

Development of a Synthetic Diesel Exhaust

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ABSTRACT

A two-phase study was performed to establish a standard diesel exhaust composition which could be used in the future development of light-duty diesel exhaust aftertreatment. In the first phase, a literature review created a database of diesel engine-out emissions. The database consisted chiefly of data from heavy-duty diesel engines; therefore, the need for an emission testing program for light- and medium-duty engines was identified. A second phase was conducted to provide additional light-duty vehicle emissions data from current technology vehicles. Engine-out diesel exhaust from four 2004 model light-duty vehicles with a variety of engine displacements was collected and analyzed. Each vehicle was evaluated using five steady-state engine operating conditions and two transient test cycles (the Federal Test Procedure and the US06). Regulated emissions were measured along with speciation of both volatile and semi-volatile components of the hydrocarbons. The results from the literature search and the engine-out emissions data were used to suggest a possible synthetic diesel exhaust formulation.

INTRODUCTION

Diesel exhaust emissions have come under increasing public scrutiny in the United States and abroad. In an effort to reduce the exhaust emissions from diesel engines, various forms of aftertreatment have become important technologies in helping to achieve lower emission levels. Since diesel exhaust has cooler exhaust temperatures relative to gasoline spark-ignited engines, leaner operation, and exhaust concentrations of oxides of nitrogen (NO_x) and particulate without the presence of a higher concentration of hydrocarbons; diesel exhaust aftertreatment cannot utilize standard gasoline aftertreatment technologies such as the three-way catalyst. Therefore, alternative methods must be sought to evaluate and develop these potential diesel aftertreatment technologies.

To establish a standard diesel exhaust composition, the first step was to develop a specification based on data from a variety of diesel engines and fuels. A literature review was performed to create a database of diesel engine-out emissions.[1] Based on this literature search, additional data was needed for current-technology light-duty diesel vehicles. Light-duty engine-out diesel

exhaust was collected and analyzed to determine the exhaust composition from four light-duty vehicles.[2] These vehicles were tested at a variety of conditions to collect information in order to suggest a standard diesel exhaust composition.

SCOPE OF WORK

For the emissions testing, four vehicles were selected for testing. These vehicles included:

- 2004 Chevrolet Silverado 2500HD with a 6.6 L Duramax diesel engine
- 2004 Ford F-350 with a 6.0 L Powerstroke (International) V8 turbodiesel engine
- 2004 Dodge Sprinter passenger van with a 2.7 L Mercedes-Benz in-line 5 cylinder engine
- 2004 Volkswagen Jetta with a 1.9 L TDI engine

These vehicles were tested over five steady-state engine operating conditions:

- Rated speed at 75 percent torque
- Rated speed at 50 percent torque
- Peak torque speed at 50 percent torque
- Peak torque speed at 25 percent torque
- Idle

and two transient test cycles: the Federal Test Procedure (FTP) and the US06 (an aggressive driving cycle) were selected to produce a range of operating conditions expected to show differences in engine-out exhaust composition. Each vehicle had at least 3100 km of vehicle operation and was tested for engine-out emissions only. The existing exhaust aftertreatment systems on the Ford, Dodge, and Volkswagen were replaced with exhaust tubing and a damper was used to simulate the exhaust restriction. In addition, the lubricating oil was not changed prior to testing.

Regulated emissions (total hydrocarbons - THC, carbon monoxide - CO, NO_x , and total particulate) as well as carbon dioxide (CO_2) were measured during each test. These emissions were analyzed according to CFR Title 40 specifications.[3] In addition to the regulated emissions, a number of hydrocarbons were characterized by speciating the volatile and semi-volatile hydrocarbons. Analytical procedures for conducting the speciation of volatile hydrocarbons (C_1 to C_{12})

hydrocarbons, aldehydes and ketones) were similar to the CRC Auto/Oil Phase II methods and were adapted for use with diesel exhaust.[4,5] Exhaust emissions samples were analyzed for the presence of more than 200 different volatile exhaust species. Measurement of the semi-volatile hydrocarbons included C₁₀ to C₂₂ hydrocarbons.

Fuel Selection

The test fuel was selected to meet average United States fuel composition and properties projected for use in 2007 diesel engines according to the Code of Federal Regulations (CFR) Title 40, Part 86, Subpart B.[3] Specifications for 2007 certification fuel, and commercial fuel, as well as the properties for the test fuel are shown in Table 1.

