

Impact of Ambient Temperature on Gaseous and Particle Emissions from a Direct Injection Gasoline Vehicle and its Implications on Particle Filtration

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ABSTRACT

Gaseous and particle emissions from a gasoline direct injection (GDI) and a port fuel injection (PFI) vehicle were measured at various ambient temperatures (22 °C, -7 °C, -18 °C). These vehicles were driven over the U.S. Federal Test Procedure 75 (FTP-75) and US06 Supplemental Federal Test Procedure (US06) on Tier 2 certification gasoline (E0) and 10% by volume ethanol (E10). Emissions were analyzed to determine the impact of ambient temperature on exhaust emissions over different driving conditions. Measurements on the GDI vehicle with a gasoline particulate filter (GPF) installed were also made to evaluate the GPF particle filtration efficiency at cold ambient temperatures. The GDI vehicle was found to have better fuel economy than the PFI vehicle at all test conditions. Reduction in ambient temperature increased the fuel consumption for both vehicles, with a much larger impact on the cold-start FTP-75 drive cycle observed than for the hot-start US06 drive cycle. Colder ambient temperatures were also found to increase CO, THC, and particle emissions over the FTP-75 drive cycle, with little impact on the emissions over the US06 drive cycle. E10 was found to decrease particle number emissions from the PFI vehicle over both test cycles and all ambient temperatures. E10 almost always led to higher particle emissions from the GDI vehicle, except over the FTP-75 drive cycle at standard temperature. Limited soot regeneration in the GPF was observed at cold ambient temperatures over the FTP-75 drive cycle. However, the particle filtration efficiency of the GPF did not significantly change during cold ambient testing. On average, the mass-based GPF filtration efficiency over the FTP-75 drive cycle was observed to vary from 62% at standard temperature to 92% at -18 °C. When based on particle number, the GPF filtration efficiency varied from 85% at standard temperature to 80% at -18 °C. Over the US06 drive cycle, multiple spontaneous soot regenerations were observed and led to lower particle filtration efficiency. Mass-based filtration efficiency of the GPF was found to vary from 36% at standard temperature to 52% at -18 °C. Number-based filtration efficiency varied from 83% at standard temperature to 60% at -18 °C.

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INTRODUCTION

Gasoline direct injection (GDI) engines lead to a significant improvement in fuel economy and thus reduce the emissions of carbon dioxide while providing more power compared to traditional port fuel injection (PFI) spark ignition engines [1, 2, 3]. Over the past decade, different auto manufacturers have released various versions of GDI vehicles

and it is expected that the number of GDI vehicles on the road will continue to increase in the near future. In North America GDI vehicles are projected to reach up to 60% of the new light-duty vehicle fleet by 2016 [4]. Compared to traditional PFI engines, GDI engines typically have higher particle emissions due to different factors such as differences in fuel injection and mixture preparation, as well as lean and

stratified operation capability [1, 3, 5, 6, 7]. In Phase 1 of this program, it was shown that a 2011 model year wall-guided GDI vehicle operated on Tier 2 certification gasoline had lower CO₂ and slightly higher CO emission rates than a comparable 2010 model year PFI vehicle over both the U.S. Federal Test Procedure 75 (FTP-75) and US06 Supplemental Federal Test Procedure (US06) drive cycles. In addition, the stock GDI vehicle had a higher particle number emission rate than the PFI vehicle over both test cycles. Phase 1 also revealed that particle number emission rates from the GDI vehicle could approach the PFI levels with the use of a gasoline particulate filter (GPF) [3, 7].

In Europe and North America, vehicular compliance emission tests are conducted using a cold-starting drive cycle at standard room temperature with some tests specifically targeting CO emissions at -7 °C. Many studies in the past investigated the impact of ambient temperature on vehicular emissions. General findings showed that emissions of carbon dioxide (CO₂), carbon monoxide (CO), total hydrocarbons (THC), methane (CH₄), nitrous oxide (N₂O), and particulate matter (PM) mass increase significantly with decreasing ambient temperature [8, 9, 10, 11, 12, 13, 14]. At cold temperatures, the viscosity of the lubricating oil increases and thus reduces the pumpability of the oil. This results in higher mechanical losses and fuel consumption of the vehicle [11]. During cold-starting, PFI vehicles have to run rich to compensate for the poor volatility of the fuel and condensation losses of gasoline on the cold cylinder walls in order to prevent misfire [1, 11, 12, 16]. The excessive mixture enrichment often leads to incomplete combustion and elevates the CO and THC emissions [8]. Also, the three-way catalyst (TWC) takes a finite amount of time to reach the "light off" temperature before it can effectively remove CO and THC. As the warm-up time for the TWC increases with decreasing ambient temperature, this delays the effective period of the TWC during the test drive cycle [11, 12]. Finally, vehicles with older technology were also observed to have higher emissions under cold temperatures compared to newer vehicles [13, 14]. A study by the U.S. Environmental Protection Agency suggested that not considering the cold temperature effect on vehicular emissions in a regional model simulation leads to an under-estimation of the volatile organic compounds emissions particularly for states that experienced cold winter temperature [17]. Many cities in Canada often experience much colder winter temperatures and, therefore, to truly assess regional air quality requires emissions measurements that are obtained at colder ambient conditions.

