MECA Demonstration Program of Advanced Emission Control Systems for Light-Duty Vehicles

Final Report

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The Manufacturers of Emission Controls Association

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EXECUTIVE SUMMARY

A program to demonstrate the performance of advanced emission control systems in light of the then proposed California LEV II light-duty vehicle standards and the U.S. EPA's consideration of Tier II emission standards was conducted at Southwest Research Institute on behalf of the Manufacturers of Emission Controls Association (MECA). For this program, two passenger cars (a six-cylinder and an eight-cylinder engine) and two light-duty pick-up trucks (a six-cylinder LDT1and an eight-cylinder LDT3) were selected for testing, modification, and emission system performance optimization. The LDT3 was 1999 Federal Tier I compliant while the other three vehicles were 1997 Federal Tier I compliant, and were purchased from local car dealerships in the San Antonio, Texas area.

The results of the test program indicate that the vehicles tested achieved emission levels consistent with both California's LEV ULEV-II and U.S. EPA's proposed Tier II standards respectively using engine-aged advanced emission control technologies and modified engine calibration strategies. The advanced emission control technologies evaluated in this program included advanced three-way catalysts, high cell density substrates, and advanced thermally insulated exhaust components. Significant reductions in toxic emissions (benzene, formaldehyde, acetaldehyde, and 1,3-butadiene) were also observed for the advanced emission technology systems relative to the stock systems supplied with the vehicles. Costs associated with the advanced systems evaluated in this program are similar to estimates made by California's Air Resources Board and the U.S. EPA as a part of their LEV-II and Tier II rulemaking processes.

I. INTRODUCTION

A program to demonstrate the performance of advanced emission control systems in light of the then proposed California LEV II light-duty vehicle standards and the EPA's consideration of Tier II emission standards was conducted at Southwest Research Institute on behalf of the Manufacturers of Emission Controls Association (MECA). For this program, two passenger cars (a six-cylinder and an eight-cylinder engine) and two light-duty pick-up trucks (a six-cylinder LDT1and an eight-cylinder LDT3) were selected for testing, modification, and emission system performance optimization. The LDT3 was 1999 Federal Tier I compliant while the other three vehicles were 1997 Federal Tier I compliant, and were purchased from local car dealerships in the San Antonio, Texas area.

Each new vehicle was driven 4,000 miles on California Phase II reformulated gasoline over the EPA ASADP RDP-II mileage accumulation driving cycle. After the initial mileage break-in was completed, each vehicle was emissions tested on the FTP-75 test cycle. In these and all other FTP tests run as part of this program, test vehicles were fueled with emissions grade California Phase II reformulated gasoline. Hydrocarbon speciation and modal emissions analyses were performed on each cycle of the FTP test. The stock baseline modal emissions were examined and various systems including advanced catalysts, insulated exhaust components, and modified vehicle controls were developed in order to lower tailpipe emissions of each test vehicle significantly below their Tier 1 emission performance levels.

After installing the advanced systems, the vehicles were again driven for 4,000 miles on California Phase II reformulated fuel using the EPA ASASP RDP-II mileage accumulation driving cycle. The base performance of the advanced catalyst system was then determined with the stock vehicle controls over the FTP-75 test cycle. As part of an effort to optimize the emission performance of these advanced emission systems, the base modal emission test results were analyzed and vehicle control modifications were formulated to reduce the remaining high emission modes of operation. Control modifications were performed using a computer controlled-signal intercept system (Emissions Reduction Intercept and Control system or ERIC). This computer intercept methodology was used to recognize and modify only driving modes associated with high tailpipe emission modes, thereby minimizing the level of modification to the stock vehicle control system. The control tuning approach developed for each vehicle was unique to the platform. The computer intercept techniques used in this program were capable of modifying selected vehicle control parameters without setting codes in the vehicles' on-board diagnostic monitoring systems. Tuned control strategies had no measurable impact on the test vehicles' fuel economy over the FTP driving cycle. The modified control strategies also did not result in any detectable changes to vehicle driveability during FTP evaluations.

