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Characterization of GDI PM During Vehicle Start-Stop Operation

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Abstract

As the fuel economy regulations increase in stringency, many manufacturers are implementing start-stop operation to enhance vehicle fuel economy. During start-stop operation, the engine shuts off when the vehicle is stationary for more than a few seconds. When the brake is released by the driver, the engine restarts. Depending on traffic conditions, start-stop operation can result in fuel savings from a few percent to close to 10%. Gasoline direct injection (GDI) engines are also increasingly available on light-duty vehicles. While GDI engines offer fuel economy advantages over port fuel injected (PFI) engines, they also tend to have higher PM emissions, particularly during start-up transients. Thus, there is interest in evaluating the effect of start-stop operation on PM emissions. In this study, a 2.5L GDI vehicle was operated over the FTP75 drive cycle. Runs containing cold starts (FTP-75 cycle Phases 1 & 2) and multiple runs containing hot starts (FTP-75 cycle Phases 3 & 4) were performed each day. Note that the FTP-75 Phases 3 & 4 are identical to Phases 1 & 2 except that the engine is warmed up. Three fuels were evaluated: an 87 AKI gasoline (E0), a 21% splash blend of ethanol and the 87 AKI gasoline (E21), and a 12% splash blend of iso-butanol and the 87 AKI gasoline (iBu12). PM mass, transient particle number concentration and size distribution, and soot mass concentration were evaluated for both start-stop operation and *no start-stop* operation on each fuel. Three Phase 1 & 2 cycles and as many as 27 Phase 3 & 4 cycles were performed for each fuel-mode combination. Composite FTP mass emissions for E0 and iBu12 showed increased total PM emissions with start-stop operation, but E21 showed no difference. Statistical analysis of the effects of start-stop on PM number and soot emissions showed different trends for different fuels. For example, when E0 is used with start-stop operation, the particle number decreased but the soot mass tended to increase. The results of this study have implications for hybrid vehicle operation as well because the internal combustion engine in hybrid vehicles must stop and re-start during normal operation.

Introduction

Vehicles equipped with Gasoline Direct Injection (GDI) engines now comprise over 50% of new light-duty vehicles sold [1] in the United States. GDI has enabled down-sized, boosted engines to replace larger displacement, normally-aspirated engines in many applications, leading to overall increases in fuel economy for the fleet. However, GDI engines also suffer from higher particulate matter (PM) emissions, particularly during cold-start and acceleration transients. Because new vehicles are also adopting start-stop technologies for fuel efficiency, there is concern that the intermittent stops could lead to an overall increase in PM emissions from GDI vehicles.

Researchers using hybrid and conventional models of the same port fuel injection (PFI) equipped sedan found that even with PFI, which isn't known to produce much PM, switching between engine and battery operation in a hybrid was shown to result in increased PN emissions. [2] Furthermore, the re-ignition events (start-up) resulted in particle number (PN) emission rates more than four times higher than stabilized PN emission rates for the hybrid vehicle.[2] Research in our laboratory [3,4] with GDI vehicles has demonstrated that the driving cycles that include cold-start as well as hard acceleration transients result in the highest PM mass and number emissions. A study with a 2013 GDI vehicle monitored both real-time particle number and soot mass instrumentation for the FTP-75 drive cycle [5] and found that the particle number concentration was about 10X higher during the initial 250s of Phase 1, the cold start portion of the FTP-75 drive cycle. In the same study, the soot mass concentration was 50X higher over the first 250s of Phase 1, compared to the rest of the Phase 1 & 2 of the FTP. Interestingly, at the start of Phase 3, when the engine re-starts after a 10 minute soak, the authors see only a threefold increase in both particle number and soot mass concentration for the first 250s of Phase 3 compared to the rest of Phases 3 & 4 (hot start).

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With the passage of the Energy Independence and Security Act (EISA 2007), the U.S. Congress set specific goals for the use of renewable fuels (36 billion gallons by 2022). The majority of this goal is expected to be met with ethanol from both starch sources like corn and "advanced biofuel" sources like cellulosic feedstocks. In 2010 and 2011, the U.S. EPA granted a partial waiver for the use of E15, 15% ethanol, in model year 2001 and later gasoline vehicles [6]. Furthermore, higher blends of ethanol and gasoline, E25-E40, have been identified as potential high-octane rating fuels that will enable fuel efficient technologies such as low-speed and highly boosted engines without end-gas knock concerns [7]. Beyond ethanol, butanol is also gaining momentum as a renewable fuel. Butanol can be made in similar production facilities to ethanol and its vapor pressure and energy density more closely match gasoline.

In this study, the effects of start-stop operation and alcohol fuel blends on the PM emissions of a GDI vehicle are examined by operating the same vehicle with start-stop enabled and disabled (*no start-stop*) for direct comparison. Gasoline, a 21% ethanol-gasoline blend (E21), and a 12% isobutanol-gasoline blend (iBu12) were used as fuels for comparison of fuel effects. Because of the transient nature of PM emissions, efforts were made to have sufficient cycles under each fuel/operation mode combination to perform statistical analysis.

Approach

For this study a 2014 vehicle (Chevrolet Malibu Eco) equipped with a 2.5L GDI engine and start-stop operation was selected. The start-stop operation is active once the engine warms up, typically after the second acceleration event known as “Hill 2” of the Federal Test Procedure. Figure 1 shows Phase 1 and 2 of the FTP; after the 10 min soak, the same cycles are driven, comprising Phases 3 & 4. It was possible to disable the start-stop operation by opening the hood, so the vehicle was able to be tested in both modes of operation (start-stop and *no start-stop*).

