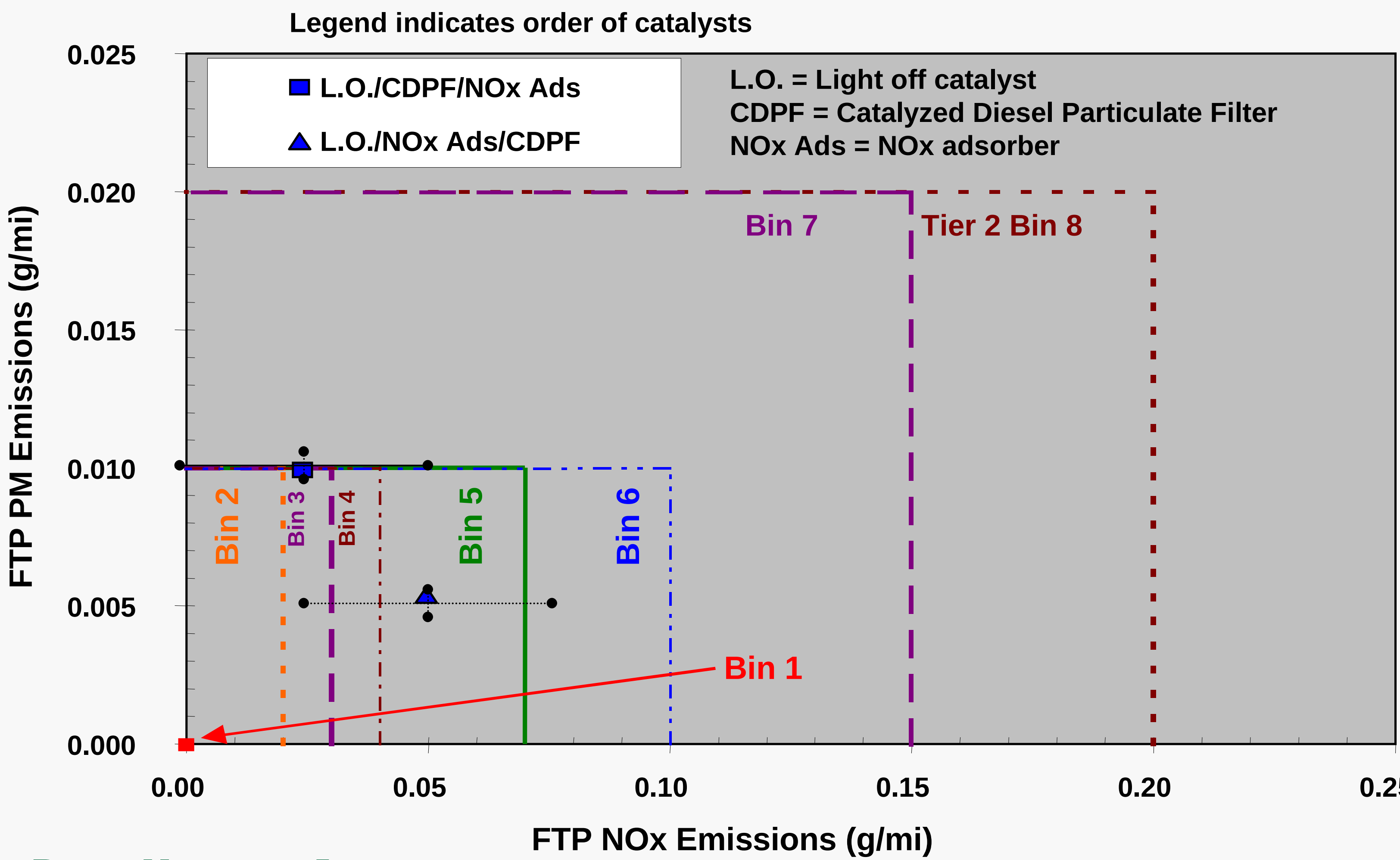
Pressure drop increased from test-to-test in Independent Phase 1 CDPF evaluations