As a continuation of the Phase 1 testing of this program [3], Phase 2 investigated the impact of ambient temperature on gaseous and particle emissions from a recent GDI vehicle and a PFI vehicle over the FTP-75 and the US06 using Tier 2 certification gasoline (E0) and gasoline blended with 10% ethanol by volume (E10). Since the GPF particle filtration efficiency was found to be dependent on the emission test procedure in Phase 1, the particle filtration efficiency of the

GPF at various cold temperatures on E0 was also investigated in Phase 2. Please note that after Phase 1 results were published, an error in the calculation of the FTP weighted particle number emissions was discovered. This computational error occurred when converting the mathematical equations to programming codes and as a result, it over-weighs the FTP Bag 1 results leading to an over-estimation of the FTP composite particle number emissions by a factor of about two. This however did not change any of the observed trends or conclusions associated with standard temperature particle emissions tests from the stock GDI, GDI equipped with a GPF, or the stock PFI test vehicles in that study. The corrected FTP weighted particle number emission levels at standard and cold ambient temperatures for the test vehicles are reported in this paper (Appendix Table A5).

MEASUREMENT PROCEDURE AND TECHNIQUE

Vehicles, GPF, and Ambient Temperatures

The test vehicles were a 2011 Hyundai Sonata wall-guided, stoichiometric GDI vehicle and a 2010 Volvo S40 PFI vehicle. Specifications of the two vehicles are given in Table A1 of the Appendix. The gasoline particulate filter (GPF) used on the GDI vehicle in Phase 2 was the same uncoated filter that was used in Phase 1, which was optimized to lower the effects on back pressure and fuel consumption of this sized engine, and was provided by the Manufacturers of Emission Controls Association (MECA). The GPF has a dimension of 5.66" (14.4 cm) in diameter and 6" (15.2 cm) in length. The GPF is made using a cordierite material to ensure superior thermal shock performance. The cell density of the GPF is 200 cpsi with 12 mil (0.3 mm) of wall thickness and approximately 50% wall porosity. When in use, the GPF was installed in the underfloor position downstream of the original equipment TWC, replacing the original equipment resonator. GDI post-gasoline particulate filter (GPF) measurements on E0 were made at all three temperatures (22 °C, -7 °C, -18 °C). For E10, only standard temperature experiments were conducted.

It was determined during Phase 1 of the program that the test procedure has a significant impact on the GPF particle filtration performance particularly on the FTP-75 drive cycle. Results in Phase 1 also showed that one US06 drive cycle was capable of triggering the GPF soot regeneration to completely clean the filter [3]. To be consistent, the same vehicle preparation procedure used during Phase 1 was adopted in Phase 2. Prior to each test date, the vehicle was prepped by a Los Angeles Route Four (LA4) drive cycle and then the vehicle was soaked overnight. On the next day, testing began with the cold-start FTP-75 drive cycle, followed by two back-to-back US06 drive cycles with the first one serving as a prep cycle. After the testing was completed, the vehicle was prepped for the next day with a

LA4 drive cycle. Based on the observations from Phase 1, the hot-start LA4 prep cycle did not generate enough soot leaving the GPF relatively clean after the LA4 prep cycle.

Drive Cycles and Fuels

The test vehicles were operated over the FTP-75 and the US06 drive cycles. The two test fuels were Tier 2 certification gasoline (E0) or a splash blended 10% by volume ethanol (E10) (Appendix Table A2). For each configuration and both drive cycles, typically three repeats were conducted unless mention otherwise. The fuel consumption results (in L/100km) were calculated based on the fuel properties and carbon mass balance:

$$FC(L/100km) = 235.22 \times [FE(miles/US\ gal)]^{-1} \quad (1)$$

$$FE(miles/US\ gal) = \frac{CFF \times 3781.8 \times SG}{CFF \times EF_{THC} + 0.429 \times EF_{CO} + 0.273 \times EF_{CO_2}} \quad (2)$$

where FE is the fuel economy in miles per U.S. gallon, CFF is the carbon fuel fraction, SG is the specific gravity, EF_{THC} , EF_{CO} , and EF_{CO_2} are the THC, CO, and CO_2 emissions in grams per mile.