After the advanced technology systems and the modified engine controls were integrated and tuned, each vehicle was tested in it's final tuned configuration over multiple modal FTP-75 tests cycles. Hydrocarbon speciation was performed on each cycle of two of the final FTP tests. These results characterized the tuned emission performance of each advanced emission system after 4,000 vehicle miles. Each advanced catalyst system was then engine aged using an accelerated thermal aging cycle. The aging cycle used was an engine/ dynamometer cycle based on the published General Motors RAT-A aging schedule. California Phase II reformulated gasoline was used for all of the engine aging done in this program. The aging cycle used in this program adjusted the inlet exhaust temperature to the first catalyst in the converter system to 820°C during the stoichiometric cruise mode of the aging cycle. For the two passenger car systems 100 hours of aging time with this schedule was used to simulate a high mileage condition. For the light-duty trucks, system aging time was extended to 125 hours in recognition of the more severe duty cycles of some light-duty pick-up trucks relative to passenger cars. The actual mileage correlation to aging hours is application specific, but as referenced in the literature,[7,8,9] 100 hours of engine aging with the RAT-A cycle can correspond to 100,000 miles of in-service use on some vehicle platforms. The systems were retested over the FTP-75 after engine aging on each test vehicle to characterize the emission performance durability of each system. No modifications to the optimized control strategies developed during the program's tuning phase were made after aging of the emission components. Results for each of the four test vehicles used in this program are summarized in the following section.

II. ADVANCED EMISSION CONTROL SYSTEM DESCRIPTIONS AND TEST RESULTS

A. Vehicle Evaluations

A-1. Vehicle 1: 1997 Ford Crown Victoria

The Ford Crown Victoria tested had an eight-cylinder (V-8), 4.6L engine with a four-speed automatic transmission. The stock exhaust emission control system included dual close-coupled and underbody catalytic converters (one set on each bank of the V-8) and dual EGO sensors (before and after the first catalyst) on each bank. The stock exhaust joined together after the converters into a single exhaust. During installation of the advanced emission control system, the following hardware modifications were made:

- Dual close-coupled and underbody high cell density, ceramic substrates, Pd-based advanced catalytic converters were installed in place of the stock system, one set on each bank, in locations similar to the stock system.

- An electric air pump (vehicle powered)with a single point air injection probe on each bank, and a UEGO sensor for feedback to the control system were added to the vehicle.

- A water-cooled EGR transfer tube was developed using the stock transfer tube component.

The strategies employed during the emissions tuning phase of the program focused on balancing cold- and hot-start enrichment, providing cold-start NO_x control, and modifying EGR control during hard accelerations. During the emissions tuning phase of the program, the following control parameters were modified and tuned:

- Closed-loop secondary air injection for exhaust A/F control during cold- and hot-start open-loop operation.

- Mode activated EGR control modification (intercept control triggered by conditions defining a moderate to hard vehicle acceleration).

- Cold-start EGR control (first 50 seconds of the FTP driving cycle).

Following the tuning phase, the advanced emission system for the Ford Crown Victoria was bench engine aged for 100 hours using the 820°C RAT-A schedule. Figure 2 shows the tuned FTP results for the Crown Victoria with the advanced catalyst system at 4,000 miles and after 100 hours of engine aging, compared to the stock 4,000-mile results and the 120,000-mile LEV II ULEV standards.

