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Fuel Sulfur Effects on a Medium-Duty Diesel Pick-Up with a NO_X Adsorber, Diesel Particle Filter Emissions Control System: 2000-Hour Aging Results

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ABSTRACT

Increasing fuel costs and the desire for reduced dependence on foreign oil have brought the diesel engine to the forefront of future medium-duty vehicle applications in the United States due to its higher thermal efficiency and superior durability. One of the obstacles to the increased use of diesel engines in this platform is the Tier 2 emission standards. In order to succeed, diesel vehicles must comply with emissions standards while maintaining their excellent fuel economy. The availability of technologies—such as common rail fuel injection systems, low-sulfur diesel fuel, oxides of nitrogen (NO_X) adsorber catalysts or NACs, and diesel particle filters (DPFs)—allows for the development of powertrain systems that have the potential to comply with these future requirements. In support of this, the U.S. Department of Energy (DOE) has engaged in several test projects under the Advanced Petroleum Based Fuels-Diesel Emission Control (APBF-DEC) activity [1, 2, 3, 4, 5]. Three of the APBF-DEC projects evaluated the sulfur tolerance of a NAC/DPF system and the full useful life implications of NAC desulferization. The test bed for one project in this activity is a 2500 series Chevrolet Silverado equipped with a 6.6L Duramax diesel engine certified to 2002 model year (MY) federal heavy-duty and 2002 MY California medium-duty emission standards.

While NAC systems have demonstrated extremely high levels of NO_X reduction in steady-state laboratory evaluations, the application of a NAC system to an actual transient engine has not been demonstrated. Such an application requires the development of an integrated engine/emissions management system [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Two previous papers detailed the thermal and NO_X adsorber management aspects of a system applied to the project test bed [1, 2]. The final control strategies applied to this project achieved over 98% reductions in tailpipe NO_X mass emission over the hot-start Urban Dynamometer Driving Schedule (UDDS). This paper discusses the emission results of the system measured over the course of 2000 hours of on-engine aging exposure. The system was evaluated over the cold-start UDDS, hot-start UDDS, Highway Fuel Economy Test (HFET) and US06 portion of the Supplemental Federal Test Procedure (SFTP). The discussion will cover the aging cycle utilized and its development, details of the desulfurization process, and regulated emission results over the test cycles of interest. After 2000 hours of on-engine aging, the NAC/DPF system demonstrated an average NO_X reduction of 89% and PM reduction of 94% over the composite Federal Test Procedure (FTP).

INTRODUCTION

The NAC/DPF concept has shown promising results with a new, but degreened emission control system (ECS). The platform development process and the control strategies were already discussed as part of SAE papers published last year [11, 12]. Following this development phase, an aging process with a target of 2000 hours was initiated. The 2000 hours represent the useful lifetime of the ECS (equivalent to 120,000 miles). Details regarding the aging procedure and the ECSs are provided in following sections.

The aging process was interrupted by evaluation cycles to monitor system performance during aging. Cold- and hot-start UDDS (the first two bags of the FTP-75) simulations, as well as US06 and HFET cycle simulations, were tested repeatedly throughout the aging process to gain statistical confidence in the emission results.

PROGRAM OBJECTIVES

The main objective of the APBF-DEC activity is to investigate the sulfur tolerance and long term performance of different ECSs such as the NAC/DPF combination. An additional project has been initiated under this activity to evaluate selective catalytic reduction technologies.

An integral part of the program is to demonstrate the capability of a state-of-the-art engine and ECS combination to achieve the Tier 2 Bin 5 emission levels.

The ECS was aged up to 2000 hours with a fuel sulfur level of 15 ppm to allow for an assessment of its impact on the durability of the systems. The detailed fuel specifications for this project are presented in Appendix A.

TEST PLATFORM

The test vehicle for this evaluation was a 2002 Chevrolet Silverado 2500 Series pick-up truck equipped with a Duramax 6.6L engine and ZF six-speed manual transmission. This engine/vehicle combination met the California medium-duty emission requirements for 2002. Table 1 provides some engine specifications, and the test vehicle is shown in Figure 1. The stock ECS included a charge air cooler, turbocharger, common rail direct fuel injection, oxidation catalyst (OC), and high-pressure exhaust gas recirculation (EGR).

Table 1. Engine Specifications for MY2002 6.6L Duramax

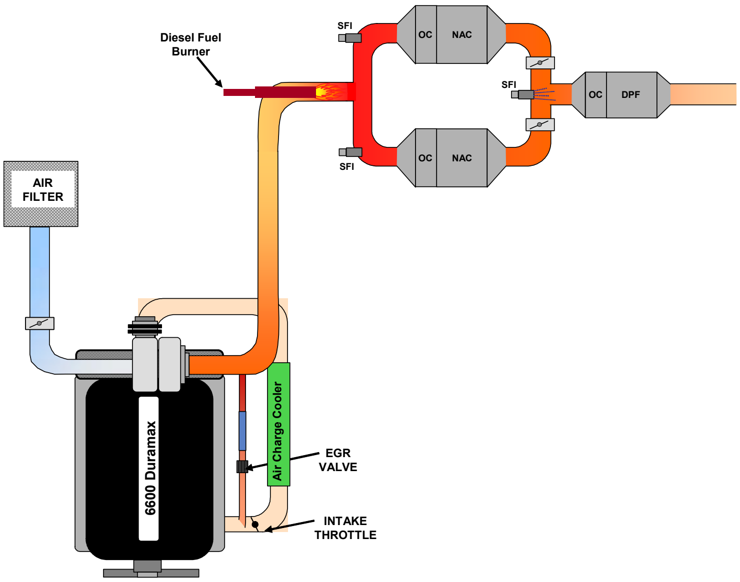
Rated Speed (rpm)	3000
Rated Power (hp)	300 ± 12
Rated Torque Speed (rpm)	1800
Rated Torque (ft-lb)	520 ± 20
Low idle (rpm)	680 ± 25

Figure 1. Project Test Vehicle—2500 Series Chevrolet Silverado

EMISSIONS CONTROL SYSTEM

The ECS components tested in this project consisted of NACs, OCs, and a catalyzed DPF. These components were integrated with the engine control to form the ECS.

The final ECS configuration utilized in this program was a dual-leg NAC with a single DPF downstream of the combined flow after the NACs. There were also OCs installed upstream of each NAC and in front of the DPF. The dual-leg NAC configuration allowed reduced flow regeneration (compared to a single-leg system) and used exhaust valves to direct flow during regeneration and desulfurization. This particular system included a single diesel fuel burner used for thermal management and for producing reductants for regeneration. Supplemental fuel injectors (SFIs) were installed in each exhaust leg to allow control of the regeneration reductant. An additional injector was installed upstream of the DPF to allow for active regeneration. Figure 2 shows a schematic of the ECS evaluated in this project. The rationale for the configuration selected and details of the ECS and the temperature management control strategies are outlined in SAE 2004-01-0584 and 2004-01-0585 [11, 12].



OC = 3.5L NAC = 7L DPF = 12.5L

Figure 2. Schematic of Emissions Control System

TEST PROCEDURES

Four different vehicle-based transient test cycles were utilized in this project for evaluating the ECS effectiveness. The four cycles were the cold and hot portions (cold-start UDDS and hot-start UDDS) of the light-duty FTP-75 referred to as the UDDS, the HFET, and the US06 portion of the SFTP. The cold-start UDDS cycle is conducted after a vehicle ambient soak period of 12-36 hours, while the hot-start UDDS cycle is conducted after a 10-minute soak period immediately following the cold-start UDDS (repeat of driving cycle). The HFET is conducted after operating over an HFET prep cycle, regardless of vehicle soak-time, while the US06 is conducted after completing one of a number of allowable different prep cycles. For this program, the US06 test cycle was preceded by a US06 prep cycle. The corresponding indicated vehicle speed versus time schedules for the different driving cycles (including the prep sequence) are shown in Appendix B.

Table 2 shows a comparison of the maximum speed, average speed, maximum acceleration, distance traveled and time for the different cycles. As can be seen in this table, the UDDS is a lightly loaded cycle where the engine spends significant time at idle conditions.

Table 2. Operational Characteristics of Select Light-Duty Chassis Dynamometer Test Cycles

Test Cycle	UDDS	HFET	US06
Average Speed, mph	19.5	48.2	48.0
Maximum Speed, mph	56.7	59.9	80.3
Maximum Accel, mph/s	3.6	3.2	8.4
Duration, sec	1372	765	600
Distance, mi.	7.5	10.26	8.01
Idle Time, %	19.0	0.8	7.3

BASELINE EMISSIONS

A summary of the baseline, as-received engine-out emissions over the light-duty FTP cycle, with and without EGR is shown in Tables 3 and 4, respectively. The engine-out emissions are presented in this fashion in order to provide an appropriate baseline for evaluating the NAC performance versus the overall ECS performance. All of the emissions results presented in the following 'TEST RESULTS' section include EGR. The standard weighting of 43% for the cold-start and 57% for the hot-start was used in calculating the composite FTP values. The calculated cold-start UDDS (bags 1 and 2) and hot-start UDDS (bags 3 and 2) results are also shown as these were the test cycles utilized in this program. Figure 3 shows a comparison of the regulated engine-out emissions and the program goals [i.e., U.S. Environmental Protection Agency (EPA) Tier 2 Bin 5]. As can be seen from this figure, meeting the 50K mile program goals required a 99% NO_X reduction, an 84% HC reduction, and an 89% particulate matter (PM) reduction over the engine-out (no EGR) emission levels. Appendix B shows the continuous engine-out NO_X emissions and exhaust gas temperature (with and without stock high-pressure EGR) for the cold-start UDDS.

Table 3. Composite LD-FTP As-Received Engine-Out Emissions with EGR

	FTP Composite (g/mi)	Cold-Start UDDS (g/mi)	Hot-Start UDDS (g/mi)
THC	0.448	0.487	0.418
NO_X	4.233	4.500	4.032
CO	3.198	3.942	2.637
CO_2	546	563	534
PM	0.083	0.084	0.082
Distance (Miles)	11.06 (total)	7.47 (total)	7.46 (total)

Table 4. Composite LD-FTP As-Received Engine-Out Emissions without EGR

	FTP Composite (g/mi)	Cold-Start UDDS (g/mi)	Hot-Start UDDS (g/mi)
THC	0.468	0.491	0.450
NO_X	5.304	5.346	5.272
CO	5.282	5.927	4.795
CO_2	551	574	535
PM	0.088	0.090	0.087
Distance (Miles)	11.00 (total)	7.43 (total)	7.42 (total)

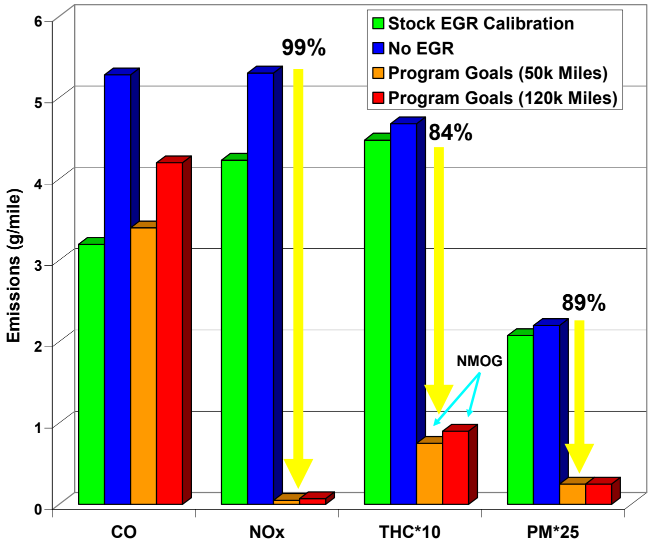


Figure 3. Comparison of Regulated Engine-Out Emissions to Program Goals (EPA Tier 2 Bin 5) for the Light-Duty FTP

TEST CELL CONTROL CYCLES

In order to speed the development of the NAC system control strategy, provide more repeatable test conditions, and conduct multiple cold-start tests in a single day, tests on the vehicle were dropped and the project was moved into a transient-capable test cell. The test cell was equipped with a General Electric Direct Current Dynamometer, capable of absorbing 350 hp and motoring 225 hp and an exhaust dilution tunnel with a nominal flow rate of 28 m^3/min. The test cell was also equipped with various raw and dilute emission equipment to measure regulated and unregulated species.

