Californias
Advanced Clean Cars
Midterm Review

Appendix K:
PM Emission Testing Results

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California Environmental Protection Agency
Air Resources Board

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I. Introduction

To assess the particulate matter (PM) emissions of currently available low greenhouse gas (GHG) emitting engines, a vehicle testing campaign was conducted at the California Air Resources Board. Vehicles were chosen to represent a variety of low-GHG technologies, particularly targeting newer engines that were expected to have powertrains representative of future technologies. These engines may have undergone recent revisions that likely would have considered compliance with the upcoming 3 mg/mi PM standard. Staff tested vehicles and conducted gravimetric PM emission measurements to look at mass emission levels during the certification driving cycles and real time PM emissions measurements to qualitatively determine where in the driving cycle PM emissions occur. A total of 15 vehicles were tested and the results of the testing are summarized in this appendix.

II. Test Procedures and Test Methods

Testing was conducted in light-duty test cells at the ARB Haagen-Smit Laboratory (HSL) in El Monte, California. Each test cell is equipped with a 48-inch single-roll electric chassis dynamometer, a constant volume sampler (CVS), and one or more $PM_{2.5}$ sampling systems that meet requirements defined by 40 CFR Part 1065. The PM gravimetric analyses meet the requirements in 40 Code of Federal Regulations (CFR) Part 1066, and followed the approved gravimetric analysis and filter media handling techniques.[1,2,3]

The typical CVS flowrate of the federal test procedures (FTP) test cycle at ARB is 350 standard cubic feet per minute (scfm). The test fuel was California Phase III certification-grade gasoline containing 10% ethanol.

Real time PM emission measurements were also drawn from the CVS tunnel near where the PM mass samples were drawn. Real time instruments were operated according to each instrument's manufacturer protocol. Solid particle number (SPN) was measured with a PMP-compliant method (d50 of 23nm) using either a Horiba Solid Particle Counting System (MEXA-2000 SPCS) or AVL solid particle counter (489 APC), both of which consist of a volatile particle removal unit and a Condensation Particle Counter (CPC). Black carbon (BC) was measured with an AVL Micro Soot Sensor (MSS 483), which quantifies BC with photoacoustic spectroscopy at 808nm. SPN measurements were recorded at 1 Hz frequency and BC measurements at 1 Hz or higher frequency. Additional PM metrics from TSI Engine Exhaust Particle Sizers (EEPS) and either TSI or Grimm CPC were also collected, but are not included in this document.

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[1] ARB, 2016a. California Air Resources Board. SOP MV-AEROSOL-145 v5.3. June 2015. https://www.arb.ca.gov/testmeth/slb/sop145v5_3.pdf
[2] ARB, 2016b. California Air Resources Board. SOPs MV-AEROSOL-156. January 2016. https://www.arb.ca.gov/testmeth/slb/sop156_xrf_v2_0.pdf
[3] ARB, 2016c. California Air Resources Board. SOPs MV-AEROSOL-158. October 2014. https://www.arb.ca.gov/testmeth/slb/sop158v3.pdf

On-board diagnostics (OBD) data was also collected from most vehicles tested. Some of the parameters that were collected include vehicle speed, engine speed, lambda ratios, mass air flow, calculated load values, cylinder 1 advance timing, and throttle and accelerator positions.

PM mass tunnel blanks (filtered dilution air sampled at the end of the CVS) were collected regularly and were generally equivalent to <0.1 mg/mile. One higher-emitting vehicle, a Ford F-150, which was tested with tunnel blanks that reached up to approximately 0.5 mg/mi, as noted in the testing results below. Earlier work has measured tunnel blank values of 2 x 10^9 particles/km for SPN and 0.15 mg/mile for BC.[4,5]

Driving Cycles

LDV PM emission standards are tied to specific driving cycles on a chassis dynamometer. The driving cycle is intended to represent a specific duty or activity of a vehicle during its operation. The two most relevant drive cycles for LDV PM emission standards are the standard Federal Test Procedure (FTP) cycle and the high speed, high acceleration portion of the Supplemental FTP (SFTP or US06).

Emission tests results presented later will be given primarily for these two cycles. Some vehicles were also tested on other cycles for research purposes. The California Unified Cycle (UC) was also used and it was originally developed by ARB for use in inventory modeling of emissions from light-duty vehicles. The Worldwide Harmonized Light Duty Test Cycle (WLTC) is of interest for comparison to European vehicle emission standards. However, testing done on the WLTC was done using FTP methods, not Worldwide Harmonized Light Vehicles Test Procedures (WLTP) methods, for determining vehicle test weights and road loads so the results are not directly comparable to testing done in accordance with the official WLTP requirements. For some vehicles, the Highway test cycle was also used. However, the test results for cycles other than the FTP and US06 are not analyzed because the data was limited and was for research purposes.

Federal Test Procedure Driving Cycle

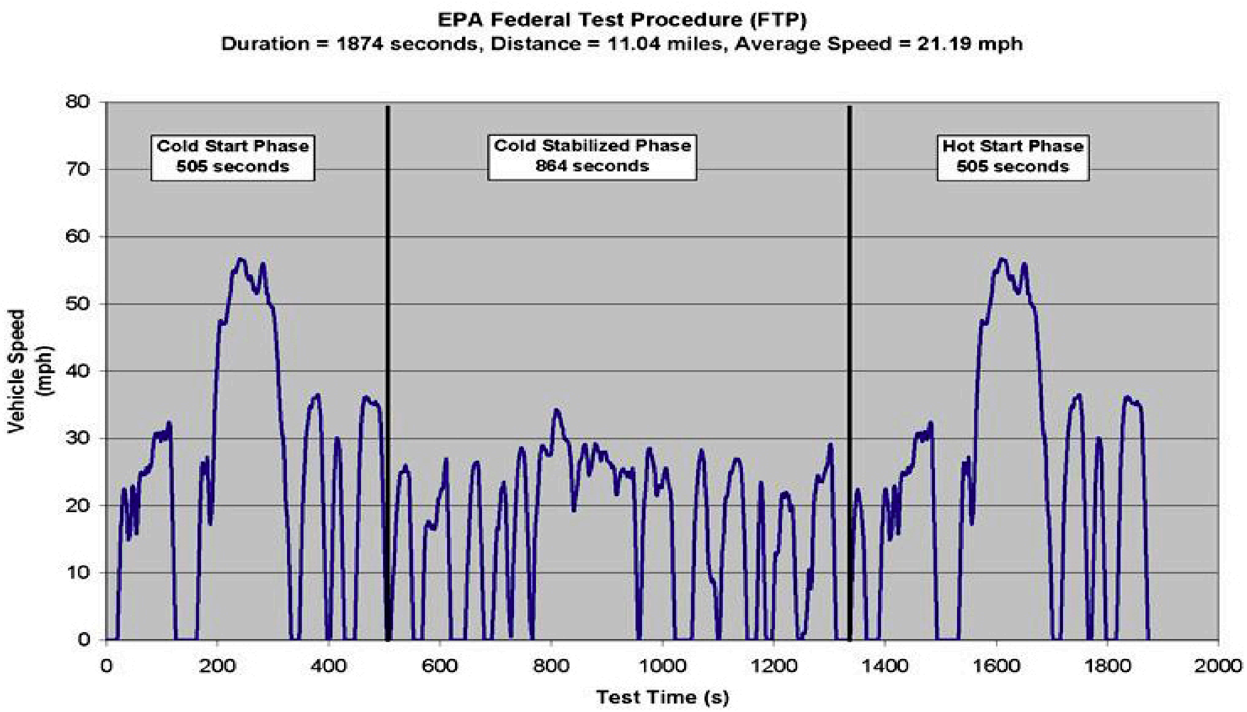
The FTP consists of two urban dynamometer driving schedules (UDDS) run in series (Figure 1). Each UDDS is divided into two phases, with a start phase running for 505 seconds and a stabilized phase running for an additional 864 seconds. The first UDDS is considered a cold start test because the engine is started in a “cold” condition after an overnight engine off ‘soak’ period. The second UDDS is considered a hot start test because it begins with a “hot” engine from a car that has been sitting with the engine off for 10 minutes after the first UDDS ends. The stabilized phase in both UDDS cycles is assumed to have the same emissions; therefore, it is typically not run after the hot start. This “three-phase” driving schedule is commonly referred

[4] ARB, 2012. California Air Resources Board. “LEV III Appendix P. Technical Support Document: Development of Particulate Matter Mass Standards for Future Light-Duty Vehicles”. January 2012. https://www.arb.ca.gov/regact/2012/leviiighg2012/levappp.pdf

[5] Kamboures, 2013. Kamboures, M. A., et.al. . (2013). “Black Carbon Emissions in Gasoline Vehicle Exhaust: a Measurement and Instrument Comparison”. Journal of the Air and Waste Management Association 63, 886-901.

to as an FTP-75. The FTP-75 has a total distance travelled of 11.04 miles, an average speed of 21.2 miles per hour (mph), and a total duration of 1874 seconds. The emission result is a weighted average where the cold start and stabilized phase (the first UDDS cycle) is weighted at 43 percent and the hot start and stabilized phase (equivalent to the second UDDS) is weighted at 57 percent.

