Technology for Advanced HD Engines

12th ETH Conference on Combustion Generated Nanoparticles

June 23, 2008

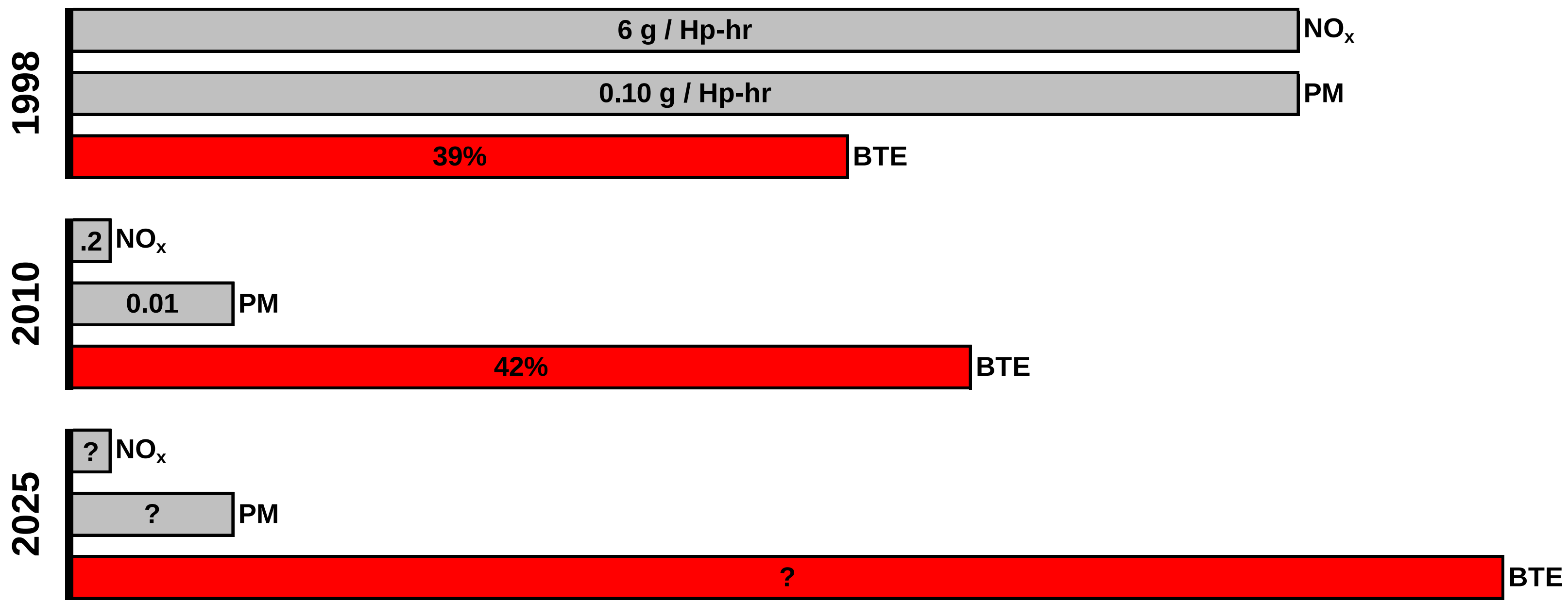
Wayne Eckerle

Our Focus has Changed

CO_2: The Next Front for Clean

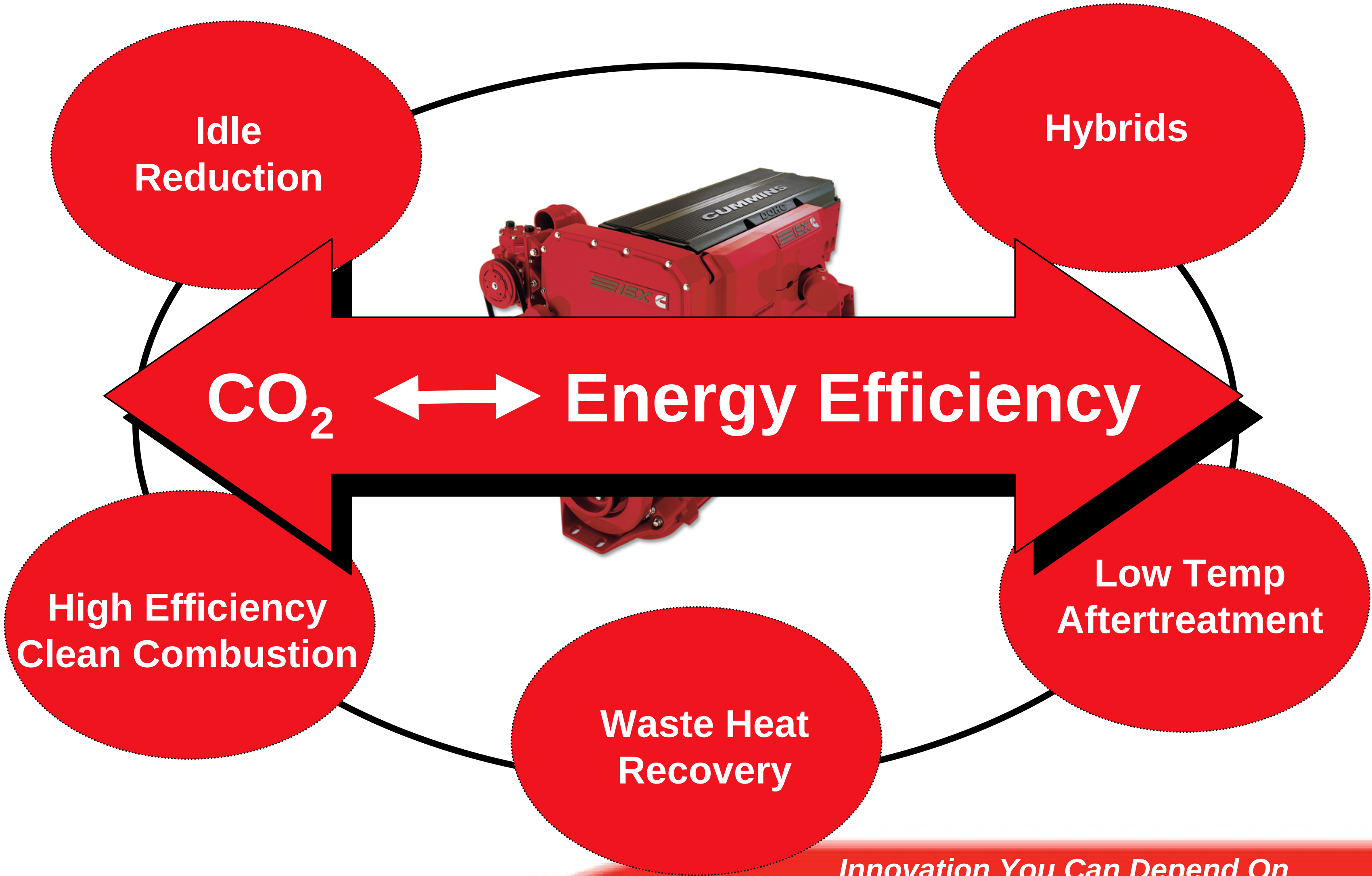
- Past focus on emissions made it hard to improve efficiency
- Focus on CO_2 reduction may require overall HD truck fuel economy improvements of 40%
- Engine improvements could account for 20%

Heavy Duty Diesel Emission verses Fuel Economy History



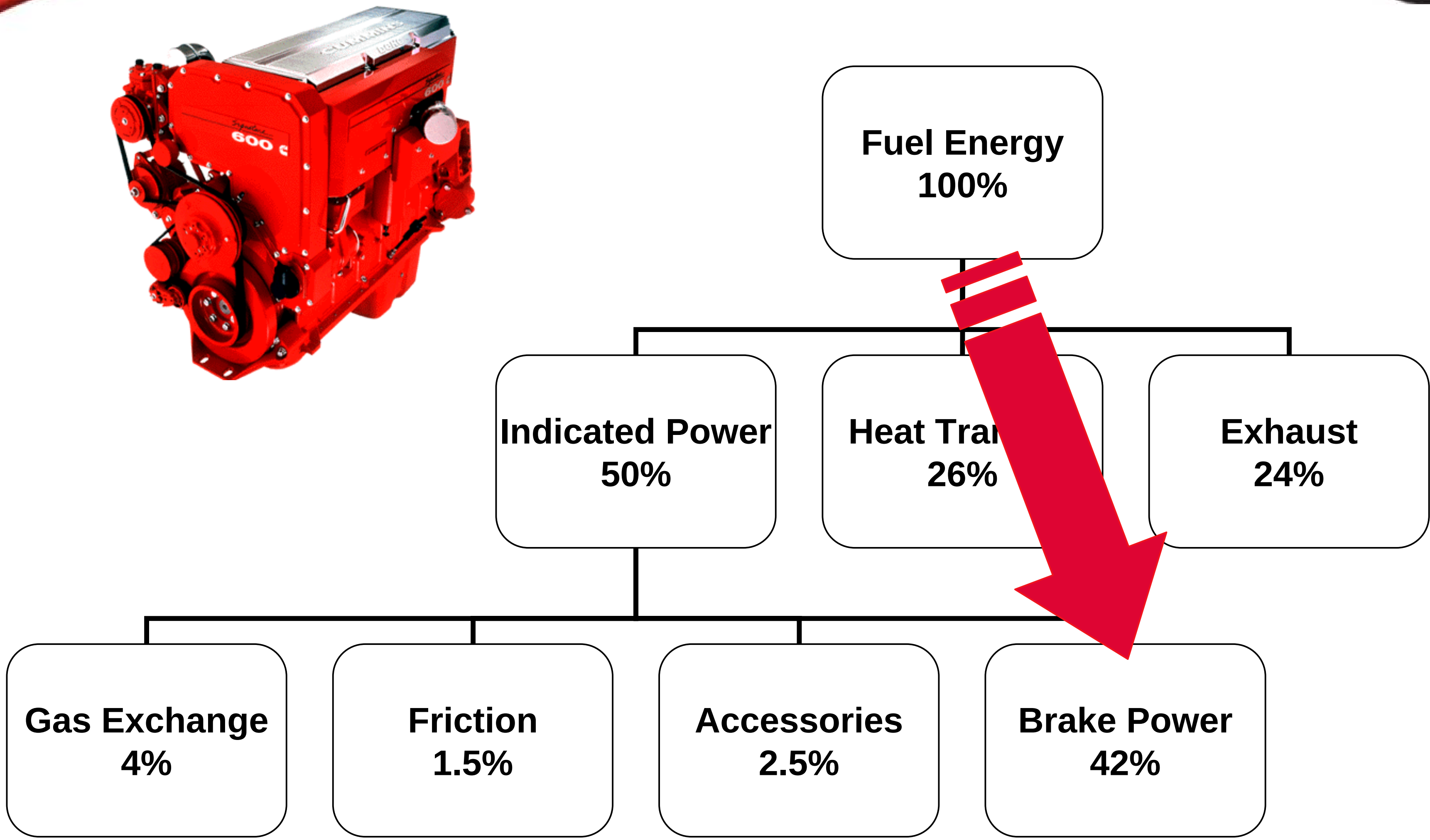
Top Five Strategies

Reducing our CO_2 Footprint



HD Energy Efficiency

2007 HD Engine Energy Balance



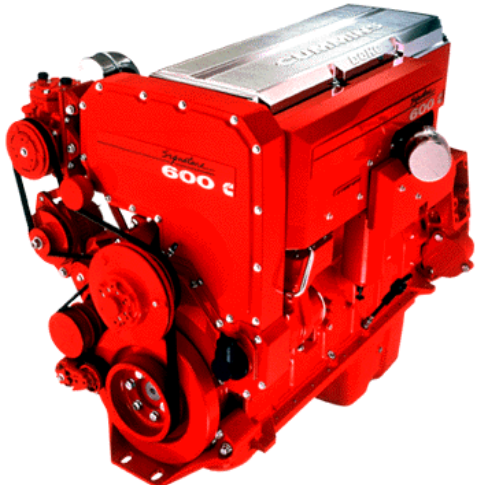
Technology Roadmap for Efficiency Improvement

Variable Valve Actuation

Fuel System
- EMI (Piezo)
-High Injection Pressure
-VSP
-SSC

Advanced Combustion
-Enhanced PCCI
-Lifted Flame Diffusion
-Stoichiometric
-Supercritical Combustion

Variable Intake Swirl



Controls
-Combustion Manager
- Physics based controls
-Sensors

EGR Loop
- Lower Pressure Drop
- Alternative Cooling

Electrically Driven Components

Turbo
- Two Stage
- Electric Boost
- Supercharging

Aftertreatment
- Low Temperature
-Low ΔP
-Calibration

Hybrid Powertrain

Waste Heat Recovery

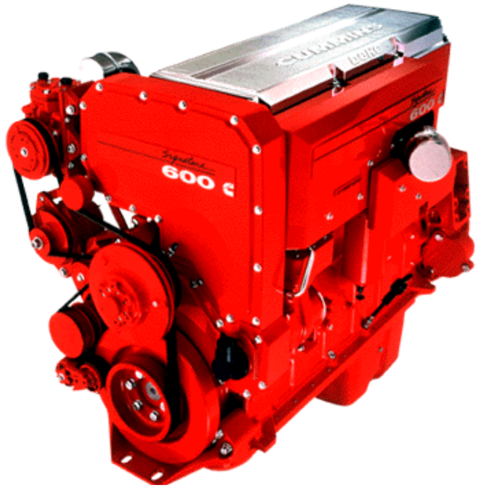
Technology Roadmap for Efficiency Improvement