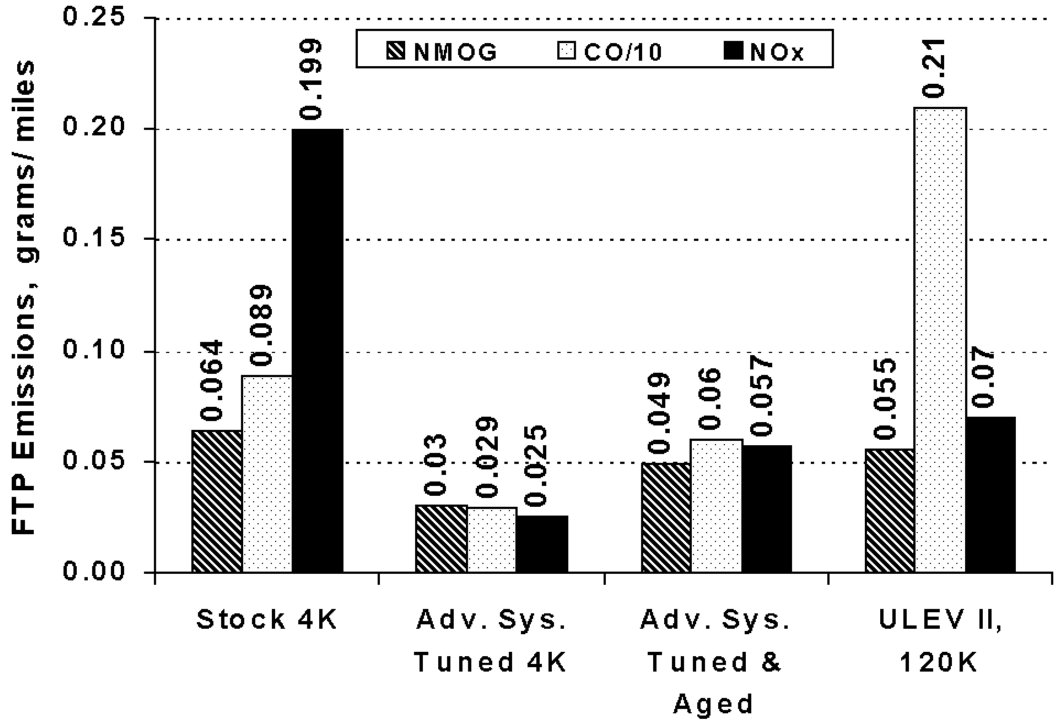

FIGURE 1. FTP EMISSIONS PERFORMANCE, 1997 FORD CROWN VICTORIA (4.6 LITER, V-8)

A-2. Vehicle 2: 1997 Toyota T100 Pick-Up

The Toyota T100 tested had a six-cylinder (V6), 3.4L engine with a single exhaust and a four-speed automatic transmission. The stock exhaust emission control system included a single underbody catalytic converter and dual EGO sensors (before and after the catalyst). This vehicle did not have an external EGR system.

During installation of the advanced emission system the following hardware modifications were made:

- Dual closed-coupled and a single underbody high cell density, metallic substrate, Pd-based advanced catalysts were installed in place of the stock underbody catalyst, thus converting the exhaust from a single to a dual configuration.

- The stock EGO sensors were moved to before and after the passenger side close-coupled catalyst.

- An additional stock EGO sensor was installed upstream of the driver side close-coupled catalyst.

- An electric air pump with port air injection probes on each bank of the V6, and dual UEGO sensors for feedback to the control system were added to the vehicle.

The strategies employed during the emissions tuning phase of the program focused on balancing cold-start engine enrichment, and correcting the effect of high speed fuel-control imbalances (caused by conversion of the exhaust from a single to a dual configuration, thereby removing A/F feedback from one bank). The following controls were modified or added and tuned:

- Closed-loop secondary air injection for exhaust A/F control during cold-start open-loop operation.

- Primary EGO sensor control switching at vehicle speeds greater than 40 mph to compensate for flow induce A/F imbalance caused by the new exhaust configuration.

Following the tuning phase, the advanced emission system for the Toyota T100 was bench engine aged for 125 hours using the 820°C RAT-A schedule. Figure 3 shows the 4,000 mile and the 125-hour aged, tuned FTP emissions results for the Toyota T100 pick-up with the advanced catalyst system compared to the stock 4,000-mile results and the proposed 120,000-mile LEV II ULEV standards.

