Advanced Collaborative Emissions Study (ACES)

Cooperative multi-party effort to characterize emissions and possible health effects of new advanced heavy duty engine and control systems and fuels in the market 2007 – 2010.

DOE Merit Review June 2013

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ID # ACE044

NETL Agreement 13919

PROJECT OVERVIEW

Phases:

1. 2007 Engine Emissions Characterization (Southwest Research Institute (SWRI®))
   - *CRC Technical Leader*
2. 2010 Engine Emissions Characterization
   - *CRC Technical Leader*
3. 2007/2010 Engine Health Effects Testing (Lovelace Respiratory Research Institute (LRRI)
   - *Short Term biological screening and Long-Term Health Effects Test on 2007 Engines*
   - *HEI Technical Leader; CRC Technical Monitor*

Funding

Overall Project: $15.5 million

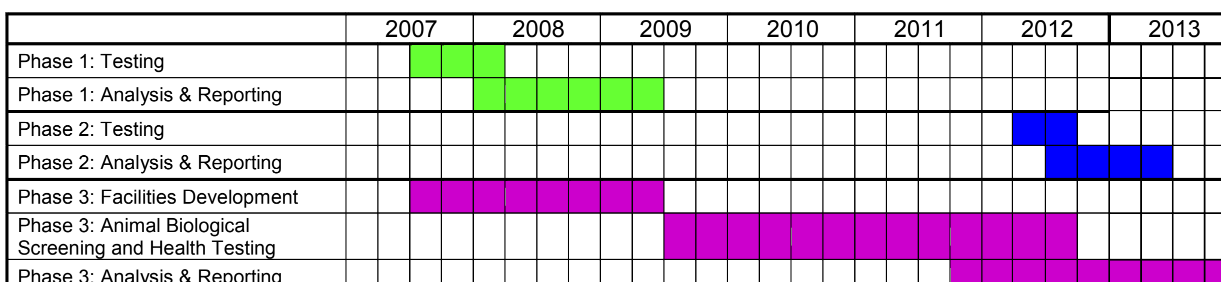
- Total DOE Contract: $5.95 million (Contractor Share: $3.98 million)
  - FY 11 DOE Funding: $500,000
  - FY 12 DOE Funding: $500,000 (Planned)

Partners

- DOE OVT and NETL
- Engine Manufacturers Association (EMA)
- US Environmental Protection Agency (EPA)
- California Air Resources Board (ARB)
- American Petroleum Institute (API)
- After-treatment Manufacturers
- Coordinating Research Council (CRC)

Overall Project Timeline

Phase 2 Completed



RELEVANCE:
Evaluating Emissions of Advanced Technology Diesels

- *DOE OVT MYPP Advanced Combustion R and D*: New Generation diesel engines are highly fuel efficient and a likely significant contributor to enhanced fuel economy for the next 15 – 20 years IF they gain wide acceptance
- The combination of advanced-technology, compression-ignition engines, aftertreatment systems, reformulated fuels and reformulated oils developed to meet the 2007/2010 emission standards will result in substantially reduced emissions.
- Substantial public health benefits and enhanced public acceptance and use are expected from these reductions.
- ***Key reviews of diesel and cancer at International Agency for Research on Cancer (IARC) and U.S. National Toxicology Program***
- With any new technology it is prudent to conduct research to confirm benefits and to ensure that there are no adverse impacts to public health and welfare.

Overall Objective

- *to characterize emissions and possible health effects of new advanced heavy duty engine and control systems and fuels in the market 2007 – 2010*

COLLABORATION WITH CRC, OTHERS

HEI ACES Oversight Committee

Mark Utell, Chair	University of Rochester	Eugene McConnell	Consultant, Former NTP Director
Ken Demerjian	SUNY Albany	Gunter Oberdorster	University of Rochester
Helmut Greim	Technical University of Munich	Charles Plopper	University of California, Davis
Uwe Heinrich	Fraunhofer Institute	Howard Rockette	University of Pittsburgh
David Kittelson	University of Minnesota	James Swenberg	University of North Carolina, Chapel Hill

CRC ACES Panel

Reynaldo Agama	Caterpillar, Inc.	Jeff Marley	Volvo
Ewa Bardasz	Lubrizol Corporation	Mani Natarajan	Marathon Petroleum Company LP
Maria Costantini	Health Effects Institute	Ralph Nine	National Energy Technology Laboratory
Christopher Dea	Caterpillar, Inc.	Jeff Shaffer	Volvo Powertrain North America
Dominic DiCicco	Ford Motor Company	Rashid Shaikh	Health Effects Institute
Timothy A. French	Engine Manufacturers Association	Shirish Shimpi	Cummins Engine Company
Rob Graze	Caterpillar, Inc.	Joseph H. Somers	US Environmental Protection Agency
Thomas D. Hesterberg	Navistar, Inc.	Chris Tennant	Coordinating Research Council
Donald Keski-Hynnila	Detroit Diesel Corporation	Steven S. Trevitz	Volvo Powertrain North America
Dan Kieffer	Paccar Inc.	Annemoon van Erp	Health Effects Institute
Ed Kulik	Ford Motor Company	Timothy Wallington	Ford Motor Company
Chris Laroo	US Environmental Protection Agency	Matt Watkins	ExxonMobil Research & Engineering
Hector Maldonado	California Air Resources Board	Andre Welch	Ford Motor Company
M. Matti Maricq	Ford Motor Company	Ken Wright	ConocoPhillips

ACES Phase I – 2007 Engines

APPROACH

- Quantify the significant reduction in both regulated and unregulated emissions from advanced diesel engines
- Provide regulated and unregulated emissions for this new engine technology,
- Provide initial guidance for ACES Phase 3 health study using the regulated and unregulated emissions information from ACES Phase 1
- Heavy Heavy Duty (Class 8) Engines from: Caterpillar, Cummins, Detroit Diesel, and Volvo

