

A Pilot Study of Fuel Impacts on PM Emissions from Light-Duty Gasoline Vehicles

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ABSTRACT

A pilot study was performed to explore the effects of PM Index, low and high molecular weight aromatics, and ethanol content on particulate matter (PM) emissions from light-duty Tier 2 gasoline vehicles. Four test vehicles from model years 2007-2009 were tested on seven fuels spanning PM Index values from 0.9 to 2.7, aromatic content from 14 to 38%, and ethanol content from 0 to 15%.

Three of the test vehicles were port fuel injected (PFI) while the fourth featured gasoline direct injection (GDI). In an earlier program, two of the PFI vehicles demonstrated high sensitivity of PM emissions to fuel property changes while the third showed low sensitivity. The sensitivity of the GDI vehicle to fuel property changes was not known prior to this study. The vehicles were tested over the LA92 and US06 test cycles at 24°C (75°F). PM and regulated gaseous emissions were measured by test phase. Second-by-second tailpipe soot emissions were measured using the AVL Micro Soot Sensor.

The results of this study support the theory behind the PM Index that low volatility compounds, particularly heavy aromatics, have the strongest influence on PM emissions from gasoline vehicles. In addition, the presence of ethanol was found to have a reinforcing interaction with PM Index in PFI vehicles, consistent with results reported in a companion paper [1]. The GDI vehicle generally produced higher PM emissions than the PFI vehicles, most notably during operation on the lower-PM-Index fuels.

CITATION: Sobotowski, R., Butler, A., and Guerra, Z., "A Pilot Study of Fuel Impacts on PM Emissions from Light-Duty Gasoline Vehicles," *SAE Int. J. Fuels Lubr.* 8(1):2015, doi:10.4271/2015-01-9071.

INTRODUCTION

It is important for the United States Environmental Protection Agency (EPA) and its stakeholders to have accurate and up-to-date fuel effects data in order to assess air quality and evaluate the effectiveness of emission control strategies. The Agency recently published an analysis of data collected in the EPA/V2/E-89 gasoline fuel effects test program, which examined emission impacts of changes in several fuel properties on a test fleet of 15 Tier 2 cars and light duty trucks from the 2008 model year [2]. Measurements included PM emissions for all fuels and vehicles, which allowed modeling of fuel effects on PM. Statistical modeling analysis showed positive terms for total aromatics, T50, T90, and ethanol, indicating that individual increases in these fuel properties are associated with higher PM emissions.

Subsequent to the launch of the EPA/V2/E-89 gasoline fuel effects program, Honda published a method for computing a PM Index parameter which characterizes the propensity of gasoline formulations to produce PM [3]. The PM Index combines detailed compositional information about the fuel with the volatility and structural characteristics of individual compounds. The Honda paper suggested that low-volatility aromatics in gasoline are responsible for a disproportionately large share of PM emissions, but the results were limited to only a few test vehicles. The motivation for this pilot study

was to investigate further the impacts of PM Index, aromatic carbon number and ethanol on PM emissions in the context of the recently-completed EPA/V2/E-89 study.

OVERVIEW OF FACTORS AFFECTING PM EMISSIONS FROM SI ENGINES

Particulate matter emissions from spark ignition (SI) engines, both PFI and GDI, are caused by incomplete fuel evaporation, inadequate air-fuel mixing and/or by rich fueling. They are affected by a multitude of factors including engine and vehicle design characteristics, control strategies and calibrations, as well as operating conditions and duty cycles. Superimposed on all these factors and interacting with them are the effects of fuel properties.

In PFI engines, the air-fuel mixture is formed in the intake ports and the cylinders. When the intake valve opens, the back flow of hot gases from the previous cycle enters the intake port and helps vaporize some of the fuel. Once the pressure between the port and the cylinder equilibrates, the fresh charge begins to flow into the cylinder. It includes fuel mist created by the injector and by shear stress of the intake flow causing strip atomization of the fuel flowing along the port and valve surfaces. It also includes fuel film which flows along the intake valve and port surfaces onto the valve face and the cylinder

head area adjacent to the valve seat. Some of the fuel flowing in the film is splashed into the cylinder by the impact of the valve lip on its seat. These fuel droplets as well as the fuel film entering the cylinder form puddles on combustion chamber surfaces and dilute engine oil on the cylinder wall.