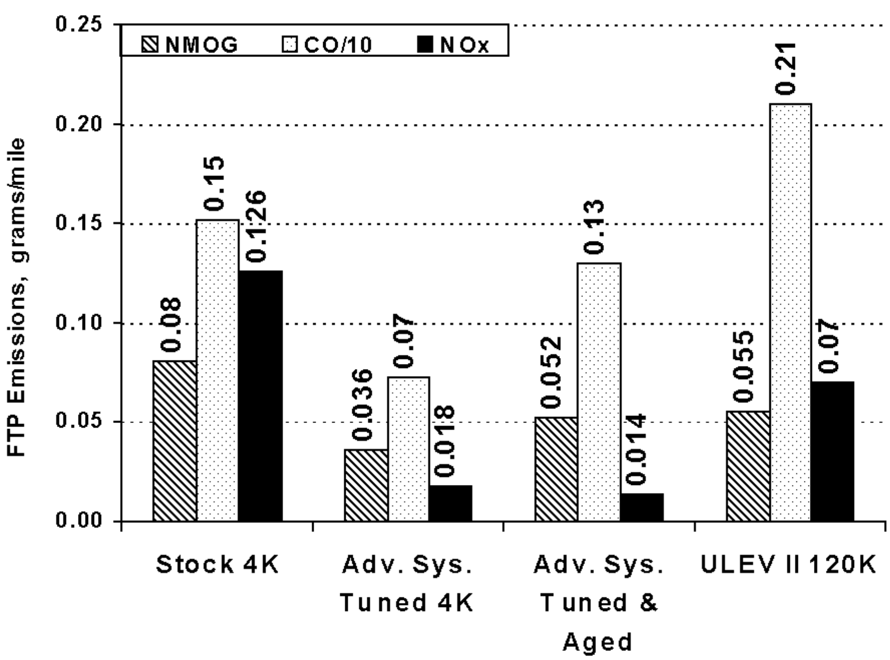

FIGURE 2. FTP EMISSIONS PERFORMANCE 1997 TOYOTA T100 (3.4 LITER, V-6)

A-3. Vehicle 3: 1997 Buick LeSabre

The Buick LeSabre tested had a six-cylinder (V6), 3.8L engine with single exhaust and a four- speed automatic transmission. The stock exhaust emission control system included an insulated air gap down pipe, single underfloor catalyst, and dual EGO sensors (before and after the catalyst). During installation of the advanced emission control system, the following hardware modifications were made to the vehicle:

- The stock exhaust manifolds and crossover pipe were replaced with air gap manifolds and crossover pipe

- A vacuum insulated metallic substrate, Pd-based, advanced catalyst system (a passive heat retention device) was installed in a similar underfloor location compared to the stock catalytic converter

- An electric air pump (vehicle powered) with port air injection probes on each bank, and a UEGO sensor for feedback to the control system were added to the vehicle.

The control strategies employed during tuning focused on balancing cold-start enrichment, and eliminating cold-start enleanment. During the tuning phase of the program, the following parameters were modified and tuned:

- Closed-loop secondary air injection for exhaust A/F control during cold-start open loop operation

- Time-activated engine coolant temperature sensor intercept to prevent excessive lean excursions during open-loop operation

The vehicle preparation cycle prior to FTP testing was modified for this test vehicle in order to achieve a converter temperature of at least 530°C near the monolith outer diameter before an extended soak period was initiated. The typical vehicle prep cycle is a single UDDS cycle. In this program, the test vehicle was driven over the 505 portion of the UDDS (corresponding to Bag 1 or Bag 3 of the FTP cycle), followed by a constant speed cruise of 65 mph to achieve the 530°C catalyst edge temperature. This 65 mph cruise was then followed by a single UDDS cycle. All data tables are in the Appendix. Results are presented for the advanced system evaluated using the stock vehicle engine controls and using the modified engine controls developed during the program's tuning phase. All emissions data for the advanced emission system made use of the special prep cycle detailed above with an extended soak period kept nearly constant at 16 hours (FTP run 16 hours after the conclusion of the preparation cycle).

The emission performance of the insulated advanced catalytic converter used on this test vehicle is dependent on both the maximum temperature achieved in the converter prior to emission testing and the length of the soak period prior to emission testing. As a part of this program, this vehicle was evaluated for FTP emissions after several soak periods of differing duration. For each soak period evaluated, the same optimized engine controls and the same special vehicle preparation cycle detailed above were maintained. The results from these FTP tests with different soak periods were used to calculate a specially weighted composite FTP result based on the EPA's previously published information on the frequency and duration of vehicle soak periods observed with in-service vehicles (i.e., Baltimore 1993 study, EPA 420-R-93-007). Soak periods of 6 hours, 16 hours, 24 hours, and 52 hours were used to calculate this weighted composite FTP result according to the following weighting formula:

> **Weighted FTP result** = 0.791× (avg. FTP result with 6-hour soak) + 0.155 × (avg. FTP result with 16-hour soak) + 0.039 × (avg. FTP result with 24-hour soak) + 0.015 (avg. FTP result with 52-hour soak to represent soaks >>24 hours)