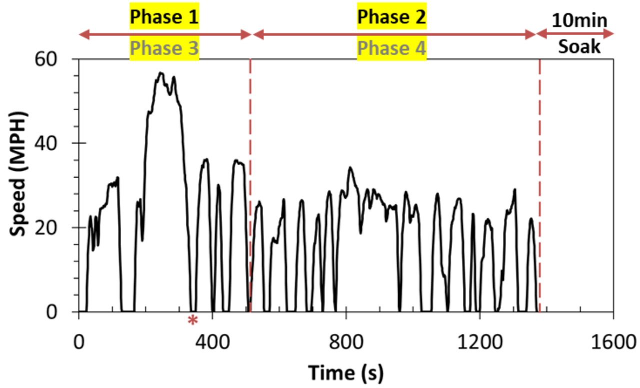

*Figure 1. Speed trace of the FTP-75 showing the division between Phases 1 and 2. Phase 3 is identical to Phase 1, except that it follows Phase 2 after just a 10 minute "soak" (engine off), so the engine is still warm. Phase 4 is identical to Phase 2. The * marks the time in the trace when the start-stop begins.*

The fuels selected for this study represented a base case 87 AKI non-oxygenated fuel and two other potential oxygenated fuels, a 21% ethanol blend in the base fuel and a 12% isobutanol blend. All blends were made by a mass-based splash blending and converted to a volumetric fraction of the final blended fuel. The E21 fuel represented a next step beyond E15 which is commercially available in some states. Isobutanol was approved by EPA in June 2018 up to 16% and butanol has an ASTM D7862 fuel quality standard for blends up to 12.5%. Isobutanol can be made from corn and cellulose using the same or very similar equipment as that used for ethanol production. Table 1 displays the fuel properties.

Table 1. Fuel properties table for the E0, E21, and iBu12

Fuel property	ASTM Method	E0	E21	iBu12
DVPE	D5191	NA	13.34	10.52
Alcohol (Vol %)	D5599	0	21.4	12.4
C%	D5291	85.88	78.44	82.4
H%	D5291	14.52	14.23	14.22
O%	D5599	<0.1	8.1	2.94
Sulfur (ppm)	D5453	39*	29	34

* Measured by ASTM D7039

Finally, the approach taken in this study emphasized repetitive data collection over the hot portion of the FTP-75 drive cycles (Phase 3 & 4) for each fuel and operating mode. Thus, for each fuel/operating mode combination, 3 Phase 1 & 2 cycles and 27 Phase 3 & 4 cycles were run. Collection of PM from multiple cycles provided sufficient mass accumulation on the sampling filters for both accurate PM weight and chemical speciation measurements. Although GDI vehicles typically emit more PM than their PFI counterparts, the overall emissions are still very low, compared to diesel vehicles.

The inherent variability of the processes which can lead to higher PM emissions in GDI engines was another a critical reason for the multiple repeats performed. Fuel injected very early in the intake cycle has the potential to pool on the piston or impinge on the cylinder wall, leading to inhomogeneous combustion events. The real-time instrumentation (1s resolution) used captured this variability, and the multiple repeats allowed statistical confidence in the results and provided a pathway to characterize the variability.

Experimental methods

Vehicle Specifications and Driving Schedules

The test vehicle was a 2014 Chevrolet Malibu ECO with a 2.5L, normally-aspirated GDI engine. The vehicle was operated over the first 1372 s of the FTP-75 drive cycle, Phases 1 & 2, when starting cold and Phases 3 & 4 when starting warmed-up, on the 300 hp, 48” roll dynamometer in our laboratory. One Phase 1 & 2 cycle and multiple Phase 3 & 4 cycles were performed each day with either the start-stop function enabled or disabled. A total of three Phase 1 & 2 cycles and 27 Phase 3 7 4 cycles were performed for each fuel/operating mode combination. Table 2 illustrates the test matrix.

Table 2. Test Matrix for three fuels, two modes

		Vehicle Tests	
Mode*	Fuel	FTP-75 Phases 1 & 2	FTP-75 Phases 3 & 4
SS	E0	3	27
no SS	E0	3	27

SS	E21	3	27
no SS	E21	3	27
SS	iBu12	3	27
no SS	iBu12	3	27

* SS indicates start-stop and no SS indicates *no star-stop.*

Particulate Emissions Measurement

Both real-time and time integrated samples of PM were taken during the experiments.

Real Time PM Characterization

Real-time particulate soot mass was obtained from a photoacoustic-based Micro Soot Sensor™ (MSS, AVL Model 483) and real-time particle size and number were obtained with an Engine Exhaust Particle Sizer (EEPS™). The probe and dilution system for the MSS was the 8 mm diameter AVL probe with dilution set at 16:1 and installed on a short length of exhaust pipe immediately downstream of the muffler and upstream of the transfer line to the dilution tunnel. For the EEPS sampling, an ejector-based double dilution sampler was mounted directly on the tailpipe prior to the transfer line to the dilution tunnel. This system was used in previous studies [3,4] and is noteworthy because the inlet to the first ejector pump is <3 cm from the sample probe and had a nominal dilution ratio of ~900:1. Actual dilution was measured for each fuel/mode combination by comparing the CO_2 in the exhaust with the CO_2 in the 2nd stage of dilution.

It is important to note the difference between PM mass data which came from gravimetric filter weights and soot mass measurements from the MSS. The PM filters represent integrated samples over multiple cycles, so the replication of samples is captured in the collection of the total sample. Furthermore, the PM mass collected by the filter includes all types of particulate, including both organic carbon and elemental carbon. In contrast, the MSS and EEPS collect 1 Hz data for each cycle, and thus, given enough cycles, statistics can be done to determine whether there are significant differences between modes or fuels. Note also that the MSS soot measurement will typically only account for the elemental carbon and not measure the organic carbon component of the particulate.

For each Phase 1 & 2 cycle or Phase 3 & 4 cycle, a separate MSS and EEPS file was taken according to the runs described in Table 2. Thus, for each fuel/mode combination, there were 27 MSS and EEPS files acquired for the Phase 3 & 4 cycles, and 3 MSS and EEPS files for the Phase 1 & 2 cycles. Both the EEPS and the MSS measure concentration (particle number/cm^3 and mg/m^3, respectively) so the real-time exhaust flow was calculated from the critical flow venturi system (CVS) measurements and used to calculate both the real-time emissions rates (#/s, mg/s) and integrated values (#/mile, g/mile) for the cycles. Figure 2 illustrates the flows that are recorded second-by-second and used to calculate the total vehicle exhaust flow, E_{car}, according to equation 1.

$$E_{car} = V_{out} + S_e + S_t - A_{in} \qquad \text{(Eq. 1)}$$

The approach for calculating the total flow by Eq. 1 and described in the Figure 2 schematic was compared with other methods, such as lambda and engine air flow from the CAN bus, lambda and time trace carbon balance in the dilution tunnel, and minimum exhaust flow estimate at idle, to insure low error for the emission rate calculation.