In GDI engines [4,5], a sufficiently homogeneous air-fuel mixture must be created in the cylinders within the time window spanning fuel injection and spark ignition. Injection timing in such engines is constrained by piston and cylinder liner impingement and the time available for injection, evaporation and mixing of air and fuel. Spark ignition is in turn constrained by the requirements to ensure best fuel economy, avoid knock combustion and enable fast warm-up of the exhaust catalyst following a cold start. At the current stage of development of GDI technology, the preparation of air-fuel mixtures in GDI engines is typically worse than in PFI engines, as evidenced by their higher PM emissions under most conditions. The wetting of combustion chamber walls, incomplete droplet evaporation and inadequate air-fuel mixing still remain a challenge. It is being addressed through a number of means including optimized charge motion, spray targeting, injector nozzle geometry, higher injection pressures, higher injection rates as well as multi-pulse injection strategies aimed at limiting spray width and penetration [5,6].

The PM emissions from SI engines are highest during accelerations, as transients disrupt the control of global air/fuel ratios and exacerbate the heterogeneity of the cylinder charge [7]. This is particularly true of accelerations occurring during the engine warm-up phase following a cold start due to the presence of fuel films on the cold intake port (in PFI engines) and combustion chamber surfaces combined with the complex effects of transients on droplet evaporation, deposition and fuel evaporation from those surfaces. Some fuel films evaporate quickly while others survive the more vigorous charge motion and higher combustion temperatures associated with accelerations. They produce fuel rich plumes, aggravate mixture heterogeneity and cause pool fires and/or pyrolysis of the fuel in the plumes following the passage of the flame front [8,9,10]. Together with diffusion combustion of droplets, they enhance PM formation. Once the engine warms up, fuel wetting lessens and its effect on global and local air/fuel ratios and, consequently, on PM emissions is considerably alleviated. Nevertheless, rich fueling during wide open throttle (WOT) operation remains a source of increased PM emissions even in warmed up engines.

Fuel properties affect PM emissions from SI engines through their additional impact on global and local air-fuel ratios. This effect is further exacerbated by the stratification of the fuel borne chemical species across the air-fuel ratio strata and by the considerable differences in the propensity of these species to form PM. Therefore, engines which control global air-fuel ratios better than others, minimize wall wetting and fuel stratification in the combustion chamber, and make less use of WOT enrichment are less susceptible to the effects of fuel properties on PM emissions.

The following properties of SI engine fuels have been shown to affect PM emissions:

- The distillation range of the fuel and the distribution of the fuel mass within that range affect every aspect of the fuel evaporation process and, consequently, the global air fuel ratio, heterogeneity of the cylinder charge as well as the persistence of liquid fuel films through the intake, compression and power strokes, especially during the engine warm-up phase. Of particular importance is the heavy end of the fuel, namely the highest molecular weight, least volatile compounds. In the EPA/V2/E-89 study [2], T90 and to a lesser degree T50 were shown to correlate with PM emissions from PFI engines.
- The hydrocarbon composition of the fuel and, in particular, the content and distribution of the various chemical species, especially the aromatics, within its distillation range strongly influence PM emissions [3,11,12]. In general, aromatic compounds are more prone to soot formation than paraffins, cycloparaffins, or olefins. This tendency is less evident in the case of light aromatics such as toluene whose boiling point falls in the vicinity of the T50 point of gasoline. It is very significant in the case of heavy aromatic compounds whose boiling points fall in the vicinity of the gasoline distillation end point.

Until a few years ago, attempts to correlate the hydrocarbon composition of the fuel to PM emissions from gasoline engines relied exclusively on total aromatic content of the fuel. Since the 2010 publication of Honda's SAE paper on this subject [3], such attempts have also featured the PM Index which integrates detailed compositional information about the fuel with the volatility and structural characteristics of individual compounds.

