New Technology Diesel Engines - Exhaust Emission Control and Animal Toxicology Study

Dr. John C. Wall
Dr. Jacob McDonald

CARB Chairman's Research Seminar Series
February 28, 2012

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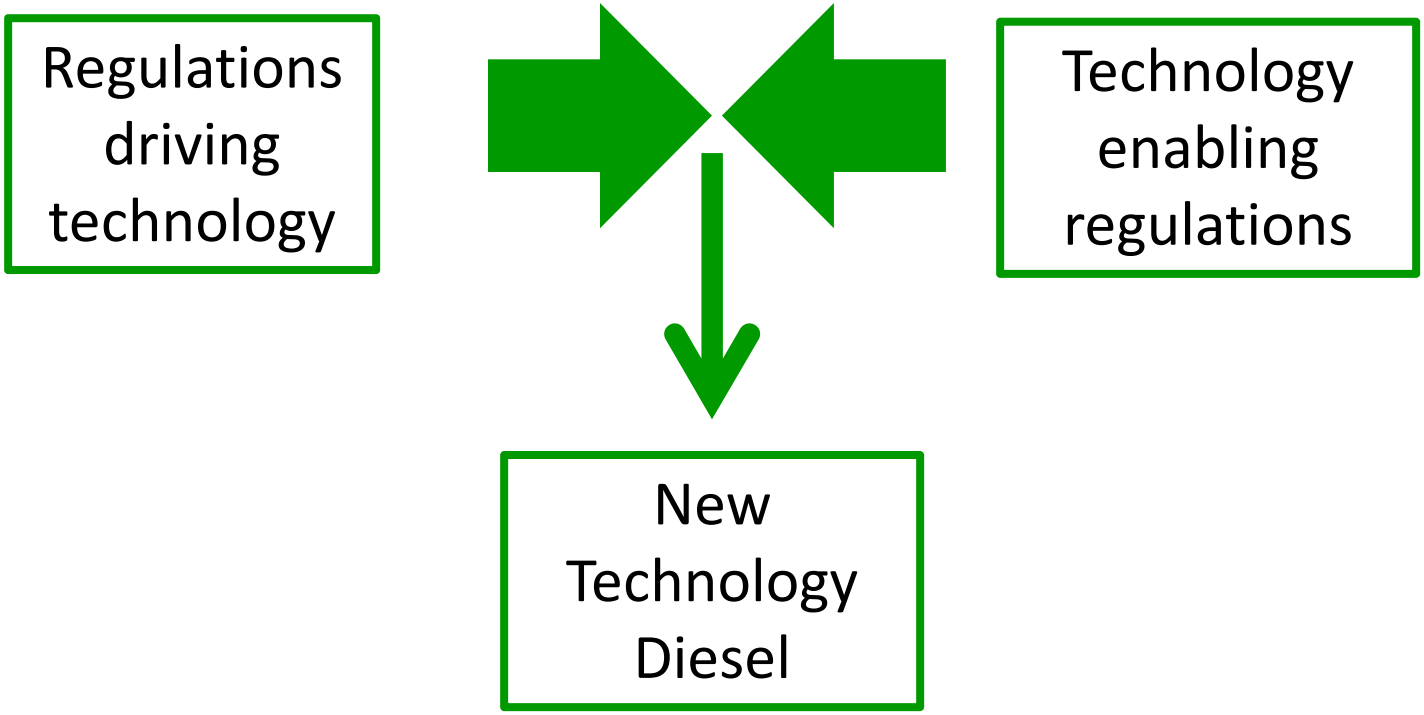
Chairman's Seminar: New Technology Diesel

- Evolution of Diesel Emission Control Technologies and Characteristics of New Technology Diesel Exhaust
  - John Wall

- Advance Collaborative Emissions Study (ACES) – The First Animal Toxicology Study of NTDE
  - Jacob McDonald

Recognize the significant progress we have made together



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Our Products Must Meet Customer Requirements

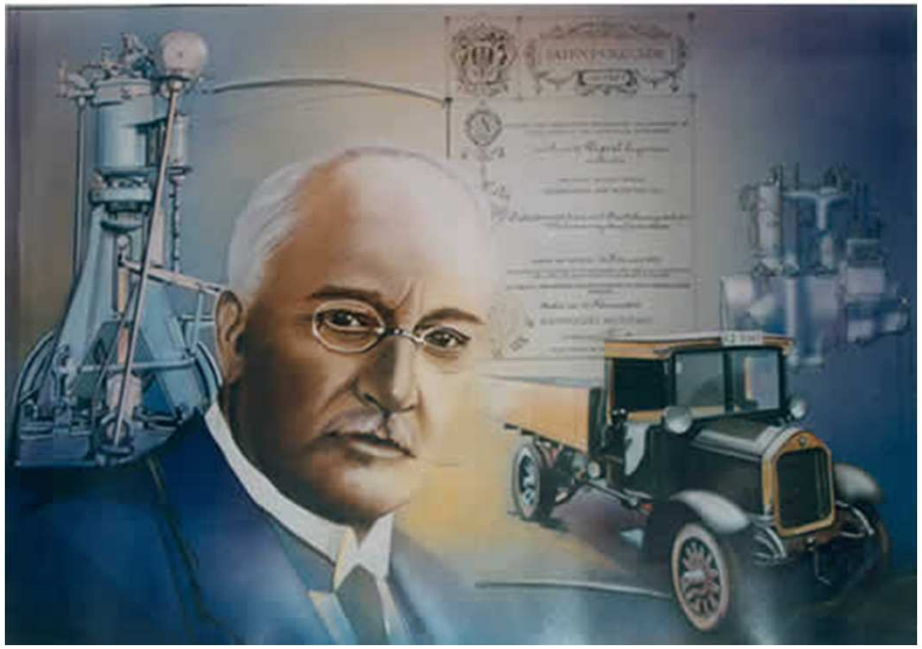
Our Products Must Meet Customer Requirements

Terminology

- TDE – “Traditional Diesel Exhaust”
- NTDE – “New Technology Diesel Exhaust”

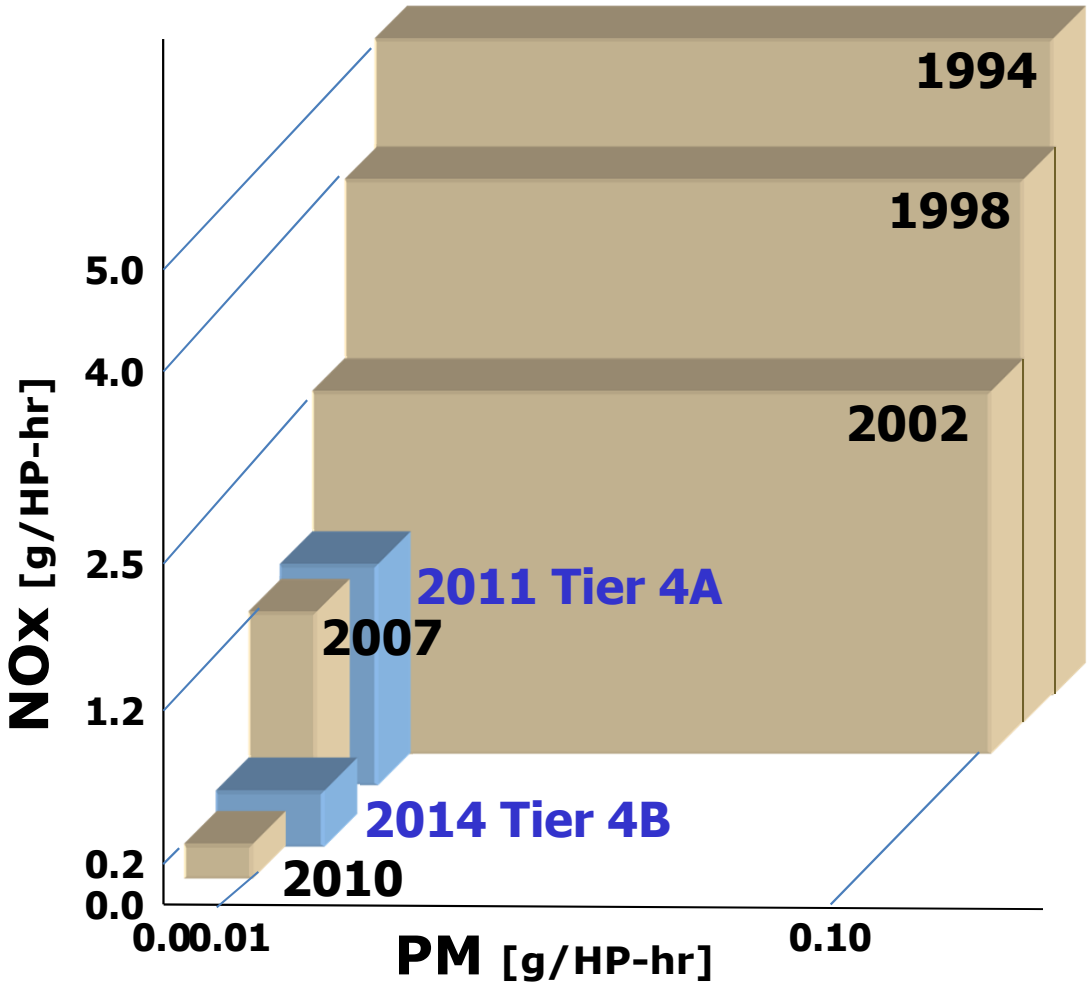
Historical Perspective

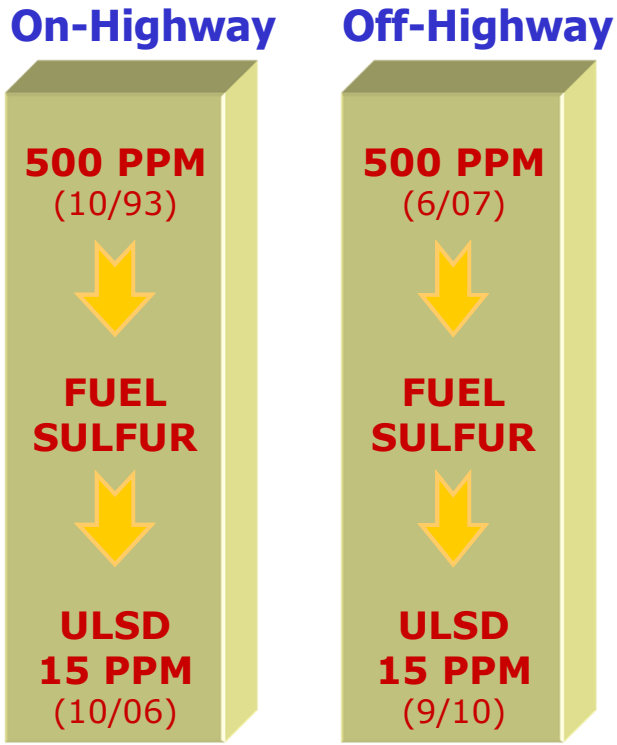
"So much has been written and said about the diesel engine in recent months that it is hardly possible to say anything new."



