Meeting of the

Mobile Sources Technical Review Subcommittee

Clean Air Act Advisory Committee

Washington, D.C.

January 17, 2001

EPA HDEWG Program

PHASES
1,2, & 3

EPA Heavy-Duty Engine Working Group *(EPA HDEWG)*

- **Established in December 1995 by MSTRS**
- **Co-Chairs:**
  - John Wall - Cummins, Tom Bond - BP Amoco
- **Steering Committee Membership**
  - EPA, Cummins, Caterpillar, International, Ford, BP Amoco, Equilon, Exxon/Mobil, Phillips, EMA, API, NPRA
- **General Membership (~30)**
  - EPA, OEMs, Refiners, States, Consultants, Academics

EPA Heavy-Duty Engine Working Group

- **Objective:**
  - Contribute to EPA's 1999 technology review of exhaust emission standards for model year 2004+ heavy-duty diesel engines by assessing relative merits of achieving the 2.5 g/HP*h NOx+NMHC emission level either through:
    - engine system modifications, or
    - a combination of engine system and fuel modifications
- **Target Completion:**
  - Mid-1999

EPA-HDEWG Program Phases

- **Phase 1** was designed to assess current literature and identify a representative (transparent) test engine; completed April 1997
- **Phase 2** was an investigation of diesel fuel and engine system effects on exhaust emissions of the "transparent" CAT 3176 engine; completed January 1999
- **Phase 3** was designed to ascertain if Phase 2 results are representative of "black box", advanced prototype, heavy-duty diesel engines currently being developed by engine manufacturers; completed October 2000

PHASE 1 PROGRAM

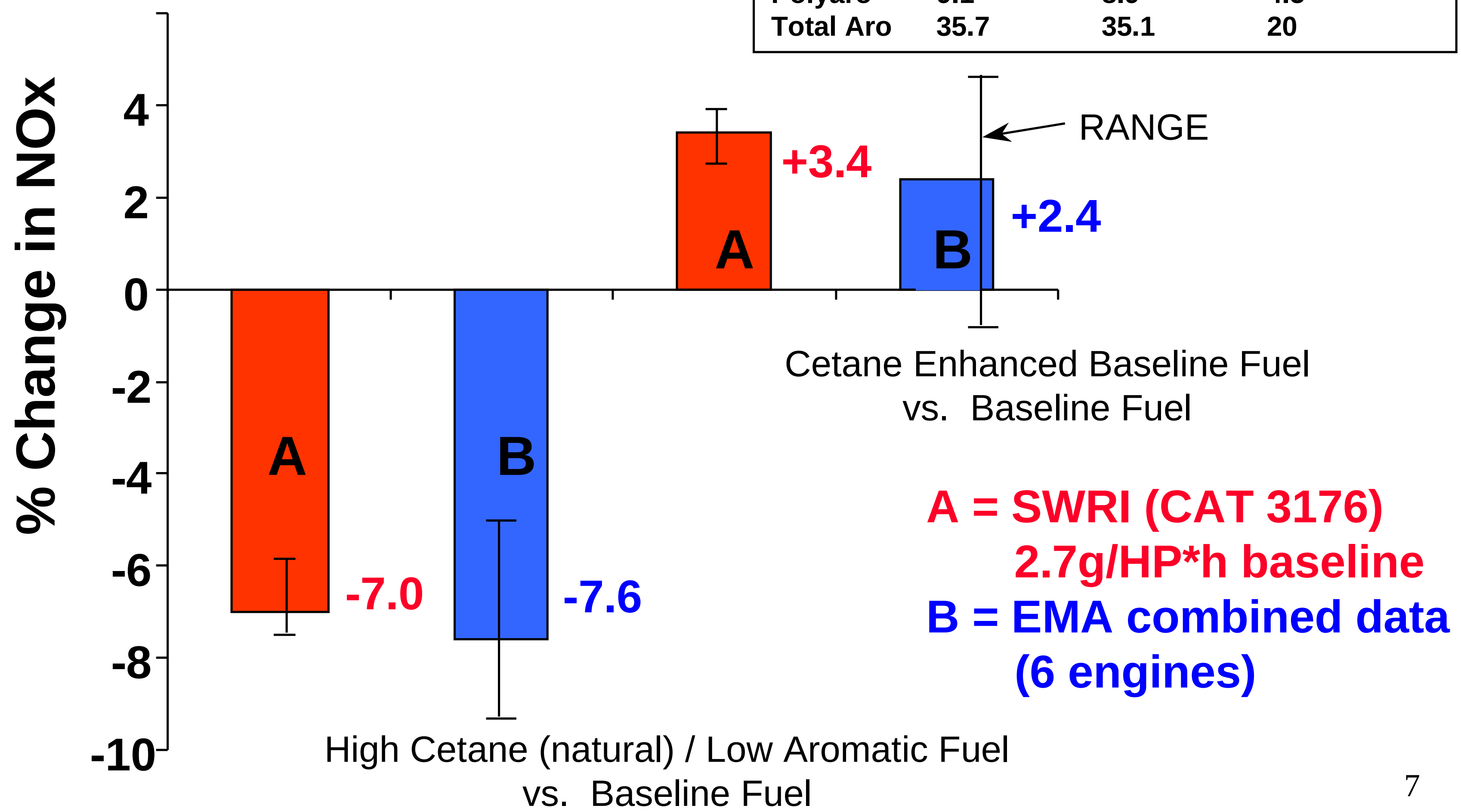
EPA HDEWG Program

- **Phase 1,** completed in April 1997, was aimed at establishing:
  - whether the combined effects of diesel fuel properties on exhaust emissions of "black box",prototype, heavy-duty diesel engines then being developed by engine manufacturers were large enough to warrant Phase 2,
  - whether the "transparent" Caterpillar 3176 heavy-duty diesel engine installed at SWRI was representative of "black box" engines with respect to diesel fuel effects on NOx emissions

Results of Phase 1 demonstrated that these criteria were met and triggered execution of Phase 2

Results of Phase 1 Testing

	Base	Base+CI	Hi CN/Lo Aro
Density	856	856	823
CN	45.9	52.4	56.9
Monoaro	26.6	26.2	15.5
Polyaro	9.1	8.9	4.5
Total Aro	35.7	35.1	20



PHASE 2 PROGRAM

Phase 2 Test Program

Fuel Matrix Design

- Based on a review of existing data and results of Phase 1, four fuel properties were selected for investigation: density, cetane number, monoaromatic and polyaromatic hydrocarbon content
- Sulfur content was not included as a variable because:
  - » Test engine was not equipped with any sulfur sensitive exhaust aftertreatment devices
  - » Particulate emission measurements were not planned (as explained below)
  - » Sulfur content has never been observed to affect engine-out NOx, HC or CO emissions

Phase 2 Test Program *(Continued)*

Fuel Matrix Design

- Effect of cetane number investigated at 3 levels (non-linear effects). Other variables evaluated at 2 levels
- Cetane number changes from base level achieved through use of ignition improver (ethylhexyl nitrate)

  Boosted cetane selected to simplify fuel blending. Literature survey indicated lack of significant differences in emission effects of natural and boosted cetane number

Phase 2 Test Program *(Continued)*

Fuel Matrix Design

- Numerous fuel matrix designs investigated with help of SwRI statistician
- Number of test fuels in fuel matrices evaluated ranged from 8 to 24. Twelve-fuel design selected
- Form of basic emission model:

