Achieving and Demonstrating FreedomCAR Engine Fuel Efficiency Goals (Agreement 13704)

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This presentation does not contain any proprietary confidential information

2008 Office of Vehicle Technologies Annual Merit Review
Bethesda, Maryland

v10+021408

Presentation Outline

- **Purpose of work**
- **Barriers**
- **Guidance from FY 2007 review**
- **Approach**
- **Results**
- **Future activities**
- **Technology transfer**
- **Summary**

Purpose of Work

Established in ACEC Tech Roadmap and Vehicle Technologies Multiyear Program Plan <u>in support of DOE objective of petroleum displacement</u>

Characteristics	FY 2008	FY 2009	FY 2010
Peak Brake Thermal Efficiency (HC Fuel)	**43%**	**44%**	**45%**
Reference Brake Thermal Efficiency	**32%**	**34%**	**35%**
Part–Load Brake Thermal Efficiency (2 bar BMEP @ 1500 rpm)	**27%**	**29%**	**31%**
Emissions	**Tier 2, Bin 5**	**Tier 2, Bin 5**	**Tier 2, Bin 5**
Thermal efficiency penalty due to emission control devices	**< 2%**	**< 1%**	**< 1%**

Activity supports a "Joule Milestone" that is recorded in the DOE budget narrative as well as the FreedomCAR partnership goals. Effort is performed in close communication with the ACEC Tech Team.

Activity addresses multiple barriers from VT MYPP

- **Market Challenges and Barriers**
  - **A. Cost.** **"… Better use of advanced LTC modes to reduce the formation of emissions in-cylinder will reduce aftertreatment system requirements and associated costs."**
- **Technical Challenges and Barriers**
  - **B. Fundamental knowledge of engine combustion.** **Engine efficiency improvement … understanding of … thermodynamic combustion losses … in-cylinder combustion/emission formation processes over a range of combustion temperature regimes of interest …**
  - **C. Emission control.** **Meeting EPA requirements for oxides of nitrogen and particulate matter emissions standards with little or no fuel economy penalty ...**
  - **D. Engine controls.** **Effective sensing and control of various parameters will be required to optimize operation of engines in advanced LTC regimes over a full load-speed map …**
- **Strategies for Overcoming Barriers/Challenges**
  - **Activity objectives are well aligned with the strategies outlined in the MYPP.**

Guidance from FY 2007 review

Positive comments …

- **Project is well-aligned with improving performance to meet DOE goals on brake thermal efficiency and fuel efficiency.**
- **Team has taken a practical approach for real systems.**
- **Thermodynamic availability analysis is a good way to understand the operation and efficiency performance of the engine.**
- **Excellent interaction with several OEMs.**

Areas for improvement …

- **Information on waste heat recovery was not supported by sound analysis and/or explanation.**
  - **We were exploring WHR options while in the process of developing analysis tools & models.**
- **Need to identify potential tools to enable efficiency soon …**
  - **Technologies are now being developed for implementation on the engine.**
- **Team should expand industry interaction.**
  - **Several new industry interactions and potential collaborations since June meeting.**
- **Need to focus on cost/benefit of heat recovery.**
  - **Cost/benefits is outside of the scope of this activity.**

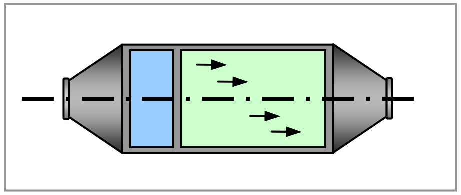
Approach

- **Establish baseline on modern common-rail light-duty diesel engine.**
- **Develop models and analysis routines to better understand loss mechanisms and corresponding efficiency opportunities.**
- **Develop and evaluate promising technologies (*e.g.*, WHR, VVA, etc.) and strategies with models and on engine, leveraging with industry when possible.**
- **Develop thermal management strategies for engine-system, which may include a combination of technologies competing for the same resources.**

Approach includes the integration of many ORNL activities

Achieving HECC in Multi-Cylinder LD Diesel Engines
(Agreement 15936)

Characterization of LNTs for LD Diesel Engines
(Agreement 9248)

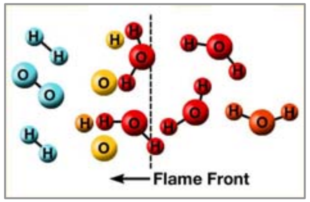


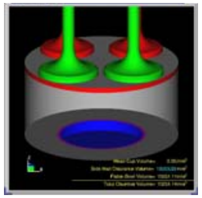
FreedomCAR

FY 2010 Goals

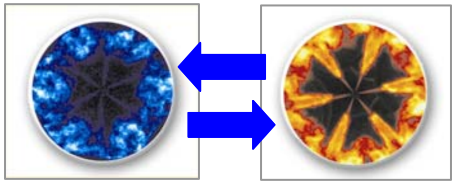
Achieving and Demonstrating FreedomCAR Engine Fuel Efficiency Goals
(Agreement 13704)

Stretch Efficiency for Combustion Engines
(Agreement 10037)





Efficient Emission Control for Multi-Mode LD Diesel
(Agreement 12249)



Findings from AEC Working Group, CLEERS, and other forums also integrated into approach

AEC & HCCI University Working Groups
(Administered by SNL)

CLEERS Working Group
(Administered by ORNL)

Achieving HECC in Multi-Cylinder LD Diesel Engines
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FreedomCAR

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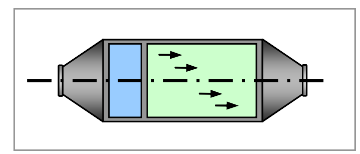

Stretch Efficiency for Combustion Engines
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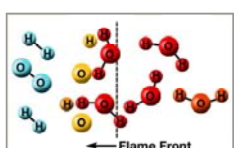
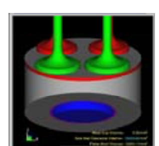




Efficient Emission Control for Multi-Mode LD Diesel
(Agreement 12249)