Figure 1 - The FTP test cycle speed trace[6]

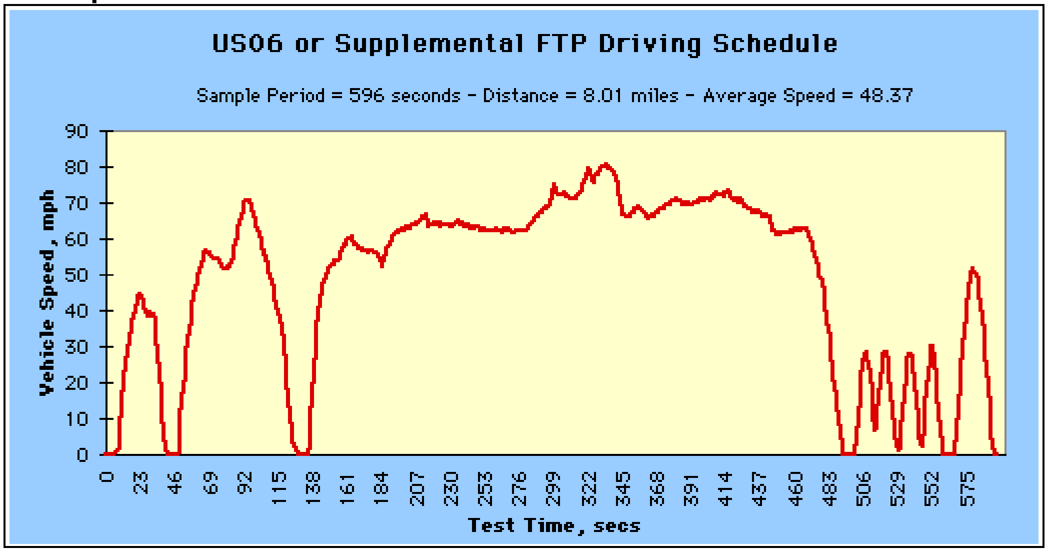


II.A.1 Supplemental Federal Test Procedure (SFTP or US06) driving cycle

The US06 was developed to reflect aggressive, high speed, and high acceleration driving behavior. The US06 driving cycle is shown in Figure 2. It is a hot start test typically run with a prep cycle to ensure the car is warmed up; the US06 test immediately follows the prep cycle without an engine off or restart. The US06 cycle represents an 8.01 mile route with an average speed of 48.4 mph, maximum speed of 80.3 mph, maximum acceleration rate of 8.46 mph/sec, and duration of 596 seconds. The higher acceleration rates and speeds of the US06 cycle lead to higher engine loads, which historically often led to higher PM emission rates.

[6] EPA, 2016a. US Environmental Protection Agency. "Emission Standards Reference Guide for On-road and Non-road Vehicles and Engines". August 2016. http://www.epa.gov/otaq/standards/light-duty/ftp.htm

Figure 2 - US06 speed trace[7]



II.A.2 Selection of Vehicles

As discussed in Appendix J, the light duty vehicle fleet is moving towards gasoline direct injection (GDI) technology to comply with the Low Emission Vehicle (LEV III) greenhouse gas (GHG) standards. GDI technology was of particular concern in terms of PM emission impacts when the more stringent standards were first adopted in 2012. Test results from early GDI equipped engines showed significantly higher PM emissions than conventional port-fuel injector (PFI) systems. The 3 mg/mi PM emission standard for the FTP starts phasing in 2017 and will be fully implemented by 2021. Some manufacturers have already redesigned their engines to meet this standard. The US06 PM standard of 6 mg/mi starts phasing in 2017 for vehicles complying with the 3mg/mi FTP standard and will be fully implemented by 2021. However, vehicles in 2017 and 2018 will be certified to interim higher standards of 10 mg/mi for the US06.

Given the rapidly increasing fraction of the fleet utilizing GDI equipped engines, testing for this program primarily targeted GDI engines. The chosen technologies included:

- Atkinson cycle GDI
- Dual PFI/GDI systems
- Downsized turbocharged GDI
- GDI with Piezo injectors
- GDI plug-in hybrid electric vehicles (PHEV)
- PFI hybrid or PHEV

Table 1 summarizes the vehicles tested and corresponding engine technologies, including fuel injection, turbocharging, engine displacement, model year, and improved control strategies.

[7] EPA, 2016b. US Environmental Protection Agency. “Dynamometer Drive Schedules US06”. April 2016. https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules

Table 1 - Overview of low-GHG engine technologies tested

Engine technology category	Model year	Make	Model	Engine
Atkinson cycle GDI, high compression ratio, small displacement	2015	Mazda	3	2.0L SkyActiv
PFI+GDI systems	2012	Lexus	IS350	3.5L 2GR-FSE
	2015	Subaru	BRZ	2.0L
	2016	Toyota	Tacoma	3.5L Atkinson V6
Downsized turbocharged high BMEP GDI	2015	Ford	F-150	2.7L turbo
	2014	Ford	Fiesta	1.0L turbo
	2014	Mini	Cooper	2.0L turbo
	2016	VW	Jetta	1.4L turbo
Downsized turbocharged GDI with Piezo injectors	2014	Daimler	CLA 250	2.0L turbo
GDI General	2015	GM	Malibu	2.5L
	2015	Honda	Accord	2.4L
PFI Hybrid/PHEV	2013	Chevy	Volt	1.4L
	2013	Toyota	Prius Plug-in	1.8L
	2016	Toyota	Prius	1.8L
GDI PHEV	2016	Hyundai	Sonata Plug-in	2.0L

III. Test Results:

Summary and Analysis of Gravimetric Test Results

A total of 15 vehicles were tested, of which 9 were GDI vehicles, 3 were dual GDI/PFI systems, and 3 were PHEV with PFI.

Average and individual test results for each vehicle for FTP-75 and US06 are presented in Table 2. In general, each vehicle was tested at least three times for FTP and US06, but due to occasional sampling or analysis issues, not all tests have valid PM mass measurements.

Table 2 - Summary of PM mass results from vehicles tested at CARB

	FTP			US06		
Vehicle	**Average Mass (mg/mi)**	**Indiv. test Mass (mg/mi)**	**SD Mass (mg/mi)**	**Average Mass (mg/mi)**	**Indiv. test Mass (mg/mi)**	**SD Mass (mg/mi)**
2015 Mazda 3 2.0 liter GDI 4,000 miles	**1.46**	1.30 1.65 1.58 1.29	0.19	**0.58**	0.46 0.90 0.36 0.59	0.23
2012 Lexus IS350 3.5 liter GDI+PFI 40,000 miles	**5.64**	5.55 5.78 5.29 5.95	0.29	**1.32**	1.28 1.35	0.05
2015 Subaru BRZ 2.0 liter GDI+PFI 15,000 miles	**0.96**	0.91 0.79 1.19	0.21	**3.07**	1.89 4.32 3.00	1.22
2016 Toyota Tacoma 3.5 liter GDI+PFI 51,000 mi	**0.40**	0.34 0.42 0.43	0.05	**2.26**	1.97 1.46 3.36	0.98
2015 Ford F150* 2.7 liter turbo GDI 15,000 mi	**5.50***	5.08* 5.63* 4.53* 6.76	0.95	**3.91***	3.44* 7.34* 2.53* 2.86* 5.02* 1.61* 4.57	1.91
2014 Ford Fiesta 1.0 liter turbo GDI 26,000 miles	**1.41**	1.01 1.52 1.42 1.56 1.55	0.23	**1.36**	1.32 1.67 1.21 1.37 1.22	0.18

2014 Mini Cooper 2.0 liter turbo GDI 28,000 mi	**0.43**	0.49 0.44 0.36	0.07	**1.21**	1.43 1.26 0.79 1.39 1.14 1.25	0.23
2016 VW Jetta TSI 1.4 liter GDI turbo 5,000 mi, L2ULV	**0.28**	0.25 0.38 0.21	0.09	**0.98**	1.00 1.09 0.84	0.13
2014 Mercedes CLA 2.0 liter GDI turbo 30,000 mi, L2ULV	**0.28**	0.12 0.37 0.34	0.14	**0.34**	0.54 0.25 0.18 0.40	0.16
2016 Chevy Malibu 2.5 liter GDI 18,000 mi, ULEV	**7.03**	6.73 6.35 8.01	0.87	**2.05**	1.71 1.51 2.94	0.77
2016 Honda Accord 2.4 liter GDI 27,000 mi	**0.89**	0.67 0.99 1.02	0.19	**1.26**	0.04 1.73 1.33 1.92	0.85
2013 Chevy Volt 1.4 liter PHEV PFI 8,000 mi	**0.32**	0.46 0.19	0.19	**0.11**	0.11	
2013 Toyota Prius 1.8 liter PHEV PFI 25,000 mi	**0.12**	0.23 0.15 0.06 0.04	0.09	**0.33**	0.24 0.35 0.39	0.08
2016 Toyota Prius 1.8 liter HEV PFI 5,000 mi	**0.19**	0.23 0.12 0.20	0.06	**0.14**	0.13 0.29 0.00	0.14
2016 Hyundai Sonata 2.0 liter PHEV GDI 6,000 mi	**1.22**	1.01 1.71 1.12 1.05	0.33	**1.60**	2.63 0.58	1.45

* Ford F-150 was tested in a CVS tunnel with higher tunnel blanks of up to 0.5 mg/mi

Most of the vehicles tested were under 1.5 mg/mi over the FTP cycle, which is significantly less than earlier fleets of GDI vehicles.[8] The three major exceptions with higher emissions were the 2012 Lexus IS350, the 2015 Chevrolet Malibu, and the 2015 Ford F-150. All three of these

[8] ARB, 2012.

vehicles had very high cold start emissions, which accounted for the majority of the total FTP emissions.

