Advanced Collaborative Emission Study (ACES)

Diesel Emissions and Health

Final Results

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Outline of the Presentation

- Introduction to ACES
- Results of ACES Emissions Characterization (Phases 1 and 2)
- Results of the ACES Health Study (Phase 3)
- Overall Conclusions and Impacts

Diesel Engines

- Dominate heavy-duty applications worldwide
- Advantages compared to spark ignition engines:
  - More efficient
  - More durable
  - Less CO_2, CO and hydrocarbons
- Disadvantages:
  - Emissions of soot/particulate matter
  - More NOx (NO_2 and NO)
  - Emissions of other toxic compounds, e.g., PAHs

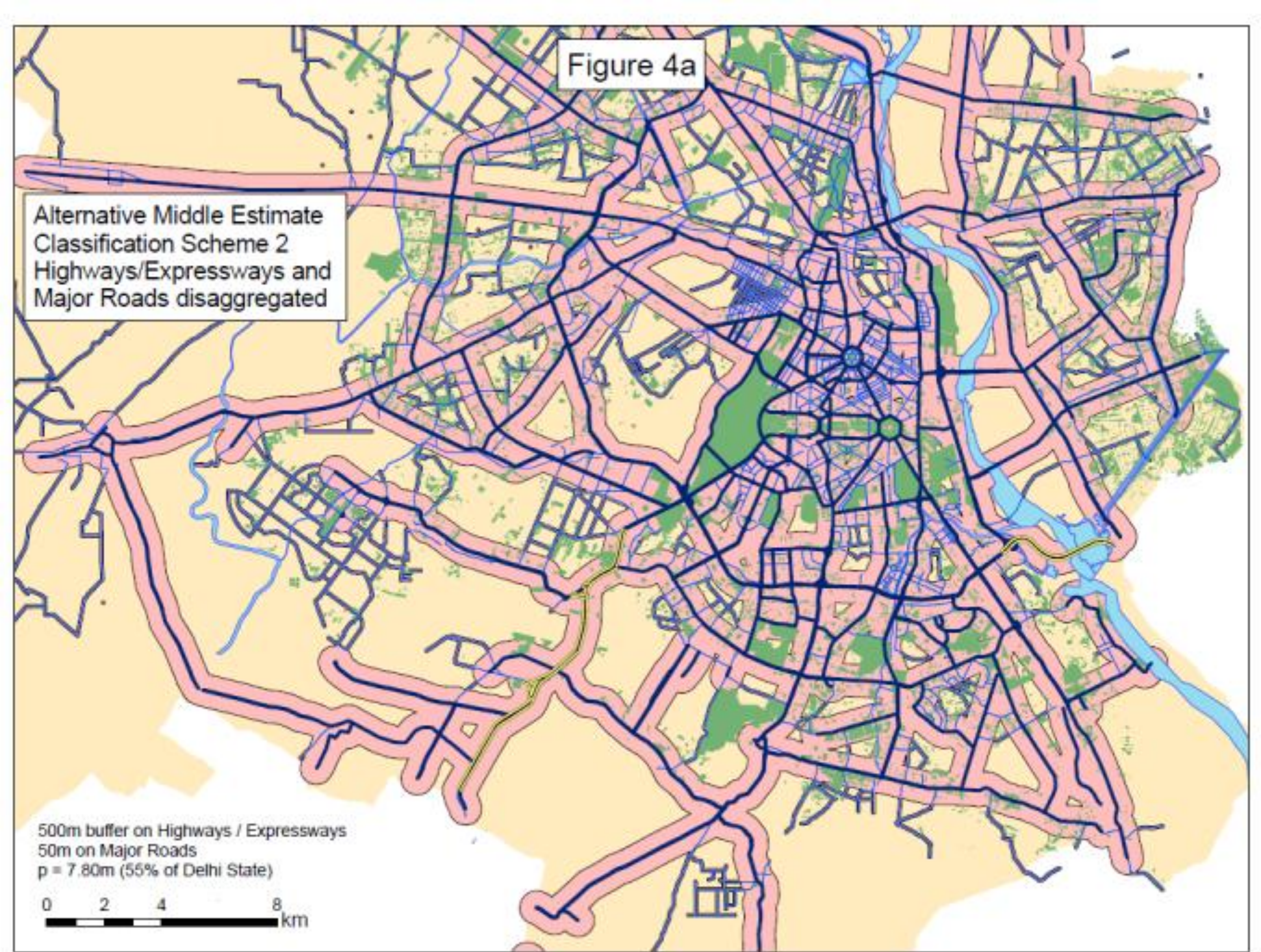
Toxicity of Diesel Emissions

- 1970s and 1980s:
  - In vitro studies with PM and its extracts $\Rightarrow$ Mutagenicity
  - Rat inhalation studies with PM $\Rightarrow$ Carcinogenicity (lung)
  - Epidemiology Studies $\Rightarrow$ Suggestive of Carcinogenicity (lung)
- World Health Organization (WHO) : International Agency for Research on Cancer (IARC)
  - 1988 Panel: DE is "probably carcinogenic to humans (category 2A)
  - 2012 Panel: DE is a "known human carcinogen" (category 1)
- Other national and regional actions