Variable Valve Actuation

FUEL SYSTEM

COMBUSTION

Variable Intake Swirl



CONTROLS

EGR Loop
- Lower Pressure Drop
- Alternative Cooling

Electrically Driven Components

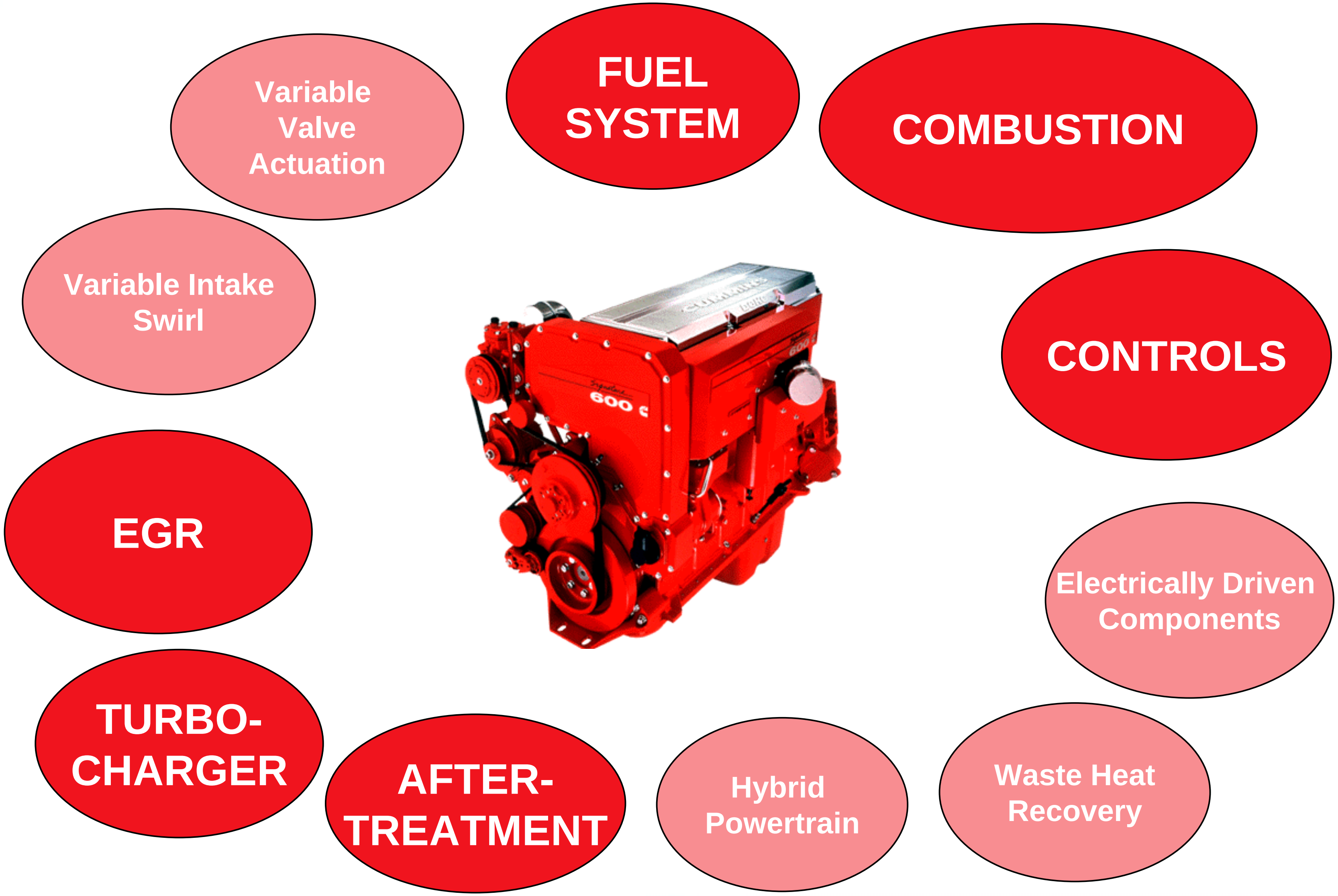
TURBO-CHARGER

AFTER-TREATMENT

Hybrid Powertrain

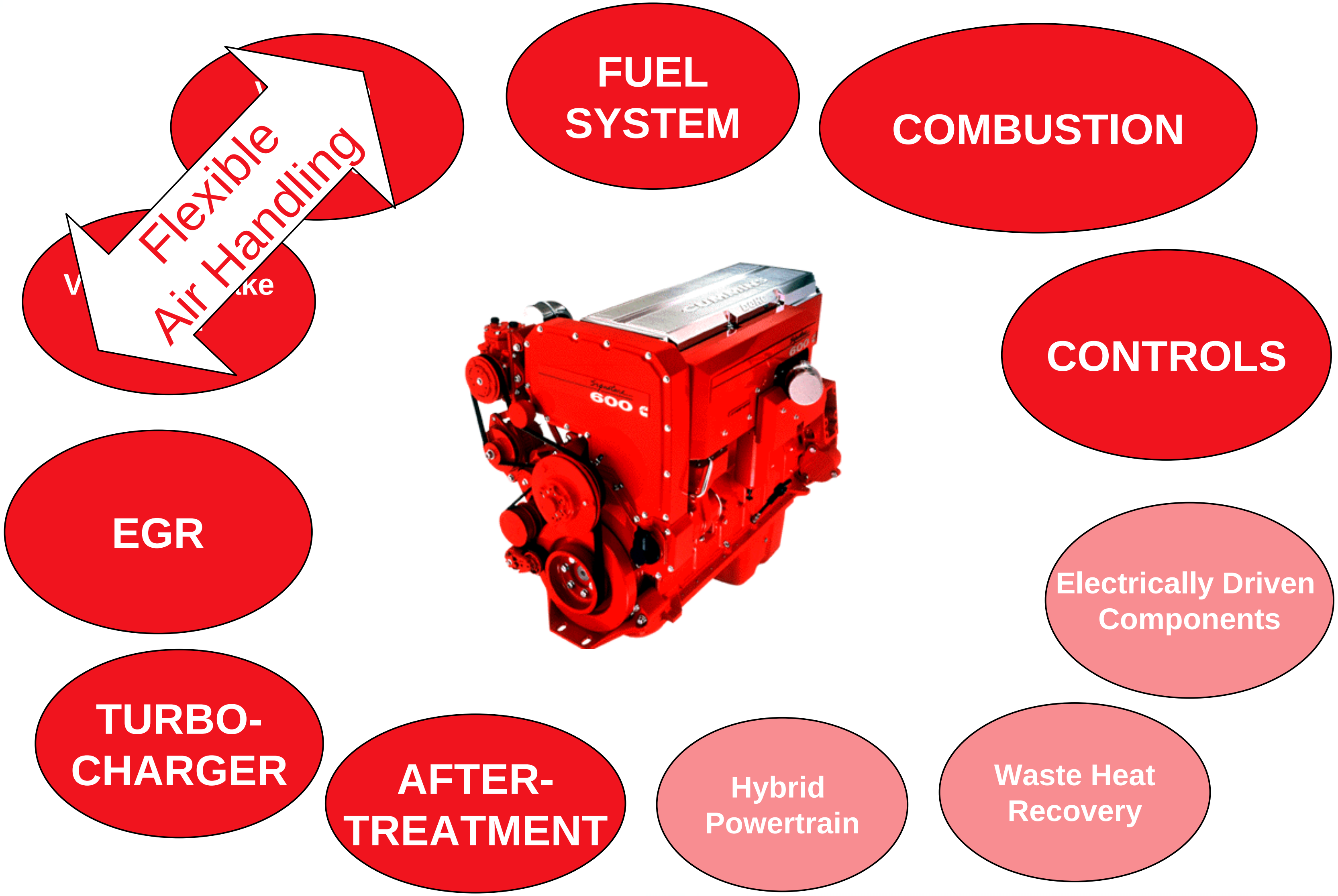
Waste Heat Recovery

Technology Roadmap for Efficiency Improvement



Innovation You Can Depend On

Technology Roadmap for Efficiency Improvement



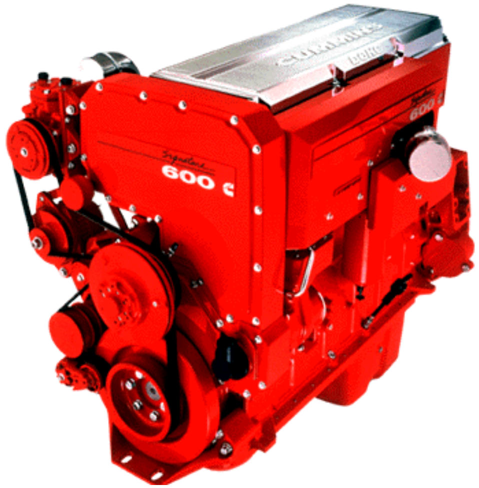
Technology Roadmap
for Efficiency Improvement

Variable Valve Actuation

FUEL SYSTEM

COMBUSTION

Variable Intake Swirl



CONTROLS

EGR

ELECTRIC COMPONENTS

TURBO-CHARGER

AFTER-TREATMENT

HYBRID

WASTE HEAT RECOVERY

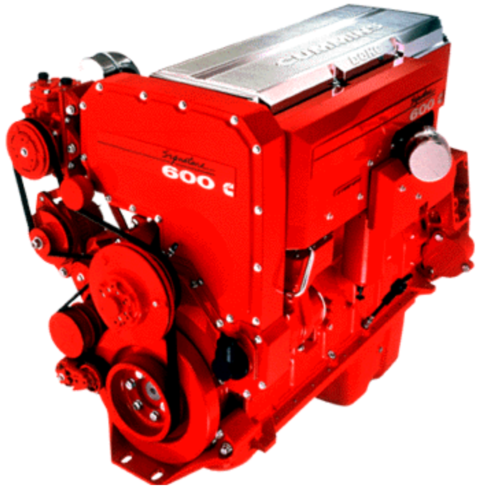
Technology Roadmap for Efficiency Improvement

Variable Valve Actuation

FUEL SYSTEM

COMBUSTION

Variable Intake Swirl



CONTROLS

EGR

EL C
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Waste Energy Recovery

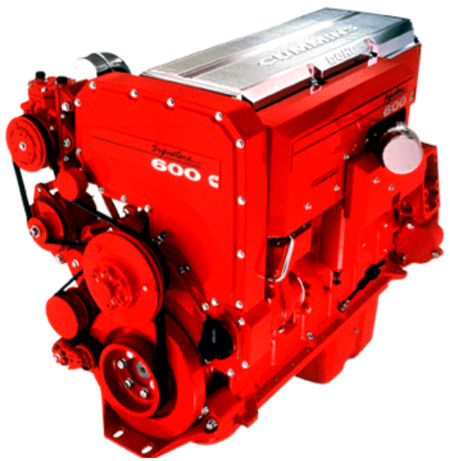
TURBO-CHARGER

AFTER-TREATMENT

HYBRID

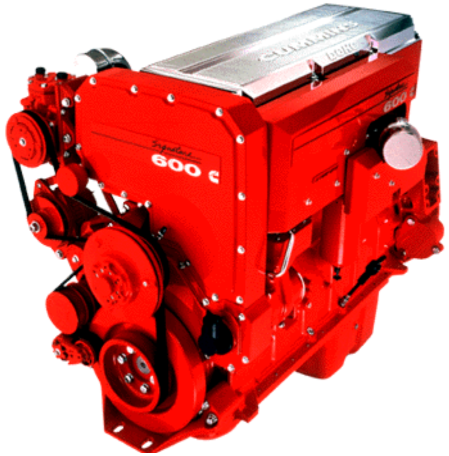
WASTE HEAT RECOVERY

2007 HD Engine Energy Balance



- **Fuel Energy 100%**
  - **Indicated Power 50%**
    - **Gas Exchange 4%**
    - **Friction 1.5%**
    - **Accessories 2.5%**
    - **Brake Power 42%**
  - **Heat Transfer 26%**
  - **Exhaust 24%**

Potential Advanced HD Engine Energy Balance



Fuel Energy
100%

Indicated Power
55.5%
(+5.5%)

Heat Transfer
23.5%
(-2.5%)

Exhaust
21%
(-3%)

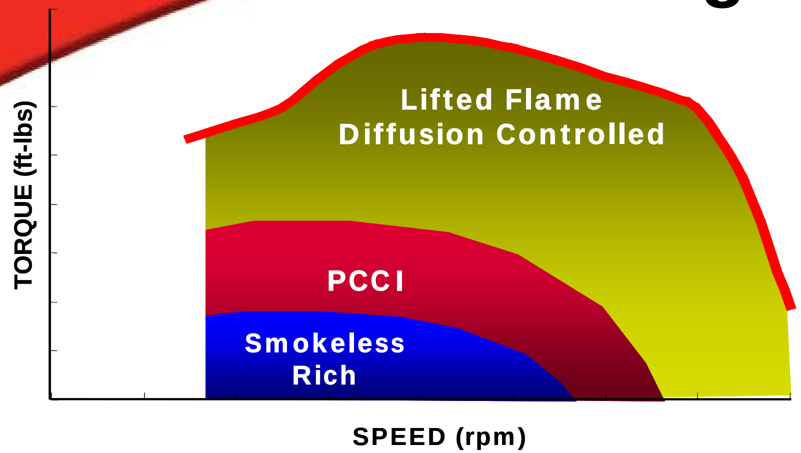
Gas Exchange
2%
(-2%)

Friction
1.0%
(-0.5%)

