Measurement and Characterization of Lean NOx Adsorber Regeneration and Desulfation and Controlling NOx from Multi-mode Lean DI engines

Agreements: 9248 and 12249

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Oak Ridge National Laboratory

February 26, 2008

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U.S. Department of Energy, FCVT

This presentation does not contain any proprietary or confidential information

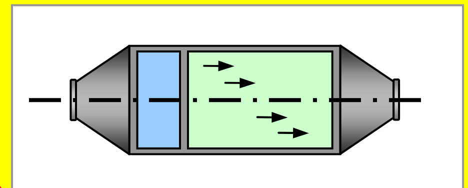
Understanding emission control devices and interactions with advanced combustion directly applies to FCVT objectives

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

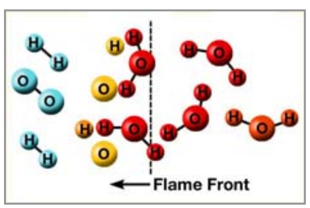
FY 2010 Goals

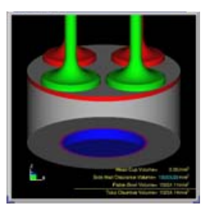
Achieving and Demonstrating FreedomCAR Engine Fuel Efficiency Goals
(Agreement 13704)

Characterization of LNTs for LD Diesel Engines
(Agreement 9248)



Stretch Efficiency for Combustion Engines
(Agreement 10037)





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

Purpose of Work: Enable efficient lean engine market penetration by meeting emission regulations with aftertreatment

- **Research of Lean NOx Trap Catalyst NOx and SOx Regeneration Chemistry and Performance (9248)**
  - Characterize H_2, CO, and HC's generated by the engine (tools: FTIR, GC/MS, SpaciMS)
  - Develop stronger link between bench and full-scale system evaluations
  - Provide data through CLEERS to improve models. Use models to guide engine research
- **Research of Multimode Engine Operation and Potential Synergies with Aftertreatment (12249)**
  - Investigate emissions from advanced engine combustion modes and study emissions control technologies
    - LNT, Urea SCR, HC-SCR, Lean NOx Catalysis, DPF, Oxidation
  - Study effect of multimode operation on system performance

Address Previous Reviewer Comments

Strengths:

- "…good target to bridge very fundamental work in other projects to more practical implementation."
- "…made good use of quality facilities…capable of total-system tests with detailed diagnostics."
- "Good progress…a relatively large number of experiments…."
- "Engine control is typically not well covered … due to proprietary nature…, but ORNL is to be commended for including this."
- "Working groups feeding information that is input into the program."

Weaknesses:

- "…measure fuel consumption accurately."
- "…can you address fuel dilution effects?"
- "It is hard to get state of the art devices…."
- "…potential exists for more substantive associations with industry particularly in the area of engine control…."
- "…definitive reasons for conducting these specific research areas need to be better justified."
- "Only general mention of next year's activities and plans…."

Address Previous Reviewer Comments

Strengths:

- "…good target to bridge very
- tests with d
- "Good prog number of
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- "Working groups feeding information that is inpu program."

Weaknesses:

- "…measure fuel consumption accurately."
- address fuel dilution effects?"
- o get state of the art devices…."
- l exists f more substantive industry particularly in the …."
- or ucting these d to be better
- "Only ge f next year's activities

Measuring fuel consumption accurately with gravimetric system. Also, improved dyno torque accuracy.

Continuing to strive to balance public aspect of project with most state-of-the-art technology.

Transition to new engines may expand collaborations

More specific plans for FY08 activities

ORNL research activities address multiple emissions control barriers

- **Technical Challenges & Barriers from FCVT MYPP:**
  - ***3.3.1.8.C. Emission control. Meeting EPA requirements for oxides of nitrogen and particulate matter emissions standards with little or no fuel economy penalty will be a key factor for market entry of advanced combustion engines. NOx adsorbers appear to be the most viable NOx reduction devices for light-duty vehicles, but they are very sulfur-sensitive, resulting in an increasingly greater energy penalty over time to compensate for loss of activity.***
  - ***3.3.1.8.E. Durability. The emission control system has to perform effectively for 120,000 miles ....***