Exhaust Particle Sampling

The exhaust sampling system used in Phase 2 (Figure 1) was the same system used during Phase 1 testing, except that CH_4 and N_2O were also measured in Phase 2. A detailed description of the sampling system was given in Chan et al. [3]. In general gaseous emissions were collected using critical flow venturi-constant volume sampling (CFV-CVS) system with a nominal CVS flow of 350 scfm (594.7 m³/h). The equipment and instrumentation used in this study met the criteria set forth in the U.S. Code of Federal Regulations (CFR), Title 40, Parts 86 [18, 19, 20]. Concentrations of CO and CO_2 were measured using non-dispersive infrared (NDIR) detection, THC was measured using flame ionization detection, and NO_x was measured with chemiluminescence detection. Additional samples of the diluted exhaust were also collected for CH_4 using the gas chromatography-flame ionization detection method and for N_2O using gas chromatography method with an electron capture detector technique.

Particles sampled from the CVS were collected on 47 mm Teflon filters for gravimetric analysis following the CFR recommendations [21]. One filter set was used to collect emissions over the entire FTP-75 drive cycle and the total particulate matter (TPM) mass emission rates calculated in this study were un-weighted mass emission rates.

Real time particle measurements were obtained by two sampling systems. The first system was a PMP solid particle measurement system, consists of a 2.5 μ m cyclone and a volatile particle remover (VPR) to remove most of the volatile components on the particles. Downstream of the

VPR, solid particle number concentration was measured by a TSI 3790 Engine Exhaust Condensation Particle Counter (EECPC) with a 50% counting efficiency at 23 nm while the number concentration for the sum of all solid and ultrafine particles was measured by a TSI 3776 ultrafine CPC (UCPC) which has a 50% counting efficiency at 2.5 nm. The second particle measurement system was a TSI 3090 Engine Exhaust Particle Sizer (EEPS), measuring real time particle number size distribution from 5 to 600 nm in diameter. A Dekati thermodenuder was installed upstream of the EEPS in order to remove the volatile components of the particles. For measurements at -18 °C, a Dekati ejector diluter was installed upstream of the thermodenuder in order to dilute the particle number concentrations to levels below the maximum detectable number concentration limit of the EEPS. A detailed comparison of the two particle measurement systems was given by Chan et al. [3]. The results illustrated that, with the sampling strategy adopted in this study, the particle number measurements reported by the two systems were very comparable when the particle number concentration (at the CVS) was within the range from 10³ to 10⁷ particles/cm³. Only during the extremely low emission conditions, such as those observed during Bag 2 and Bag 3 of the FTP-75 drive cycle for the PFI vehicle that the EEPS measurements may have over-estimated the particle emissions due to the impact of electrical noise.

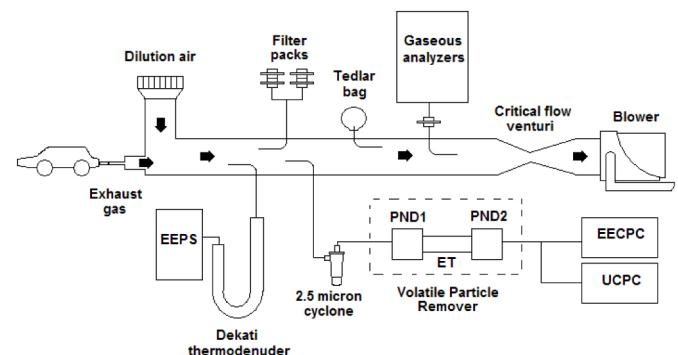


Figure 1. Schematic diagram of the emission testing and sampling system.

RESULTS AND DISCUSSION

Fuel Consumption at Cold Temperatures

Figures 2(a) to 2(d) show the comparison of the fuel consumption for the stock GDI, GDI post-GPF, and PFI configurations operated on E0 and E10 at various ambient temperatures over the FTP-75 and US06 drive cycles, respectively. Also included in the figures are the percentage changes in fuel consumption at cold ambient temperatures compared to the standard temperature at each configuration. All data points are also given in Appendix Tables A3 and A4. In general, results showed that the stock GDI configuration had lower fuel consumption than the PFI configuration on both E0 and E10 at all testing temperatures. The use of the