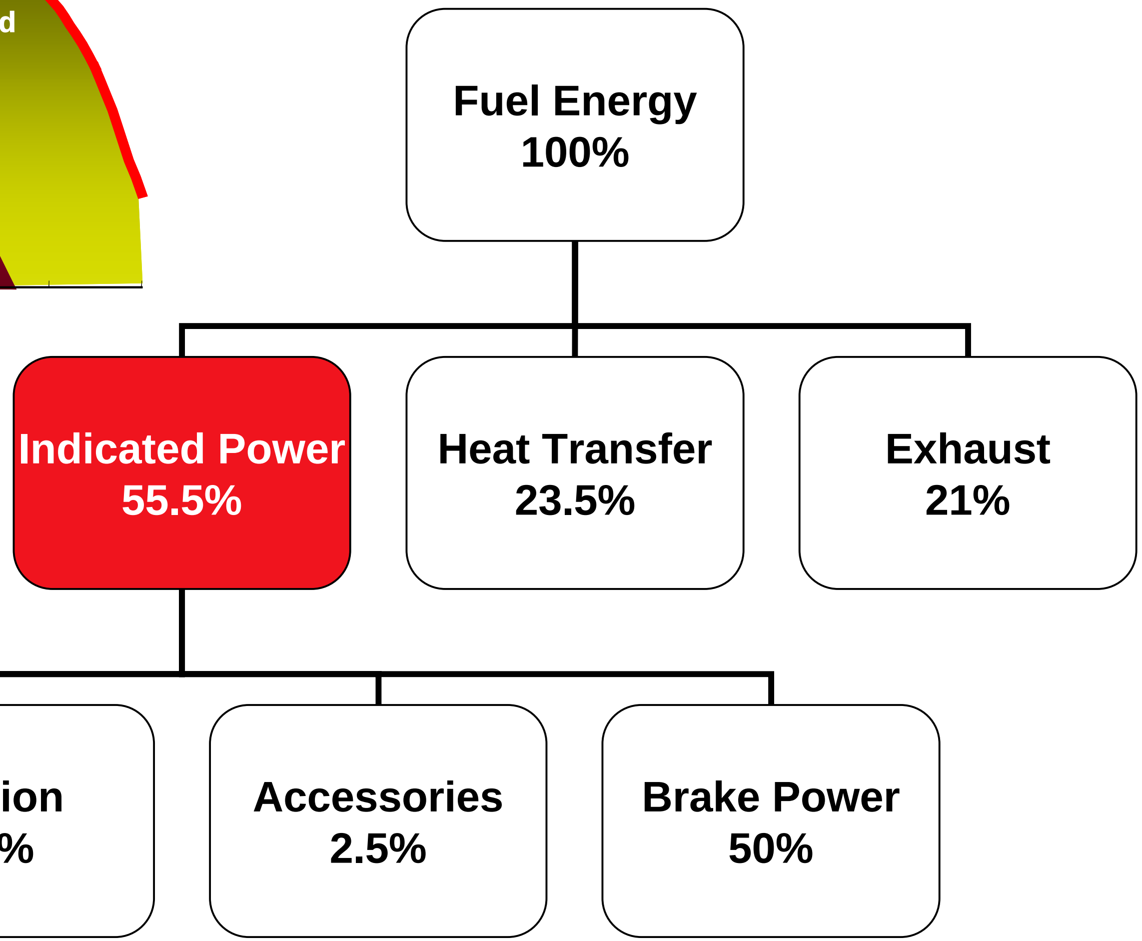
Accessories
2.5%

Brake Power
50%
(+8%)

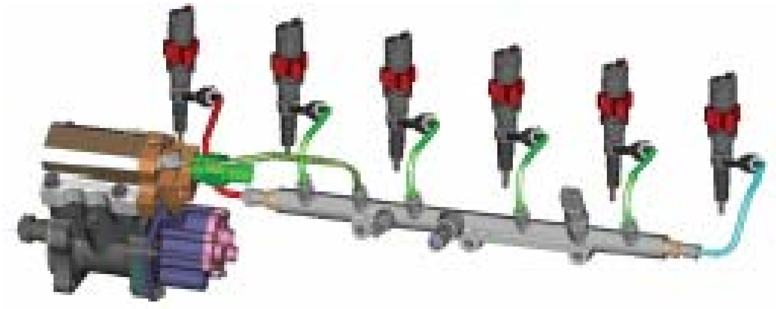
Enabling Technology for Efficiency Improvement



Advanced Combustion (Mixed Mode)
- Stoichiometric
- Early PCCI
- Lifted Flame



Enabling Technology for Efficiency Improvement



Fuel Energy
100%

- Indicated Power 55.5%
  - Gas Exchange 2%
  - Friction 1.0%
  - Accessories 2.5%
  - Brake Power 50%
- Heat Transfer 23.5%
- Exhaust 21%

Advanced Combustion → Indicated Power
- FIE (Higher Inj. Pressure, Multiple Inj)
- CEGR Cooling Systems
- Air Handling (Elec assist turbo)
- Increased Cylinder Pressure
- Closed Loop Combustion Control

Enabling Technology for Efficiency Improvement

Fuel Energy
100%

Indicated Power
55.5%

Heat Transfer
23.5%

Exhaust
21%

Gas Exchange
2%

Friction
1.0%

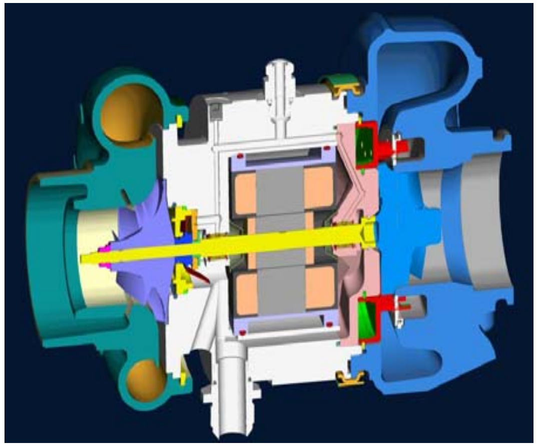
Accessories
2.5%

Brake Power
50%

Exhaust Energy Loss Reduction

- Efficient PM Aftertreatment
  - lower soot loading
  - low pressure drop
  - regen controls/strategy
- Exhaust Port Heat Transfer (liners)

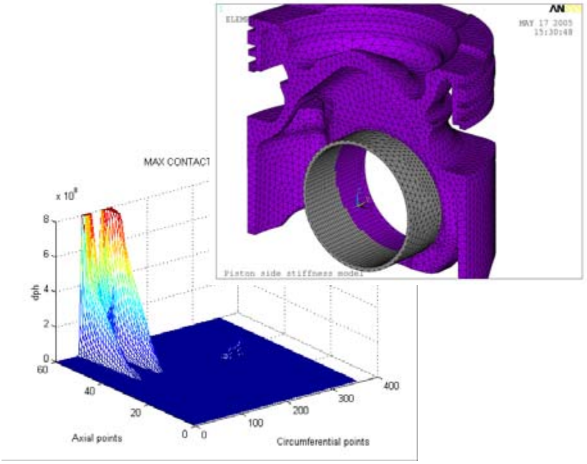
Enabling Technology for Efficiency Improvement



- Fuel Energy 100%
  - Indicated Power 55.5%
    - Gas Exchange 2%
    - Friction 1.0%
    - Accessories 2.5%
    - Brake Power 50%
  - Heat Transfer 23.5%
  - Exhaust 21%

Gas Exchange
- Electrically assisted turbo
- EGR pump
- Variable valve actuation

Enabling Technology for Efficiency Improvement



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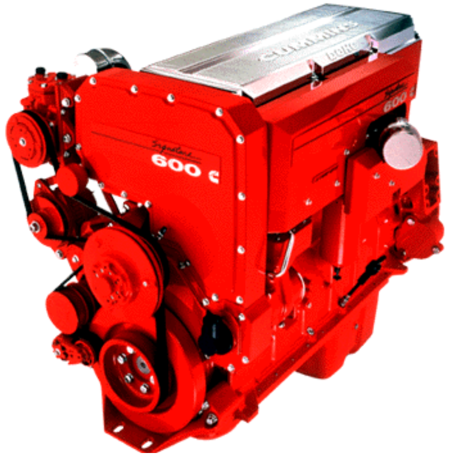
  - **Indicated Power 55.5%**
    - **Gas Exchange 2%**
    - **Friction 1.0%**
    - **Accessories 2.5%**
    - **Brake Power 50%**
  - **Heat Transfer 23.5%**
  - **Exhaust 21%**

Friction Reduction
- Piston and rings
- Bearings
- Surface treatment
- Lube oil

Potential Advanced HD Engine Energy Balance

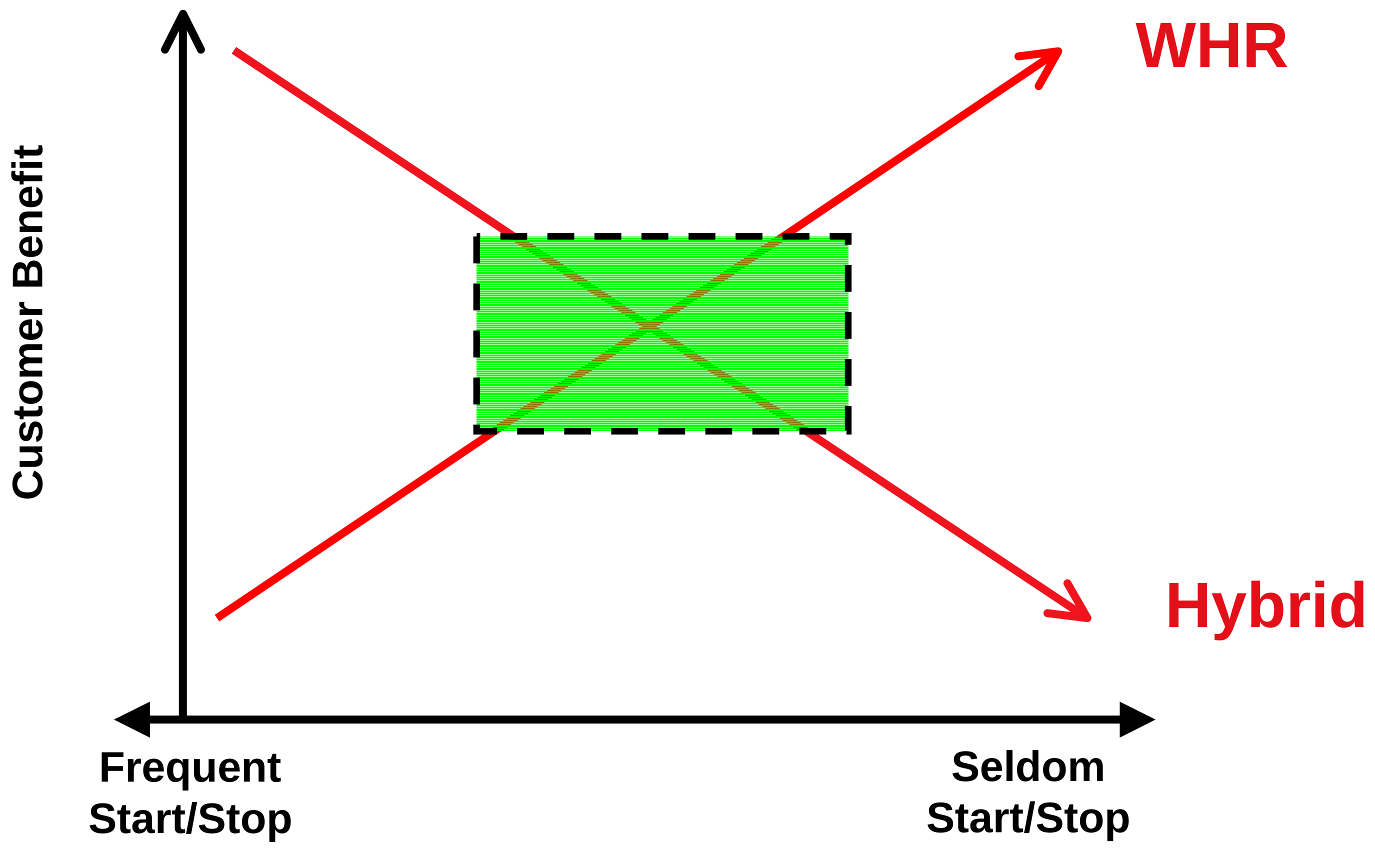


Fuel Energy 100%

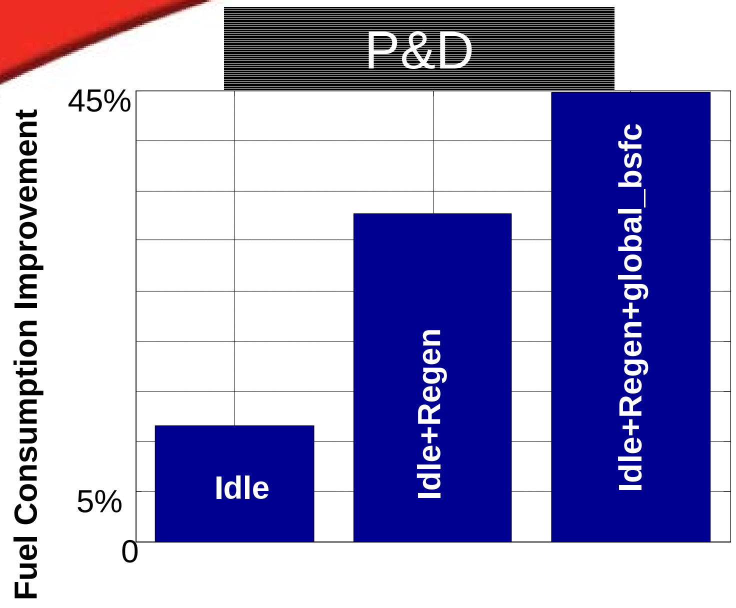
- Indicated Power 55.5% (+5.5%)
  - Gas Exchange 2% (-2%)
  - Friction 1.0% (-0.5%)
  - Accessories 2.5%
  - Brake Power 50% (+8%)
- Heat Transfer 23.5% (-2.5%)
- Exhaust 21% (-3%)