  Emission = Intercept + a_1* Density + a_2* Cetane +

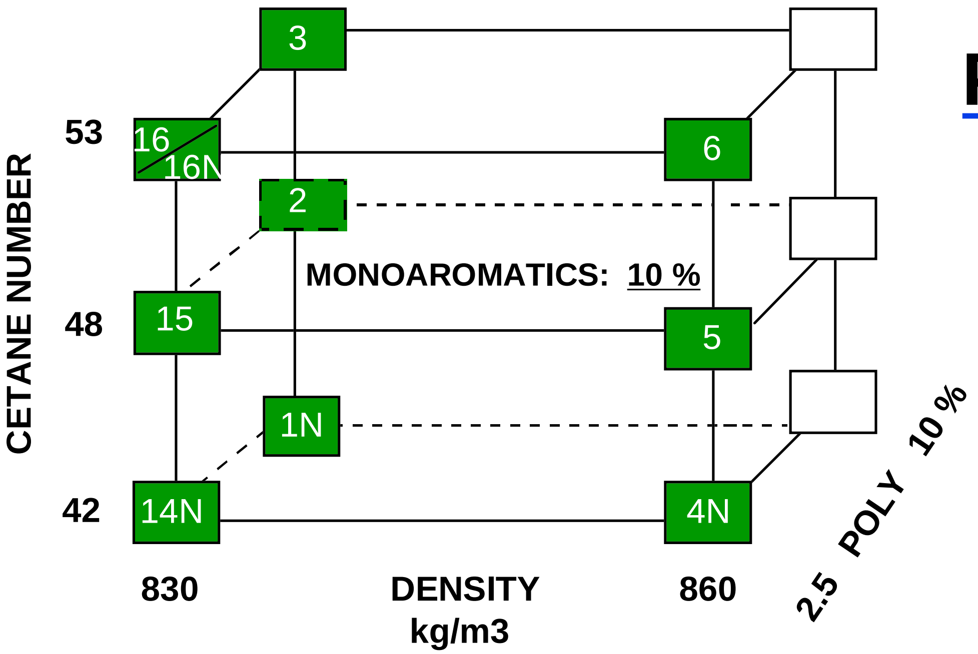
  a_3*Monoaro + a_4*Polyaro + a_5*(Cetane * Density) +

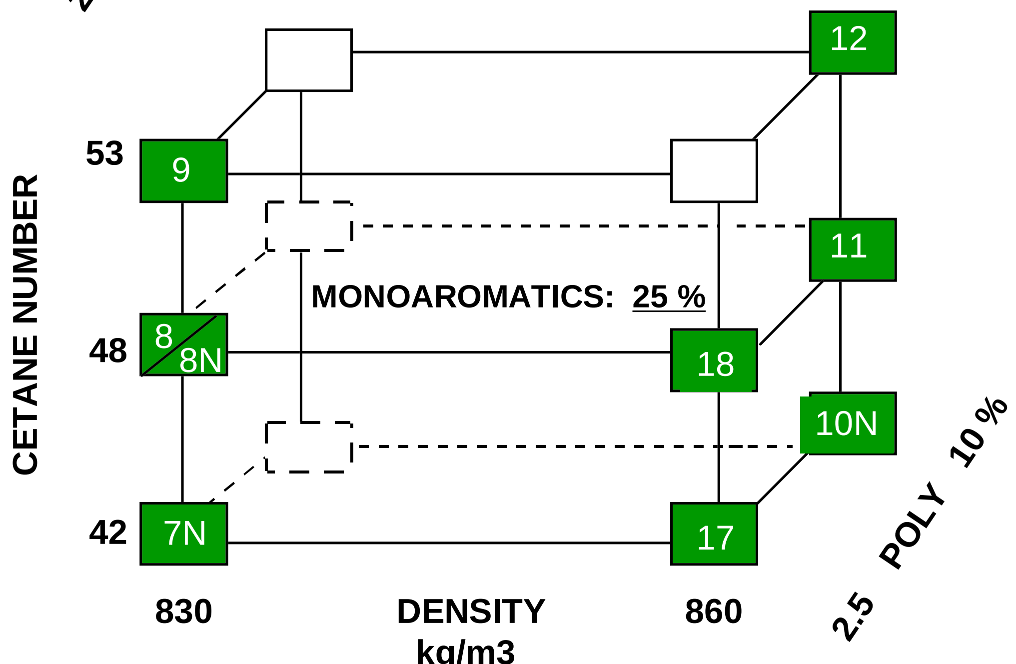
  a_6*(Cetane* Monoaro) + a_7*(Cetane* Polyaro)

- Additional fuels incorporated in the matrix to enable direct comparison of density effects as well as those of natural and boosted cetane number

Phase 2 Test Program

Test Fuel Matrix





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Phase 2 Test Program *(Continued)*

Test Fuel Development

- Based on adopted design of the fuel matrix, 18 test fuel were developed: 7 base fuels and 11 cetane boosted fuels
- Density: 830 and 860 kg/m^3
- Cetane Number: 42, 48 and 53
- Monoaromatics: 10 and 25%
- Polyaromatics: 2.5 and 10%
- Distillation properties were tightly controlled
- Sulfur content capped at 470ppm, otherwise uncontrolled
- Fuels developed with sole purpose of investigating fuel effects on emissions. Commercial viability was not considered