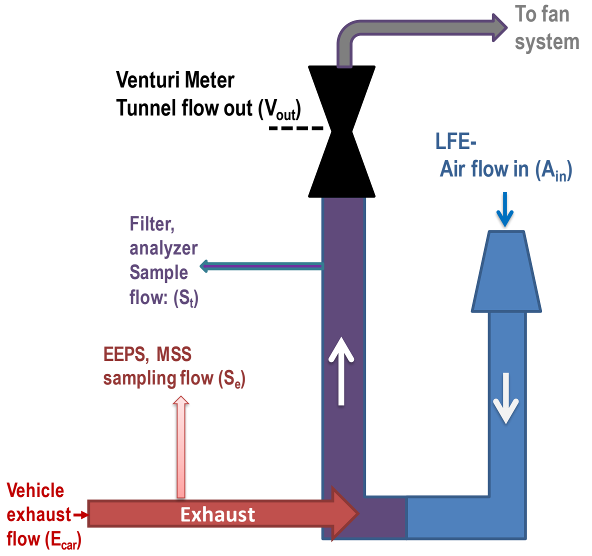

Figure 2. Schematic of the CVS system showing flows that are used to calculate vehicle exhaust flow (E_{car}) at 1 Hz.

Filter Sampling for PM

The tailpipe of the vehicle was connected with a 2.5" ID flexible stainless-steel line to the full-flow dilution tunnel. The transfer line temperature was maintained at 121 °C by a blanket heater to avoid condensation of HCs during cold operation. The temperature of the diluted exhaust did not go above 50 °C throughout the test. Filter samples were collected on 70 mm supported polytetrafluoroethylene (PTFE) membrane filters (Zefluor™ 2.0 µm, Pall Corp.) following full-flow dilution by a critical flow venturi system (CVS). The 70 mm OD circular filters were cut from sheets of the Zefluor™ filter material. After PM collection, the filters were weighed on a balance located in an isolated chamber after the filters had been conditioned to the chamber environment overnight. The balance used had 1 µg sensitivity.

There were two filter positions on the tunnel which allowed simultaneous PM sampling on two filters. For each fuel/mode combination shown in Table 2, a Phase 1 & 2 cycle was collected on each of the two filters and stored in the refrigerator until the next cold start, so after three days, each of the two filters had three Phase 1 & 2 cycles on it for that fuel/mode combination. Similarly, for the Phase 3 & 4 cycles, one filter collected PM from just the 9 Phase 3 & 4 cycles in a given day, while the second filter, which also collected PM from the 9 Phase 3 & 4 cycles, was stored in the refrigerator until the next test day and used again. This approach resulted in the second filter containing PM from 27 Phase 3 & 4 cycles and three filters with PM from 9 Phase 3 & 4 cycles for each fuel/mode combination.

The PM mass weights on each filter were then divided by the number of runs to get PM mass per Phase 1 & 2 cycle, or the PM mass per Phase 3 & 4 cycle. This approach allowed greater PM mass to be collected on a single filter without affecting the weighted calculation of cycle emissions. The composite (hot + cold) FTP Cycle PM emissions were calculated in the standard weighted manner: 0.43×(Phase 1 & 2) + 0.57× (Phase 3 & 4). Conventionally, FTP-75 emissions tests omit the hot stabilized Phase 4 cycle and substitute Phase 2 results, using Phase 2 twice in the calculation.

Although 47 mm PTFE membrane filters are commonly used now when the mass emissions are expected to be low, 70 mm Zefluor™ filters were used to increase PM collection which was needed for 2 reason: (1) increased PM mass collection to facilitate more accurate gravimetrical mass analysis and (2) for an increased volume of PM sample material required for chemical speciation. The supported PTFE membrane of the Zefluor™ filter enables soot harvesting directly from the filter for solvent-less analysis by gas chromatography-mass spectrometry. This technique is described in detail in a previous publication [8]. Detailed speciation of the filter PM was not completed in time for this publication and will be the subject of a future publication.

Gaseous Emissions Measurement

For each day of a fuel/mode combination, bag samples were obtained for both the Phase 1 & 2 cycle and one Phase 3 & 4 cycle, as well as a background bag. Criteria emissions (CO, CO_2, NOx, and HC) were measured with conventional instrumentation.

Statistical Methods

The large amount of real-time data for soot and particle number was obtained in order to identify variability as well as to give confidence in mean values. Because the sample size was large, we were able to perform analysis of variance (ANOVA) on much of the data to test interactions. A key part of the real-time data analysis was the time alignment of the data. There are inherent sampling delays in both the MSS and the EEPS, so, in order to compare data from individual runs, the data had to first be aligned to some reference 0 value. The most reliable way to do this was to align the PM production to acceleration events, in particular "hills" 1 and 2 of the FTP Phase 1 or Phase 3. The tip-in of the accelerator reliably produced a spike of PM. Figure 1 shows an example of a time alignment for EEPS particle data with the acceleration events during the first 350 s of the FTP-75 drive cycle.

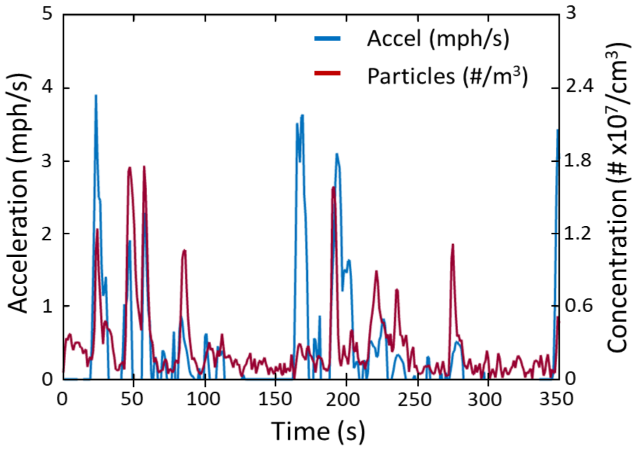

Figure 3. Time-aligned EEPS data. The blue curves are acceleration and the red curves are total number concentration (dilute).