RESULTS

- Regulated PM, CO, and NMHC emissions were at least 90% below the 2007 standard, and NO_x was 10% below standard
- Most ***unregulated emissions at least 90% below 2004 technology***
- Average NO_2 emission of 0.68 g/hp-hr was 2 to 7 times higher than the emissions from 2004 engines
  - However, 2010 engine technology NO_x limit of 0.20 g/hp-hr will force NO_2 emissions to be substantially lower than both 2007 and 2004 technology engines
- ***Particle number emissions <u>average</u> was at least 90% below 2004 technology engines***, even when DPF regeneration occurred
- ***Elemental carbon represented only 7 % of total PM mass***, and the hydrated sulfuric acid determined from measured sulfate was the dominant PM component for the 16-Hour Cycle, 70 percent of total PM mass
- Comprehensive final report issued June 30, 2009; ***JAWMA Paper April 2011***
  - Khalek IA, Bougher TL, Merritt PM, Zielinska B. 2011 Regulated and Unregulated Emissions from Highway Heavy-Duty Diesel Engines Complying with U.S. Environmental Protection Agency 2007 Emissions Standards J. Air & Waste Manage. Assoc. 61:427–442

ACES PHASE 2: APPROACH AND OBJECTIVES
2010 Compliant Engines

- 2010 engines offer substantial improvements in NOx emissions
- Phase 2, now completed, is conducting Emissions Characterization
- Engines were prepared (degreened) by three manufacturers and delivered to SwRI in Fall 2012
- SwRI completed emissions testing in December 2012
- Final reporting on Phase 2 characterization study anticipated in Spring 2013

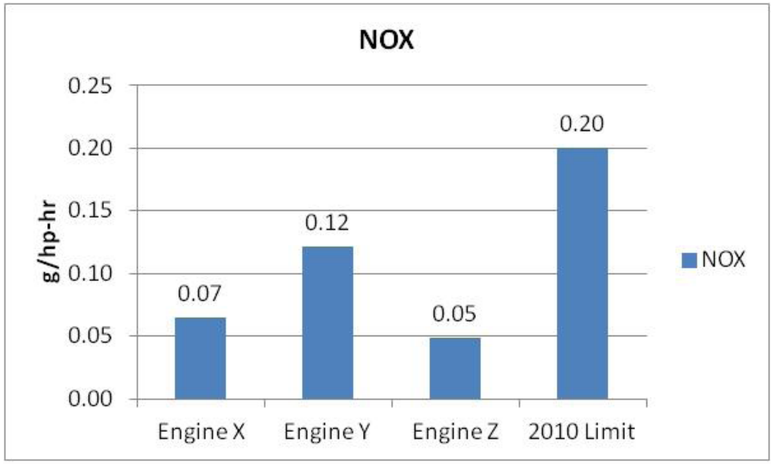
PHASE 2:(2010) ENGINES

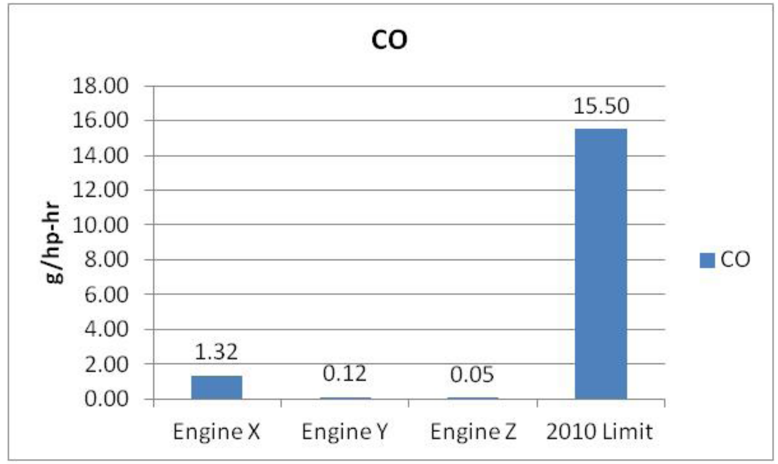
Engine Series	ISX	DD15®	MP8-415C
Manufacturer	Cummins	Detroit Diesel	Volvo Powertrain
Emissions Compliance	2010	2010	2010
Model year	2011	2011	2011
Displacement, liter	15	15	13
Rated Power, hp	500	455	415
Exhaust System	Turbocharged	Turbocharged	Turbocharged
Induction System	Compressed/Air to Air Cooled	Compressed/Air to Air Cooled	Compressed/Air to Air Cooled
Exhaust Configuration	(DOC+DPF)+SCR + AMOX	(DOC+DPF)+SCR + AMOX	(DOC+DPF)+SCR + AMOX
Blow-By Configuration	Separator/Vented to Atmosphere	Separator/Vented to Atmosphere	Separator/Vented to Atmosphere
SCR Exhaust Fluid	Urea	Urea	Urea
DPF Active Regneration Exhaust Fluid	Diesel	Diesel	Diesel

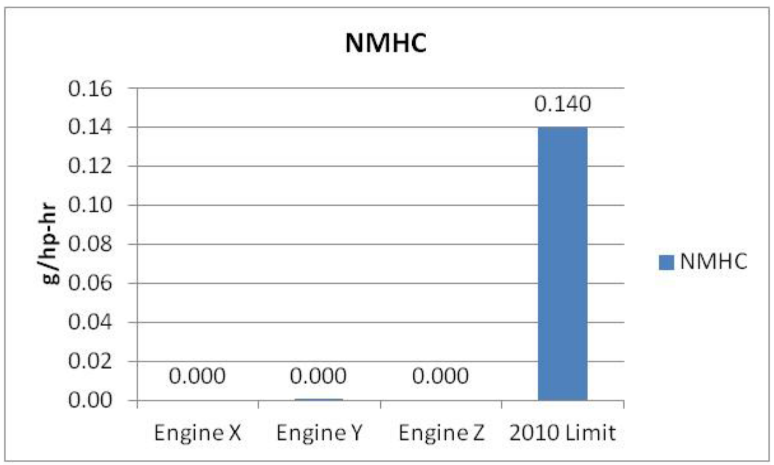
Engines (randomized) will be referred to as Engine X, Engine Y, and Engine Z