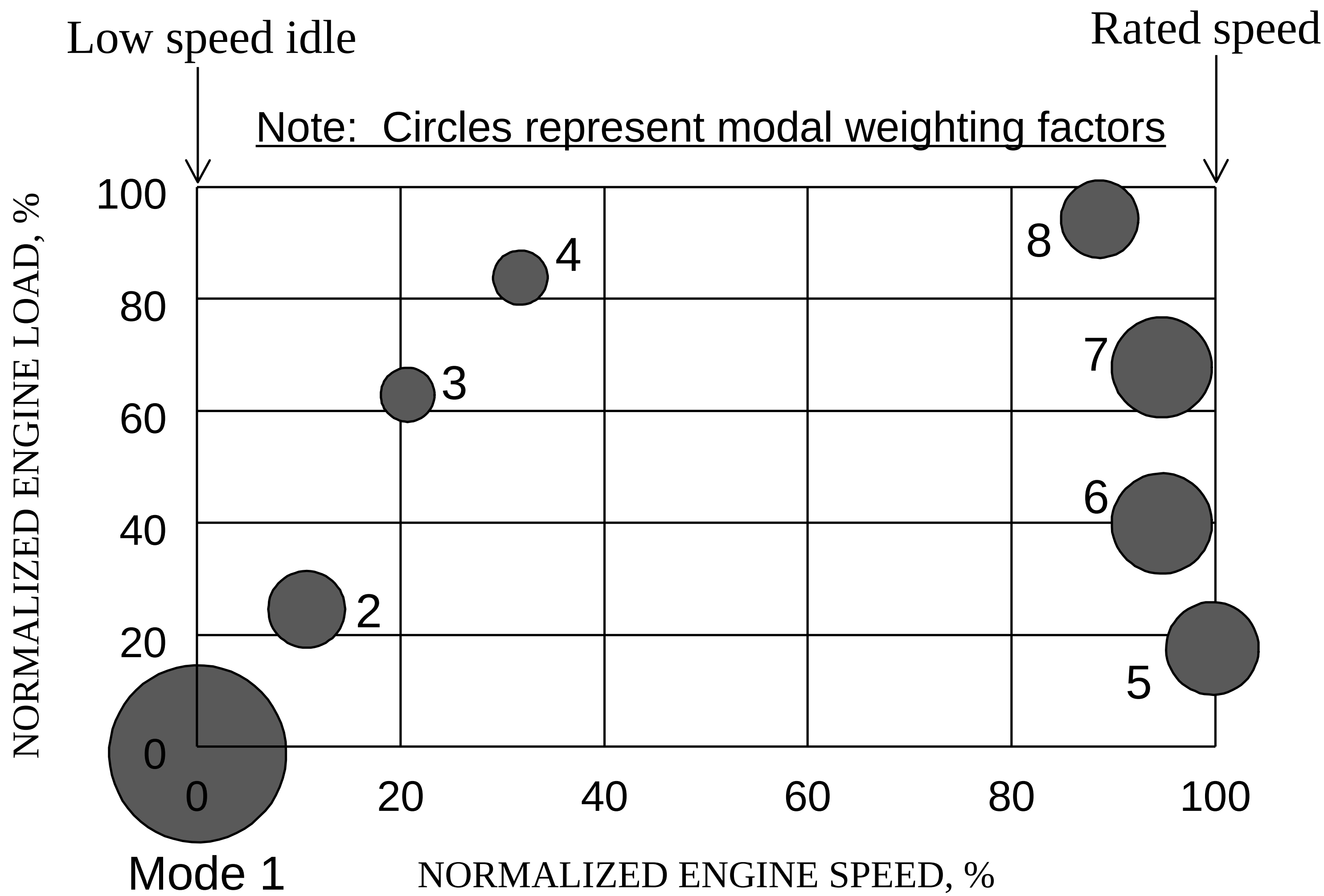
Phase 2 Test Program

Exhaust Emission Testing

- Emission test program executed by SwRI
- Effects of fuel properties, injection timing and EGR on exhaust emissions were evaluated
- AVL 8-mode test procedure used exclusively. (Prototype EGR system of the test engine was not compatible with the EPA transient test). The same modal engine speed and load settings were used for all test fuels
- Testing conducted on CAT 3176 engine previously identified in Phase 1 as a useful test bed

Phase 2 Test Program (*Continued)*

AVL 8-Mode Emission Test Cycle



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Phase 2 Test Program (*Continued)*

CAT 3176 Test Engine

- 10.3 liter displacement
- 355 HP @ 1800 rpm
- Equipped with electronically controlled unit injectors
- Cooled EGR
- No exhaust aftertreatment

Phase 2 Test Program (*Continued*)

Exhaust Emission Testing

- Engine calibrated to approach NOx level of 2.5 g/HP*h
- Some tests repeated w/o EGR (Direct comparison of emission effects of natural and boosted cetane number)
- NOx, HC, CO and Bosch smoke emissions were measured
- Particulate emissions were not measured (Poor correlation between AVL 8-mode test and EPA transient test for particulates), engine technology not transient compatible

Phase 2 Test Program (*Continued*)

Statistical Analysis of Test Data

- Prediction models developed for NOx, HC, NOx+HC,CO emissions and BSFC
- Development of models based on four parameters: Density, cetane number, mono- and polyaromatics
- Other fuel parameters and two-way interactions between density, cetane number, mono- and polyaromatics were subsequently tested in each model. With one exception, none were found to further improve the models
- All statistical analyses were performed using a 5% significance level.

Results of Phase 2 Testing

Fuel Effects

Results of Phase 2 Testing *(Continued)*

NOx Emission Model

- Density, cetane number, monoaromatics and polyaromatics are statistically significant predictors of NOx emissions. They account for 92% of NOx variation.

$$NOx = -1.334 + 0.00413*Density + 0.00337*Cetane$$

$$+ 0.00646*Monoaromatics + 0.00763*Polyaromatics$$

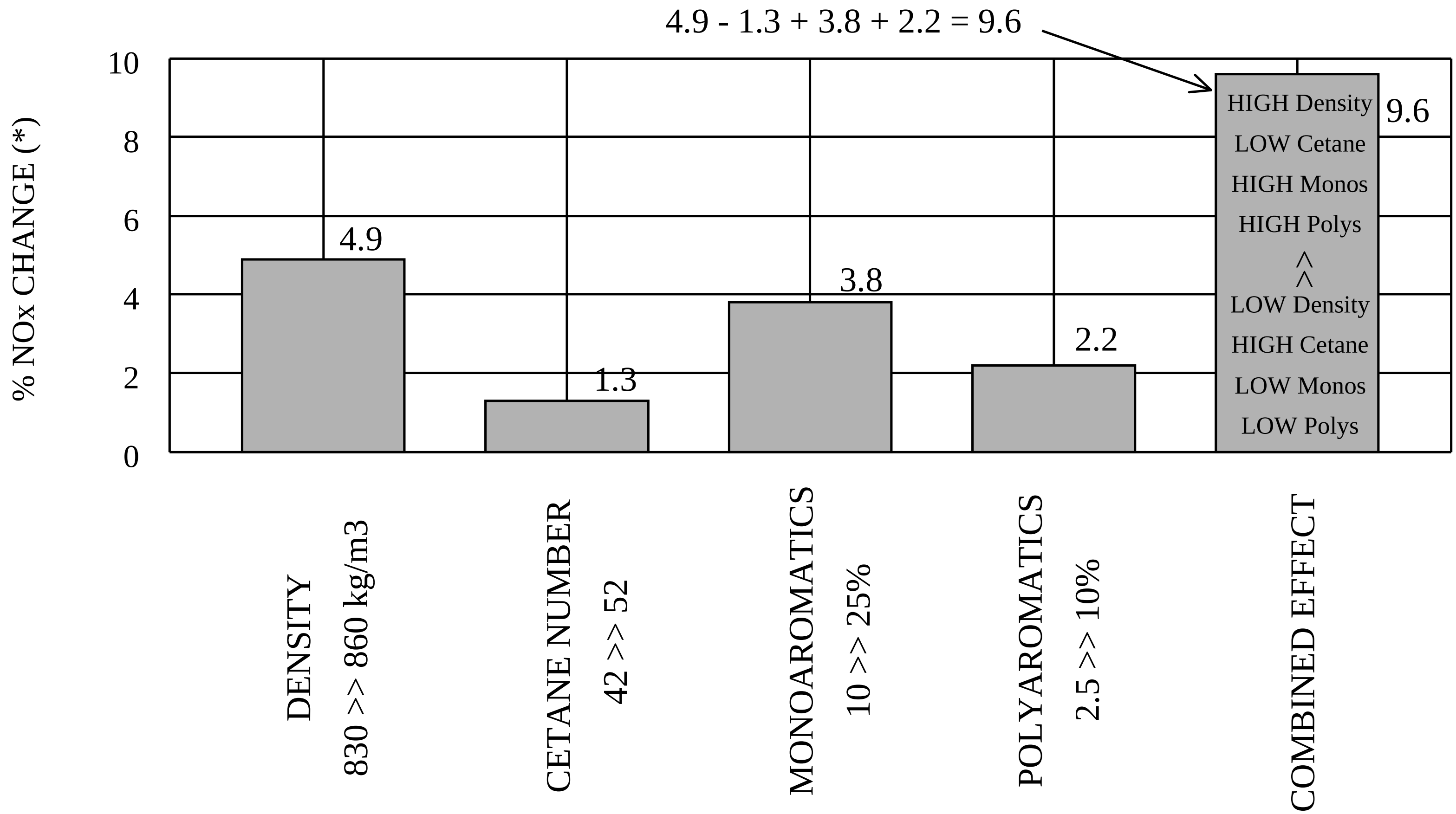
where NOx is in g/HP*h, density in kg/m^3, mono- and polyaromatics in %m.