GPF did not result in an increase in fuel consumption of the GDI vehicle mainly because the GPF was optimized and did not significantly increase the back pressure. Low pressure drop across GPF was also observed in two other studies. These studies showed that the pressure drop across a GPF can be reduced by increasing the open frontal area and/or reducing the wall thickness and cell density of the filter [39, 40]. Further, the much higher gasoline exhaust temperature compared to typical diesel exhaust temperature also permits passive soot regeneration and helps to reduce back pressure caused by the accumulated soot. During this study, a typical maximum pressure drop of 4.1 kPa was observed across the resonator (i.e., stock GDI) during a FTP-75 drive cycle compared to a pressure drop of 5.5 kPa through the GPF. Over the US06 drive cycle, the maximum pressure drops across the resonator and GPF were 11.0 kPa and 15.9 kPa, respectively. These changes did not result in any statistically different fuel consumption (Table A3 and A4).

Over the FTP-75 drive cycle, the averaged fuel consumption from the GDI vehicle on E0 was 6% (22 °C) to 3% (−7 °C and −18 °C) less than that of the PFI vehicle. Over the US06 drive cycle, the averaged fuel consumption for the GDI vehicle was 2% (22 °C), 4% (−7 °C), and 1% (−18 °C) lower compared to the PFI vehicle.

Trends for E10 were generally similar to those observed with E0. When the engine was warmed-up, fuel consumption on E10 compared to E0 for both vehicles at cold ambient temperatures over the US06 drive cycle was either unchanged or slightly higher by less than 2%, likely due to the lower energy content in the ethanol-containing fuel [22]. For the FTP-75 drive cycle, the fuel consumption on E10 and E0 at −7 °C for both vehicles was the same. But at −18 °C, both vehicles used 4% more fuel when comparing E10 to E0.

Fuel consumption typically increases with decreasing ambient temperature as more energy is needed to overcome friction when operating the dynamometer at cold ambient temperatures. When involving a cold-starting or aggressive driving condition, additional fuel is also needed. Figure 3 shows the fuel consumption of the stock GDI and PFI vehicles at the two extreme temperatures over the cold- (Bag 1) and hot-start (Bag 3) portions of the FTP-75 drive cycle. The results in Figure 2 and 3 provide insights about the relative importance of the different factors in contributing to the fuel consumption of the two vehicles. In general it required 10% and 9% more fuel to operate the hot-start US06 drive cycle at −18 °C than to operate at standard temperature for both vehicles (Figure 2(c)). When comparing the Bag 3 results at 22 °C and −18 °C, it showed that the extreme cold temperature only resulted in a 7% and 8% increase in fuel consumption for both vehicles. Part of the increase in fuel consumption could be contributed by the fact that the engine was slightly cooler to begin the Bag 3 test due to the 10 minutes of idling as compared to the US06 drive cycle testing. However, this still implies that the aggressive driving condition only contributes marginally to the fuel consumption

of a warmed engine, and this contribution is much less than the impact from lowering ambient temperature.

