Update on Phase 1 of the Advanced Collaborative Emissions Study (ACES Phase 1)

by

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In 2007, US on-highway heavy-duty diesel engines (HDDE) were required to meet a particulate matter (PM) emission standard of 0.01 g/hp-hr, a 90 percent reduction from the previous level established in 1994. The nitrogen oxides (NO_x) level in 2007 was limited to 1.5 to 1.2 g/hp-hr, a 37 to 50 percent reduction from the 2004 NO_x standard. In 2007, HDDE were equipped with filtered crankcase ventilation, exhaust gas recirculation (EGR) or clean gas induction (CGI), and high efficiency catalyzed diesel particulate filters (DPF) with some means of active regeneration.

With all these changes to on-highway diesel engines, it was important to perform a detailed exhaust emission characterization as called for in ACES Phase 1 in order:

- to quantify the significant reduction in both regulated and unregulated emissions that can be achieved by advanced diesel engines, and
- to help conduct a meaningful health effects study as planned under Phase 3 of the ACES using the most current information and in consideration of issues identified from ACES Phase 1.

ACES Phase 1 focused on the measurement and characterization of regulated emissions and as many as 700 compounds of unregulated emission species present in the exhaust of four modern (model year 2007) HDDE. The engines were supplied by four major engine manufacturers that include Caterpillar, Cummins, Detroit Diesel, and Volvo, and the 2007 engine lube oil was provided by Lubrizol. Engine testing under ACES Phase 1 was recently completed and data analysis is currently underway. At the conclusion of the data analysis for all four engines, one engine will be selected, based on a defined statistical criterion, for a detailed health study at the Lovelace Respiratory Research Institute, under Phase 3 of the ACES.

The federal test procedure (FTP) transient cycle, two CARB cycles, and one 16-hour transient cycle, developed to be used for the health study, were used for emissions characterization from all four engines. Regulated emissions of NO_x, carbon monoxide (CO), non-methane hydrocarbons (NMHC), and PM were measured in accordance with EPA code of federal regulations Part 1065. Unregulated emission species such as particle size and number, organic carbon, elemental carbon, elements, nitrogen dioxide (NO_2), nitrous oxide (N_2O), volatile and semivolatile hydrocarbons, carbonyls, nitrosamines, polycyclic aromatic hydrocarbons (PAH), nitro-PAH, and dioxins/furans were all measured using best established measurement and analytical techniques.

ACES Phase 1 will provide a unique and very essential database on regulated and unregulated emissions from modern on-highway HDDE. The data acquired from each of the engines in ACES Phase 1 will be used to select an engine suitable for animal testing in Phase 3 of the ACES. The final report on ACES Phase 1 is scheduled to be released in March, 2009.

ACES Phase 1 is sponsored by the Coordinating Research Council and the Health Effects Institute. Funding for the ACES has been provided by the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), the California Air Resources Board (CARB), the American Petroleum Institute (API), the Engine Manufacturers Association (EMA), and Manufacturers of Emissions Control Equipment (MECA).

ACES Phase 1 was performed by Southwest Research Institute in collaboration with Desert Research Institute.

The poster presented below contains some background information about the ACES Phase 1 project. It also contains results on regulated emissions for the FTP transient cycle and the 16-hour transient cycle, with some limited information on unregulated emissions species such as NO_2 and particle number.

In brief, all engines met the regulatory limit on NOx. NMHC, CO, and PM were substantially lower than the regulatory limit. NO_2 to NOx ratio was high, and it ranged from 0.30 to 0.65, depending on the engine technology used. Total particle number was generally low, except during DPF regeneration events.

More detailed information about this project will be available in the final report and in future publications.

Update on Phase 1 of the Advanced Collaborative Emissions Study (ACES Phase 1)

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Background

▪In 2007, US on-highway heavy-duty diesel engines (HDDE) were required to meet a particulate matter (PM) emission standard of 0.01 g/hp-hr, a 90 percent reduction from the previous level established in 1994. The nitrogen oxides (NOx) level in 2007 was limited to 1.2 g/hp-hr, a 50 percent reduction from the 2004 NOx standard.

▪In 2007, HDDE were equipped with:
- ✓Filtered crankcase ventilation,
- ✓Exhaust gas recirculation (EGR) or clean gas induction (CGI)and
- ✓High efficiency catalyzed diesel particulate filters (DPF) with some means of active regeneration.