Rudolf Diesel, c. 1910

Evolution of US Heavy Duty Diesel Emission Standards





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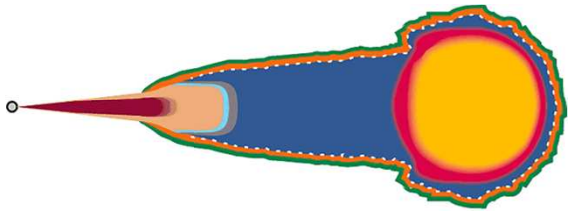
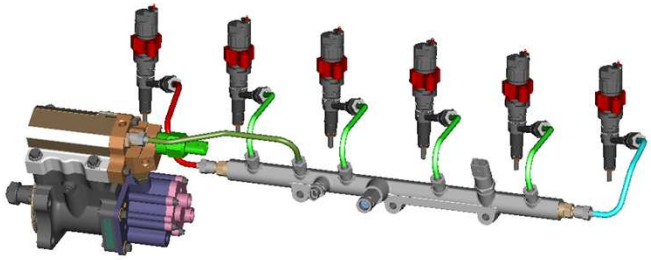
Diesel Technology Development: Critical Subsystems





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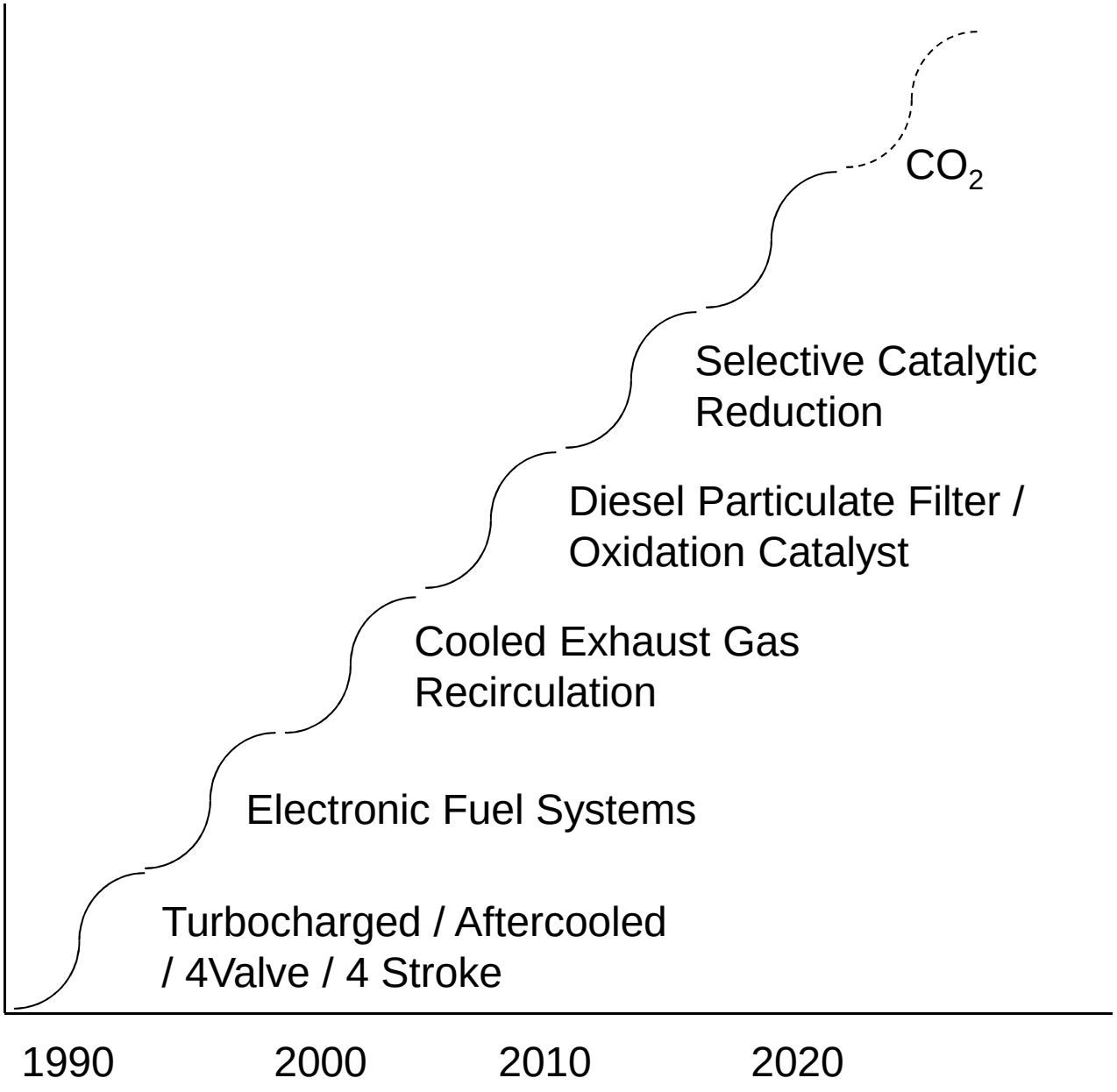
Evolution of Diesel Technology



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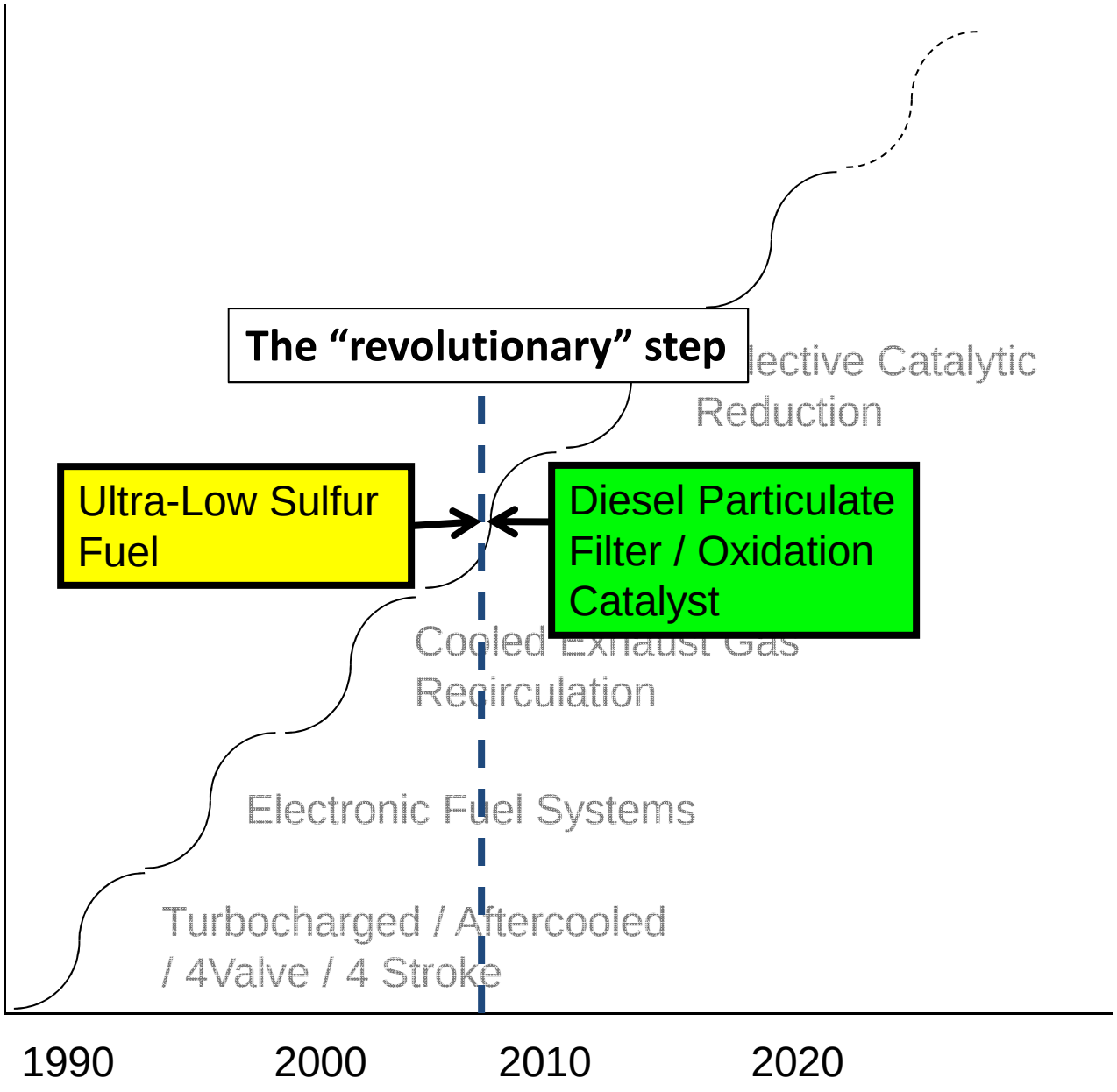
Evolution of Diesel Technology