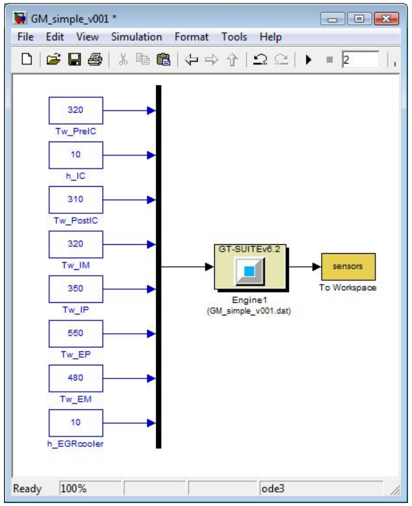
Summary of technical accomplishments (since June 2007)

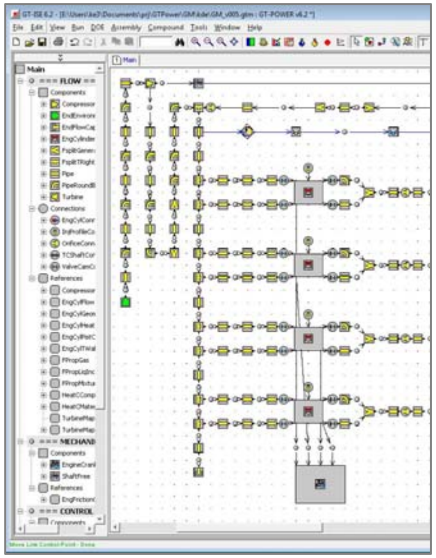
- ✓ **Achieved and demonstrated 2007 FreedomCAR goal of 42% peak BTE on two light-duty diesel engines.**
- ✓ **Commissioned more flexible control system for GM engine which allows the integration of custom control algorithms.**
- ✓ **Characterized availability of exhaust stream, EGR system, intercooler, etc. of a GM 1.9-L across the entire speed-load map.**
- ✓ **Extensive literature review and modeling of WHR for estimating potential efficiency improvements and selection of working fluids.**
- ✓ **Construction of bench-top WHR system which will be transferred to GM engine later this FY.**
- ✓ **Continued and new interactions with industry on turbocharger technology, turbo-compounding systems, and controls.**

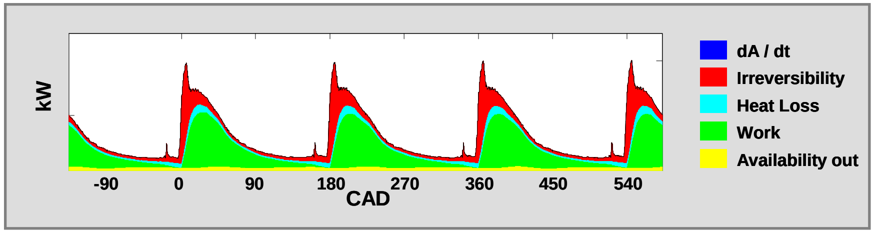
Modeling & analysis

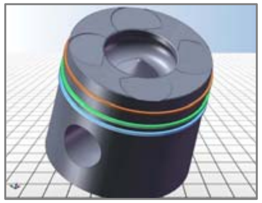
To evaluate potential technologies for improving efficiency and to better understand loss mechanisms.

- **GT-Power and WAVE models of engine and components.**
  - **Allows evaluation and provides guidance for strategies such as turbo-compounding and waste-heat recovery before entering the laboratory.**
  - **Organic Rankine Cycle (ORC) model being integrated into engine system model.**
- **Routines for 1st and 2nd Law thermodynamic analysis of experiments and model results.**



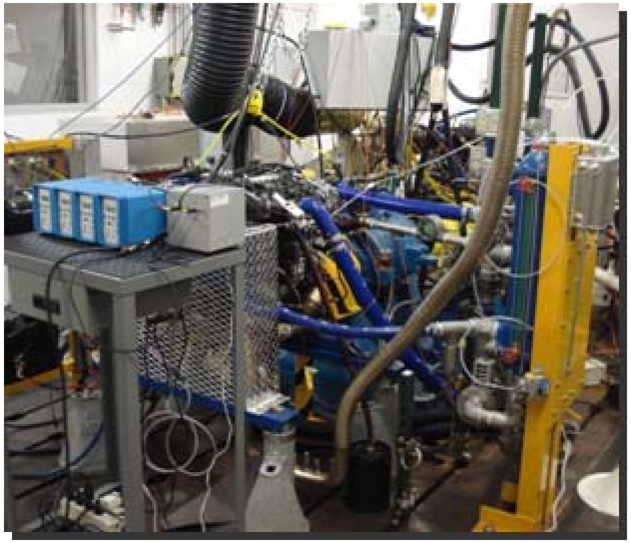




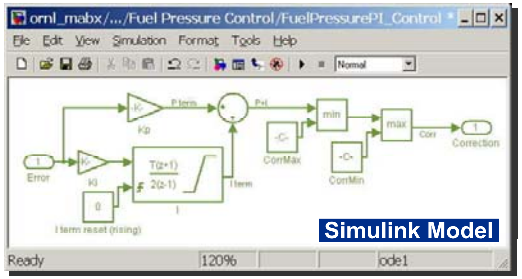


GM engine & controls

- **GM 1.9-L engines installed in ORNL Cells 2 & 4.**
- **Instrumentation for combustion and thermodynamic analyses.**
- **Comprehensive exhaust characterization.**
- **Two flexible control systems in use.**
  - **ECUs donated by GM are capable of monitoring and manipulating base calibration.**
  - **Discussions with Bosch to obtain customer neutral calibration.**
  - **More flexible microprocessor based dSpace systems for improved control and integration of custom algorithms.**