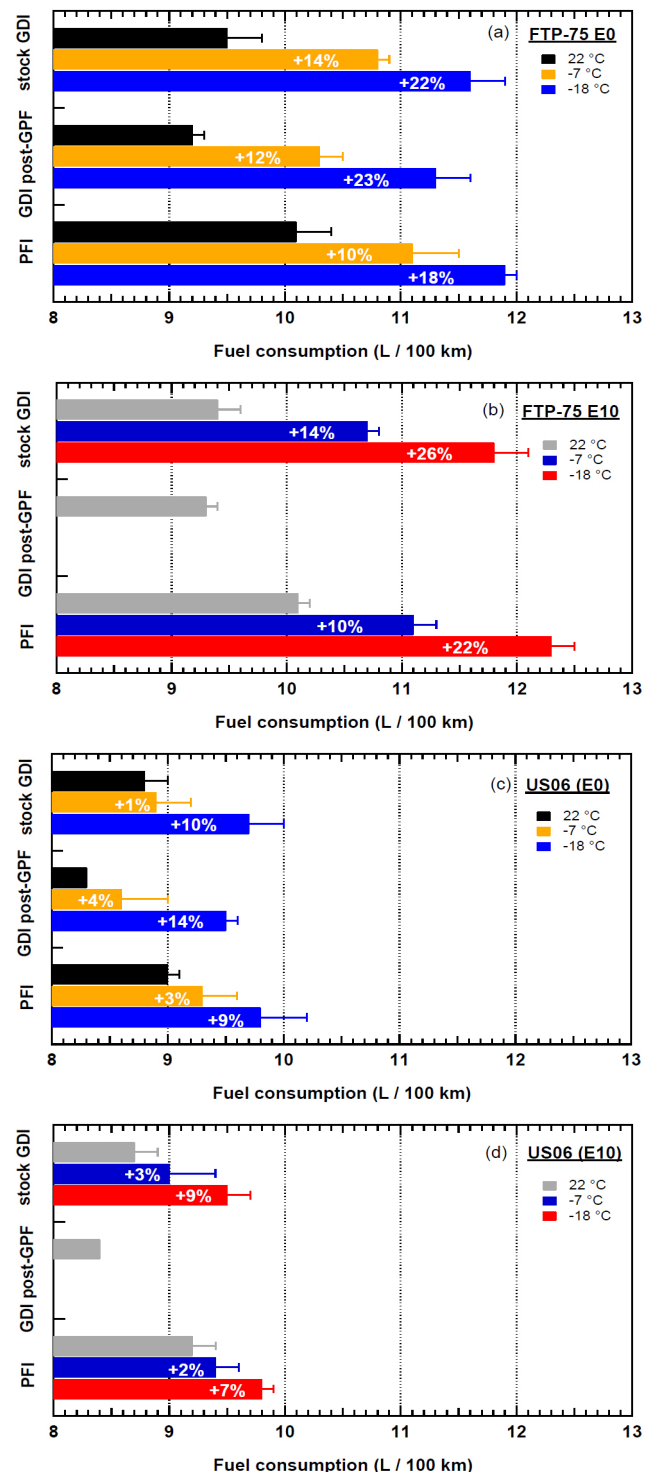


Figure 2. Fuel consumption for various configurations over the FTP-75 (a and b) and US06 (c and d) drive cycles operated on E0 and E10.

When comparing results between Bag 1 and Bag 3 (Figure 3), it indicates that the fuel consumption at standard temperature increased by 31% and 21% as a result of cold-starting alone for the stock GDI and PFI vehicles, respectively. At -18°C , cold-starting led to an increase in fuel consumption of 52-53% for both vehicles. This suggests that the impacts of cold-starting are significantly worsened at cold ambient temperatures. The impacts of colder ambient temperatures on cold-start fuel consumption were observed to be larger with this PFI vehicle compared to this GDI vehicle.

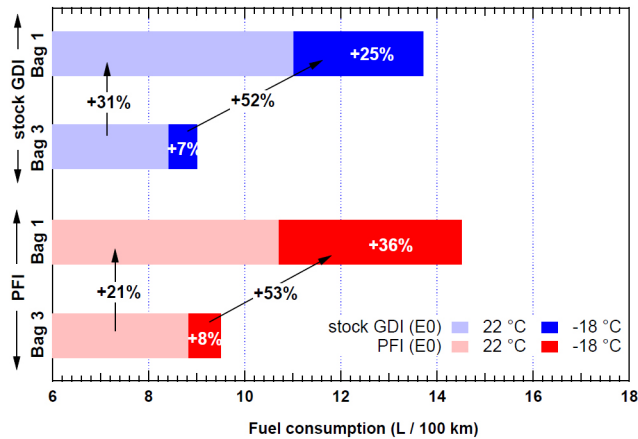


Figure 3. Fuel consumption for the stock GDI and PFI configurations over the FTP-75 Bag 1 and 3 operated on E0.

Regulated Gaseous Emissions at Cold Temperatures

The US06 CO emissions at different ambient temperatures for the same vehicle configuration (Figure 4(c)) were generally not found to be statistically different mainly due to the large test-to-test variability. Interestingly, lower CO emission levels were observed over the US06 drive cycle at cold ambient temperatures for the stock GDI vehicle, particularly at -7°C . Additional baseline measurements (E0 at 22°C) were conducted after the cold ambient temperature testing and it was found that the CO emissions were consistent with the baseline values obtained at the beginning of the program. Therefore, it is only a speculation that the lower CO emissions observed for the stock GDI configuration at cold ambient temperature may be related to the engine emission control strategy in response to the cold ambient temperature environment.