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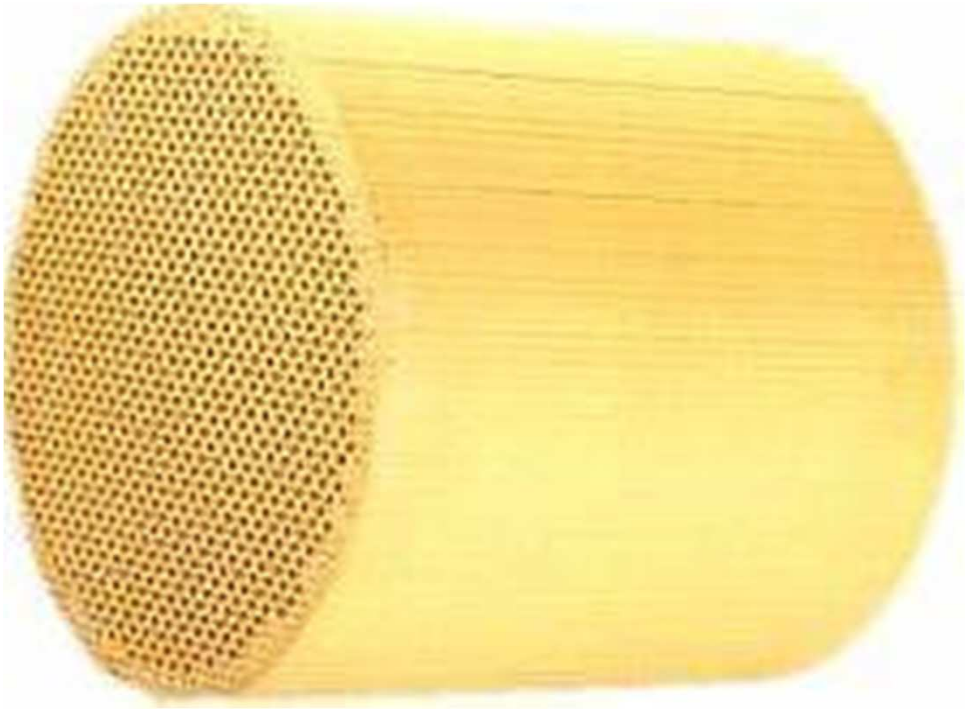
2007 And Beyond . . .
Integrating Engine and Aftertreatment

Active Particulate Filter



2007 And Beyond . . .
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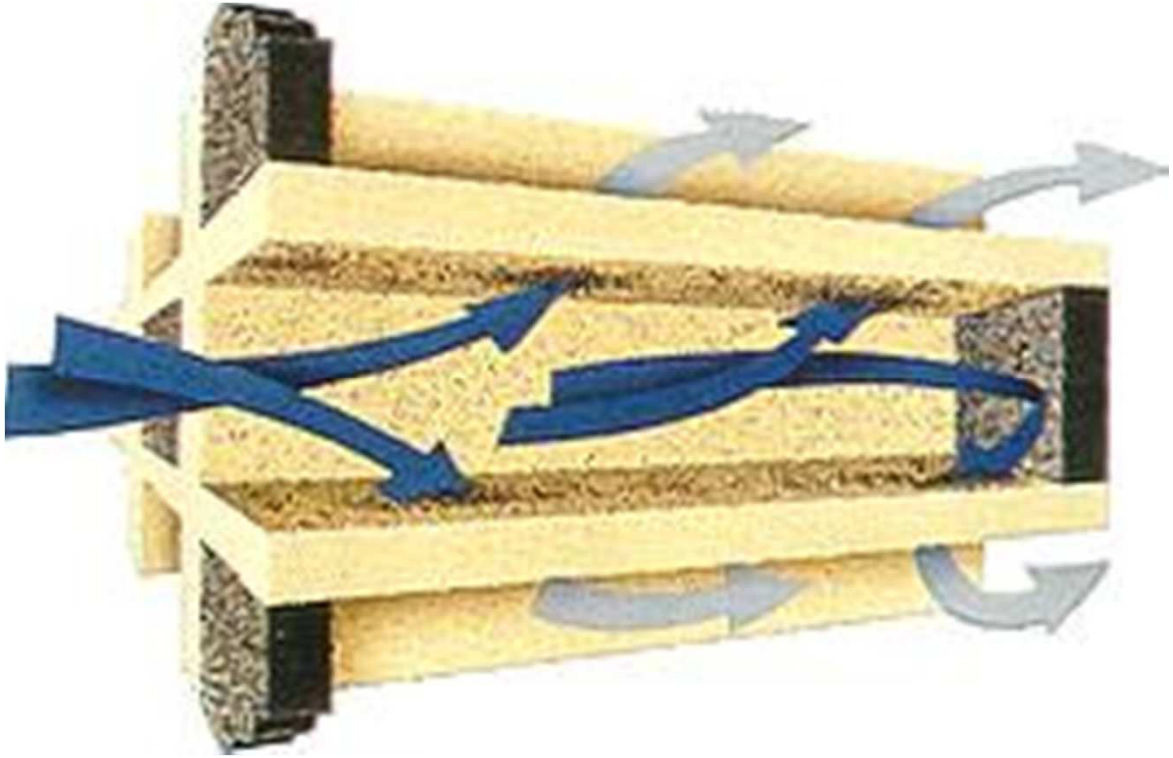

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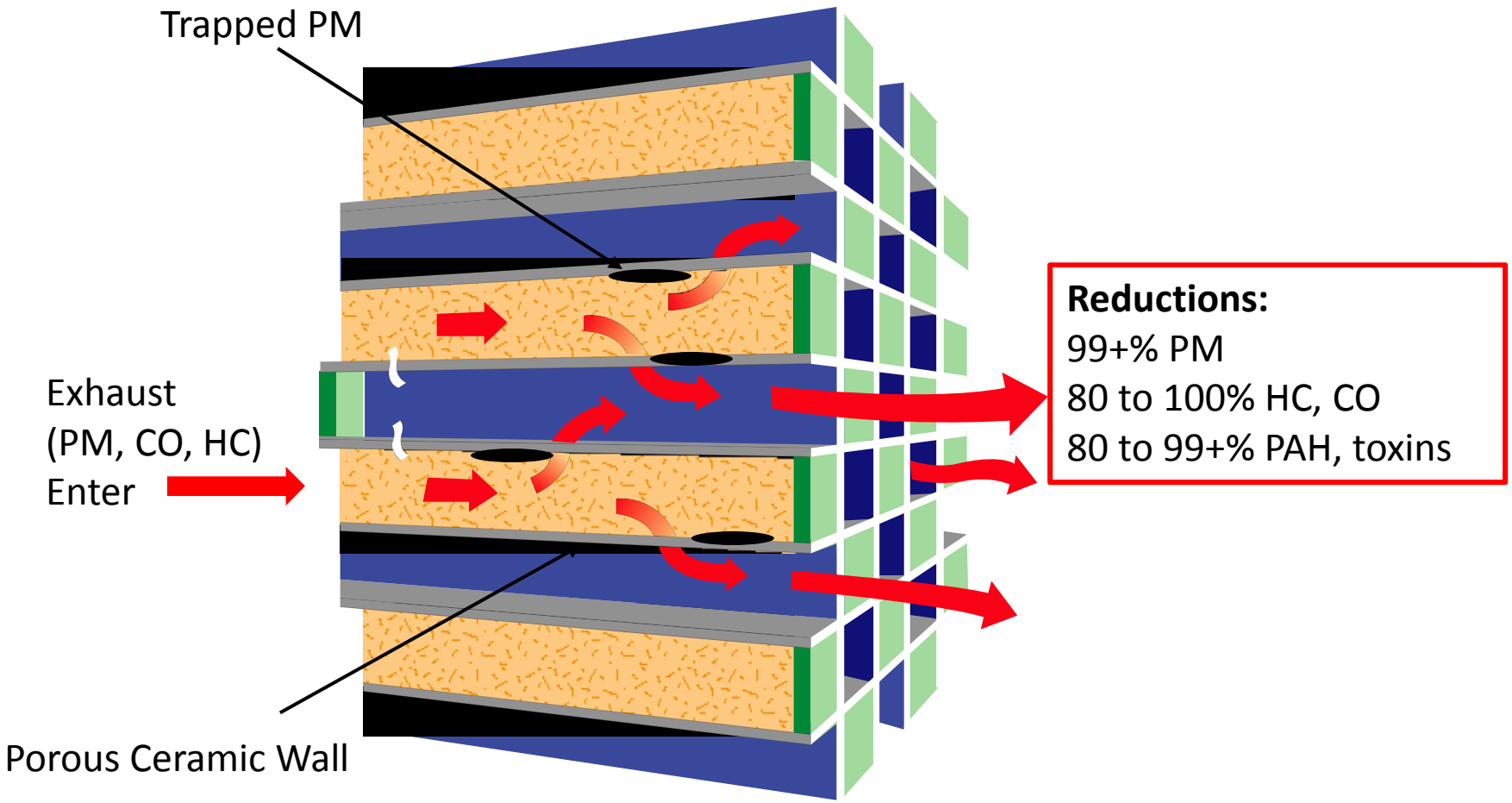
Key to Emissions Reductions in NTDE