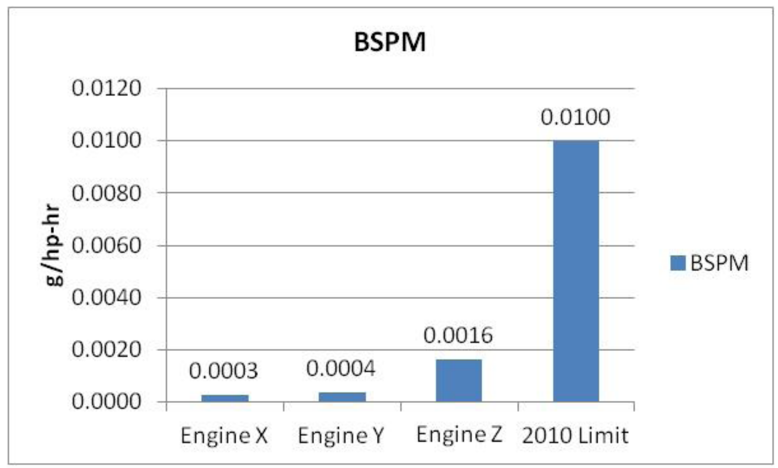
DOC: Diesel Oxidation Catalyst; DPF: Diesel Particulate Filter; SCR: Selective Catalytic Reduction Catalyst; AMOX: Ammonia Slip Catalyst