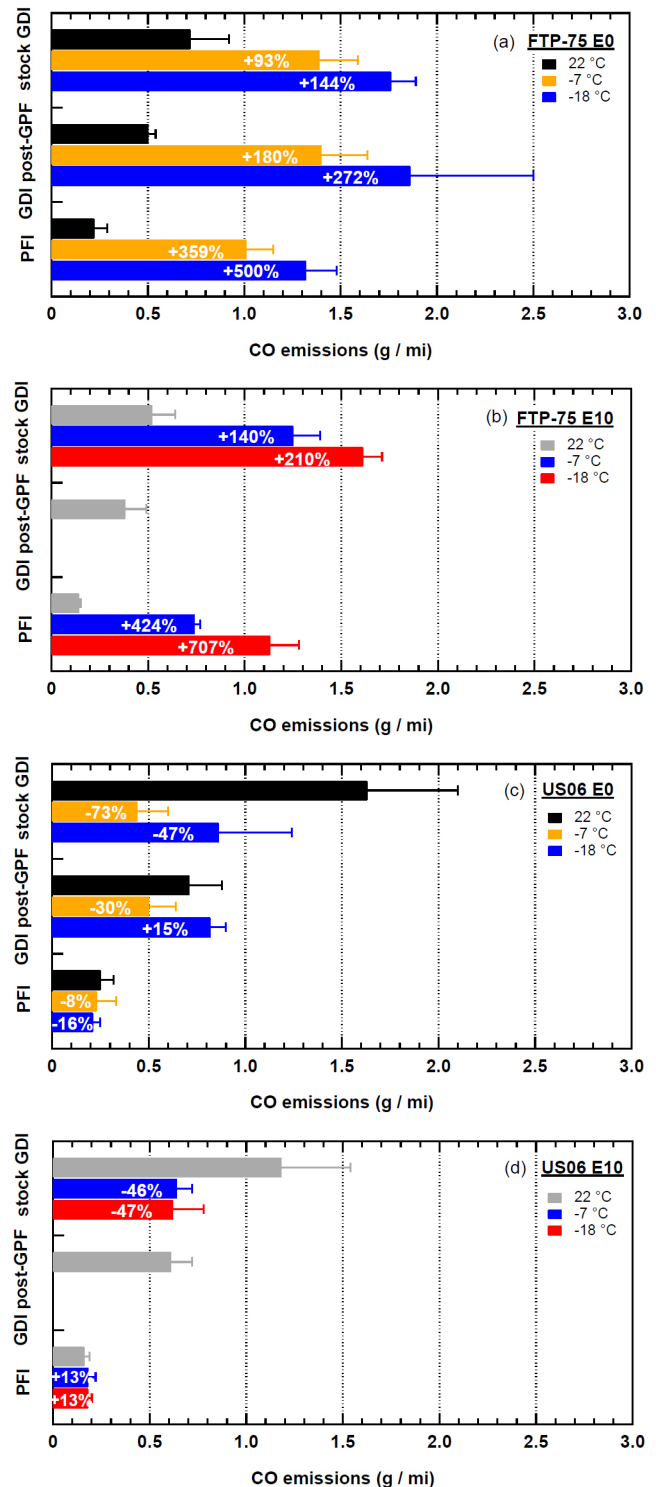


Figure 4. CO emissions for various configurations over the FTP-75 (a and b) and US06 (c and d) drive cycles operated on E0 and E10.

In comparison, CO emissions at cold ambient temperatures were much higher for both vehicles over the FTP-75 drive cycle (Figure 4(a)) due to the incomplete combustion and also the longer warm-up time for the TWC to “light-off” during cold ambient test conditions [8, 11, 12]. On a relative basis, the increase in CO emissions at cold ambient temperatures over the FTP-75 drive cycle for the GDI vehicle was much smaller than for the PFI vehicle. For example, the PFI CO emission rate at -18°C was 500% higher than the CO emissions at 22°C . This compares to the 144-272% increase in CO emissions observed for the GDI vehicle over the same test conditions depending on whether the GPF was installed or not.

Results from Phase 1 of this program showed that operating with E10 at standard temperature led to lower CO emissions for both the GDI and PFI vehicles over both drive cycles. Cold temperature data from Phase 2 of the program showed that the CO reduction benefit for the PFI vehicle operated on E10 decreased with decreasing ambient temperature. This is because the ethanol-gasoline mixture has a lower heat of combustion, and therefore, a typically larger volume of ethanol-gasoline mixture is needed to provide the same amount of energy [22]. Increasing fuel consumption at lower temperature worsens this problem and causes the vehicle to operate much richer at cold ambient temperatures. For the PFI configuration, the changes in CO emissions on E10 with respect to E0 at 22°C for both cycles were -36% . At -7°C the changes in CO emissions due to the use of E10 were -27% (FTP-75) and -22% (US06) while at -18°C , they changed to -14% (both cycles). For the stock GDI configuration, a smaller CO reduction benefit on E10 over cold ambient temperatures was observed for the FTP-75 drive cycle, but mixed results were observed for the US06 drive cycle. For example, the reductions in CO emissions at 22°C due to the use of E10 were -28% (both cycles). At -7°C , they were -10% (FTP-75) and $+45\%$ (US06) whereas at -18°C , the changes were -9% (FTP-75) and -28% (US06).

