Diesel Engine Alternatives

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Background
Engine Combustion Modes

- Three Fundamental Modes of Combustion in Reciprocating Engines
  - Diffusion Combustion
    - Conventional Diesel
    - Stratified Direct Injection SI
  - Flame Propagation Combustion
    - Conventional Gasoline SI
    - Lean Burn SI
  - Homogeneous Reaction
    - HCCI

Basic Question

- How will future emissions regulations affect the selection of the most cost effective engine and powertrain system for the various on-road and off-road applications?

US On-Road Emissions Standards

- Light Duty Standards through Tier I Differentiated Between Gasoline and Diesel Fuel
  - Tier II Light Duty Standards are Fuel Neutral
- US Heavy Duty Market is Historically Diesel
  - Heavy Duty Standards have Historically Aimed at Diesel Engines
  - Will Future HD Standards be Fuel Neutral?

Situation

- Emissions Standards for All Categories of Engines and all Applications have continually become more Stringent, Approaching Zero Emissions
  - In Fact, California Defined ZEV's and PZEV's
- As Each category comes into Compliance, the other Categories Tend to become Larger Contributors to the Ambient Air Inventory
  - Becoming Targets for Additional Regulation

Definition of Ambient Air Quality from the EPA Website

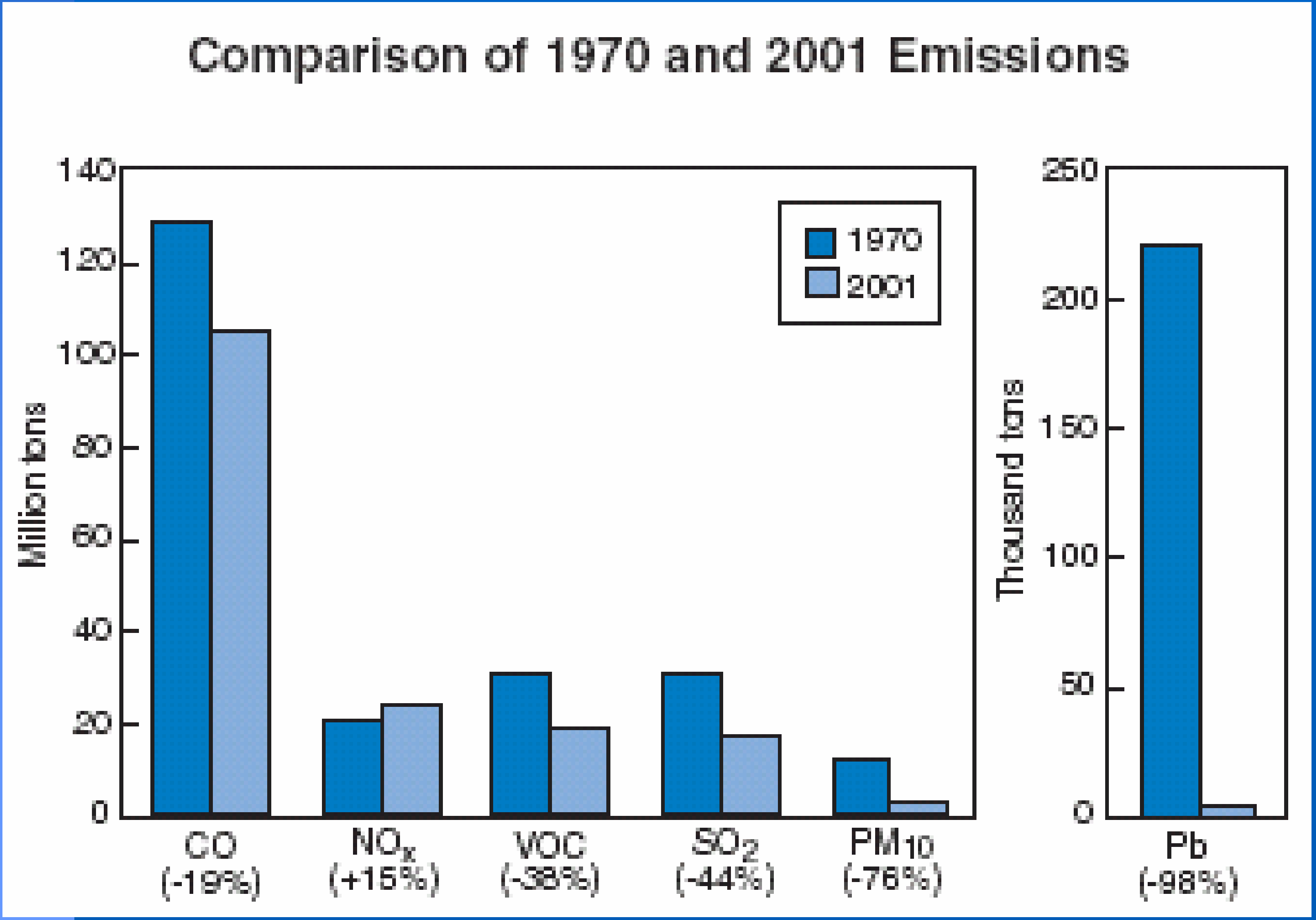
An ambient air quality standard is a national target for an acceptable concentration of a specific pollutant in air. Under the Clean Air Act, EPA develops two standards for each pollutant of concern:

- A **primary standard** to protect public health. The Clean Air Act mandates that primary standards be based entirely on health-related information, without considering the costs of attaining the standard.
- A **secondary standard** to protect public welfare. Public welfare includes effects on soils, water, crops, vegetation, buildings, property, animals, wildlife, weather, visibility, transportation, and other economic values, as well as personal comfort and well-being.

Definition of "Criteria" Pollutants

EPA has set national air quality standards for six common pollutants (also referred to as "criteria" pollutants). Click on one of the pollutants below for information on sources of the pollutant, why the pollutant is of concern, health and environmental effects, efforts underway to help reduce the pollutant, and other helpful resources.

Effect of Regulations on Ambient Air Quality



Summary

- EPA is Focused on Ambient Air Quality and Achieving the Ambient Air Quality Standards
  - This will not Change unless there is a New Law Approved by the US Congress and the Current Administration
  - CO_2 Standards are not Likely to be Approved in this Administration
  - Some CAFÉ Changes (Minor) are Likely, Possibly including LDT's in the same Category as LDV's
- Current Trends and Air Quality Model results indicate that the Ambient Air Quality Standards will still not be Achieved, even with the Current Regulations that are in Place

Background Statement

- EPA will continue to promulgate lower emissions standards for diesel engines.
- The EPA always considers the best available technology for lowest emissions, with some consideration of the economic and social impact
- SI and CI Treated the same in TIER II
  - Fuel Neutral
- SI engines with 3-way catalyst are the proven lowest emission commercial technology available

Possible Future Action

- 2010 EPA can Announce New HD Standards for Implementation in 2014
- Future HD Standards are Likely to be Fuel Neutral
- Possible 2014 Standards
  - 0.05 gm/hp-hr NOx
  - 0.001 gm/hp-hr PM

SwRI Estimate of the Emissions Levels of HD SI Engine

HD SI Estimate:

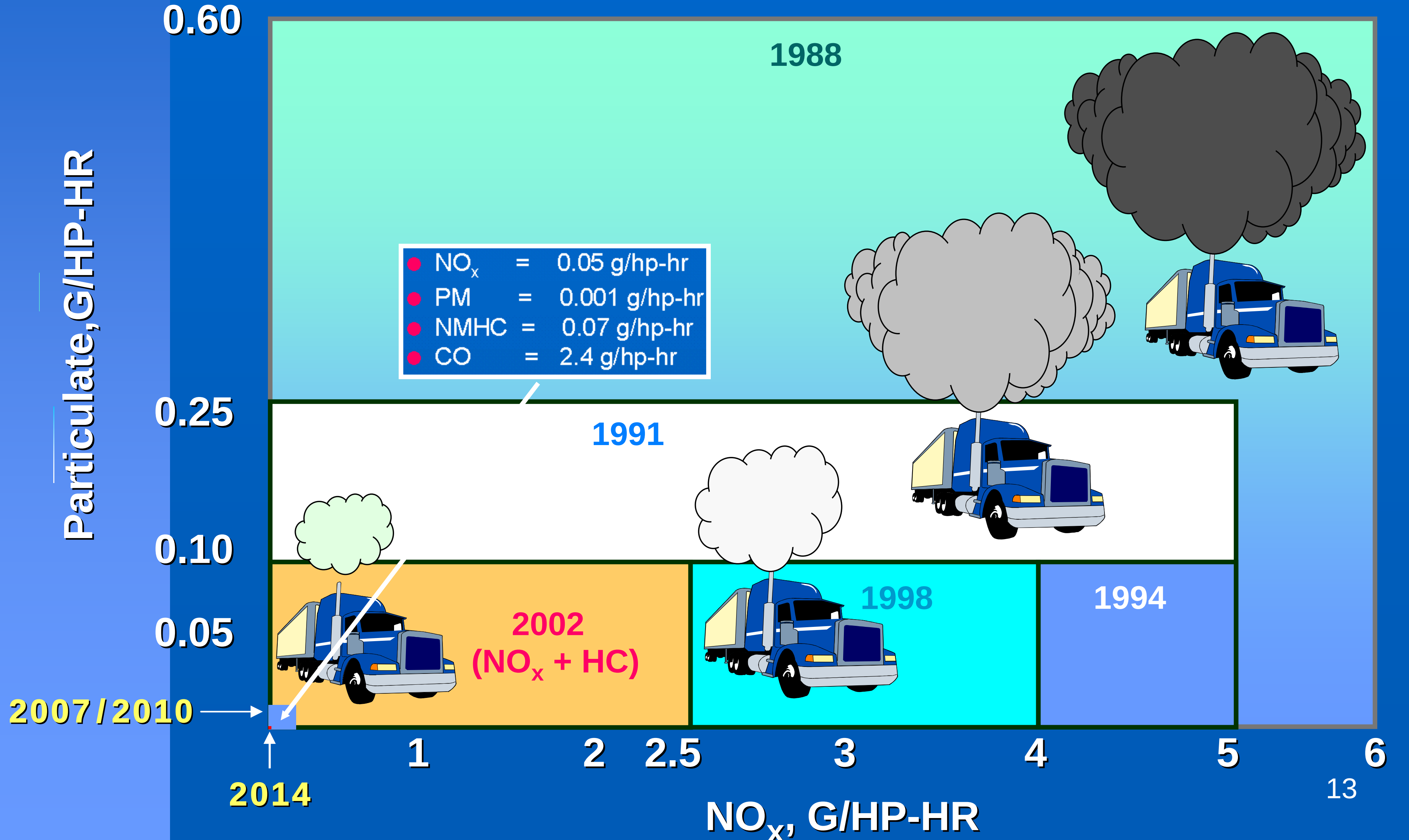
- NO_x = 0.05 g/hp-hr
- PM = 0.001 g/hp-hr
- NMHC = 0.07 g/hp-hr
- CO = 2.4 g/hp-hr

versus

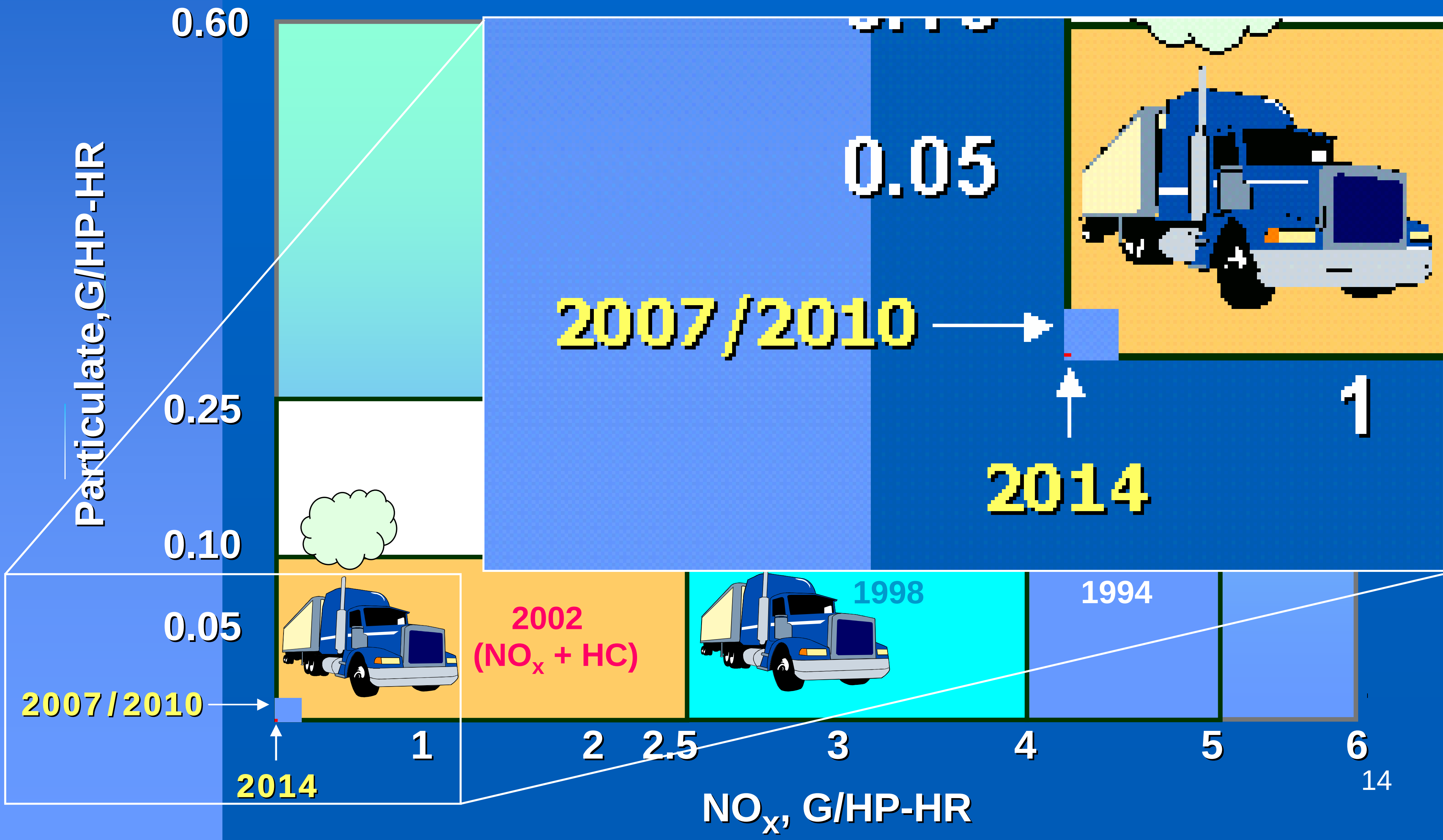
HD CI Standard:

- NO_x = 0.20 g/hp-hr
- PM = 0.01 g/hp-hr
- NMHC = 0.14 g/hp-hr
- CO = 15.5 g/hp-hr

Heavy-Duty Diesel Emissions Standards



Heavy-Duty Diesel Emissions Standards



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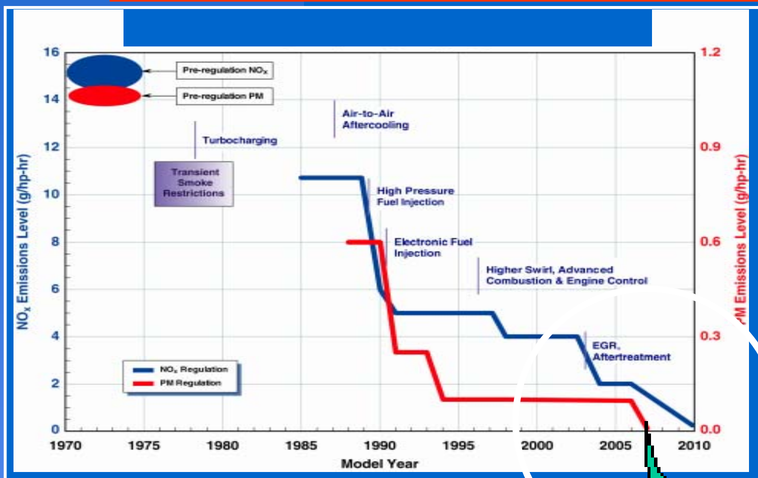
Diffusion Burn Engines