Wall-flow Diesel Particulate Filter



Adapted from MECA May 2000

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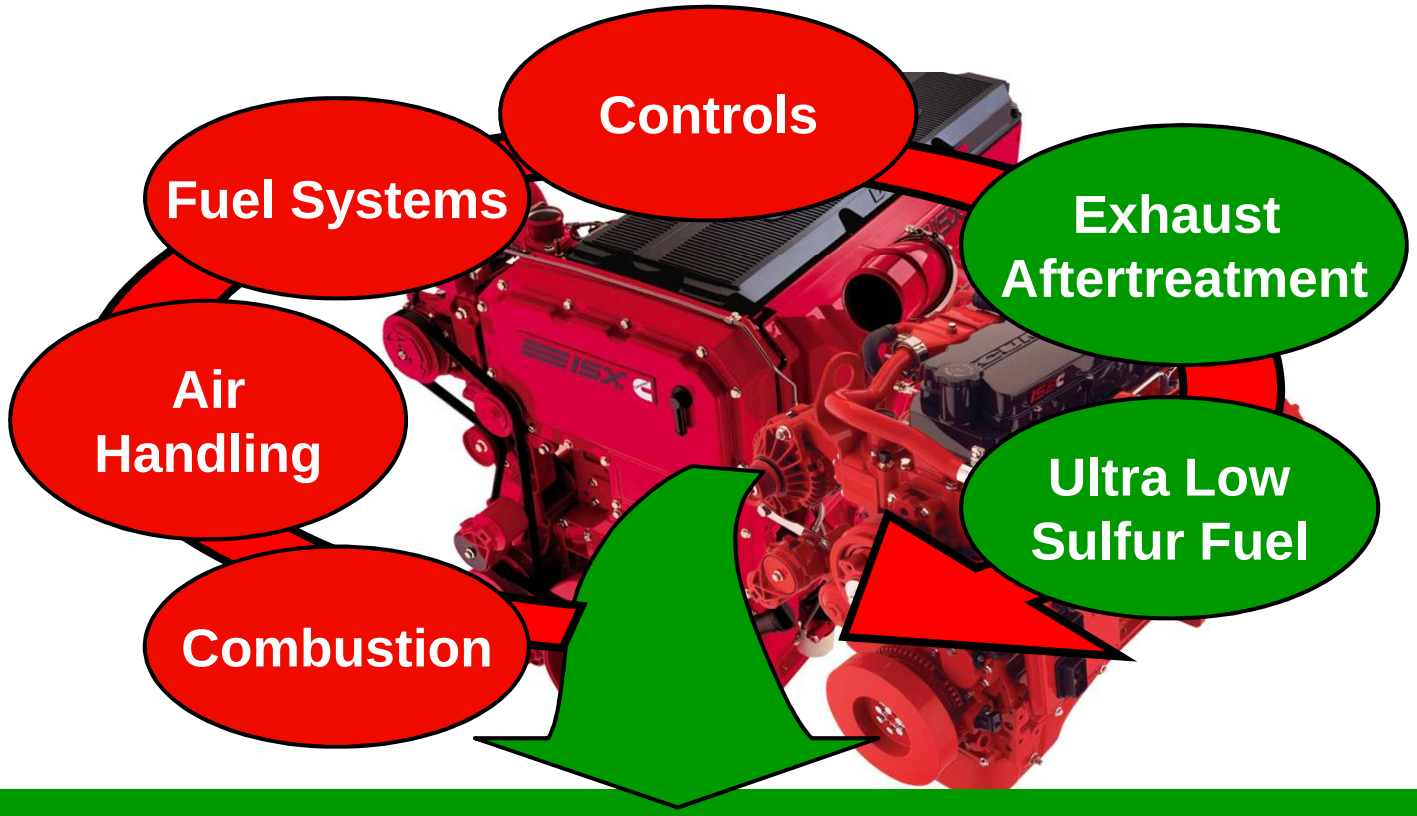
Transition to Clean "New Technology" Diesel: Advanced Component Technologies and System Integration

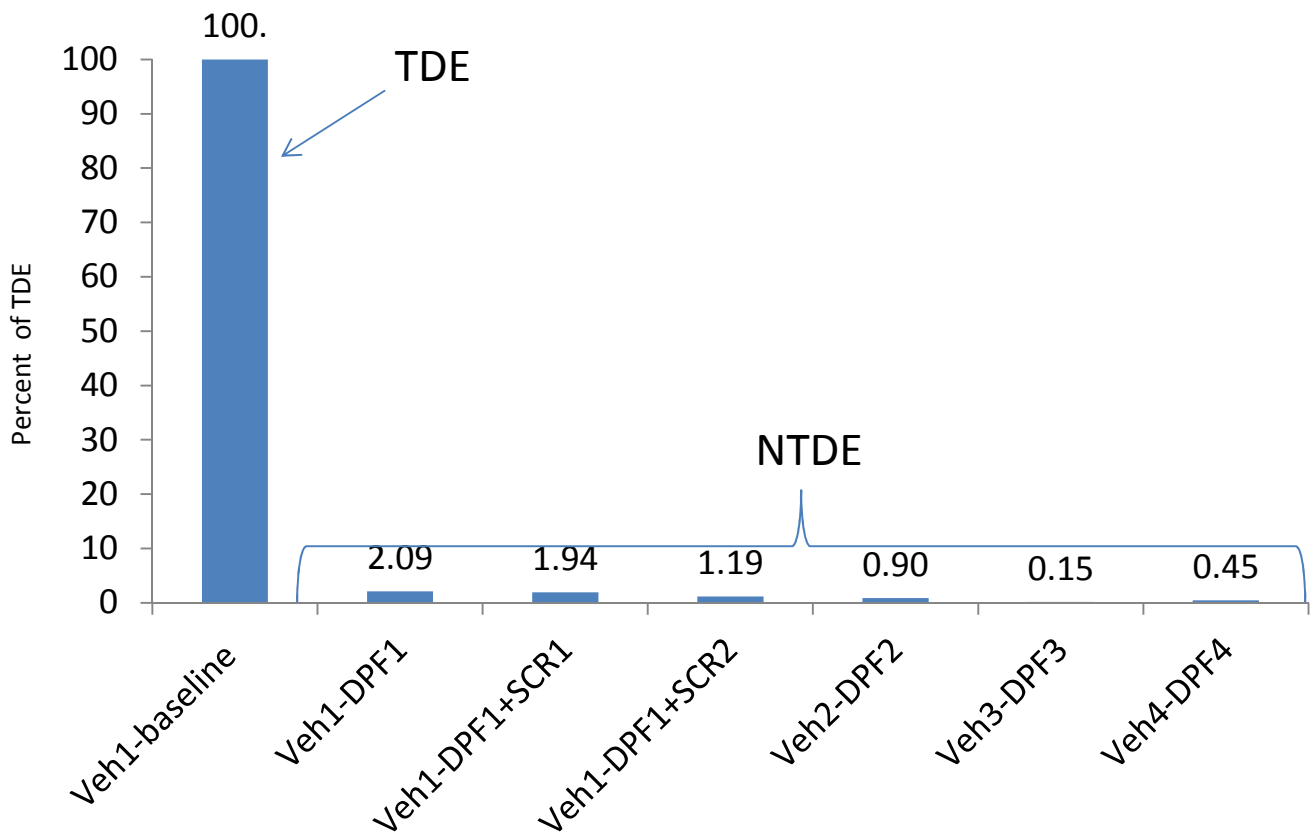


New Technology Diesel

New Technology Diesel

- PM levels in New Diesel Technology Exhaust (NTDE) are more than 100-fold lower than in TDE
  - NTDE NOx and PM mass emissions are comparable to CNG and gasoline
- NTDE PM is chemically different from TDE PM

NTDE: Lower Particulate Emissions



CARB Study: Herner et al., EST 43:5928-5933, 2009, data from Table 2. Transit Buses: UDDS Test Cycle

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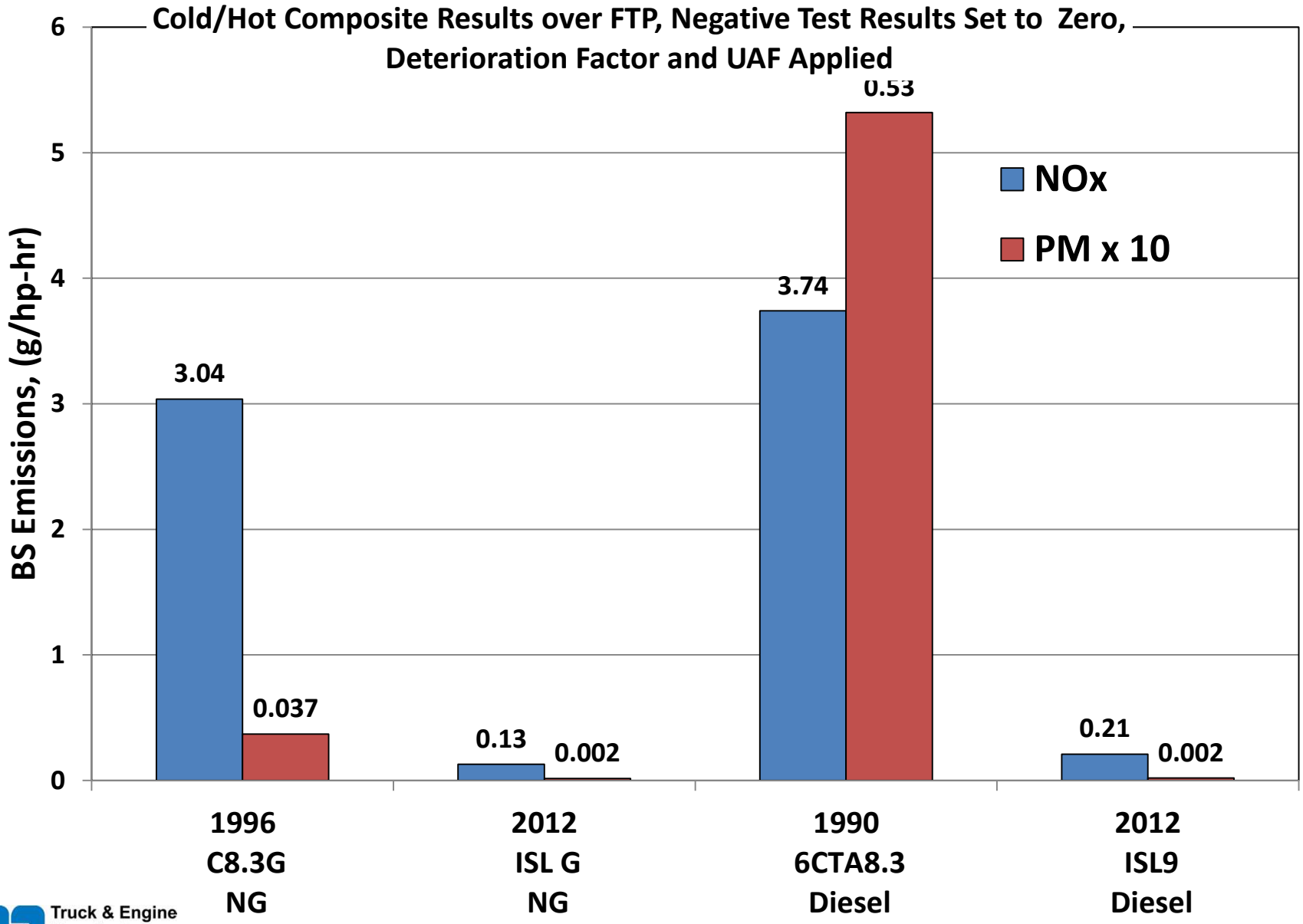
Cummins Certification Emissions Levels