The 2015 Mazda 3 with an Atkinson cycle GDI engine emitted 1.5 mg/mi over the FTP cycle, but US06 emissions were very well controlled at 0.6 mg/mi. As with many GDI vehicles, emissions were cold start dominant, although at a significantly lower level than earlier generation GDI vehicles.

The Lexus IS350 was an early implementation of a dual GDI/PFI systems, and calibration may not have targeted low PM emissions for the 2012 model year – although emissions were over 5 mg/mi, these results were not atypical for GDI engines at the time. Like many earlier GDI vehicles, the majority of these emissions were on cold start, and US06 emissions (with no cold start) were significantly lower at 1.3 mg/mi.

It is worth noting that more recently introduced GDI/PFI engines such as the 2015 Subaru BRZ and 2016 Toyota Tacoma, were much lower emitting on the FTP just a few model years later. The Toyota Tacoma, in particular, was very low emitting with average FTP emissions below 0.5 mg/mi while the Subaru BRZ emitted an average of 1.0 mg/mi over the FTP cycle. However, both of these more recent GDI/PFI vehicles were found to have US06 emissions that were higher than many of the GDI only vehicles tested in this campaign, a characteristic which is more similar to a conventional PFI only vehicle.

The Ford F-150 with a 2.7-liter turbocharged GDI engine was also measured at over 5 mg/mi over the FTP cycle, once again with the vast majority of emissions occurring during cold start. In this case, the catalyst light-off strategy and calibration used by Ford for this particular vehicle may have traded off higher PM emissions for quicker catalyst light off to minimize hydrocarbon and oxides of nitrogen emissions as staff observed indications that the vehicle remained in and/or returned to a modified spark timing and engine speed strategy commonly associated with a catalyst light-off strategy even after the completion of the first hill on the FTP. This vehicle was tested in a CVS tunnel with higher tunnel blanks, equivalent of up to 0.5 mg/mi, but the overall emissions were significantly higher than the tunnel blanks. This vehicle was also tested with a prototype GPF as described below, which was tested in a CVS tunnel with near-zero tunnel blanks.

Like the Ford F-150, the Ford Fiesta was equipped with a downsized, turbocharged GDI 'EcoBoost' Ford engine. However, the small displacement 1.0-liter engine in the Fiesta was found to have much lower PM emissions especially at cold start, with an average of 1.4 mg/mi over both the FTP and US06 cycles which appears to be more representative of the newer GDI fleet. This vehicle was also equipped with a small close-coupled catalytic converter that was located close to the exhaust manifold and the vehicle appeared to rely less on an extended use of a catalyst light-off strategy like the F-150.

The 2014 Mini Cooper S is equipped with a 2.0 liter direct injected turbocharged engine and results show emissions were very well controlled on the FTP at 0.4 mg/mi and slightly higher on the US06 at 1.2 mg/mi. As with many other well-controlled GDI vehicles, the Mini showed good control over all portions of the FTP cycle, with somewhat higher emissions during cold start.

The 2016 Volkswagen Jetta and 2014 Mercedes CLA were the lowest emitting GDI vehicles tested, both averaging 0.3 mg/mi over the FTP cycle. As with the Honda Accord, both the VW and Mercedes appear to have very well controlled PM emissions on cold start. The Mercedes, which is equipped with Piezo fuel injectors, also had very low US06 emissions at 0.3 mg/mi. The VW Jetta averaged 1.0 mg/mi over the US06 cycle.

The 2016 Chevrolet Malibu emissions were more similar to the earlier GDI fleet, with FTP emissions of 7.0 mg/mi and US06 emissions of 2.1 mg/mi. As with the 2012 Lexus, a major proportion of the PM emissions occurred during cold start. This vehicle was also tested after being retrofit with a prototype GPF as described below.

Although the 2015 Honda Accord is the same model year, naturally aspirated and similar displacement to the Chevy Malibu, FTP emissions were significantly lower for the Accord at an average of 0.9 mg/mi. The difference appears to be due especially to much lower PM emissions on cold start with the Honda. US06 emissions were only moderately lower at 1.3 mg/mi versus 1.6 mg/mi for the Chevy Malibu.

A total of four hybrid electric vehicles were tested, the 2013 Chevrolet Volt, 2013 Toyota Prius and 2016 Hyundai Sonata were PHEVs tested in charge sustaining mode to mimic a conventional HEV. The 2016 Toyota Prius was a conventional HEV. The two Priuses and the Volt were equipped with PFI systems and were very low emitting over both test cycles. The PFI hybrids were found to have average mass emissions of no higher than 0.3 mg/mi over both FTP and US06 cycles. The fourth PHEV vehicle tested, a 2016 Hyundai Sonata, was equipped with a GDI engine and resulted in emissions more similar to other current GDI vehicles at 1.1 mg/mi over the FTP cycle and 1.6 mg/mi over the US06.

Staff also tested prototype gasoline particulate filters (GPFs) for controlling PM emissions. This technology appears capable of meeting the future 1 mg/mi standard, even for particularly challenging engines. For this testing, two newer GDI engines were selected that had gone through a partial redesign cycle, but would not yet readily meet the 3 mg/mile standard. The two vehicles selected were the 2015 Ford F-150 and 2016 Chevrolet Malibu, with emission rates of 5.6 mg/mi and 7 mg/mi respectively over the FTP cycle. Both vehicles were retrofit with catalyzed GPFs that replaced the second catalyst in the exhaust stream. On the F-150, this catalyst is housed in the same can as the first converter (see Figure 3) while on the Malibu, it is mounted in a typical underfloor position (see Figure 4).

Figure 3 - F-150 GPF Configuration

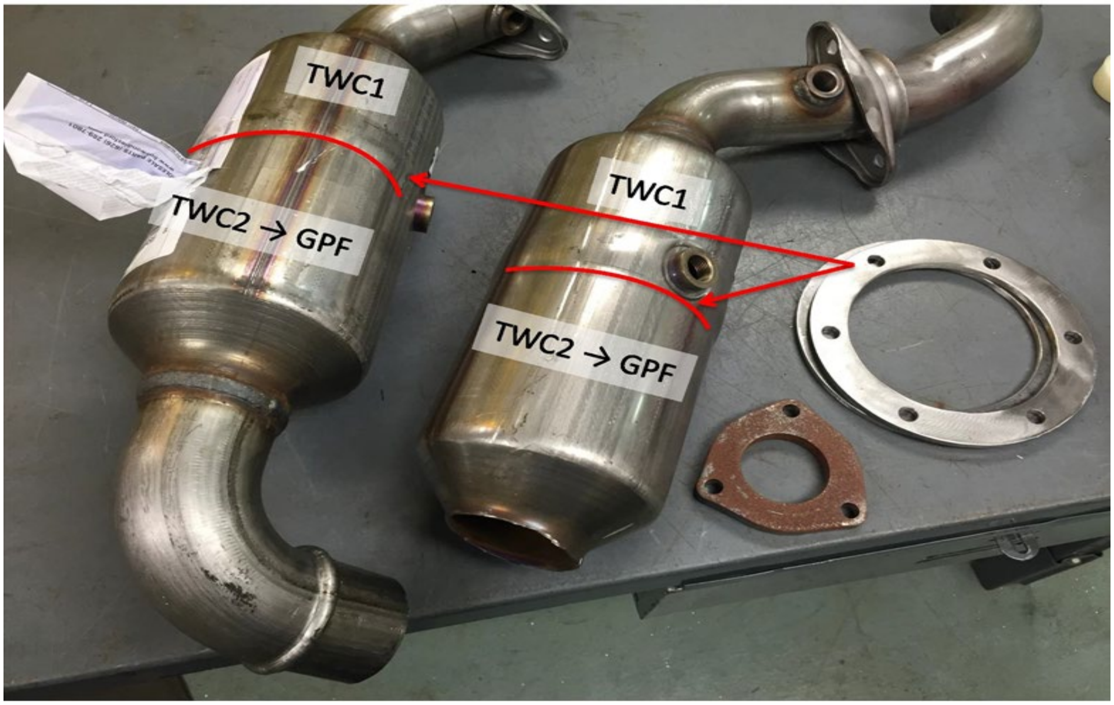
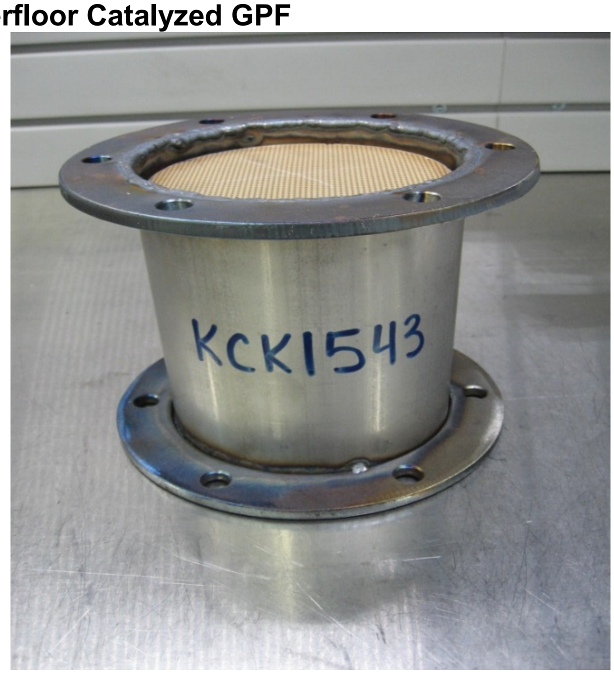