▪With all these changes to on-highway diesel engines, it was important to perform a detailed exhaust emission characterization as called for in the ACES Phase 1 in order:
- ✓to quantify the significant reduction in both regulated and unregulated emissions that can be achieved by advanced diesel engines, and
- ✓to help conduct a meaningful health effects study as planned under Phase 3 of the ACES using the most current information and in consideration of issues identified from ACES Phase 1.

▪ACES Phase 1 focused on the measurement and characterization of:
- ✓Regulated emissions
- ✓Particle Number and Size
- ✓Up to 795 compounds of unregulated emission species

▪The engines were supplied by four major engine manufacturers that include Caterpillar, Cummins, Detroit Diesel, and Volvo Powertrain

▪2007 engine lube oil was provided by Lubrizol.

▪The fuel was an EPA compliant ultra low sulfur diesel (ULSD) fuel

▪Engine testing under ACES Phase 1 was completed in February, 2008.

▪After completing the data analysis for all four engines, one engine will be selected, based on a defined statistical criterion, for a detailed health study at the Lovelace Respiratory Research Institute, under Phase 3 of the ACES.

▪ACES Phase 1 is sponsored by the Coordinating Research Council and the Health Effects Institute.
- ✓Funding for the ACES has been provided by the:
  - ✓ U.S. Department of Energy (DOE)
  - ✓U.S. Environmental Protection Agency (EPA)
  - ✓California Air Resources Board (CARB)
  - ✓American Petroleum Institute (API)
  - ✓Engine Manufacturers Association (EMA)
  - ✓Manufacturers of Emissions Control Equipment.

▪ACES Phase 1 was performed by Southwest Research Institute in collaboration with Desert Research Institute.

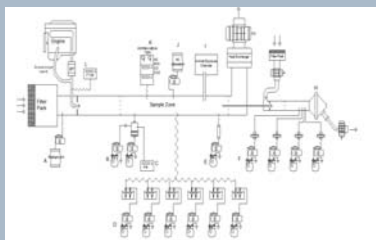
Series 60 by Detroit Diesel

MP7 by Volvo Powertrain

C13 by Caterpillar

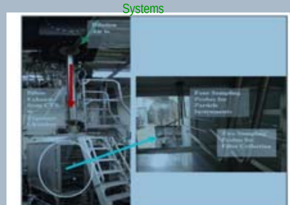
ISX by Cummins

Experimental Setup



A Background bag sample of dilution air for HC, CO, CO_2, NO_x, lHC
B Double Dilution for PM, 47mm 2007 System with Standard Residence Time
C Regulated PM Following CFR Part 1065
D Impingers: carbonyls and alcohols
E Sorbent traps for nitrosamines, hazardous air pollutant compounds
F Auxiliary PM samples on 47 mm Fluoropore filters and impingers for elements, ions, inorganic acids, pH, cyanide, mercury (only if previously found in fuel), hexavalent chromium, SO_2
G XAD traps for semi-volatile compounds: PAH, N-PAH, , hopanes, steranes, carpanes, polar organics, high molecular weight alkanes and cycloalkanes, etc.
H Filter (8x10-inch Zefluor) for particulate-phase semi-volatile compounds: PAH, N-PAH, dioxins, hopanes, steranes, carpanes, polar organics, high molecular weight alkanes and cycloalkanes, etc.
I Animal Exposure Chamber (No Animals Present): PM mass using Teflo filter, size and number using EEPS, real time PM using DMM-230, and OC/EC collection using a pair of quartz filters will be taken from this chamber. The connection between the chamber and the full flow CVS will have a similar setup to that between the CVS and the 8 by 10 inch filter.
J Proportional bag sample for hydrocarbon speciation of C_1 through C_{12} compounds
K Horiba MEXA 7200 for THC, CO, CO_2, NO_x; Secondary NO_x analyzer in NO mode for determining NO_2 by difference
L FTIR for nitrogen compounds

Engine Experimental Setup and Sampling Systems



Animal Exposure Chamber (Same as the ones that will be used at Lovelace) for Sampling Different Exhaust species

High Volume Sampling for PAH, N-PAH, Oxy-PAH, and Dioxins/Furans

Experimental Test Matrix

Cycle	Regulated Pollutants	Unregulated
Hot-Start FTP	3	*
Mode 1 (rated speed, 100 % load)	3	*
Mode 3 (rated speed, 50 % load)	3	*
Mode 5 (peak torque speed, 100 % load)	3	*
Cold-Start FTP	1	*
Hot-Start FTP	6†	6†
Composite CARB HHDDE Cycle Mode 1, 2, and 5 (creep, transient, and idle)	2	2
Composite CARB HHDDE Cycle Mode 3 and 4 (cruise and high-speed cruise)	2	2
16-Hour Transient Cycle	3	3
Tunnel Blanks‡	3	3
Tunnel Background Dilution Air		1†