At the completion of the tuning phase of the program, the advanced emission system for the Buick LeSabre was engine bench aged for 100 hours using the 820°C RAT-A schedule. FTP emission performance for the 100-hour aged system used the same optimized engine controls developed during the tuning phase. Figure 4 shows the 4,000-mile and the 100-hour aged, tuned results for the Buick LeSabre with the advanced technology system (16-hour soak) compared to the stock 4,000-mile results and California's LEV II 120,000-mile ULEV standard. Figure 5 shows a similar comparison for the soak weighted performance of the advanced technology system. The emission results in this table were obtained using the same special vehicle preparation cycle used at 4,000 vehicle miles at various soak periods. After aging, FTP tests were performed using only 6-, 16-, and 24-hour soak periods. The aged weighted emissions were obtained by combining the 24 and >>24-hour weight factors and applying them to the 24-hour soak.

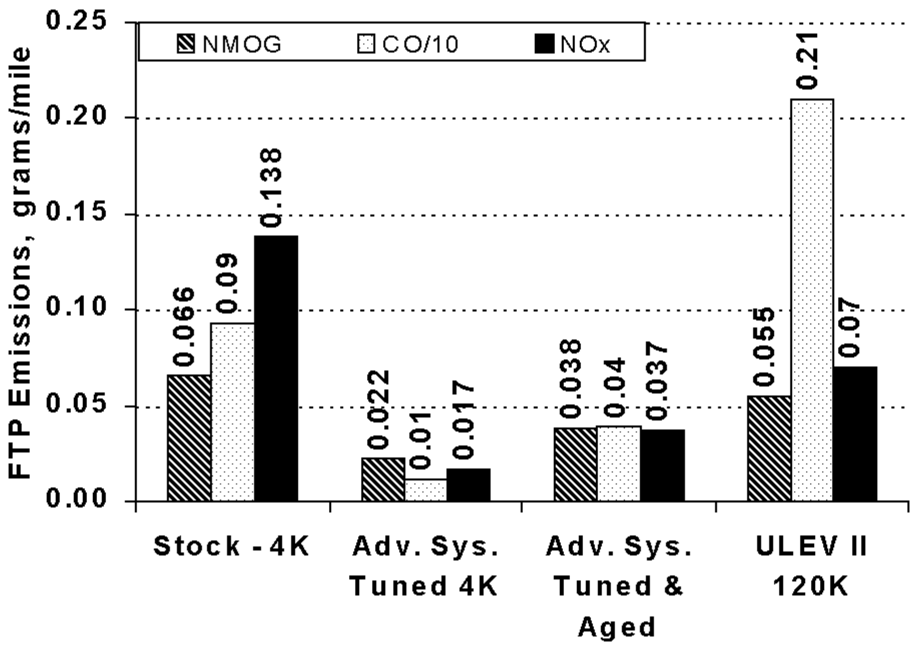

FIGURE 3. FTP EMISSIONS PERFORMANCE, 1997 BUICK LESABRE (3.8 LITER, V-6)