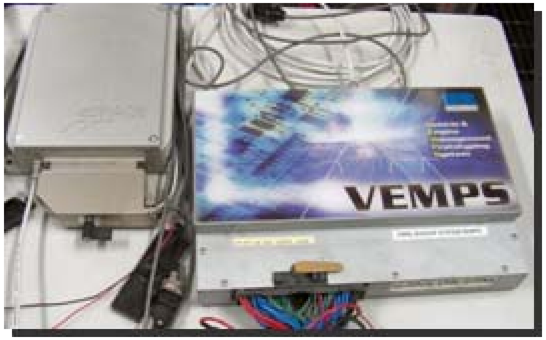


GM 1.9-L in ORNL Cell 4



Simulink control model

ECU/ETAS controller

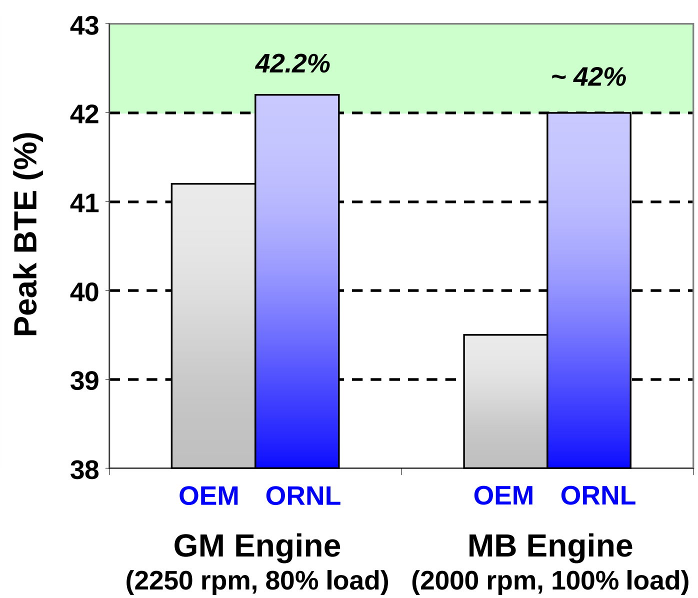


dSpace based controller

OAK RIDGE National Laboratory

Demonstrated 2007 FreedomCAR engine efficiency milestone of 42% Brake Thermal Efficiency (BTE)

- **Milestone achieved on a modified 2005 GM 1.9-L diesel engine and a modified 1999 Mercedes 1.7-L diesel engine.**
- **Approach included improved thermodynamic analysis, full-engine simulation, and modifications to engine hardware and/or calibrations.**
- **Enablers included variable geometry turbochargers (VGT), revised fuel injection parameters, and more aggressive combustion phasing (as compared to OEM calibration).**

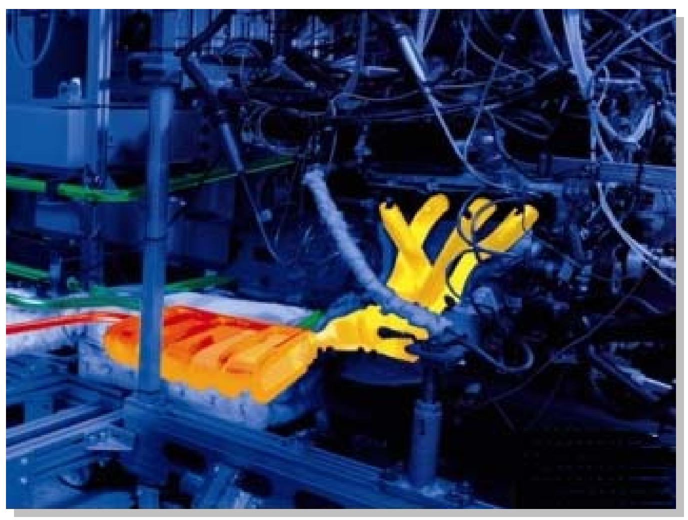


Meeting 2010 and interim BTE milestones will require some form of energy recovery

Issues to consider with respect to energy recovery:

- **Source, quality, recovery method.**
- **Potential benefits across speed-load range of engine.**
- **Integration with other technologies such as LTC operation, turbochargers, variable valve actuation, aftertreatment, etc.**
- **Making use of recovered energy.**