Different test cell control cycles for the cold-start UDDS, hot-start UDDS, HFET, and US06 were developed in order to duplicate engine operation in the vehicle. The vehicle was first operated on the chassis dynamometer over the test cycles of interest while recording important operational information such as engine speed, accelerator pedal position, manifold absolute pressure, intake mass airflow, exhaust temperatures, etc. (with EGR disabled). Graphical representations of the resultant engine speed and torque output versus time for the cold-start UDDS (with increased cold-idle speed), hot-start UDDS, HFET, and US06 are shown in Appendix B. These data were then utilized to develop a desired torque/engine speed control cycle for use in the test cell. These control cycles resulted in engine-out emissions, fuel consumption, and exhaust gas temperatures similar to those observed on-vehicle. Appendix B also shows a comparison of the engine-out accumulated NO_X mass, carbon dioxide (CO_2) mass, and exhaust gas temperature for a cold-start UDDS on the vehicle and in the test cell.. A summary of the cycle work for the different test cycles is shown in Table 5.

Table 5. Equivalent Test Cycle Work for Light-Duty Chassis Dynamometer Test Cycles

Test Cycle	Work (hp-hr)	Equivalent Distance (miles)
Cold UDDS	6.67	7.5
Hot UDDS	6.53	7.5
HFET	7.39	10.26
US06	9.57	8.01

DESULFURIZATION

One of the drawbacks to a NAC-based aftertreatment system is the requirement to intermittently “desulfurize” or “desulfate” the adsorber due to its high affinity for adsorbing sulfur oxides. The accumulation of sulfur on the available adsorption sites inhibits the NAC’s ability to reduce NO_X by reducing its nitric oxide to nitrogen dioxide (NO_2) conversion performance and blocking NO_2 adsorption sites. In order to maintain a high level of NO_X reduction, the NAC must be intermittently cleansed of this sulfur accumulation.

During this program approximately 660 kg of fuel were consumed upstream of the NACs (engine, burner, and SFI) over the course of every 100 hours of aging. A fuel sulfur level of 15 ppm, this resulted in a total fuel sulfur mass exposure of approximately 9.9 g total over 100 hours. This mass of sulfur was assumed to be split evenly between the two exhaust legs, resulting in a fuel sulfur mass exposure for each NAC of approximately 4.95 g. The engine oil consumption rate was approximately 0.35 liters (315 g) every 100 hours. Given an oil sulfur level of 6400 ppm, this resulted in a total oil sulfur mass exposure of approximately 2 g for 100 hours of aging (1 g for each leg). Therefore the total sulfur mass exposure for each NAC over 100 hours of aging was approximately 6 g (assuming an equal split of exhaust between the two exhaust legs).

The desulfurization process was conducted off-line on a gasoline engine. This was done in order to maintain precise and efficient desulfurization control. This cycle used a rich/lean perturbated approach and desulfated one NAC at a time. The engine was run at a constant speed and load with an exhaust flow rate of approximately 52 g/s. The fuel sulfur content was less than 30 ppm. The engine was run under rich conditions (lambda = 0.9) during the warm-up phase until the three NAC bed temperatures (2.5 cm, 7.5 cm, and 12.5 cm deep) reached 600°C. At this point the engine air-fuel ratio was then perturbated between lambda of 0.9 and 1.05 (5 seconds at each air-fuel ratio). The measured NAC bed temperatures (at a depth of 2.5 cm) typically reached approximately 650-660°C (the desired desulfurization temperature) 2 minutes after beginning the perturbation. The air-fuel perturbation was continued for an additional 5 minutes, after which it was stopped, and the engine held at lambda of 0.9 for approximately 90 seconds. At this point in time, the engine was brought to idle conditions (still at lambda of 0.9) and allowed to idle until the NAC bed temperatures dropped below 520°C (the typical peak temperature observed during transient emission evaluations). This idle period typically lasted 800-900 seconds. The entire process was then repeated on the second oxi-cat/NAC combination. An example of the engine-out lambda and NAC system temperatures during desulfurization is shown in Figure 4.

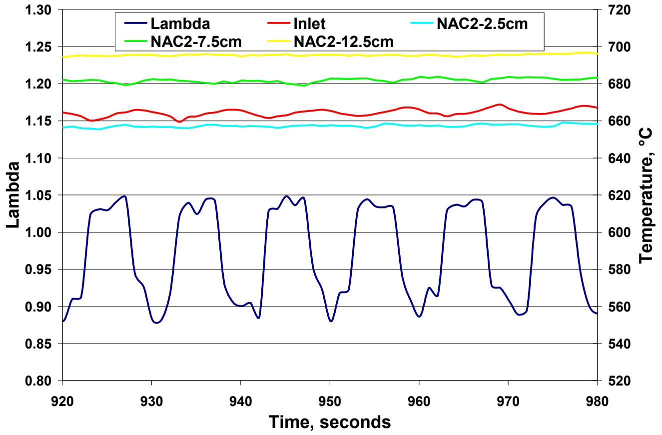


Figure 4. Example of Engine-Out Lambda and NAC System Temperatures during Desulfurization

SUMMARY OF TEST PLAN

In order to evaluate the effectiveness of the aftertreatment system after exposure to sulfur over an extended period of time, emission tests were conducted at regular intervals. Initially, emissions evaluations were conducted at intervals of every 50 hours through the first 300 hours of aging. During this time desulfurization was only conducted after the 200- and the 300-hour aging points. Starting with the 300-hour aging point, the frequency of desulfurizations and emissions evaluations was timed to occur at intervals of every 100 hours of aging until a total of 2000 hours of aging had been completed. Emissions tests were conducted both before and after every desulfurization.

AGING CYCLE

In order to evaluate the impact of long-term operation on the ability of the NAC system to achieve high levels of NO_X reduction, it was necessary to develop an aging cycle as there are no industry standards for aging NO_X adsorber systems. As this program was a light-duty-based program, an aging cycle was developed that reflected more on light-duty-type operation (i.e., no extended high-load operation). Also, since the primary functions of the NAC are to adsorb, desorb, and reduce NO_X, it was not known exactly how the aging of this device could be accelerated while still exercising these functions. Aging at elevated temperature is known to deactivate the NAC, but a correlation of elevated temperature exposure to miles was not known. Also it was not clear that thermal acceleration of aging alone would adequately simulate the aging process of the NAC. In addition, sulfur exposure of the NAC is a critical issue, and the frequency of desulfurization events was unknown at the start of testing. Therefore, the aging cycle was not intended to be an accelerated-type aging cycle; instead the cycle was to focus on exercising the emissions control system in a manner similar to what would be expected in-use. In the interest of repeatability and automated operation, a stepped, steady-state mode type of cycle was deemed appropriate (as opposed to a transient-type cycle).

The aging cycle developed in this program was obtained by examining the top ten modes of operation [engine speed and accelerator pedal position (APP)] during a vehicle test operating over the California Air Resource Board (CARB) Unified Driving Cycle (speed versus time trace shown in Figure 5). This cycle was expected to expose the engine/vehicle to more “real-world” type driving conditions than seen on the FTP. The test vehicle was operated over the CARB Unified Driving Cycle on a chassis dynamometer to obtain engine operating information (speed, APP, exhaust temperatures, etc.). Table 6 shows a summary of the frequency of operation for various engine speed and APP “bins” where the 11 most frequent bins of operation are highlighted. The 1,350 rpm / 5% APP point was determined to be a motoring phase and was not included in the aging cycle. An engine dynamometer-based aging cycle was developed utilizing the remaining 10 bins of most frequent operation. The cycle was developed by fixing the desired total cycle length at 10 minutes, and basing each mode length on its corresponding percentage of total operation over the CARB Unified Driving Cycle.

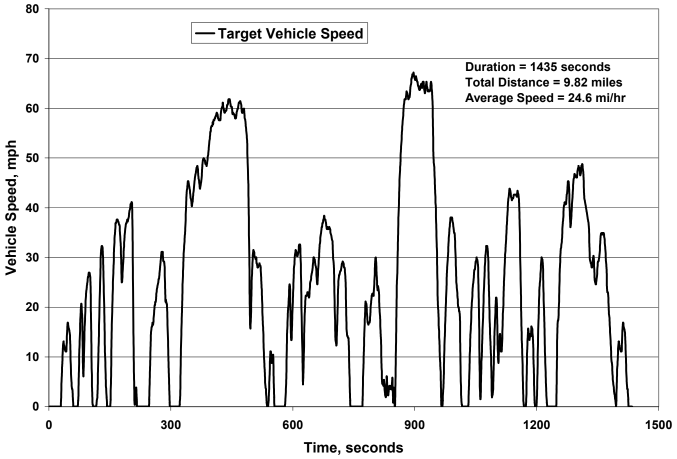


Figure 5. Vehicle Speed versus Time for CARB Unified Driving Cycle Schedule

Table 6. RPM and APP Analysis of the CARB Unified Driving Cycle for Test Vehicle

Engine Speed RPM	Accelerator Pedal Position (APP - %)									
	5	15	25	35	45	55	65	75	85	95
450	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
750	**9.2%**	1.7%	0.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1050	2.7%	**3.6%**	**4.0%**	2.7%	0.8%	0.3%	0.0%	0.0%	0.0%	0.0%
1350	**4.0%**	**6.0%**	**8.0%**	**8.2%**	**6.8%**	3.7%	0.3%	0.0%	0.0%	0.0%
1650	1.6%	1.5%	1.5%	2.4%	3.1%	**4.3%**	1.1%	0.1%	0.0%	0.0%
1950	0.6%	0.3%	1.7%	**5.5%**	**5.7%**	3.1%	1.1%	0.4%	0.0%	0.0%
2250	0.1%	0.1%	0.1%	0.4%	0.4%	0.2%	0.3%	0.3%	0.1%	0.0%
2550	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.2%	0.1%	0.0%
2850	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
3150	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

In an effort to harmonize the aging cycle developed for the medium-duty SUV and light-duty passenger car APBF-DEC programs, the aging cycle was modified to include a 20-minute, steady-state evaluation mode. The final aging cycle maintained the original 10 steady-state points and their relative weighting, but was expanded to include a steady-state evaluation point. The selected steady-state evaluation point was the highest speed and load point of the 10 cycle modes (1950 rpm and 45% APP or 244 lb-ft torque). The steady-state evaluation point chosen had the highest space velocity and was expected to magnify any loss in performance of the NAC due to sulfur accumulation. In addition, this point had one of the highest fuel consumption rates and increased the sulfur mass exposure of the system. The evaluation point was also used to verify continuous DPF regeneration throughout the aging cycle. This point was run for 20 minutes, once every 4 hours (22, 10-minute cycles followed by the 20-minute, steady-state point). Table 7 provides the operating characteristics of the steady-state evaluation point. Figure 6 shows the percentage of time spent at each operating point for the aging cycle as a four-hour set (22, 10-minute cycles plus one 20-minute evaluation).