- Observed increase of NOx emissions with cetane number is a confirmation of Phase 1 results.

Results of Phase 2 Testing *(Continued)*

Effect of Fuel Properties on NOx Emissions

(*) Calculated relative to "average" US diesel fuel (Density of 845 kg/m3, cetane number of 45, monoaromatic content of 25% and polyaromatic content of 9%)



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Results of Phase 2 Testing *(Continued)*

HC Emission Model

- Cetane number, monoaromatics and polyaromatics are statistically significant predictors of HC emissions. They account for 78% of the HC variation.

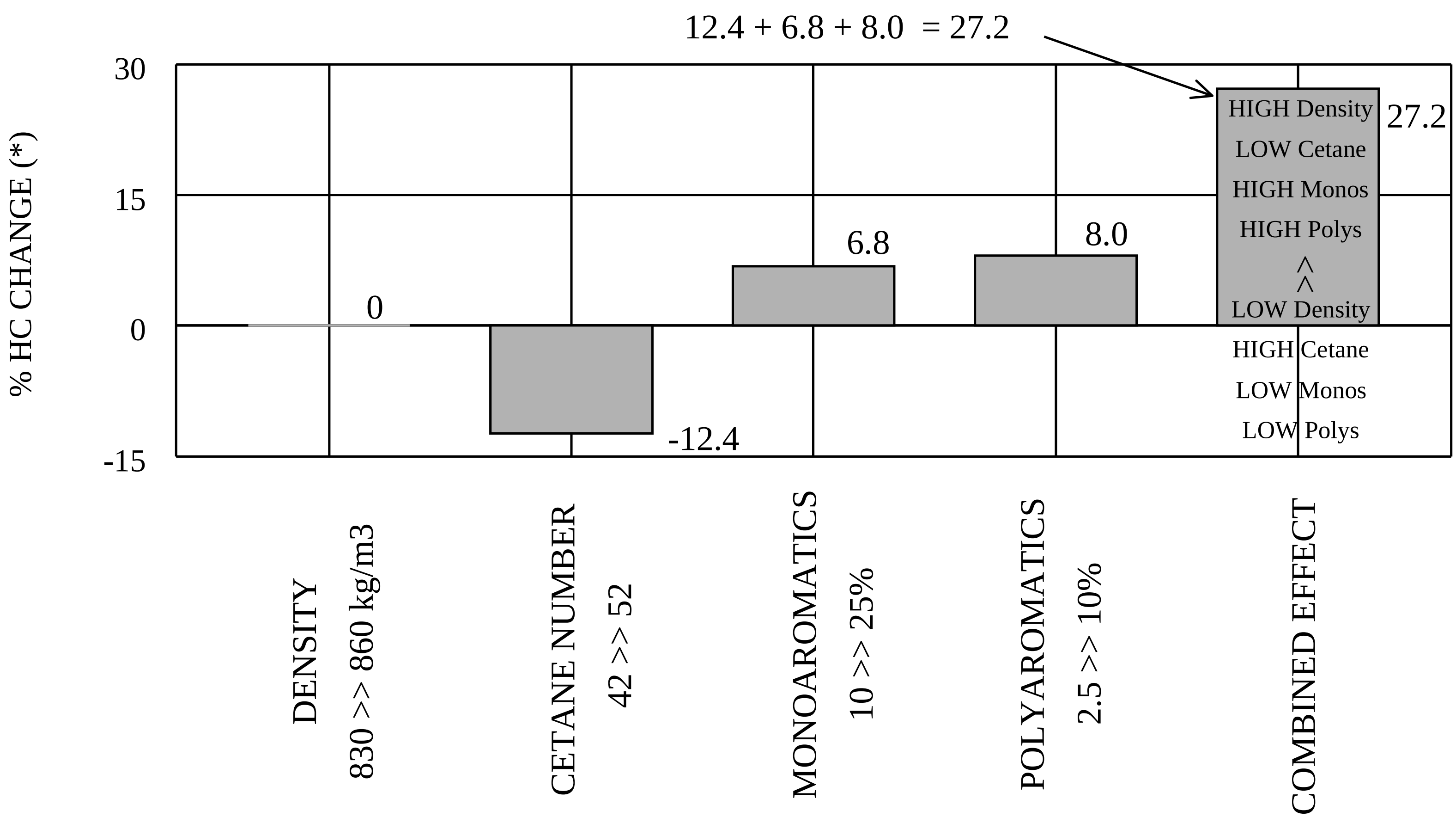
HC = 0.2027 - 0.00186*Cetane + 0.00677*Monoaromatics + 0.00160*Polyaromatics

Where HC is in g/HP*h, mono- and polyaromatics are in %m.

Results of Phase 2 Testing *(Continued)*

Effect of Fuel Properties on HC Emissions

(*) Calculated relative to "average" US diesel fuel (Density of 845 kg/m3, cetane number of 45, monoaromatic content of 25% and polyaromatic content of 9%)



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Results of Phase 2 Testing *(Continued)*

<u>NOx+HC Emission Model</u>

- Density, monoaromatics and polyaromatics are statistically significant predictors of NOx+HC emissions. They account for 90% of NOx+HC variation.