- The properties of ethanol differ significantly from those of E0 gasoline (Table 1). Its energy content expressed in terms of volumetric net heat of combustion is about a third lower, resulting in longer durations of fuel injections. The heat of vaporization of ethanol per unit mass of stoichiometric mixture with air is over 4 times higher. Its higher density, surface tension and viscosity imply greater spray penetration and coarser fuel atomization. Yet spray penetration studies of gasoline-ethanol blends have so far produced contradictory results [13], possibly due to ethanol's high heat of vaporization, the wide variety of base fuels used in such studies, and the effect of ethanol on the evaporation of the heaviest hydrocarbon fractions of the fuel. Additional investigations are needed to fully understand this issue.

Similarly, ethanol has been shown to suppress soot formation in most flame studies but to enhance it in others or at certain concentrations [16,17]. In vehicle studies, neat ethanol and E85 almost always produce lower PM emissions than E0 fuels. However, low ($\leq 10\%$) or mid-level ($>10\%$, $\leq 70\%$) ethanol/gasoline splash blends yield mixed results. In two studies by Storey et al. [18,19], consistent reductions in PM emissions were observed over the E0-E20 range. Maricq et al. [20] reported statistically significant reductions in PM emissions with E32 and E45 fuels in comparison to base E0 gasoline. However, the effects were mixed and not statistically significant for E10 and E17.

fuels evaluated in that study. Vuk et al. [21] tested two GDI vehicles and one PFI vehicle on E0 and E30 fuels over the FTP test cycle and observed reductions in PM emissions associated with the increase in ethanol content of the fuel. One of the GDI vehicles was also tested on E0, E10, E30 and E50 fuels over the US06 test cycle and produced a considerable reduction in PM emissions between E0 and E10, followed by a steady increase in PM as ethanol content of the test fuels was augmented to E30 and E50. Test-to-test variability cannot be ruled out as a factor in these results, since each vehicle/fuel combination was only tested once in this study. However, the authors also note that the heat of vaporization of ethanol in higher level blends could have impeded vaporization of the heaviest fuel components resulting in higher PM emissions. The latter view has recently been reinforced by spray vaporization modeling and droplet vaporization experiments performed by Kobashi et al. [22], who concluded that the heat of vaporization of ethanol suppresses the evaporation of ethanol-heptane blends. Karavalakis et al. [23] measured PM mass emissions from one PFI vehicle and two GDI vehicles operated on E10, E15 and E20 fuels over the LA92 and FTP test cycles. They reported consistent reductions in PM emissions as the ethanol content of test fuels was increased from E10 to E20 but mixed results at the E15 level. Chen et al. [24] conducted steady-state tests of a V8 GDI engine on E0 and E10 fuels and demonstrated that PM mass emissions can increase or decrease with ethanol content depending on fuel injection timing. Their results illustrate the broad range of emissions effects that can be produced by the interactions between fuel properties and engine/vehicle design characteristics, control strategies, and calibrations. Stone et al. [25] tested E0, E10, E20, E50, E70 and E85 blends in a single-cylinder, optical-access GDI engine to evaluate their spray characteristics, combustion performance, and PM emissions. They reported gradual increase in PM emissions with ethanol content of the blends, attributing the observed effects to ethanol impacts on fuel spray and vaporization characteristics. Stone et al. also noted that ethanol increases the injected volume and heat of vaporization of the fuel, thus aggravating heterogeneity of the air/fuel mixture and increasing PM emissions.

It is worth stressing that all investigations cited in the preceding paragraph, as well as the vast majority of other published studies exploring the effects of ethanol blends on PM emissions from SI vehicles, have exclusively used splash blends of ethanol and gasoline, and were predominantly focused on GDI engine technology. The EPA/V2/E-89 study which utilized a statistically designed fuel matrix and PFI-only vehicles has been one of the very few exceptions.