Results

FTP Gaseous Emissions

The gaseous emissions results and calculated fuel mileage (MPG) are shown in Table 3. Volumetric fuel economy, in terms of miles per gallon (MPG) can be compared between fuel/mode combinations when calculated over an identical drive cycle like was done in this study. Results in Table 3 show that the fuel economy decreases as expected with the lower energy densities of the oxygenate blends, especially for E21. Fuel economy is consistently higher for the SS mode.

Table 3. Weighted average criteria emissions and MPG for FTP-75 drive cycle*

Fuel/Mode**	CO	CO2	NOx	THC	MPG
E0 SS	1.17	283	0.0031	0.030	29.9
E0 No SS	1.30	298	0.005	0.031	28.6
E21 SS	0.75	284	0.0075	0.028	27.2
E21 No SS	1.06	292	0.0080	0.032	26.4
iBu12 SS	0.92	284	0.0066	0.024	29.0
iBu12 no SS	0.94	293	0.0067	0.024	28.0

* Emissions in g/mile

** SS indicates start-stop and no SS indicates *no start-stop.*

FTP Cycle PM Emissions

Mass Sampling

The results from the PM filter mass sampling during the FTP drive cycle are shown in Figure 4. Since only two PM filters were collected for each fuel/mode combination, which contained PM from 3 Phase 1 & 2 runs, the weighted masses shown in Figure 4 all had to use the same average of PM mass for a given fuel/mode combination. The min/max error bars came from the 3 weighted mass calculations which used the same Phase 1 & 2 mass value but the PM mass per hot start came from the three different day filters that contained PM from 9 Phase 3 & 4 cycles on each, thus reflecting the variability in the Phase 3 & 4 data only. Of note is that, for all fuel/mode combination, with the exception of the iBu12 in start-stop mode, the weighted PM mass emissions are below the Tier 3 PM emission limit of 3 mg/mile, despite phase-in for Tier 3 beginning in 2017 and this test being run on a MY2014 vehicle. In comparison to the MY2007 GDI vehicle in the previous study [4], the E0 emissions are about 60% lower, while, the E21 emissions are about 30% higher. Figure 5 shows the breakdown between the Phase 1 & 2 cycle with the cold start (Figure 5a) and the Phase 3 & 4 cycle with the hot start (Figure 5b), highlighting how the PM emissions during the cold start phases are dominant.

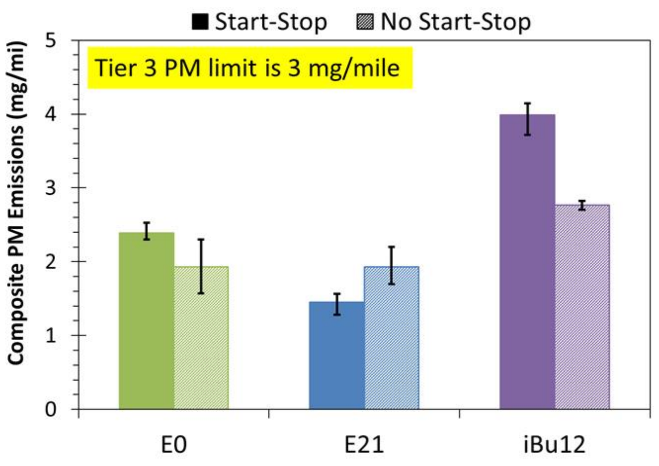

Figure 4. FTP-75 cycle PM emissions for both start-stop and no start-stop operation with the three fuels, based on gravimetric measurements of filters. Error bars represent max and min values.

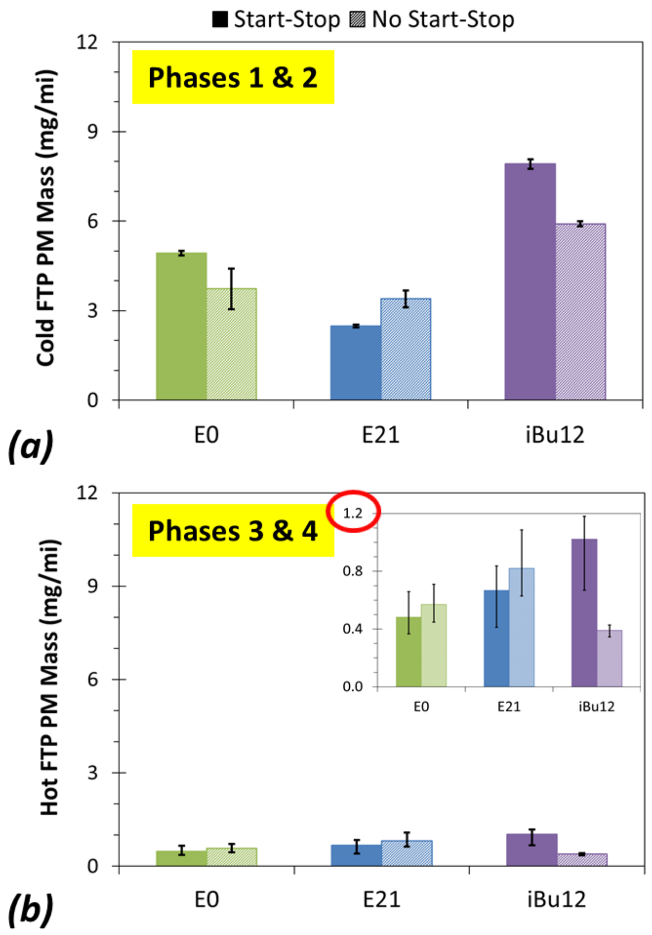

Figure 5. Average, non cycle-weighted, PM mass emissions measured gravimetrically from filter sample loading for 2 Phase 1 & 2 filters (a) and 3 Phase 3 & 4 filters (b), per fuel/mode combination. Error bars represent min/max masses. Inset (b) zooms into Phase 3 & 4 to show differences and has a 10x smaller scale than the cold (a).

