2004-01-1791

Progress in the Development of Tier 2 Light-Duty Diesel Vehicles

Joseph McDonald
U.S. EPA – Office of Transportation and Air Quality

ABSTRACT

The U.S. Environmental Protection Agency (U.S. EPA) has been conducting a test program to evaluate efforts to bring light-duty diesel vehicles into compliance with U.S. Federal Tier 2 Light-duty Emission Standards. Between April 2002 and October 2003, five advanced prototype light-duty diesel vehicles equipped with NOx adsorption catalysts, PM-traps, and diesel oxidation catalysts were tested at the U.S. EPA's National Vehicle and Fuel Emission Laboratory (NVFEL). The vehicle testing was conducted using low sulfur (<15 ppm) diesel fuel. All of the tested vehicles demonstrated the considerable progress recently made by vehicle manufacturers and systems integrators in applying advanced NOx and PM emission control technology to light duty diesel vehicles in anticipation of the U.S. Light-duty Tier 2 emission standards. PM emissions for all of the vehicles were well below the Tier 2 Bin-5 emission levels. The most recently tested vehicle demonstrated intermediate-useful life (50,000 miles) PM, NOx, and NMHC emissions at or below the Tier 2 Bin-5 levels. This paper represents an early survey of emissions from the first generation of prototype clean diesel vehicles.

INTRODUCTION

The Office of Transportation and Air Quality (OTAQ) of the U.S. EPA is evaluating progress in the development and application of NOx exhaust emission control systems for heavy-duty diesel trucks, buses, and light-duty diesel vehicles. This evaluation will assess progress towards meeting new U.S. Federal Heavy-duty Engine emissions standards for heavy-duty buses and trucks that begin to phase-in for model year 2007. In addition, light-duty diesel technology evaluation provides information to EPA on progress being made to introduce clean, fuel-efficient diesel technology that can meet new U.S. Federal Light-duty Tier 2 emission standards that are now beginning to phase-in for passenger vehicles. This report summarizes testing conducted at the U.S. EPA-NVFEL with light-duty diesel passenger vehicles incorporating recently developed technology to control NOx and PM emissions to very low levels.

TEST PROCEDURES

VEHICLE DESCRIPTION

The vehicles tested were developmental-prototype, light-duty diesel vehicles provided to EPA for testing by four vehicle manufacturers and one automotive development and systems integration firm. EPA has preserved the anonymity of one of the vehicles that participated in the technology evaluation at the request of the manufacturer. The letter-names (A-E) assigned to the vehicles during testing also designated the order in which the vehicles were tested, beginning with Vehicle-A in April 2002 and concluding with Vehicle-E in October 2003. The vehicles tested included three small station wagons (Vehicles A, B, and E), a mid-size passenger car (Vehicle-C), and a compact car (Vehicle-D). Results for Vehicle-A have been previously published.[1] Vehicle specifications are summarized in Table 1.

Vehicle-D was provided to EPA for testing as part of the U.S. Department of Energy (U.S. DOE) Advanced Petroleum-based Fuels – Diesel Emission Control (APBF-DEC) program. The vehicle's engine and emission control systems design and integration were implemented by FEV Engine Technology. Vehicle specifications, engine control and calibration, and additional emissions data for Vehicle-D are described in detail in a separate paper.[2] For the other vehicles tested, many of the specific engine and emission control system and calibration details were considered proprietary and confidential by the manufacturers due to the developmental nature of these vehicles. The manufacturer of Vehicle-A has published extensively on the development of the engine and emission control systems used on this vehicle.[3,4,5]

All of the vehicles tested should be considered part of a "first generation" in the development of clean diesel vehicles. The vehicles had common engine technologies (cooled EGR, high-pressure fuel injection, multi-valve turbocharged DI diesel engines, electronic engine management systems), but a range of control strategies for both the engines and the exhaust emission control systems were represented among these vehicles. Vehicle-D was the only vehicle tested that used a NOx-sensor for closed loop NOx regeneration control. The NOx regeneration strategies for Vehicles-A and E were proprietary, but did not include use of NOx sensors. Vehicles B and C used relatively simple, timer-based NOx regeneration approaches.

Vehicles A through D were tested with relatively new emission control system hardware (<4,000 miles). Vehicle-C was also tested using an aged (equivalent of approximately 60,000 miles) emission control system.

Table 1: Summary of major vehicle specifications.