Figures 5(a) to 5(d) show the THC emission levels for various configurations for the FTP-75 and US06 drive cycles, respectively. All general trends that were observed from the CO emissions were also observed for the THC emissions except that the THC emissions from the US06 drive cycle were much lower in magnitude than that from the FTP-75 drive cycle. Over the FTP-75 drive cycle, the THC emissions at cold ambient temperatures were significantly higher by more than 6 to 20 times than emissions at standard temperature. In the case of the PFI vehicle, liquid gasoline may enter the chamber during the cold-start and form a fuel film that does not evaporate and burn completely during flame passage [1, 16]. For the wall-guided GDI vehicle, fuel is injected into the cylinder in a swirling fashion through a side-mounted injector. The fuel mixture is then guided towards the spark plug by the reverse tumble turbulent motion as well as the bowl-shaped piston crown [23, 24]. For both types of engines, wall wetting could be significant during cold-start when the engine is cold and has to run

richer. These issues get worse at cold ambient temperatures when the engine runs even richer. The observations shown in Figure 5 suggest that when operating at cold ambient temperature during cold-start, a large portion of the excess fuel with possible contributions from lubricating oil, could be emitted and be measured in the form of gaseous total hydrocarbons.

Interestingly, small increases in THC emissions at cold ambient temperatures were observed over the US06 drive cycle for both vehicles. Since the CO emissions show no clear trend at various ambient temperatures over the US06 drive cycle (Figure 4(c-d)), the additional THC emissions at sub-ambient temperature over the US06 drive cycle may not be caused by incomplete combustion. One possible explanation may be due to the hydrocarbon storage in the combustion chamber crevices which some authors suggest can be a significant source for THC emissions in a spark ignition engine, even if it is completely warmed-up, because the entrances are too narrow for the flame to enter and combust the fuel in these crevices [16, 25, 38].

For both vehicles, once the engines were warmed, there was no significant change in THC emissions when switching between E10 and E0. But for the FTP-75 drive cycle, E10 has different impacts on the test vehicles. For the PFI vehicle, the changes in THC emissions on E10 with respect to E0 over the FTP-75 drive cycle at 22°C , -7°C , and -18°C were $+5\%$, -16% , and -30% . The use of E10 fuel appeared to result in lower THC emissions at colder ambient temperatures for the PFI configuration.

For the stock GDI vehicle, the change in THC emissions over the FTP-75 drive cycle on E10 at 22°C , -7°C , and -18°C compared to E0 were -11% , 19% , and 7% , respectively. Therefore, no evidence of THC emissions reduction was observed for the GDI vehicle with the use of E10 fuel at cold ambient temperatures.

Some previous studies showed that gasoline vehicles typically emit higher NO_x at sub-ambient temperatures [8, 10] while some studies showed that NO_x emissions can either increase or decrease with decreasing ambient temperature [9, 12, 14]. In some cases NO_x emissions were found to be insensitive with ambient temperature [11, 13]. In this study, NO_x emissions from both vehicles at all ambient temperatures were very low but both cars exhibited an increasing trend of NO_x emissions with decreasing ambient temperature for both the FTP-75 and US06 drive cycles on both fuels (Tables A3 and A4).