The Traffic Impact Area

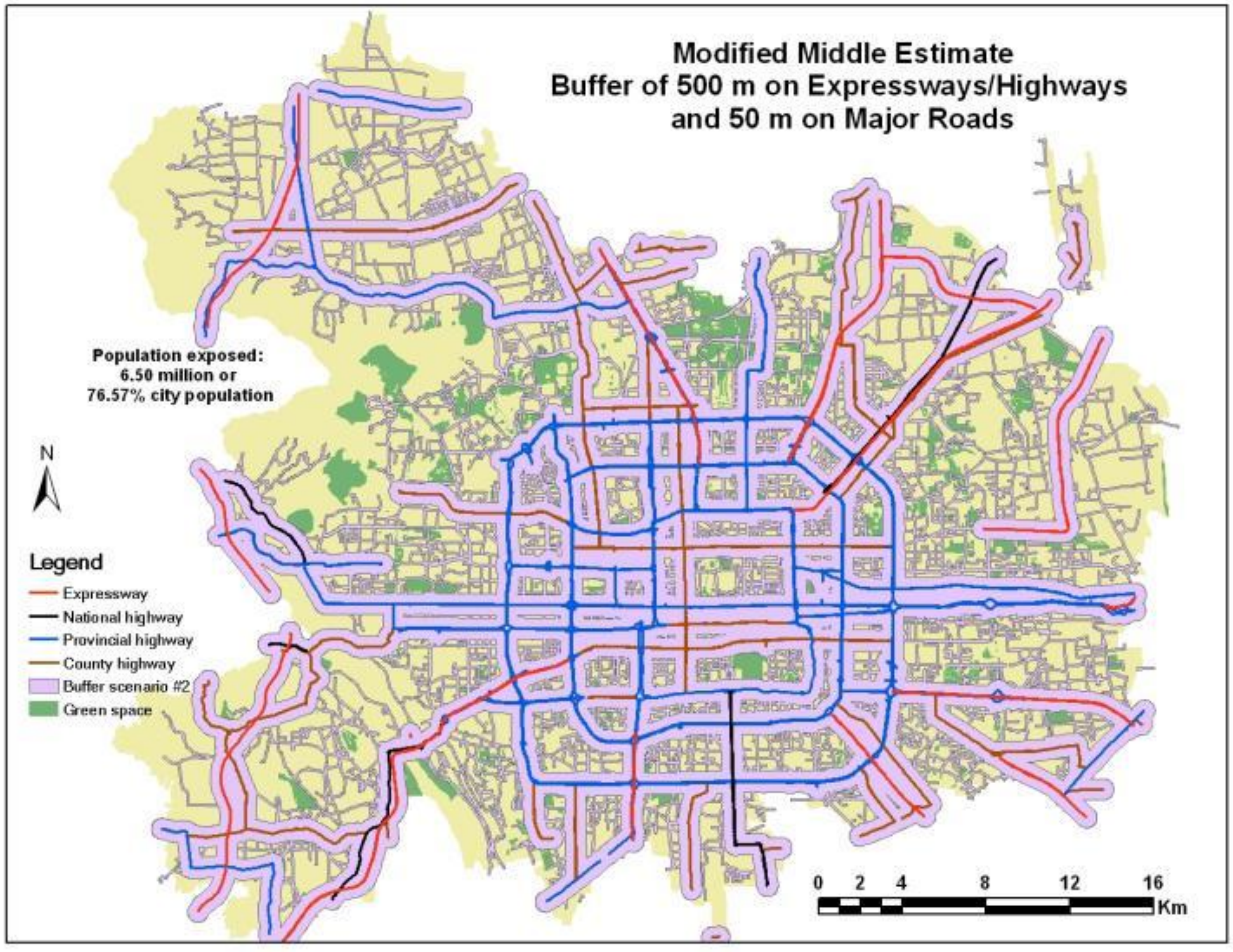
*HEI Analysis: **55% of the Population** within 500 meters of a Freeway; 50 meters of a Major Road*

(Delhi)

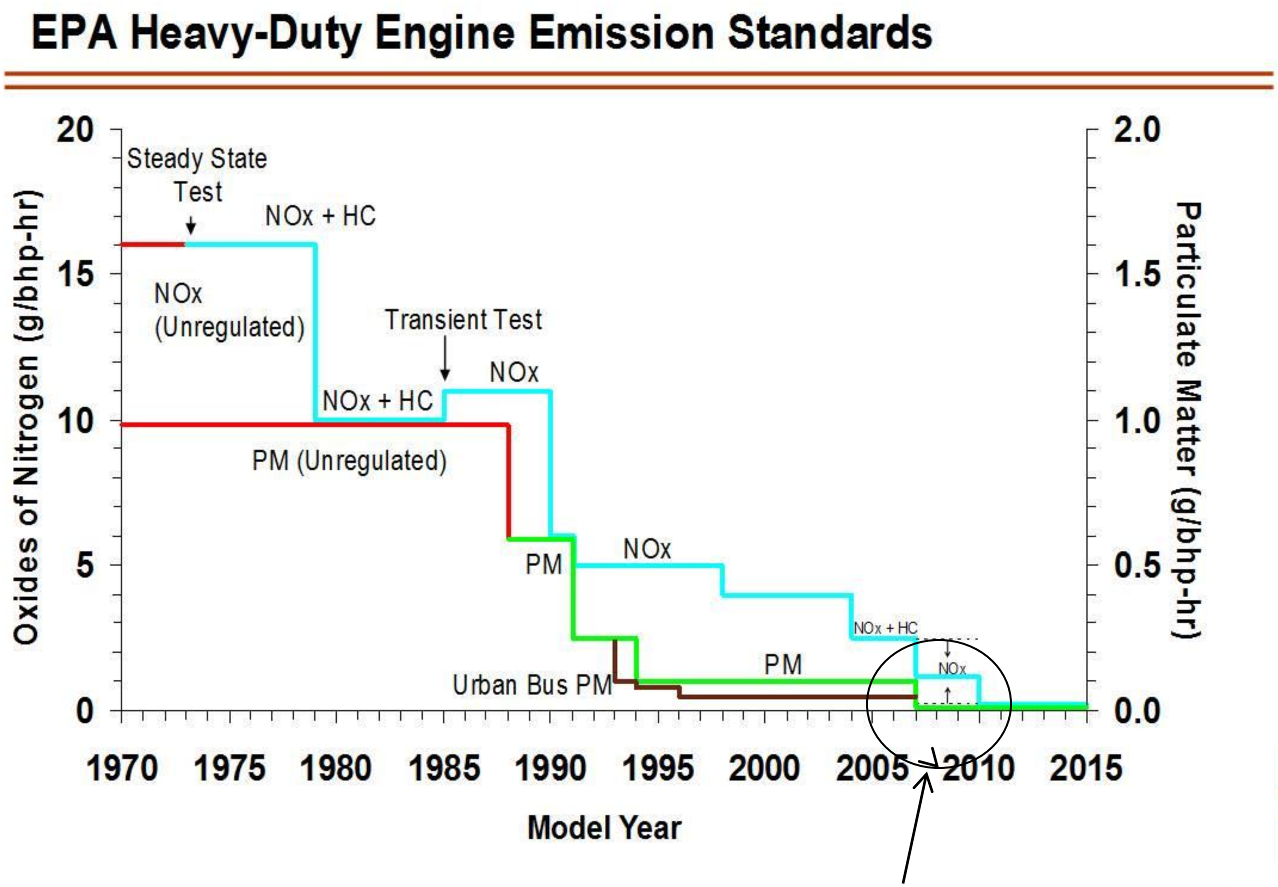


The Traffic Impact Area in Beijing

HEI Analysis: 76% of the Population within 500 meters of a Freeway; 50 meters of a Major Road



Regulation of Diesel Emissions



ACES engines

Emission Control Systems in Modern Diesel Engines

2004:

- Exhaust gas recirculation (EGR) – reduces NOx emissions
- Diesel Oxidation Catalyst (DOC) – reduces PM, NOx, CO, organics, but increases NO_2

2007

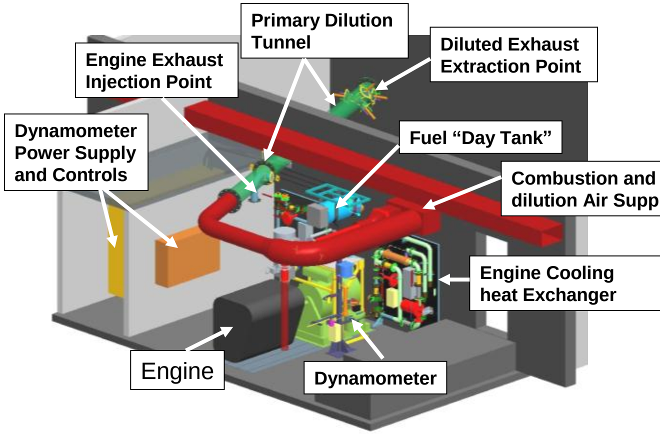
- Diesel particulate filter DPF – removes PM by filtering and oxidation; accumulated PM needs to be cleaned or “regenerated”; increases NO_2

2010

- Selective Catalytic Reduction SCR: reduces NO_2 using urea (NH_3)
- Ammonia oxidative catalyst (AMOX): removes any remaining ammonia

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.



Phase 1: *2007 Emissions Characterization*

Phase 2: *2010 Emissions Characterization*

Phase 3: 2007/2010 Engine Emissions Health Effects Testing

- Short Term health biological screening
  - Few to no health effects observed
- Lifetime Emission Exposure (Cancer)

Design of ACES Study

Phase 1: ***Characterization of emissions***

-from four heavy-duty on-road diesel engines (HDDEs) that met the 2007 PM standards

Phase 2: ***Characterization of emissions***

-from a group of HDDE that met the 2010 NOx standards

Overseen by the Coordinated Research Council (CRC) and funded by the USDOE, the Truck and Engine Manufacturers Association (EMA), CARB, and the American Petroleum Institute (API).

Phase 3: ***Assessment of health effects in rodents***

-Inhalation of NTDE from a 2007-technology HDDE that was among the four tested in Phase 1

-1. Chronic study assessing cancer and non-cancer effects in rats

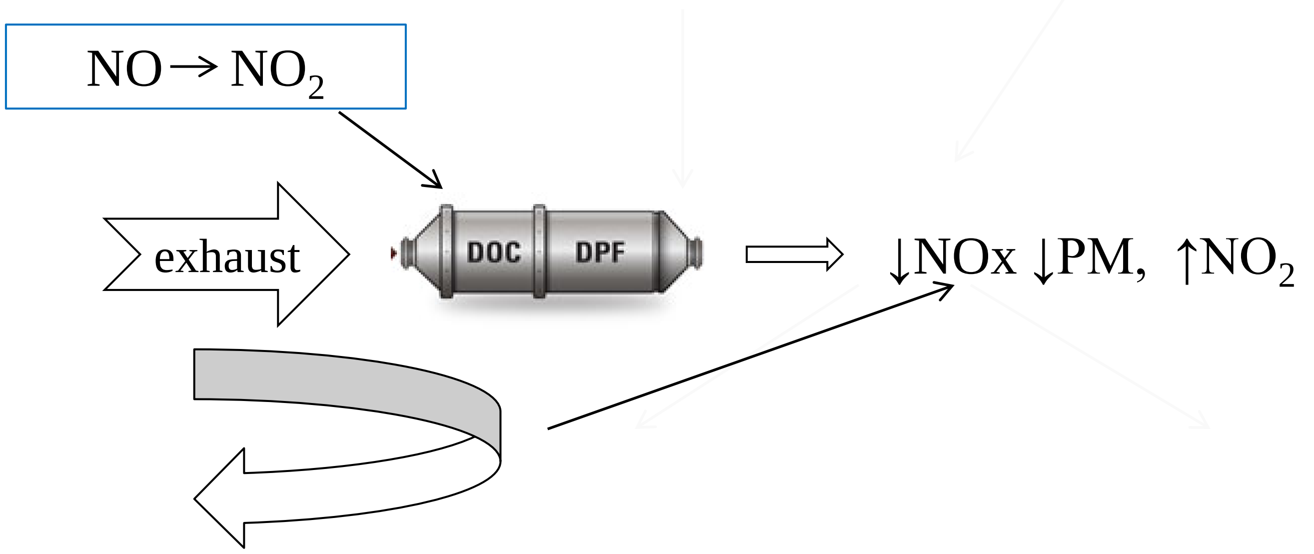
-2. Shorter term study in mice

Overseen by HEI and funded by EPA, EMA, CARB, DOE, and API.