Vehicle:	Vehicle-A (Prototype Toyota Avensis *D-CAT*)	Vehicle-B (Prototype VW Golf TDI)	Vehicle-C (Prototype Mercedes E320CDI)	Vehicle D (Audi A4 modified by FEV-NA)	Vehicle E
Vehicle Type:	Small station wagon	Small station wagon	Midsize car	Compact car	Small station wagon
Power Transmission:	Front-drive, 5-speed manual transmission	Front-drive, 5-speed manual transmission	Rear-drive, 5-speed automatic transmission	Front-drive, 5-speed manual transmission	Rear-drive, 5-speed automatatic
Engine:	2.0 L, 4-cyl. Turbocharged, charge-air-cooled DI Diesel w/DOHC and 4 valves/cyl.	1.9 L, 4-cyl. Turbocharged, charge-air-cooled DI Diesel w/DOHC and 4 valves/cyl.	3.2 L, 6-cyl. Turbocharged, charge-air-cooled DI Diesel w/DOHC and 4 valves/cyl.	1.9 L, 4-cyl. Turbocharged, charge-air-cooled DI Diesel w/DOHC and 4 valves/cyl.	2.8L, 6-cyl., Turbocharged, charge-air-cooled DI Diesel w/DOHC and 4 valves/cyl.
Power/Torque Rating:	81 kW @ 4000 rpm / 250 N-m @ 2000 rpm	75 kW @ 4000 rpm / 240 N-m	150 kW @ 4000 rpm / 500 N-m @ 1800-2600 rpm	75 kW @ 4000 rpm	150 kW @ 4000 rpm
Fuel System:	Denso HPCR	N/A	HPCR	HPCR	HPCR
Emission Control Systems:	DPNR system, cooled EGR	NOx adsorption catalyst, PM-trap, diesel oxidation catalyst, cooled EGR	NOx adsorption catalyst, PM-trap, diesel oxidation catalyst, cooled EGR	NOx adsorption catalyst, PM-trap, diesel oxidation catalyst, cooled EGR	NOx adsorption catalyst, PM-trap, diesel oxidation catalyst, cooled EGR
Catalyst Volume:	DPNR: 2.8 L DOC: 2.0 L	N/A	N/A	NAC: 3.84 L PM-trap: 2.5 L	N/A
Inertia Weight (as tested):	1590 kg	1530 kg	1930 kg	1725 kg	1590 kg

Notes on Table 1:
- *Some vehicle information has not been provided in this table due to the proprietary nature of the vehicles tested.*
- *The mileage reported for vehicles C and E refers to emission control system configurations that were thermally aged to equivalent mileage conditions.*

Table 2: Summary of fuel properties. Fuels for vehicles B and C were provided by the manufacturer. The fuel for Vehicle D was one of the two fuels specified as part of the U.S. DOE APBF-DEC project. EPA provided the fuel for testing vehicles A and E.

Test Method	**Fuel for Vehicle A**	**Fuel for Vehicle B**	**Fuel for Vehicle C**	**Fuel for Vehicle D**	**Fuel for Vehicle E**
Net Heat of Combustion, ASTM D3338-92 (MJ/kg)	43.1	43.2	43.4	43.1	43.1
Density @ 15.5 ºC, ASTM D4052 (g/cm^3)	0.819	.8226	.8202	0.8371	0.8318
Cetane Number, ASTM D613	50.2	52.1	56.2	51.1	50.8
Cetane Index, ASTM D976	51.7	51.3	58.4	48.8	51.5
Olefins, FIA D1319 (% Vol.)	2.7	1.1	0.8	4.6	3.9
Aromatics, D1319 (% Vol.)	27.5	20.7	9.7	29	24.2
Sulfur, ASTM D2622 (ppm mass)	9	10	5	13.3	12
Carbon, ASTM D3343 (mass fraction)	0.8654	0.8634	0.8587	N/A	0.8648
Distillation Properties, ASTM D86					
IBP (ºC):	189	188	167	164	188
10 % (ºC):	218	209	215	201	215
50 % (ºC):	260	246	272	259	259
90 % (ºC):	316	294	335	322	309
End Point (ºC):	347	317	345	346	346

Table 3: Summary of laboratory analytical equipment

Category	LD Test Site-A001 Analytical Equipment (Vehicle E)	LD Test Site-A003 Analytical Equipment (other vehicles)
CO	Horiba AIA-210/220 NDIR	Horiba AIA-23 NDIR
CO_2	Horiba AIA-220 NDIR	Horiba AIA-23 NDIR
HC	Horiba FIA-220 FID	Beckman 400 FID
CH_4	Horiba GFA-220 GC/FID	Bendix 8205 GC/FID
NOx	Horiba CLA-220 CLD	Beckman 951A CLD
THC	Horiba FIA-220 HFID	Horiba FIA-220 HFID
NOx	Horiba CLA-220 HCLD	Rosemount 955 HCLD
PM	EPA sampling system	EPA sampling system
CVS	Horiba VETS 9000 subsonic venturi	PHILCO CFV

Figure 1: Testing of vehicles A and B at U.S. EPA – NVFEL.