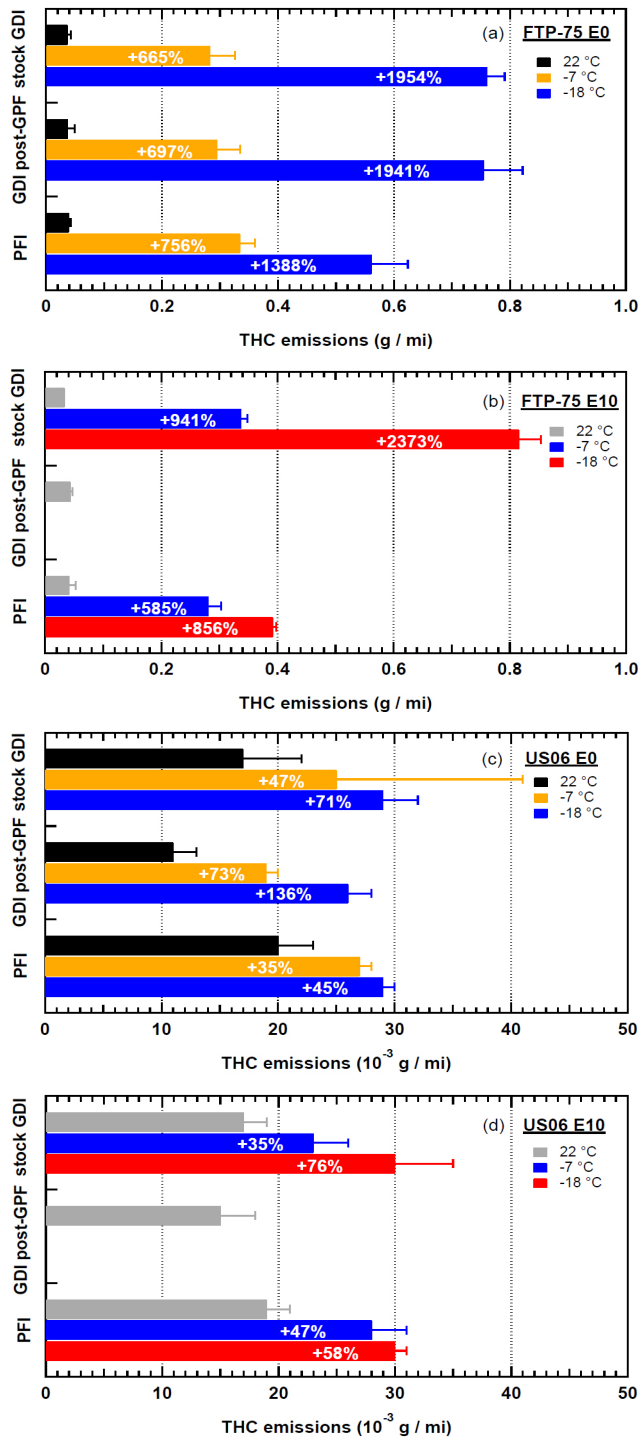


Figure 5. THC emissions for various configurations over the FTP-75 (a and b) and US06 (c and d) drive cycles operated on E0 and E10.

CH₄ and N₂O Emissions at Cold Temperatures

Along with CO₂, greenhouse gas measurements of CH₄ and N₂O were also made. Figures 6(a) to 6(d) summarize the CH₄ emission rates for the FTP-75 and US06 drive cycles over the various ambient temperatures, fuels, and vehicle configurations. In vehicular exhaust, CH₄ is often formed due to incomplete fuel combustion and the CH₄ emissions rise rapidly when the engine is running rich [16, 26]. Results in Figure 6(c) show that there were no significant changes in CH₄ emissions at cold ambient temperatures for a warmed engine. This is consistent with the CO emissions trends over the US06 drive cycle (Figure 4(c)). For the FTP-75 drive cycle, CH₄ emissions were typically higher at cold ambient temperatures for both vehicles. This is consistent with the expectation that it was more difficult to vaporize the fuel at cold ambient temperatures and this led to incomplete combustion. This agrees with other observations as well [27, 28] and is also consistent with the THC and CO emission trends from the two vehicles (Figures 4(a) and 5(a)).

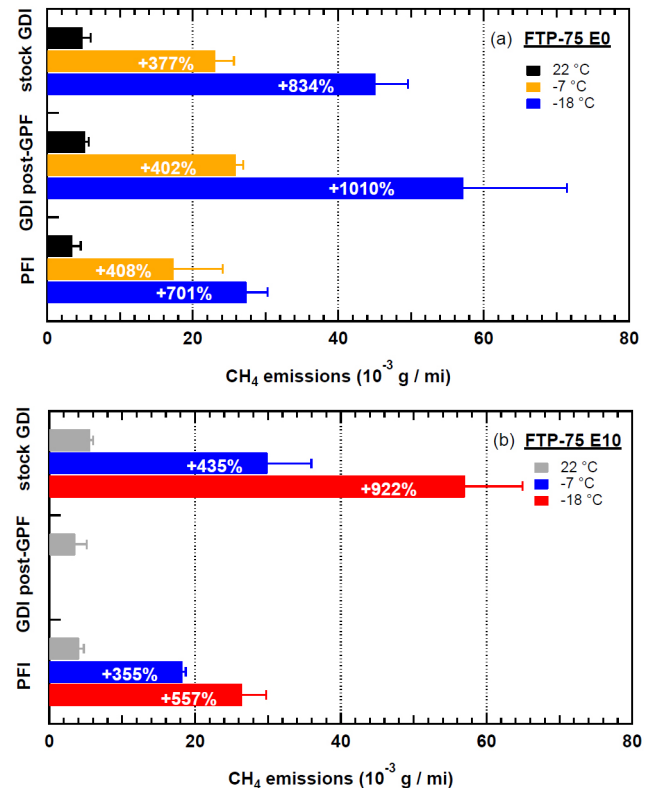


Figure 6. CH₄ emissions for various configurations over the FTP-75 (a and b) and US06 (c and d) drive cycles operated on E0 and E10.