Table 7. Summary of Modified CARB Unified Driving Cycle Based Aging Cycle Operating Conditions and Mode Order

Step	Original Mode Number	Engine Speed, rpm	APP (%)	% of CARB Unified Cycle	% of Aging Cycle	Mode Time, sec
1	1	680	0	9.2	12.8	84
2	Ramp	680-1950	0-35	- - -	0.8	5
3	9	1950	35	5.5	7.8	51
4	Ramp	1950-1050	35-15	- - -	0.8	5
5	2	1050	15	3.6	4.9	32
6	Ramp	1050-1650	15-55	- - -	0.8	5
7	8	1650	55	4.3	6.0	39
8	Ramp	1650-1050	55-25	- - -	0.8	5
9	3	1050	25	4.0	5.5	36
10	Ramp	1050-1350	25-45	- - -	0.8	5
11	7	1350	45	6.8	9.6	63
12	Ramp	1350-1350	45-15	- - -	0.2	1
13	4	1350	15	6.0	8.4	55
14	Ramp	1350	15-35	- - -	0.2	1
15	6	1350	35	8.2	11.6	76
16	Ramp	1350	35-25	- - -	0.2	1
17	5	1350	25	8.0	11.3	74
18	Ramp	1350	25-45	- - -	0.2	5
19	10 (SS)	1950	45	5.7	16.3	52
20	Ramp	1950-680	45-0	- - -	0.8	5
	Totals	- - -	- - -	61.3	100	600

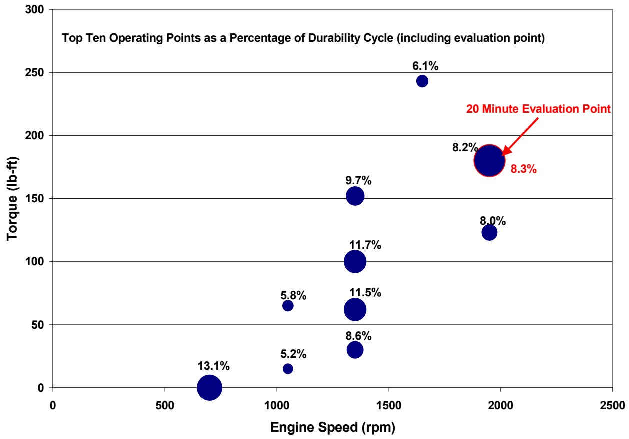


Figure 6. Aging Cycle Operating Points with Steady-State Evaluation Point (Based on CARB Unified Driving Cycle)

TEST RESULTS

ENGINE DYNAMOMETER TEST CELL

The average NO_X emission results are displayed in Figures 7 and 8. Observations at the beginning and end of a single aging cycle are connected. Tier 2 Bin 5 useful life standards are included for reference and appear as a horizontal line.

Cold- and hot-start UDDS (or LA4) cycles were performed at the aging marks depicted in Figure 7.

The composite FTP emissions, which comprised 43% cold-start emissions and 57% hot-start emissions, are illustrated in Figure 8.

With the given desulfurization frequency, the composite FTP tailpipe NO_X emission number post desulfurization after 2000 hours could not be maintained below the emission standard for 120,000 miles of 0.07 g/mi beyond the first 2500 hours of aging. A detailed statistical analysis of NO_X emissions results from the test cell is discussed in the 'STATISTICAL ANALYSIS' section.

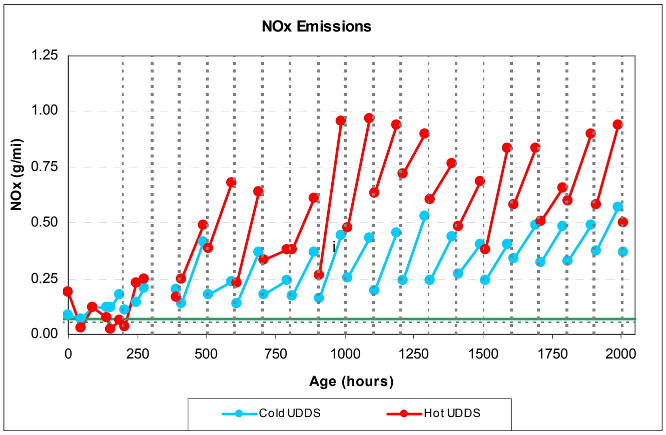


Figure 7: Cold and Hot UDDS NO_X Emissions

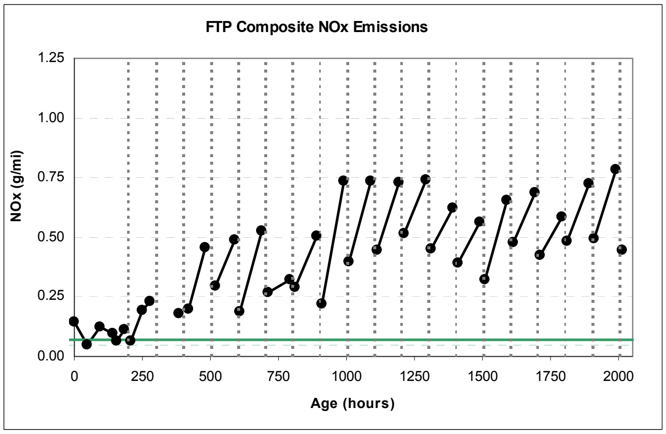


Figure 8: Composite FTP Emissions

The evaluation of the PM filters showed the high degree of filtration efficiency of the DPF. In all instances throughout the aging, the average composite PM numbers were below the emission standard of 0.01 g/mi.

The remaining UDDS-regulated emissions and fuel economy results, as well as the results for the US06 and HFET simulation cycles, are presented in Appendix C.

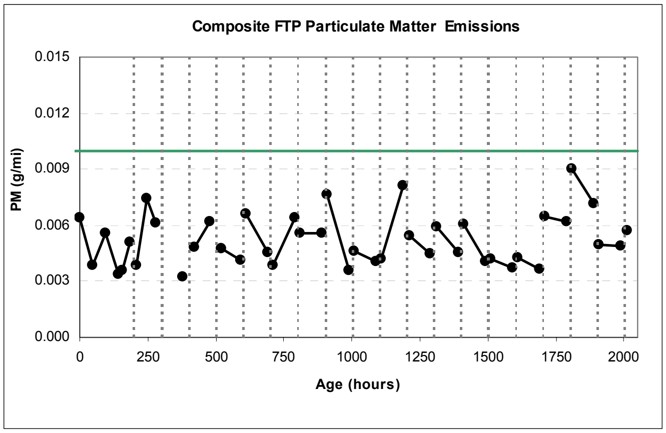


Figure 9: Composite PM Emissions

STATISTICAL ANALYSIS

Statistical analyses were performed to characterize trends in emissions levels over the 2000 hours of testing. The trend analysis was performed using only the data collected after the second desulfurization at 300 hours. Prior to 300 hours, evaluations were performed every 50 hours. After 300 hours, the data were collected using a 100-hour aging/desulfurization cycle.

Figure 10 illustrates the degradation in catalyst performance between desulfurizations. A log-linear model was fit to estimate average trends and evaluate statistical significance. The upper graph demonstrates that the loss in NO_X reduction efficiency (FTP composite) between desulfurizations is generally about 6% of the engine-out without EGR emissions, with a slight trend ranging between 4% and 6%. Figure 11 illustrates the effectiveness of the desulfurization process at restoring performance. There is a 6% improvement in NO_X reduction efficiency at each desulfurization event, with NO_X a slight trend ranging between 3% and 6%. Although these trend lines show slight changes in NO_X reduction efficiency, the slopes of the regression lines were not statistically different from zero. Combined, these figures indicate that after 300 hours of aging, the desulfurization process generally compensates for the increased degradation in catalyst performance between desulfurizations throughout the 2000-hour test.

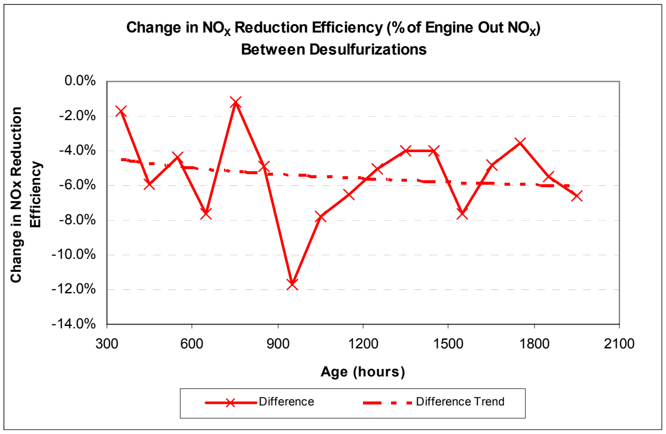


Figure 10: Change in NO$_X$ Reduction Efficiency between Desulfurization over Time

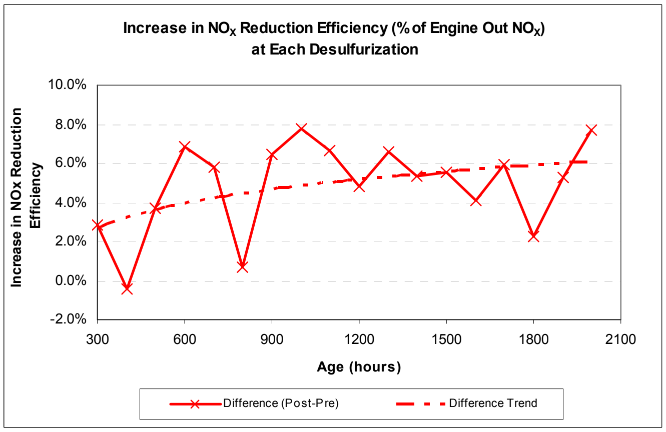


Figure 11: Increase in NO$_X$ Reduction Efficiency at Desulfurizations over Time

The trends in FTP composite NO$_X$ emissions between 300 hours and 2000 hours of aging are shown in Figure 12, and trends in FTP composite NO$_X$ reduction efficiency relative to engine-out between 300 hours and 2000 hours of aging are shown in Figure 13. To account for the effects of the desulfurization process, separate log-linear models were fit to three sets of NO$_X$ emissions data: (1) measurements made before a desulfurization event, (2) measurements made after a desulfurization event, and (3) the average of measurements made at the beginning (post-desulfurization) and end (pre-desulfurization) of each aging period. The latter results plotted at the midpoint of the aging period represent the best estimate of the average emissions over time; however, we could not verify that the increase in NO$_X$ emissions within an aging period is linear.