- **FreedomCAR ACEC Tech Team 2006 Roadmap:**
  - ***Development and optimization of catalyst-based aftertreatment systems are inhibited by the lack of understanding of catalyst fundamentals (e.g., surface chemistry, deactivation mechanisms...) and catalysts modeling capabilities.***

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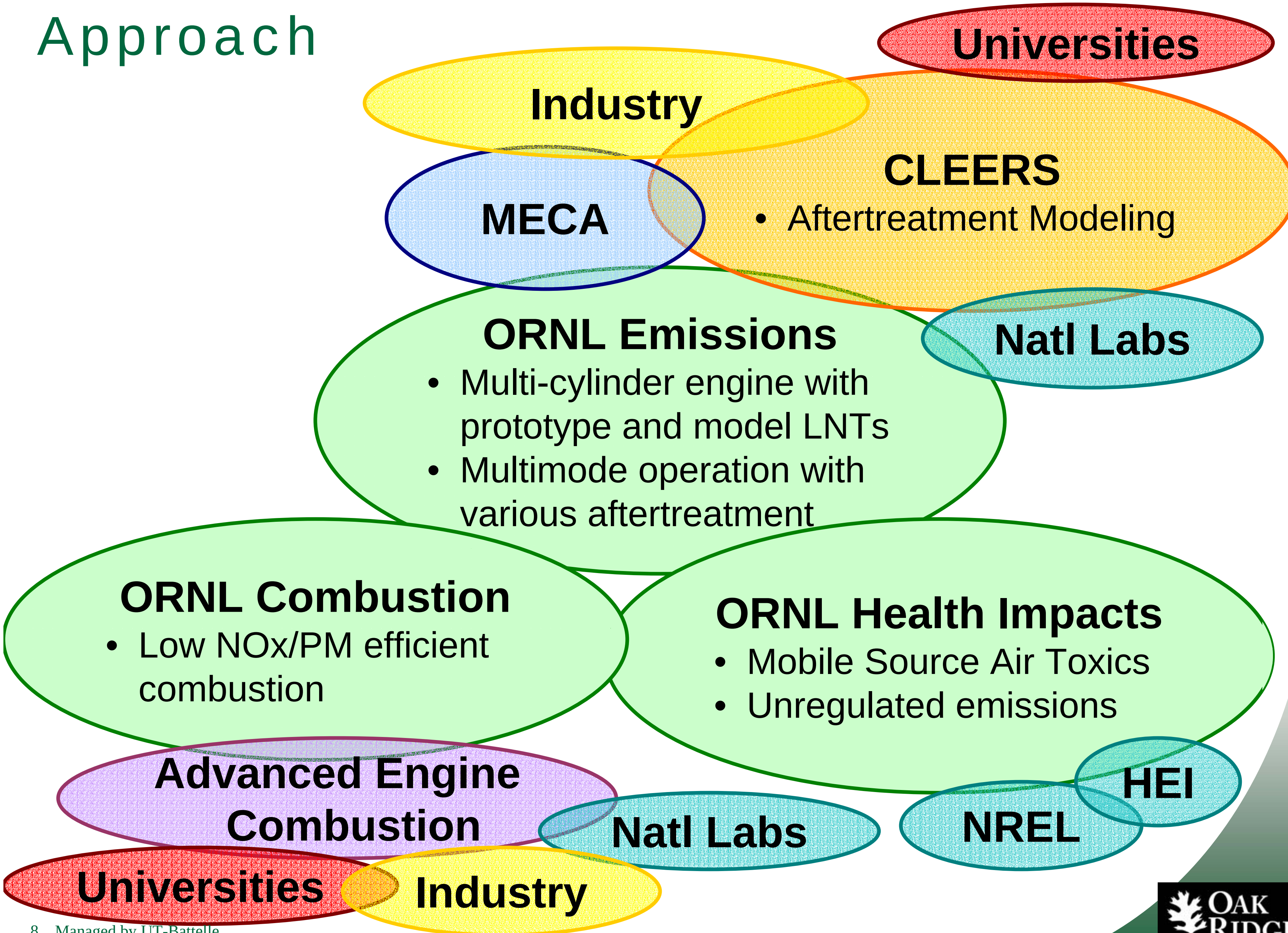
Approach