PHASE 2: REGULATED EMISSIONS





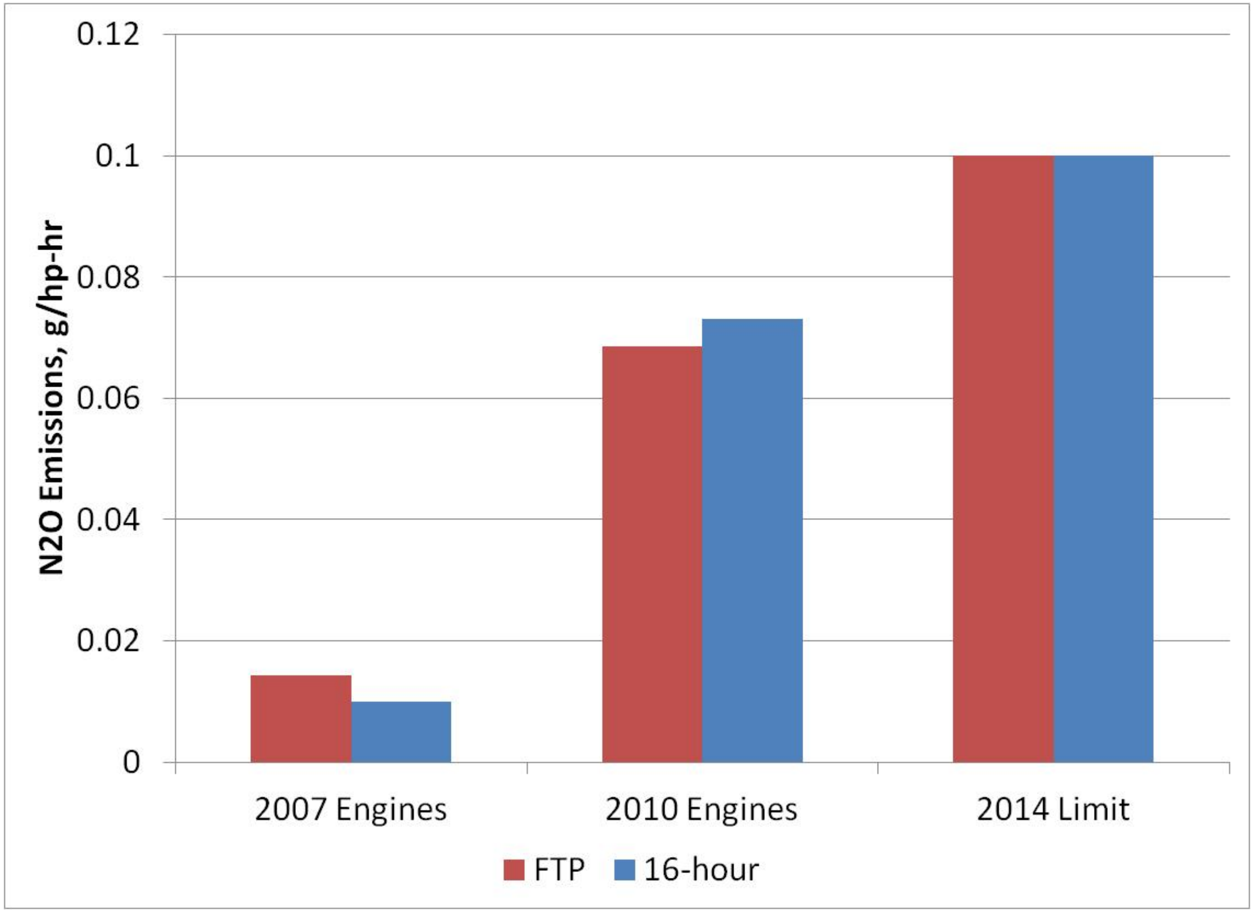




Emissions from all three engines were substantially lower than the 2010 standard

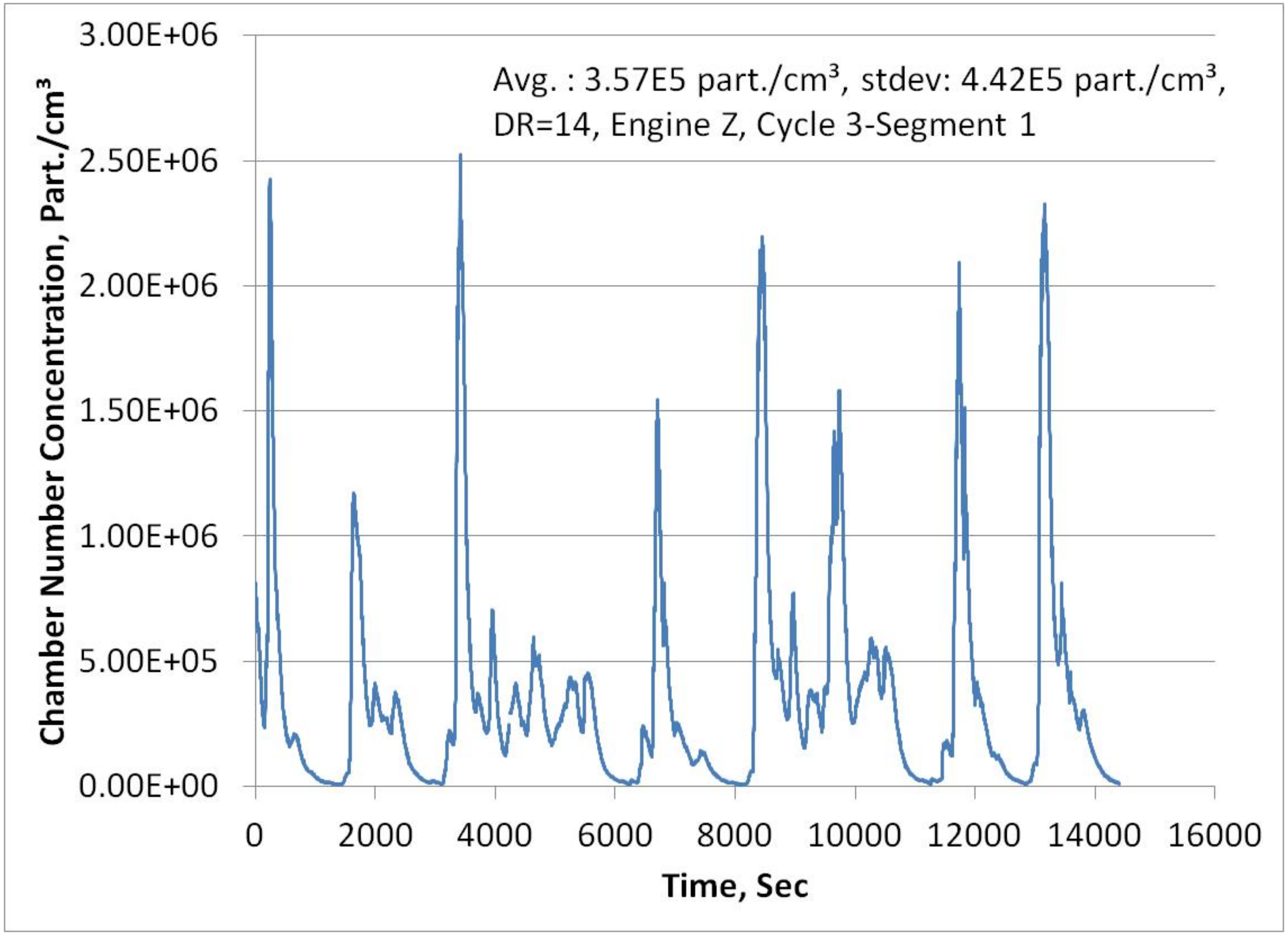
PHASE 2: N_2O EMISSIONS

- N_2O emissions increased with the 2010 engines vs. 2007, but still 26% to 31% below the 2014 EPA emissions limit



Standard based on FTP cold/hot composite. Data above based on hot-start only.

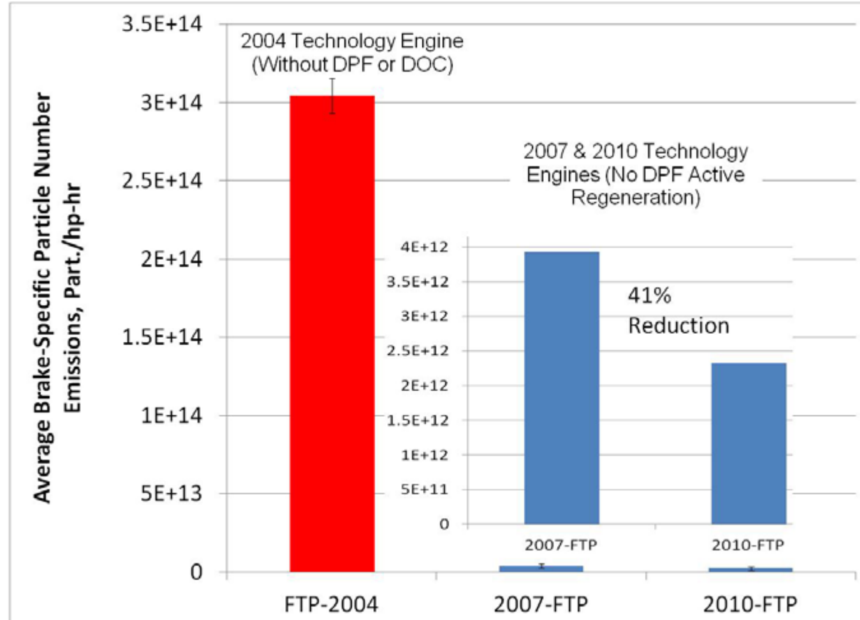
PHASE 2: EXAMPLE - PARTICLE NUMBER



Engine Z, 3rd 16-hour cycle, 1st 4-hour segment (hot-start)