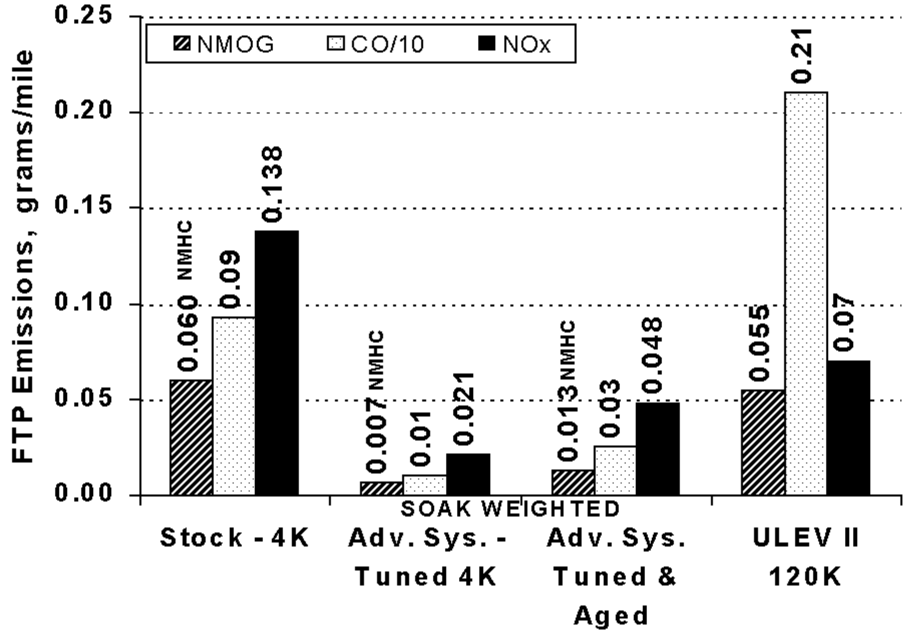

FIGURE 4. SOAK WEIGHTED FTP EMISSIONS PERFORMANCE, 1997 BUICK LESABRE (3.8 LITER, V-6)

A-4. Vehicle 4: 1999 Chevrolet Silverado

The Silverado tested was classified as a LDT3 truck and was certified as an EPA Tier 1 vehicle. The vehicle had a new generation 5.3 liter Vortec V-8 engine with dual exhaust, and a four-speed automatic transmission. The stock exhaust emission control system included two closed-coupled cylindrical catalysts (one per bank), and four EGO sensors (before and after each catalyst). During installation of the advanced emissions control system, the following hardware modifications were made:

- The stock catalysts were replaced with dual closed-coupled high cell-density ceramic substrates with advanced Pd-based washcoats.
- The stock front EGO sensors were moved about one foot closer to the engine to accommodate the new installation.
- An electric air pump, (operated using vehicle power) with single point air injection probes on each bank, and dual UEGO sensors for feedback to the control system were added to the vehicle.

The strategies employed during the emissions tuning phase of the program focused on balancing cold-start engine enrichment, providing NO_x control during cold-start, shifting the overall exhaust A/F bias slightly, and eliminating hot-start engine enleanment strategies. The following controls were modified or added and tuned:

- Closed-loop secondary air injection for exhaust A/F control during cold-start open-loop operation.

- Closed-loop EGR control during cold-start (the stock EGR system was inactive during cold-start phase).

- EGO switch point shifting to allow for exhaust bias adjustment.

- Fuel injector interception during hot-start to eliminate engine enleanment.

Following the tuning phase, the advanced emissions system was bench-aged for 125 hours using the 820°C RAT-A schedule. Figure 6 shows the 4,000 mile and the 125-hour aged, tuned FTP emissions results for the Chevrolet Silverado with the advanced system. Also shown in the figure are the FTP results for the stock system at 4,000 miles and the 120,000-mile LEV II ULEV standards.