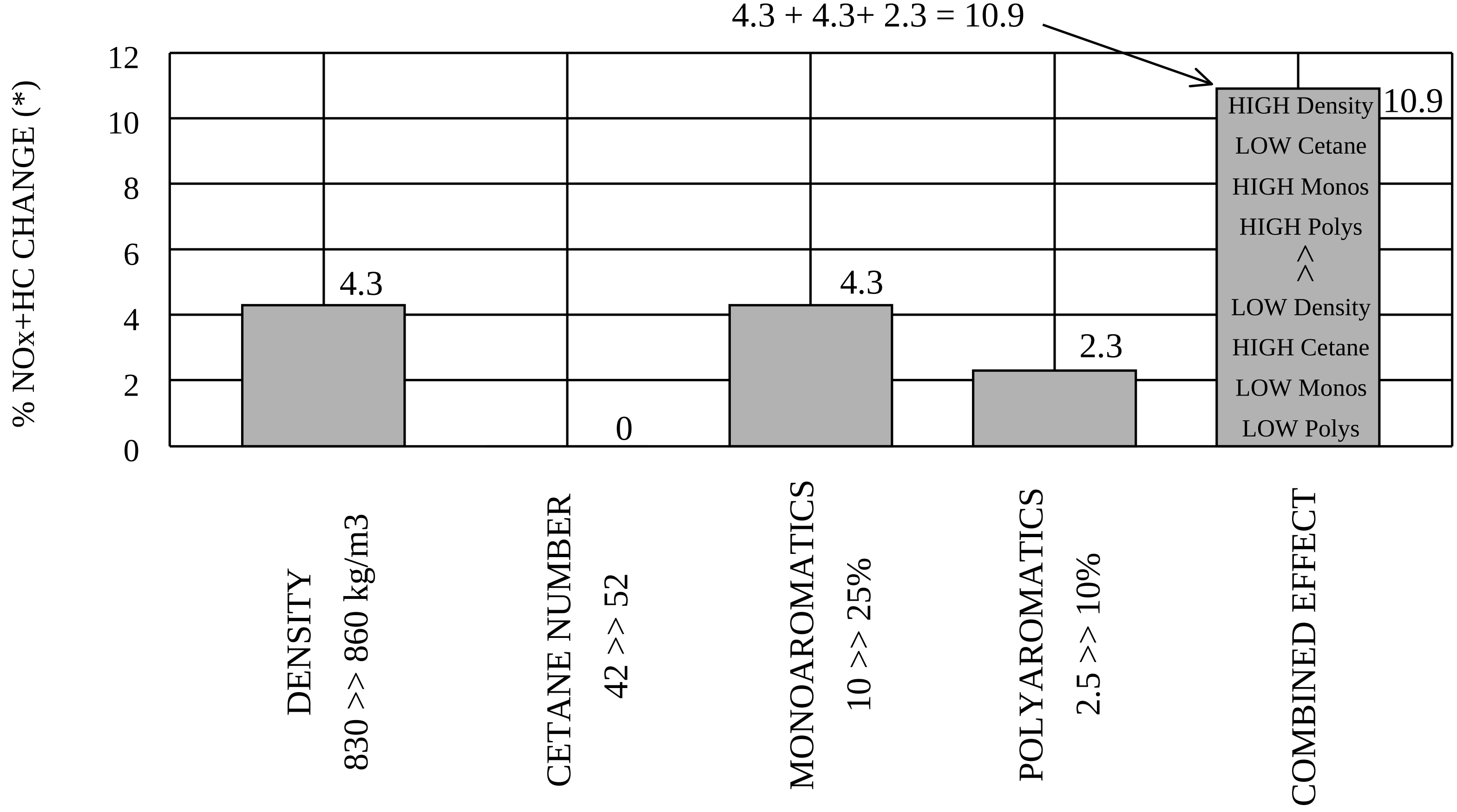
  NOx+HC = - 0.811 + 0.00384*Density+
  0.00766*Monoaromatics + 0.00842*Polyaromatics

  Where NOx+HC is in g/HP*h, density in kg/m^3, mono- and polyaromatics in %m.

Results of Phase 2 Testing *(Continued)*

Effect of Fuel Properties on NOx+HC Emissions

(*) Calculated relative to "average" US diesel fuel (Density of 845 kg/m3, cetane number of 45, monoaromatic content of 25% and polyaromatic content of 9%)



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Results of Phase 2 Testing *(Continued)*

CO Emission Model

- Cetane number is the only statistically significant predictor of CO emissions. It accounts for 77.8% of CO variation.

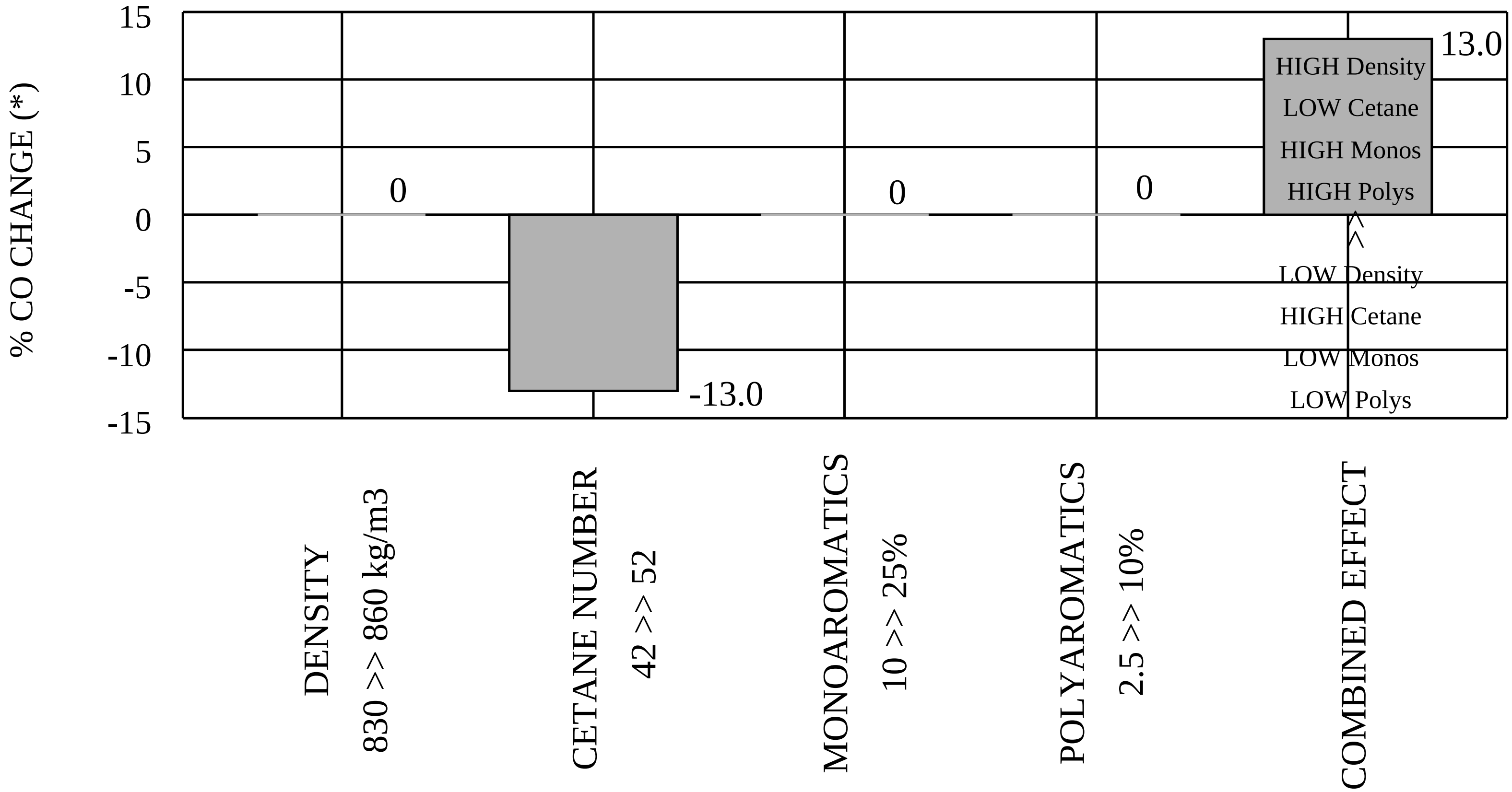
  CO = 1.28 - 0.0105* Cetane

  where CO is in g/HP*h.