Vehicle-E was only tested in a configuration with the emission control system aged to an equivalent of 50,000 miles. The specific aging protocols for the emission control systems were considered proprietary by both manufacturers that provided such systems. Both sets of protocols included accumulation of desulfurization and forced PM regeneration events comparable to the stated equivalent mileage accumulation, but no further details have been provided on the aging protocols. Emission control system aging protocols, particularly accelerated aging protocols, are typically correlated to data obtained from in-use fleet mileage accumulation in order to adequately predict emission control system deterioration to a target vehicle mileage.

Vehicles A and E used "advanced combustion concepts" to control emissions under certain operating conditions, and to control exhaust composition during NOx regeneration or other periodic events necessary to maintain emission control system performance. In the case of Vehicle-E, any further details with respect to specific modes of engine operation were considered proprietary by the manufacturer. In the case of Vehicle-A, the use "low-temperature-combustion" (LTC) operating modes and other engine calibration details have been previously published by the manufacturer.[3,4,5] Use of LTC allowed the vehicle to operate at light loads and low to moderate engine speeds at near-stoichiometric conditions with very low engine-out smoke levels.[4] Depending on engine operating conditions, combinations of exhaust port injection and either LTC or "normal" combustion were used with Vehicle-A to accomplish de-NOx, de-SOx, or forced PM regeneration events.[5]

TEST FUEL

Test fuel properties are summarized in Table 2. The fuel used during the testing of Vehicle-A has been previously described.[1] All of the test fuels had low sulfur content (<15 ppm). The fuels for Vehicles A, D, and E were formulated to the fuel specifications used in the U.S. DOE APBF-DEC program. The fuels for these vehicles are similar to the current Federal specifications for light-duty vehicle certification-grade diesel fuel, with two exceptions:

1. reduced fuel sulfur content made necessary by the emission control systems
2. slightly higher cetane number

The aromatic content of the fuel for Vehicle E was slightly lower than current certification specifications.

Fuels similar to Swedish Class-1 ultra-low sulfur diesel fuel were used for Vehicles B and C. The fuels were provided by the manufacturers of these vehicles and the manufacturers requested that only these fuels be used during testing of their vehicles by EPA. The fuels for Vehicles B and C had very low aromatic content and high cetane number.

DRIVE CYCLES

The vehicles were tested using the full range of chassis dynamometer test cycles required for Tier 2 certification. This included the FTP, US06, SC03, and highway fuel economy driving cycles. Vehicles C, D and E were tested using all 4-phases of the FTP in place of the more typical, abbreviated 3-phase FTP (i.e., two complete UDDS cycles – see Appendix Figure 1). This allowed integration of emissions over a combination of phase-1/phase-2 and phase-3/phase-4 during testing, and increased PM sample-filter mass during testing. Vehicles A and B were tested with the typical 3-phase FTP. The environmental conditions of the SCO3 test were simulated using a modified version of the AC2 test procedure as previously described.[1] Testing was repeated 3 to 4 times over the FTP and US06 drive cycles, and 5 to 6 times over the SC03 drive cycle. The results from each drive cycle were averaged and 95 % confidence intervals were calculated based on a two-sided (α=±0.025) Student's t-test.

FACILIITIES

Vehicle testing was conducted at the U.S. EPA-NVFEL in Ann Arbor, MI USA (Figure 1). The vehicles were tested using a 48"-diameter single-roll, electric chassis dynamometer. Laboratory analytical systems for Vehicles A through D have been previously described.[1] Vehicle-E was tested using a recently upgraded diesel test site (Site-A001). Table 3 contains a summary of the analytical systems used for both vehicle test sites.

RESULTS

FTP RESULTS

Emissions and fuel economy results over the FTP are summarized in Table 4. NOx and PM emissions for each of the tested vehicles and current light-duty diesel vehicles are also compared in Figure 2. PM emissions over the FTP were very low for all of the vehicles tested, and ranged from approximately 10% to 60% of the Tier 2 Bin-5 PM standards. NOx and NMHC emissions were at or just under the Tier 2 Bin-5 50,000 mile emission standards for all of the tested configurations except for the 60,000 mile configuration of Vehicle-C. Although only Vehicles C and E were tested with exhaust emission control systems thermally aged to 50,000 miles or more, all of the vehicles tested still demonstrate the significant progress that has been made in light-duty diesel NOx emission control, with NOx reduction efficiencies that are likely in the range of 50 to 80% over the FTP. Vehicle-E was the first light-duty diesel vehicle tested by EPA to demonstrate the level of NOx emissions control and system durability that will be needed to meet 50,000 mile Tier 2 Bin-5 emission standards.