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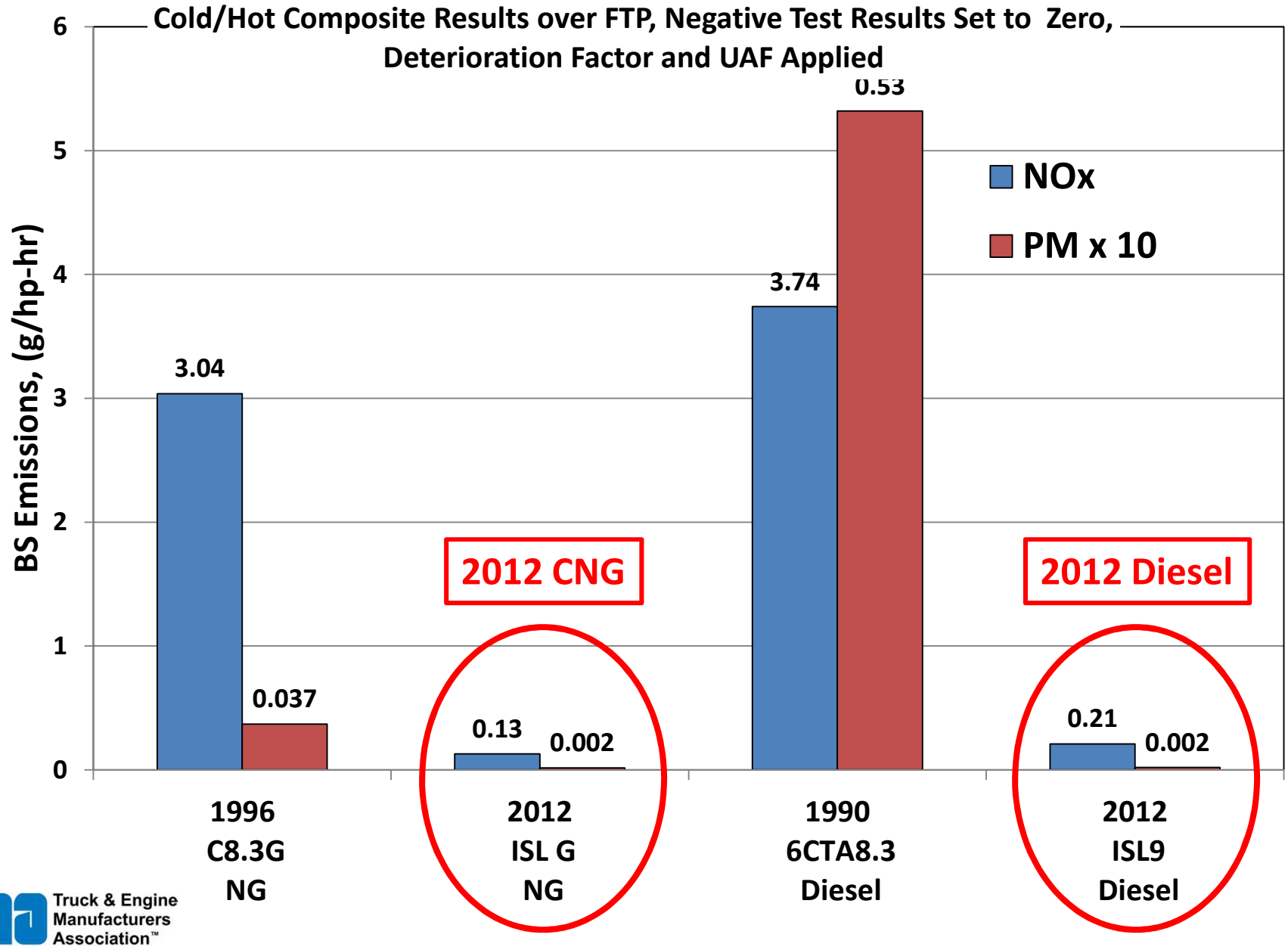
Cummins Certification Emissions Levels



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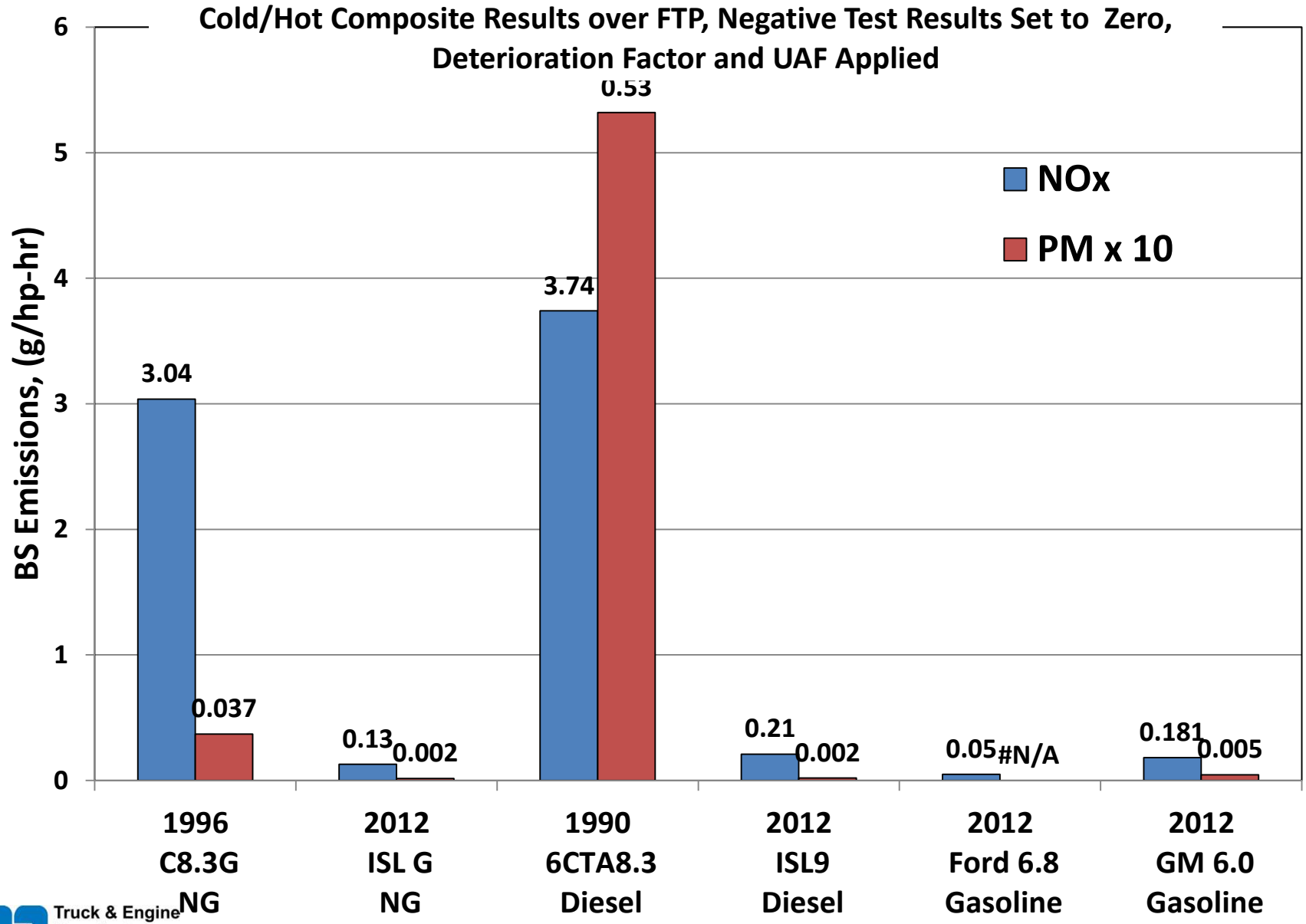
Cummins and Others - Certification Emissions Levels