*Only real time particle size, number, total mass, solid mass, and semi-continuous OC will be performed for these modes of engine operation
†Three hot-start FTP runs with blow-by and three without blow-by
‡One tunnel blank after cleaning CVS tunnel but before running the engine (only one time after tunnel cleaning). A second tunnel blank after finishing the six hot-start FTP runs, which is also before starting the CARB composite modes. A third tunnel blank after finishing the CARB composite modes but before the 16-hour transient cycle. A fourth tunnel blank after finishing the 16-hour transient cycle.
†one 16 hour tunnel background collection using 8 x 10 inch filter plus XAD

The Test Matrix includes three repeats of several transient engine tests, including a 16-hour transient cycle that will be used in Phase 3 of ACES (Health Study)

Measured Gas and Particle Phase Exhaust Species

Parameter: Analytical Method(s)	Media	FTP Hot Start	CARB HHDDE Mode 1	CARB HHDDE Mode 2	CARB HHDDE Mode 3	CARB HHDDE Mode 4	CARB HHDDE Mode 5	16-hr Transient Cycle	Tunnel Blanks*	Total
Total Hydrocarbon (THC)	Per CFR Part 1065	3	2	2	2	2	2	1	3	17
Oxides of Nitrogen (NOx)	Per CFR Part 1065	3	2	2	2	2	2	1	3	17
Carbon Monoxide (CO)	Per CFR Part 1065	3	2	2	2	2	2	1	3	17
Particulate Matter (PM)	Per CFR Part 1065	3	2	2	2	2	2	1	3	17
NO2	Chemiluminescent	3	2	2	2	2	2	1	3	17
N2O	FTIR	3	2	2	2	2	2	1	3	17
OC/EC	Quartz	3	2	2	2	2	2	1	3	17
Particle Size and Number	EEPS	3	2	2	2	2	2	1	3	17
Metals, elements, ICP-MS	Fluoropore filter + DI Water Impinger	3	2	2	2	2	2	1	3	17
[illegible]	Fluoropore filter	3	2	2	2	2	2	1	3	17
Inorganic ions and acids, IC	Fluoropore filter + DI Water Impinger	3	2	2	2	2	2	1	3	17
[illegible]	DI Water Impinger	3	2	2	2	2	2	1	3	17
[illegible]	KOH Impinger	3	2	2	2	2	2	1	3	17
[illegible]	H2O2 Impinger	3	2	2	2	2	2	1	3	17
Gas phase hydrocarbons [illegible] GC-FID	Tedlar Bag	3	2	2	2	2	2	1	3	17
Carbonyl compounds,* HPLC-UV	DNPH Impinger	3	2	2	2	2	2	1	3	17
Alcohols,* GC-FID	DI Water Impinger	3	2	2	2	2	2	1	3	17
Dioxins and Furans, HRGC/HRMS	Zefluor Filter + XAD Cartridge	0	0	0	0	0	0	1	1	2
Hazardous Air Pollutant Compounds GC/MS	Tenax Cartridge	3	2	2	2	2	2	1	3	17
PAH, GC/MS	Zefluor Filter + XAD Cartridge	3	2	2	2	2	2	1	3	17
nitro-PAH, GC/MS		3	2	2	2	2	2	1	3	17
Hopanes/Steranes/Carpanes, GC/MS		3	2	2	2	2	2	1	3	17
Alkanes, Alkenes, Alkynes, (Cyclic and branched) [illegible] GC/MS		3	2	2	2	2	2	1	3	17
Polar compounds, Oxygenated PAH, Organic Acids, GC/MS		3	2	2	2	2	2	1	3	17
Nitrosamines, GC/MS	Thermosorb	3	2	2	2	2	2	1	3	17

Regulatory Limits

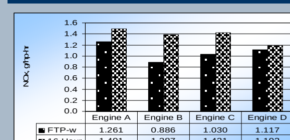
Regulated emissions from heavy-duty diesel engines are typically reported in unit mass divided by the work produced by the engine. E.g. g/hp-hr.