Total Particle Number

The particle number (PN) concentration of the exhaust was measured with the EEPS after a double dilution sampler that removed volatile particles. The EEPS measures a size distribution between 5.6 nm and 560 nm at 1 Hz. It also calculates a total particle concentration (within that size range) at 1 Hz. A time-resolved exhaust flow was calculated from the tunnel according Eq.1. Thus, the concentration of particles at 1 Hz can be converted to a number flow rate (#/min), integrated over the time of the cycle, and divided by the mileage to obtain a #/mile for each fuel/mode combination. Figure 6 shows the particle number emissions for both the Phase 1 & 2 and Phase 3 & 4 cycles. The Phase 3 & 4 cycles represent the average of 27 runs in most cases for a given fuel/mode. There is more variability in the Phase 1 & 2 runs that include cold starts, but there are only three runs for each combination. More detailed statistical analysis will follow on the 27 Phase 3 & 4 cycles, but the average data shown in Figure 6 suggests the mode (start-stop and *no start-stop*) makes little difference for the E0 and E21 for both the Phase 1 & 2 and Phase 3 & 4 cycle PN emissions.

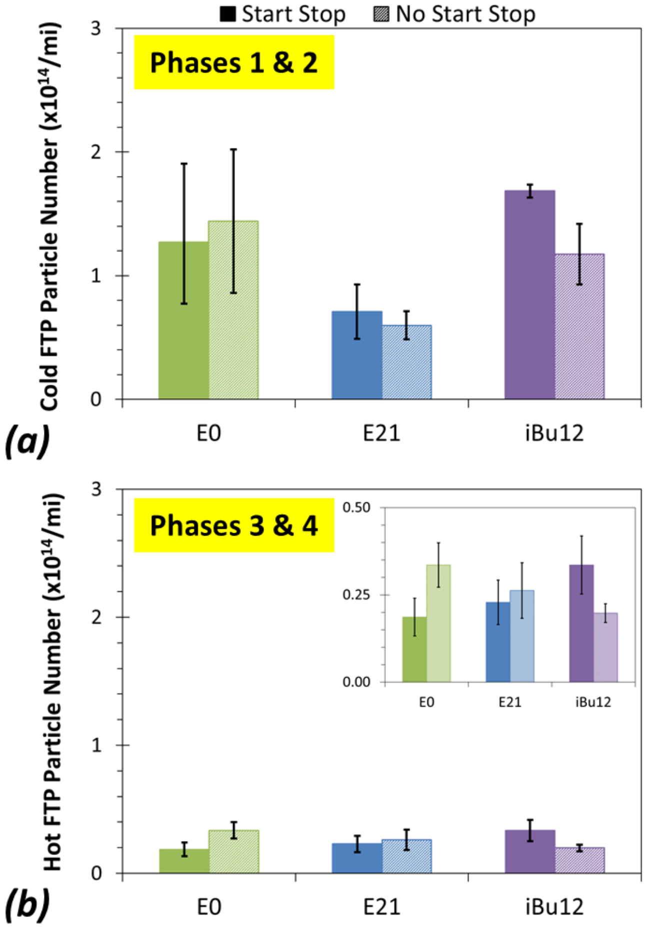

Figure 6. Average particle number/mile for both the (a) FTP-75 Phases 1& cycles,) and the (b) FTP-75 Phases 3& 4 cycles. EEPS total particle number measurements included particles from 5.6 nm to 560 nm. Error bars represent min/max values from 3 Phase 1 & 2 cycles (a) and standard deviation from 27 Phase 3 & 4 cycles (b). Inset zooms into Phase 3 & 4 to show differences.

Soot mass emissions

The AVL-MSS analyzes soot concentration in the raw exhaust at 2 Hz. A rolling average was used to reduce the noise in the data to enable direct correlations with the 1Hz EEPS data. Like the particle number, the soot mass can be integrated with exhaust flow to determine an integrated soot mass emissions value for the cycle in mg/mile. These values are shown in Figure 7 for the average Phase 1 & 2 and Phase 3 & 4 cycles. Note that the scale for the Phase 3 & 4 cycles (Figure 7b inset) is 10X lower than the scale for the Phase 1 & 2 cycles which include cold starts (Figure 7a). Also, there is high variability for soot emissions during start-stop, even during the warm operation of Phases 3 & 4. There is no clear influence of start-stop on the soot emissions for any of the fuels during Phase 1 & 2 cycles. However, there does appear to be soot emissions impact from the mode during Phases 3 & 4, especially for the iBu12 fuel which saw a significant soot mass increased during start-stop operation, as can be seen in Figure 7b.

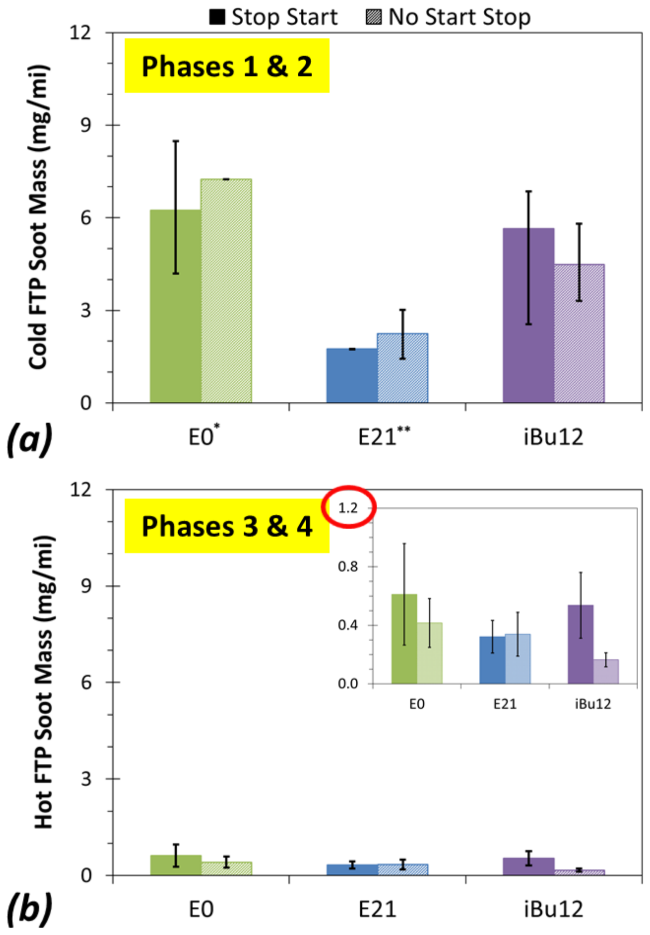

*Figure 7. Average soot mass emissions from MSS data for both the (a) FTP-75, Phases 1&2 and the (b) FTP-75, Phases 3&4. Error bars represent min/max values from 3 Phase 1 & 2 cycles (a); *except E0 'no start-stop' which only had 1 start and **E21 'start-stop' which only had 2 starts. Error bars represent standard deviation for the Phase 3 & 4 cycles (b). Inset (b) zooms in to show differences on a 10X smaller scale than the (a).*