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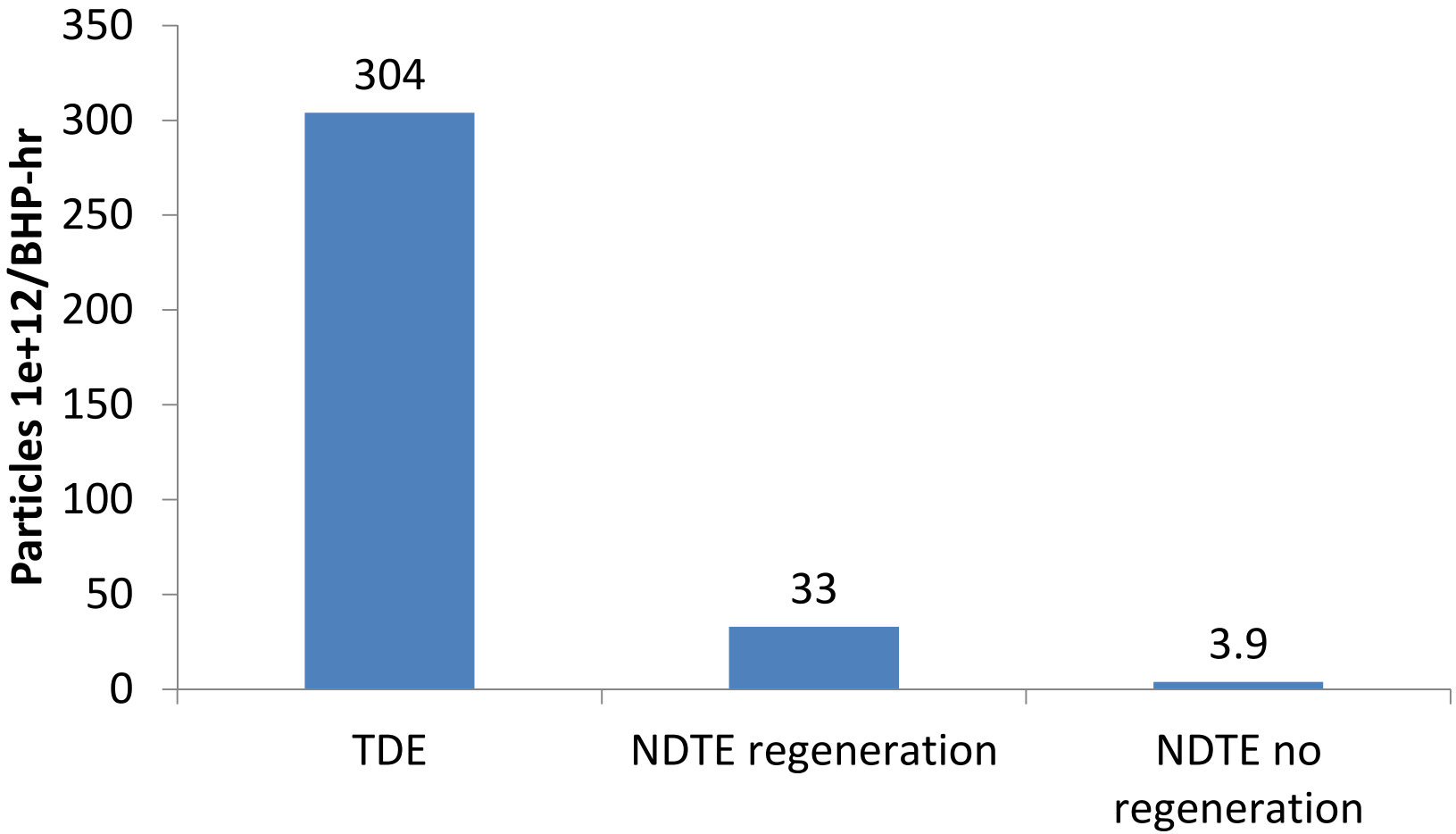
NTDE: Lower Particulate *Numbers*



ACES Study: Khalek et al., CRC, 2009.

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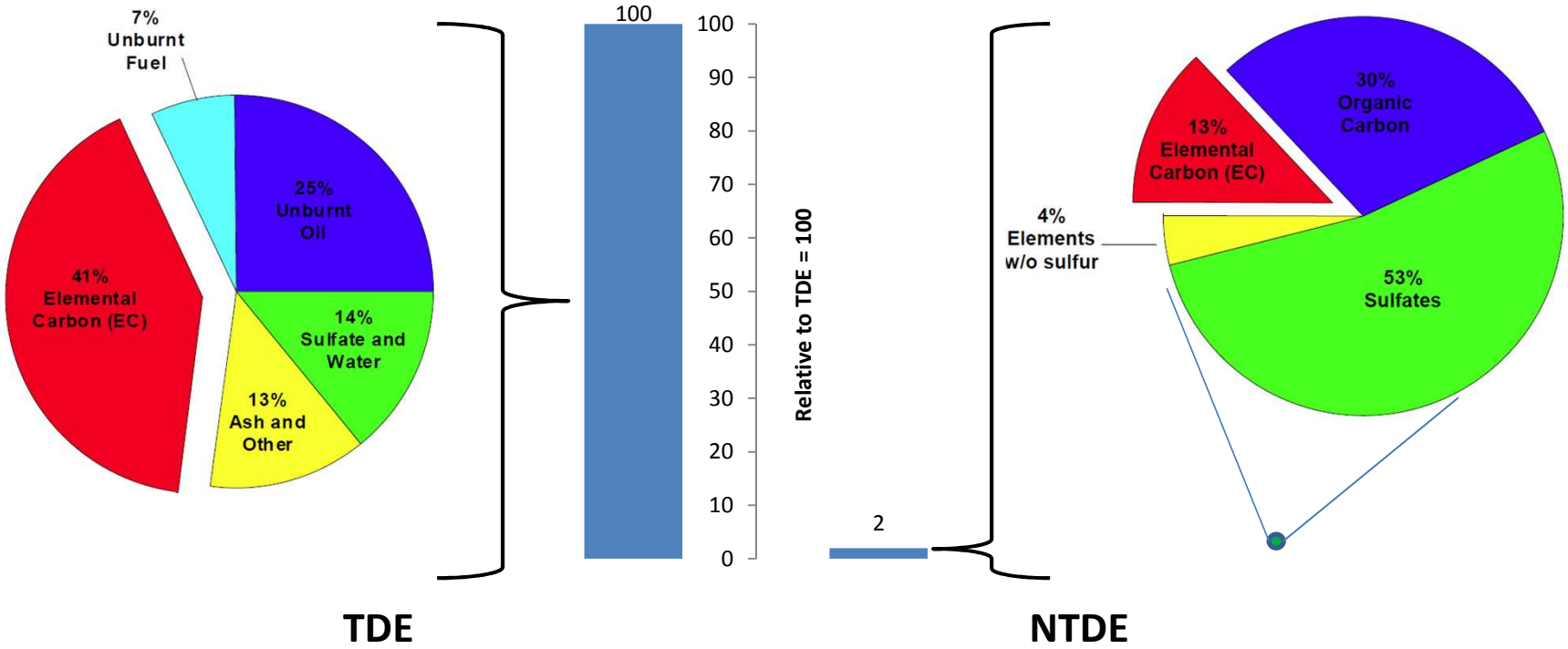
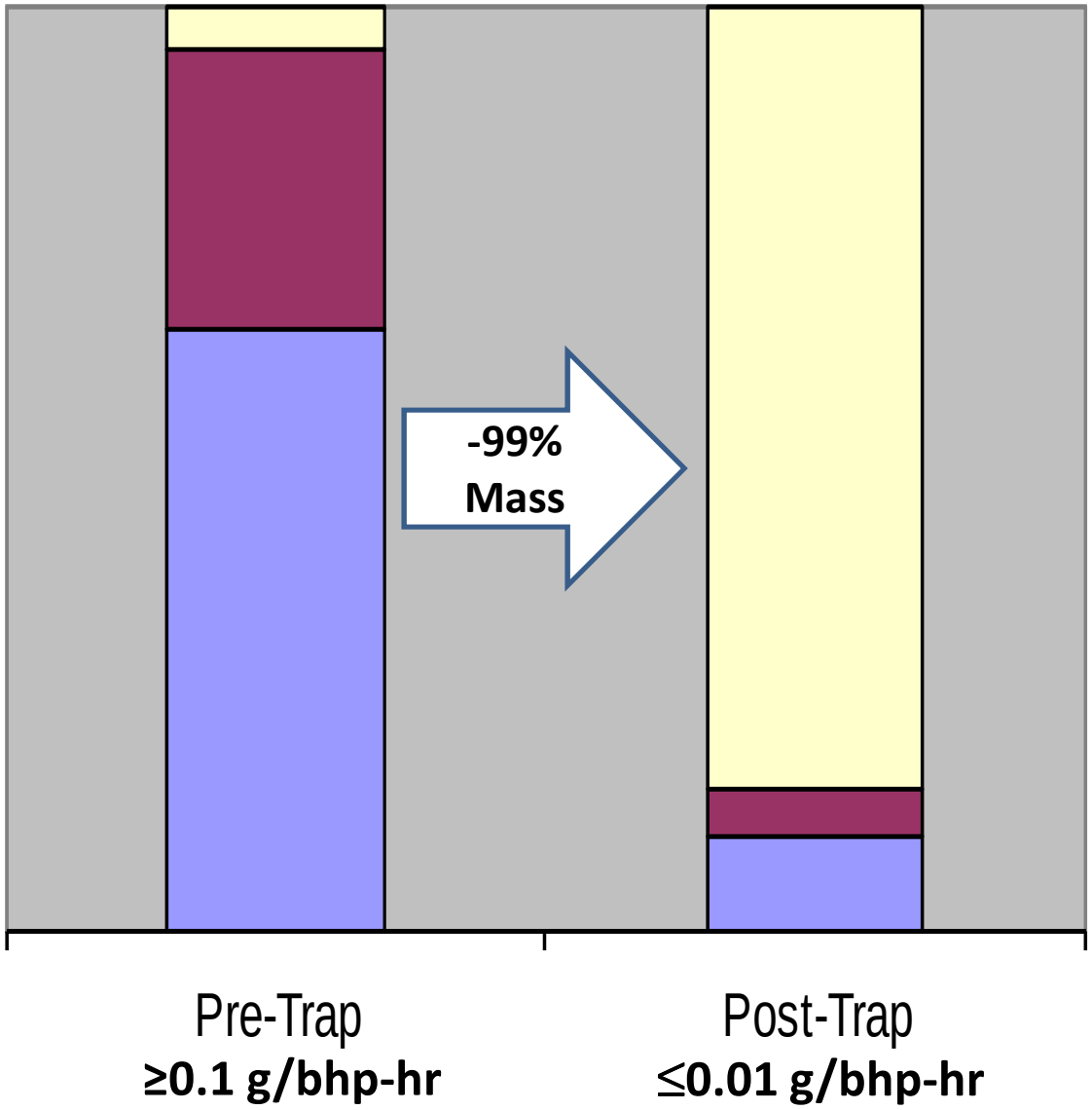
NTDE: Less PM and Composition Very Different