When discussing the effect of ethanol on PM emissions, it is important to consider which hydrocarbon species it is replacing in the fuel and which other fuel parameters are being affected. For example, splash blending of ethanol, so ubiquitous in fuel effects studies, produces complex changes in the physical and chemical properties of the fuel. It affects the distillation properties of the fuel and results in the dilution of its hydrocarbon components, among other effects. Splash blending depresses T50 and T90. It affects equally the concentrations of aromatic and aliphatic species (paraffins, cycloparaffins, and olefins) in the fuel. With all these collateral changes, it is impossible to determine to what degree an emission effect is due to the presence of ethanol, reduced content of the

hydrocarbon fraction in the fuel or a change in other fuel properties. Furthermore, given an infinite variety of possible base fuel compositions, a particular splash blend is just a single example in an infinite number of cases that can be explored. As such, it can only provide very limited insights into the performance of market fuels in SI engines.

Table 1. Selected properties of typical US Tier 2 emissions certification gasoline.

Property	US Tier 2 Cert Gasoline	Ethanol
Density @ 293 K, kg/m ³	739	789
Surface Tension @ 298 K, mN/m	19.80	21.99 [14]
Dynamic Viscosity @ 293 K, mPa·s	0.44	1.20 [13]
Boiling Range/Point, K (°F)	305-480 (90-404)	351.5 (173.0) [14]
Heat of Vaporization @ 298 K, kJ/kg	~ 350	920 [15]
Heat of Vaporization @ 298 K, kJ/kg stoich. mixture	~22	92
Net Heat of Combustion @ 298 K, MJ/kg	43.4	26.8 [14]
Net Heat of Combustion @ 298 K, MJ/dm ³	32.1	21.1
Net Heat of Combustion @ 298 K, MJ/kg air at stoichiometry	2.97	2.98
Stoichiometric A/F Ratio	14.6	9.0

As mentioned above, the results of the EPA/V2/E-89 study [2] indicate that increasing total aromatic content, T50, T90, or ethanol content of the fuel is associated with increased PM emissions from typical light-duty, Tier 2, PFI vehicles. EPA/V2/E-89 PM models can, of course, be used to predict the individual or combined impacts of these fuel parameters. They can also be used to assess the effects of replacing any combination of aromatic or aliphatic components in the fuel with ethanol, including all such cases represented by splash blends.

All fuels used in the EPA/V2/E-89 program were blended to specific DVPE, T50, T90, aromatic content and ethanol content targets. This approach was also applied to most fuels used in this pilot study as it enables emission impacts to be associated with specific fuel parameters.

Since PM emissions from SI engines are mainly caused by wall wetting, incomplete vaporization of wall films and fuel droplets, inadequate mixing of air and fuel as well as rich operation, any fuel property that affects these processes will affect PM formation. For a given SI engine and a given operating condition or duty cycle, the degree of wall wetting and the ability of the wall films and fuel droplets to vaporize and mix with air depend on the distillation characteristics of the fuel, i.e. its distillation range and the distribution of fuel mass within that range. The degree of wall

boiling point (FBP) of the fuel and the larger the fraction of fuel concentrated in its heavy end, the less volatile will the fuel be and the higher the PM emissions.

The effect of hydrocarbon composition of the fuel on PM emissions is superimposed on its distillation characteristics. This is particularly true of aromatic species whose impact on PM emissions has been shown to increase with their carbon number. The higher the carbon number of an aromatic species, the higher its boiling point, the lower its volatility and the higher its propensity to produce PM.

The effect of ethanol on PM emissions from SI engines operated on low-level ethanol-gasoline blends is further superimposed on the effects of the distillation characteristics and hydrocarbon composition of the fuel. While ethanol may chemically suppress the formation of soot precursors, it seems to impede evaporation of the fuel (through the impact of its high heat of vaporization), exacerbating heterogeneity of the cylinder charge and increasing PM emissions.

DESIGN OF THE TEST PROGRAM

Test Vehicles

Four light-duty vehicles spanning model years 2007-2009 were used in this study. Three of the four vehicles were equipped with PFI engines, namely the Nissan Altima, Honda Civic and Ford Explorer. The make, model, and test group of the Nissan Altima and Ford Explorer matched those of vehicles used previously in the EPA/V2/E-89 program [2]. The emissions control system of the Honda Civic was carried over from 2008 (model year of the EPA/V2/E-89 vehicle) to 2009. Of those three vehicles, two (Nissan Altima and Honda Civic) had demonstrated relatively high sensitivity of PM emissions to fuel properties in the EPA/V2/E-89 program, while the third (Ford Explorer) showed relatively low sensitivity. The fourth vehicle (BMW 335i) was powered by a spray-guided GDI engine, and its PM emissions sensitivity to fuel properties was unknown prior to this study. Additional details for the test vehicles are given in [Table 2](#).