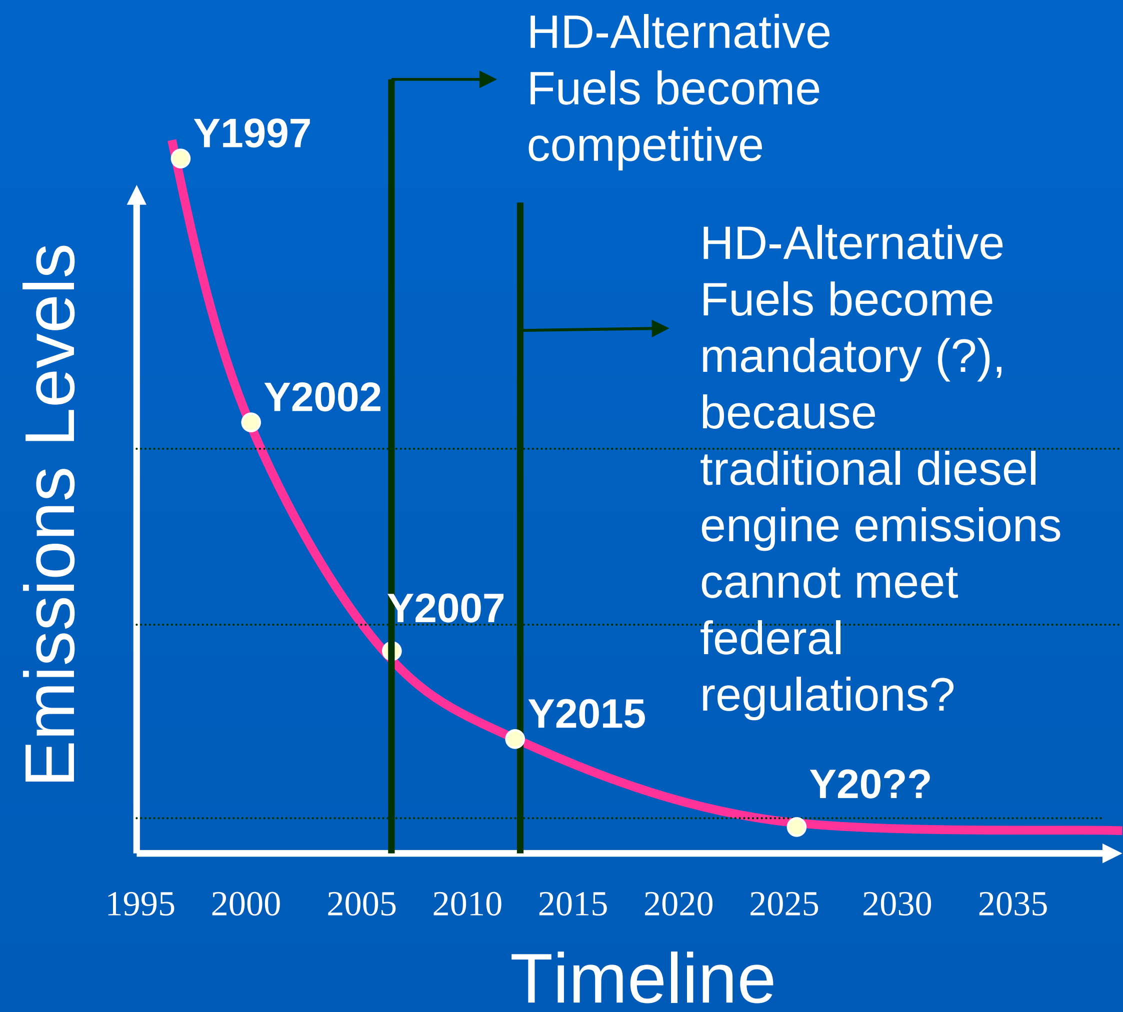
Diffusion Combustion
The Future Diesel (~Y2010)

- Advanced Fuel Systems, with high pressure injection ($)
- Advanced Controls ($), with engine tuned to keep aftertreatment devices Efficient
- PM Aftertreatment ($)
- NO_x Afterteatment ($)
- UHC/HAPS Aftertreatment ($)
- **The Result - Emissions are met, price goes way up, and efficiency suffers…**
  - BTE drops 10 percentage points

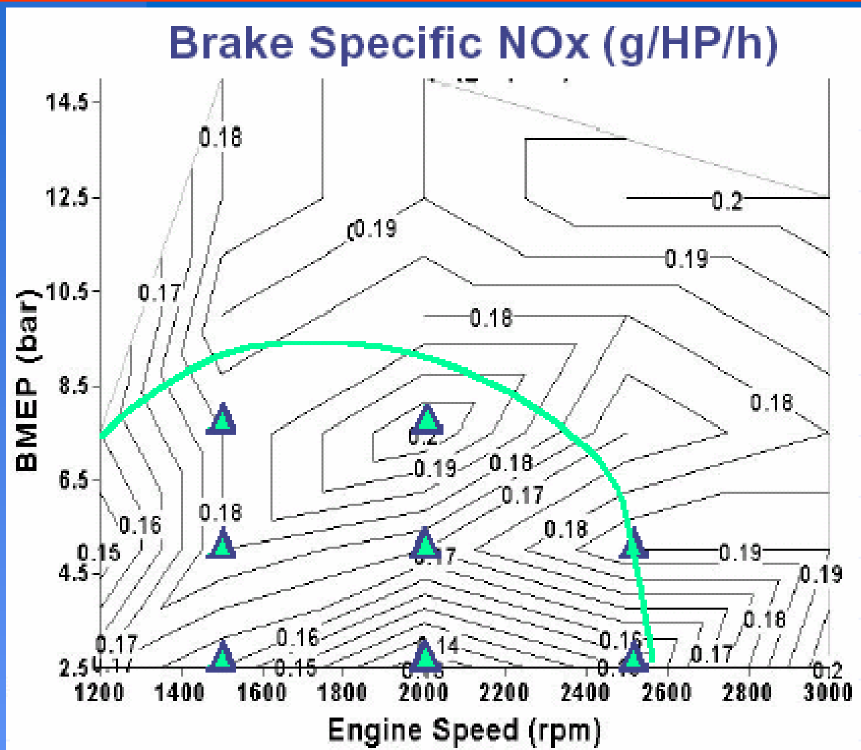
DIESEL EMISSIONS TECHNOLOGY EVOLUTION

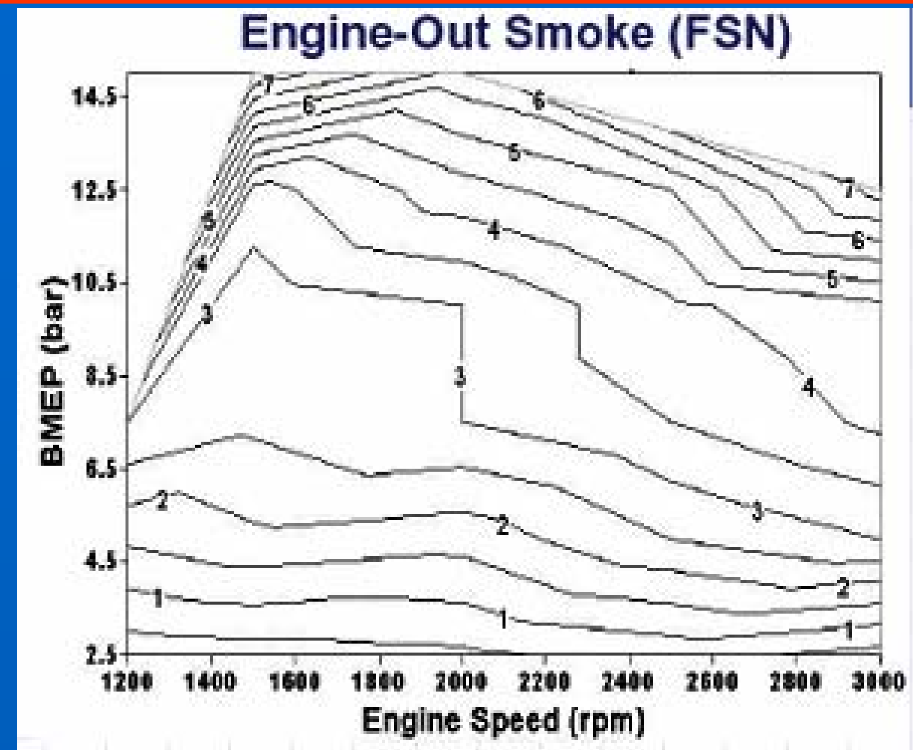


- As emissions levels become ever-more strict, the diesel engine efficiency will continue to drop