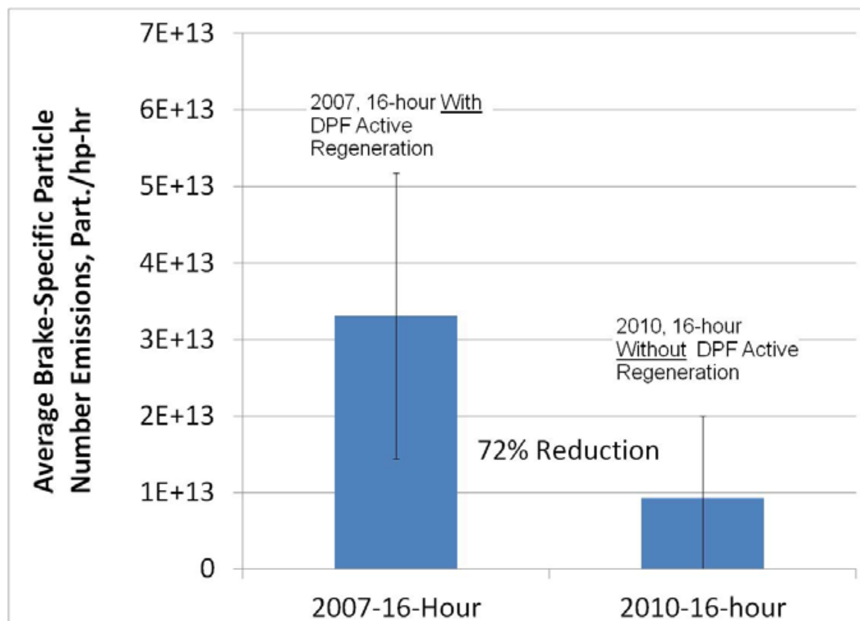
PHASE 2: TOTAL PARTICLE NUMBER

• 2010 FTP Particle Number was 41% & 99% below 2007 and 2004 technology engines, respectively



• DPF active regeneration frequency with 2007 technology engines was 1 to 3 times per 16-hour cycle

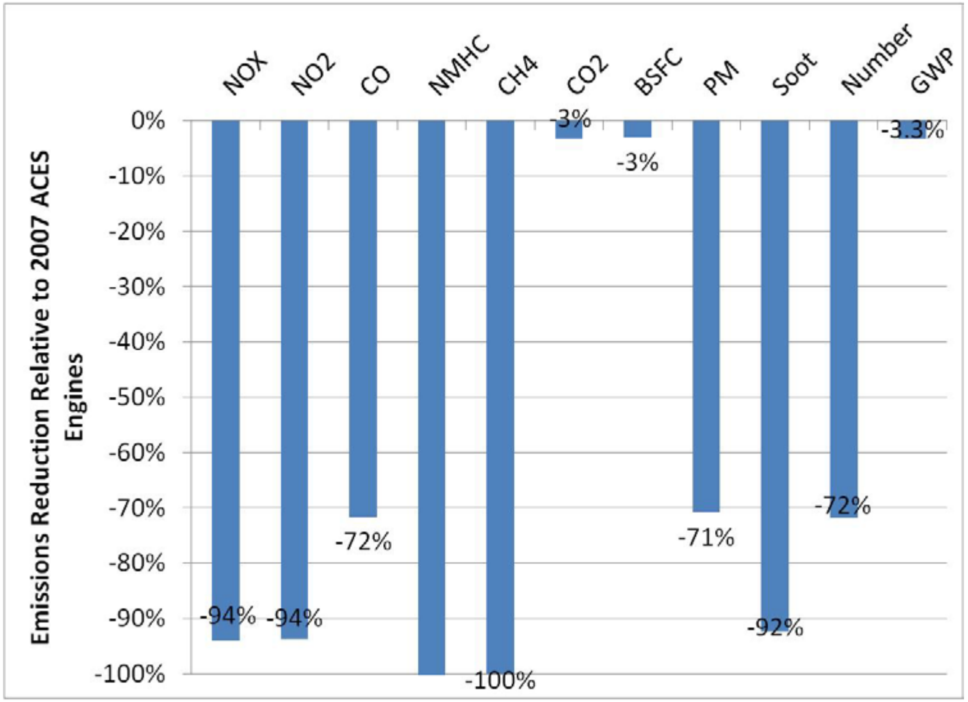
• No DPF regeneration was encountered with the 2010 engine, even after 3 consecutive 16-hour cycles. This led to even more reduction (72%) in particle number for 2010 vs. 2007



The lack of active DPF regeneration and the presence of SCR led to a substantial reduction in particle number with 2010 vs. 2007 & 2004 technology engines

PHASE 2: EMISSIONS REDUCTION (vs. PH. 1)

- Four 2007 ACES Engines
- Three 2010 ACES Engines



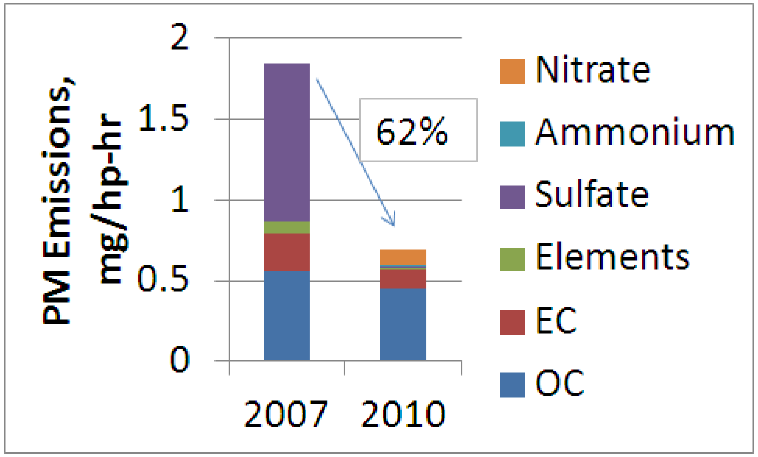
• Substantial reduction in large number of emissions species was observed with the 2010 technology engines.
• Diesel fuel consumption was slightly lower, but can be similar when urea consumption is included.

Greenhouse Gas

• CO_2 emissions were 3 percent lower and CH_4 was virtually absent.
• N_2O increased, but still lower than the 2014 standard as shown in previous slide.