Table 2. Test vehicles.

Make/Model	Model Year	Engine Displacement, dm ³	Tier 2 Bin	Odometer, km (miles)
Nissan Altima	2008	2.5 I4	5	201k (125k)
Honda Civic	2009	1.8 I4	5	200k (124k)
Ford Explorer	2008	4.0 V6	4	132k (82k)
BMW 335i	2007	3.0 I6 twin turbo	5	166k (103k)

The three PFI vehicles were acquired from the US Department of Energy following completion of an unrelated test program. Check-out tests were performed at EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, MI, to make sure they met regulatory requirements. Their odometer readings were at or near full useful life. The GDI vehicle was purchased by EPA from a vehicle dealer after being screened to ensure its exhaust emissions were

within regulatory limits. Its odometer reading was within the range of the other three test vehicles. The decision to test vehicles with mileage at or near full useful life was dictated by the difficulty of sourcing low mileage vehicles identical to those used in the EPA/V2/E-89 program, given the time elapsed since that study.

In preparation for the test program, all vehicles underwent routine maintenance followed by conditioning of the fresh engine oil over a distance of 2,000 miles to stabilize its impact on PM emissions. This conditioned engine oil was retained in the vehicles until the completion of this study to eliminate the possibility of engine oil changes affecting the results of PM emissions measurements.

Test Fuels

Eight test fuels were used in this study. Their properties are provided in [Table A-1](#) in the [Appendix](#). Fuels 7, 13 and 26 were identical to fuels which bore the same designations in the EPA/V2/E-89 program as a tie-back to its results. Fuels 100, 101 and 102 were new formulations and Cert Fuel 1 and Cert Fuel 2 came from two different batches of the EPA Tier 2 emissions certification fuel. Cert Fuel 1 was tested in the PFI vehicles, while Cert fuel 2 in the GDI car when the earlier batch was no longer available.

Fuels 7, 13, 26, and 100 were designed to allow examination of the interaction between ethanol and the PM index, and its effect on PM emissions. Fuels 101 and 102 were developed with the aim of assessing the PM emissions effect of the addition of light and heavy aromatic components to a low PM Index fuel. The certification fuels were used to fill in the gap in the PM Index range of this fuel set and provide a recognizable reference.

The ethanol level used in this study (15 volume %) was chosen at the time when EPA was considering specifying a future E15 emissions certification test fuel. An ethanol level higher than E10 was also expected to highlight the impacts of this oxygenate on exhaust emissions.

The low T50, low T90, low aromatic content, E0 Fuel 7 was selected for its low PM Index previously measured in the EPA/V2/E-89 program. Its E15 companion, Fuel 100, was formulated to match the T90, DVPE, total aromatic content, and C6/C7/C8/C9/C10+ aromatic carbon number distribution of Fuel 7. It was expected that the values of their PM Indices would also match, which turned out to be true.

The high T90, high aromatic content, E0 Fuel 13 and its companion E15 Fuel 26 were selected for their relatively high and matching PM Indices. These fuels were rebled to even better match their T90 distillation points, DVPEs, total aromatic contents, and C6/C7/C8/C9/C10+ aromatic carbon number distributions.

The T50 distillation points of E15 Fuels 100 and 26 matched at roughly 73°C (163°F), as did the T50s of E0 Fuels 7 and 13 at approximately 96°C (206°F), the difference reflecting the expected effect of ethanol on the shapes of the distillation curves. In addition, the C6/C7/C8/C9/C10+ aromatic carbon number distributions of Fuels 7, 13, 26 and 100, were designed to replicate those in the EPA/V2/E-89 program.