Fuel In

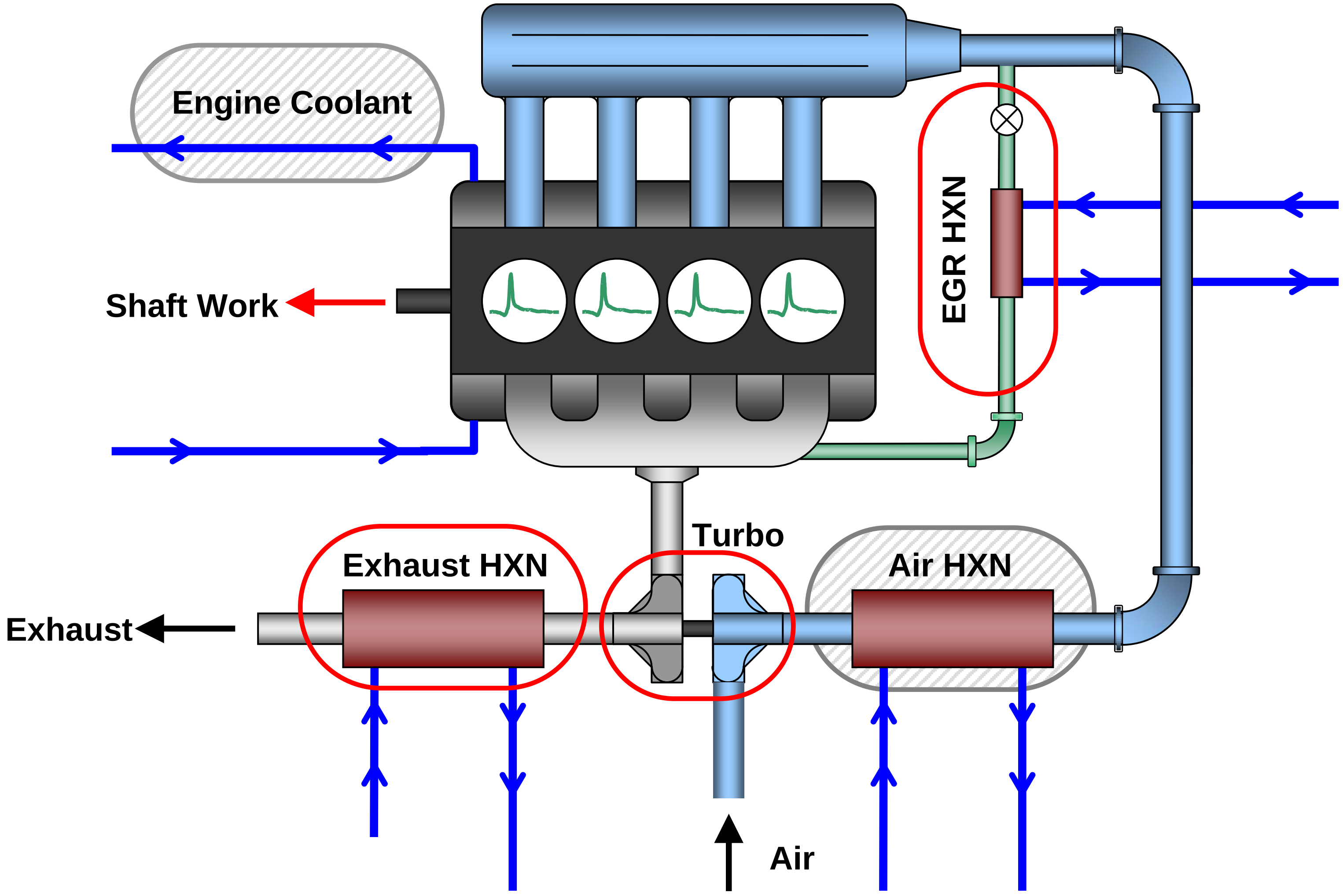


Heat Loss ~29%

Exhaust ~29%

Power ~42%

Many opportunities for improved energy use and/or recovery

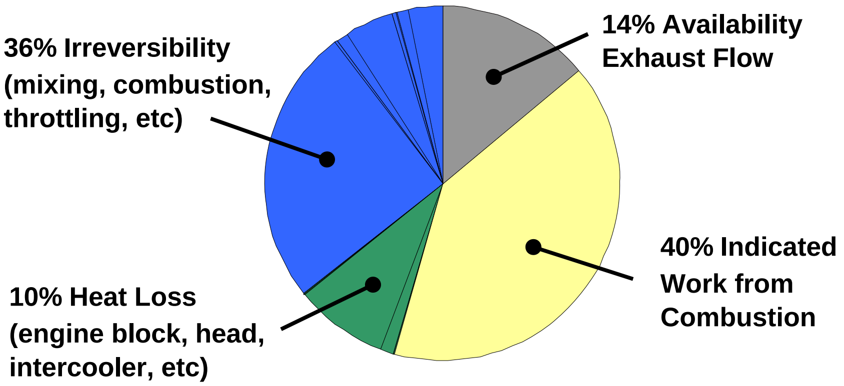


Second Law perspective (*i.e.*, Availability) used for evaluating efficiency opportunities

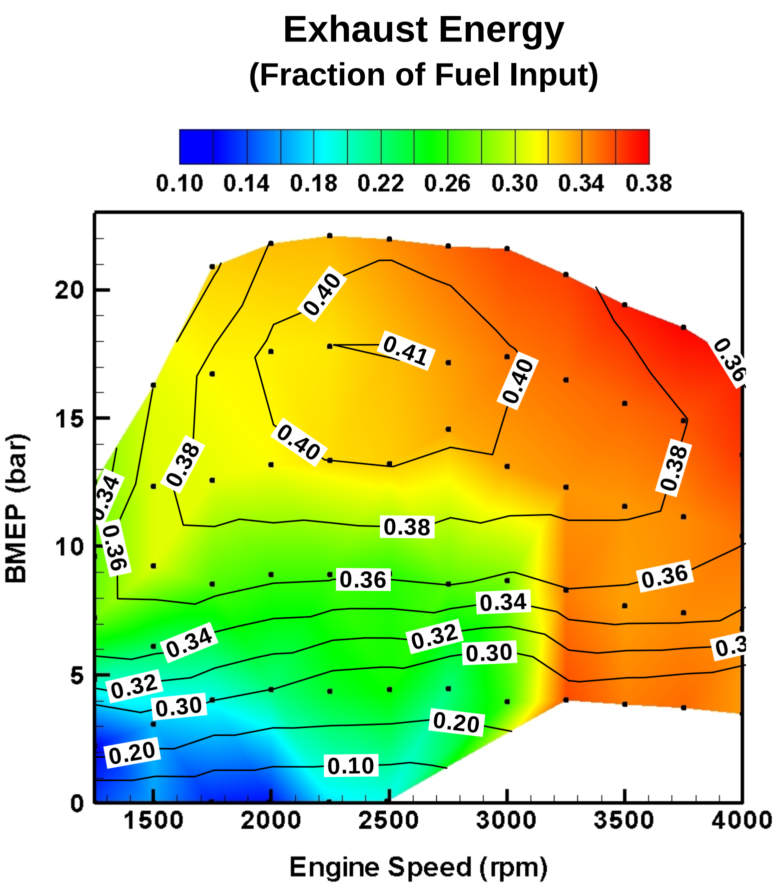
- **Evaluate recovery potential of waste energy sources (experiments & simulation).**
- **Analysis routines developed for use with GT Power & WAVE engine simulation codes to compute availability & help identify loss mechanisms.**
- **Essential in thermal management of complicated engine-system, which compete for the same thermal resources.**
  - **Low temperature combustion, bottoming cycles, variable valve actuation, turbo-compounding, aftertreatment, etc.**

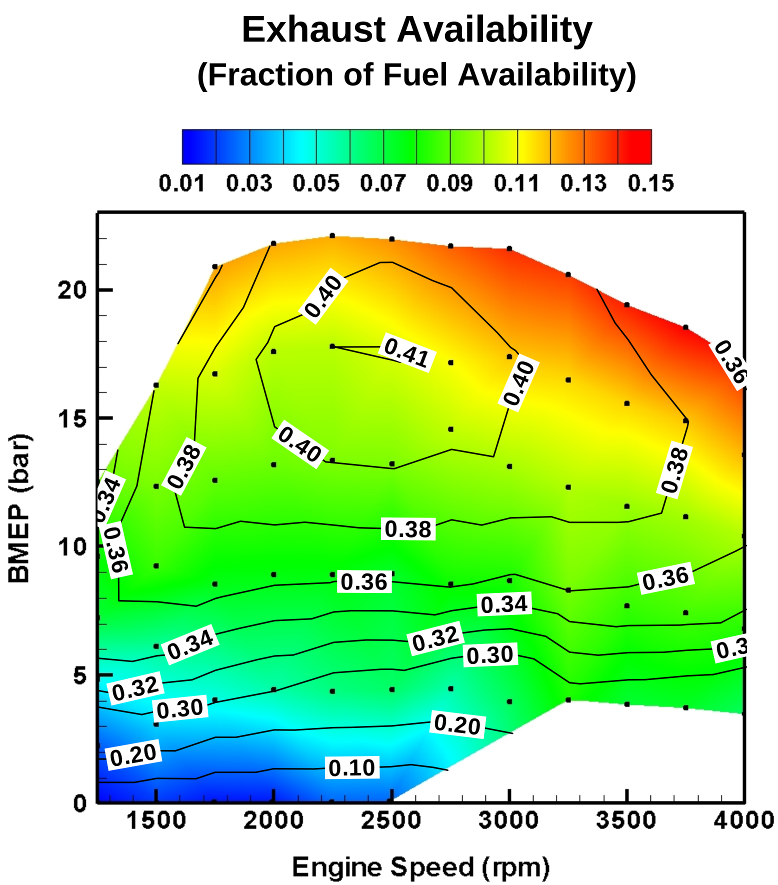
<u>Working Definition</u>: ***Availability* (a.k.a. exergy) is a measure of a system's potential to do useful work due to physical (P, T, etc.) and chemical differences between the system and the ambient environment.**