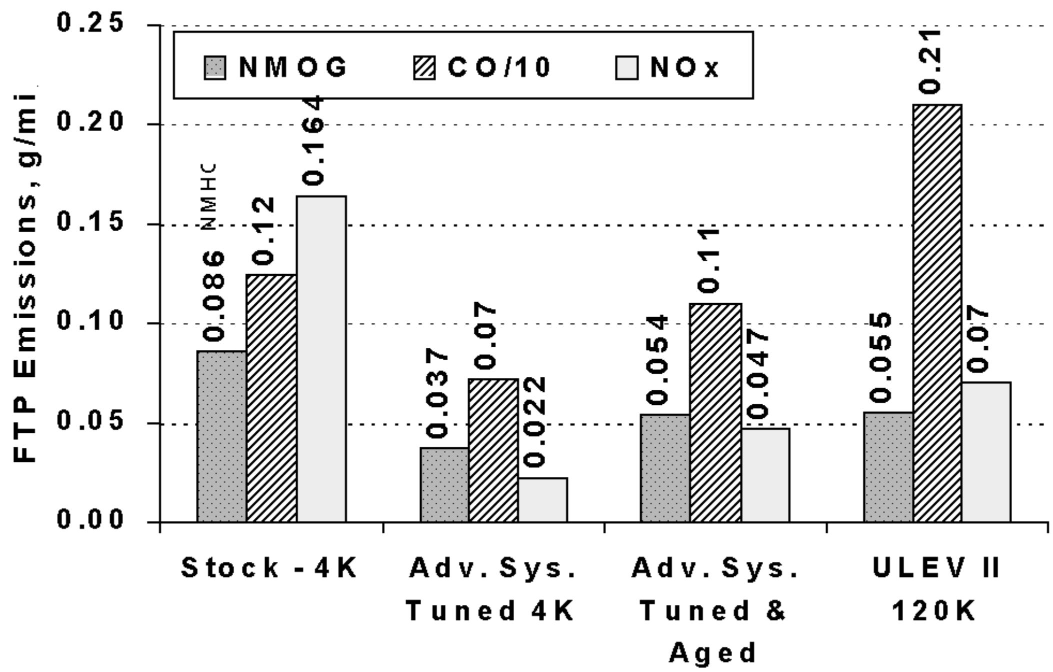

FIGURE 5. FTP EMISSIONS PERFORMANCE
1999 CHEVROLET SILVERADO (5.3 LITER, V-8)

B. Toxic Emissions

Since hydrocarbon speciation was included in the analyses of this program, information on the emissions of many different hydrocarbon species is available for each of the three test vehicles. Emission values for each toxic compound (benzene, formaldehyde, acetaldehyde, and 1,3-butadiene) are included at the 4,000-mile evaluation point for the test vehicle's stock emission system (evaluated with the vehicle's stock engine controls) and the advanced emission system (evaluated with the tuned engine controls). Reductions in the individual, as well as the total toxic emissions were achieved with the advanced emission systems at 4,000 miles for all three vehicles, when compared to the stock vehicle configurations at 4,000 miles. The largest reduction in toxic emission was accompanied by the largest reduction in NMHC and NMOG emission over stock. Although there was no toxics data for the stock Silverado, because there was a large decrease in NMHC with the tuned, advanced system, it was anticipated that the vehicle would also have demonstrated a large decrease in toxic emissions over the stock configuration. Figure 7 compares the FTP composite total toxic emissions (benzene + formaldehyde + acetaldehyde + 1,3-butadiene) for the three stock vehicle systems at 4,000 miles and the four 4,000-mile tuned advanced technology systems, all operating on California Phase II gasoline. Table 1 gives a summary of the measured toxic compound results for the four program vehicles. Reductions in formaldehyde and 1,3-butadiene emissions were greater than the overall NMOG reductions achieved with the unaged advanced emission systems when compared to the stock vehicle.

TABLE 1. MEASURED TOXIC EMISSIONS OVER THE FTP-75 TEST CYCLE

Vehicle System	Condition	Engine Controls	Emissions, milligrams/mile (Average of two tests)					
			Benzene	Form-aldehyde	Acet-aldehyde	1,3-Butadiene	Total Toxics	NMOG
1997 Tier 1 Buick LeSabre 3.8L (16-hr soak)								
Stock Vehicle	4,000 mile	Stock	2.01	0.50	0.11	0.46	3.08	66
Advanced Emission System	4,000 mile	Tuned	0.51	0.02	0.01	0.03	0.57	22
Advanced Emission System	100 hour aged	Tuned	1.10	0.18	0.06	0.07	1.41	38
1997 Tier 1 Ford Crown Victoria 4.6L								
Stock Vehicle	4,000 mile	Stock	2.14	0.19	0.08	0.18	2.59	64
Advanced Emission System	4,000 mile	Tuned	1.18	0.05	0.06	0.02	1.31	30
Advanced Emission System	100 hour aged	Tuned	2.33	0.26	0.07	0.11	2.77	49
1997 Tier 1 Toyota T100 3.4L								
Stock Vehicle	4,000 mile	Stock	2.88	0.70	0.22	0.72	4.52	80

Advanced Emission System	4,000 mile	Tuned	0.66	0.10	0.09	0.08	0.93	36
Advanced Emission System	125 hour aged	Tuned	0.99	0.40	0.18	0.18	1.75	52
1999 Tier 1 Chevrolet Silverado 5.3L								
Stock Vehicle	4,000 mile	Stock	NO DATA					
Advanced Emission System	4,000 mile	Tuned	0.87	0.19	0.11	0.03	1.19	37
Advanced Emission System	125 hour aged	Tuned	1.25	0.65	0.18	0.22	2.30	55