Fuels 101 and 102 were derivative of Fuel 100. Fuel 101 was blended by adding a nominal 15 volume % of a C10+ aromatic blending component to Fuel 100. Fuel 102 was blended by adding a nominal 15 volume % of toluene to Fuel 100. The sulfur and ethanol contents of both blends were subsequently adjusted to match the specifications of Fuel 100. No other fuel parameters were adjusted in either blend. The magnitude of the incremental increase in the aromatic content of Fuel 102 relative to Fuel 100 was based on the assumption that the toluene content in Fuel 102 should not exceed its highest concentration in market fuels, which sometimes approaches 20 volume %. The same increment was assumed for Fuel 101.

The addition of toluene to Fuel 100 to create fuel 102 had a very minor effect on the PM Index, an increase from 0.92 to 0.97, reflecting the relatively high volatility of toluene. On the other hand, the addition of the C10+ aromatic component to Fuel 100 boosted the PM Index of the resulting blend to 2.72, reflecting the low volatility of C10+ aromatic species.

Fuels 7, 13, 26, 100, 101, and 102 were formulated to an anti-knock index (AKI) target of ≥ 87.0 , as the three PFI test vehicles were designed to operate on regular gasoline. When the BMW 335i was considered for inclusion in the test vehicle fleet, the issue of Fuels 7 and 13 was discussed in detail, as they did not meet the manufacturer's octane requirement for this vehicle, namely $\text{AKI} \geq 91.0$. At 88.5 each, these two fuels also missed by 0.5 the minimum AKI rating of 89.0 allowed by the manufacturer. Nevertheless, Fuels 7 and 13 were subsequently tested in the BMW, as their octane rating was not expected to affect the emissions performance of such a high power-to-weight ratio vehicle, especially in the relatively lightly loaded LA92 test cycle.

All fuels used in this study were blended by Halterman Solutions. Following delivery to NVFEL, they were kept at a temperature of $<10^\circ\text{C}$ (50°F) in a dedicated cold storage chamber.

Aromatic content by ASTM D5769 was exclusively used in the development of Fuels 7, 13, 26, 100, 101, and 102. It is also used exclusively throughout the remainder of this paper. Aromatic content by ASTM D1319 is reported in Table A-1 only for comparative purposes. Detailed composition of all test fuels was also determined using ASTM method D6729 for use in calculating the PM Index.

Driving Cycles and Test Protocol

All vehicle/fuel combinations were tested using the two-phase LA92 test, followed by the US06 test (consisting of a warm-up cycle followed by a sampled cycle). Vehicle speed traces for these cycles are provided in Figures 1 and 2, respectively. The LA92 test (also called the California Unified Cycle) was used in this study to enable comparisons of its results with those of the EPA/V2/E-89 program. It is more aggressive than the FTP cycle, features higher speeds and accelerations, but fewer stops and less idle time. It was run as a cold start test and only included phases 1 and 2. Both tests were performed at a nominal temperature of 24°C (75°F).

A minimum of four LA92 and four US06 tests were conducted on each vehicle/fuel combination to assure statistically valid results. All tests of a given vehicle/fuel combination were performed back-to-back. The same driver drove all tests in this study.

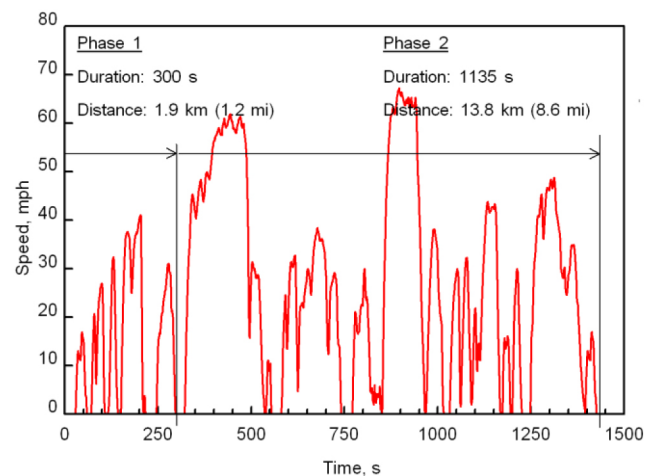


Figure 1. LA92 test cycle.