In contrast to Vehicle-E, the NOx emissions for the 60,000 mile configuration of Vehicle-C were much higher, and NOx control appears to have degraded considerably from the relatively low-mileage configuration of Vehicle-C. EPA has not yet tested configurations of the other vehicles at higher accumulated mileages, but published data from testing of other Toyota Avensis D-CAT vehicles similar to Vehicle A indicates considerably less degradation of NOx emissions performance at 60,000 miles than what was observed for Vehicle-C.[5]

The coefficient of variance for PM emissions was significantly reduced for testing with Vehicle-E. This was likely due to sampling system improvements and improvements to analytical techniques implemented immediately prior to the testing of this vehicle. Coefficients of variance for NOx and NMHC emissions were also marginally improved for Vehicle-E in comparison to the other vehicles tested. The methane correction applied for the calculation of NMHC was very high for all of the vehicles tested, ranging from approximately 50% to 80% of the THC measured versus the typical sub-5% methane correction for conventional light-duty diesel vehicles. Methane emissions decreased for the 60,000 mile configuration of Vehicle-C when compared to the low-mileage configuration of Vehicle-C. The manufacturer confirmed that vehicle calibration and NOx regeneration frequency did not change between the 60,000 and low mileage configurations that were tested, thus it appears that catalyst activity may have an impact on methane emissions levels from this vehicle. Further study of this phenomenon is warranted.

SFTP RESULTS

Emissions and fuel economy results over the US06 and SC03 drive cycles and the calculated Tier 2 SFTP composite results are summarized in table 5. The Tier 2 4,000 mile SFTP emission standards are included in the table for comparison with the low-mileage results for Vehicles A through D. The optional Intermediate-Life Tier 2 Bin-5 and Bin-6 SFTP emission standards are included in the table for comparison with the Vehicle-C/60,000 mile and Vehicle-E results. Under the Tier 2 program, light-duty diesel vehicles may optionally certify to Intermediate-Life Standards in lieu of 4,000 mile SFTP Standards through model year 2006.

Vehicle-E demonstrated NMHC+NOx and PM emissions levels capable of meeting Tier 2 SFTP Intermediate-Life Standards. The SFTP NMHC+NOx emissions for Vehicle-E were at approximately half the Tier 2 Intermediate-Life standard. It is not known if this vehicle met the 4,000 mile Tier 2 SFTP standard as the vehicle was only tested in a 50,000 mile configuration. The NMHC+NOx emissions for the 60,000 mile configuration of Vehicle C were just above the Tier 2 Intermediate-Life Standards. NMHC+NOx emissions of the lower-accumulated-mileage configurations of Vehicles A through D were at or just below than the Tier 2 4,000 mile standard over the SC03, but NMHC+NOx emissions for Vehicles A through D ranged from near the standard to almost 4 times the Tier 2 4,000 mile standard over the US06.

NOx emissions for the low-mileage configuration of Vehicle-C were highly variable over the SC03. Modal hydrocarbon emissions analysis indicated variation in the occurrences of NOx regeneration events from test-to-test. This phenomenon was not observed during testing of the vehicle in the 60,000 mile configuration, and the manufacturer indicated that calibration did not change between the two tested conditions. No specific cause was identified.

Table 4: Summary of FTP exhaust emission and fuel economy results. Tier 2 Bin-5 and Bin-6 50,000-mile emission standards are shown for comparison. A summary of the Tier 2 FTP standards covering all emissions "bins" is included in the appendix.

Vehicle Tested	PM (mg/mi)	NOx (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	FE (mi/gal)
Vehicle A (<4k-miles)	5.7 (± 0.8)	0.05 (± 0.01)	0.07 (± 0.03)	0	273 (± 2)	37.2 (± 0.2)
Vehicle B (<4k-miles)	<2	0.04 (± 0.02)	<0.03	<0.1	277.4	36.6 (±0.4)
Vehicle C (<4k-miles)	3	<0.06	<0.02	<0.03	329 (±1.4)	30.9 (±0.1)
Vehicle C (@60k-miles)	3 (±1)	0.26 (±0.04)	0.018 (± 0.009)	0.07 (±0.01)	337 (±8)	30.2 (±0.7)
Vehicle D (<4k miles)	< 2	< 0.03	<0.02	0.018 (±0.007)	298 (±15)	34 (±2)
Vehicle E (@50k-miles)	1.0 (±0.1)	0.05 (±0.01)	0.07 (±0.01)	2.3 (±0.2)	317 (±2)	31.0 (±0.3)
Tier 2 Bin-5 (@50k-miles)	*10*	*0.05*	*0.075*	*3.4*		
Tier 2 Bin-6(@50k-miles)	*10*	*0.08*	*0.075*	*3.4*		

Notes on results reported in Tables 4 and 5:

- *The letter-names (A-E) designate the order in which the vehicles were tested, beginning in April 2002 (Vehicle A) and concluding in October 2003 (Vehcile E)*
- *PM emissions are reported in mg/mi*
- *The "±" values represent 95% confidence intervals for repeat tests*
- *Bag-sampled results are shown for NOx, CO, and CO2, while NMHC was derived from continuous HFID-HC and bag-sampled CH_4.*
- *The mileage for vehicles C and E refers to emission control system configurations that were thermally aged to equivalent mileage conditions*
- *Fuel economy (FE) was not adjusted for in-use driving*
- *Vehicle D was not tested over the SC03 cycle, thus composite SFTP results are not available*
- *The minimum detection limits for hydrocarbon emissions and the calculated NMHC varied dependening on the measured hydrocarbon background levels.*

Table 5: Summary of US06, SC03, and composite SFTP results. Tier 2 emission standards at 4,000 miles and 50,000 miles are shown for comparison.