ACES Phase 1 and 2 Background

Schematic Representation of HDDE Emission Controls

2007-technology engines

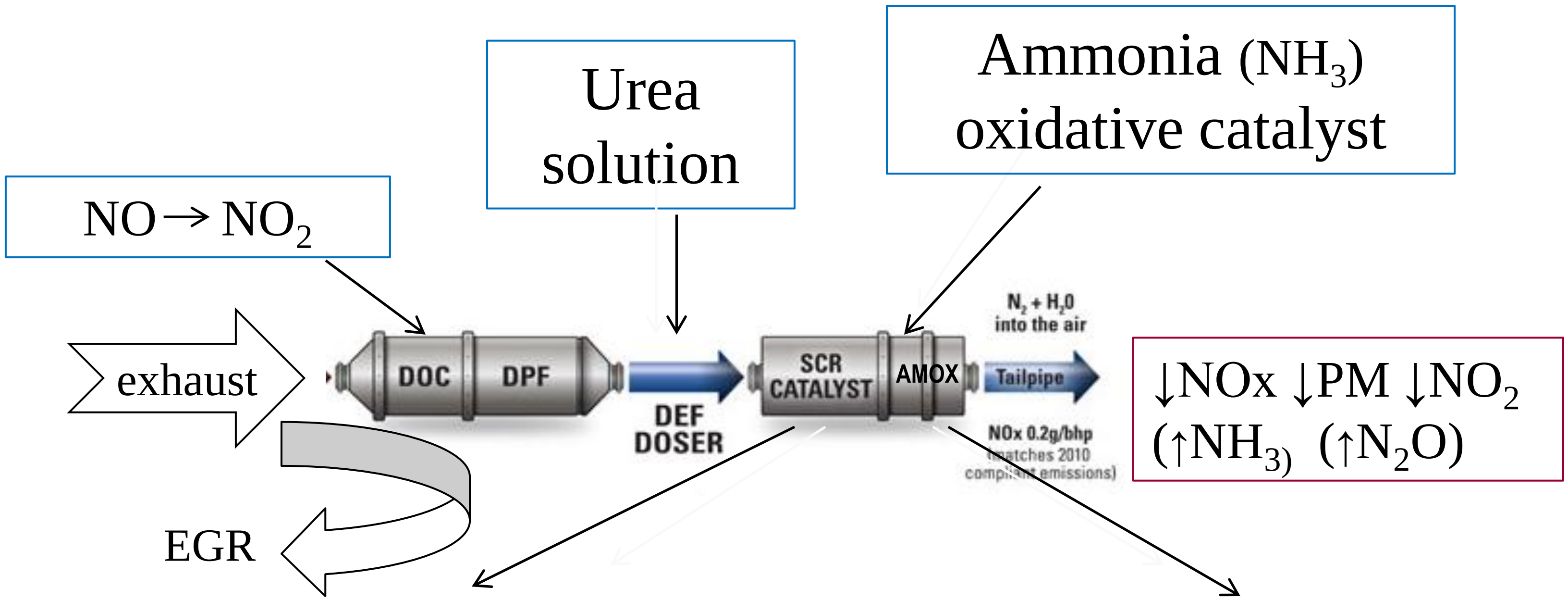


Exhaust Gas Recirculation

Figure adapted from http://www.factsaboutscr.com/scr/default.aspx

Schematic Representation of HDDE Emission Controls

2010-SCR technology engines



$CO(NH_2)2 \rightarrow NH_3$

$NH_3 + NO + NO_2 \rightarrow N_2 + H_2O$ (+NH_3 slip)

$NH_3 \rightarrow NO + N_2O + N_2$

Figure adapted from http://www.factsaboutscr.com/scr/default.aspx

Phase 1 and 2

Set up and Design

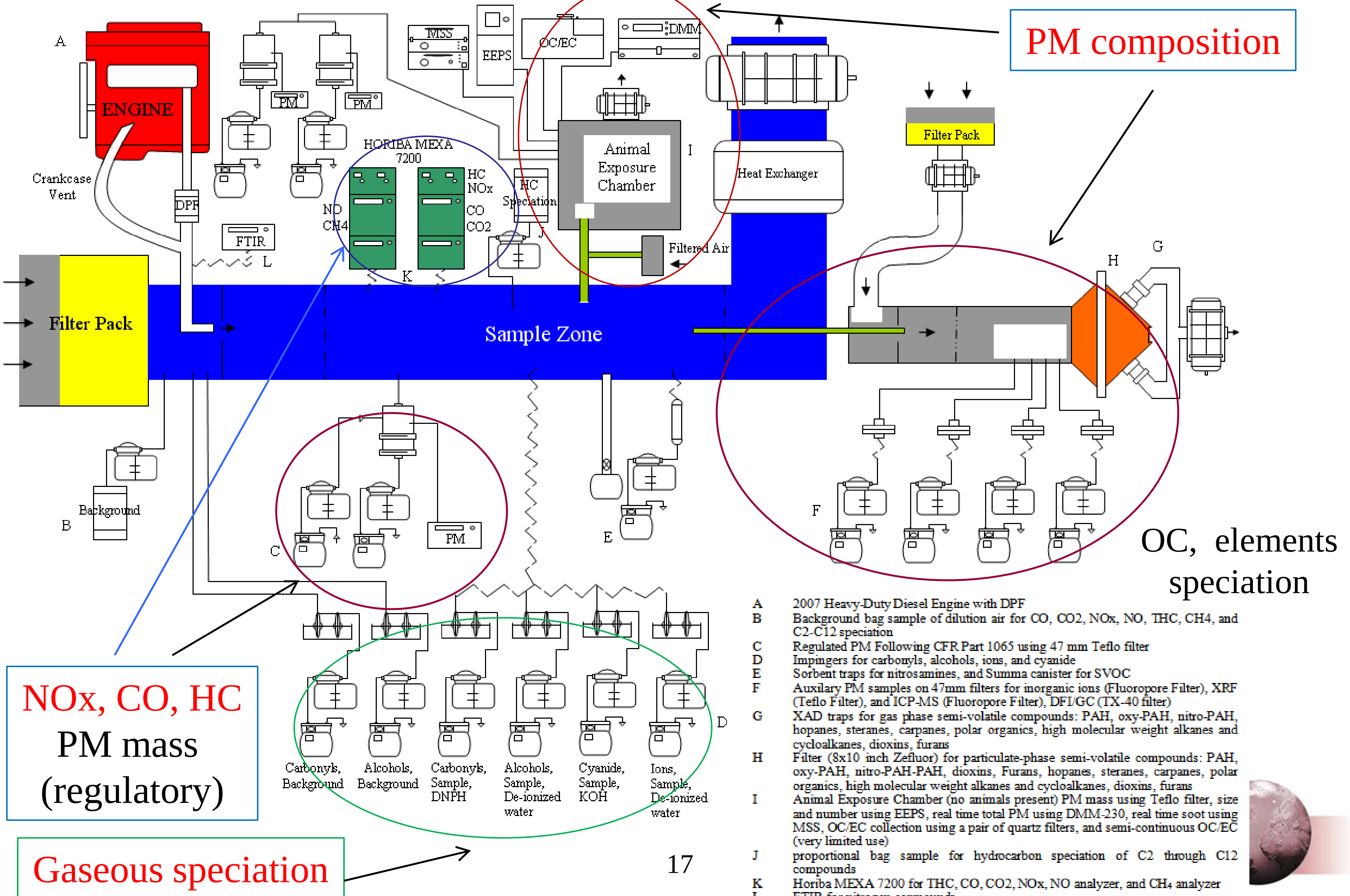
Engines Tested

- Phase 1
  - Four model year 2007 HDDE provided by Caterpillar, Cummins, Detroit Diesel, and Volvo
- Phase 2
  - Three 2010 model-year HDDE provided by Cummins, Detroit Diesel Corporation, and Mack (Volvo Powertrain.)