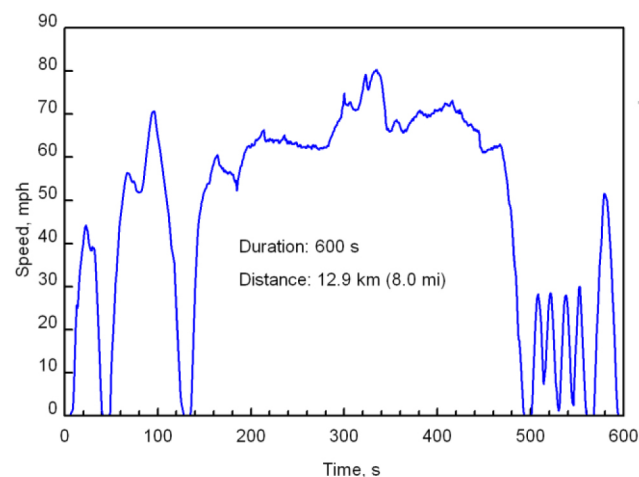


Figure 2. US06 test cycle.

Test Equipment

All tests were conducted in a single test cell using a 48-inch Horiba, single-roll electric dynamometer.

Measured emissions included THC, NMHC, NO_x , CO, CO_2 , CH_4 , PM mass, and sec/sec soot. Gaseous emissions were determined in a manner consistent with CFR, Title 40, Part 86. A constant volume sampler was used to collect proportional dilute exhaust in Kynar bags for analysis of THC, NMHC, NO_x , CO, CO_2 , and CH_4 . For the determination of PM mass emissions, a proportional sample of dilute exhaust was drawn through Whatman Teflon membrane filters. The PM sampling method was compliant with CFR, Title 40, Part 1065. PM samples were simultaneously collected in triplicate for each US06 test and each phase of the LA92 cycle. Dilution air PM samples were collected as well, at weekly intervals. These background PM measurements varied around zero and their impact on PM emissions results would have been negligible. Therefore, the PM emissions results were not corrected for background in this study.

Second-by-second tailpipe soot emissions were measured using a Model 483 AVL Micro Soot Sensor (MSS) and one of two Sensors SEMTECH High Speed Exhaust Flow Meters (2.5 or 3.0 inch diameter, depending on vehicle). The exhaust flowmeter was attached to the tailpipe of each vehicle via a short segment of flex pipe. It was immediately followed by the sampling probe of the AVL MSS.

Selected OBD parameters were logged in all test vehicles at a frequency of 10 Hz using either a HEM Data Corporation DAWN OBD Mini Logger or DashDAQ XL Series II OBD logger.

The information which could be gleaned from second-by-second tailpipe soot emissions data generated by the AVL MSS was of particular interest in this study, as it enabled additional insights into the processes involved on the generation of the PM. In this context, it was important to know what carbonaceous species this instrument measures. According to its manufacturer, the MSS is tuned to measure the concentration of black carbon in the exhaust and is insensitive to the presence of hydrocarbons. However, studies are currently underway to precisely establish the nature of the species to which the MSS responds. As a result, and for the purposes of this paper, a decision was made to apply the term “MSS soot” to the output of this instrument.

Following each test, the second-by-second data from the AVL MSS and the Sensors SEMTECH exhaust flowmeter were aligned and processed to produce an MSS soot emissions rate, which was then integrated over the respective test cycle or its phase and compared to PM emissions measured using the filter method. The results of this comparison drawn from all emissions tests of PFI vehicles reported in this study are provided in [Figure 3](#). The figure is a compilation of data generated in Phases 1 and 2 of the LA92 test and in the US06 test. The correlation between MSS soot and PM is very tight, with an R-squared value of 0.997.