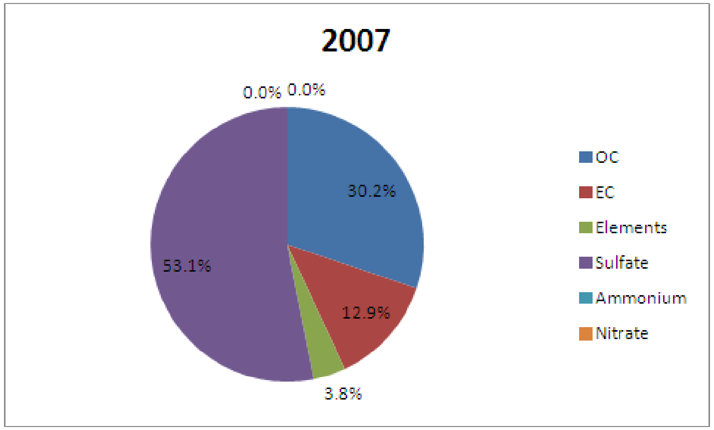
When calculating the 100 year global warming potential (GWP) taking into account CH_4, CO_2, and N_2O emissions, the GWP of the 2007 and 2010 technology engines was similar.

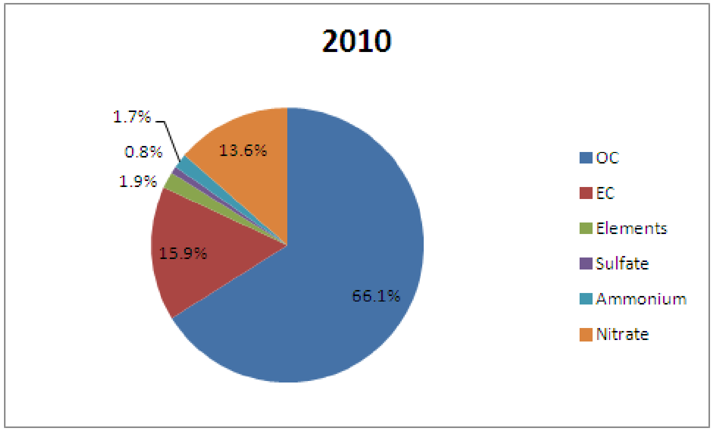
PHASE 2: PM COMPOSITION (vs. PH. 1)



- 2010 Engine achieved 62 percent reduction of PM (16-hour cycle)
  - Lower sulfate, EC, and elements
  - Higher nitrate and ammonium

- 2007 was dominated by sulfate (53%) while 2010 engines were dominated by organic carbon (66%)





PHASE 2: SUMMARY

- In ACES Phase 1, 2007 diesel engine emissions were:
  - Substantially lower than the 2007 standard
  - Substantially lower than pre-2007 technology engines for many regulated and unregulated emission species

- In ACES Phase 2, 2010 diesel engine emissions were:
  - Substantially lower than the 2010 standard
  - Substantially lower than 2007 and pre-2007 technology engines for many regulated and unregulated emission species

ACES PHASE 3 APPROACH AND OBJECTIVES
Health Bioscreening

Phase 3A: Characterization of emissions and exposure atmospheres

Phase 3B: Conduct of animal bioscreening studies

DOE Funding:

- Characterization of animal exposures
- 3 month mouse pulmonary bioscreening

EPA Funding (leveraged by DOE investment):

- Long-term rat carcinogenesis bioassay (30 mo)
- Pulmonary bioscreening at 1, 3, 12 & 24 mo

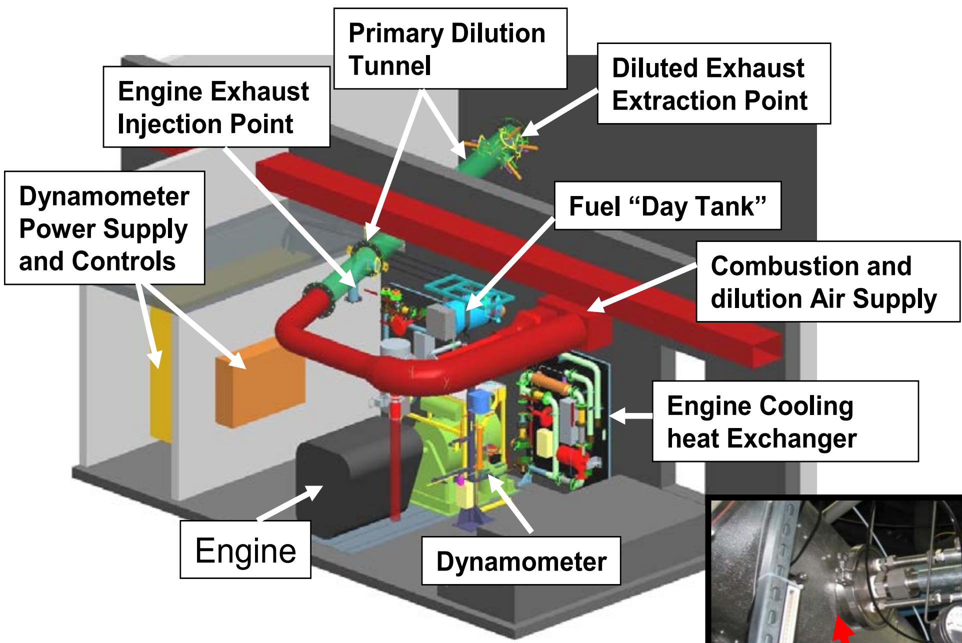
PHASE 3A – TECHNICAL APPROACH

- 2007-compliant “engine B' ” (selected from four candidates)
  - Confirmed that engine/control systems met performance criteria