EPA-Ford Data





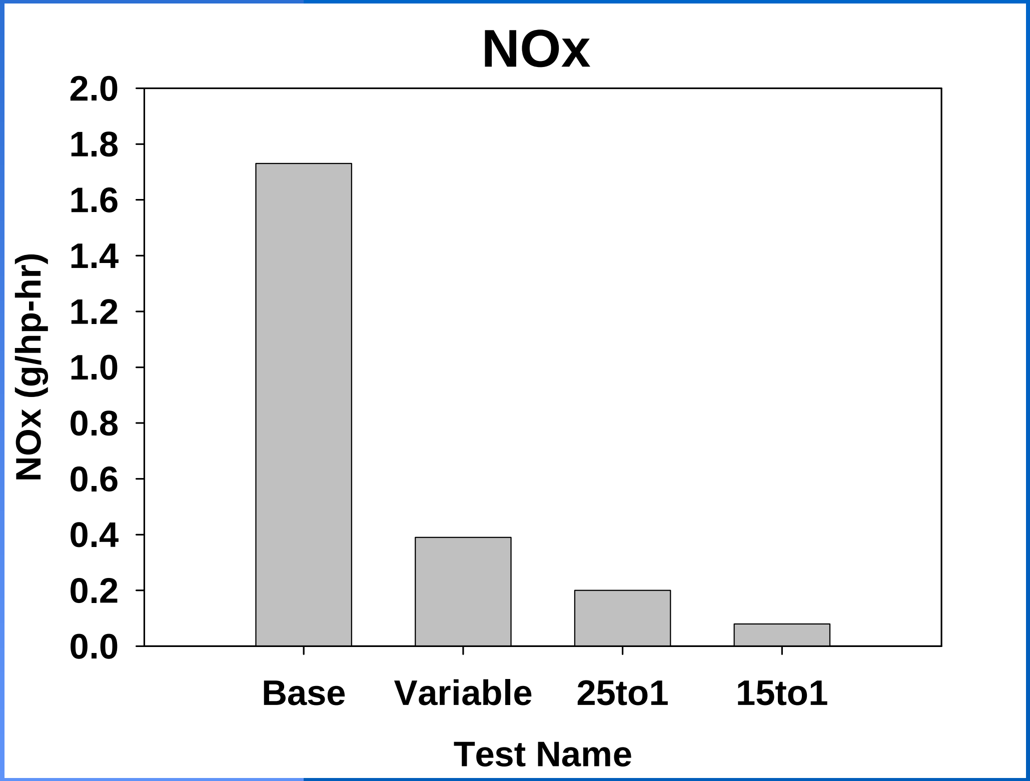
Type	4-cylinder, 2 valve/cyl OHC
Displacement	1896 cm^3
Bore	79.5 mm
Stroke	95.5 mm
Comp. Ratio	19.5:1

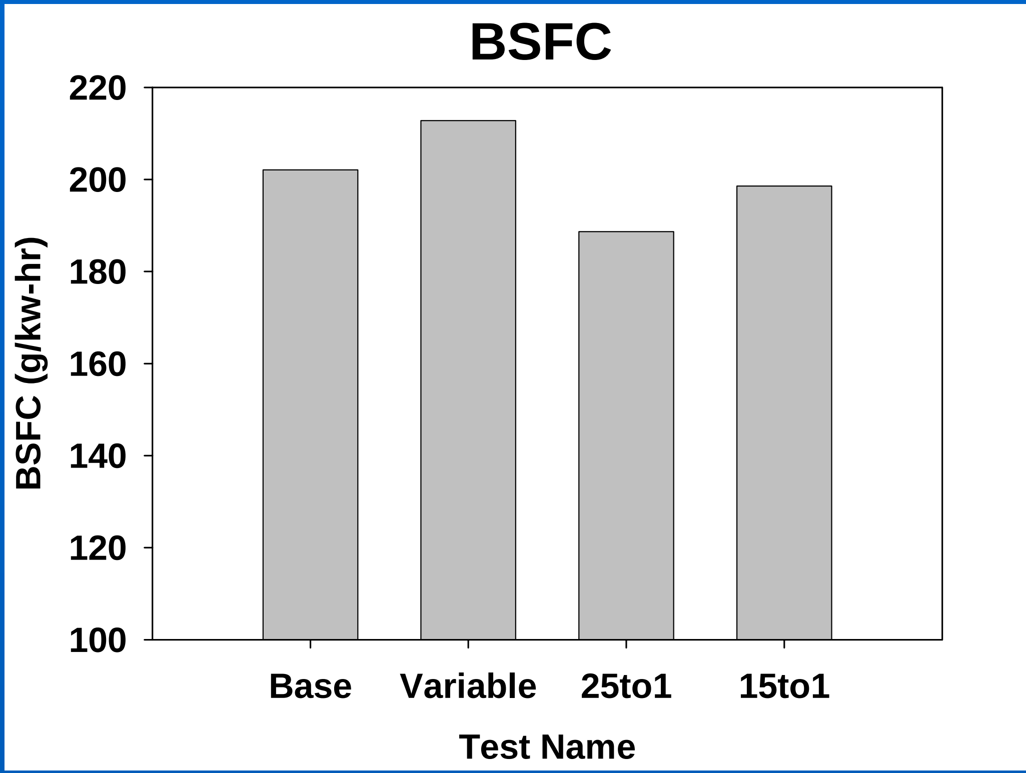
EPA Fuel System - Hydraulically Intensified
Injector Location - 7mm offset w/ 26° Inclin.
Boost Systems - externally supplemented
($P_{exh} = P_{int}$ + 0.1Bar)
- partial map TC matched
(Initial effort)

Massive EGR Diffusion Burn Engine
(Alternative to NOx After treatment)

- SwRI Has Extensive Data Base of 8-Mode Data for Cat 3176 2.5 g/hp-hr NOx + HC Engine
- Use Cycle Simulation to Model Different Levels of EGR
- Assumed LP Loop EGR After DPF
- Conditions Examined
  - Baseline - Good Prediction of Existing Data
  - Baseline A/F and Timing + EGR + Boost
  - Baseline Timing + A/F=25:1 + EGR + Boost
  - A/F=15:1 + EGR + Boost + Timing Advance

Massive EGR





- Baseline Engine Around 2 g/hp-hr
- BSFC Penalty with Variable Due to Back Pressure Increases
- 25:1 A/F Produced Lots of Turbine Energy
- 15:1 A/F Lowered the Air Flow and Boost Requirements

Massive EGR
Independent Variables

Table 1. Independent Variables Examined in the Cycle Simulation Calculations

Test\Mode	1	2	3	4	5	6	7	8
Baseline	70.13* 50 100 3.2	46.27 12.5 103.4 2.8	22.19 6.1 126.2 2.7	19.96 4.9 186.9 2.8	44.84 19.9 125.5 4.8	32.44 16.1 166.2 4.6	31.7 6 239.3 4.7	27.43 4.1 288.2 7.6
Variable	70.13 50 100 3.2	46.27 50 103.4 2.8	22.19 45 215.7 2.7	19.96 30 253.8 2.8	44.84 40 200 4.8	32.44 40 280 4.6	31.7 40 440 3.1	27.43 37 530 15
25:1	70.13 50 100 3.2	25 50 103.4 2.8	25 40 240 2.7	25 30 310 2.8	25 52 125 4.8	25 40 190 4.6	25 35 300 4.7	25 37 380 7.6
15:1	70.13 50 100 3.2	15 60 103.4 2.8	15 50 160 2.7	15 40 240 2.8	15 70 140 20	15 55 150 15	15 50 220 15	15 50 300 7.6