Transient Soot and Particle Number

Since the EEPS and the MSS data were both in 1 Hz resolution, we examined transient behavior of both soot and PM number. In Figure 8, the first 350 seconds (i.e. until end of 'Hill 2', reference Figure 1) of Phase 1 and Phase 3 are compared for E21/*no start stop* data. Since the start-stop operation is not activated until after "Hill 2" at ~300s, the start-stop and *no start-stop* modes are identical for the initial 5 minutes (300s) therefore the impact of mode is not relevant. Like Figure 6, the particle number count is much higher for the Phase 1 cycle which has a cold start, suggesting that the particle production during the first two acceleration points, "Hill 1" and "Hill 2" (Figure 1) is suppressed during the Phase 3 cycle due to warm operation. The particle number rate during Phase 1 is close to 10X higher during this initial 300s compared to Phase 3, mirroring the total number/mile rate difference seen over the entire 1372s Phase 1 & 2 and Phase 3 & 4 cycles in Figure 6, highlighting the influence of the firsts 300s of the full FTP-75 cycle on total particulate production.

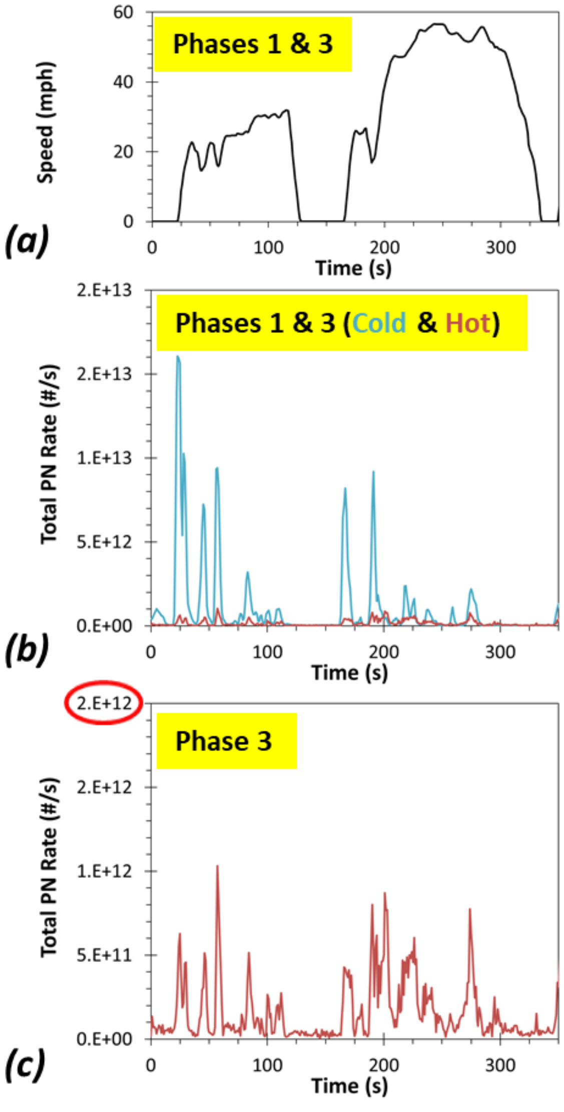

Figure 8. (a) The speed trace for the first 350s of the FTP Phases 1 & 3. Graphs compare the total particle number rate for E21 no start-stop mode from EEPS for the first 350 s of (b) Phase 1 (Cold, blue) and (c) Phase 3(Hot, red) of the FTP-75. Note that the Phase 3(c)

scale is 10X lower than the Phase 1 scale (b). A similar trend was seen for all fuel/mode combinations.

In Figure 9, E21/*no start-stop* is compared with E21/start-stop over a section of the Phase 3 & 4 cycle. Particle number emissions dropped to zero when the engine was shut off, as expected. In addition, the re-start from the engine-off condition does not appear to result in a larger spike of particles. Spikes in particle numbers during Phase 3 & 4 cycles were associated with the acceleration events, likely during tip-in, and can be seen for both start-stop and *no start-stop* modes in Figure 9.

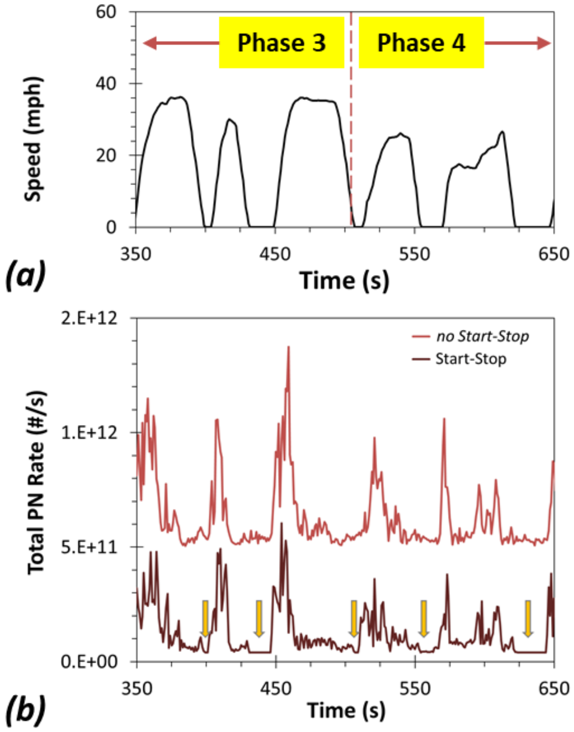

Figure 9. (a) The speed trace from 350-650s of Phases 3 & 4. The red dash line shows where Phase 3 ends and Phase 4 begins. The following graph (b) compares EEPS total particle number rate for E21 for no start-stop ((b), top) to start-stop ((b), bottom) operation during Phases 3 & 4. The arrows indicate where the particle numbers drop to zero during engine shut-off at 0 mph in the start-stop mode. Note that particle number rate data was offset for clarity.