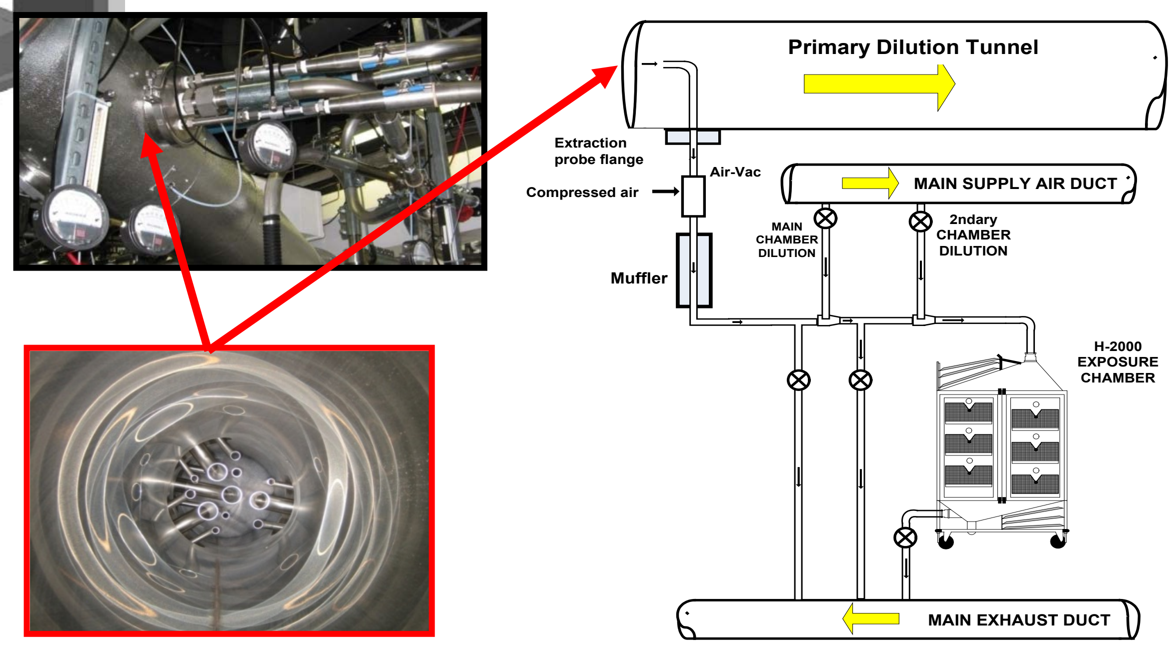
    Steady-state (SS) and Federal Test Procedure (FTP) cycles
    16-hr ACES cycle (4 repeats of 4 hr cycle with cold start)
- Evaluated diluted emissions in empty animal chamber, and compared to SwRI results (using same fuel)
  - Emissions = exhaust + crankcase blow-by
  - FTP, SS modes 1, 3 & 5, ACES cycle
  - Constant pressure primary dilution tunnel
- Determined dilutions required to meet targets set by HEI
  - Dilutions set to achieve 4.2, 0.8 & 0.1 ppm NO_2
  - Dilutions ≈ 40:1, 210:1 & 1680:1
- PM levels are <u>very low</u>; study may primarily detect effects of NO_2 if any effects are seen
- ***Report published as HEI Communication 17 in February 2012***

PHASE 3A – TECHNICAL APPROACH

Engine and Primary Dilution System



Exhaust Extraction and Secondary Dilution Systems



(Note: Drawing is not to scale)

PHASE 3A - RESULTS

AVERAGE EXPOSURE CONCENTRATIONS OVER 12 MONTHS

	High		Mid		Low	
Gases:	Mean	Stdev	Mean	Stdev	Mean	Stdev
NO_2 (ppm)	4.2	0.5	0.91	0.11	0.109	0.013
NO (ppm)	5.8	1.1	1.40	0.23	0.293	0.160
NOx (ppm)	9.9	1.4	2.30	0.29	0.402	0.159
CO (ppm)	6.8	2.9	n/a	n/a	n/a	n/a
THC (ppm)	0.5	0.4	n/a	n/a	n/a	n/a
SO_2	23.9	4.4				
PM ($\mu g/m^3$):						
Chamber Inlet (filter)	9	5	3	3	2	1
Chamber (filter)	27	10	31	20	21	12

PHASE 3B – APPROACH AND STATUS

CORE BIOSCREENING STUDY

APPROACH

Chronic Carcinogenicity Bioassay of Wistar Han Rats:

- Expose 288/group 16 hr/day, 5 days/wk for up to 30 months

Accommodate ancillary biological studies

- Markers of potential cancer, vascular inflammation effects

STATUS

- Results of 1- and 3-month exposures published as HEI Report 166
- 12- and 24-month health evaluations completed at all Ancillary Study Sites;
    - Draft reports submitted to HEI in March 2013; in review
- Lifetime 30-month exposures completed at LRRI; Health Analyses underway
    - Preliminary 24-month results included here, 30-month results pending
- Animals were generally healthy and gained weight as expected
    - Females exposed for 30 months, males for 28 months due to overall lower survival rates
    - No overt clinical signs of disease other than normal aging

LUNG HISTOPATHOLOGY – PREVIEW

(These results still subject to HEI Peer Review)

- No treatment-related lung lesions in low or mid dose groups
- Little progression of lung lesions at high exposure level between 12 and 24 months
- Lung lesions at high level severity defined by the Study Pathologist as minimal to mild
  - On 1-4 scale 1 = minimal, 2 = mild

HISTOPATHOLOGY IN RATS

Incidence and Types of Findings in the Lung

No effects seen in animals exposed to filtered air, low, or middle diesel exhaust concentration
(0 of 10 animals per group, per gender)

Minimal to *mild* effects seen at the *high* concentration only

Gender	Males	Males	Males	Females
Exposure duration	3 mo	12 mo	24 mo	24 mo
Hyperplasia in Periacinar Epithelium	**10**/10	**10**/10	**10**/10	**10**/10
Bronchiolization	**3**/10	**4**/10	**1**/10	**1**/10
Interstitial Fibrosis	**4**/10	**10**/10	**10**/10	**10**/10

ROLE OF NO_2 IN OBSERVED EFFECTS?