Results of Phase 2 Testing *(Continued)*

Effect of Fuel Properties on CO Emissions

(*) Calculated relative to "average" US diesel fuel (Density of 845 kg/m3, cetane number of 45, monoaromatic content of 25% and polyaromatic content of 9%)



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Results of Phase 2 Testing *(Continued)*

Natural vs. Boosted Cetane Number

- Boosted cetane number had the same effect on NOx emissions as natural cetane number, with and w/o EGR

Results of Phase 2 Testing *(Continued)*

Effects of Natural and Boosted Cetane on NOx Emissions with EGR

FUEL	Cetane Number	Measured (*) NOx g/HP*h	NOx Difference g/HP*h	% NOx Difference vs. Natural	Statistical Significance of Natural vs. Boosted
HDE-8N	**48.0** Natural	2.411	2.411 -2.421 -0.010	-0.4	no
HDE-8	**48.1** Boosted from 42.8	2.421			
HDE-16N	**53.4** Natural	2.334	2.334 -2.359 -0.025	-1.1	no
HDE-16	**52.2** Boosted from 42.1	2.359			

(*) Average of two tests

Results of Phase 2 Testing *(Continued)*

Effects of Natural and Boosted Cetane on NOx Emissions w/o EGR

FUEL	Cetane Number	Measured (*) NOx g/HP*h	NOx Difference g/HP*h	% NOx Difference vs. Natural	Statistical Significance of Natural vs. Boosted
HDE-8N	**48.0** Natural	3.793	3.793 -3.813 -0.020	-0.5	no
HDE-8	**48.1** Boosted from 42.8	3.813			
HDE-16N	**53.4** Natural	3.686	3.686 -3.681 0.005	0.1	no
HDE-16	**52.2** Boosted from 42.1	3.681			

(*) Average of two tests

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Results of Phase 2 Testing *(Continued)*

vBSFC Model

- Density and monoaromatic content are statistically significant predictors of volumetric brake specific fuel consumption, vBSFC. They account for 94% of vBSFC variation

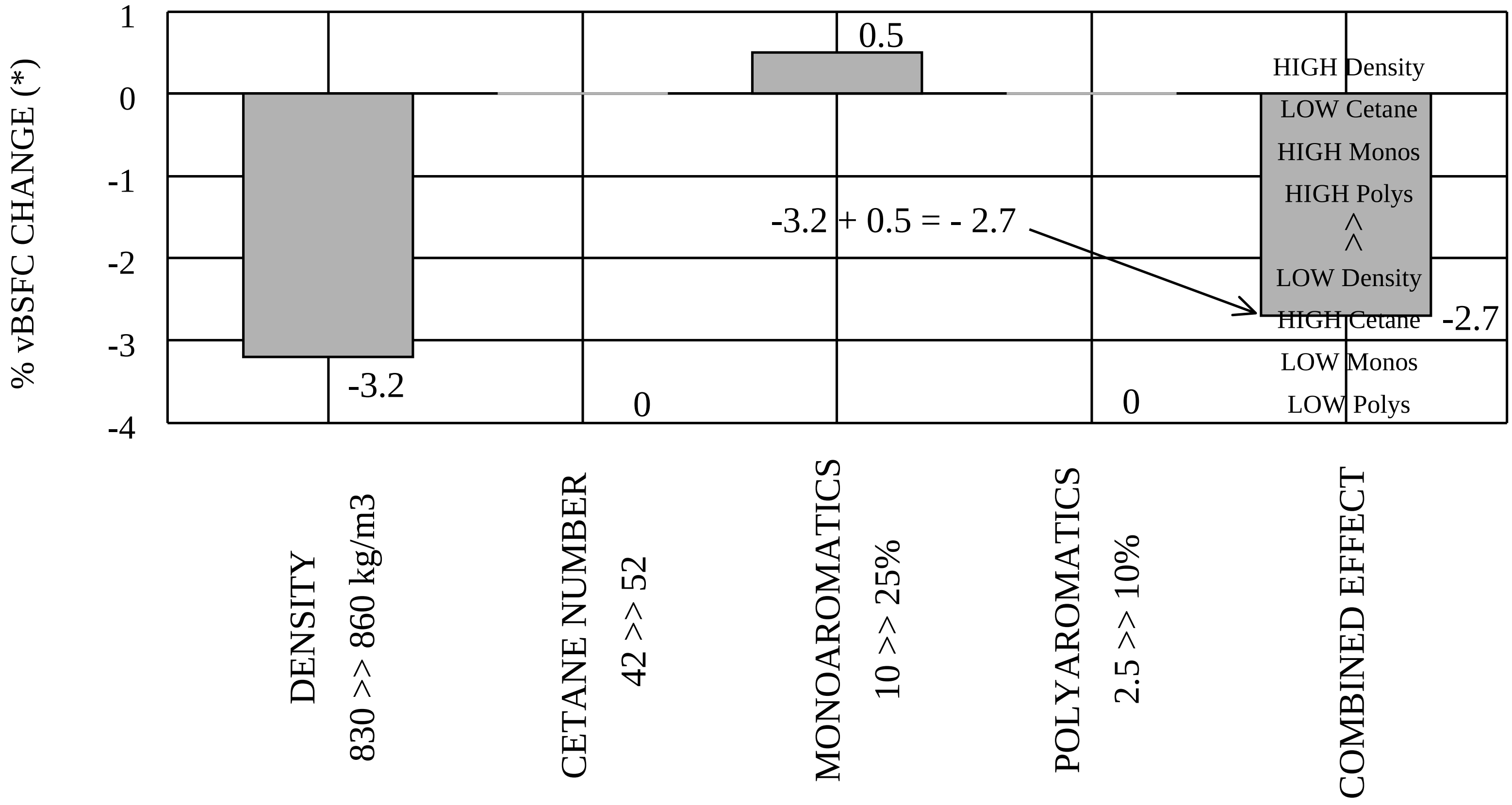
$$vBSFC = 487.9 - 0.274*Density + 0.0793*Monoaromatics$$

where vBSFC is in g/kW*h, density in kg/m^3 and monoaromatics in %m.

Results of Phase 2 Testing *(Continued)*

Effect of Fuel Properties on vBSFC

(*) Calculated relative to "average" US diesel fuel (Density of 845 kg/m3, cetane number of 45, monoaromatic content of 25% and polyaromatic content of 9%)



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Results of Phase 2 Testing *(Continued)*

Engine Hardware Effects

Results of Phase 2 Testing *(Continued)*

Effect of EGR

- EGR had a strong effect on NOx emissions, but no statistically significant effect on fuel consumption

Results of Phase 2 Testing *(Continued)*

Effect of EGR on NOx Emissions

FUEL	Measured (*) NOx w/EGR g/HP*h	Measured (*) NOx w/o EGR g/HP*h	NOx Difference g/HP*h	% NOx Difference vs. w/o EGR	Statistical Significance of EGR Effect
HDE-R	2.538	4.000	-1.462	-36.6	yes
HDE-7N	2.397	3.819	-1.422	-37.2	yes
HDE-8	2.420	3.813	-1.393	-36.5	yes
HDE-8N	2.410	3.793	-1.383	-36.5	yes
HDE-14N	2.338	3.660	-1.322	-36.1	yes
HDE-16	2.358	3.681	-1.323	-35.9	yes
HDE-16N	2.334	3.686	-1.352	-36.7	yes

(*) Average of two tests, with the exception of fuel HDE-R which was tested five times

Results of Phase 2 Testing *(Continued)*

Effect of EGR on gravimetric brake specific fuel consumption, gBSFC

FUEL	Measured (*) gBSFC w/EGR g/kW*h	Measured (*) gBSFC w/o EGR g/kW*h	gBSFC Difference g/kW*h	% gBSFC Difference vs. w/o EGR	Statistical Significance of EGR Effect
HDE-R	220.4	218.4	2.0	0.9	no
HDE-7N	216.5	215.7	0.8	0.4	no
HDE-8	219.2	217.1	2.1	1.0	no
HDE-8N	218.2	215.2	3.0	1.4	no
HDE-14N	216.6	215.3	1.3	0.6	no
HDE-16	216.4	215.3	1.1	0.5	no
HDE-16N	216.7	214.3	2.4	1.1	no