TABLE 1. 2007 FUEL SPECIFICATIONS AND PROPERTIES

Property	Certification Specifications[3]	Commercial Specifications	Test Fuel
Cetane Number	40-50	38-58	45.4
Cetane Index	40-50	40 min.	ND ^a
Gravity, °API	32-37	30-39	34.5
Total sulfur, ppm	15 max.	15 max.	6.9
Aromatics, % min.	27	NA ^b	35.8
Flashpoint, °C min.	54.4	54.4	80
Boiling Point Distribution			
Initial, °C	171.1-204.4	NA	194
10 %, °C	204.4-237.8	NA	227
50 %, °C	243.3-282.2	NA	266
90 %, °C	293.3-332.2	282.2-332.2	320
End Point, °C	321.1-365.6	NA	346
^a ND – not determined			
^b NA – Not applicable			

Regulated Emissions

Four vehicles were each tested with the FTP, US06, and five steady-state modes. The regulated emissions obtained during testing with the transient cycles and with the five steady-state modes are presented in Tables 2 and 3, respectively. Mass rates are presented in g/km for the transient cycles, and in g/min for the steady-state modes.

A comparison of the regulated emissions was made for the literature and actual test data. In this group of emissions, only carbon monoxide is composed of a single compound. THC is composed of unburned or partially burned fuel and oil and is present at relatively low concentrations. A detailed examination of the THC allows the selection of a simpler mixture of individual compounds to represent this complex mixture of compounds. In the case of NO_x, the NO_x is a mixture of nitric oxide (NO) and nitrogen dioxide (NO₂), with NO being the major constituent. Particulate is a complex mix of particles and condensed semi-volatiles. It is

composed primarily of carbon and hydrogen; however, particulate also contains sulfate/sulfuric acid, water, absorbed or condensed hydrocarbons, and inorganic ash components. To simplify the results and allow comparisons to the literature data, emissions from each vehicle and test condition were combined and weighted equally. Different results may be obtained if different weightings are utilized.

TABLE 2. TRANSIENT CYCLE EMISSIONS SUMMARY

Transient Cycles	Emissions, g/km				
	THC	CO	NO _x	Particulate	CO ₂
Chevrolet Silverado					
Cold UDDS	0.29	1.7	3.8	0.09	513
Hot UDDS	0.28	1.2	3.8	0.07	478
Composite FTP	0.29	1.4	3.8	0.08	493
US06	0.14	0.9	4.0	0.10	518
Ford F-350					
Cold UDDS	0.43	2.1	3.4	0.08	496
Hot UDDS	0.39	1.4	2.3	0.06	447
Composite FTP	0.41	1.7	2.8	0.07	469
US06	0.19	0.9	2.3	0.04	479
Dodge Sprinter Van					
Cold UDDS	0.23	1.1	1.6	0.07	340
Hot UDDS	0.22	0.9	1.6	0.09	359
Composite FTP	0.22	1.0	1.6	0.08	351
US06	0.16	0.7	1.7	0.14	447
Volkswagen Jetta					
Cold UDDS	0.40	1.8	0.1	0.09	154
Hot UDDS	0.25	1.4	0.1	0.15	145
Composite FTP	0.32	1.6	0.1	0.12	149
US06	0.07	0.9	0.6	0.07	162

TABLE 3. STEADY-STATE EMISSIONS SUMMARY

Steady-State Mode		Emissions, g/min				
Speed, rpm	Percent Torque	THC	CO	NO _x	Particulate	CO ₂
Chevrolet Silverado						
3100	75	0.34	3.2	8.6	0.47	2107
3100	50	0.42	2.0	7.3	0.39	1046
1800	50	0.17	1.0	5.6	0.07	627
1800	25	0.35	3.4	2.1	0.07	226
Idle		0.10	0.2	0.6	0.02	54
Ford F-350						
3300	75	0.57	2.0	9.0	0.39	1977
3300	50	0.60	2.1	4.5	0.25	1407
2000	50	0.31	0.7	3.7	0.06	827
2000	25	0.35	1.2	2.0	0.06	411
Idle		0.08	0.3	0.6	0.02	74
Dodge Sprinter Van						
3800	75	0.38	3.3	3.6	0.20	1170
3800	50	0.77	4.1	2.1	0.14	788
1600	50	0.17	0.5	0.6	0.05	164
1600	25	0.18	0.5	0.3	0.03	59
Idle		0.05	0.2	0.4	0.01	32
Volkswagen Jetta						
4000	75	0.18	0.6	1.0	0.10	384
4000	50	0.16	0.6	3.7	0.08	384
1800	50	0.05	0.5	2.4	0.09	325
1800	25	0.05	0.3	1.2	0.03	23
Idle		0.04	0.2	0.1	0.01	23