When HEI designed the study, it was expected that at the high concentration (16 hr/day 4.2 ppm NO_2) some NO_2-related effects may be observed. This was based on results of previous studies, including:

HEI Study (Mauderly et al., 1989) F344 rats exposed (7hr/day, 5 days/week) to 9.5 ppm NO_2

Pulmonary function, histopathology, and, immune response assessed after 12, 18, 24 mo (1820, 2730, 3640 hr) of exposure

Findings: NO_2 caused epithelial hyperplasia, thickening of walls of terminal bronchioles, inflammation, and oxidative stress.
There was little effect on respiratory function.

Effects at 12 mo not significantly different than at 24 months

How do the NO_2 "doses" compare at 12 mo?

Mauderly et al: 17,290 ppm-hr.

ACES: 17,472 ppm-hr

SUMMARY OF HEALTH RESULTS

- Exposures produced minimal inflammatory and tissue remodeling in lungs of rats.
  - Tissue injury was considered *minimal to mild* at 3 and 12 months (1 on scale of 1-4). *Minimal* lesions at 24 months are similar to minimal lesions at 12 months. Some *mild* lesions at 24 months.
  - No pre-neoplastic lesions observed.
  - No 'soot' accumulation in macrophages. Although unexpected in the current study, this was a hallmark of TDE lungs due to high soot exposure levels.
- Remainder of health analyses at 28-30 months under way
  - Note: in previous studies significant lung tumors were observed only after 24 months.
  - Note: When designing the study, it was expected that at the high concentration (at 4.2 ppm NO_2) some NO_2-related effects might be observed. Results so far are not inconsistent with that.

REMAINING TASKS

- **Phase 2**
  - Final Report Spring 2013
- **Phase 3**
  - Submission of Core Study Draft Report (Summer 2013)
  - Extensive Review (Summer and Fall 2013)
  - Final Report Publication early 2014

SUMMARY

- The progressive changes in the composition and decreases in magnitude of emissions from new technology diesel is changing the landscape of the debate over potential health effects of diesel exhaust
- 2007 compliant diesel exhaust studied in the ACES program shows low particle emissions. The only measurable particle emissions occur during trap regeneration. The emissions have low volatile and semivolatile organics, and an increase in the proportion of NO_2 compared with older technologies.
- Exposures produced no effects in most tests; minimal inflammatory, tissue remodeling and respiratory function changes in rats.
  - Tissue injury was considered minimal (1 on scale of 1-4)
  - Statistically significant findings observed primarily at high level
  - Respiratory function effects were trends only, and only significant when genders were pooled to enhance statistical power
- No genotoxic effects were observed.
- Communication to key decision forums underway.

For further information, contact:

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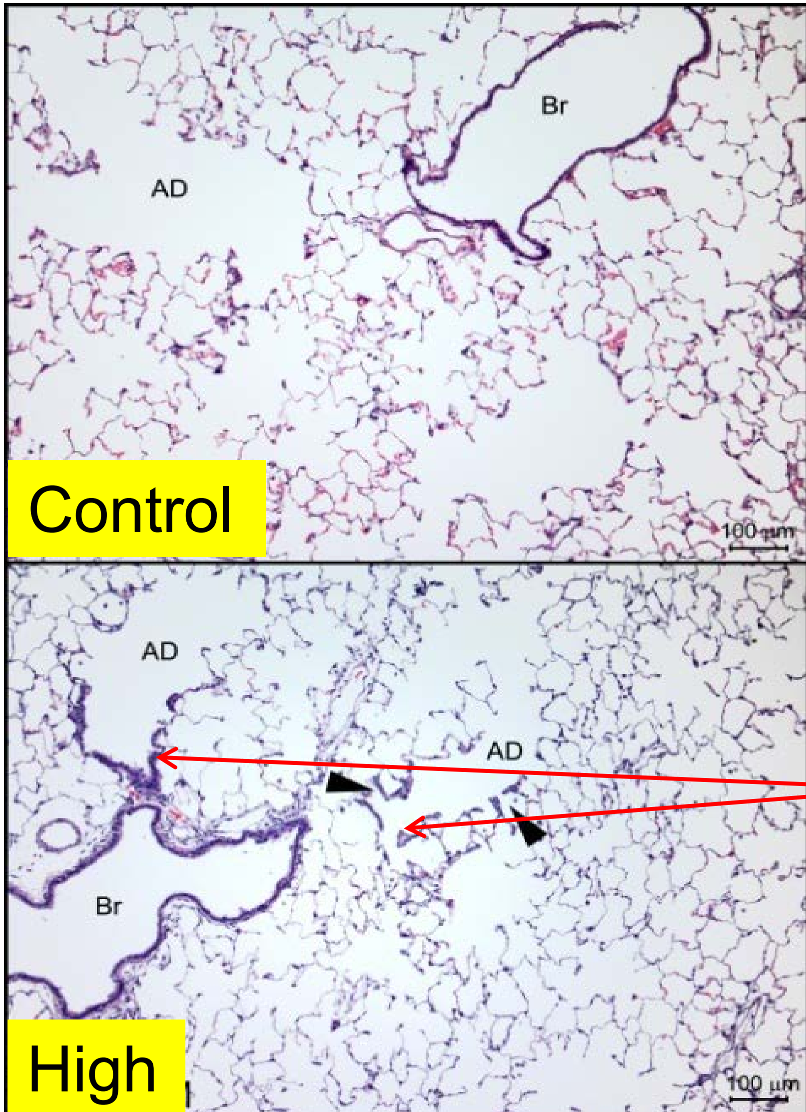
Technical Back-up Slides

Minimal Epithelial Hyperplasia



AD = Alveolar Duct; Br = Bronchiole

Epithelial hyperplasia observed at high exposure level (associated with alveolar ducts)

Findings generally mild

Thickening of alveolar duct septae

Mild Inflammation and Alveolar Duct Thickening in Terminal Bronchioles