MB Engine – Simulation 2000 rpm, 100% load



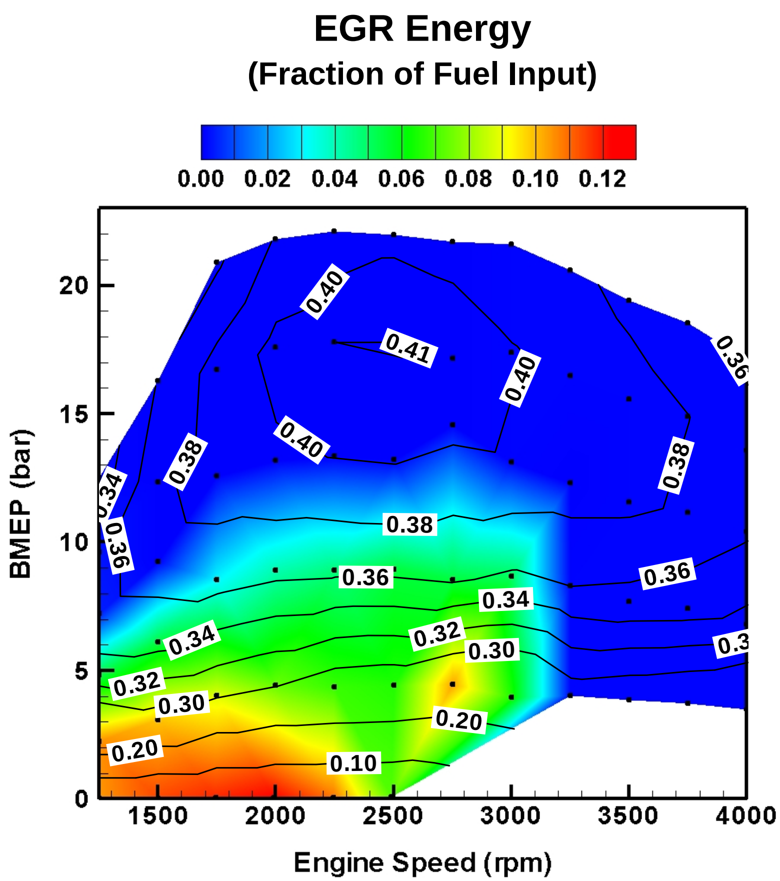
A significant amount of the fuel energy is exhausted to the environment, particularly under high BMEP conditions

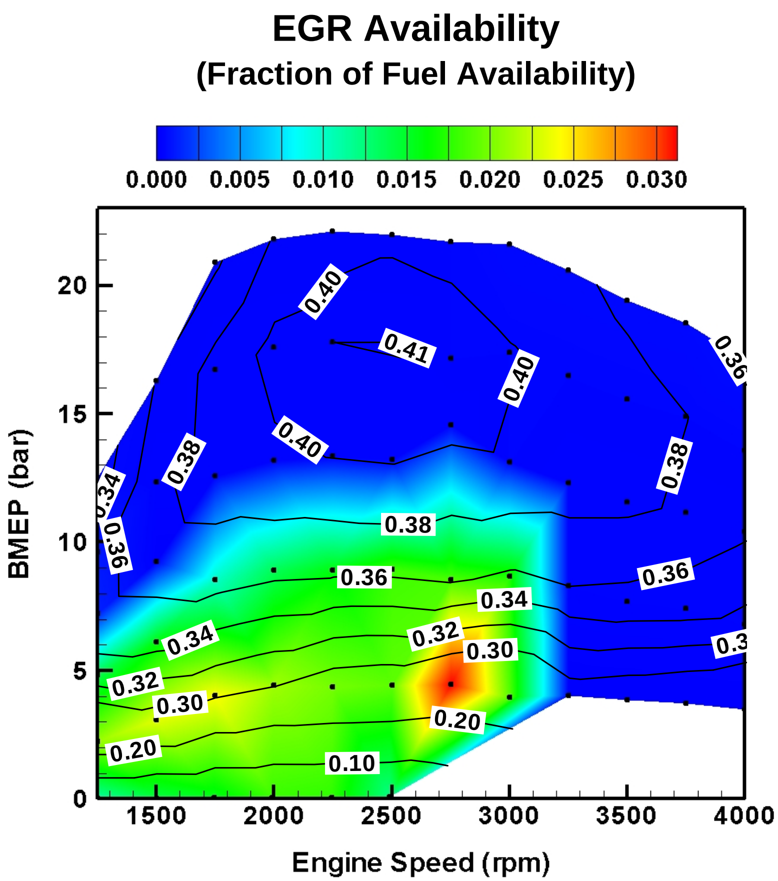




Solid contour lines correspond to BTE.