Figure 4 - Malibu Underfloor Catalyzed GPF



Without the GPF, both vehicles had fairly high FTP PM emissions and would need further improvements to meet the 3 mg/mi standard. The emission reductions from GPF testing are shown in Table 3. On the FTP, an 88% reduction was observed for both vehicles and brought emissions to a level below 1 mg/mi. The effectiveness of the GPFs on the US06 were somewhat lower, reducing PM emissions by 72% and 54% respectively for the F-150 and Malibu. The results from both vehicles show that GPFs are an effective control technology to meet future 1 mg/mi PM standards, even for vehicles that are substantially higher in PM emissions.

Table 3 - GPF Emissions Results

Description	Average of FTP (mg/mi)	Average of US06 (mg/mi)	FTP GPF Effectiveness (%)	US06 GPF Effectiveness (%)
2015 FORD F150	5.5	3.9		
2015 FORD F150 W/GPF	0.6	1.1	88%	72%
2016 CHEV MALIBU	7.0	2.1		
2016 CHEV MALIBU W/GPF	0.8	0.9	88%	54%

As part of the GPF testing, CO_2 and gaseous pollutant emissions were also measured, with the CO_2 results tabulated in Table 4. While the data shows a slight decrease in CO_2 emissions, the magnitude is within the typical driver and measurement variability, particularly as testing was done with different drivers and in different test cells. These results confirm that the increased backpressure from the GPF, even in a retrofit application, did not have a significant impact on CO_2 over the FTP and US06 cycles. In addition, gaseous pollutant emissions were generally equivalent or better than the stock exhaust configuration.

Table 4 - CO_2 Emissions Analysis for GPFs

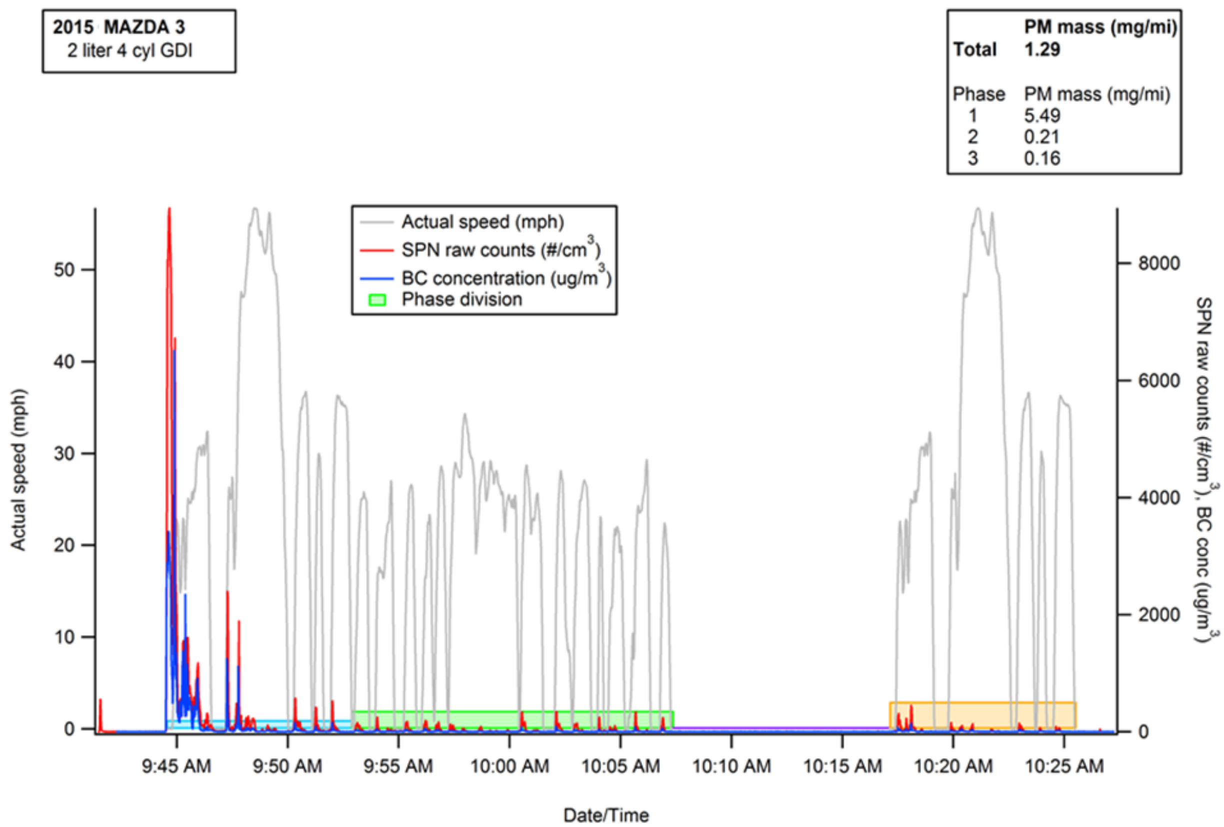
Description	Average of FTP CO2 (g/mi)	Average of US06 CO2 (g/mi)	FTP Percent CO2 increase	US06 Percent CO2 increase
2015 FORD F150	391	476	NA	NA
2015 FORD F150 W/GPF	386	455	-1%	-4%
2016 CHEV MALIBU	333	321	NA	NA
2016 CHEV MALIBU W/GPF	330	314	-1%	-2%

III.B Real time Measurement Summary and Analysis

While not an equivalent substitute to gravimetric analysis for accurately determining PM mass, real time measurements allowed an investigation of when PM emissions were occurring within the test cycles. While PM emissions are generally known to be generated primarily during cold start or under high engine load, which held true for the vehicles tested in this program, the emission profiles varied. For many of the tested GDI vehicles, the overall FTP emissions were dominated by cold start while high engine speed/load transients were well controlled. These vehicles generally resulted in higher FTP emission results, but lower US06 emission results. At the other extreme were vehicles with low cold start emissions, but with higher emissions under high load, which was most common with some of the combination GDI/PFI vehicles and is a similar trend to results from traditional PFI system vehicles.

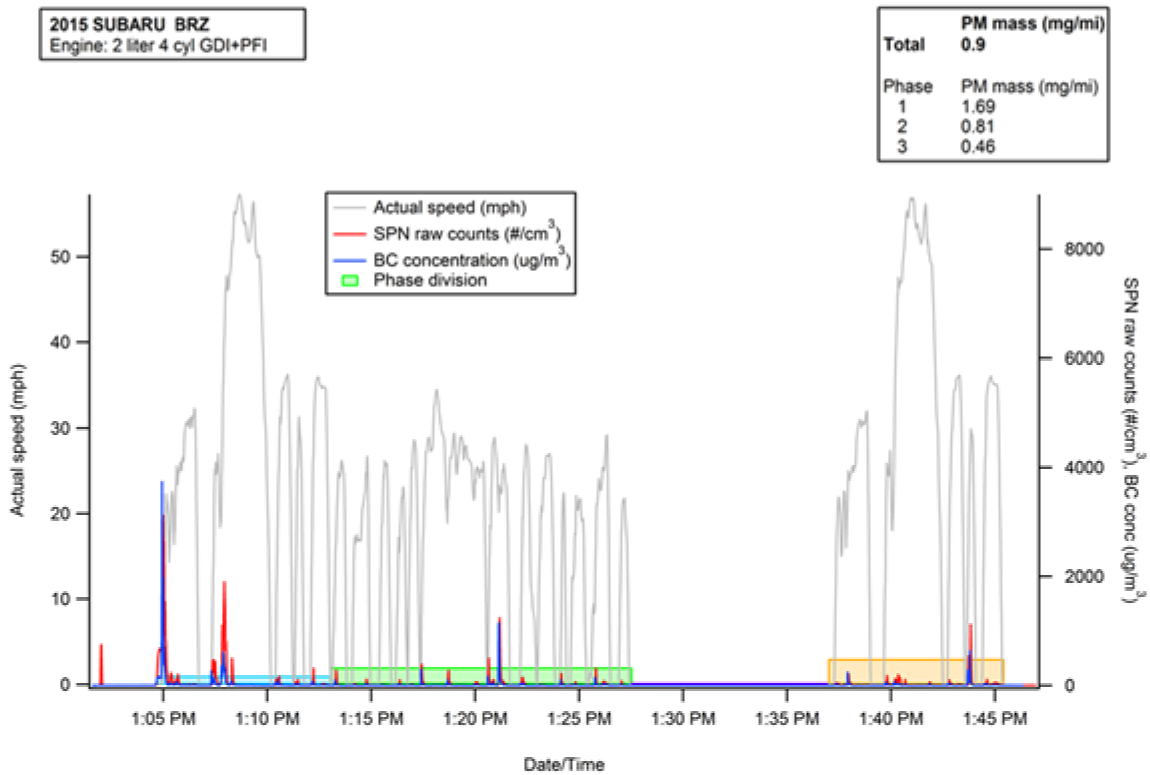
An example of a cold-start dominant emission profile is shown in Figure 5. These measurements were taken from a 2015 Mazda 3, which had phase-weighted PM emissions of approximately 1.3 mg/mi in this test. Both the PM mass from filter weights and the real-time PM measurements show that most of the PM emissions occurred on cold start, with phase 1 emissions of over 5 mg/mi, and very low phase 2 and 3 emissions of approximately 0.2 mg/mi. The real-time plots indicate that PM emissions were well controlled within a few minutes of the cold start.