Engine Test Cycles

- **Federal Test Procedure (FTP)**, also referred to as the composite FTP, used to certify that engines comply with the emission standards– includes a cold start and hot start
- **FTP with hot start only,** used for characterizing both regulated and unregulated emissions
- **16-Hour Cycle.** Developed by researchers at West Virginia University for ACES to represent more closely the real-world operations of modern engines, used for characterizing both regulated and unregulated emissions and for exposing the animals

Overall Experimental Setup



A 2007 Heavy-Duty Diesel Engine with DPF
B Background bag sample of dilution air for CO, CO2, NOx, NO, THC, CH4, and C2-C12 speciation
C Regulated PM Following CFR Part 1065 using 47 mm Teflo filter
D Impingers for carbonyls, alcohols, ions, and cyanide
E Sorbent traps for nitrosamines, and Summa canister for SVOC
F Auxilary PM samples on 47mm filters for inorganic ions (Fluoropore Filter), XRF (Teflo Filter), and ICP-MS (Fluoropore Filter), DFI/GC (TX-40 filter)
G XAD traps for gas phase semi-volatile compounds: PAH, oxy-PAH, nitro-PAH, hopanes, steranes, carpanes, polar organics, high molecular weight alkanes and cycloalkanes, dioxins, furans
H Filter (8x10 inch Zefluor) for particulate-phase semi-volatile compounds: PAH, oxy-PAH, nitro-PAH-PAH, dioxins, Furans, hopanes, steranes, carpanes, polar organics, high molecular weight alkanes and cycloalkanes, dioxins, furans
I Animal Exposure Chamber (no animals present) PM mass using Teflo filter, size and number using EEPS, real time total PM using DMM-230, real time soot using MSS, OC/EC collection using a pair of quartz filters, and semi-continuous OC/EC (very limited use)
J proportional bag sample for hydrocarbon speciation of C2 through C12 compounds
K Horiba MEXA 7200 for THC, CO, CO2, NOx, NO analyzer, and CH_4 analyzer
L FTIR for nitrogen compounds

Phase 1 and 2
Results and Conclusions

Phase 1: Characteristics of New vs. Old Diesel PM

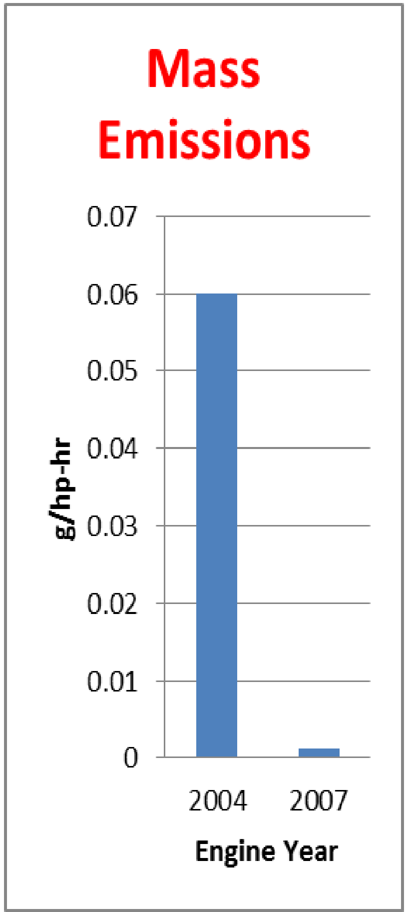
HEI ACES Results Compared to Earlier Testing:

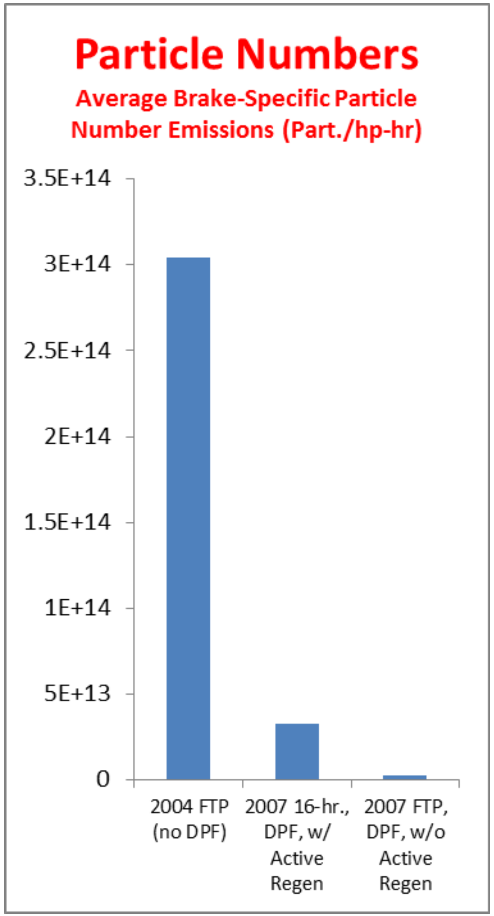
Dramatic Reductions

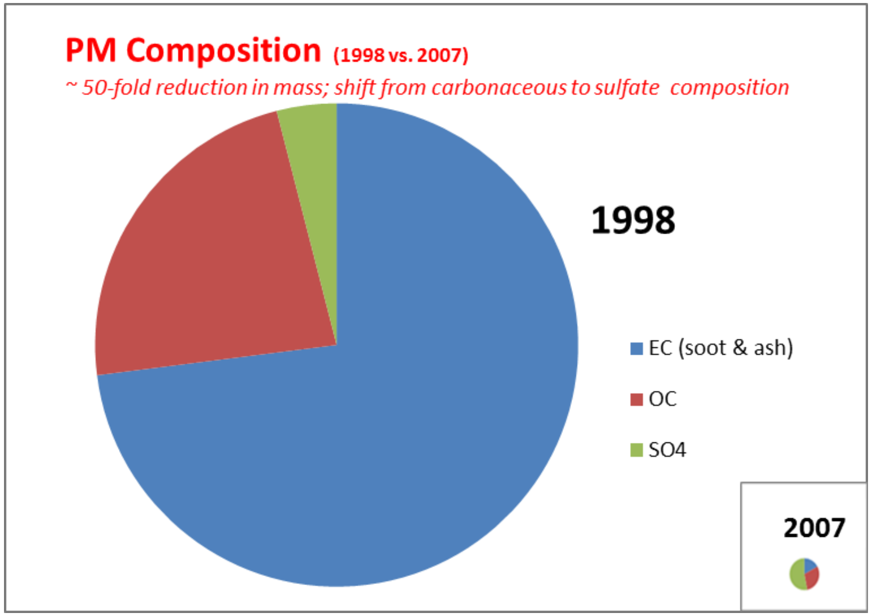
98% reduction in mass

90% - 99% reduction in Ultrafine Particles

Substantial reduction in carbon particles







Greater than 90% reduction in PAHs (including known carcinogens)
Many PAHs now below detection limits (Khalek et al 2011)