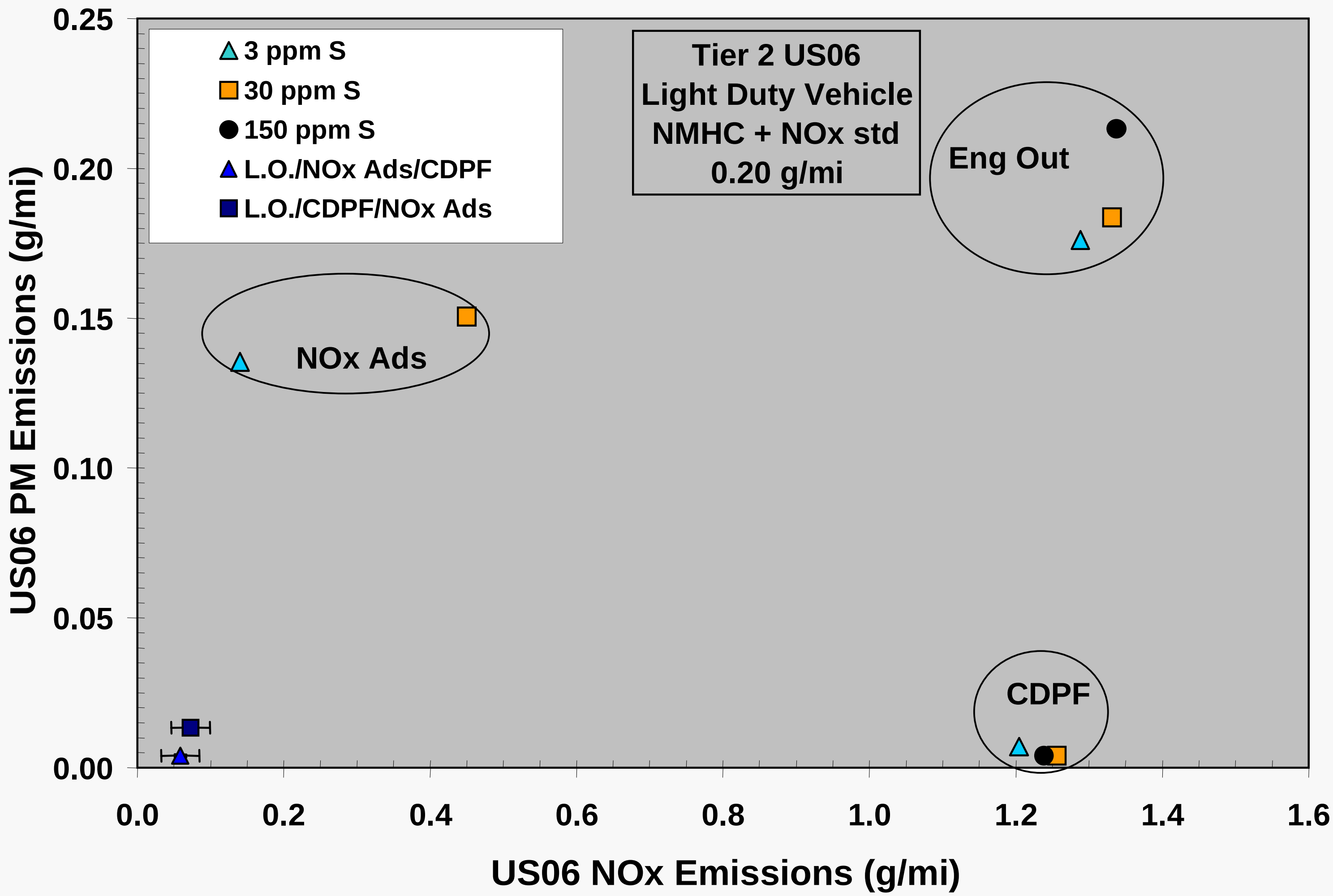
In combined CDPF/NOx adsorber system evaluation, active NOx adsorber control appears to promote continuous CDPF regeneration.
(No appreciable increase in CDPF DP from test-to-test)