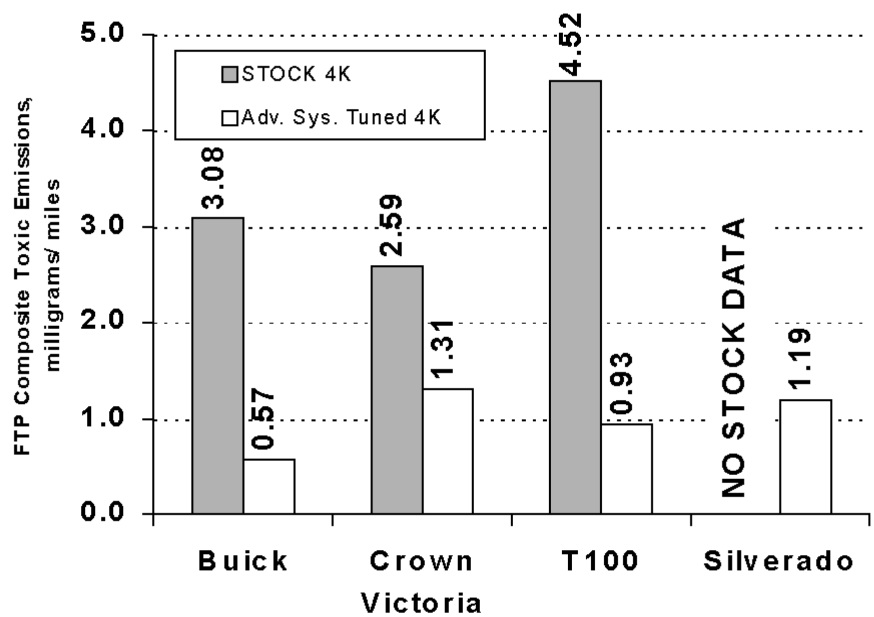

FIGURE 7. FTP COMPOSITE TOXIC EMISSIONS FOR THE LOW MILEAGE VEHICLES

III. Summary of Test Program

In summary, the composite FTP emissions for the 100-hour aged Buick LeSabre and Ford Crown Victoria, and the 125-hour aged Toyota T100 and Chevrolet Silverado with tuned advanced technology systems, were less than the California light-duty vehicle LEV II ULEV 120,000-mile and the U.S. EPA's proposed Tier II standards. The total toxic emissions for each vehicle with the tuned 4,000-mile advanced technology systems were also considerably lower than 4,000-mile stock vehicle systems. The largest reduction in toxic emission was accompanied by the largest reduction in NMHC and NMOG over stock. Although there was no toxics data for the stock Silverado, because there was a large decrease in NMHC with the tuned, advanced system, it is anticipated that the vehicle would also have demonstrated a large decrease in toxic emissions over the stock configuration. The large reductions observed in toxic emissions with the advanced catalyst systems on each of the vehicles tested highlights the synergy between improved hydrocarbon performance and improved performance in reducing toxic emissions. Technologies aimed at improved cold-start hydrocarbon emission performance also provide significant reductions in toxic emissions.

The results from this test program provide clear evidence that advanced emission control technologies are available to significantly lower tailpipe emission levels from today's Federal Tier 1 levels to ULEV emission levels outlined in the California LEV II program and the U.S. EPA's Tier II proposal. This program was especially successful in demonstrating very low NO_x tailpipe emission levels (below 0.07 g/mi for each of the four aged systems evaluated), a key feature of California's light-duty LEV II program and the U.S. EPA's proposed Tier II standards. Also, this program provides evidence that light-duty trucks, when equipped with an advanced emission control system, are capable of reaching similar ultra-low emission levels as the passenger cars evaluated in this program, another key feature of the California LEV II program and the U.S. EPA's proposal.

The program results also exhibit the importance of the system design aspects on vehicle emission performance. In order to reach the ultra-low emission levels demonstrated by each of the four test vehicles, it was important and necessary to install advanced emission control systems and to integrate these systems with the engine controls. In each case, the test vehicles made use of advanced converter technologies that were passive in design. They incorporated advanced catalyst formulations, high cell density ceramic and metallic substrates, and exhaust component insulation technologies. Finally, it is important to note that all vehicles were operated and tested on California Phase II reformulated gasoline.