The signals from the MSS for soot mass production rate during the first 300 s of Phase 1 and Phase 3 are shown in Figure 10 along with the speed trace. Like Figure 8, the spikes are associated with accelerations. The soot mass rate is greater than 20X higher for Phase 1, similar to the 10X increases in particle number rate seen in Figure 8.

In Figure 11, E21 *no start-stop* is compared with E21 start-stop. Soot emissions drop to zero when the engine is off, as expected. In addition, the re-start from the engine-off condition does not result in a larger spike of soot emissions. The spikes in soot emissions during the Phase 3 & 4 cycles are associated with the acceleration events, likely during tip-in, and can be seen for both modes in Figure 11.

For the E0 and iBu12, very similar trends were observed for both the real-time particle emissions and real time soot emissions.

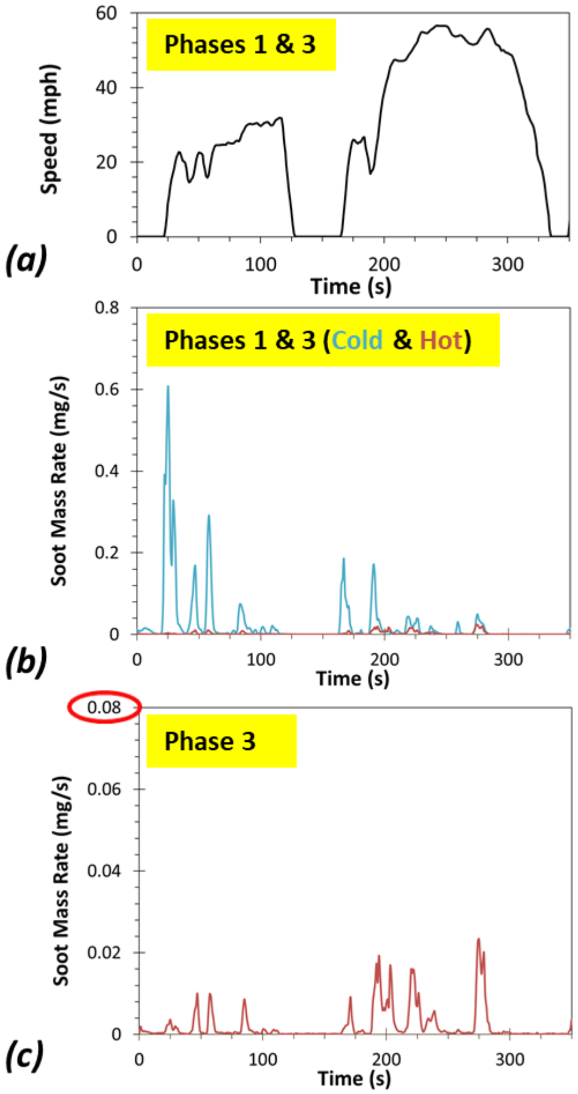

Figure 10. (a) The speed trace for the first 350s of the FTP Phases 1 & 3. Graphs compare the soot mass rate for E21 no start-stop mode from MSS for the first 350 s of (b) Phase 1 (Cold, blue) and (c) Phase 3 (Hot, red) of the FTP-75. Note that the Phase 3(c) scale is 10X lower than the Phase 1 scale (b). A similar trend was seen for all fuel/mode combinations.

Statistical Analysis

The 27 hot start runs (phases 3 & 4) for each fuel/mode combination provide enough data for statistical analysis to be performed on the dataset. Analysis of Variance (ANOVA) is commonly used to compare datasets by comparing the difference of means between groups. The assumptions for ANOVA included a normal distribution of data, and similar variance of the data for each group (i.e. the variability within the EEPS data for E0 is similar to the variability within the EEPS data for E21). For each comparison between two groups, the p statistic was calculated and then compared with a significance level, in this case 0.05, which equates to the 95% confidence level. The p statistic enables one to test the "null hypothesis" which assumes that there is no difference between the two groups being compared. If the $p < 0.05$, then the null hypothesis was accepted, and the two means were not statistically different. If p

>0.05, then the null hypothesis was rejected, and there was a difference between the means of the two datasets. The ANOVA p statistic values calculated for comparisons of ‘mode vs mode’ and ‘fuel vs fuel’ are shown in Tables 4 and 5 for particle number emissions (EEPS) and soot emissions (MSS) and respectively.

The statistical analysis identified some differences between modes and between fuels for both PN and soot mass emissions during Phases 3 & 4, the hot portion of the FTP drive cycle. In Table 4, PN emissions were significantly different between start-stop and *no start-stop* for E0 and iBu12, with the E0 having higher PN emissions for *no start-stop* and the iBu12 having higher PN emissions for the start-stop modes. In terms of fuel effects on PN emissions, the only pair showing no difference was the E0 and E21 for the start-stop mode. Figure 6b illustrates the fuel differences – iBu12 has the highest PN emissions for start-stop and the lowest for *no start-stop*. In Table 5, soot emissions were significantly different for start-stop operation vs. *no start-stop* operation with the iBu12 fuel, with higher soot emissions for start-stop operation (Figure 7b). In terms of fuel differences, iBu12 soot emissions were significantly different than E0 and E21soot emissions, with only one exception; in start-stop mode, there was no significant difference between E0 and iBu12 emissions. However, the iBu12 soot emissions were actually lower for *no start-stop* mode than the E0 and E21 fuels. Figure 7b illustrates the differences that the ANOVA confirms.