For low BMEP operation a non-negligible fraction of fuel energy is rejected through the EGR system





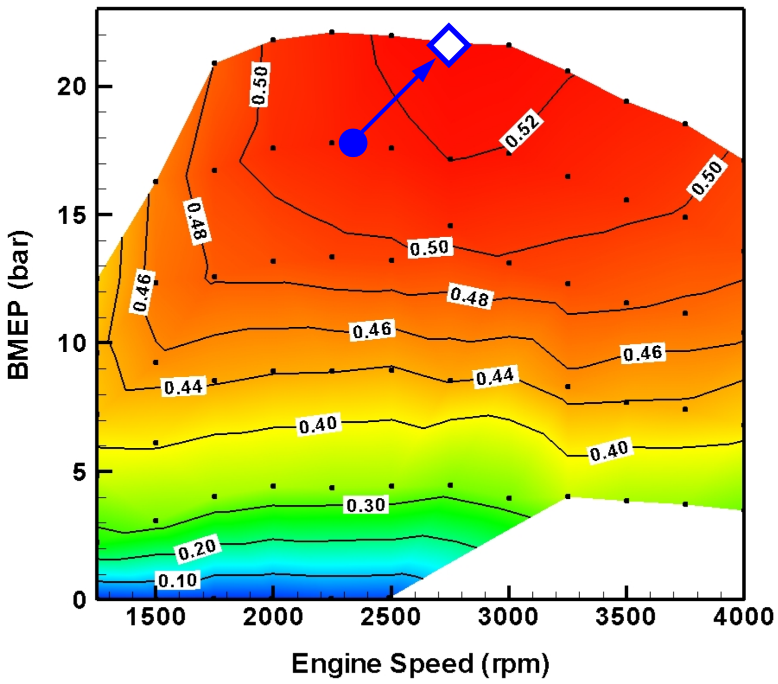
Solid contour lines correspond to BTE.

Potential improvements in BTE estimated with exhaust availability

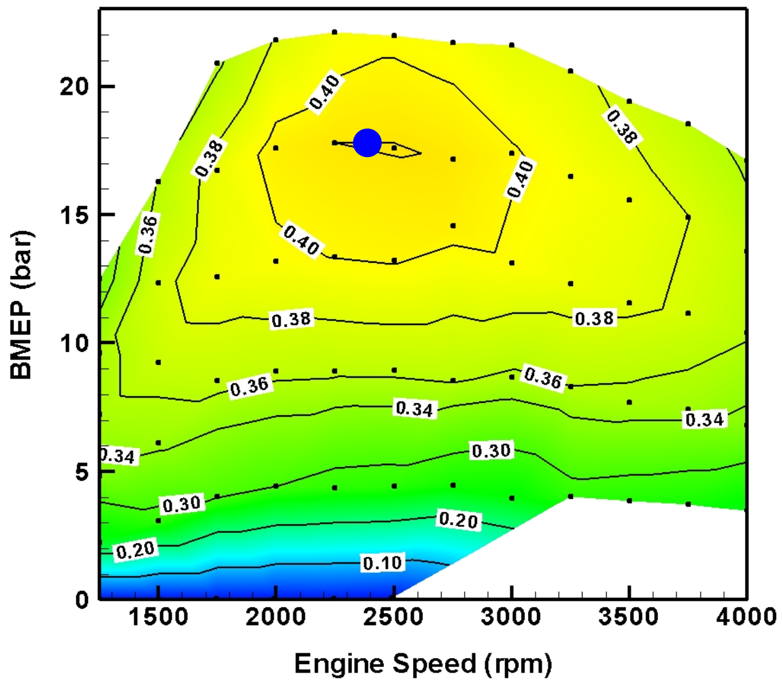
- **Estimated BTE of combined engine/WHR system using exhaust availability estimations from across the speed/load range.**
- **Assumptions/disclaimers for estimations …**
  - **Engine system efficiency improvements estimated based on BTE and availability.**
  - **Reference BTE is for OEM engine configuration.**
  - **WHR efficiency is assumed fixed across the speed/load range for simplification of the estimates.**
- **Note that WHR may change the BTE/speed/load relationship.**

Maximum BTE location is different for combined system

Combined BTE assuming 100% of exhaust availability is recoverable



Engine BTE based on experimental data & OEM calibration

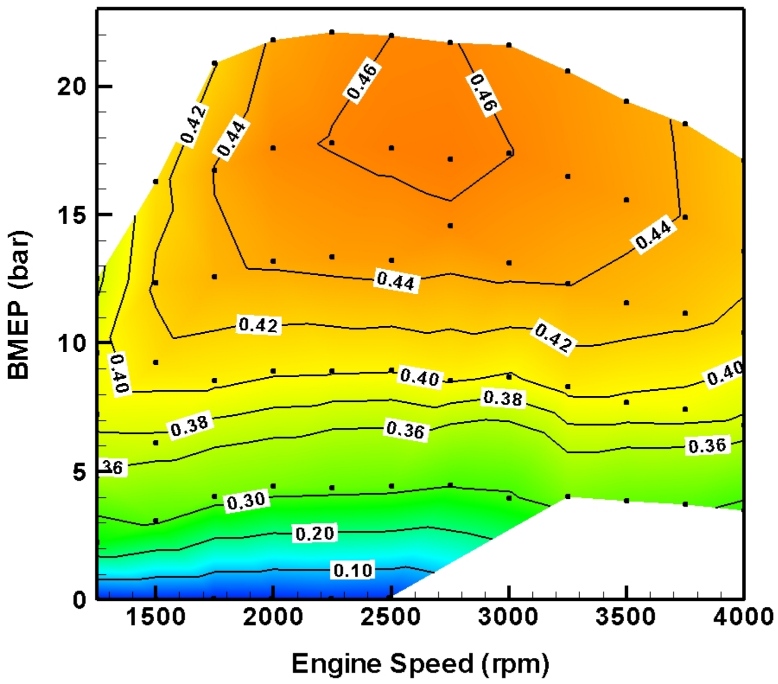


- **Peak BTE location, no WHR**
- **Peak engine+WHR BTE location.**

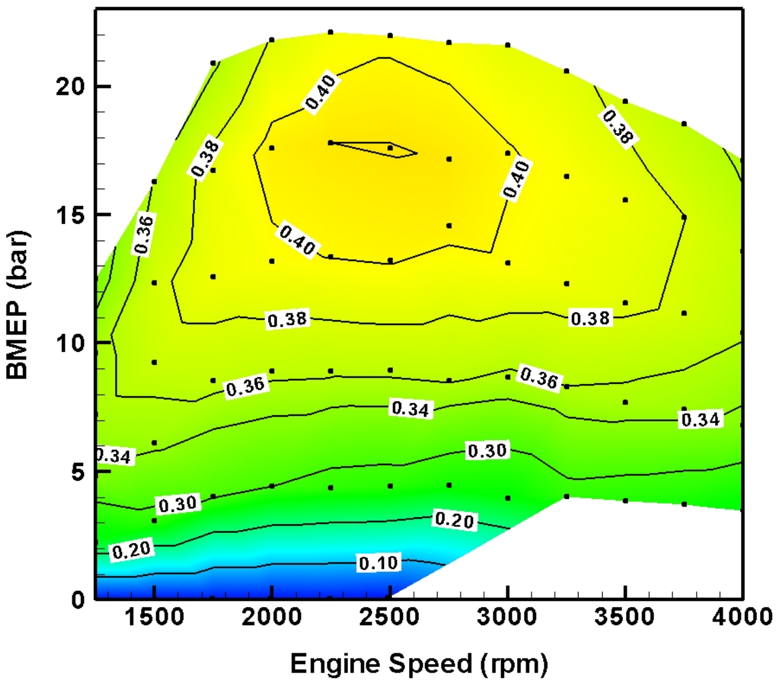
BTE data based on OEM calibration which has a peak BTE of ~41.0% as compared to the ORNL calibration which has a maximum of 42.3%.