Vehicle Tested	Test	PM (mg/mi)	NOx+ NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	FE (mi/gal)
Vehicle A (<4k-miles)	US06	5 (± 3)	0.33 (±0.08)	0	289 (± 7)	35.2 (± 0.8)
	SC03	7 (±2)	0.15 (±0.03)	0	367 (±3)	27.7 (±0.3)
	SFTP-composite	6 (±1)	0.19 (±0.04)	0		
Vehicle B (<4k-miles)	US06	<2	0.54 (0.09)	0	272 (±7)	37.3 (±0.9)
	SC03	1.2 (±0.5)	0.20 (±0.02)	0.13 (±0.04)	370 (±2)	26 (±1)
	SFTP-composite	<2	0.24 (±0.03)	0.09 (±0.04)		
Vehicle C (<4k-miles)	US06	<2	0.28 (±0.04)	0	340 (±20)	30 (±2)
	SC03	3 (±1)	0.2 (±0.3)	0	413 (±4)	24.6 (±0.3)
	SFTP-composite	3	0.15 (±0.11)	0		
Vehicle C (@60k-miles)	US06	1.2 (±0.6)	0.82 (±0.02)	0.010 (±0.003)	340 (±5)	30 (± 0.5)
	SC03	4.2 (±0.4)	0.61 (±0.04)	0.0200 (±0.007)	410 (±4)	24.8 (±0.3)
	SFTP-composite	3 (±0.4)	0.55 (±0.02)	0.036 (±0.005)		
Vehicle D (<4k-miles)	US06	<3	0.15 (±0.05)	0	280 (±10)	37 (±2)
Vehicle E (@50k-miles)	US06	8 (±4)	0.41 (±0.07)	1.6 (±0.6)	360 (±10)	27.2 (±0.8)
	SC03	1.0 (±0.4)	0.14 (±0.05)	2.1 (±0.2)	319 (±10)	30.9 (±0.2)
	composite	2.9	0.21 (±0.03)	2.0 (±0.2)		
Tier 2 US06 Standard (@4k-miles)			*0.14*	*8.0*		
Tier 2 SC03 Standard (4k miles)			*0.20*	*2.7*		
Tier 2 Bin-5 SFTP Standard (@50k-miles)		*70*	*0.47*	*3.4*		
Tier 2 Bin-6 SFTP Standard (@50k-miles)		*70*	*0.48*	*3.4*		