Figure 5 - 2015 Mazda 3 GDI emissions on FTP cycle.



Some vehicle emission results were dominated by high load transients, such as the Subaru BRZ with a 2.0 liter engine equipped with both GDI and PFI systems, as shown in Figure 6. Although overall emissions are only moderately lower than the Mazda 3 at approximately 0.9 mg/mi, these emissions were more evenly distributed throughout the test with phase 1 emissions about 1/4th of those observed from the Mazda and phase 2 and 3 emissions approximately 4 times those of the Mazda.

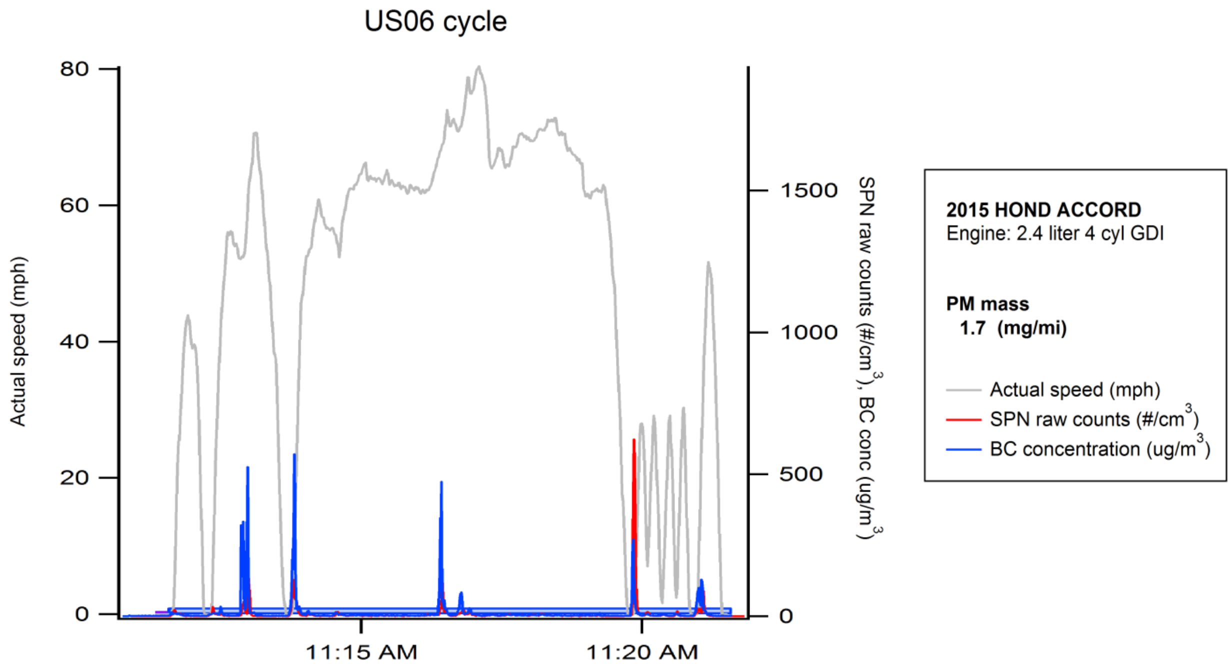
Figure 6 - 2015 Subaru BRZ GDI/PFI over the FTP cycle.



The US06 cycle does not include a startup event, so PM emissions are primarily generated during high load transients (periods of acceleration). Figure 7 shows an example of US06 emissions from the 2015 Honda Accord.

While a number of the earlier generation of GDI vehicles as well as PFI vehicles often generated higher emissions during US06 than on FTP cycles, this was not the case for many of the newer GDI vehicles tested. In this GDI fleet, US06 emissions were often similar or less than the corresponding FTP emissions, although test-to-test variability was higher.

Figure 7 - 2015 Honda Accord on US06 cycle.



III.C Summary of BC results

Earlier work had suggested that the ratio of black carbon (BC) to total PM mass may vary slightly depending on engine technology, for example PFI versus GDI, so this correlation was also investigated for this test fleet. BC was measured using AVL Micro Soot Sensors (MSS), with full results for all tests presented in the Attachment Table A-1.

As with earlier test vehicles, black carbon and PM mass was well correlated over the FTP cycle with a BC/mass ratio of 0.73, with R^2 of 0.89, as shown in Figure 8. However, over the US06 cycle a number of vehicles were found to have significantly lower black carbon to PM mass ratios, though this again was comparable to earlier results. The US06 correlation is shown in figure 9, with an overall BC/mass ratio of 0.42 with an R^2 of 0.72.

The BC to total PM mass ratio for GPF equipped vehicles shows that the GPFs appear to reduce PM mass and black carbon approximately proportionally, as both the Ford F-150 and Chevy Malibu do not have significantly altered BC/mass ratios when equipped with a GPF.

Figure 8 - Correlations between PM mass and black carbon emissions on the FTP cycle