Combined BTE estimates for 50% availability recovery

Combined BTE assuming 50% of exhaust availability is recoverable

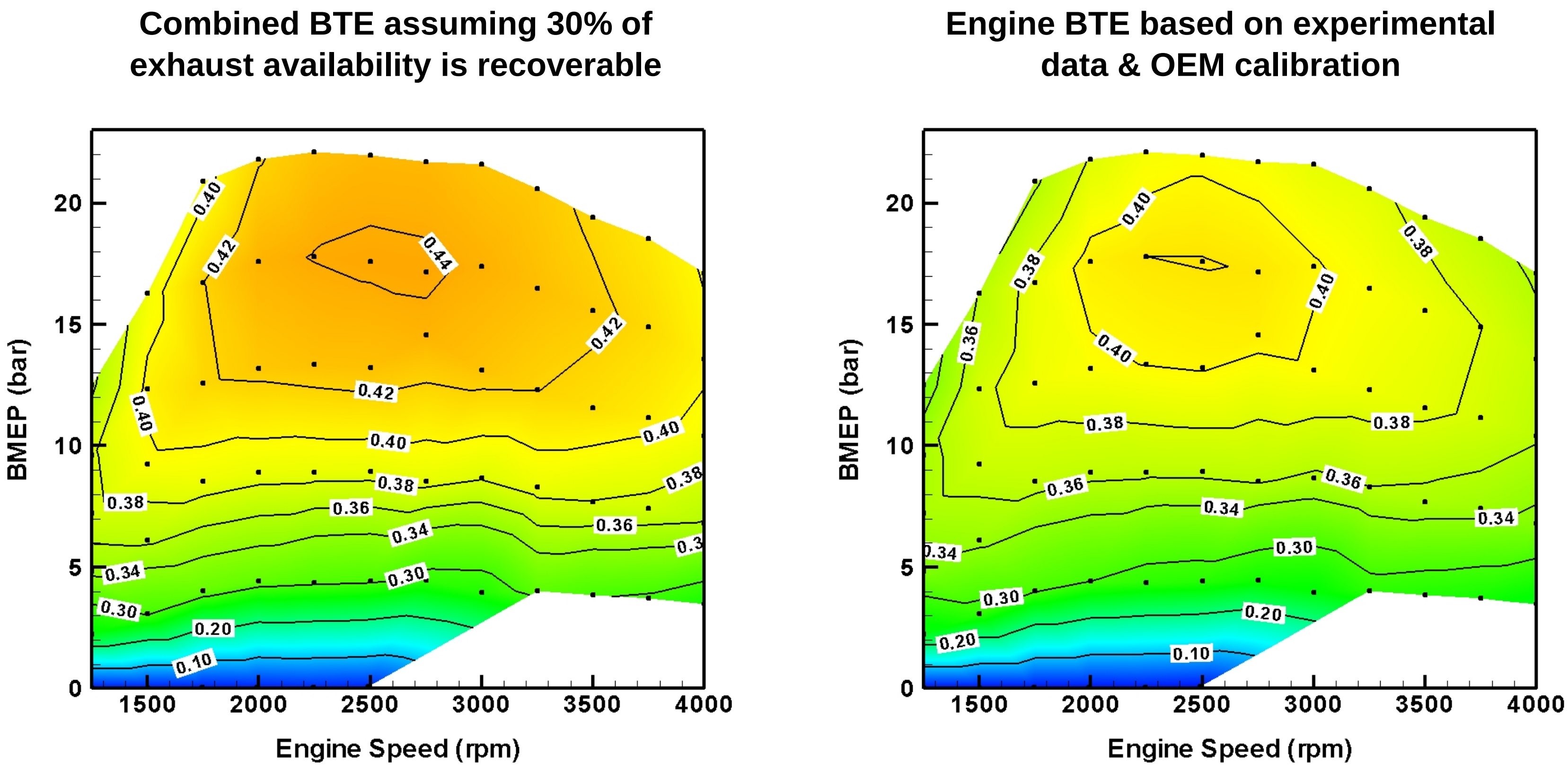


Engine BTE based on experimental data & OEM calibration



Similar approach used to estimate potential BTE improvements with energy recovery from EGR system, intercooler, etc.

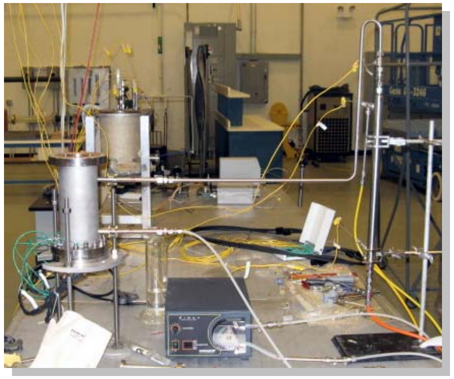
Final example for 30% availability recovery

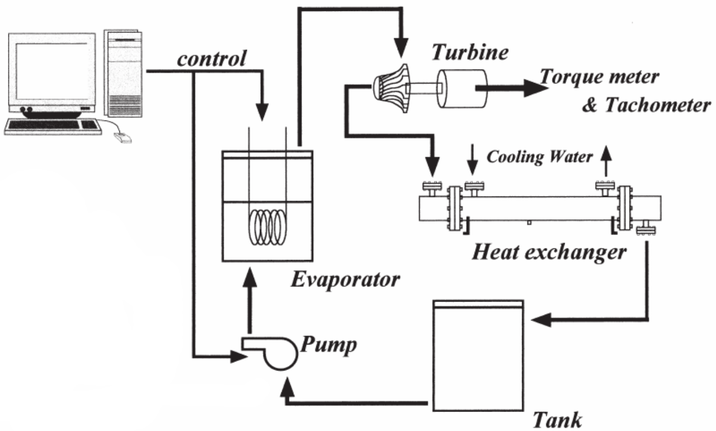


Recall that the modified calibration has a maximum BTE which is approximately 1.3% higher than the OEM calibration.