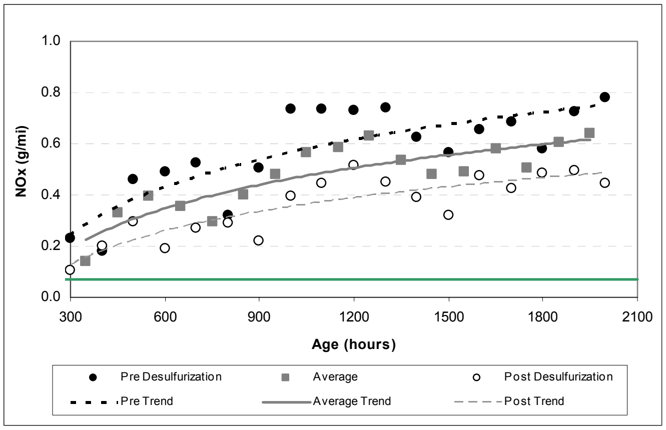


Figure 12: NO$_X$ Emission Trends over Time

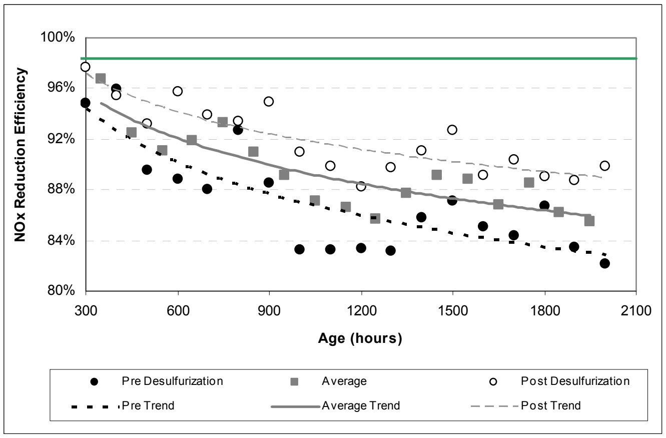


Figure 13: NO$_X$ Reduction Efficiency Trends over Time

The plots in Figures 12 and 13 show the performance stabilization for the system over time. All three of the regression lines were found to have statistically significant trends at the 95% confidence level. However, because of the curvature in the trends, we performed additional analyses to determine if there were any persistent trends in the emissions results over time. This was accomplished by iteratively truncating the leftmost data from each of the three data sets; then refitting the regression model and evaluating the significance of the regression slope parameter. Through this process we determined that when the analysis is applied to data collected after 800 or 900 hours, the trends were no longer statistically significant.

A similar analysis strategy was applied to the observed fuel efficiency and CO, PM, and HC emissions results. There was a statistically significant increase in fuel efficiency and THC, NMHC, and CO emissions over the 300- to 2000-hour aging period; however, using the same iterative analysis approach described above, the trend in fuel economy was not statistically significant using only the data collected after 1100 hours; and the trends in THC, NMHC, and CO emissions were not statistically significant using only the data collected after 1400 hours. There were no observed trends for observed PM emissions.

Table 8 shows the average composite FTP emissions from the seven engine-out tests (six without EGR and one with EGR); the 18 tailpipe tests conducted prior to the first desulfurization at 200 hours; and the estimated FTP composite emissions results at 1950 hours as determined by the average trend line based upon measurements taken between 350 and 1950 hours. Emission reductions are calculated relative to engine-out with and without EGR. Emission reduction does not necessarily equate to NO_X conversion because back pressure affects engine-out emissions by changing the amount of EGR in use.

The initial and 1950-hour estimated reductions in NO_X, carbon monoxide (CO), and PM emissions due to the ECS were all statistically significant, as was the reduction in fuel economy (initially 18.7% relative to engine-out without EGR and 16.7% relative to engine-out with EGR). Although initially the average tailpipe NO_X emissions of 0.095 g/mi were higher than the regulated emissions standard of 0.07 g/mi, the difference was not statistically significant. The 1950-hour estimate of 0.616 g/mi was significantly above the standard. Initial average non-methane hydrocarbon (NMHC) emissions of 0.165 g/mi was 83% higher than the applicable standard and the estimated 1950-hour average NMHC of 0.372 g/mi was over four times the applicable standard. Tailpipe emissions for total hydrocarbon (THC) were greater than engine-out THC emissions, and average PM emissions were 50% lower than the applicable standard throughout.

Table 8. Average Engine-Out, Initial, and Estimated 1950 Hour Tailpipe Composite FTP Regulated Emissions and Fuel Economy

Emission Parameter	EGR	Engine Out	Tailpipe (0-200 Hours)		Tailpipe Average (Post-Pre) (1950 Hours)		Regulated Emission Standard [4]
		Avg.[1]	Avg.[2]	Percent Reduction	Avg.[3]	Percent Reduction	
NO_x (g/mi)	Without	4.38	0.095	97.8%	0.616	85.9%	0.07
	With	2.12		95.5%		70.9%	
NMHC (g/mi)	Without	0.198	0.165	16.7%	0.372	-87.6%	0.09
	With	Missing		Missing		Missing	
THC (g/mi)	Without	0.204	0.463	-126.9%	0.730	-257.8%	N/A
	With	0.264		-75.1%		-176.2%	
CO (g/mi)	Without	2.02	0.258	87.2%	0.620	69.3%	4.2
	With	4.43		94.2%		86.0%	
PM (g/mi)	Without	0.065	0.005	91.6%	0.005	91.8%	0.01
	With	0.145		96.2%		96.3%	
FE (mi/gal)	Without	18.4	15.0	18.7%	15.5	16.0%	N/A
	With	18.0		16.7%		13.9%	

[1] Engine-out average without EGR is based on 6 tests; Engine-out average with EGR is based on 1 test.

[2] Average of 18 tests performed prior to first desulfurization at 200 hours

[3] Estimate at 1950 hours based upon the trend of average results between 350 and 1950 hours

[4] Tier 2 Bin 5 Full Useful Life

N/A = Not applicable

CONCLUSION

During the course of this program, it was demonstrated that the NAC/DPF system evaluated, in conjunction with a 15 ppm sulfur fuel and appropriate control strategies and calibrations, could achieve high NO_X and PM reduction efficiencies. After 2000 hours of on-engine aging, the NAC/DPF system demonstrated an average NO_X reduction of 89% and PM reduction of 94% over the composite Federal Test Procedure (FTP). While the PM emissions were below the Tier 2 Bin 5 emission standard, the NO_X emissions were outside of this limit after full aging. The desulfurization strategy employed was successful in recovering NO_X adsorber performance with some deterioration through 2000 hours of aging.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

APBF-DEC:	Advanced Petroleum Based Fuels-Diesel Emission Control Activity
APP:	Accelerator Pedal Position
C:	Celsius
CARB:	California Air Resources Board
CM:	Centimeter
CO:	Carbon Monoxide
CO_2:	Carbon Dioxide
DESCE:	Diesel Emission Control Sulfur Effects Program
DOE:	U.S. Department of Energy
DPF:	Diesel Particulate Filter
ECS:	Emission Control System
EGR:	Exhaust Gas Recirculation
EPA:	U.S. Environmental Protection Agency
FTP	Federal Test Procedure
FTP-75:	Light-Duty Federal Test Procedure
G:	Gram
G/MI:	Gram per Mile
G/S:	Gram per Second
HC:	Hydrocarbon
HFET:	Highway Fuel Economy Test
KG:	Kilogram
LA-4:	Bag 1 and Bag 2 of the FTP-75 Cycle
MY:	Model Year
NAC:	NO_X Adsorber Catalyst
NMHC:	Non-Methane Hydrocarbon
NO_x:	Oxides of Nitrogen
NO_2:	Nitrogen Dioxide
OC:	Oxidation Catalyst
PM:	Particulate Matter
RPM:	Revolutions per Minute (engine speed)
SFI:	Supplemental Fuel Injectors
SUV:	Sport Utility Vehicle
THC:	Total Hydrocarbon
UDDS:	Urban Dynamometer Driving Schedule
US06:	An aggressive chassis dynamometer emissions test procedure, part of the Supplemental FTP

APPENDIX A: FUEL PROPERTIES

The base fuel used in this study is an ultra-low sulfur (0.6-ppm) fuel with properties that are representative of diesel fuels used in the United States, except for its sulfur content. Table A-1 summarizes the properties of the fuel. To achieve higher sulfur levels, without otherwise impacting other fuel properties, a mixture of the sulfur containing compounds (listed in Table A-2) typically found in diesel fuel is doped into the base fuel. The dopant mixture contains a variety of classes of sulfur containing molecules that is in the same boiling range as diesel fuel, with an emphasis on thiophenes. Careful addition of this dopant mixture yields fuels containing 8 ppm and 15 ppm sulfur for use in the catalyst aging experiments that follow this development activity.

Table A-1. Test Fuel Properties

Fuel Property	**ASTM Method**	**Base Fuel**	**BP15**
Density (kg/m^3)	D4052	826.2	837.1
Viscosity @40^{o}C (mm^2/s)	D445	2.3	2.5
Distillation			
IBP (^{o}C)	D86	180	164
10% recovery (^{o}C)	D86	203	201
20% recovery (^{o}C)	D86	219	218
30% recovery (^{o}C)	D86	233	233
40% recovery (^{o}C)	D86	244	246
50% recovery (^{o}C)	D86	251	259
60% recovery (^{o}C)	D86	257	272
70% recovery (^{o}C)	D86	265	286
80% recovery (^{o}C)	D86	279	302
90% recovery (^{o}C)	D86	312	322
FBP (^{o}C)	D86	352	346
Cloud point (^{o}C)	D2500	-26	-12
Pour point (^{o}C)	D97	-23	-18
Flash point, PMCC (^{o}C)	D93	69	64
Sulfur (ppm)	D5453	0.6	13.3
Aromatics (vol. %)	D1319	23.9	29
Olefins (vol. %)	D1319	4.6	
Saturates (vol. %)	D1319	71.4	
Aromatics (vol. %)	D5186	26.9	25
Polyaromatics (vol. %)	D5186	8.4	4.2
Non-aromatics (vol. %)	D5186	64.7	70.8
Cetane number	D613	42.5	51.1
Cetane index	D976	51.5	48.8

Table A-2. Properties of Sulfur Doping Compounds

Concentration (mass %)	**Compound**	**Chemical Formula**	**Boiling Point (^{o}C)**
50	Dibenzo[b,d]thiophene	$C_{12}H_8S$	333
30	Benzo[b]thiophene	C_8H_6S	222
10	Di-t-butyl disulfide	$C_8H_{18}S_2$	200
10	Ethyl phenyl sulfide	$CH_{10}S$	206