ORNL Emissions

- **Study LNTs on multi-cylinder engine with full control for in-cylinder regeneration**
  - MECA-supplied and model LNTs
  - Non-proprietary regeneration strategies
- **Operate multi-cylinder engine in multimodes (traditional + HECC/LTC)**
  - Study synergies of aftertreatment (LNT, SCR, HC-SCR) with multimode operation
  - Identify technologies and combined approaches that meet DOE goals

Approach


Universities
Industry
CLEERS
• Aftertreatment Modeling
MECA
ORNL Emissions
• Multi-cylinder engine with prototype and model LNTs
• Multimode operation with various aftertreatment
Natl Labs
ORNL Combustion
• Low NOx/PM efficient combustion
ORNL Health Impacts
• Mobile Source Air Toxics
• Unregulated emissions
Advanced Engine Combustion
Natl Labs
NREL
HEI
Universities
Industry

Performance Measures and Accomplishments

Since last review (June 2007):

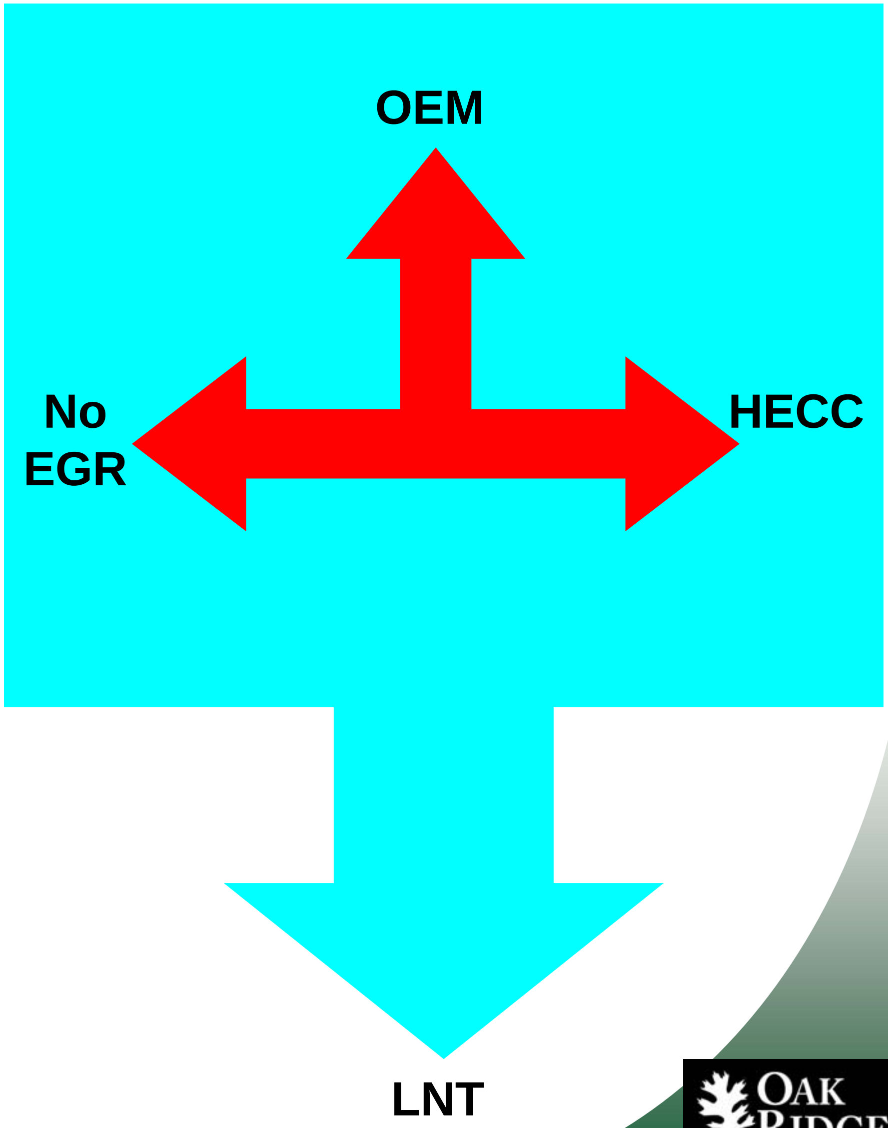
- **Studied LNT technology for multimode engine operation at various operating conditions**
  - **Measured performance for OEM vs. HECC operation**
  - **Measured LNT oxidation efficiency of MSATs**
- **Studied Ce-based LNT on bench flow reactor**
  - **Characterized NOx reduction and capacity vs. temperature**
  - **Measured deSulfation temperature profile**