[Kittelson, 1998]

[ACES, 2009]

Particulate Matter Composition Breakdown



- Sulfate/Nitrate
- Hydrocarbons (Fuel + Lube derived)
- Elemental Carbon + Ash

Cummins ISM 2007; Liu et al. , Aerosol Science and Technology, 43/11: 1142-52 2009

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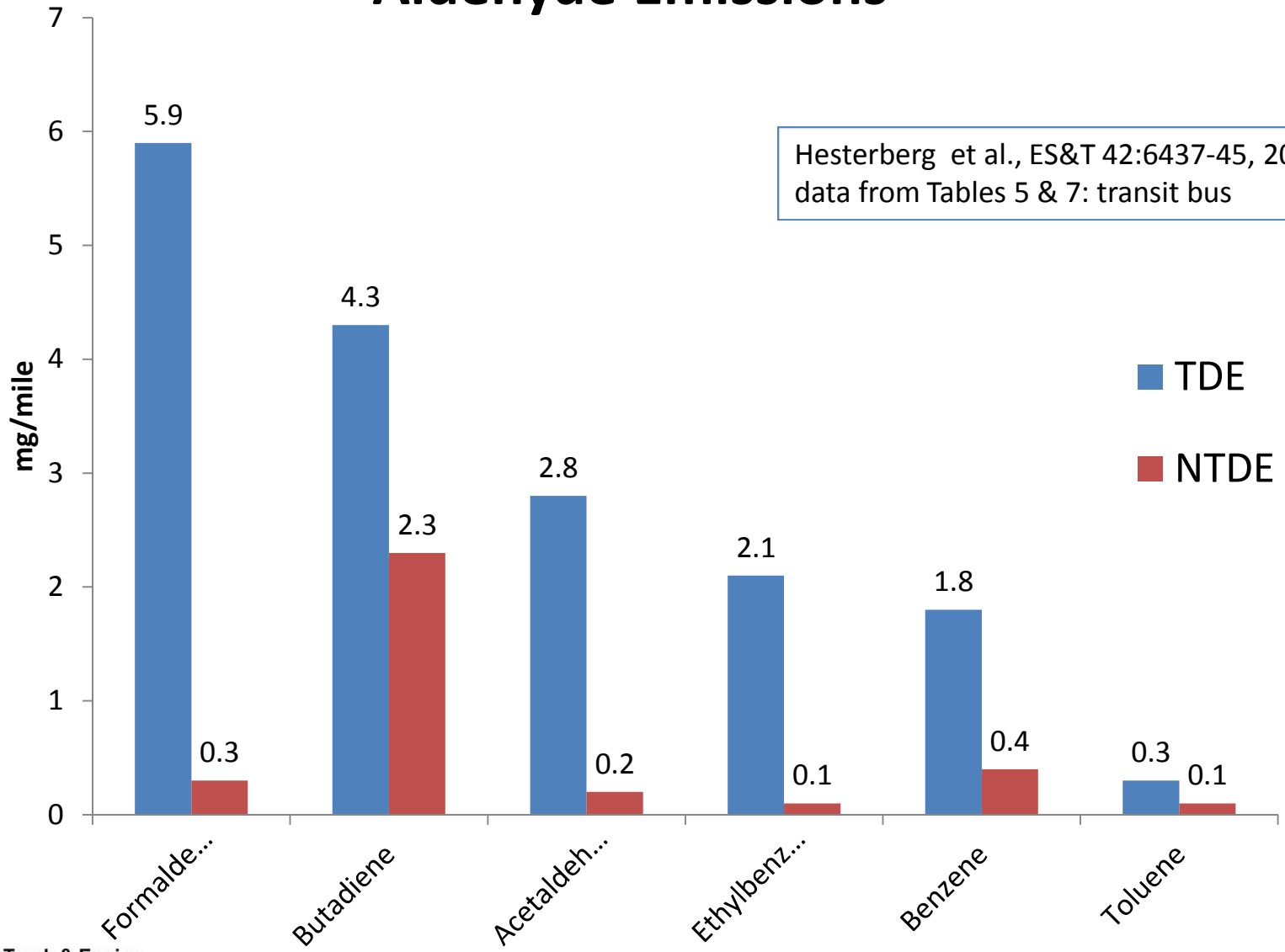
NTDE: Lower Volatile Organic Compound and Aldehyde Emissions



Hesterberg et al., ES&T 42:6437-45, 2008, data from Tables 5 & 7: transit bus

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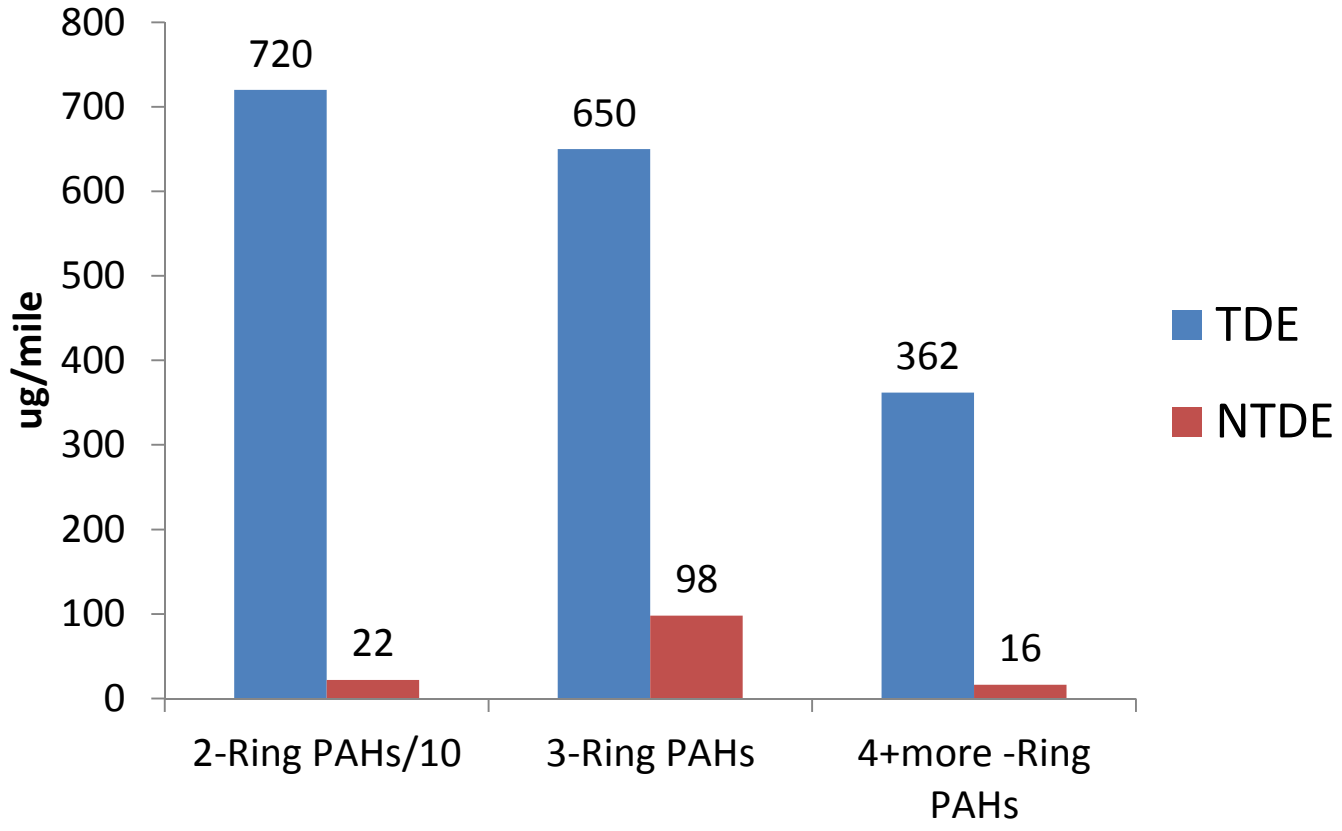
NTDE: Lower Polycyclic Aromatic Hydrocarbon Emissions



Hesterberg et al., ES&T 42:6437-45, 2008, data from Tables 8 & 9: transit bus

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Comprehensive exhaust chemical assays have been published documenting orders of magnitude reduction in complex hydrocarbon and nitro-PAH concentrations for NTDE …