APPENDIX B

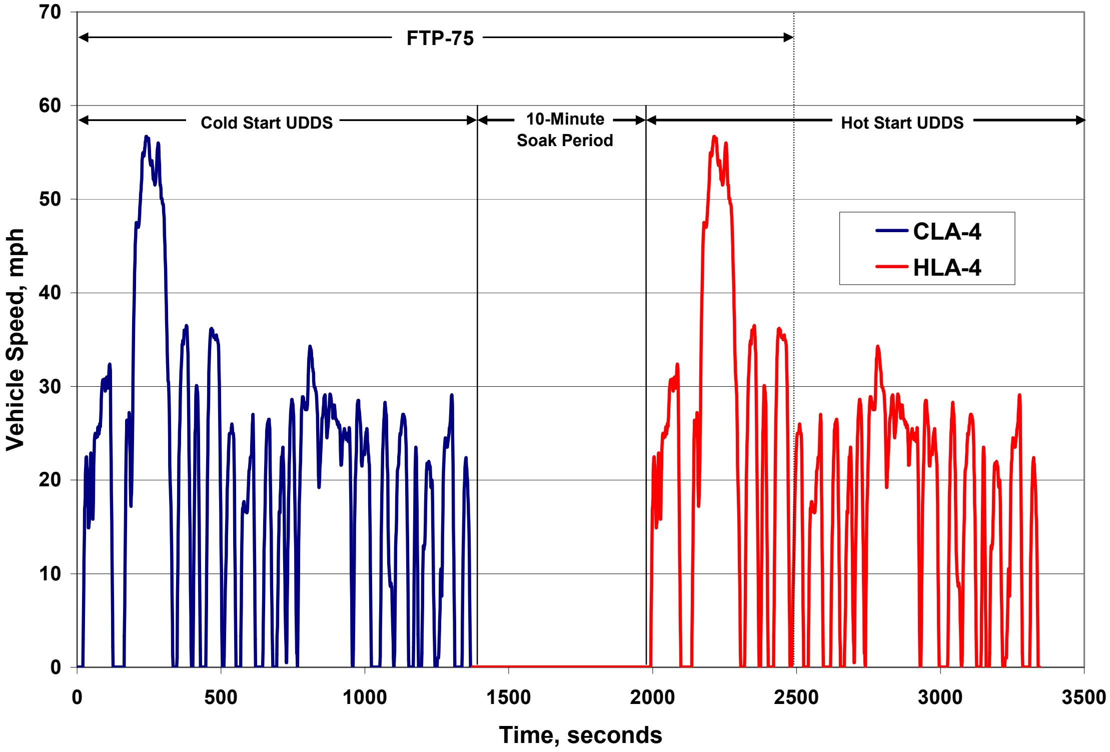

Figure B-1. Indicated Vehicle Speed versus Time for Cold-Start UDDS and Hot-Start UDDS Driving Schedules

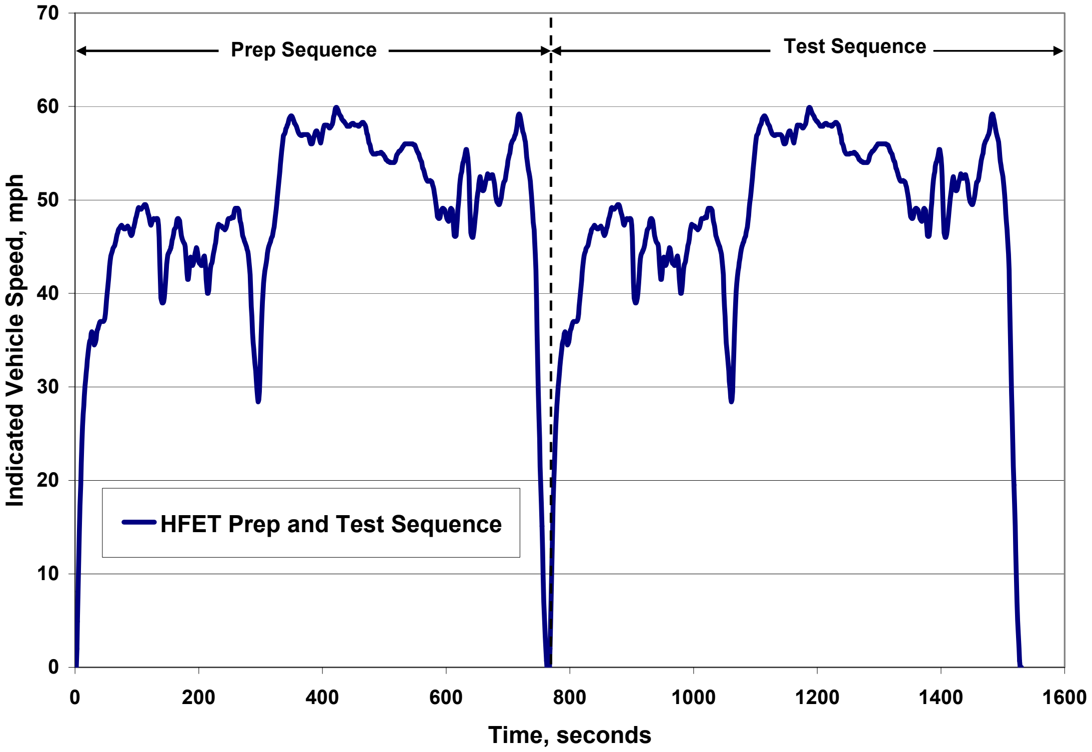

Figure B-2. Indicated Vehicle Speed versus Time for HFET Prep and Test Driving Schedule

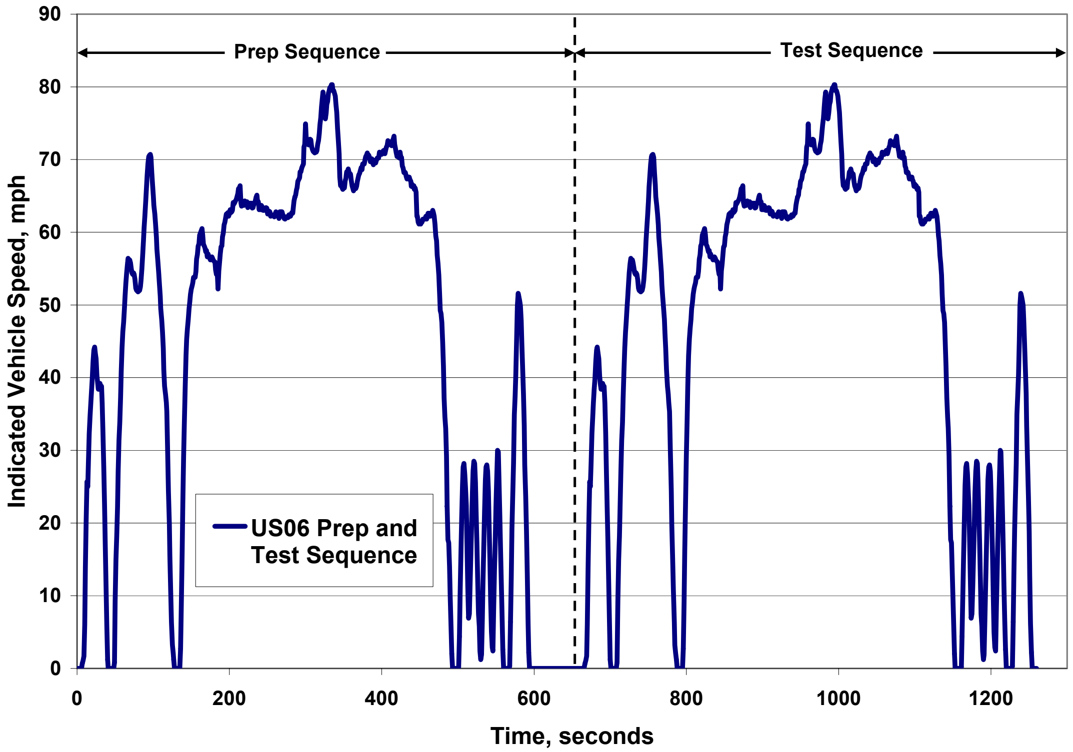

Figure B-3. Indicated Vehicle Speed versus Time for US06 Prep and Test Driving Schedule

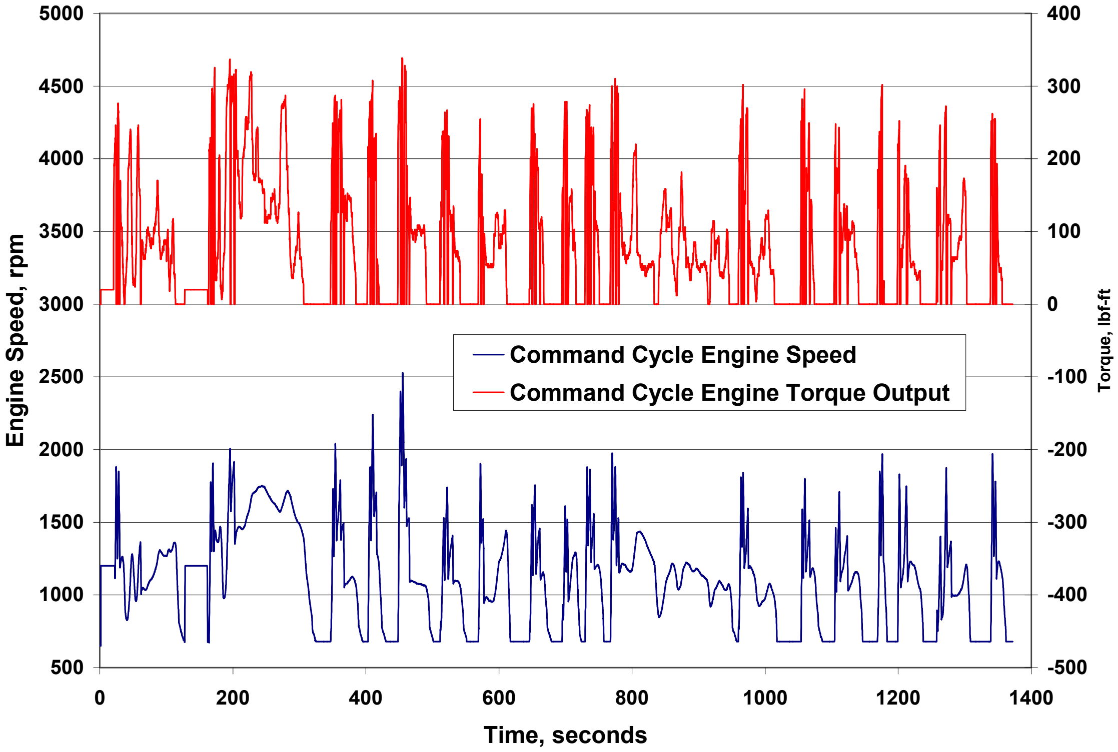

Figure B-4. Test Command Cycle (Engine Speed and Torque) for Cold-Start UDDS Cycle