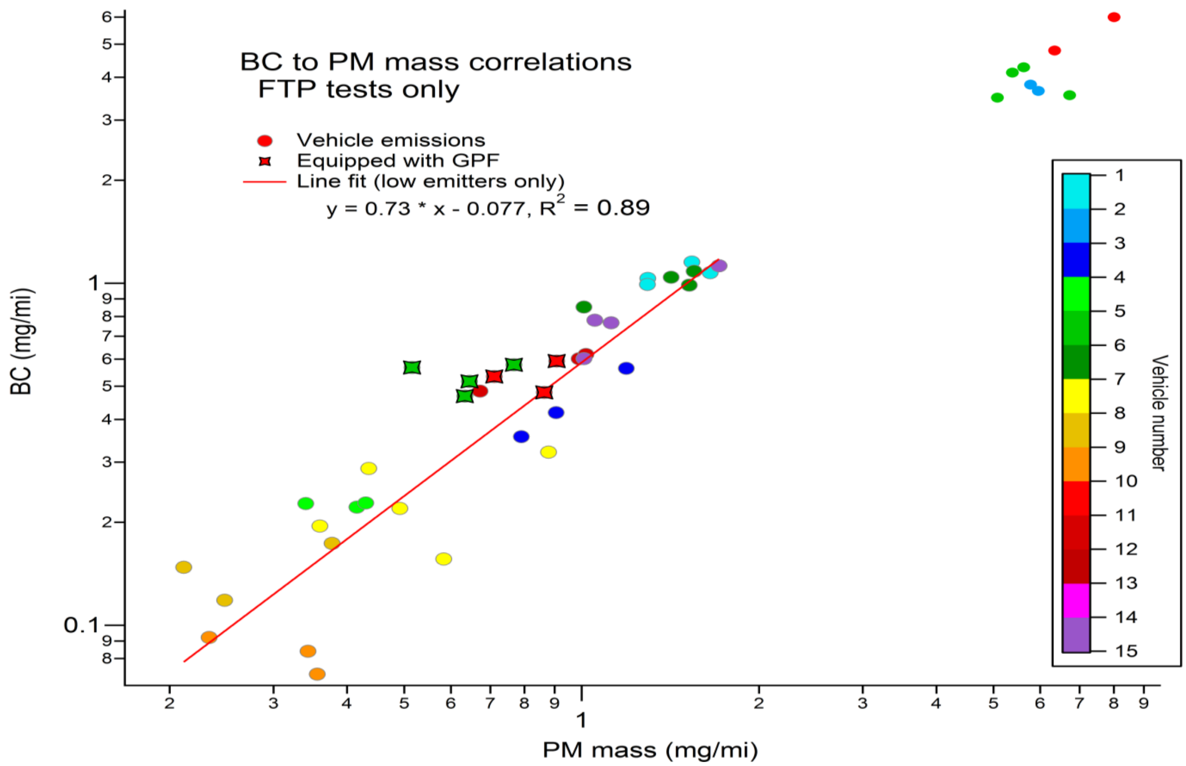
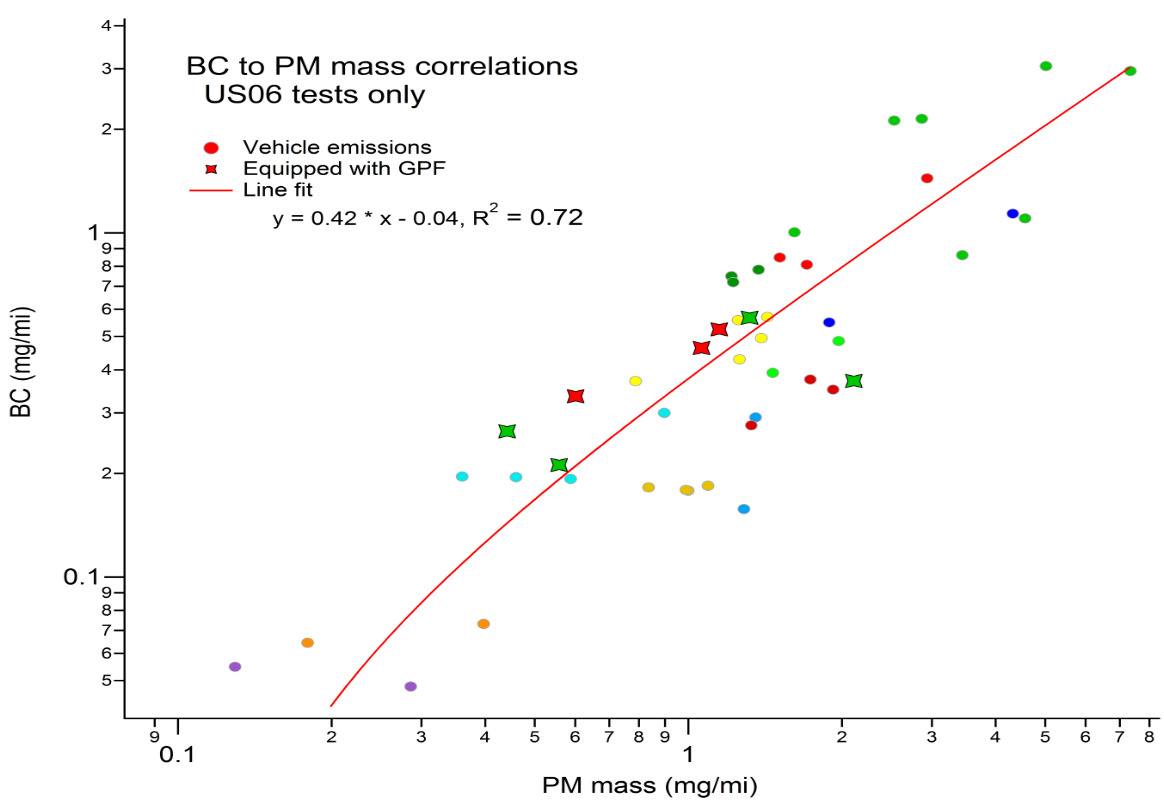


Figure 9 - Correlations between PM mass and black carbon emissions on the US06 cycle



III.D Variability

One of the major concerns expressed by vehicle manufacturers with meeting stringent future PM standards is variability. However, the PM emissions of GDI vehicles are usually dominated by cold-start emissions on the FTP cycle, which is relatively consistent from test-to-test. Since US06 cycles have no cold start event, PM emissions primarily occur during acceleration events (high load transients). This can lead to more variability, particularly since the US06 cycle includes much more aggressive speeds and accelerations, which can contribute to greater driver variability.

Table 5 summarizes the standard deviations and coefficient of variance (COV) for the vehicles tested in this program, with total averages and standard deviations shown at the bottom. Although overall average emissions were similar between the two cycles, with an average of 1.8 mg/mi for the FTP cycle and 1.4 mg/mi for US06, the standard deviation of all FTP cycles is much lower at 0.26 mg/mi, compared to 0.60 mg/mi for the US06 cycle.

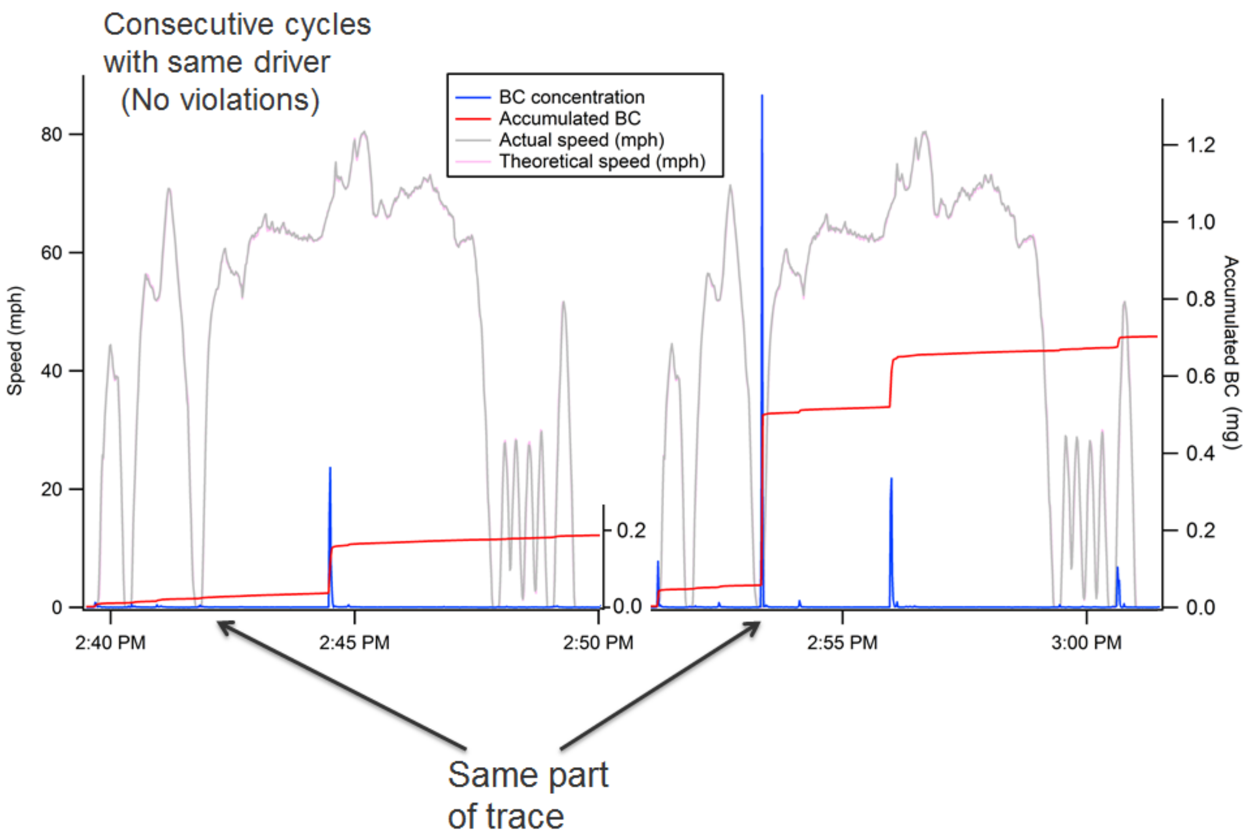
Table 5 - Standard deviations over FTP and US06 cycles

Vehicle	FTP			US06		
	Average Mass (mg/mi)	SD (mg/mi)	COV	Average Mass (mg/mi)	SD (mg/mi)	COV
2015 Mazda 3	1.46	0.19	13%	0.58	0.23	40%
2012 Lexus IS350	5.64	0.29	5%	1.32	0.05	4%
2015 Subaru BRZ	0.96	0.21	21%	3.07	1.22	40%
2016 Toyota Tacoma	0.40	0.05	12%	2.26	0.98	43%
2015 Ford F150	5.50	0.95	17%	3.91	1.91	49%
2014 Ford Fiesta	1.41	0.23	16%	1.36	0.18	14%
2014 Mini Cooper S	0.43	0.07	15%	1.21	0.23	19%
2016 VW Jetta TSI	0.28	0.09	31%	0.98	0.13	13%
2014 Mercedes CLA	0.28	0.14	49%	0.34	0.16	47%
2016 Chevrolet Malibu	7.03	0.87	12%	2.05	0.77	38%
2016 Honda Accord	0.89	0.19	21%	1.26	0.85	67%
2013 Chevy Volt	0.32	0.19	58%	0.11	n/a	n/a
2013 Toyota Prius	0.12	0.09	71%	0.33	0.08	23%
2016 Toyota Prius	0.19	0.07	30%	0.14	0.14	103%
2016 Hyundai Sonata	1.22	0.33	27%	1.60	1.45	90%
Total average		**0.26**			**0.60**	

Figure 9 presents an example of how real-time measurements can show where the variability is coming from. This figure shows two consecutive US06 cycles with the same car, same driver, and no violations. The blue trace is real-time black carbon, and the red trace is the accumulated total BC. The most important difference is at the beginning of the third hill, indicated by the black arrows at the bottom. On the left hand trace, there is very little black carbon emitted at that point, but on the right, the same part of the test accounts for the largest spike of BC in that test. The accumulated total shows just how significant that spike was in the overall BC emissions. However, one caveat of this example is that this was a very low PM emitting vehicle, so small events like this can contribute proportionally more to the total than they would for higher emitting vehicles.