- Polycyclic Aromatic Hydrocarbons (PAHs) have been of major concern in diesel exhaust
- Many known to cause cancer
- Some of the most toxic are so low they can no longer be measured

Table 8. PAH and nitroPAH average emissions for all 12 repeats of the 16-hr cycles for all four 2007 ACES engines and for a 2000-technology engine running over the FTP transient cycle.[16]

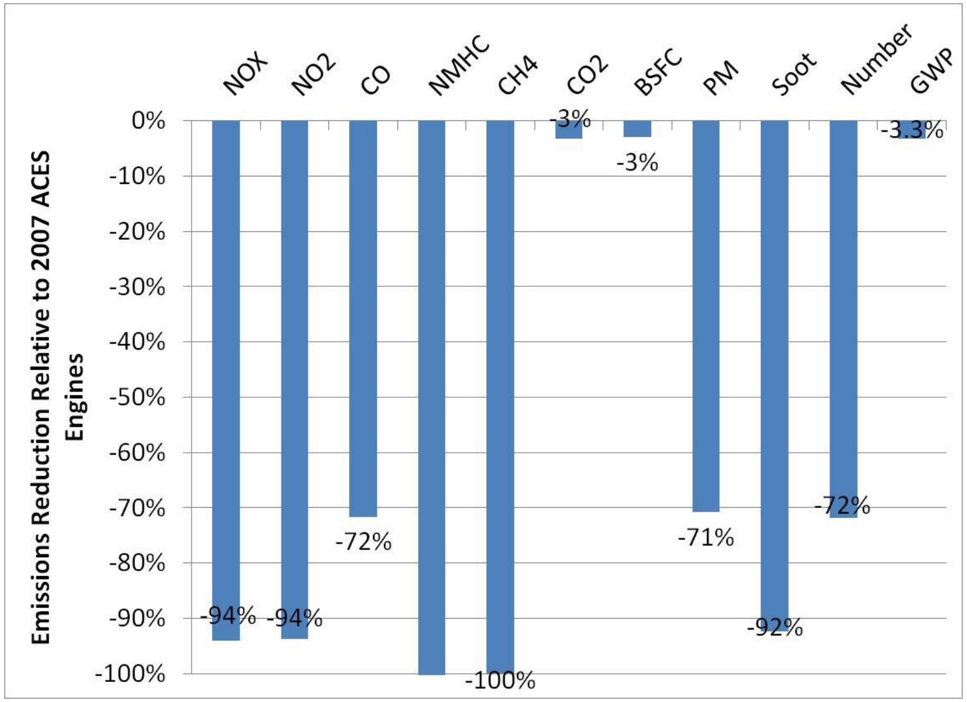
PAH and NitroPAH Compounds	2007 Engines[a] (mg/bhp-hr)	2000-Technology Engine[a, b] (mg/bhp-hr)	Percent Reduction
Naphthalene	0.0982000 ± 0.0423000	0.4829	80
Acenaphthylene	0.0005000 ± 0.0005000	0.0524	98
Acenaphthene	0.0004000 ± 0.0001000	0.0215	98
Fluorene	0.0015000 ± 0.0009000	0.0425	96
Phenanthrene	0.0077000 ± 0.0025000	0.0500	85
Anthracene	0.0003000 ± 0.0001000	0.0121	97
Fluoranthene	0.0006000 ± 0.0006000	0.0041	85
Pyrene	0.0005000 ± 0.000400	0.0101	95
Benzo(*a*)anthracene	<0.0000001	0.0004	>99
Chrysene	<0.0000001	0.0004	>99
Benzo(*b*)fluoranthene	<0.0000001	<0.0003	>99
Benzo(*k*)fluoranthene	<0.0000001	<0.0003	>99
Benzo(*e*)pyrene	<0.0000001	<0.0003	>99
Benzo(*a*)pyrene	<0.0000001	<0.0003	>99
Perylene	<0.0000001	<0.0003	>99
Indeno(123-*cd*)pyrene	<0.0000001	<0.0003	>99
Dibenz(*ah*)anthracene	<0.0000001	<0.0003	>99
Benzo(*ghi*)perylene	<0.0000001	<0.0003	>99
2-Nitrofluorene	0.00000360 ± 0.00000410	0.0000650	94
9-Nitroanthracene	0.0000148 ± 0.0000213	0.0007817	98
2-Nitroanthracene	0.00000040 ± 0.00000090	0.0000067	94
9-Nitrophenanthrene	0.00002110 ± 0.00002090	0.0001945	89
4-Nitropyrene	<0.00000001	0.0000216	>99
1-Nitropyrene[c]	0.00001970 ± 0.00002430	0.0006318	97
7-Nitrobenz(*a*)anthracene	0.00000020 ± 0.00000020	0.0000152	99
6-Nitrochrysene	<0.00000001	0.0000023	>99
6-Nitrobenzo(*a*)pyrene	<0.00000001	0.0000038	>99

Notes: [a]The significant figures signify the detection limit in mg/bhp-hr; [b]SD data were not provided by ref 15. [c]Previous work showed artifact formation during filter collection of the compounds highlighted in bold.

<u>Phase 2</u> ACES Results

Average Emissions Reduction of 2010 Engines Relative to 2007

Four 2007 ACES Engines
Three 2010 ACES Engines



Substantial reduction in large number of emissions species with the 2010 technology engines

Source Khalek 2013

Main Difference Between Phase 1 and 2

- Trap regeneration occurred 1-3 times during the 16-hr cycle in 2007 engines, but did not occur in 2010 engines
  - emissions of PM were higher during regeneration
- Lack of regeneration was thought to be associated with
  - Reduction <u>of SO2 and sulfate </u>and overall reduction of <u>PM mass and number</u> because desorption of sulfur from the DPF can only occur at the high temperature that occur only during regeneration.

  - Reduction in <u>EC, PM number, and metals </u>due to higher filtration efficiency of the loaded DPF

Phase 3 **Health Effects Testing**

Goals:

- **Health effects of lifetime exposure of rats** to emissions from 2007-compliant diesel engines (**New Technology Diesel Exhaust)**

- **Hypothesis:** ***Emissions will not cause an increase in tumor formation or substantial toxic health effects… although some biological effects may occur.***

- **Characterize exposure atmospheres** throughout the exposure period

Phase 3 – Animal Exposures to NTDE

- Expose male and female rats (Wistar Han strain, 140 of each sex/exposure group).
- Duration - Lifetime = 28 months for males, 30 months for females, 16 hr/day, 5 days/wk.