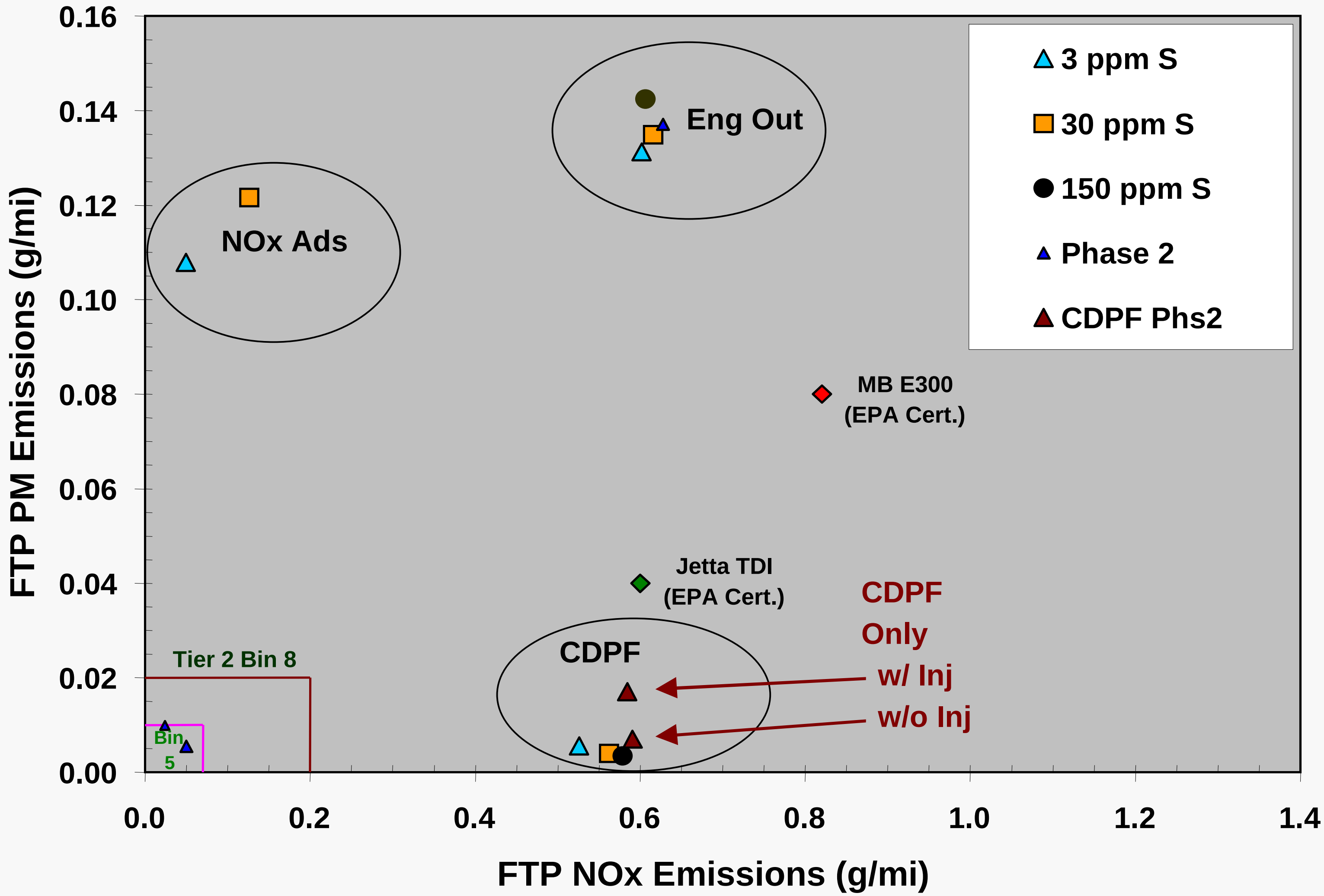
Combining NOx adsorber and CDPF reduced both PM and NOx. Regeneration of NOx adsorber can increase PM over independent CDPF evaluations



System tests on US06 also resulted in excellent NOx and PM control



CDPF was re-tested separately in Phase 2 to verify that NOx adsorber regeneration was causing higher PM



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Summary and Conclusions

- **Tier 2 emissions levels appear achievable in research situation with small diesel vehicles and advanced controls, but much more work is still required**
- **Fuel sulfur greatly reduced the effectiveness of the NOx adsorber, but had minimal effects on the OEM catalysts and the CDPF in these *short-term* tests**
- **Current-technology NOx adsorbers will require desulfurization, sulfur traps, or other sulfur sequestration technology to be viable**
- **Under Tier 2, larger vehicles may require greater reductions than smaller vehicles to meet the same standards**

Acknowledgments

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