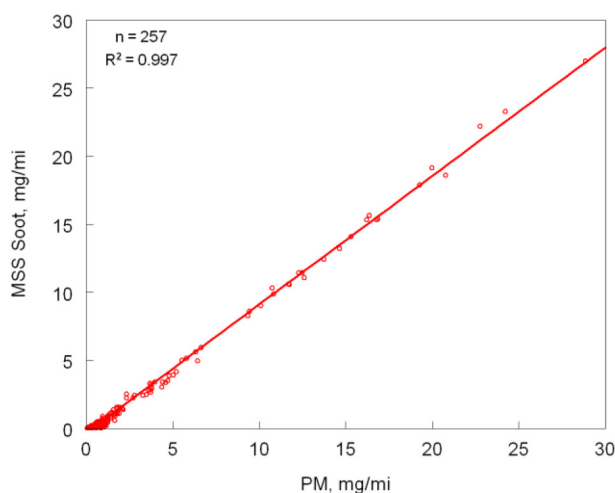


Figure 3. MSS Soot vs. PM emissions (PFI vehicles).

Results and Discussion

PM mass emissions from the four test vehicles measured in Phase 1 of the LA92 test cycle are presented in [Figures A-1, A-2, A-3](#) of the [Appendix](#), as a function of T90, total aromatic content and the PM

Index, respectively. The data points shown in these figures represent individual emissions tests. These results corroborate the roughly linear relationship between PM emissions and the PM Index reported by others [[3,12](#)]. They also reveal a relatively linear relationship between PM and T90, but a more complex one between PM and total aromatic content. In particular, the example of Fuels 101 and 102 shown in [Figure A-2](#) demonstrates that total aromatic content is an inadequate indicator of the fuel's propensity to form PM emissions. The same conclusions can be drawn from similar plots (not included here) showing PM emissions generated in Phase 2 of the LA92 test cycle and in the US06 test. As a result, throughout the remainder of this paper, PM emissions data will be presented as a function of the PM Index, especially because the latter captures the impacts of both the volatility and molecular structure of fuel constituents.

PM mass emissions observed in Phase 2 of the LA92 test cycle and in the US06 test are shown in [Figures A-4 and A-5](#) of the [Appendix](#), respectively. Together with the Phase 1 results presented in [Figure A-3](#), they confirm the wide range of PM sensitivity to fuel property changes observed in the vehicle population tested in the EPA/V2/E-89 program and, more specifically, the high sensitivity of Honda Civic and Nissan Altima and the low sensitivity of Ford Explorer which were also tested in this study. In the case of the Honda Civic and the Nissan Altima, the range of fuel effects observed in Phase 1 of the LA92 test spans at least an order of magnitude, as do BMW 335i results in Phase 2 of the LA92 test. In all other cases these fuel effects remain considerable, with the possible exception of the Ford Explorer which displayed essentially no sensitivity to fuel property changes in Phase 2 of the LA92 test and in the US06 test.

A shift in PM emissions was observed during testing of the BMW which affected Fuels 13 and 101, the last two fuels tested in the series. An investigation, which included retests on several fuels, ascertained that BMW tests performed on Fuels 7, 100, 102, 26, and Cert Fuel 2 over the LA92 test cycle were not affected. The results of these tests are included in this paper, while those conducted on Fuels 13 and 101 have been voided. That shift did not affect US06 tests of the BMW and those results are included here.

The test data shown in [Figures A-3, A-4, and A-5](#) confirm yet another observation made originally in the EPA/V2/E-89 program based on test data generated using 15 PFI vehicles and 27 test fuels, that if the PM Index is low enough (e.g. <1 in Phase 1 of the LA92 test), PM emissions are not only the lowest but, in the majority of cases, also independent of the vehicle. The sole exception in this study was the GDI BMW 335i in the LA92 test. Yet, as illustrated in [Figure A-5](#), it produced PM emissions on par with the PFI vehicles in the fully warmed up US06 test. In addition, as further shown in [Figure A-4](#), once the PFI engines were warmed up to some degree (as in Phase 2 of the LA92 test), PM emissions still remained low and independent of vehicle over a broad PM Index range, up to approximately 1.8. This observation remains largely true of the PFI vehicles in the fully warmed up US06 test cycle (See [Figure A-5](#)) though the Honda Civic produces somewhat higher PM emissions than the other two PFI vehicles, due in part to fuel rich WOT operation during one of the accelerations¹.

1. Neither the Nissan Altima nor the Ford Explorer required WOT enrichment in US06 tests