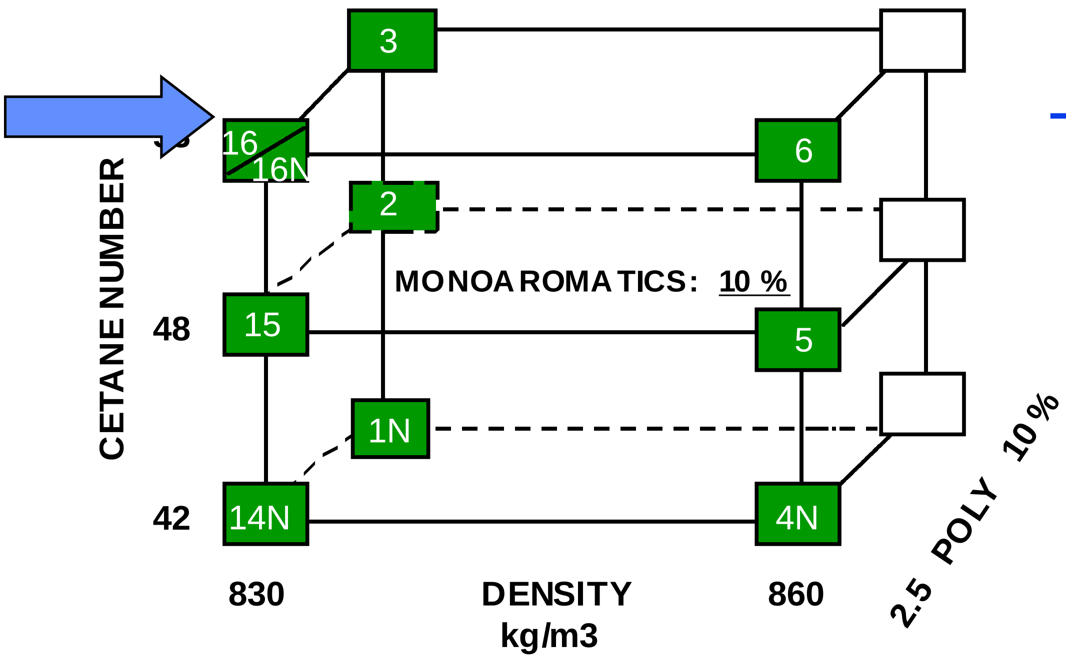
(*) Average of two tests, with the exception of fuel HDE-R which was tested five times

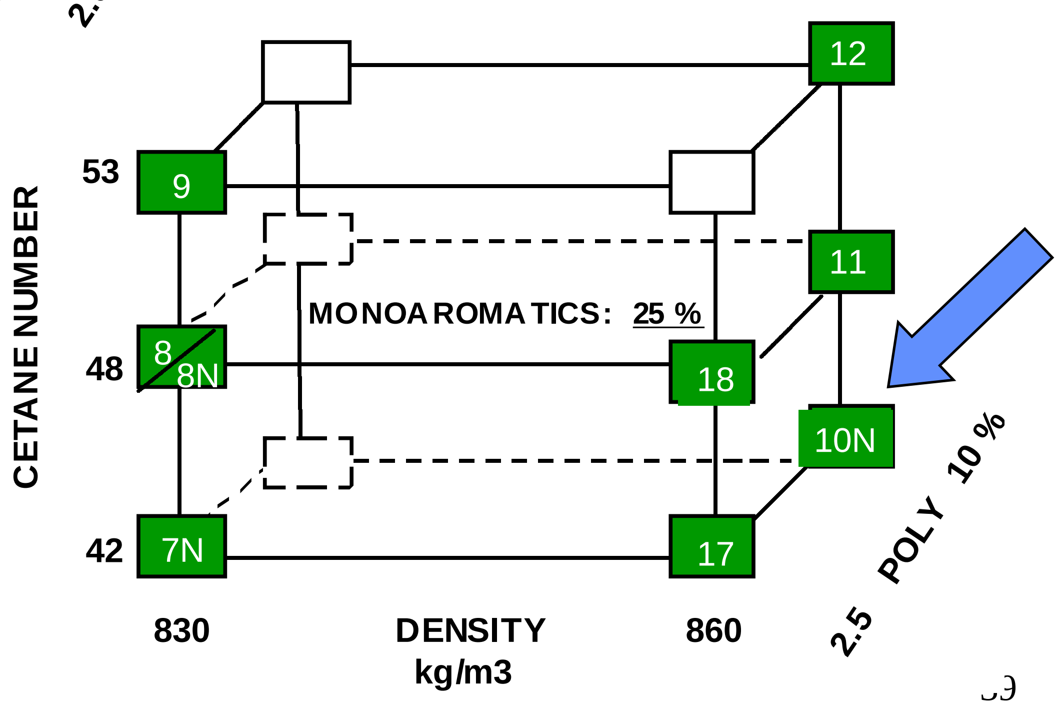
PHASE 3 PROGRAM

Phase 3 Test Program

- Purpose: Determine whether Phase 2 results are representative of advanced "black box", prototype diesel engines currently being developed by manufacturers
- Exhaust emission testing of four 2004 "black box" engines (2.5 g/bhp-hr HC+NOx and 0.10 g/bhp-hr PM) was conducted by manufacturers
- 3 test fuels and the reference fuel were evaluated
- EPA transient test procedure and AVL 8-mode used
- Focus was on assessing NOx and PM impacts
- Program completed October 2000

Phase 3 Test Fuels





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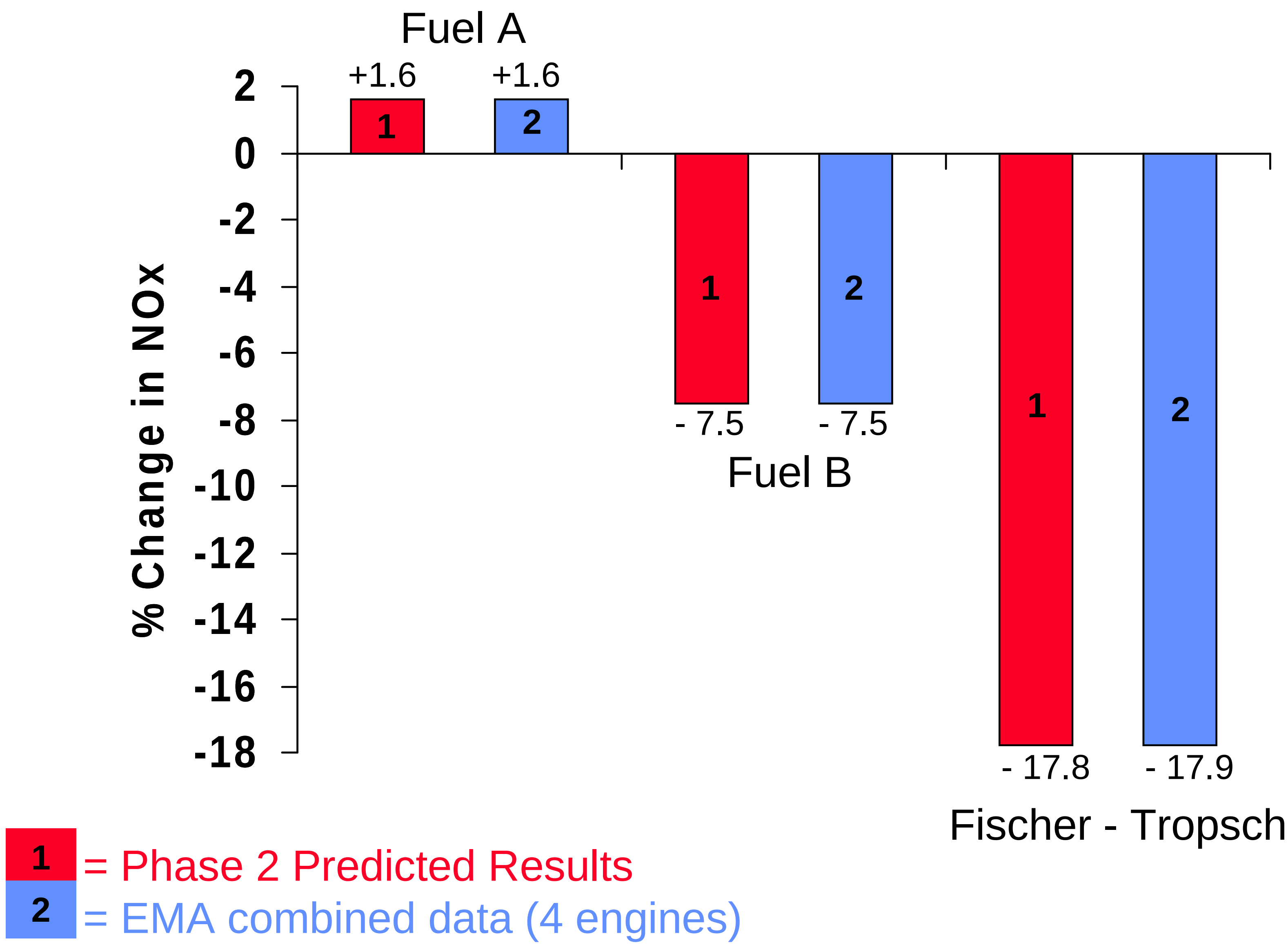
PHASE 3 FUEL PROPERTIES