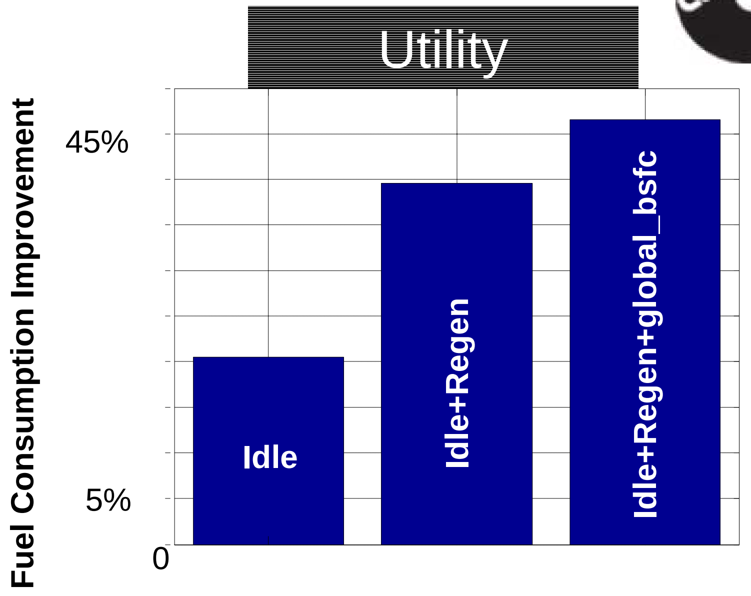
Engine Waste Heat Recovery

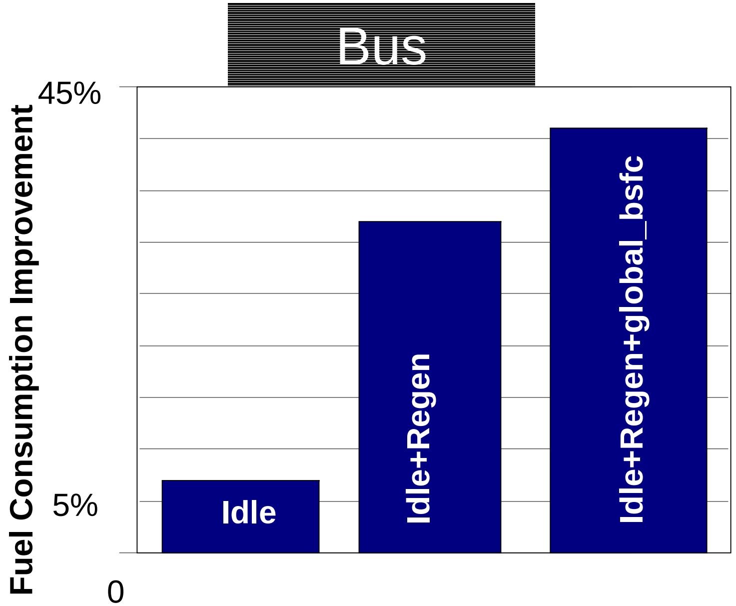
Waste Heat Recovery vs. Hybrid

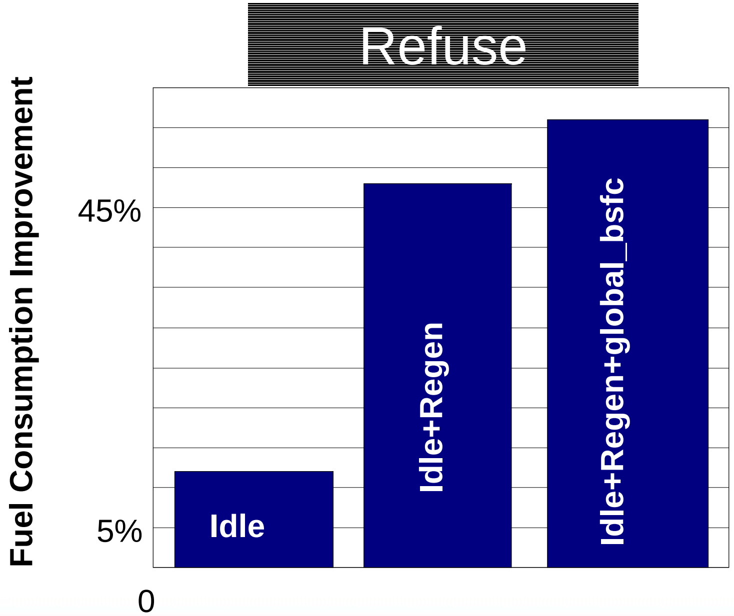


Hybridization Potential

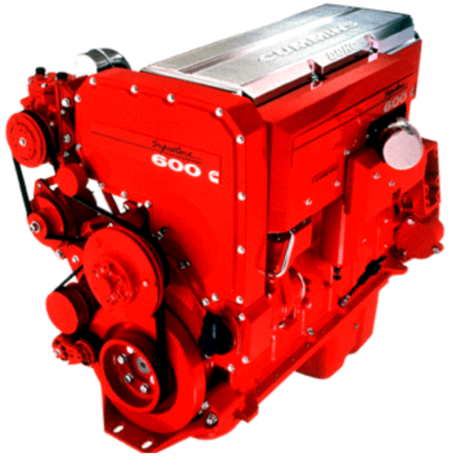








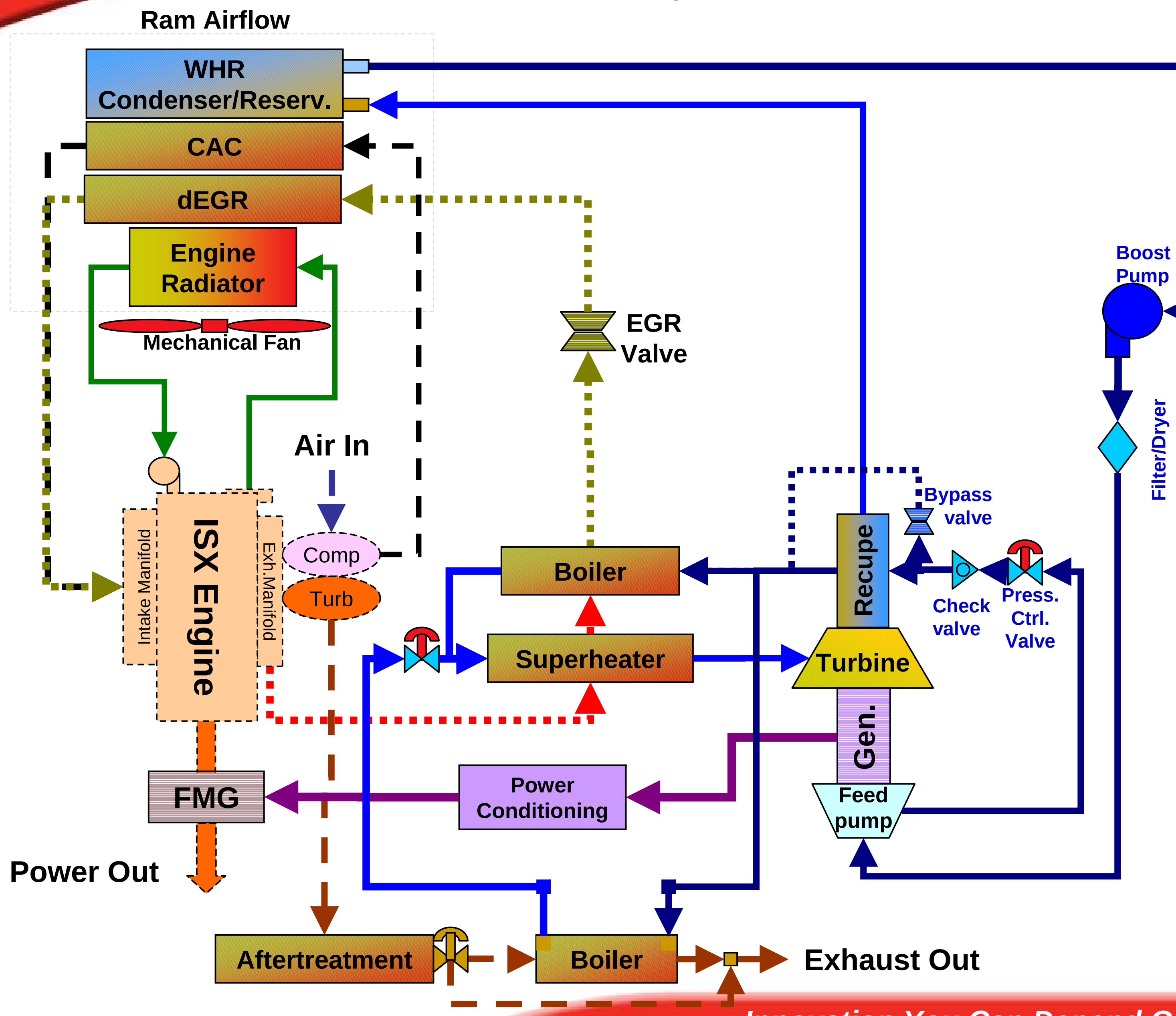
Waste Heat Recovery for Advanced HD Engine



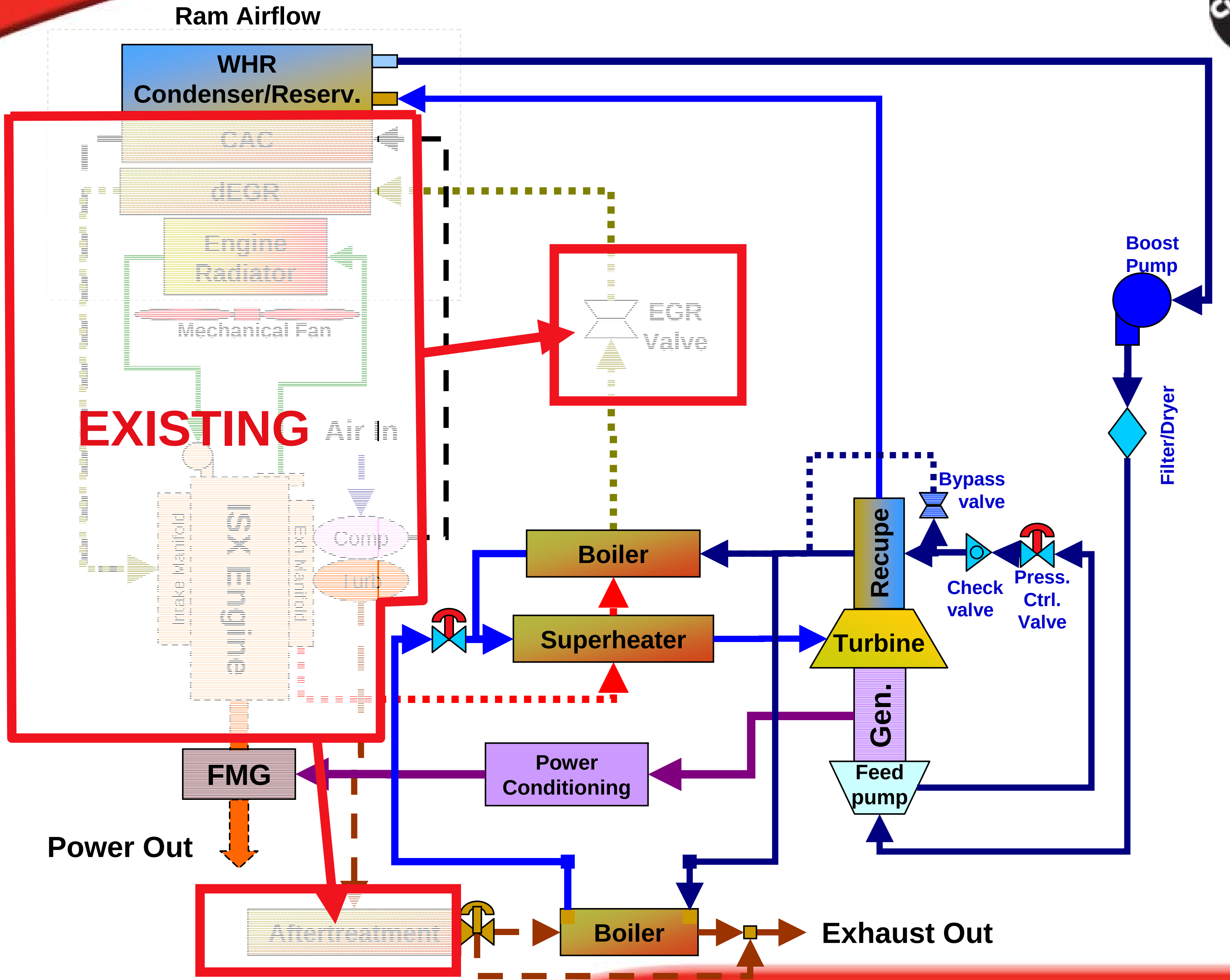
- **Fuel Energy 100%**
  - **Indicated Power 55.5%**
    - **Gas Exchange 2%**
    - **Friction 1.0%**
    - **Accessories 2.5%**
    - **Brake Power 50%**
  - **Heat Transfer 23.5%**
  - **Exhaust 21%**