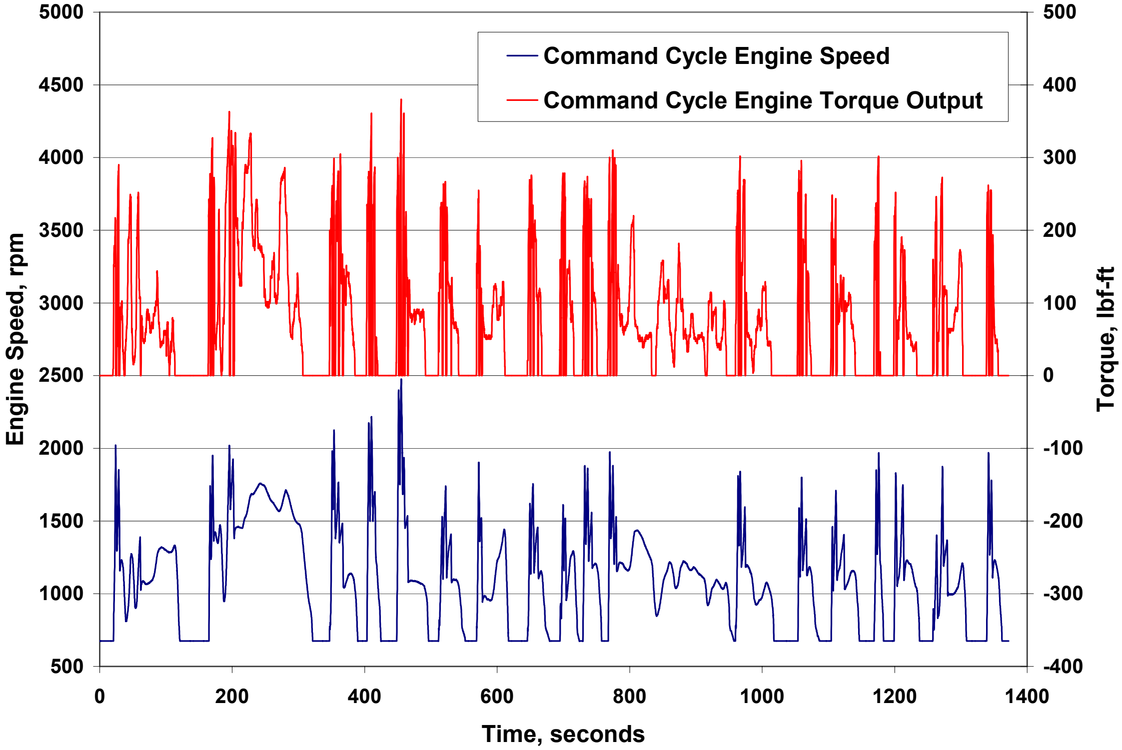

Figure B-5. Test Cell Command Cycle (Engine Speed and Torque) for Hot-Start UDDS

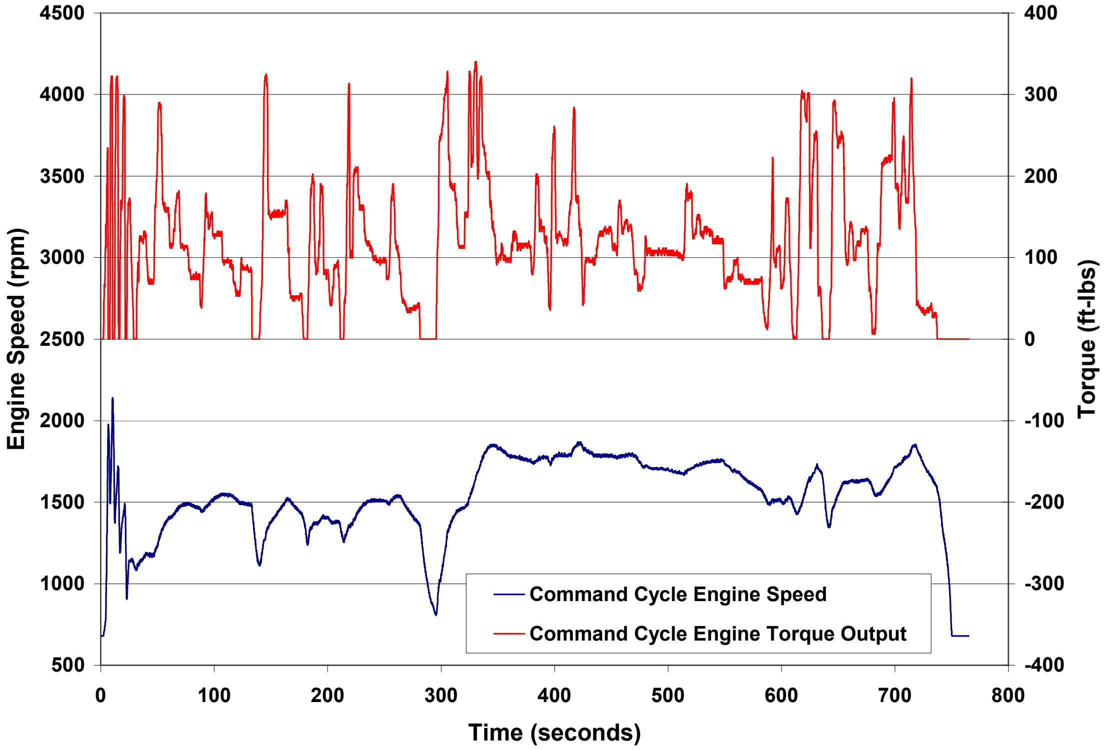

Figure B-6. Test Cell Command Cycle (Engine Speed and Torque) for HFET Cycle

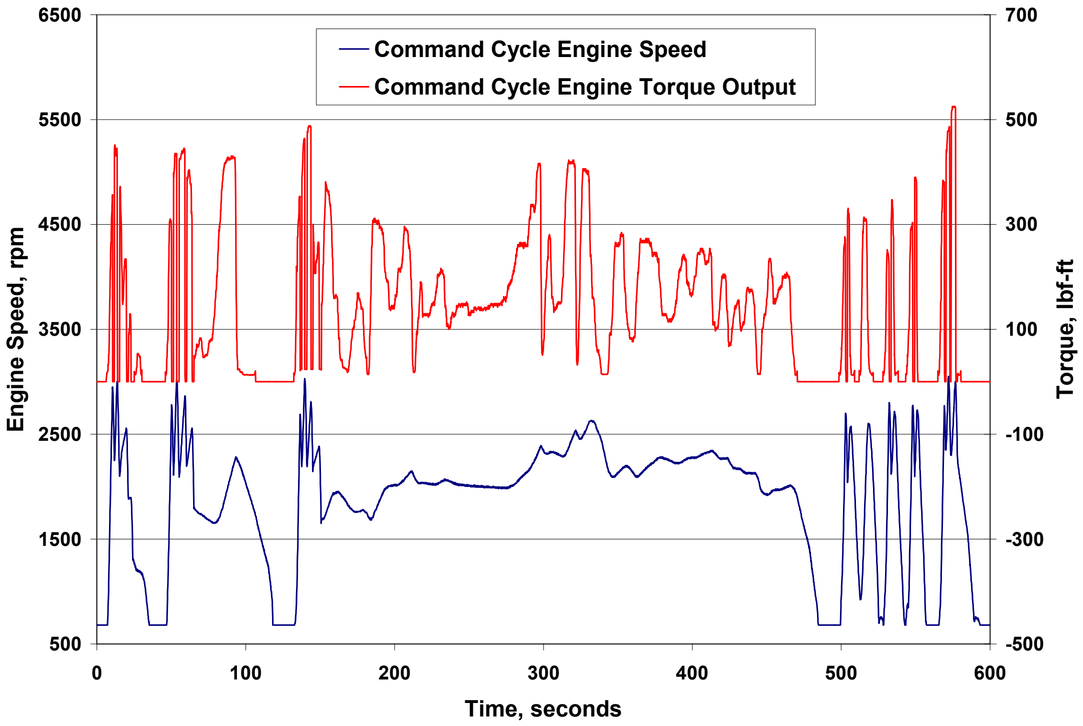

Figure B-7. Test Cell Command Cycle (Engine Speed and Torque) for US06 Cycle

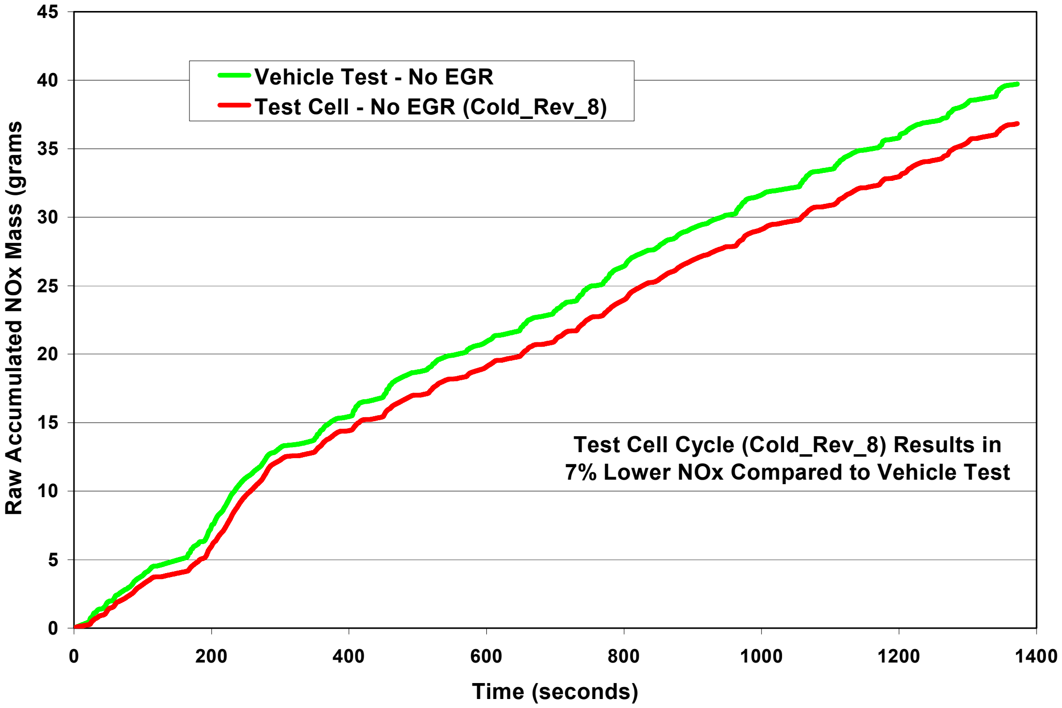

Figure B-8. Comparison of Accumulated Engine-Out NO_X Mass over the Cold-Start UDDS for a Vehicle Test and Test Cell Run