Synergies
of
Lean NOx Trap
and
Multimode Combustion

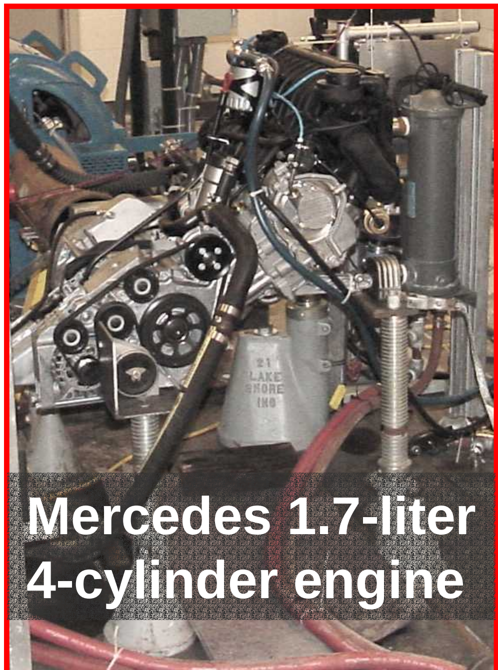
What are synergies between HECC combustion and lean aftertreatment?

<u>Combustion Modes:</u>

- **No EGR:**
  - no EGR, lean combustion
  - low PM and CO/HCs, high NOx
- **OEM (EGR):**
  - OEM EGR level and injection timing
  - moderate PM, NOx, and CO/HCs
- **Low Temperature Combustion (LTC):**
  - high EGR level, OEM injection timing
  - low PM and NOx, high CO/HCs
- **High Efficiency Clean Combustion (HECC):**
  - high EGR level, advanced timing, higher fuel rail pressure
  - low PM and NOx, high CO/HCs
  - HECC efficiency closer to OEM than LTC