Waste Heat Recovery

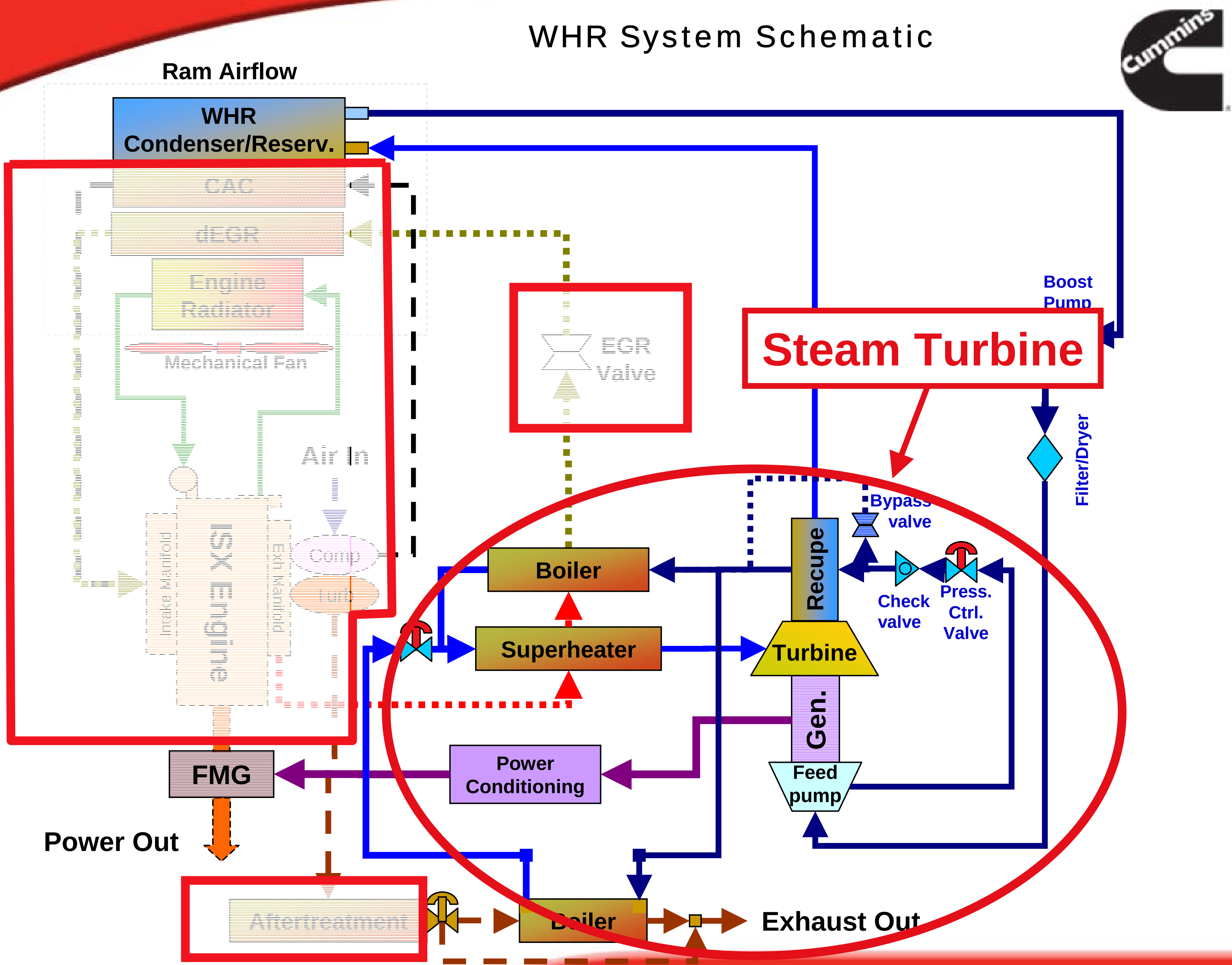
WHR System Schematic



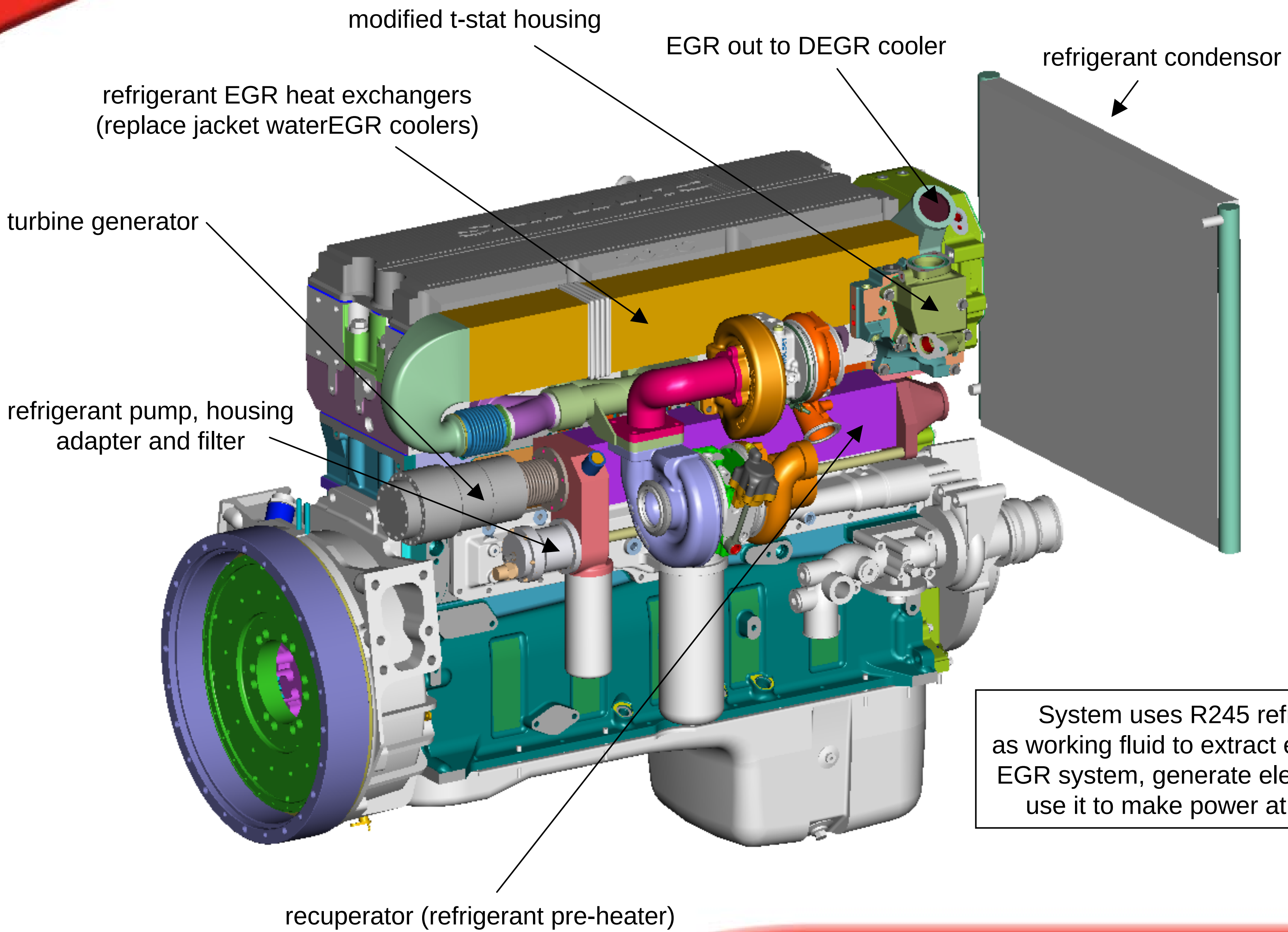
WHR System Schematic



WHR System Schematic

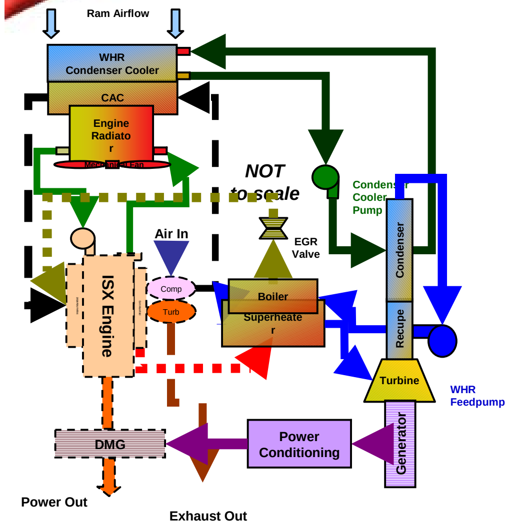


Engine with WHR Installed



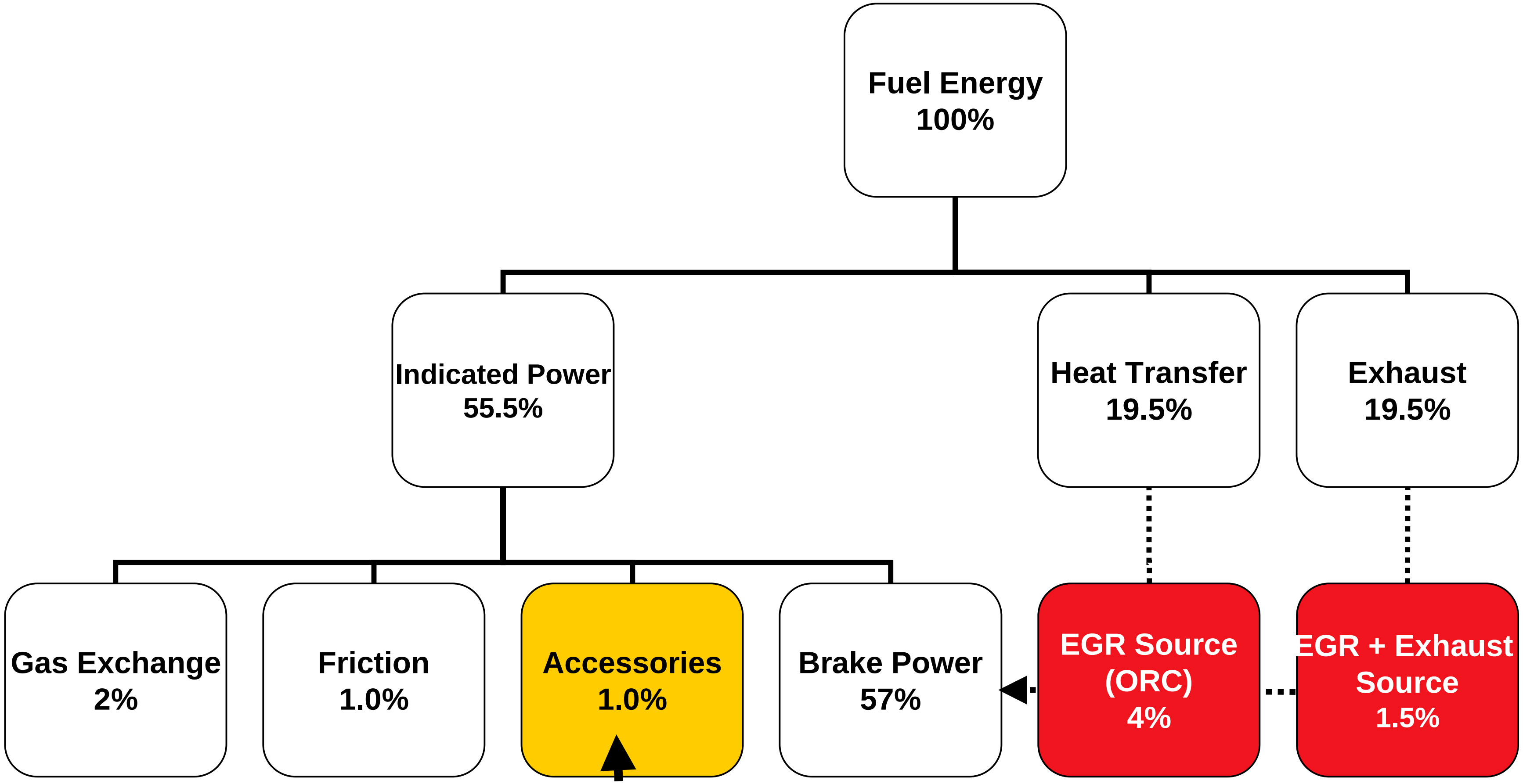
System uses R245 refrigerant as working fluid to extract energy from EGR system, generate electricity and use it to make power at flywheel

Waste Heat Recovery for Advanced HD Engine



- Fuel Energy 100%
  - Indicated Power 55.5%
    - Gas Exchange 2%
    - Friction 1.0%
    - Accessories 2.5%
    - Brake Power 55.5%
  - Heat Transfer 19.5%
    - EGR Source (ORC) 4%
  - Exhaust 19.5%
    - EGR + Exhaust Source 1.5%

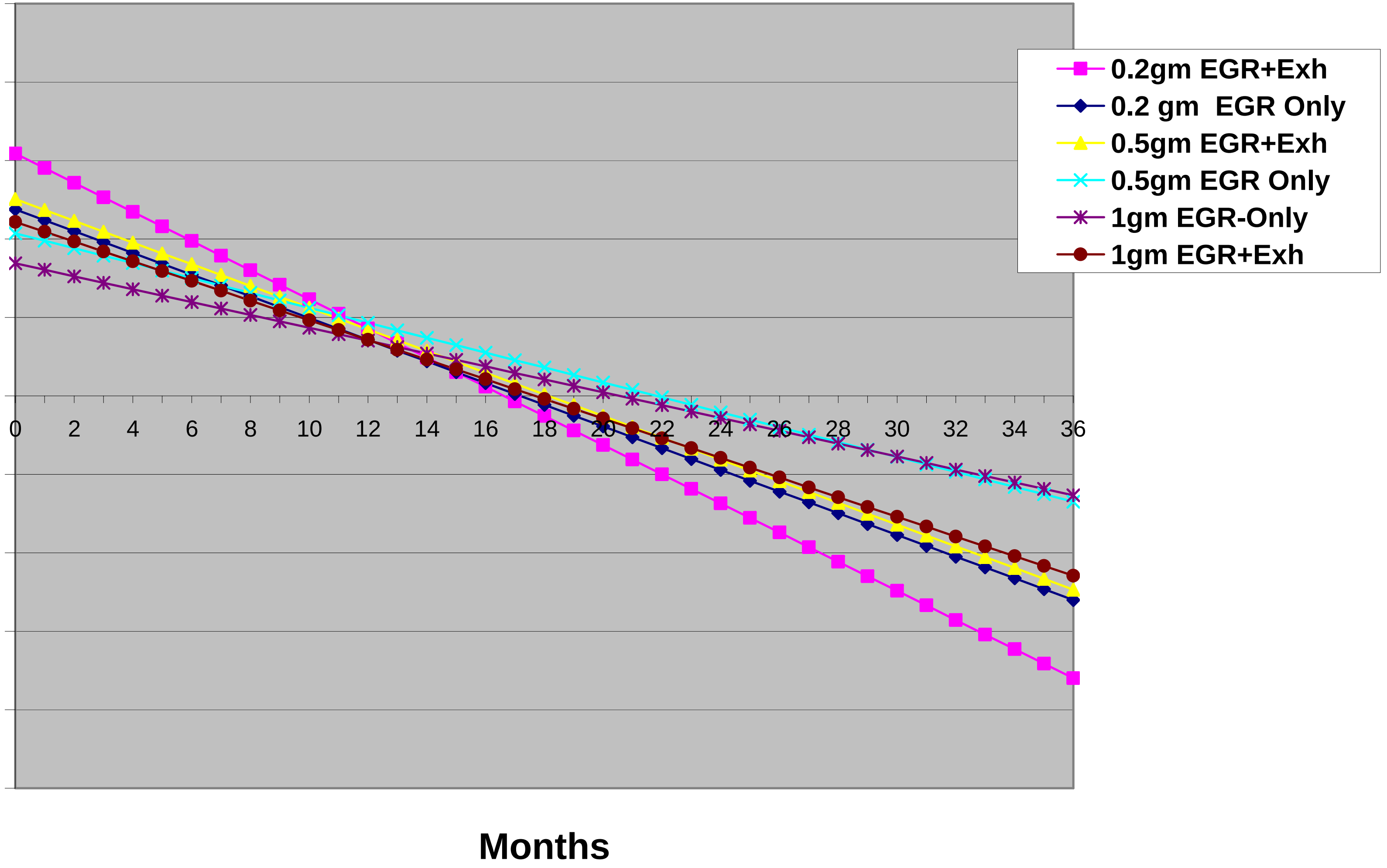
Energy Balance for Advanced HD Engine with Electrification of the Vehicle