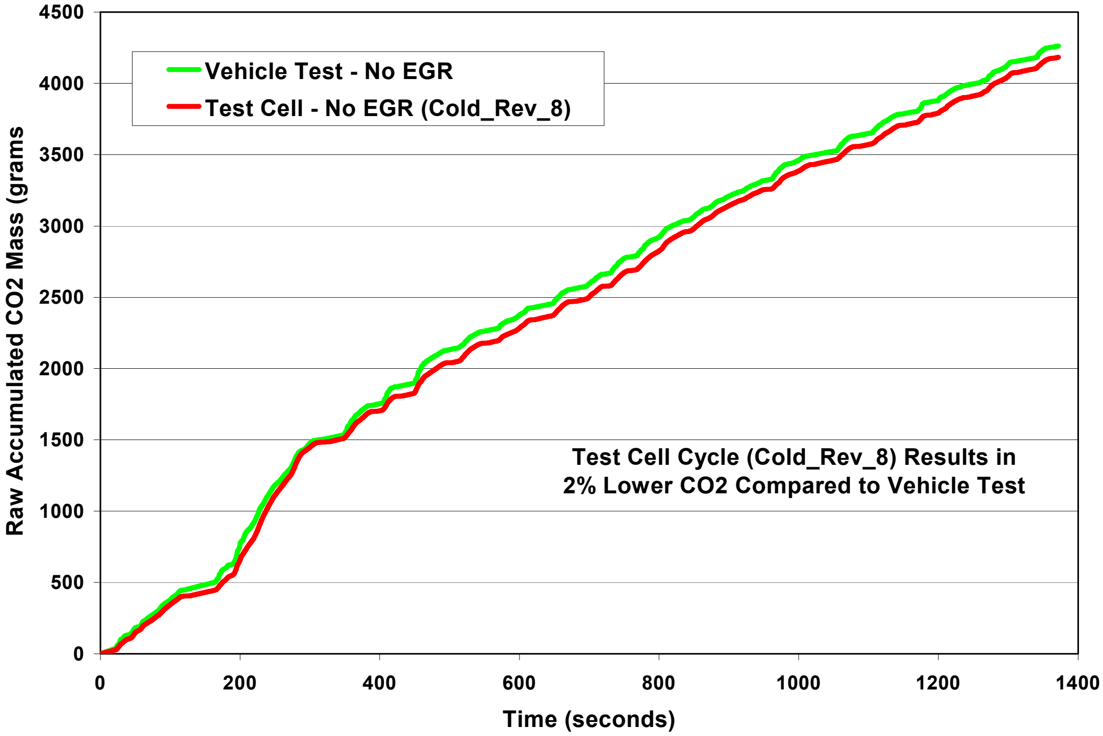

Figure B-9. Comparison of Accumulated Engine-Out CO_2 Mass over the Cold-Start UDDS for a Vehicle Test and Test Cell Run

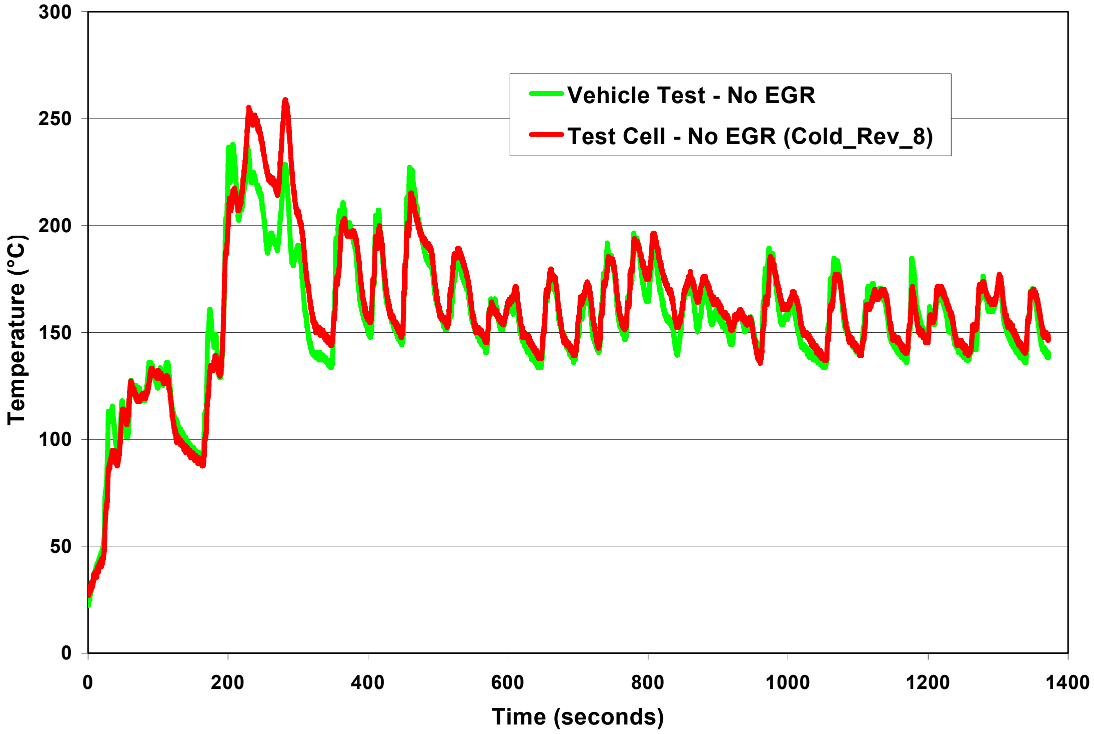

Figure B-10. Comparison Exhaust Gas Temperature over the Cold-Start UDDS for a Vehicle Test and Test Cell Run

APPENDIX C: TEST CELL EMISSION RESULTS

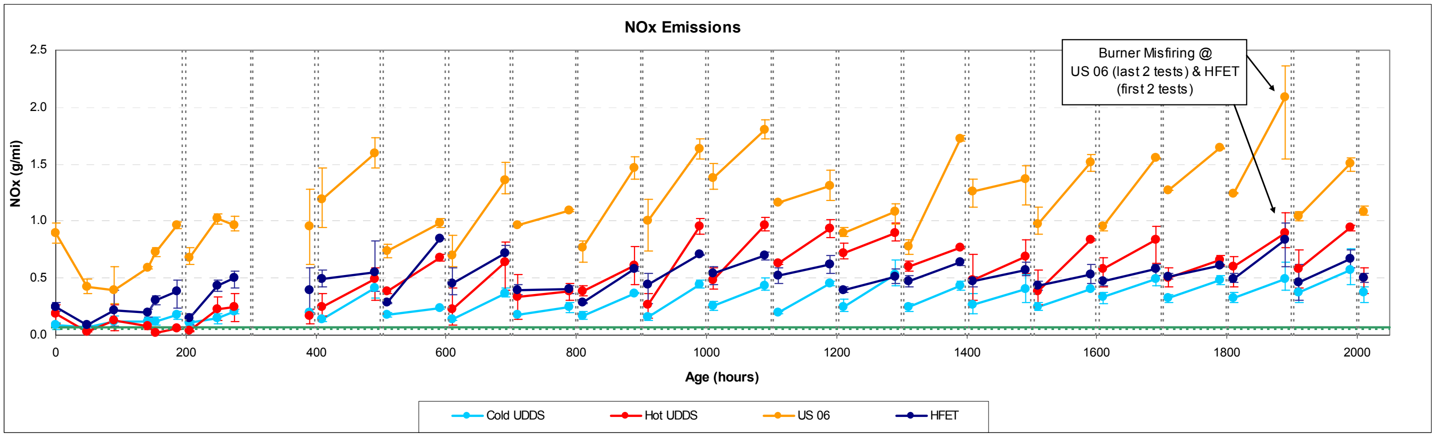

Figure C-1. NO_x Emissions versus ECS Age (Vertical Lines Identify Desulfurization Events) by Test Cycle

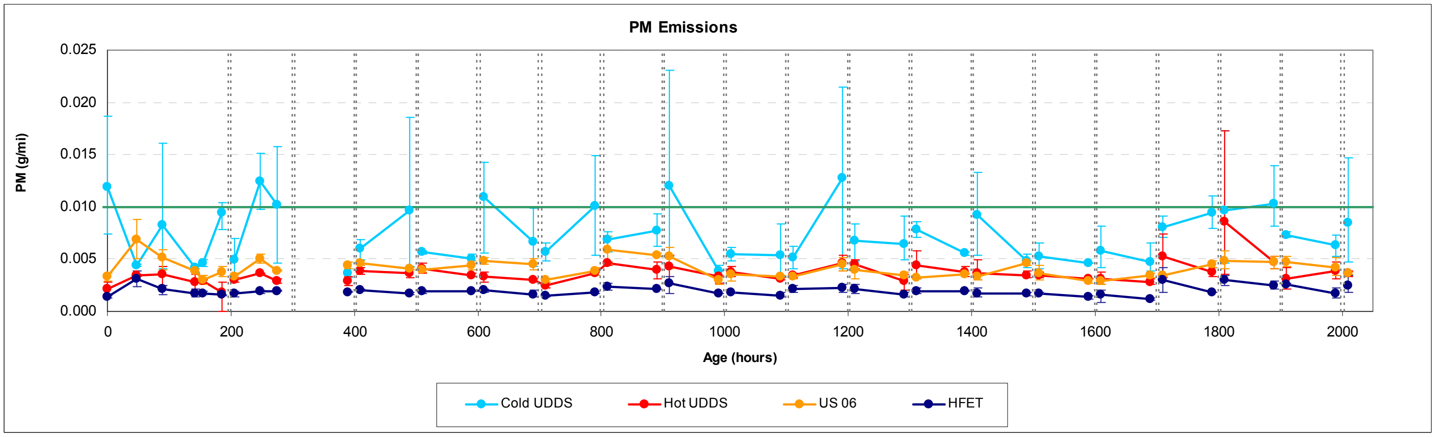

Figure C-2. PM Emissions versus ECS Age (Vertical Lines Identify Desulfurization Events) by Test Cycle

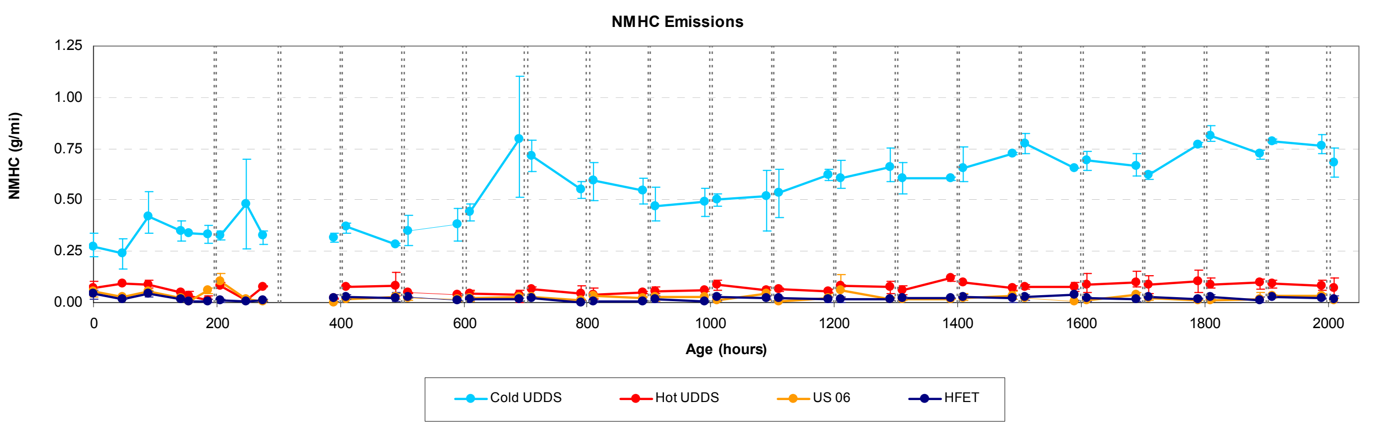

Figure C-3. NMHC Emissions versus ECS Age (Vertical Lines Identify Desulfurization Events) by Test Cycle