Compound (carbon number)	2004 Engine[a]			2007 Engine[a]			% Reduced
Elemental carbon	49 700	±	3550	150	±	38.2	99.7 ± 7.2
Organic carbon	37 800	±	4360	213	±	101	99.4 ± 11.8
Organic mass	45 300	±	5230	256	±	121	99.4 ± 11.8
n-Alkanes							
n-Undecane (11)	< 0.01	±	2.97	1.04	±	1.76	–
n-Dodecane (12)	<0.01	±	0.795	0.279	±	0.286	–
n-Tridecane (13)	2.25	±	0.859	<0.01	±	0.186	>99.6 ± 46.4
n-Tetradecane (14)	10.4	±	2.64	<0.01	±	0.203	>99.9 ± 27.3
n-Pentadecane (15)	34.4	±	5.52	<0.01	±	0.00	>99.9 ± 16.0
n-Hexadecane (16)	84.6	±	13.4	<0.01	±	0.00	>99.9 ± 15.8
n-Heptadecane (17)	96.5	±	10.7	<0.01	±	0.193	>99.9 ± 11.3
n-Octadecane (18)							
n-Nonadecane (19)							
n-Eicosane (20)							
n-Heneicosane (21)							
n-Docosane (22)							
n-Tricosane (23)							
n-Tetracosane (24)							
Branched alkanes							
Norpristane (18)							
Pristane (19)							
Phytane (20)							
Saturated cycloalkanes							
Dodecylcyclohexane (18)							
Pentadecylcyclohexane (21)							
Hexadecylcyclohexane (22)							
Heptadecylcyclohexane (23)							
Octadecylcyclohexane (24)							
Nonadecylcyclohexane (25)							
Aromatics							
Biphenyl (12)							
2-Methylbiphenyl (13)							
3-Methylbiphenyl (13)							
4-Methylbiphenyl (13)							
PAHs, POM, and Derivatives							
Naphthalene (10)							
2-Methylnaphthalene (11)							
1-Methylnaphthalene (11)							
Dimethylnaphthalenes (12)							
Trimethylnaphthalenes (13)	935	±	45.9	38.8	±	3.95	95.9 ± 5.3
1-Ethyl-2-methylnaphthalene (13)	115	±	14.1	4.25	±	1.18	96.3 ± 13.3
2-Ethyl-1-methylnaphthalene (13)	6.83	±	1.59	0.673	±	0.193	90.1 ± 26.1
Anthracene (14)	7.38	±	1.00	0.862	±	0.385	88.3 ± 18.8
Phenanthrene (14)	78.6	±	11.3	12.3	±	3.62	84.4 ± 19.0
Methylphenanthrenes (15)	85.4	±	9.49	3.30	±	0.460	96.1 ± 11.7
Dimethylphenanthrenes (16)	66.9	±	5.33	1.17	±	0.239	98.3 ± 8.3
Fluorene (13)	131	±	20.6	12.9	±	3.54	90.2 ± 18.4
Methylfluorenes (14)	0.00	±	0.00	10.9	±	3.91	–
Fluoranthene (16)	4.31	±	0.137	1.13	±	0.564	73.8 ± 16.3
Pyrene (16)	11.7	±	1.20	0.979	±	0.649	91.6 ± 15.8
Acenaphthalene (12)	30.5	±	1.88	2.18	±	1.42	92.9 ± 10.8
Acenaphthene (12)	45.5	±	6.55	22.0	±	21.1	51.6 ± 60.8
Chrysene + triphenylene (18)	1.05	±	0.133	0.123	±	0.109	88.3 ± 23.0
Benz[a]anthracene (18)	0.586	±	0.0579	0.0632	±	0.0698	89.2 ± 21.8
Benzo[g,h,i]fluoranthene (18)	0.607	±	0.593	0.258	±	0.270	57.5 ± 142
Benzo[b + k + j]fluoranthene (20)	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]
Benzo[a]pyrene (20)							
Benzo[e]pyrene (20)							
Benzo[g,h,i]perylene (22)							
Nitro-PAHs							
1-Nitronaphthalene (10)							
2-Nitronaphthalene (10)							
Methylnitronaphthalenes (11)							
2-Nitrobiphenyl (12)							
4-Nitrobiphenyl (12)							
1-Nitropyrene (16)							
9-Nitroanthracene (14)							
Oxygenated PAHs							
Acenaphthenequinone (12)							
9-Fluorenone (13)							
Xanthone (13)							
Perinaphthanone (13)	29.7	±	4.33	1.01	±	0.288	96.6 ± 15.5
Anthraquinone (14)	5.16	±	0.886	1.30	±	0.506	74.8 ± 27.0
9-Anthraaldehyde (15)	1.56	±	0.829	0.0388	±	0.0291	97.5 ± 55.0
Benzanthrone (17)	1.89	±	0.109	0.0154	±	0.00973	99.2 ± 6.3
Aliphatic aldehydes							
Formaldehyde (1)	5160	±	2440	<0.01	±	58.1	>99.9 ± 48.4
Acetaldehyde (2)	1480	±	783	<0.01	±	43.1	>99.9 ± 55.8
Hopanes							
17α(H)-22,29,30-Trisnorhopane (27)	0.430		0.0658	<0.01		0.00	97.7 ± 15.3
17α(H),21β(H)-Hopane (30)	1.67		0.0558	0.0109		0.0109	99.3 ± 4.0
22S-17α(H),21β(H)-29-Homohopane (31)	0.925		0.0309	<0.01		0.00	98.9 ± 3.3
22R-17α(H),21β(H)-29-Homohopane (31)	0.545		0.284	<0.01		0.00	98.2 ± 52.1
22S-17α(H),21β(H)-29,30-Bishomohopane (32)	2.11		1.60	<0.01		0.00	99.5 ± 75.8
22R-17α(H),21β(H)-29,30-Bishomohopane (32)	0.288		0.144	<0.01		0.00	96.5 ± 50.0
22R-17α(H),21β(H)-29,30,31-Trishomohopane (33)	5.33		5.33	<0.01		0.00	–
Steranes							
20S-5α(H),14α(H),17α(H)-Cholestane (27)	5.89		4.87	<0.01		0.00	99.8 ± 82.7
20R-5α(H),14β(H),17β(H)-Cholestane (27)	0.576		0.0438	<0.01		0.00	98.3 ± 7.6
20S-5α(H),14β(H),17β(H)-Cholestane (27)	0.749		0.0729	<0.01		0.00	98.7 ± 9.7

[a] Values are reported in μg (bhp*h)$^{-1}$, uncertainty is given as the standard error of the test results.

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Liu, et al. (2010), Atmospheric Environment, 44: 1108-15.

NTDE Reduces Emissions Across a Broad Spectrum of Compounds

Category	Reduction Relative to TDE
Single Ring Aromatics	82%
PAH	79%
Alkanes	85%
Hopanes/Steranes	99%
Alcohols & Organic Acids	81%
Nitro-PAHs	81%
Carbonyls	98%
Inorganic Ions	71%
Metals & Elements	98%
Organic Carbon	96%
Elemental Carbon	99%
Dioxins/Furans	99%

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Khalek et al. 2010, Table 6

Conclusions

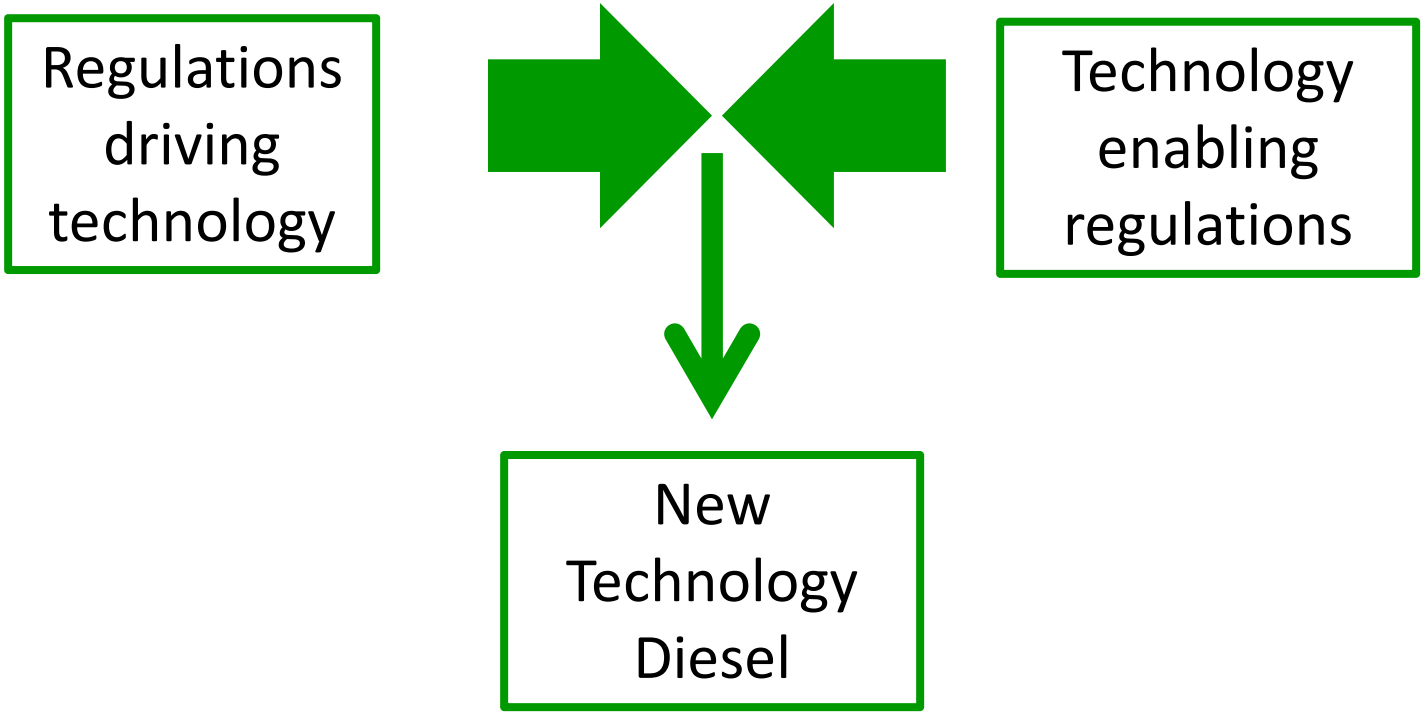
- New Technology Diesel Engines, specifically engines operating on Ultra Low Sulfur Diesel fuel and employing oxidation catalysts and wall-flow particulate filters, have fundamentally different (and significantly better!) exhaust characteristics than Traditional Diesel Engines
  - 99+% reduction in particulate mass
  - Chemically different particulate composition

Conclusions

- The best emissions policy and technology come through effective and deep collaboration between government regulatory agencies and industry...

… and Meet the Needs of Our Customers

Recognize the significant progress we have made together



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