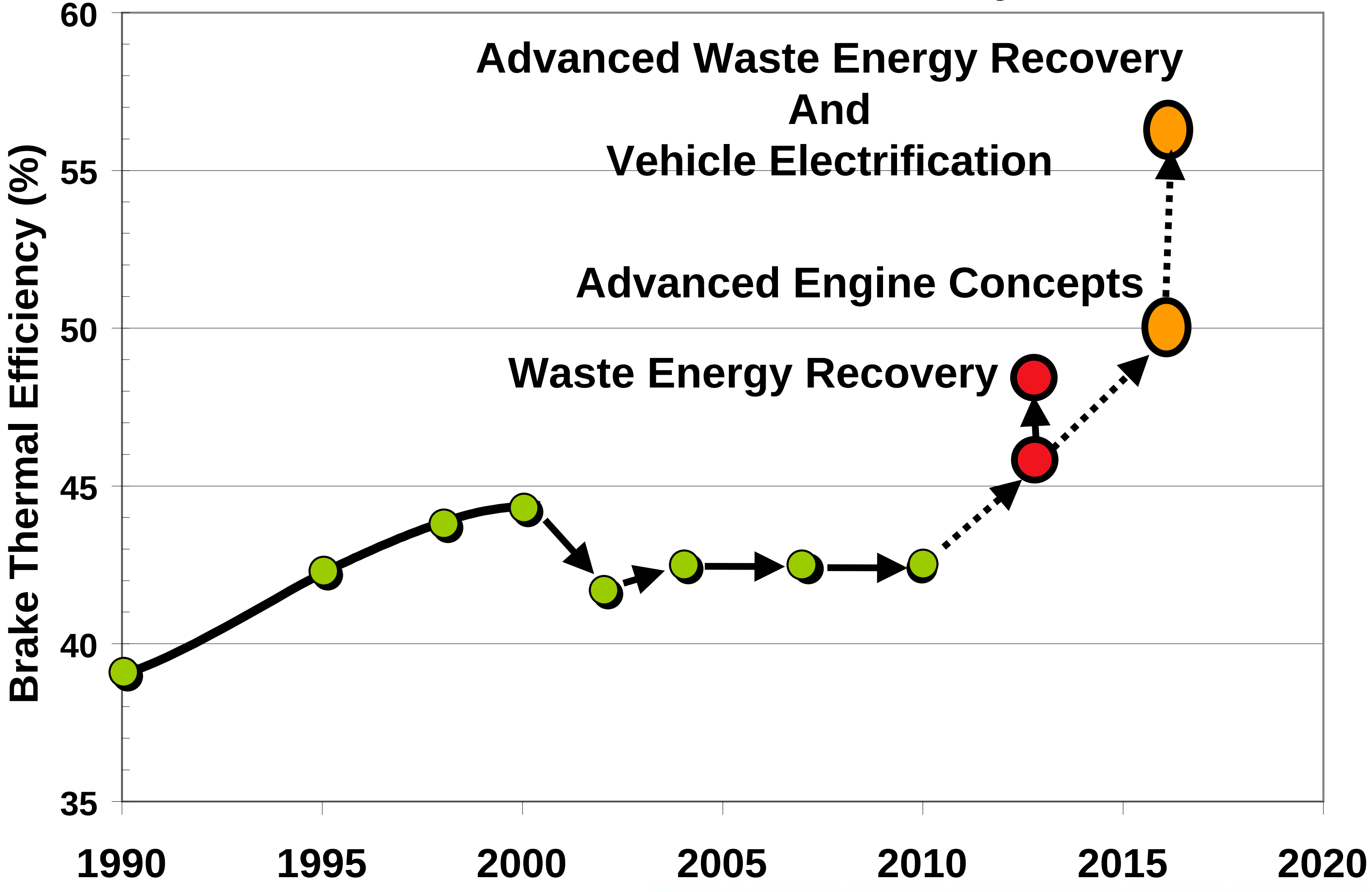
Electrified Vehicle

- HVAC
- Water pump
- Oil Pump
- APU

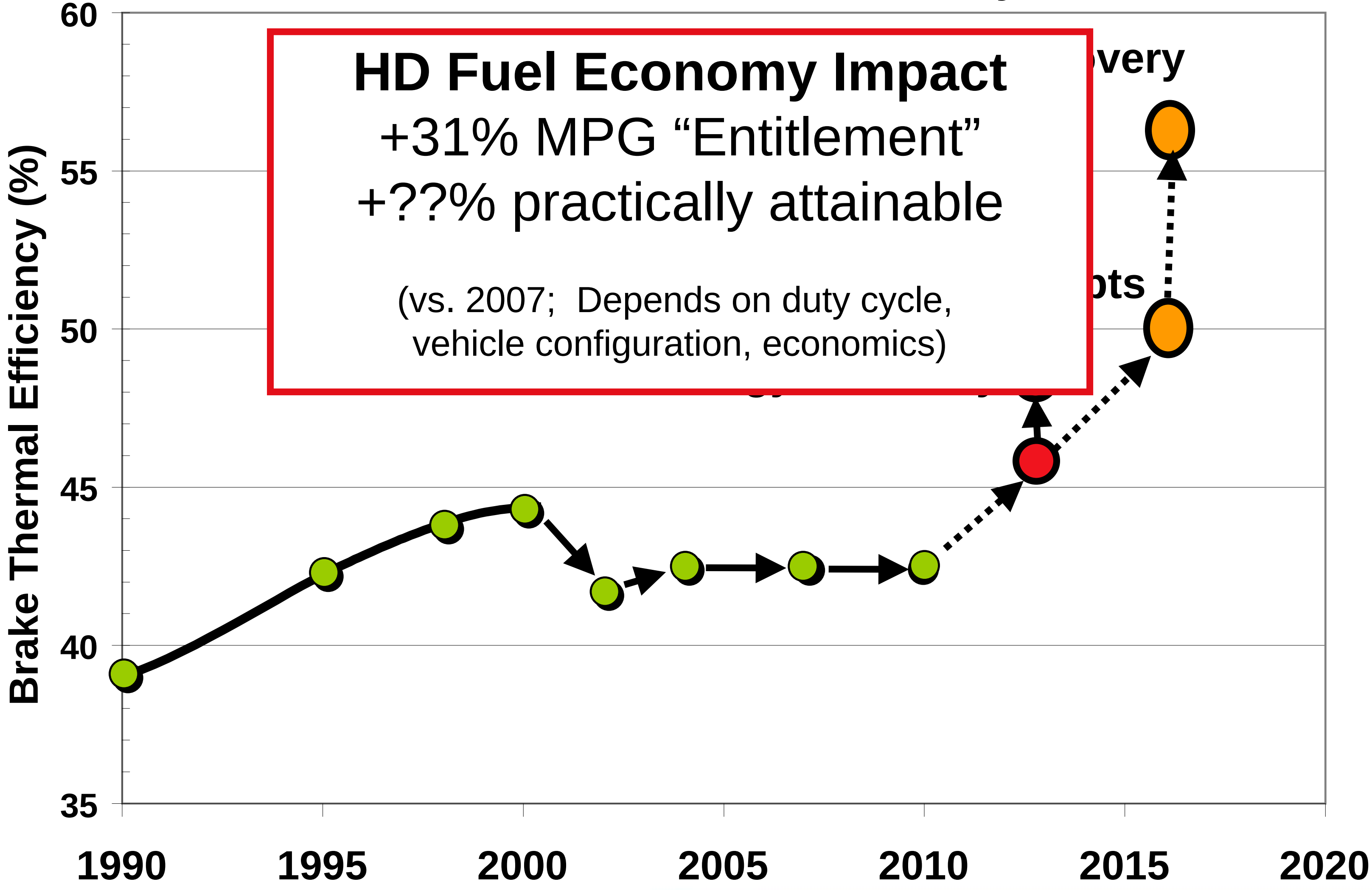
WHR TCO Model



Historical and Projected HD Brake Thermal Efficiency



Historical and Projected HD Brake Thermal Efficiency



Particulate Measurements

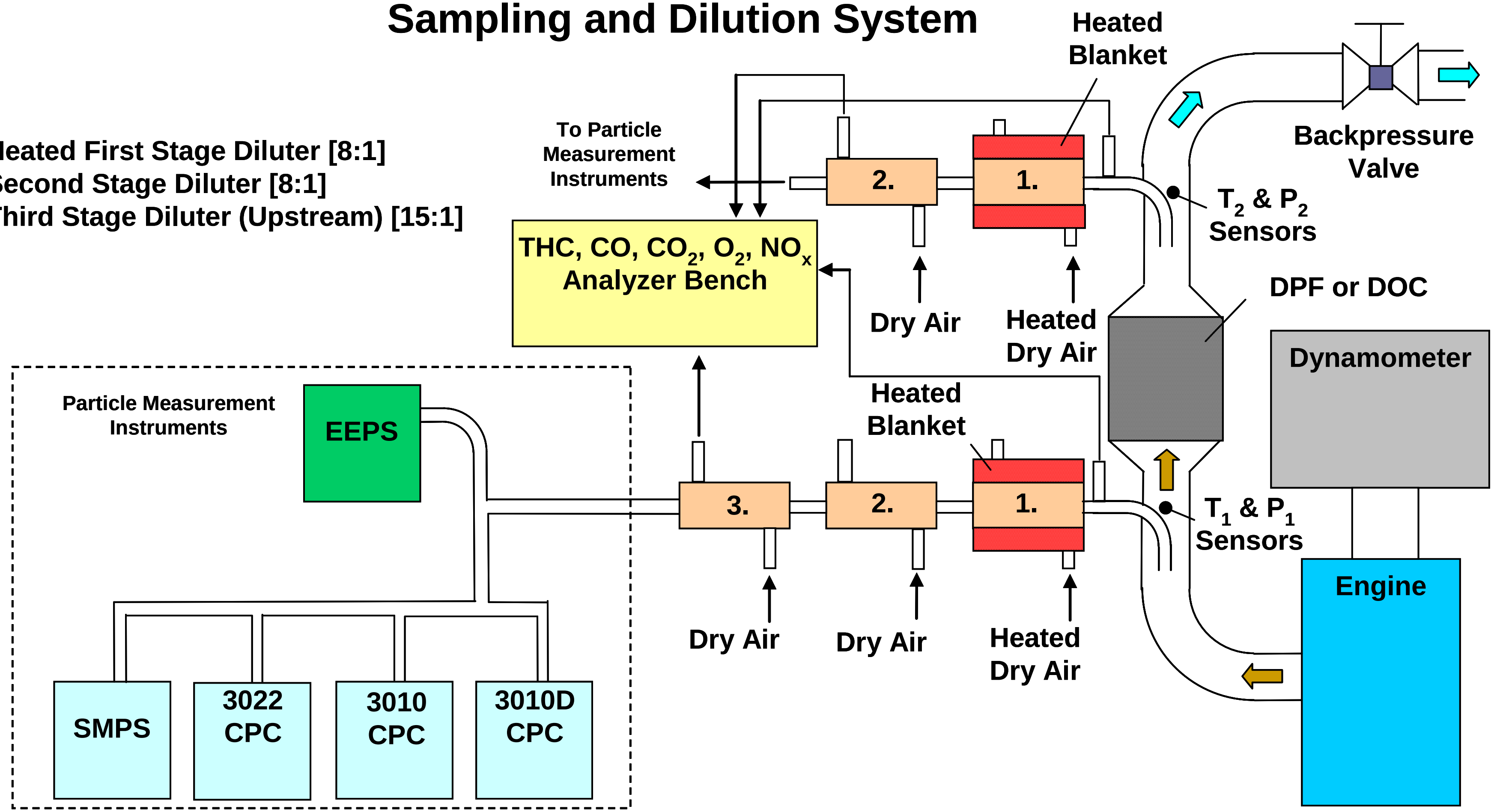
Dr. Jerry Liu
Thaddeus Swor
Victoria Vasys
Prof. Dave Kittelson

Cummins®

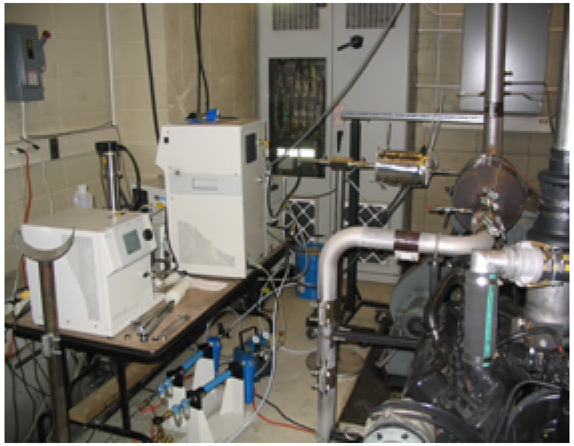
Experimental Setup

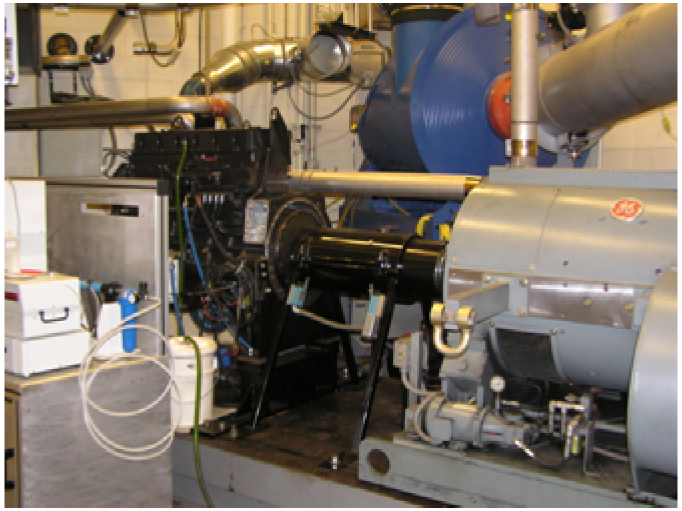
Sampling and Dilution System

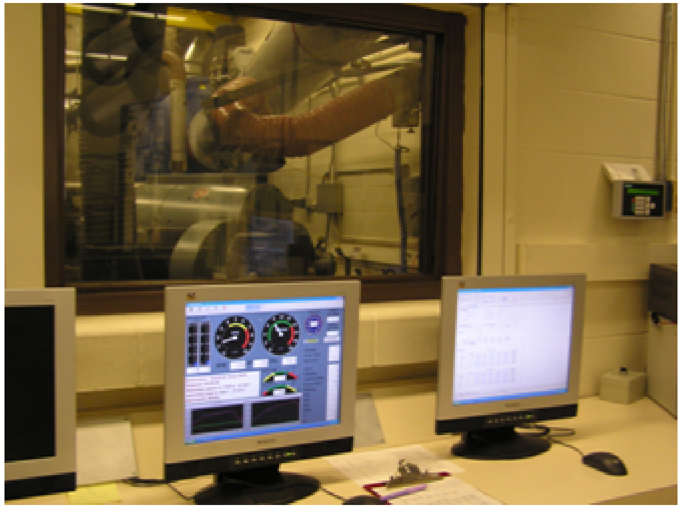
1. Heated First Stage Diluter [8:1]
2. Second Stage Diluter [8:1]
3. Third Stage Diluter (Upstream) [15:1]