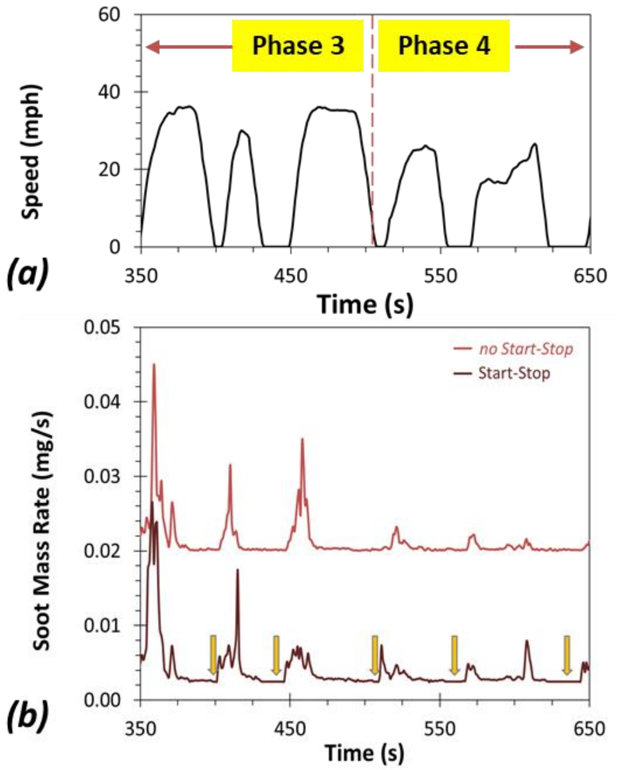

Figure 11. (a) The speed trace from 350-650s of FTP-75 which includes parts of Phase 3 and Phase 4. The red dash line shows where Phase 3 ends and Phase 4 begins. The following graph (b) compares MSS soot mass rate for E21 for no start-stop ((b), top) to start-stop ((b), bottom) operation during Phases 3 & 4. The arrows indicate where the soot mass rate drop to zero during engine shut-off at 0 mph in the start-stop mode. Note that soot mass rate data was offset for clarity.

Table 4. ANOVA results comparing mode vs. mode and fuel vs. fuel for particle number emissions during Phases 3 & 4 of the FTP-75 cycle

Particle Number (PN) Emissions		
Mode Effects		p
E0, no SS	E0, SS	0.0000
E21, no SS	E21, SS	0.2783*
iBu12, no SS	iBu12, SS	0.0000
Fuel Effects		p
E0, no SS	E21, no SS	0.0051
E0, no SS	iBu12, no SS	0.0000
E21, no SS	iBu12, no SS	0.0074
E0, SS	E21, SS	0.4007*
E0, SS	iBu12, SS	0.0000
E21, SS	iBu12, SS	0.0000

* No significant difference
SS= start-stop; no SS = *no start-stop*

Table 5. ANOVA results comparing mode vs. mode and fuel vs. fuel for soot mass emissions during Phases 3 & 4 of the FTP-75 cycle.

Soot Mass Emissions		
Mode Effects		p
E0, no SS	E0, SS	0.4121*
E21, no SS	E21, SS	0.9995*
iBu12, no SS	iBu12, SS	0.0000
Fuel Effects		p
E0, no SS	E21, no SS	0.8806*
E0, no SS	iBu12, no SS	0.0354
E21, no SS	iBu12, no SS	0.0047
E0, SS	E21, SS	0.0063
E0, SS	iBu12, SS	0.9322*
E21, SS	iBu12, SS	0.0022

* No significant difference
SS= start-stop; no SS = *no start-stop*

Discussion

Overall, the study identified some differences in particulate based emission between stop-start and *no start-stop* modes which are summarized in Table 6. The studied measured emission differences related to PM mass (gravimetric filter weights), PN emissions (EEPS), and soot mass (MSS) which can be seen in Figures 5, 6, and 7, respectively. The iBu12 fuel produced more PM mass, soot mass and PN emissions in the start-stop mode than in the *no start-stop* mode. In contrast, the E0 fuel had higher PM mass for the start-stop mode and lower PN emissions for the *no start*-stop mode. The E21 fuel only showed a difference in PM mass between the two modes with *no start-stop* showing an increase over the start-stop mode. There were relatively few PN and soot measurements made for the Phases 1 & 2 cycles which contained cold starts, and, as shown in Figures 6a and 7a, there didn’t appear to be significant differences between start-stop and *no start-stop* for any of the fuels, except the iBu12 impact on PN. However, E21 clearly had lower soot and PN emissions during Phases 1 & 2 than the other fuels for both start-stop and *no start-stop* modes.

Table 6. Summary of differences by fuel

	E0	E21	iBu12
PM mass (composite FTP)	S-S, higher	*No S-S* higher	S-S, higher
Particle Number (PN) *	*No S-S* higher	Similar	S-S, higher
Soot Mass*	Similar	Similar	S-S, higher

* Phases 3 & 4 only

Although there were large numbers of datasets for Phase 3 & 4 runs (~27 per fuel-mode), there was still variability which can be seen from the large error bars in Figures 6b and 7b. Part of the variability likely stems from the relatively low levels of both soot and particle number emissions during 'warmed-up' operation in Phases 3 & 4. In addition, the origin of soot in GDI engines is likely more stochastic than in a modern, high pressure common rail diesel engine that also injects fuel directly into the cylinder. In GDI operation, fuel is injected during the down stroke of the piston and can potentially collect in crevice volumes during one cycle and then be ejected during a different cycle, leading to a locally rich combustion zone that produces soot. In contrast, a diesel injects near top dead center and results in a diffusion flame where the majority of the soot is burned out before the exhaust valve opens. The relatively large differences in particulate-based emissions seen in this study between the cold start and hot start phases of the FTP are related to the injection of fuel during the down stroke and subsequent collection on the cold surfaces as well as the extra fuel injected to enable rapid catalyst light-off. A forthcoming paper from this laboratory will describe the effects of the initial part of the cold start on GDI PM emissions.

A major conclusion of this study was that while some difference could be seen in particulate emissions, the difference in PM mass emissions was not very large between start-stop and *no start-stop* operation for this vehicle, suggesting that the additional starts are unlikely to significantly increase the PM emissions. If this vehicle is representative of the market, this finding is important as GDI engines penetrate the light-duty market and more manufacturers adopt start-stop for fuel economy.

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Notice:

Definitions/Abbreviations

ASTM - American Society for Testing and Materials

AKI - anti-knock index

CAN – Controller Area Network

E0 - 100% gasoline

E21 - 21% ethanol in gasoline

EEPS – Engine Exhaust Particle Sizer

EtOH - ethanol

FTP - Federal Test Procedure

GM – General Motors

GDI - gasoline direct injection

HC - hydrocarbon

iBu12 - 12% isobutanol in gasoline

LHV - lower heating value

PAH - polycyclic aromatic hydrocarbons

PFI - port fuel injected

PM - particulate matter

PN – Particle number

PTFE - polytetrafluoroethylene

RPM - repetitions per minute

SG - specific gravity

SMPS - Scanning Mobility Particle Sizer