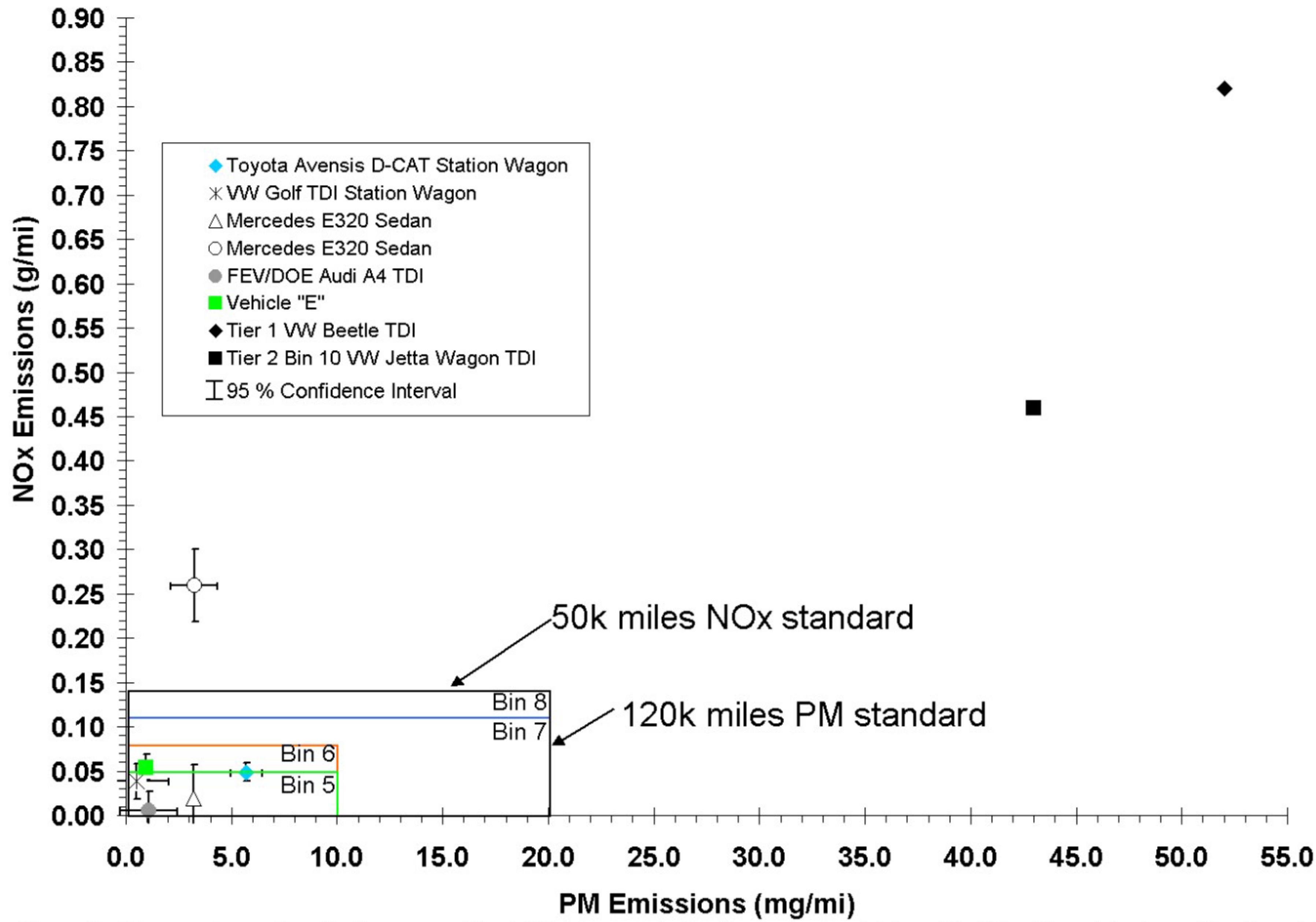


Figure 2: Comparison of emissions over the FTP drive cycle for the tested vehicles. Certification data from Tier 1 and Tier 2 Bin 10 light-duty diesels are included for comparison. The boxes represent the Tier 2 Bin 5-8 50,000 mile NOx and 120,000 mile PM emission standards.

Table 6: Summary of EPA City and Highway Fuel Economy for the tested vehicles.

Vehicle	Type	Engine	Transmission /Drive	Test Weight (kg)	City FE, Adjusted (mi/gal)	Hwy FE, Adjusted (mi/gal)
Vehicle-A (Toyota Avensis D-CAT)	Small Station Wagon	2.0-L turbo-diesel	5-speed Manual /Front-drive	1590	33.5 (±0.2)	41.2 (±0.5)
Vehicle-B (VW Golf TDI)	Small Station Wagon	1.9-L turbo-diesel	5-speed Manual /Front-drive	1530	33 (±0.4)	42.9 (±0.03)
Vehicle-C (Mercedes E320CDI)	Midsize Car	3.2-L turbo-diesel	5-speed Auto /Rear-drive	1930	27.8 (±0.1)	37 (±1)
Vehicle D (Audi A4)	Compact Car	1.9-L turbo-diesel	5-speed Manual /Front-drive	1725	31 (±2)	45 (±1)
Vehicle E	Small Station Wagon	2.8-L turbo-diesel	5-speed Auto /Front-drive	1590	27.9 (±0.3)	35 (±1)

Notes on Table 6

- *During calculation of City and Highway fuel economy, adjustment factors of 10% and 22% are applied to the FTP and HwFET results to reflect differences between laboratory results and in-use fuel economy.*
- *The adjusted fuel economy is directly comparable to data reported in the "Fuel Economy Guide".[6]*
- *The "±" values in table 6 represent 95% confidence intervals for repeat tests*

FUEL ECONOMY

Fuel economy for the tested vehicles is summarized in Table 6. The primary focus of EPA's light-duty diesel testing has been on emissions performance. A detailed analysis of the fuel economy of the tested vehicles with comparisons to current vehicles of comparable size, weight, interior volume, performance, aerodynamic drag, emissions and intended usage was beyond the intended scope of this work. The tested vehicles were emissions development prototypes and thus by nature represent a first generation of "work in progress". The resulting fuel economy of these vehicles may differ considerably from that of fully developed, production-ready vehicles. Still, general comparisons of measured fuel economy to that of current U.S. light-duty vehicles may be useful in determining if the fuel economy advantage of diesel vehicles over conventional gasoline SI vehicles can be largely maintained as light-duty diesels begin to approach relative parity with respect to emissions.