Experimental Setup

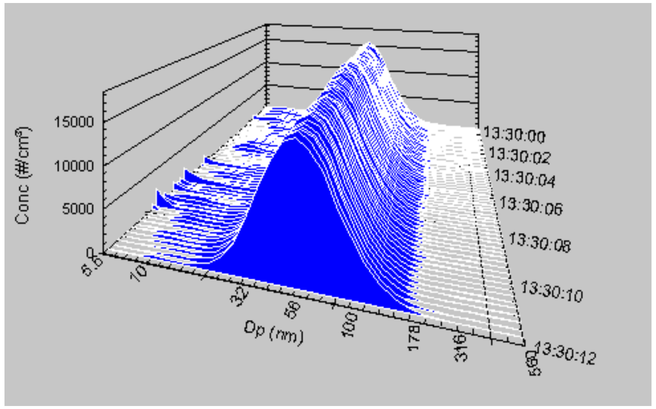




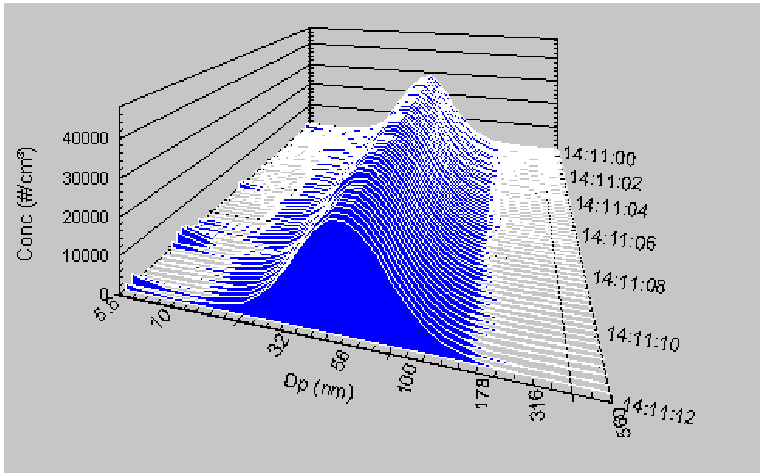


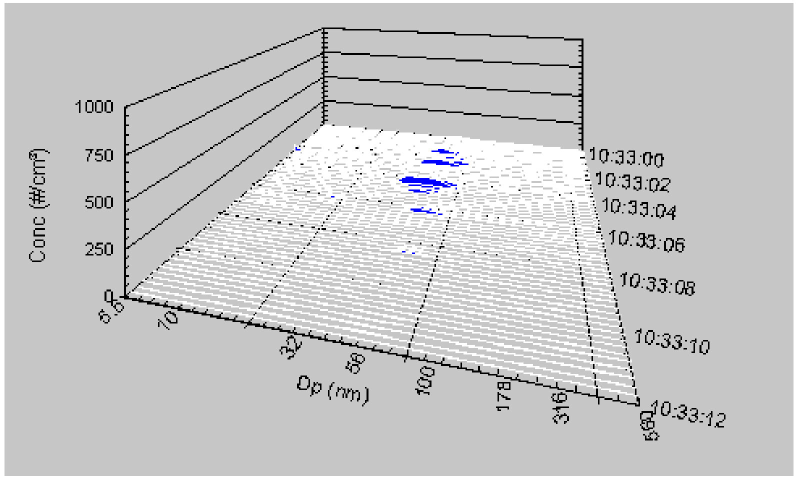
Transient PM Size Distributions

DOC Out



Engine Out





DPF Out

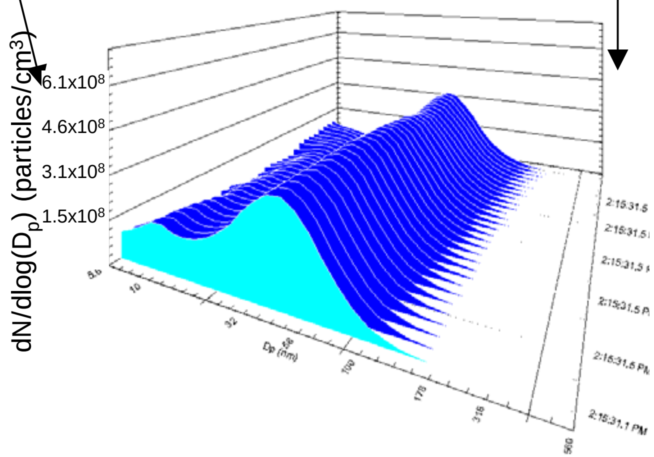
Results and Discussion 1

225-228 seconds of FTP HD cycle:

- Fairly constant high speed and medium load

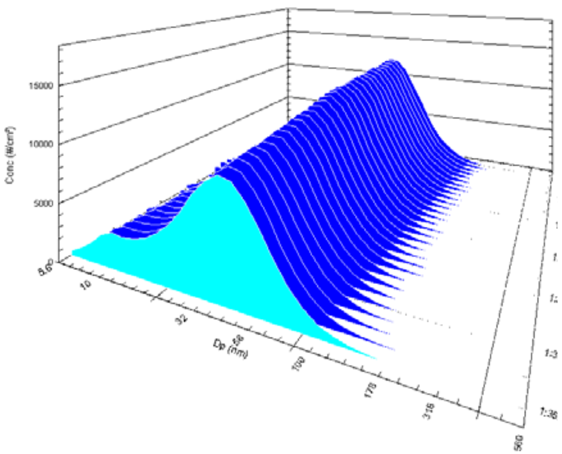
6.1 x10^8 particles/cm^3

Upstream 228 seconds



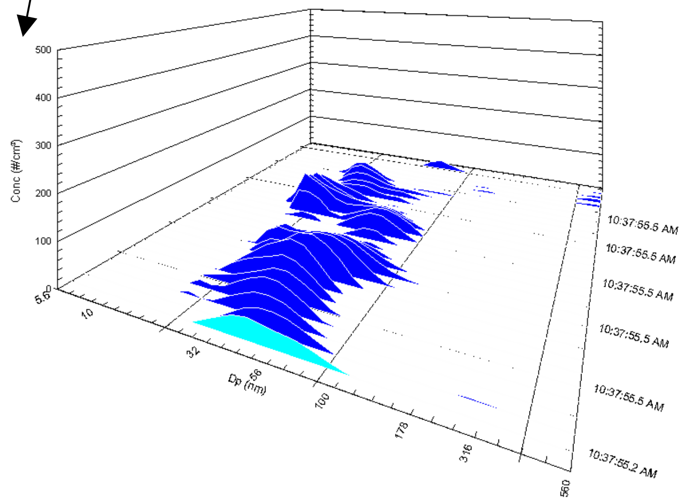
2.3 x10^8 particles/cm^3

DOC 228 seconds



5.1 x10^5 particles/cm^3

Cordierite 228 seconds



Results and Discussion 1

225-228 seconds

- Upstream contains both nuclei and accumulation modes
- Downstream of DOC the levels are reduced across the board but especially in nuclei mode
- Downstream of the DPF the levels are *vastly* reduced and the main peak is coincident with that of the upstream measurement

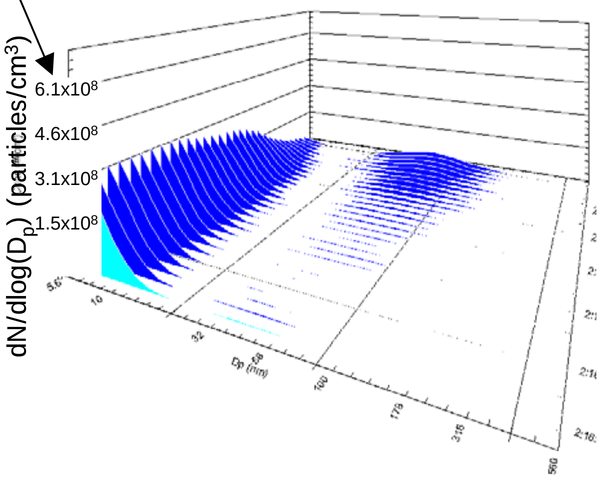
Results and Discussion 2

253-256 seconds of FTP HD cycle

- Engine decelerating from high speed/load down to idle conditions

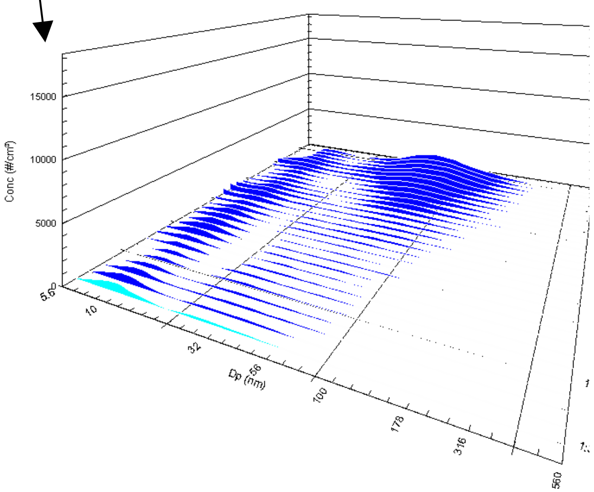
Upstream 256 seconds

4.0 x10^4 particles/cm^3



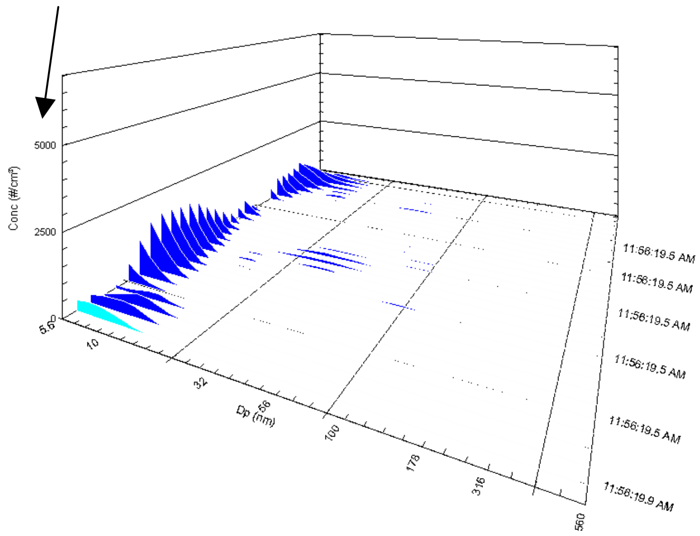
DOC 256 seconds

1.5 x10^4 particles/cm^3



Cordierite 256 seconds

5.0 x10^3 particles/cm^3



Results and Discussion 2

253-256 seconds

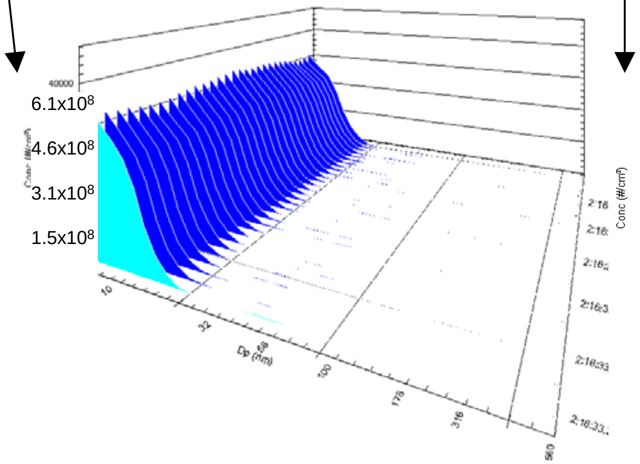
- Upstream transition to idle conditions clearly seen by transition from accumulation mode to nuclei mode
- Similar trend seen downstream of DOC, though relative nuclei mode count is much lower
- DPF measurement does not show trend but greatly reduced particle counts

Results and Discussion 3

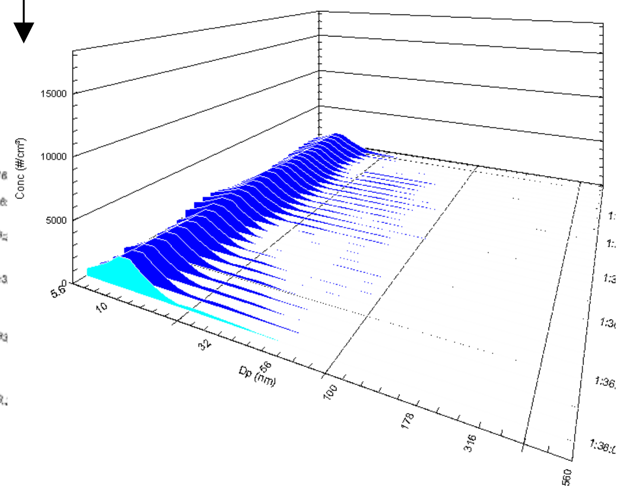
287-290 seconds of the FTP HD cycle

- Engine experiences idle conditions

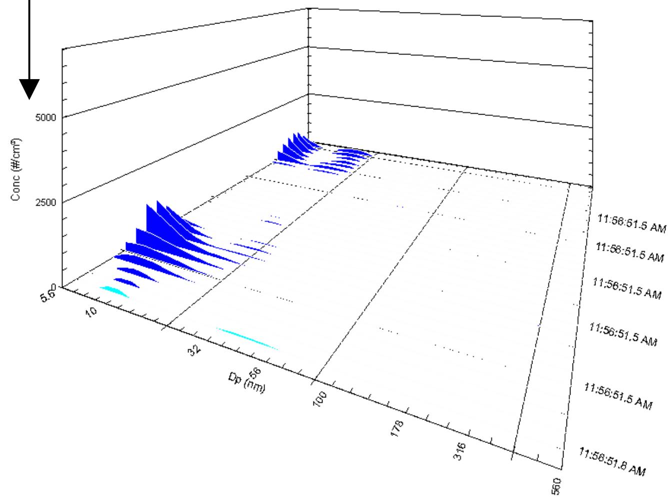
4.0 x10[4] particles/cm[3] **Upstream 290 seconds**