* Listed are: A/F, Percent EGR, MAP (kPa), SOI (^{o}CA)

Massive EGR
Dependent Variables

Table 2. Dependent Variables Computed in the Cycle Simulations

Test\Mode	1	2	3	4	5	6	7	8
Baseline	6.79* 100 4412	3.80 214 4917	2.97 196 5690	2.85 188 8164	1.86 213 6120	1.44 190 7763	2.66 182 11275	3.14 176 14829
Variable	6.79 100 4412	1.22 271 5327	0.04 197 9133	0.17 188 10849	0.90 235 9851	0.28 205 12930	0.32 218 21800	0.24 201 29184
25:1	6.79 100 4412	0.05 215 4507	0.11 191 10223	0.30 186 13352	0.03 218 5619	0.09 194 8590	0.15 188 13632	0.13 186 17573
15:1	6.79 100 4412	0.001 227 4136	0.001 206 6512	0.001 198 10004	0.001 218 5907	0.001 195 7038	0.001 185 10875	0.001 193 13054

*Listed are: NOx (g/hp-hr), BSFC (g/kw-hr), and P_{max} (kPa)

Flame Propagation Engine

Diffusion Combustion
The Future Diesel (~Y2010)

- Advanced Fuel Systems, with high pressure injection ($)
- Advanced Controls ($), with engine tuned to keep aftertreatment devices Efficient
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- **The Result - Emissions are met, price goes way up, and efficiency suffers…**
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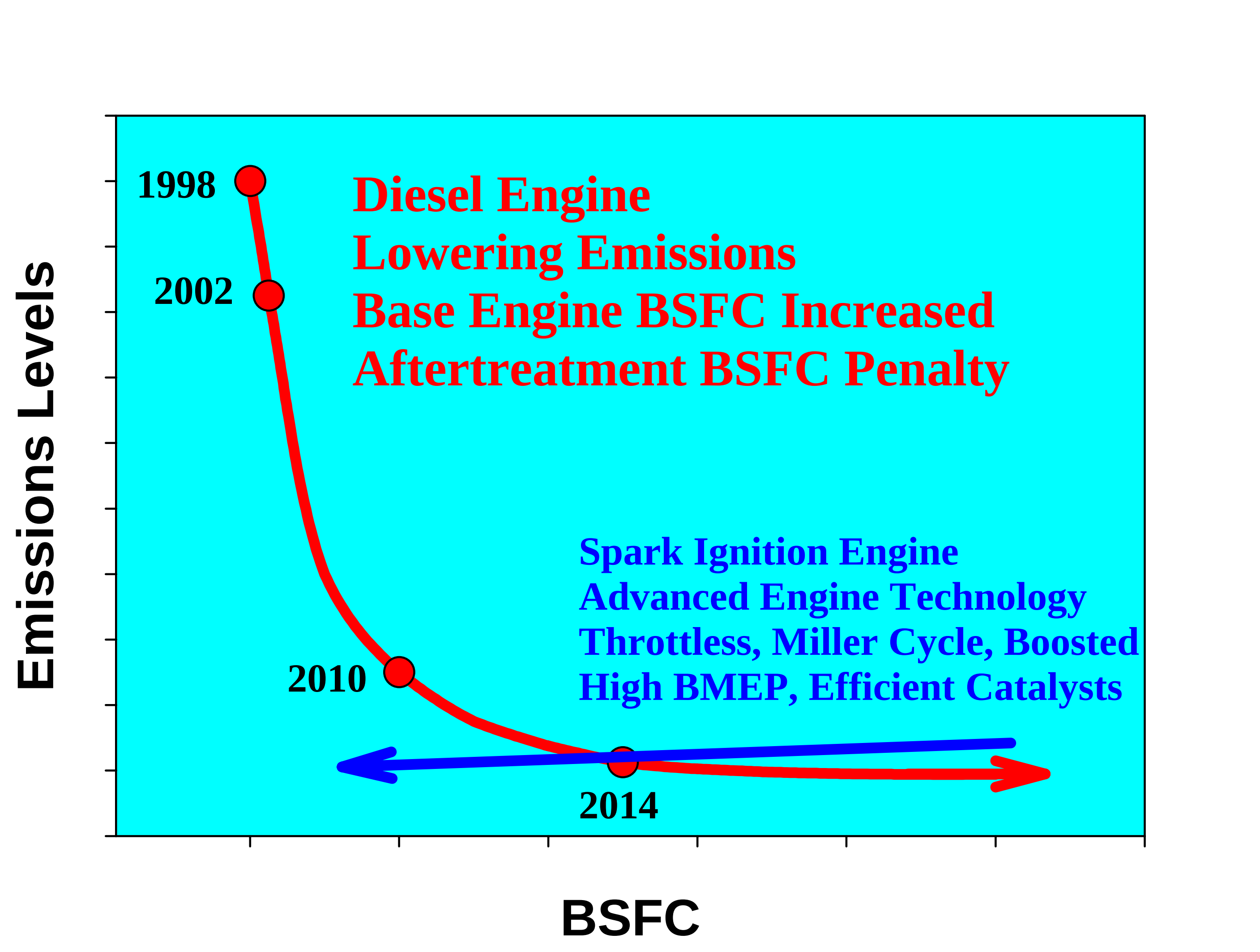
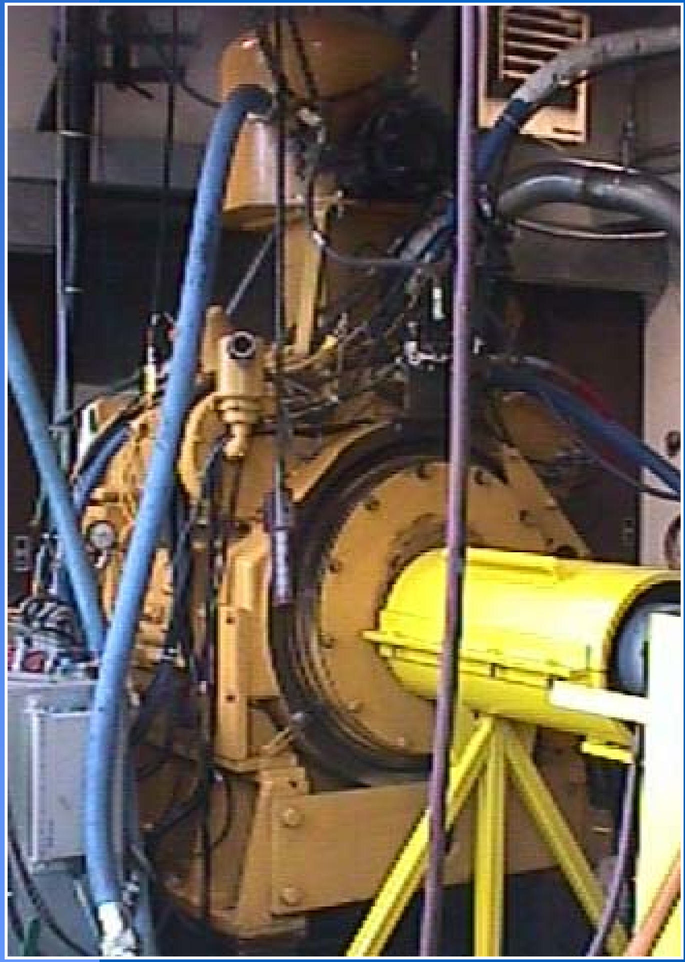
Flame Propagation Combustion

At What Emissions Level do the efficiencies Converge?