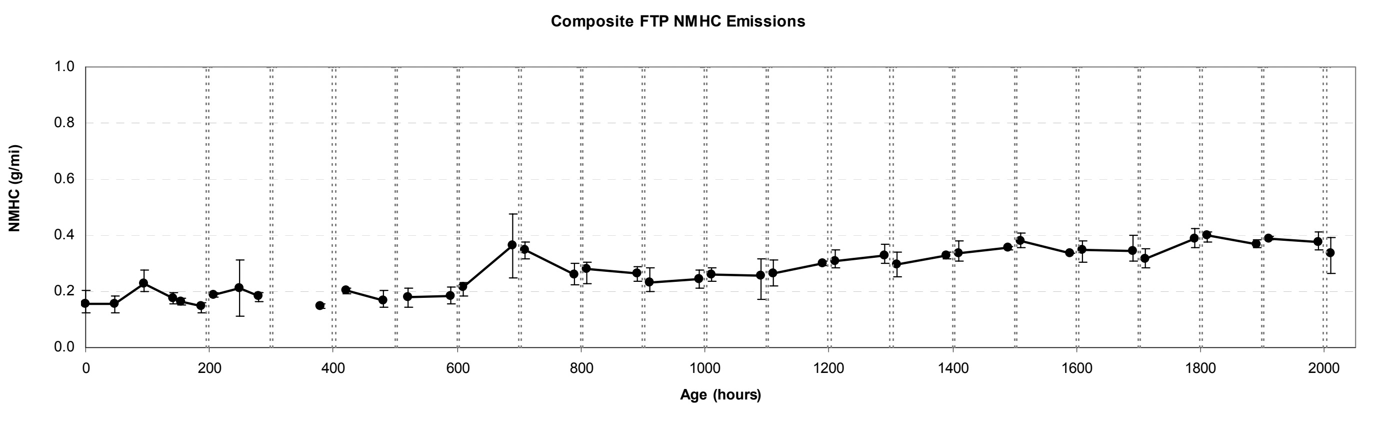

Figure C-4. FTP Composite NMHC Emissions versus ECS Age (Vertical Lines Identify Desulfurization Events)

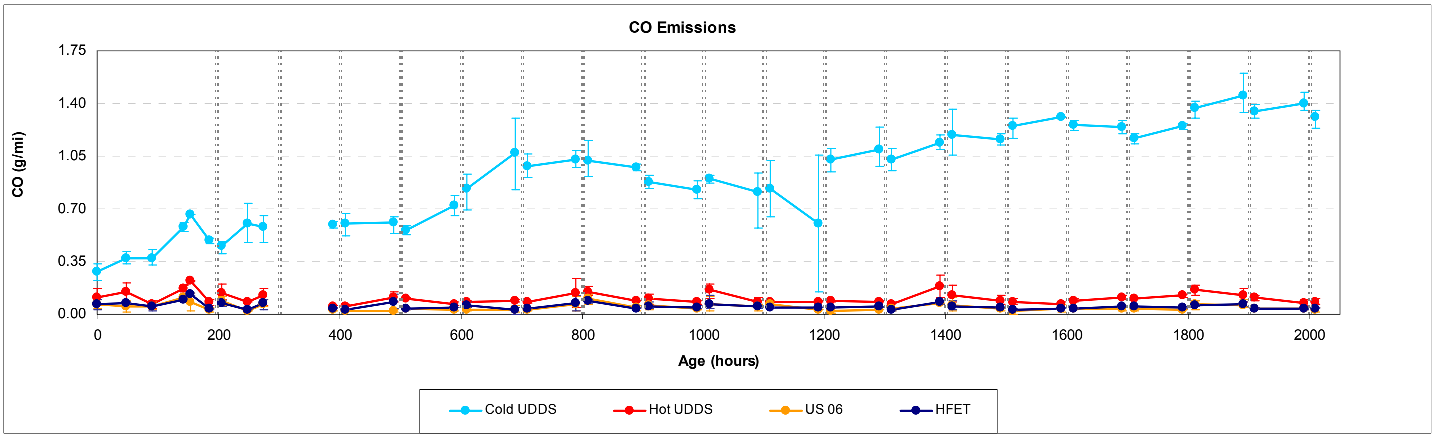

Figure C-5. CO Emissions versus ECS Age (Vertical Lines Identify Desulfurization Events) by Test Cycle

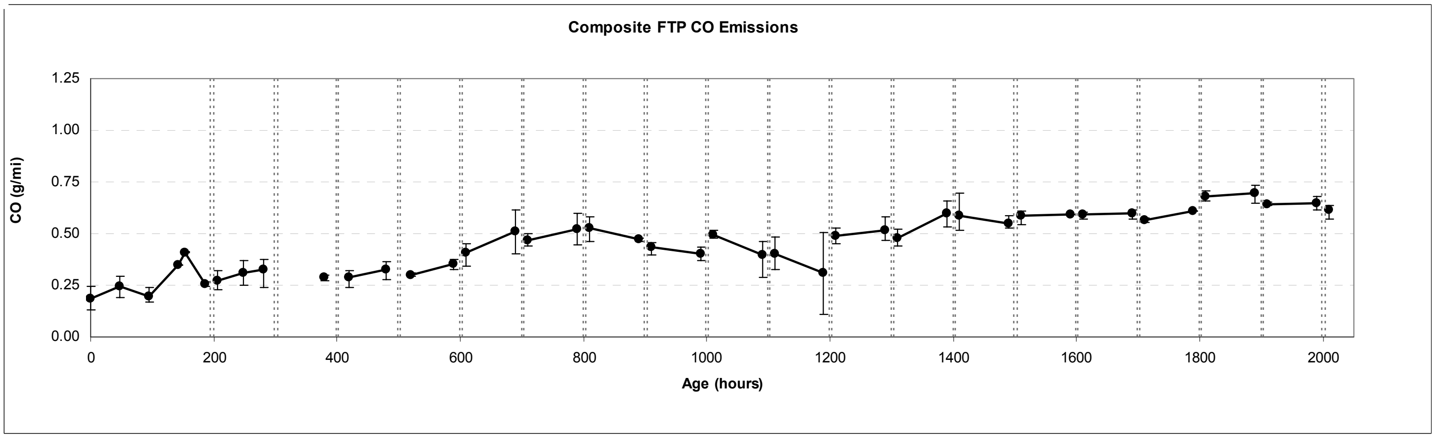

Figure C-6. FTP Composite CO Emissions versus ECS Age (Vertical Lines Identify Desulfurization Events)

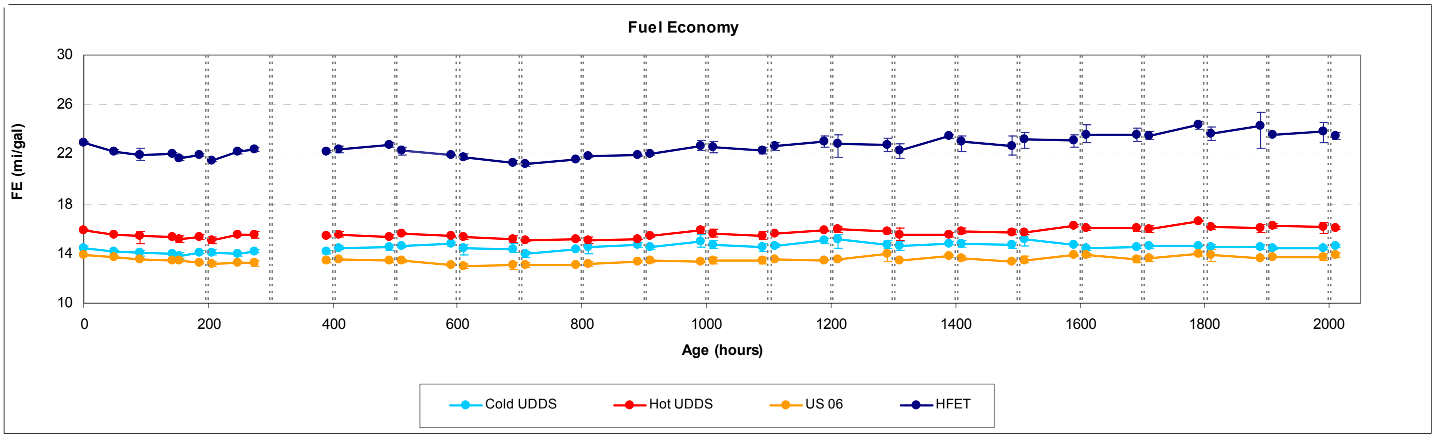

Figure C-7. Fuel Economy Emissions versus ECS Age (Vertical Lines Identify Desulfurization Events) by Test Cycle

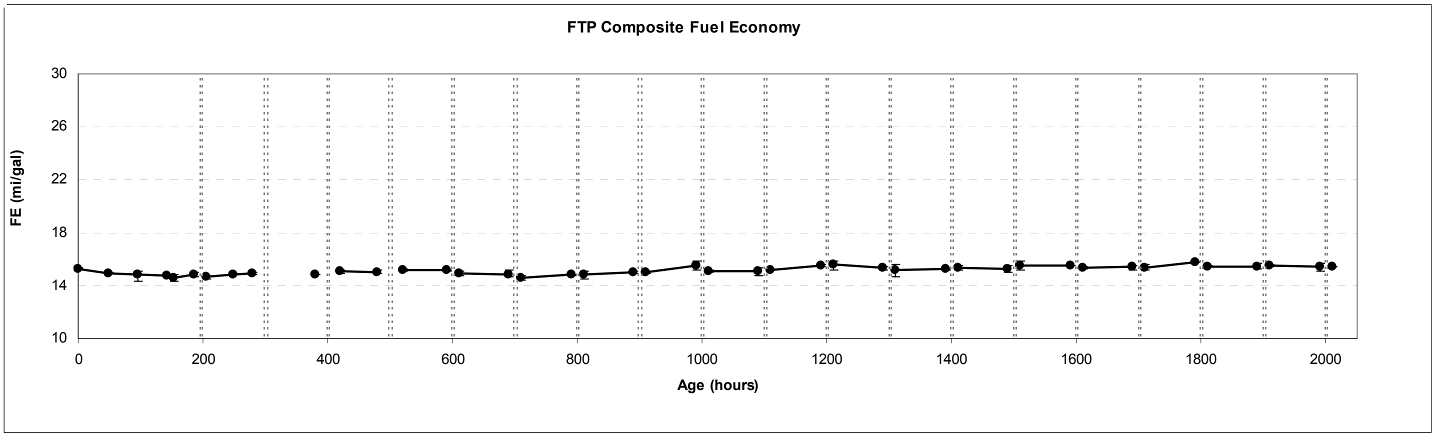

Figure C-8. FTP Composite Fuel Economy Emissions versus ECS Age (Vertical Lines Identify Desulfurization Events)