  10 rats/exposure group evaluated at 1, 3, 12, 24 months.

  Remainder (=100+) evaluated at terminal sacrifice

- **NTDE: Three dilutions of whole emissions** + clean air controls
  – 4.2 ppm NO_2 = High
  – 0.8 ppm NO_2 = Medium
  – 0.1 ppm NO_2 = Low

NO_2, rather than PM, chosen as target pollutant

ACES Phase 3
2007 Engine Health Results

- First-ever lifetime animal study of effects of New Technology Diesel
- Substantially more rigorous than normal National Toxicology Program cancer tests:
  - 80 hours of exposure per week
  - Tough Engine operating cycle
  - Twice as many animals
  - Exposures up to 30 months
- Study found no evidence of lung cancer
  - In contrast to previous studies of older diesel
- Mild inflammation, likely due to NO_2 emissions
  - Which have been further substantially reduced in 2010 and later model years

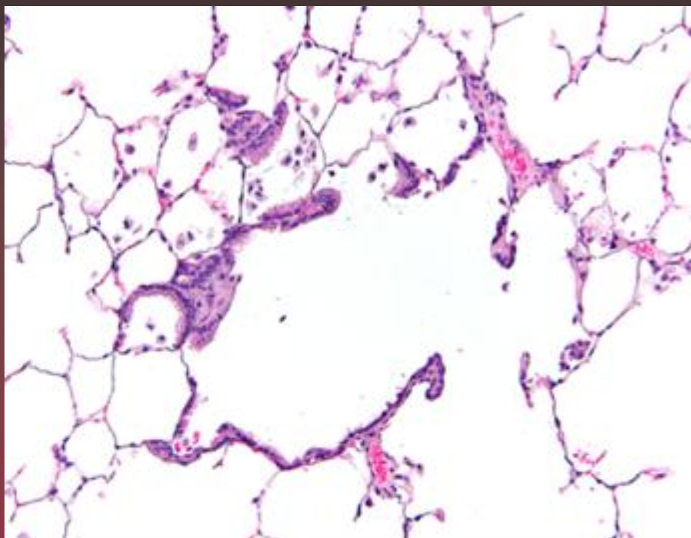
2015

Full Report available at: www.healtheffects.org

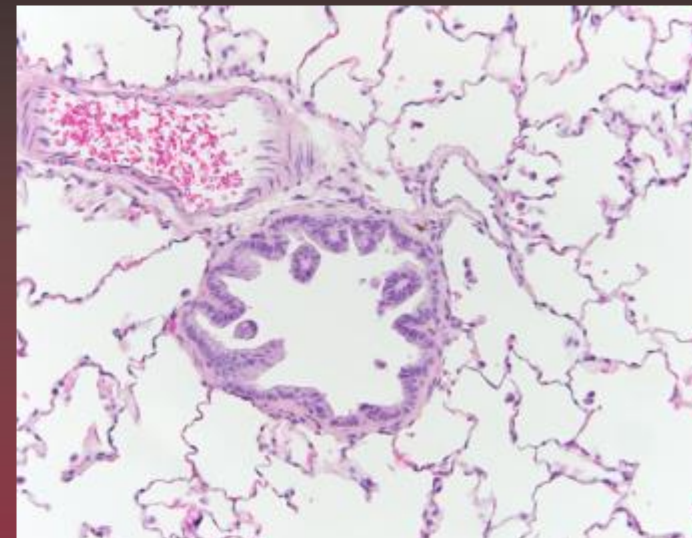
ACES Lifetime Animal Exposure Health Results:

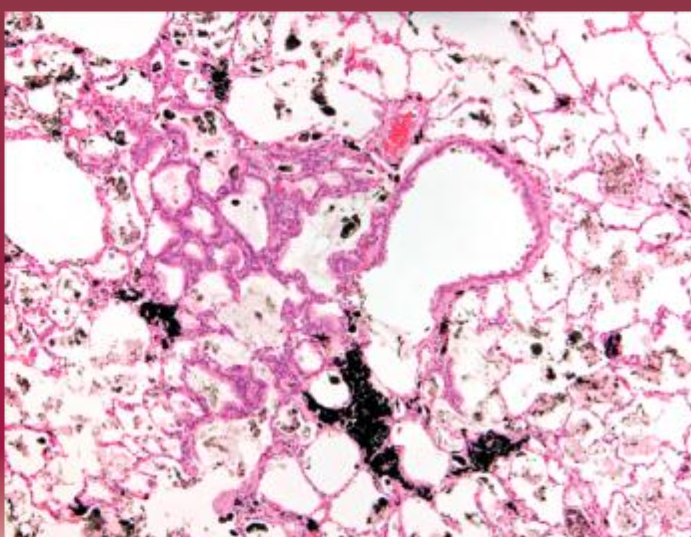
Mild Inflammation (likely NO2);

NO Lung Tumors

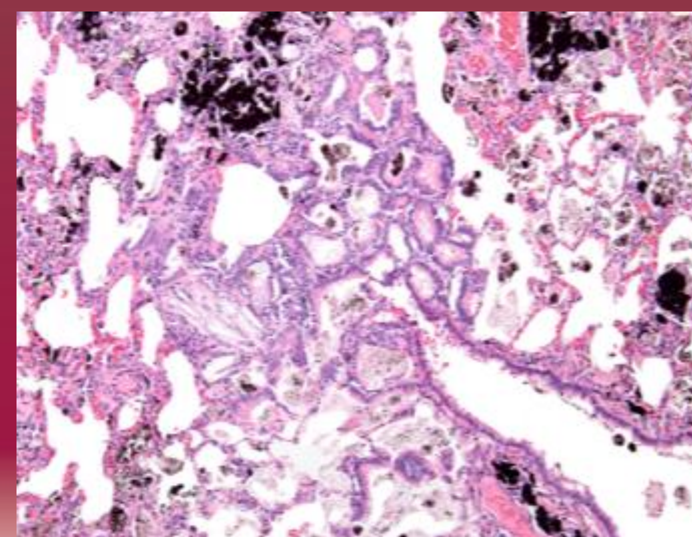


New Technology Diesel Engines (2007)





Traditional Diesel Engines (high particle loading)



Larger Impacts

- Diesel emissions – still an issue from older engines, but progress
  - Diesel fleet turnover currently at ~35% but highly variable geographically
  - Ambient levels of PM, EC and NOx going down – e.g. in MATES IV study
- Promise for developing countries
  - Technology yet to be deployed in developing world
  - India, China and others taking steps to reduce fuel sulfur levels