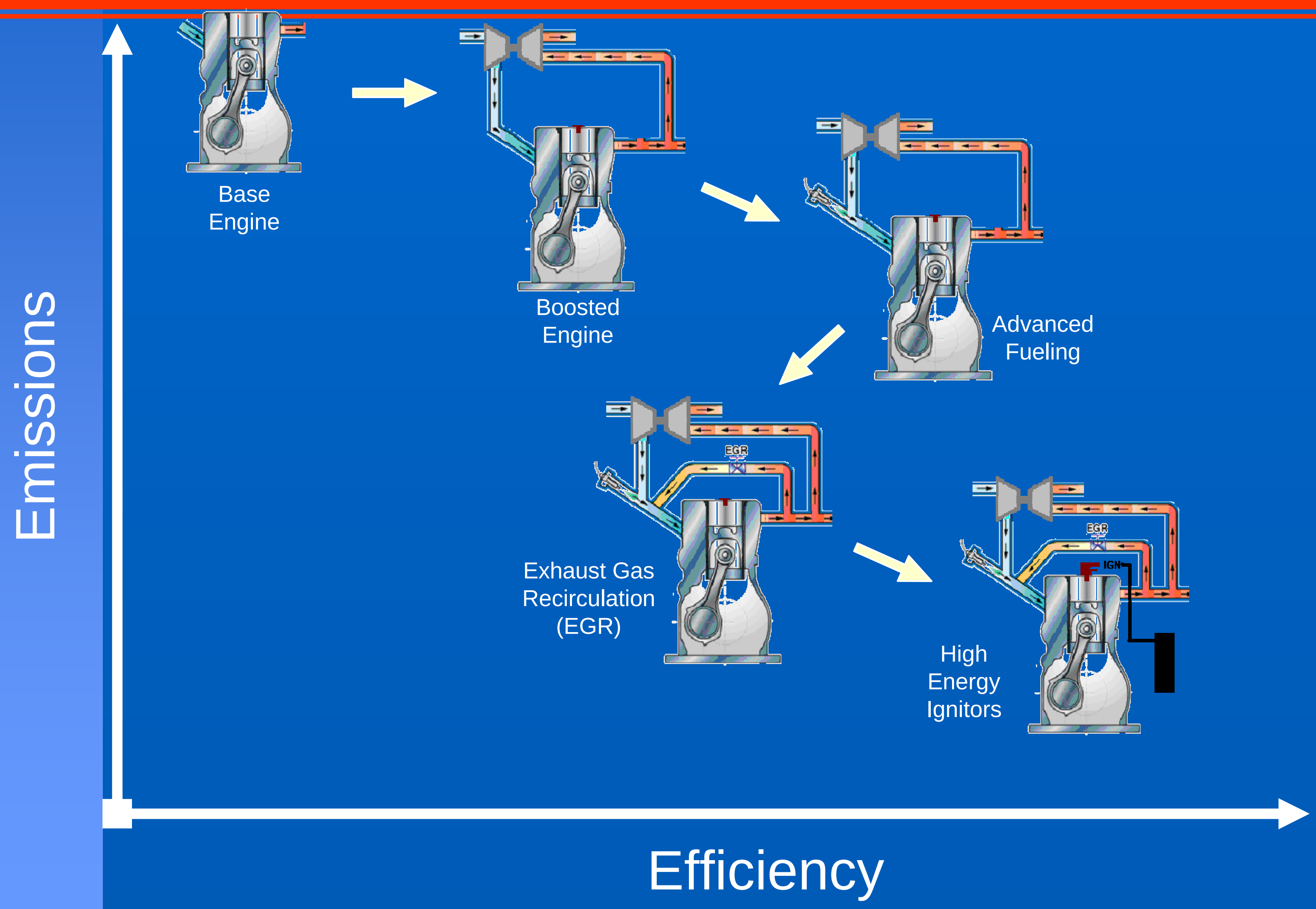
Further Details of Lab Setup



CAT 3501 at SwRI

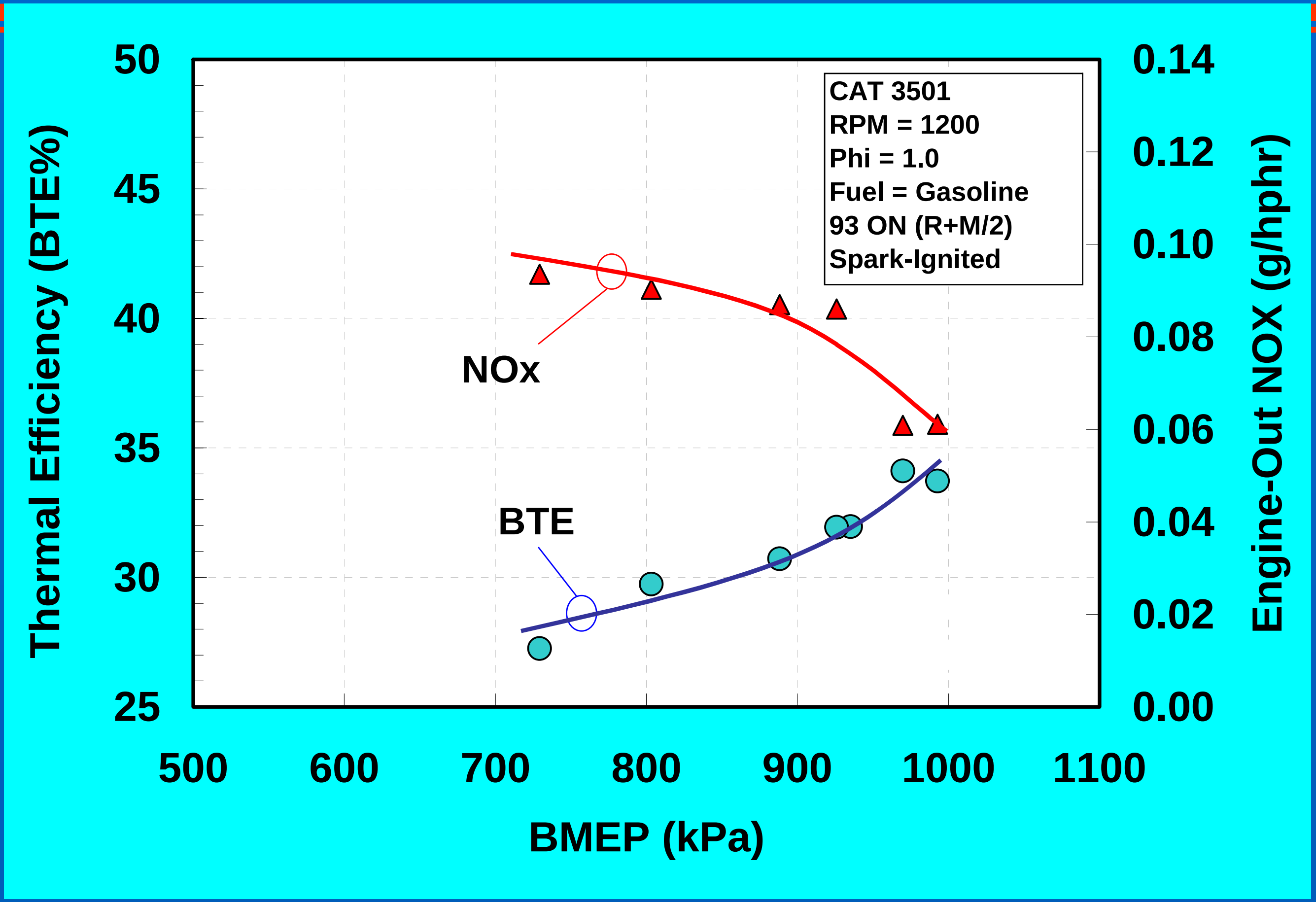
- Test Setup
  - Spark ignition available
  - Diesel Micropilot ignition system (~1% fueling)
  - Geometric Rc = 15/1
  - LIVC Miller-cycle camshaft
    - Effective Rc = ~10/1 and ~12/1
- Test Fuels
  - DF-2 micropilot
  - 93 ON gasoline (Howell EEE)

The Research Path



HD-Gasoline Results
(High Energy Ignition)