Research Platform

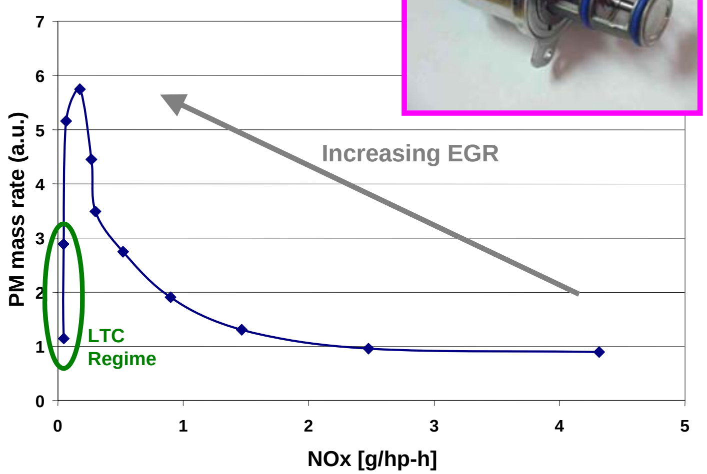


FY07 Improvements

- **Variable Geometry Turbo**
- **Custom Exhaust Header**

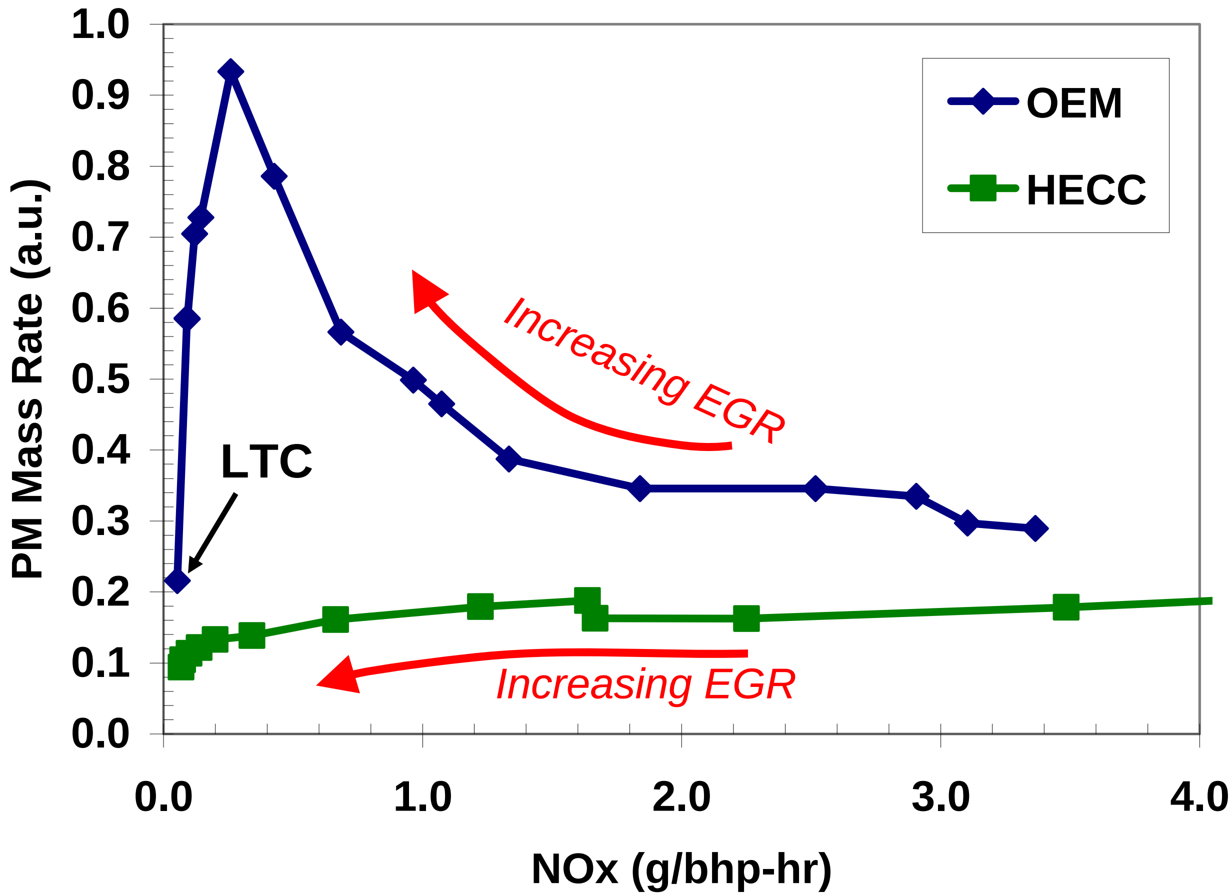
Advanced Technologies

- **Model-Based Full-Pass Control System**
  - **unlimited software flexibility**
- **Advanced Fuel Injection Capabilities**
  - **high pressure common rail**
  - **up to 8 injections per combustion event**
  - **no injection timing window limitations**
- **Electronic Intake Throttling Valve**
- **Electronic Solenoid Controlled EGR**
  - **low flow and high flow valves**
  - **EGR from 0% to ~60% (depending on engine condition)**
  - **EGR gas cooling**
- **Advanced Combustion Regimes (LTC/HECC)**



HECC Enables Low PM and NOx

- **EGR sweep conducted with OEM and HECC injection parameters**
  - **NOx-PM tradeoff curve shown**
- **HECC enables low PM emissions across span of EGR rates**
- **Less sensitivity of PM emissions to EGR rate for HECC is an advantage for PM control**