In this case, there was a subtle difference in acceleration rate, though it is not visible in these figures. The second test was somewhat closer to the theoretical acceleration of the cycle while on the first test, the driver smoothed out the acceleration slightly, but was still within bounds of acceptable driving.

Figure 9 - Example of US06 variability with the same vehicle and driver



This may appear to suggest that differences between actual speeds of the vehicle will help constrain variability. However, Figure 10 shows another example of US06 variability, once again with consecutive US06 tests. In this example, the green and orange boxes below are zoomed-in versions of the area in question, with arrows pointing to their location in the test, once again highlighting the same part of two different tests.

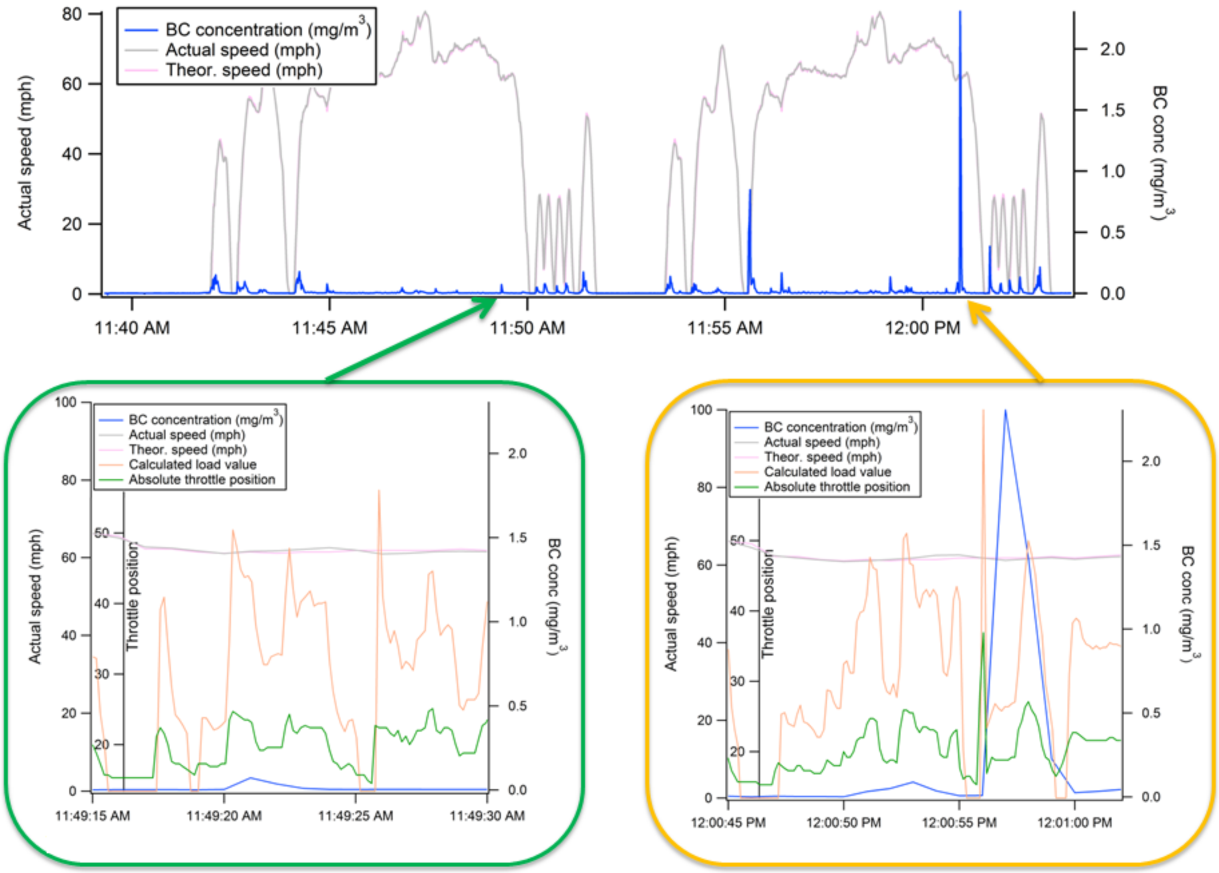
In this case, there was no appreciable difference in acceleration rate – here, the actual speed is shown in grey and the theoretical speed in pink. The left and right hand sides are virtually identical regardless of zoom level. However, there were observable differences in some OBD parameters – here showing the calculated load value in orange, and the throttle position in green. Although the vehicle speed was consistent on either test, the driver applied a more aggressive throttle movement in the second test. Calculated load briefly hit 100%, and throttle position was significantly higher at that point than the first trace. This seems to have a big impact on the black carbon emissions immediately afterwards.

This example seems to indicate that even very brief throttle activity can lead to differences in PM emissions, even when actual speed shows very little difference from test to test – so this variability is not random, but is created because the driver input can vary. This additional variability in the US06 cycles is part of the rationale that was used to justify the higher US06 standards.

However, such events are not observed for all vehicles, suggesting that some vehicles may have a PM control strategy that is less sensitive to driver actions than others. ARB will continue to investigate such strategies, to identify possibilities that might be capable of minimizing in-use PM emissions.

It should also be noted that, although both of these examples show higher emissions on the second run-through of the test, that isn't always the case. In some other cases, the first US06 cycle produced higher PM emissions.

Figure 10 - Example of US06 variability with calculated load and throttle position data.



IV. Summary of Results

The testing conducted at ARB indicates that many of newer GDI vehicles are emitting significantly lower PM levels than the first generation of GDI technologies. For the FTP cycle, most of the newer GDI vehicles tested here would easily meet the upcoming 3 mg/mi standard. As most GDI vehicles (particularly higher-emitting GDI vehicles) have cold-start dominant PM emissions, controlling cold start PM emissions appears to be the most critical factor to robustly meet the future 1 mg/mi standard. In lieu of or in combination with good PM control, GPFs are a feasible alternative to reduce PM emissions to below 1 mg/mi.

For US06 emissions, most of the newer GDIs tested are emitting well below the upcoming 6 mg/mi standard, with an average of only 1.6 mg/mi. However, with no cold start and more aggressive driving, test-to-test variability is significantly higher with the US06 cycle than it is for FTP cycle. Much of the US06 variability could be due to driver activity, which may not always be reflected in the actual speed of the vehicle. However, aggressive throttle activity is likely to also occur in the real world, and some PM control strategies may be less sensitive to driver input than others thereby providing more robust in-use control.

V. References

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VI. Attachment: All test results

Most vehicles were tested at least three times each on the FTP and US06, sometimes up to six times per cycle. For most vehicles, additional test cycles were also completed including the Worldwide Harmonized Light Duty Test Cycle (WLTC), Unified Cycle (UC), and/or Highway (HW15) cycle. Table 6 shows all vehicle results, both as the average for each test cycle for each car, as well as individual test results. Total mass is phase-weighted gravimetric PM mass, total BC is collected with AVL microsoot sensors, and total SPN is collected with either AVL or Horiba solid particle counters (PMP-compliant method, 23nm d50). The two vehicles tested with prototype GPFs are separately listed for testing with and without the GPFs and denoted with bold and darker shading.

Table 6 - Full PM test results

Vehicle	Test Type	Average Mass (mg/mi)	Average BC (mg/mi)	Average SPN (#/mi)	Test #	Total Mass (mg/mi)	Total BC (mg/mi)	Total SPN (#/mi)
2015 Mazda 3 2.0 liter GDI 4,000 miles, L2SUL	FTP	1.46	1.06	2.07E+12	1	1.30	1.03	2.09E+12
					2	1.65	1.07	2.33E+12
					3	1.58	1.15	2.12E+12
					4	1.29	0.99	1.75E+12
	US06	0.58	0.22	2.82E+11	1	0.46	0.20	2.57E+11
					2	0.90	0.30	2.98E+11
					3	0.36	0.20	3.21E+11
					4	0.59	0.19	2.50E+11
	WLTC	1.98	1.39	2.55E+12	1	1.57	1.13	2.30E+12
					2	2.34	1.47	2.46E+12
					3	2.03	1.56	2.88E+12
	HW15				1		0.06	9.00E+10
					2		0.04	5.73E+10
2012 Lexus IS350 3.5 liter GDI+PFI 40,000 miles, L2ULV	FTP	5.64	3.73		1	5.55		
					2	5.78	3.81	
					3	5.29		
					4	5.95	3.65	
	US06	1.32	0.22		1	1.28	0.16	
					2	1.35	0.29	
2015 Subaru BRZ 2.0 liter GDI+PFI 15,000 miles, L2LEV	FTP	0.96	0.45	1.96E+12	1	0.91	0.42	1.79E+12
					2	0.79	0.36	1.68E+12
					3	1.19	0.56	2.41E+12
	US06	3.07	0.84	2.75E+12	1	1.89	0.55	1.76E+12
					2	4.32	1.14	
					3	3.00		3.74E+12
	WLTC	0.82	0.47	1.68E+12	1	0.80	0.46	1.82E+12