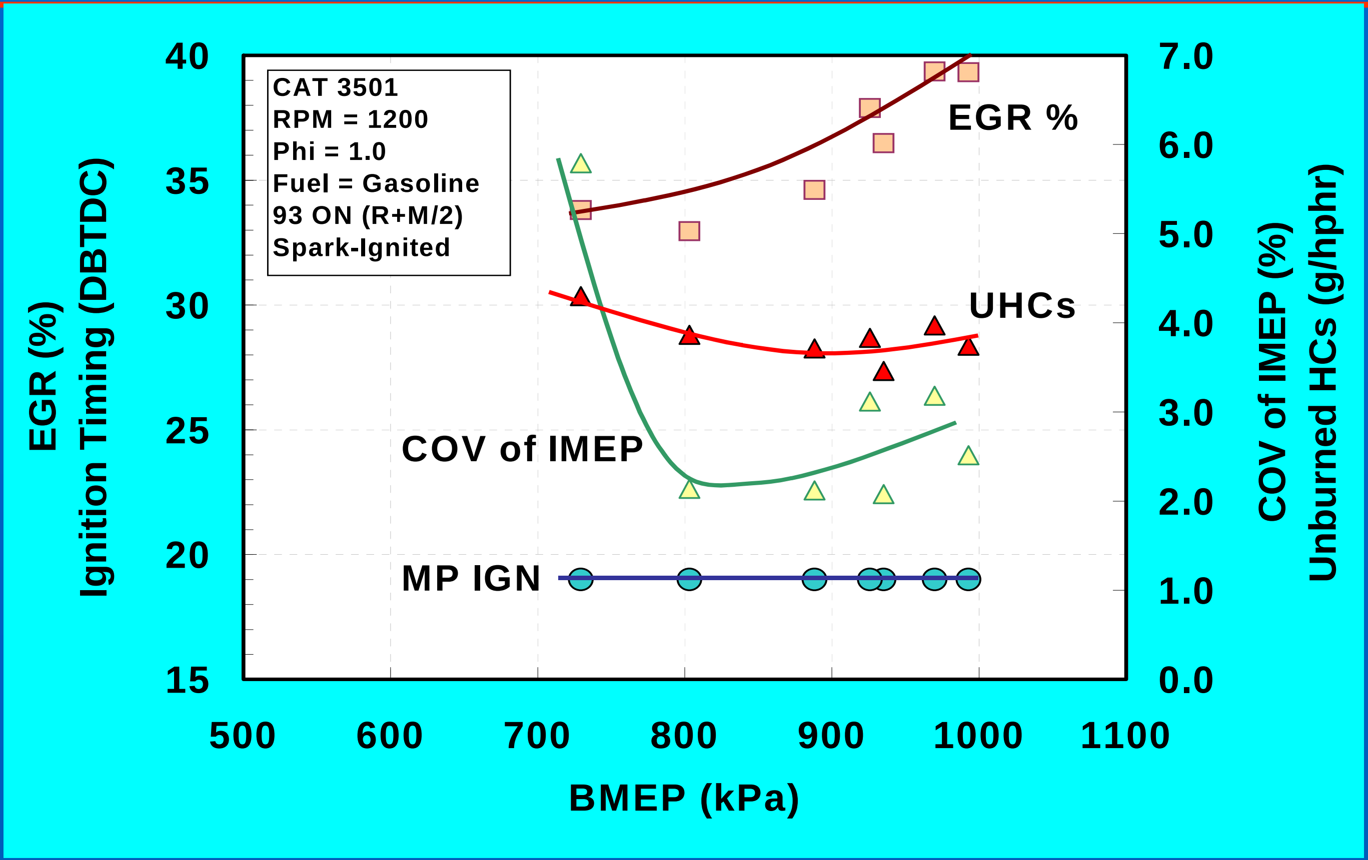
- High Energy, MicroPilot Ignited Operation
- NOx decreases as load is Increased
- Efficiency continues to increase with load
  - Better EGR tolerance
  - Ignition-related misfires cured



- Notice peak BTE approaching 35%, with potential for more...

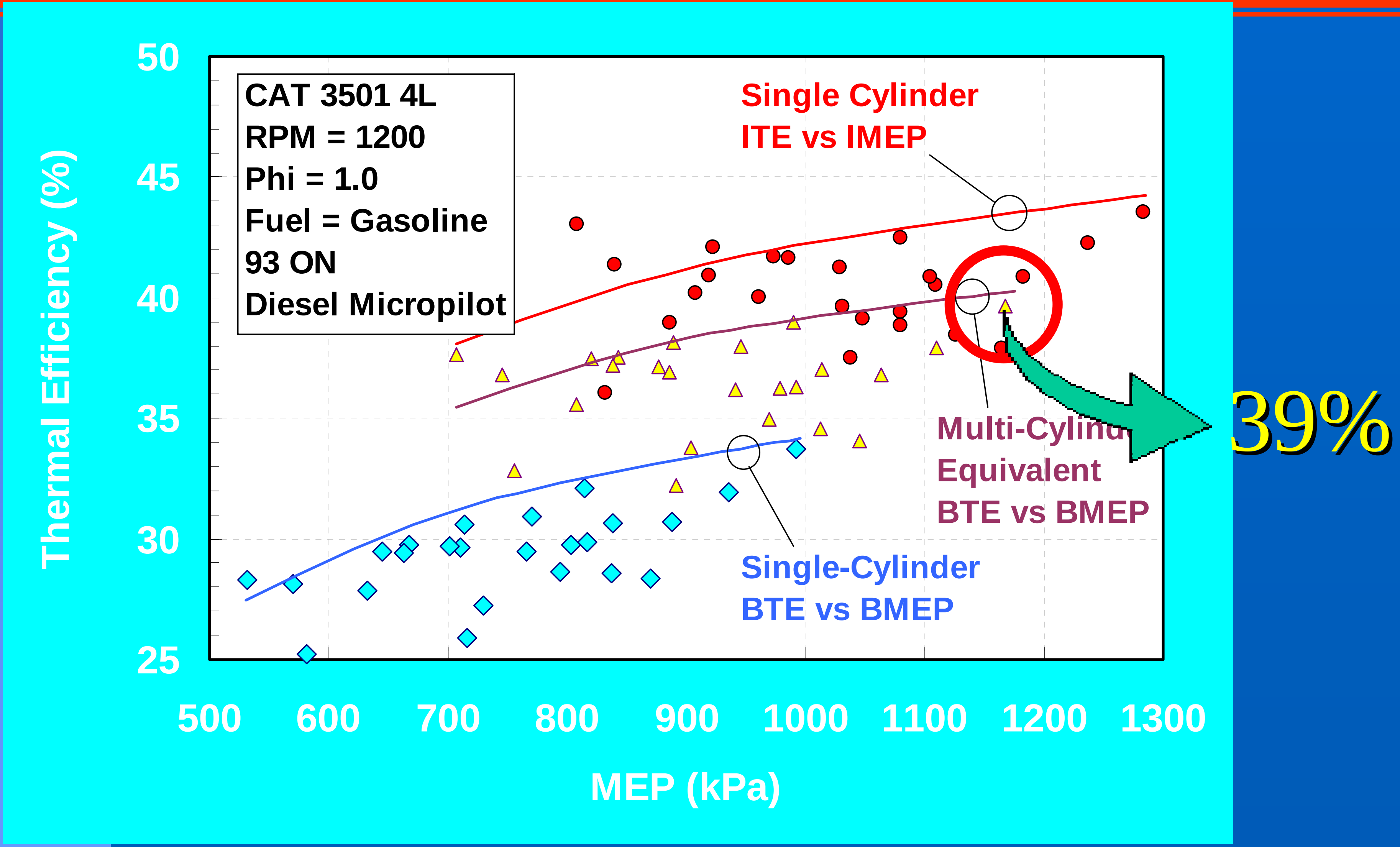
HD-Gasoline Results
(High Energy Ignition)

- High Energy, MicroPilot Ignited Operation
- Peak EGR of 39%
- Engine Coefficient of Variance (COV) at normal levels
- No optimization of MP timing



- Unburned hydrocarbons are an issue, but would be handled easily by 3-way catalyst