Key Needs: Ultra Low Sulfur Diesel; In Use Performance

- Clean fuel essential to enable *enhanced advanced control technology (DPF)*
  - Excess Sulfur can block particle filters, coat NOx controls and cause reduce effectiveness
  - De facto world standard moving to 15 ppm or lower

In use monitoring important to ensure real world performance of filters, NOX emissions

E
F
CLEAN DIESEL
Powers America's Trucking Fleet
More than 37% are near zero for particulate emissions (2007 and later model year)
37%
22% are near zero for both particulate matter and nitrogen oxides emissions (2010 and later model year)
22%
It's no surprise the nation's trucking fleet is moving to the next generation of clean diesel.
Improved fuel economy
Less greenhouse gas emissions
Fewer emissions
THE BENEFITS ARE CLEAR. Between 2007 and 2014, diesel-powered Class 3-8 trucks:
SAVED
880 million gallons of diesel fuel
9 million tons of CO2
REDUCED
1.45 million tons of NOx
29,500 tons of particulate matter

Thank you

ACES Reports

Reports can be downloaded from:

Health Effects Institute

www.pubs.healtheffects.org

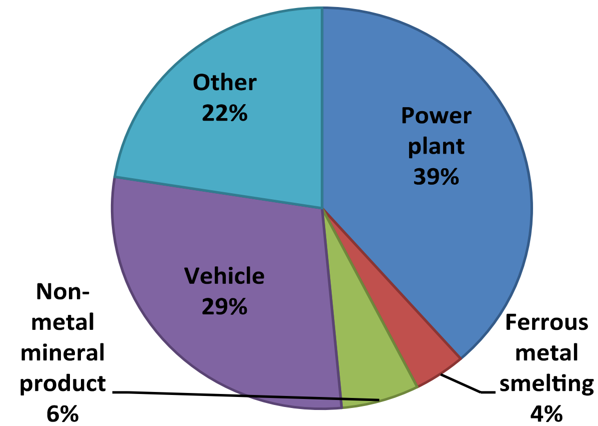
Coordinating Research Council

http://crcao.org/publication/index.html

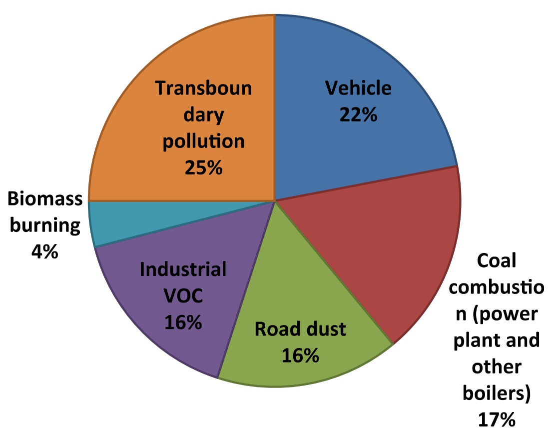
Vehicles are key to Solving the $PM_{2.5}$ Problem

- Vehicles contribute 22-34% of PM2.5 in megacities and 30% of NOx nationwide, but:
  - Percentage is growing
  - Actual impacts much higher when considering secondary pollution
  - Roadside exposure much higher in dense urban areas

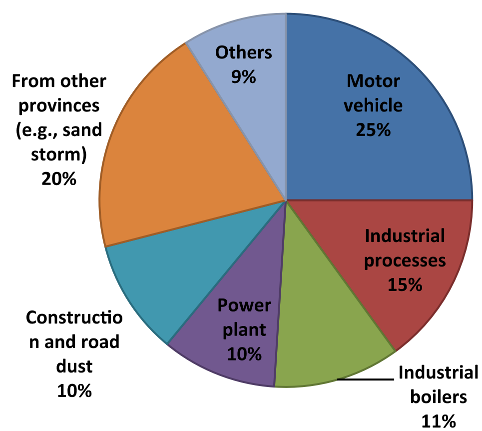
National - NOx emission sources



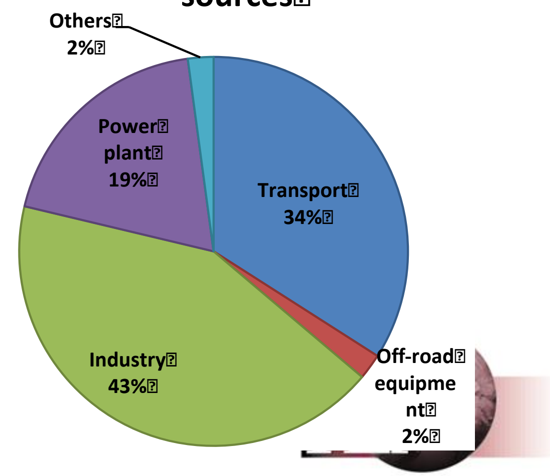
Beijing PM2.5 sources



Shanghai PM2.5 sources



Pearl River Delta PM2.5 sources



Micheal Walsh, 2012

Conclusions of ACES
Phase 3

- Goal: Assessment of health effects in rats
  - Life-time inhalation exposure in rats to emissions from a MY 2007 engine
  - Produced no increase in tumors or any precancerous changes in the lung
  - A few effects were observed, most likely associated with NO_2 present in 2007 engine exhaust
  - No consistent changes seen in 100+ other markers of toxicity
  - Stark contrast with studies with traditional diesel exhaust $\Rightarrow$ carcinogenic

US Diesel Emission Standards from 1998 to 2010 (g/bhp-hr)

Regulated pollutants	Model Year of Implementation (HDDE) ~540 hp			
	1998	2004	2007	2010
PM	0.1	0.1	**0.01**	0.01
CO	15.5	15.5	15.5	15.5
NOx	4.0	2.0	**1.2**	**0.2**
NMHC*	1.3**	0.5	0.14	0.14

Regulated pollutant	Model Year of Implementation (Off-Road DE)				
	Tier 2/3	Tier 4			
	2001-2008 <11hp ≥750	2008 <11 hp <25	2013 ≥ 25 hp <75	2012-2014 ≥75 hp ≤750	2015 ≥750 hp
PM	0.6-0.15	0.3	0.022	**0.015**	**0.022-0.03**
CO	6-2.6	6-4.9	4.1-3.7	3.7-2.6	2.6
NOx				**0.3**	**0.5-2.6**
MMHC				0.3	0.14
NMHC+NOx	5.6-4.9	5.6	5.6-3.5		

*Nonmethane hydrocarbons
**Included methane