1.5 x10[4] particles/cm[3] **DOC 290 seconds**



5.0 x10[3] particles/cm[3] **Cordierite 290 seconds**



Results and Discussion 3

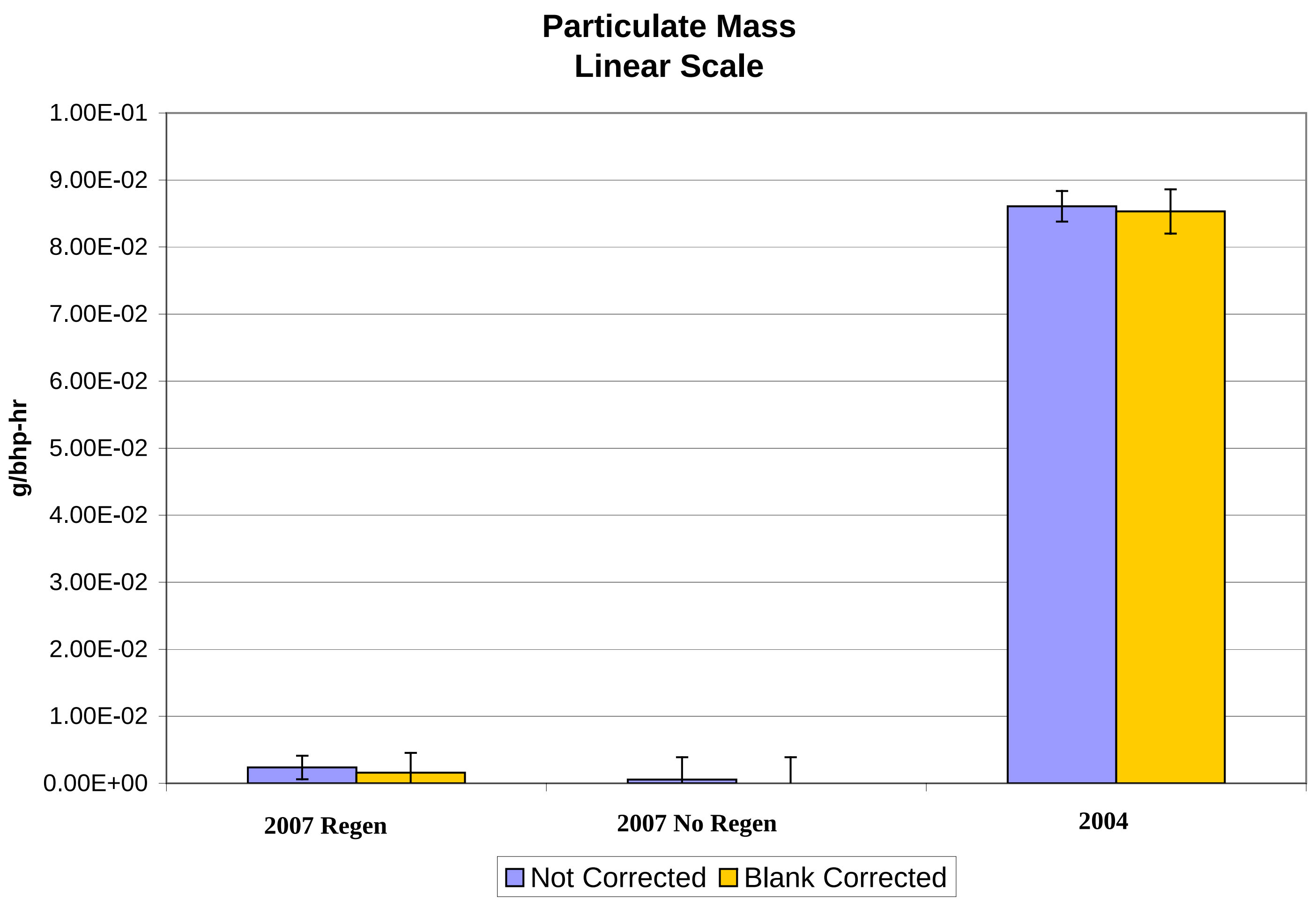
287-290 seconds of the FTP HD cycle

- Engine experiences idle conditions – lone nuclei mode peak upstream
- Downstream of DOC shows similar pattern of reduced magnitude, especially for smaller nuclei mode particles
- Intermittent pulses of penetrating particles through DPF in nuclei mode

Recent Tests Completed on an ISX EPA 2007 Compliant Engine

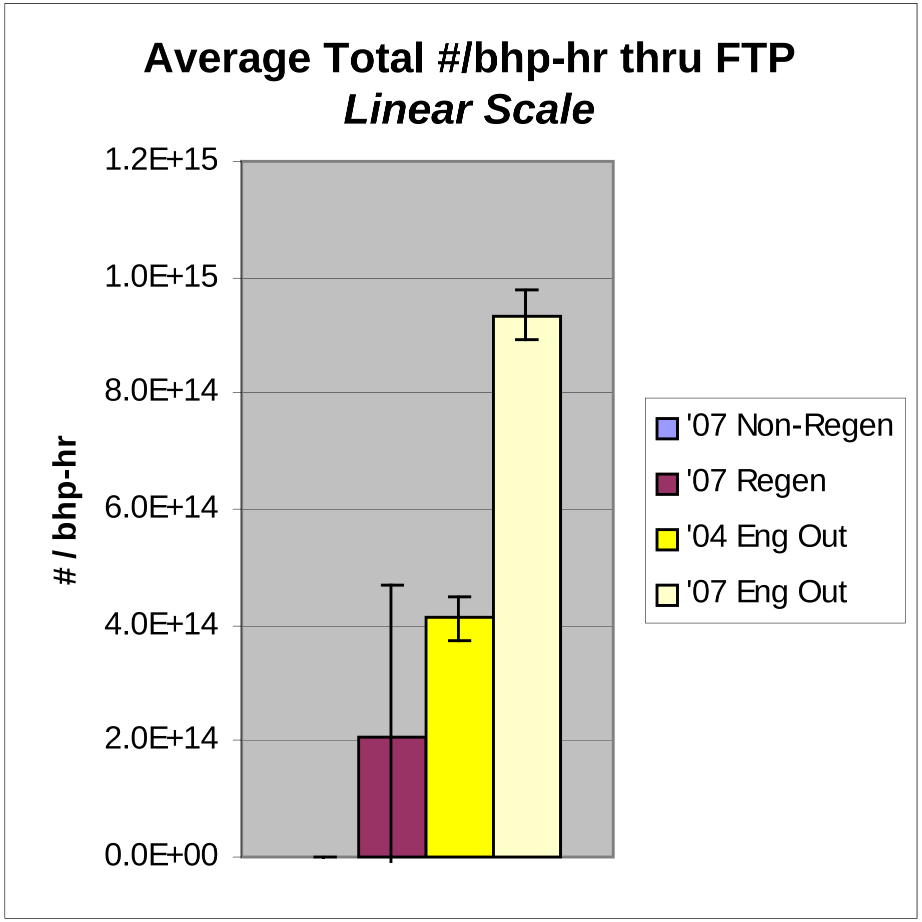
Data acquired both with and without a regeneration

Mass Emissions

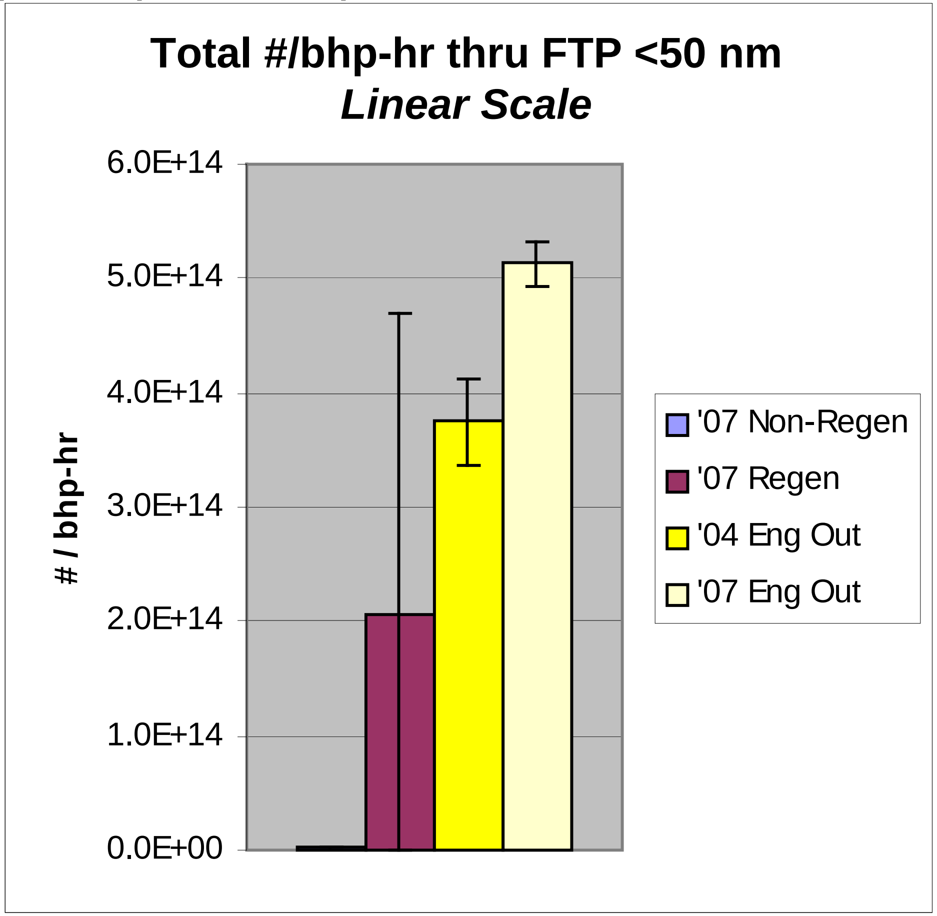


Error bars are in 2 sigma

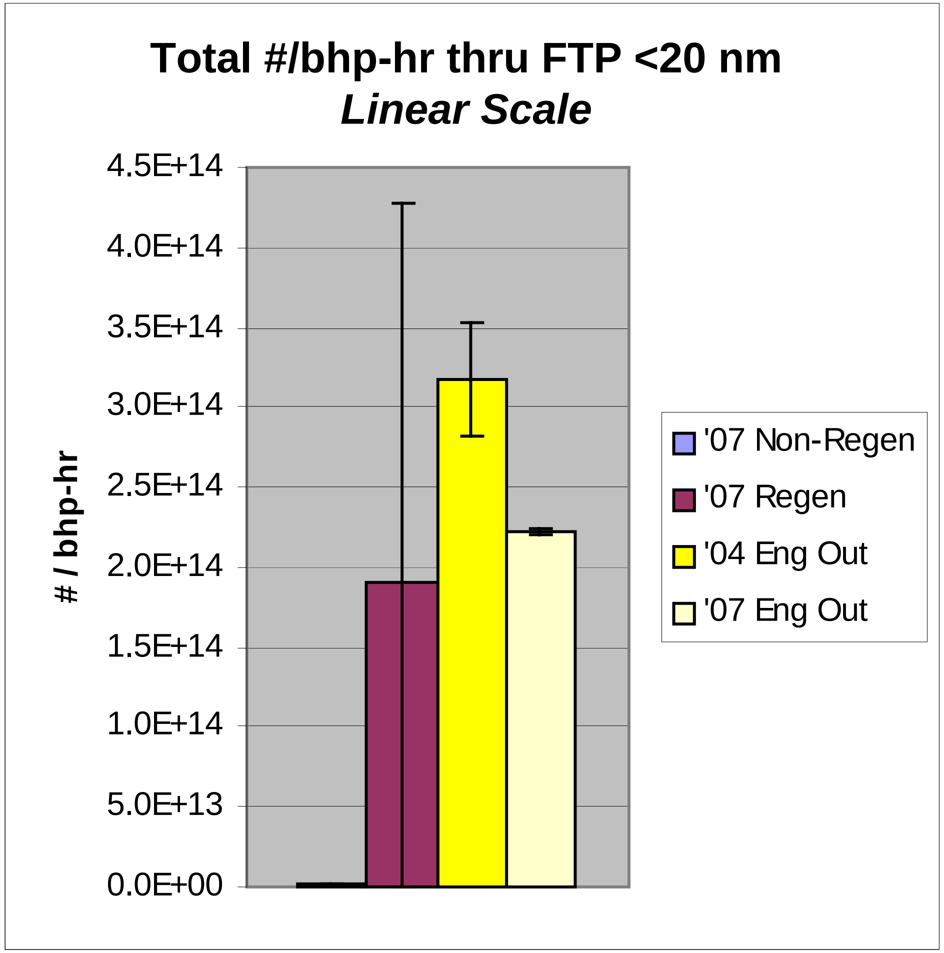
Total Particle/bhp-hr



Total #/bhp-hr (<50nm)



Total #/bhp-hr (<20nm)



Conclusions

Significant engine efficiency gains are possible

Engine Load, Speed, and Exhaust Gas Temperature determine the size distribution

During transient operation, the size distribution could be either mono- or bi-modal

Torque is the dominant factor in PM emission patterns.

Idle, deceleration, and low and negative torque conditions are principal factors in the formation of nuclei mode particles with fewer (if any) accumulation mode particles present.

During very high engine speeds with low or negative torque being produced, nuclei mode particles are predominant with a small but well defined accumulation mode peak present.

Conclusion (cont'd)

A cake layer forms quickly with a clean granular DPF, resulting in higher efficiency and pressure drop.

A PM penetration pattern is generally a function of the associated engine-out PM emission pattern.

If an engine's output of accumulation mode particles cannot be reduced, the best method to further decrease total PM mass emissions is to improve the removal efficiency of accumulation mode particles of aftertreatment devices.

The DPF is effective in reducing both PM mass and particle number as well as non-regulated compounds.

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Conclusion (cont'd)

Idle, deceleration, and low and negative torque conditions are principal factors in the formation of nuclei mode particles with fewer (if any) accumulation mode particles present. While at idle, moderate, or overspeed conditions, the majority of particles form a peak at or below 5.6 nm in diameter, as measured by the EEPS. Low exhaust gas temperatures, which are often caused by these conditions, assist in the gas-to-particle conversion process.

During very high engine speeds with low or negative torque being produced, nuclei mode particles are predominant with a small but well defined accumulation mode peak present. This secondary peak is not seen while the engine is under idle speeds.