WHR system will make use of an Organic Rankine Cycle (ORC) on the exhaust system and EGR HXN (next FY)

- **Literature review shows significant prior research in the heavy-duty industry and much less from light-duty industry.**
- **Model shows possibility of achieving 45% BTE with exhaust energy recovery.**
  - **Benchmarked against literature with working fluids R134a, R123, and R245fa.**
- **Working fluid selection based on efficiency and environmental considerations.**
  - **R134a significantly less efficient than R123 and R245fa.**
  - **R123 to be used for benchmarking against published studies but is being phased out.**
  - **<u>R245fa is long-term candidate</u> fluid with high efficiency, low global warming potential, non-flammable, good heat transfer characteristics, low viscosity, and compatible with AC tool sets in service shops.**
- **Bench top system is undergoing preliminary experiments and evaluation.**





ORC system will be transitioned to the GM 1.9-L engine

- **Initial focus (FY 2008) is on exhaust energy recovery for peak BTE operation.**
- **Issues include …**
  - **Frictional losses in pump and expander.**
  - **Backpressure of exhaust heat exchanger and effect on BTE.**
  - **Insufficient heat transfer in heat exchanger.**
- **Component selection**
  - **Exhaust heat exchanger – EGR HXN from medium duty diesel engine.**
  - **Expander – Scroll compressor (in reverse) from automotive AC system.**
  - **Power measurement – Small water-brake dynamometer with computer control.**
- **Installation on engine will begin in May 2008.**

Scroll compressor from automotive AC system

Exhaust HXN

Other relevant FY 2008 activities not yet mentioned

- **Thermal Management**
  - **Balancing of systems competing for same thermal resources for maximum efficiency with acceptable emissions.**
- **Friction Reducers**
  - **Multiple projects at ORNL and elsewhere to evaluate coatings for advanced combustion and novel lubricants including ionic fluids.**
- **Turbocharger Technology (resource limited)**
  - **Informal collaborations with BorgWarner on multi-stage turbochargers and Woodward on hydraulically coupled turbo-compounding. ORNL is NOT developing these technologies but simply making use of them as appropriate.**
- **Variable Valve Actuation (resource limited)**
  - **Potential of this approach for improved efficiency is being evaluated with engine simulation models. Implementation would most likely be cam phase system.**

On-going and future plans

- **FY 2008 and beyond**
  - **Remove auxiliary components from engine to "bound" maximum and part-load BTE potential of engine.**
  - **Complete bench evaluation of ORC for WHR of the exhaust system.**
  - **Transition ORC to engine and evaluate recovery potential on the exhaust stream.**
  - **Continue development and/or evaluation of WHR, turbocharger options, turbo-compounding, VVA, and thermal management concepts on GT Power model of GM engine.**
  - **Complete FTP estimates of HECC modes on GM engine.**
  - **Continue to interact with advanced combustion, aftertreatment, stretch efficiency, and friction reduction teams to ensure collaborative path toward achieving FCVT 2010 efficiency & emissions milestones.**
- **Anticipated path to 2010 goals**
  - **WHR of exhaust and EGR streams.**
  - **More aggressive combustion strategies.**
  - **Coatings and/or lubricants (moderate improvements).**
  - **Advanced combustion for low-load efficiency and emissions.**
  - **Aftertreatment on some level for HC/CO, NOx, and PM.**

Results from this activity are regularly discussed with industry and the DOE

- **One-on-one industry/university interactions.**
  - **BorgWarner on turbocharger technology and low pressure EGR.**
  - **Woodward Governor on turbo-compounding.**
  - **Caterpillar on energy recovery methods and thermodynamic analysis.**
  - **Gamma Technologies and Ricardo on engine model software improvements.**
  - **General Motors on preparation of USCAR/ACEC presentations and support of GM engine at ORNL.**
  - **University of Wisconsin on GM engine setup and controls.**
- **Presentations to DOE/industry technical teams and merit reviews.**
  - **Advanced Engine Combustion (AEC) Working Group.**
  - **Advanced Combustion & Emissions (ACEC) Technical Team.**
  - **Diesel Cross-Cut Team.**

Members of AEC Working Group (admin by Sandia)

Sources for more information

- **FY 2007 Progress Report**
  http://www1.eere.energy.gov/vehiclesandfuels/resources/printable_versions/fcvt_reports.html
- **Recent conference publications/presentations**
  - **SAE 2008-01-0293**
  - **2007 Ricardo Software North American Users Conference**
- **DOE highlights …**
  - **ACEC Technical Team Highlight.**
  - **FreedomCAR Technical Highlight.**
  - **DOE EERE Weekly Report.**
- **Other relevant presentations at this review**
  - **"Achieving High-Efficiency Clean Combustion in Multi-Cylinder Light-Duty Engines" (immediately following this presentation)**
  - **"Stretch Efficiency – Thermodynamic Analysis of New Combustion Regimes" (Today, 8:50 am, this room)**
  - **"Measurement and Characterization of Lean NOx Adsorber Regeneration and Desulfation" (Today, 9:40 am, Salon G)**
  - **"Controlling NOx from Multi-Mode Lean DI Engines" (Today, 10:00 am, Salon G)**

Project Summary

- **Purpose**

  Demonstrate fuel efficiency & emissions milestones established in Vehicle Technologies multiyear plan in support of DOE objective of petroleum displacement.

- **Approach**

  Modeling & analysis for improved understanding and design of WHR system. Leveraging of ongoing LD diesel activities on advanced combustion, aftertreatment technologies, and stretch efficiency concepts.

- **Technical Accomplishments**

  Achieved FY 2007 efficiency milestone. Established path for meeting FY 2008 and beyond milestones.

- **Technology Transfer**

  Results from this activity are regularly communicated to DOE, industry, and others.

- **Future**

  Demonstrate 43% BTE by end of FY 2008 using WHR of exhaust stream and 45% by end of FY 2010. Potential technologies to be used in meeting 2010 milestones include WHR, friction reducers, improved turbocharger technology, advanced combustion, aftertreatment, etc.

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