Scaling HD-Gasoline Results to Approximate Multi-Cylinder

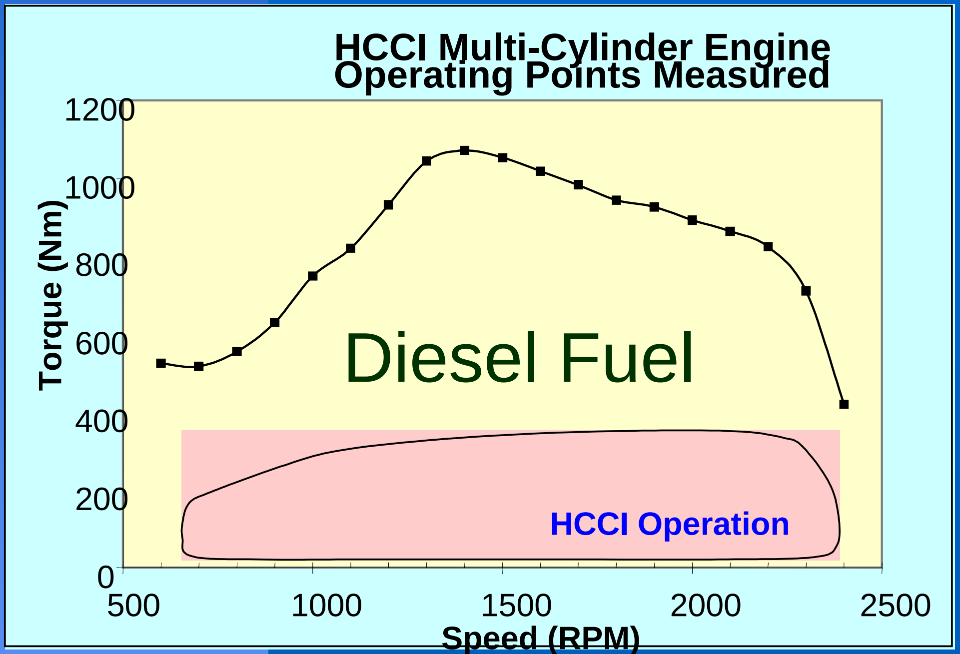


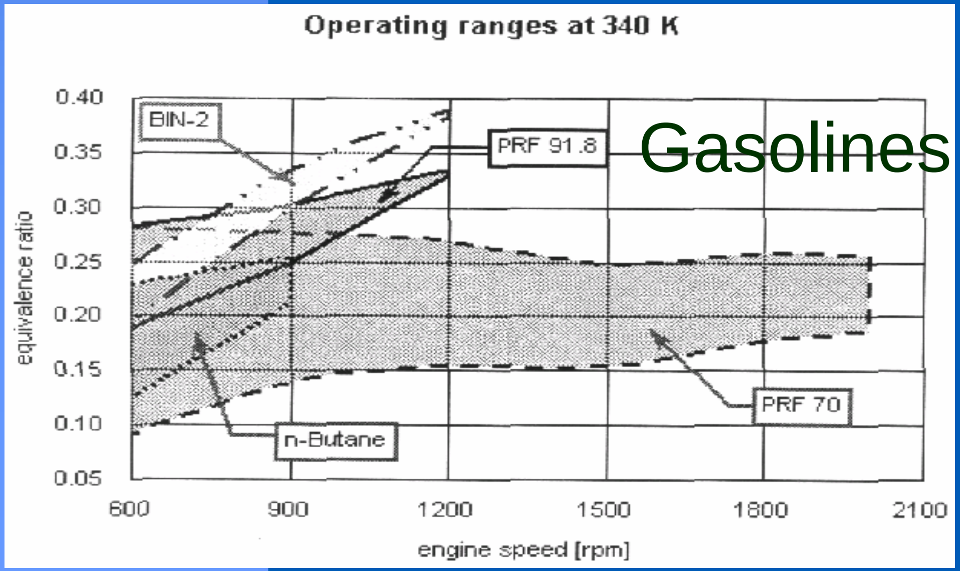
Enabling Technologies

- SwRI has identified technologies necessary to make SI competitive with diesel
- Enabling technologies identified through modeling and experimental studies
  - Boosted Operation
  - High EGR
  - High Energy Ignition System
  - Variable Valve Actuation
  - Active Fuel, VVA, and Knock Mitigation Controls
    - Possibly model+sensor based

Homogeneous Reaction Engines

Homogeneous Reaction



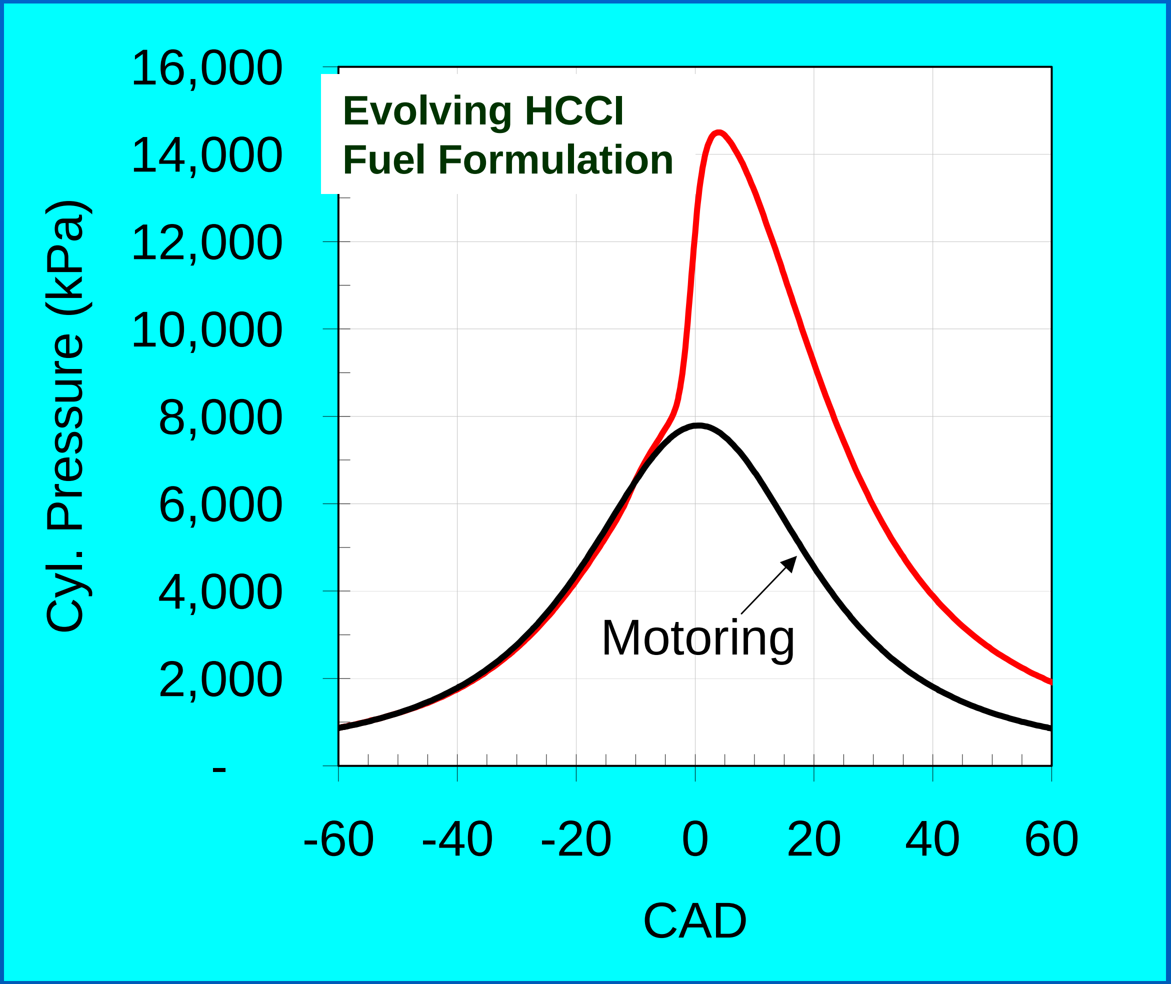


- HCCI will Remain a Part Load Option for Mixed Mode Engines as Long as Gasoline or Diesel Fuel are Used
- Practical Full Time HCCI Operation will only be Possible When and HCCI Fuel is Available - See Last Year's DEER

HCCI Fuel Formulation - High Load

- HCCI Fuel Formulation
  - 11.3 Bar NMEP
  - 0.02 g/kWh $ISNO_x$
  - 0.0 BSU Smoke

- Highest load to date
- Standard output Cummins Diesel approx. 15 Bar NMEP



Conclusions

- All Modes of Combustion Must be viewed as Potential Options for Meeting Future Emissions Standards
- Diffusion Combustion Engines are Likely to Become Less Efficient and More Expensive
  - Aggressive EGR May Help
- Flame Propagation Combustion Engines can Become More Efficient and More Durable
- Full Time HCCI Engines will Become Practical When there is a Specific HCCI Fuel