	Base	Fuel A	Fuel B	Fischer - Tropsch
	Normal Cert Diesel	Lo CN/Hi Aro (HDE–10 mod)	Hi CN/Lo Aro (HDE–16 mod)	Ultra Hi CN /Ultra Lo Aro
Density (kg/m3)	848	860	830	770
Cetane Number	46.9	42.7	51.1	73
Monoaromatics (% m)	20.2	23.8	10.6	- -
Polyaromatics (%m)	12.1	9.8	2.9	- -
Total Aromatics (%m)	32.3	33.6	13.5	0.4

Comparison of Phase 2 Predicted vs. Phase 3 Results



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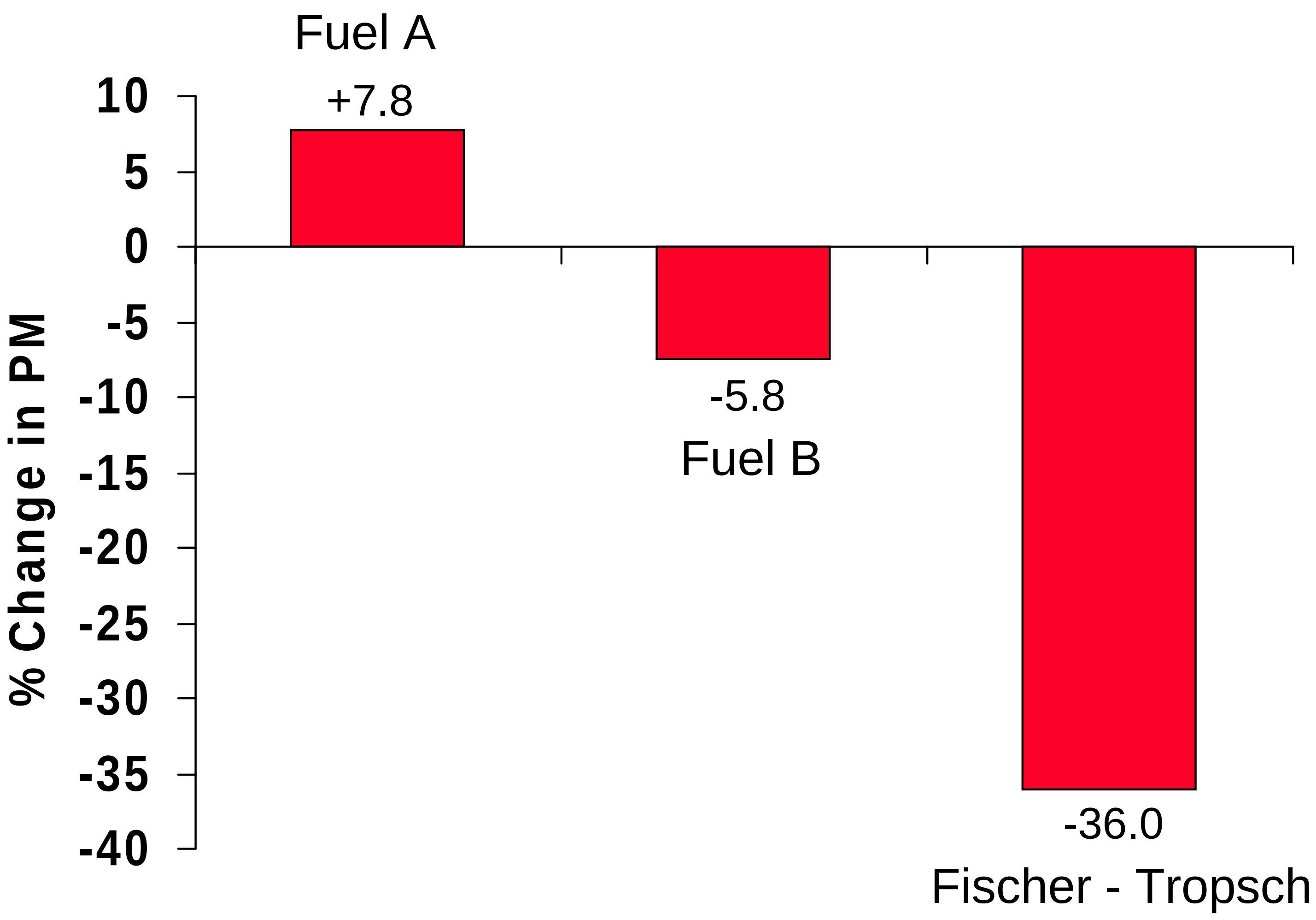
Results of Phase 3 PM Testing (4 engines)



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SUMMARY

- Program initially implemented in response to EPA/ industry HDE NOx SOP
- Phase 1and 2 results demonstrated that for 2004 type technology
  - increasing cetane number (natural or enhanced) increases NOx emission rates
  - decreasing aromatics or density decreases NOx emission rates
  - Phase 1 indicated that engines responded a bit differently to fuel changes
- Based on these results EPA did not propose any diesel fuel controls in the 2004 technology review
- Phase 3 confirmed that the technology and fuel quality relationships found in Phases 1 and 2 were still valid

SUMMARY

- Correlation of Phase 3 results with Phase 2 predictions is remarkable
  - confirms that likely magnitude of fuel-based NOx impact on EGR engines does not justify regulatory action

- Results not applicable to current diesel fleet
- More work needs to be done to assess overall impact on 2004 and future fleet
  - advanced prototypes not fully 2004 compliant
  - technology effects were seen in the data for some engines