General comparisons were made of the fuel economy of the tested vehicles to values reported in the U.S. DOE/U.S. EPA "Model Year 2004 Fuel Economy Guide".[6] The comparisons were primarily limited to vehicles certified to Tier 2 Bin-8 or cleaner emission standards. There were distinct differences in vehicle performance when comparing Vehicles A, B, and D to Vehicles C and E. Vehicles C and E were "high performance" vehicles with power-to-weight ratios and high torque-outputs sufficient for near-8-seocnd 0 to 60 mph acceleration, thus they were treated separately as high performance vehicles and compared to vehicles in the "Fuel Economy Guide" of somewhat similar acceleration performance. Comparisons to vehicles in the "Fuel Economy Guide" were also limited to vehicles that were in the same "Vehicle Class", which is determined solely by vehicle interior volume.

Fuel economy for Vehicles A, B, and D was approximately 16 to 20% higher than conventional gasoline SI vehicles of comparable vehicle class. Fuel economy for Vehicles C and E was approximately 25% to 42% higher than comparable gasoline SI high performance vehicles.

There are currently no light-duty diesel vehicles sold in the U.S. certified to Tier 2 Bin-8 or cleaner. The 2004 VW Jetta Diesel (both "Small Wagon" and "Compact Car" models) is certified to Tier 2 Bin-10. Fuel economy for Vehicles A, B, and D was approximately 8% less than that of 2004 VW Jetta Diesel models of comparable "Vehicle Class". EPA expects that this gap will begin to close with further vehicle development. There are currently no "high performance" light-duty diesel passenger cars sold in the U.S. comparable to Vehicles C and E.

CONCLUSIONS

All five of the light-duty diesel vehicles tested have demonstrated the significant progress in NOx and PM emission control that has been achieved recently by vehicle manufacturers and automotive systems integrators. All of the vehicles tested relied primarily on NOx adsorption catalyst technology for NOx control and PM-trap technology for PM control. In all cases, PM emissions were very low, and ranged from approximately 10% to 60% of the Tier 2 Bin-5 PM emission standard. The most significant demonstration of progress was the improved durability of catalytic NOx emission control demonstrated by vehicle E, which was the most recently tested vehicle. Vehicle-E was the first vehicle tested by EPA that demonstrated Tier 2 Bin-5 NOx emissions levels following a significant degree of aging of the emission control system.

NOx control over the US06 continues to be a primary focus of attention in the development of clean diesel vehicles due to high NOx emission rates at both the high space velocities and high temperatures encountered, and the resulting short time windows available for NOx storage and regeneration. Vehicle-E demonstrated emissions that would meet the interim (2004-2006) Tier 2 SFTP standards. Additional testing will be necessary to determine the level of NOx emission control at the statutory full-useful-life (120,000 miles) for this new class of clean light-duty diesel vehicles.

EPA is working jointly with the U.S. DOE through its APBF-DEC program to evaluate progress made with improved NOx adsorption catalyst formulations. Future testing will be conducted using Vehicle-D, and will include the effects of the accumulation of approximately 10,000 miles, 50,000 miles and 120,000 miles of vehicle operation. EPA also has plans to evaluate additional "second generation" prototype light-duty diesel vehicles from vehicle manufacturers in order to assess their progress in meeting the full-useful-life Tier 2 emission standards.

ACKNOWLEDGMENTS

The author wishes to thank:

- Dr. Matthew Thornton of the National Renewable Energy Laboratory for providing access to the extensively modified Audi A4 diesel vehicle for testing at EPA-NVFEL, and Dr. Ing. Tatur Marek for his assistance during laboratory testing of this vehicle
- the Toyota Motor Corporation and the Toyota Technical Center for providing the prototype Toyota Avensis D-CAT, especially Dr. Kiyoshi Nakanishi, Dr. Koichiro Nakatani, Mr. Taro Aoyama, Mr. Tadao Shimbori and Mr. Thomas Beiershmitt
- Volkswagen AG and Volkswagen North America for providing the prototype Golf Wagon, especially Dr. Ing. Achim Freitag for his assistance during laboratory testing of this vehicle
- DaimlerChrysler for providing the prototype Mercedes E320 diesel, including the first thermally aged light-duty diesel NOx adsorption catalyst system tested by EPA; with special thanks to Dr. Ing. Oliver Erlenmayer for his assistance during laboratory testing of this vehicle
- and the engineers and technicians of the Laboratory Operations Division at the U.S. EPA-NVFEL facility in Ann Arbor, especially Mr. John Menter, Mr. David Bochenek and Ms. Maria Peralta.