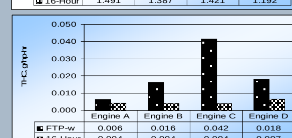
The US regulatory limits for 2007-2009 are as follows:

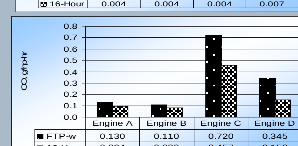
NOx	NMHC	CO	PM
g/hp-hr			
~1.2-1.5	0.14	15	0.01

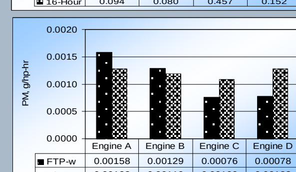
The NOx limit for 2010 and beyond is reduced to 0.20 g/hp-hr.

Results

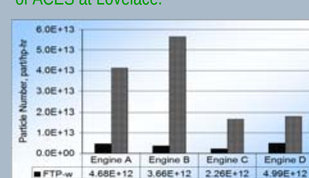








All engines met the regulatory emissions limit for the FTP and for the 16-hour transient cycle that will be used in Phase 3 of ACES at Lovelace.



The particle number emissions for the 16-hour cycle is different from engine to engine, depending on the DPF regeneration strategy implemented by each engine manufacturer.

Average Exposure Chamber Concentration for the 16-hour Cycle

Engine A

DR	NOx [ppm]	NO2 [ppm]	THC [ppm]	BGTHC [ppm]	CH4 [ppm]	BGCH4 [ppm]	CO [ppm]	CO2 [%]	EEPS [µg/m³]	EEPS [part/cm³]
37.79	8.60	5.40	3.66	3.80	2.00	1.98	1.54	0.39	22.81	4.84E+05
44.71	8.98	5.62	4.06	4.46	1.55	1.62	1.65	0.39	20.03	4.22E+05
39.85	9.11	5.97	3.46	3.63	1.61	1.59	1.53	0.39	23.22	4.64E+05

Engine B

DR	NOx [ppm]	NO2 [ppm]	THC [ppm]	BGTHC [ppm]	CH4 [ppm]	BGCH4 [ppm]	CO [ppm]	CO2 [%]	EEPS [µg/m³]	EEPS [part/cm³]
35.37	8.59	5.63	3.78	3.92	2.15	1.50	1.29	0.40	10.57	5.27E+05
35.44	8.15	5.43	3.97	4.17	2.24	2.23	1.37	0.41	12.68	7.60E+05
31.17	8.37	5.35	4.40	4.83	2.89	2.63	1.63	0.42	14.99	7.40E+05

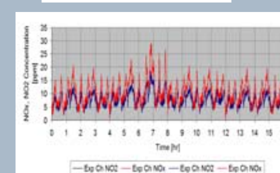
Engine C

DR	NOx [ppm]	NO2 [ppm]	THC [ppm]	BGTHC [ppm]	CH4 [ppm]	BGCH4 [ppm]	CO [ppm]	CO2 [%]	EEPS [µg/m³]	EEPS [part/cm³]
44.40	8.47	3.67	3.91	4.27	2.23	1.75	4.58	0.36	9.71	2.08E+05
40.97	7.95	2.89	4.60	4.82	2.42	2.52	5.10	0.36	8.86	2.44E+05
41.26	8.37	2.53	4.20	4.08	2.04	1.80	4.75	0.36	3.68	1.11E+05

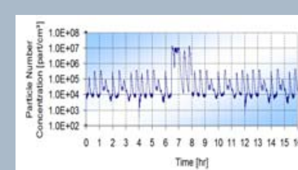
Engine D

DR	NOx [ppm]	NO2 [ppm]	THC [ppm]	BGTHC [ppm]	CH4 [ppm]	BGCH4 [ppm]	CO [ppm]	CO2 [%]	EEPS [µg/m³]	EEPS [part/cm³]
48.07	7.79	3.71	3.76	3.87	2.17	2.15	2.19	0.40	9.89	3.12E+05
47.45	7.87	3.74	4.06	4.14	2.56	2.59	2.48	0.41	3.02	2.78E+05
47.17	7.80	3.54	4.00	4.22	2.36	2.28	2.06	0.40	7.42	3.02E+05

NOx and NO2 Concentration Profile for the 16-hour cycle



Particle Number Concentration Profile for the 16-hour cycle



Summary

•Unregulated emissions data are currently under review. More data will be reported before the end of 2008.

•Regulated emissions such as THC, CO, and PM were much lower than the regulatory limits.

•NO_x met the regulatory limit, but the NO_2 to NO_x ratio ranged from 0.30 to 0.65 during the 16-hour transient cycle, depending on the engine technology.

•Exhaust particle number concentrations were generally low, except during DPF regeneration.

Program Schedule, 2007, 2008, and 2009