					2	0.81	0.46	1.50E+12
					3	0.85	0.48	1.71E+12
	HW15	0.24	0.14	5.00E+11	1	0.42	0.20	8.60E+11
					2	0.20	0.12	3.47E+11
					3	0.11	0.09	2.93E+11
2016 Toyota Tacoma 3.5 liter GDI+PFI 51,000 mi, ULEV70	FTP	0.46	0.23	6.86E+11	1	0.34	0.23	4.31E+11
					2	0.42	0.22	6.78E+11
					3	0.43	0.23	6.86E+11
					4	0.50		
					5	0.40		
					6	0.55		
					7	0.57		
					8	0.50		
	US06	1.47	0.44	1.38E+12	1	1.97	0.48	1.29E+12
					2	1.46	0.39	1.41E+12
					3	3.36		1.44E+12
					4	1.02		
					5	1.02		
					6	0.65		
					7	0.79		
	UC	0.65	0.28	1.19E+12	1	0.65	0.28	1.19E+12
2015 Ford F150 2.7 liter turbo GDI 15,000 mi, ULEV70	FTP	5.50	3.77	6.11E+12	1	5.08	3.49	6.46E+12
					2	5.63	4.28	
					3	4.53		
					4	6.76	3.55	5.77E+12
	US06	3.91	1.89	1.81E+12	1	3.44	0.86	1.78E+12
					2	7.34	2.96	
					3	2.53	2.12	
					4	2.86	2.15	
					5	5.02	3.05	
					6	1.61	1.00	
					7	4.57	1.10	1.84E+12
	UC	8.55	9.96		1	9.02		
					2	7.54	9.96	
					3	9.10		
	HW15	1.30	0.38		1	1.74	0.61	
					2	1.18	0.21	
					3	1.30	0.33	
					4	1.00		
2015 Ford F150 **With GPF**	FTP	0.64	0.53	1.09E+12	1	0.65	0.52	1.06E+12
					2	0.52	0.57	1.23E+12

					3	0.63	0.47	9.71E+11
					4	0.77	0.58	
	US06	1.11	0.35	6.80E+11	1	2.11	0.37	
					2	1.32	0.57	9.56E+11
					3	0.56	0.21	4.49E+11
					4	0.44	0.27	6.35E+11
2014 Ford Fiesta 1.0 liter turbo GDI 26,000 miles, L2ULV	FTP	1.41	0.99	2.05E+12	1	1.01	0.85	1.94E+12
					2	1.52	0.99	2.37E+12
					3	1.42	1.04	2.15E+12
					4	1.56		1.47E+12
					5	1.55	1.08	2.31E+12
	US06	1.36	0.76	2.45E+12	1			
					2	1.32	0.77	2.35E+12
					3	1.67	0.80	
					4	1.21	0.75	2.52E+12
					5	1.37	0.78	2.75E+12
					6	1.22	0.72	2.17E+12
	WLTC	2.05	1.36	3.34E+12	1	2.01		
					2	1.92	1.28	3.01E+12
					3	2.34	1.51	3.92E+12
					4	1.93	1.29	3.24E+12
					5	2.03	1.35	3.17E+12
	HW15	0.98	0.73	1.91E+12	1	0.98	0.72	1.88E+12
					2	1.05	0.79	1.95E+12
					3	0.92	0.67	
2014 Mini Cooper S 2.0 ltr turbo GDI 28,000 mi L2ULV	FTP	0.43	0.23	9.02E+11	1	0.49	0.22	8.84E+11
					2	0.44	0.29	1.04E+12
					3	0.36	0.20	7.78E+11
	US06	1.21	0.48	1.57E+12	1	1.43	0.57	7.41E+11
					2	1.26	0.43	1.54E+12
					3	0.79	0.37	1.60E+12
					4	1.39	0.49	2.26E+12
					5	1.14	0.48	1.58E+12
					6	1.25	0.56	1.67E+12
	UC	0.69	0.41	1.78E+12	1	0.67	0.43	1.74E+12
					2	0.70	0.39	1.81E+12
					3	0.69		
2016 VW Jetta TSI 1.4 liter GDI turbo 5,000 mi, L2ULV	FTP	0.28	0.15	8.44E+11	1	0.25	0.12	
					2	0.38	0.17	9.39E+11
					3	0.21	0.15	7.49E+11
	US06	0.98	0.18	1.01E+12	1	1.00	0.18	9.95E+11

					2	1.09	0.18	9.24E+11
					3	0.84	0.18	1.12E+12
	UC	0.85	0.27	1.22E+12	1	1.14	0.25	1.42E+12
					2	0.98	0.23	1.32E+12
					3	0.66	0.30	1.11E+12
					4	0.63	0.29	1.02E+12
2014 Mercedes CLA 2.0 liter GDI turbo 30,000 mi, L2ULV	FTP	0.28	0.08	3.57E+11	1	0.12		3.99E+11
					2	0.37	0.07	2.93E+11
					3	0.34	0.08	3.79E+11
	US06	0.34	0.07	2.99E+11	1	0.54		4.60E+11
					2	0.25		
					3	0.18	0.06	1.39E+11
					4	0.40	0.07	
	UC	0.53	0.17	7.9E+11	1	0.41	0.18	9.46E+11
					2	0.64	0.16	6.34E+11
	WLTC	0.48	0.08	3.26E+11	1	0.48	0.08	3.26E+11
2016 Chevy Malibu 2.5 liter GDI 18,000 mi, ULEV	FTP	7.03	5.39	1.00E+13	1	6.73		9.51E+12
					2	6.35	4.79	9.32E+12
					3	8.01	6.00	1.13E+13
	US06	2.05	1.03	2.40E+12	1	1.71	0.81	2.25E+12
					2			
					3	1.51	0.85	2.55E+12
					4	2.94	1.44	
	UC	9.10	7.86	1.67E+13	1	9.62	8.42	1.77E+13
					2	8.95	7.75	1.68E+13
					3	8.74	7.40	1.57E+13
2016 Chevy Malibu **With GPF**	FTP	0.83	0.54	9.39E+11	1	0.71	0.53	9.15E+11
					2	0.86	0.48	7.86E+11
					3	0.91	0.59	1.12E+12
	US06	0.94	0.44	8.97E+11	1	1.15	0.52	
					2	1.06	0.46	1.01E+12
					3	0.60	0.34	7.87E+11
2016 Honda Accord 2.4 liter GDI 27,000 mi, SULEV	FTP	0.89	0.57	2.51E+12	1	0.67	0.48	2.68E+12
					2	0.99	0.60	2.35E+12
					3	1.02	0.62	2.51E+12
	US06	1.26	0.35	2.89E+11	1	0.04	0.41	
					2	1.73	0.38	4.26E+11
					3	1.33	0.28	1.49E+11
					4	1.92	0.35	2.91E+11
	UC	1.18	0.75	2.77E+12	1	0.92	0.60	2.35E+12
					2	1.34	0.86	3.12E+12

					3	1.28	0.78	2.84E+12
2013 Chevy Volt 1.4 liter PHEV PFI 8,000 mi, PZEV	FTP	0.32		1.05E+12	1	0.46		
					2	0.19		1.05E+12
	US06	0.11		4.71E+11	1	0.11		4.71E+11
2013 Toyota Prius 1.8 liter PHEV PFI 25,000 mi L2SUL	FTP	0.12		1.88E+11	1	0.23		
					2	0.15		1.88E+11
					3	0.06		
					4	0.04		
	US06	0.33		2.04E+11	1	0.24		
					2	0.35		2.04E+11
					3	0.39		
2016 Toyota Prius 1.8 liter HEV PFI 5,000 mi LEV3 SULEV30	FTP	0.19			1	0.23		
					2	0.12		
					3	0.20		
	US06	0.14	0.05		1	0.13	0.05	
					2	0.29	0.05	
					3	0.00		
	UC	0.18			1	0.18		
					2	0.19		
					3	0.17		
2016 Hyundai Sonata 2 liter PHEV GDI 6,000 mi, L2LEV	FTP	1.22	0.82	2.29E+12	1	1.01	0.60	1.98E+12
					2	1.71	1.12	2.55E+12
					3	1.12	0.77	2.31E+12
					4	1.05	0.78	2.31E+12
	US06	2.31	1.27	3.30E+12	1	2.63	0.86	1.21E+12
					2	0.58	0.29	9.27E+11
					3	3.14	2.19	7.77E+12
					4	2.89	1.74	
	UC	1.84	1.22	3.70E+12	1	1.60	1.13	3.64E+12
					2	1.65	1.03	3.51E+12
					3	2.27	1.49	3.97E+12