REFERENCES

1. J. McDonald, B. Bunker, "Testing of the Toyota Avensis DPNR at the U.S. EPA-NVFEL", SAE Technical Paper No. 2002-01-2877.
2. D. Tomazic, M. Tatur, M.J. Thornton, "Development of a Diesel Passenger Car Meeting Tier 2 Emissions Legislation", SAE Technical Paper No. 2004-01-0581.
3. 1. S. Sasaki, T. Ito, S. Iguchi, "Rußarme fette Verbrennung mit Niedertemperatur-Oxydation in Diesel Motoren", 9th Aachen Colloquium Automobile and Engine Technology, 2000.
4. T. Fujimura, S. Matsushita, T. Tanaka, K. Kojima, "Entwicklung in Richtung Serienproduktion eines Diesel-PKWs für Europa mit einem System für gleichzeitige NOx und Partikel-reduktion", 23rd International Vienna Motor Symposium, 2002.
5. T. Paquet, J. Tahara, T. Sugiyama, H. Matsuoka, T. Fujimura, "Erste Feldversuchsergebnisse eines Diesel-Pkw, ausgerüstet mit der DPNR Abgasnachbehandelung", Aachener Kolloquium Fahrzeug und Motorentechnik, 2002.
6. U.S. DOE/U.S. EPA "Fuel Economy Guide", via the Internet at: http://www.fueleconomy.gov

CONTACT

Joseph McDonald
U.S. EPA – Office of Transportation and Air Quality
E-mail: mcdonald.joseph@epa.gov

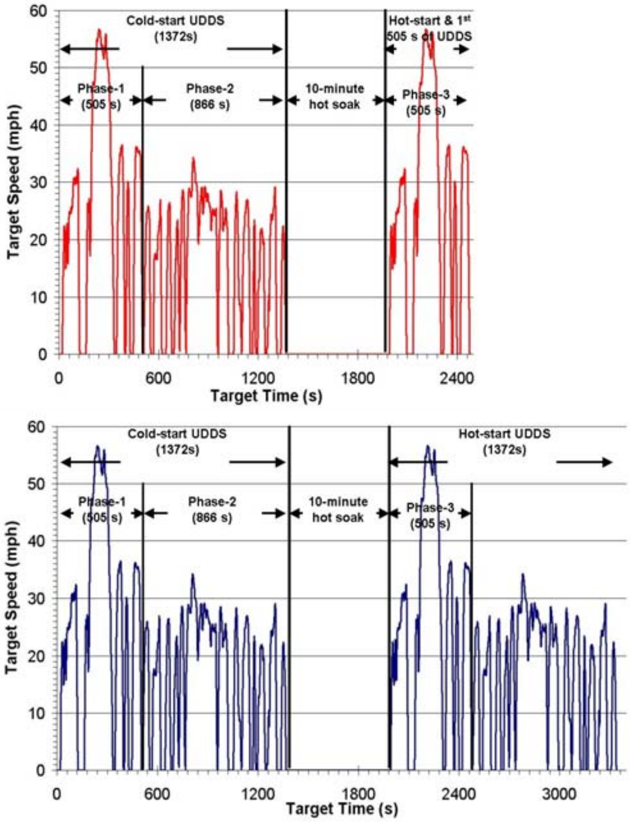
APPENDIX

Appendix Table 1: Summary of U.S. Federal Tier 2 Light-Duty Vehicle and Truck Intermediate-Life (50,000 mile) FTP Emission Standards.

Bin Number	NOx (g/mi)	NMOG (g/mi)	CO (g/mi)	HCHO (g/mi)
10	0.4	0.125	3.4	0.015
9	0.2	0.075	3.4	0.015
The above temporary bins expire in 2006 (for LDVs and LLDTs) and 2008 (for HLDTs)				
8	0.14	0.100	3.4	0.015
7	0.11	0.075	3.4	0.015
6	0.08	0.075	3.4	0.015
5	0.05	0.075	3.4	0.015

Appendix Table 2: Summary of U.S. Federal Tier 2 Light-Duty Vehicle and Truck Full-Life (120,000 mile) FTP Emission Standards.

Bin Number	NOx (g/mi)	NMOG (g/mi)	CO (g/mi)	HCHO (g/mi)	PM (g/mi)
10	0.6	0.156	4.2	0.018	0.08
9	0.3	0.090	4.2	0.018	0.06
The above temporary bins expire in 2006 (for LDVs and LLDTs) and 2008 (for HLDTs).					
8	0.20	0.125	4.2	0.018	0.02
7	0.15	0.090	4.2	0.018	0.02
6	0.10	0.090	4.2	0.018	0.01
5	0.07	0.090	4.2	0.018	0.01
4	0.04	0.070	2.1	0.011	0.01
3	0.03	0.055	2.1	0.011	0.01
2	0.02	0.010	2.1	0.004	0.01
1	0.00	0.000	0.0	0.000	0.00



Appendix Figure 1: A comparison of the chassis dynamometer drive traces for a typical FTP test (top) and an FTP with two complete runs of the Urban Dynamometer Driving Schedule (UDDS) (bottom).