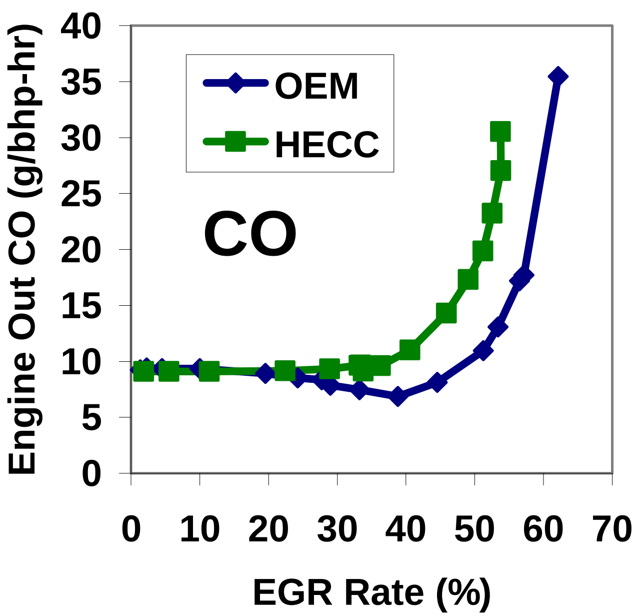


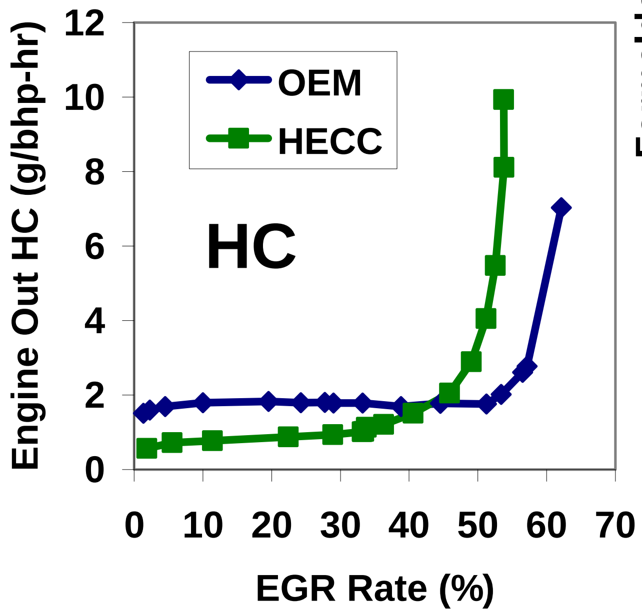
1500 rpm
2.6 bar

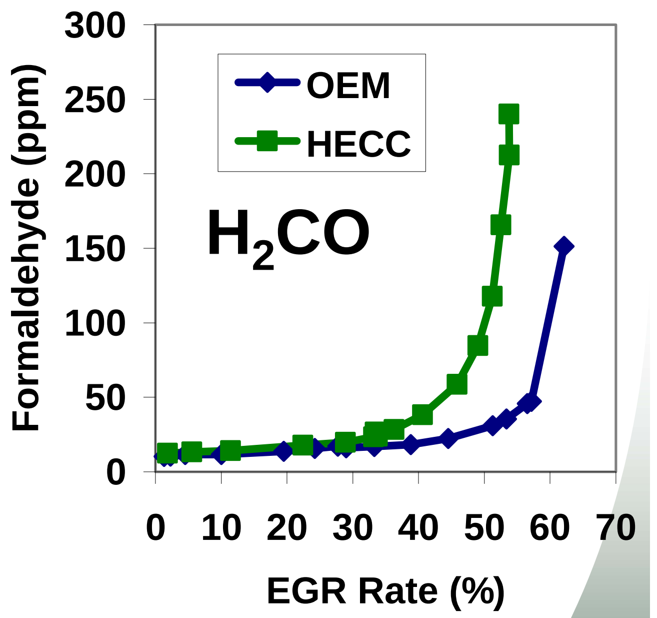
Downside of HECC is Higher HC and CO Emissions

- **At high EGR rates, CO and HC emissions increase with HECC combustion relative to OEM and lean combustion modes**
- **Formaldehyde, a Mobile Source Air Toxic (MSAT), also increases for HECC relative to OEM**
  - **In-depth MSAT emissions addressed in ORNL Health Impacts project**
- **Catalytic oxidation of these emissions dependent on temperature**

1500 rpm
2.6 bar

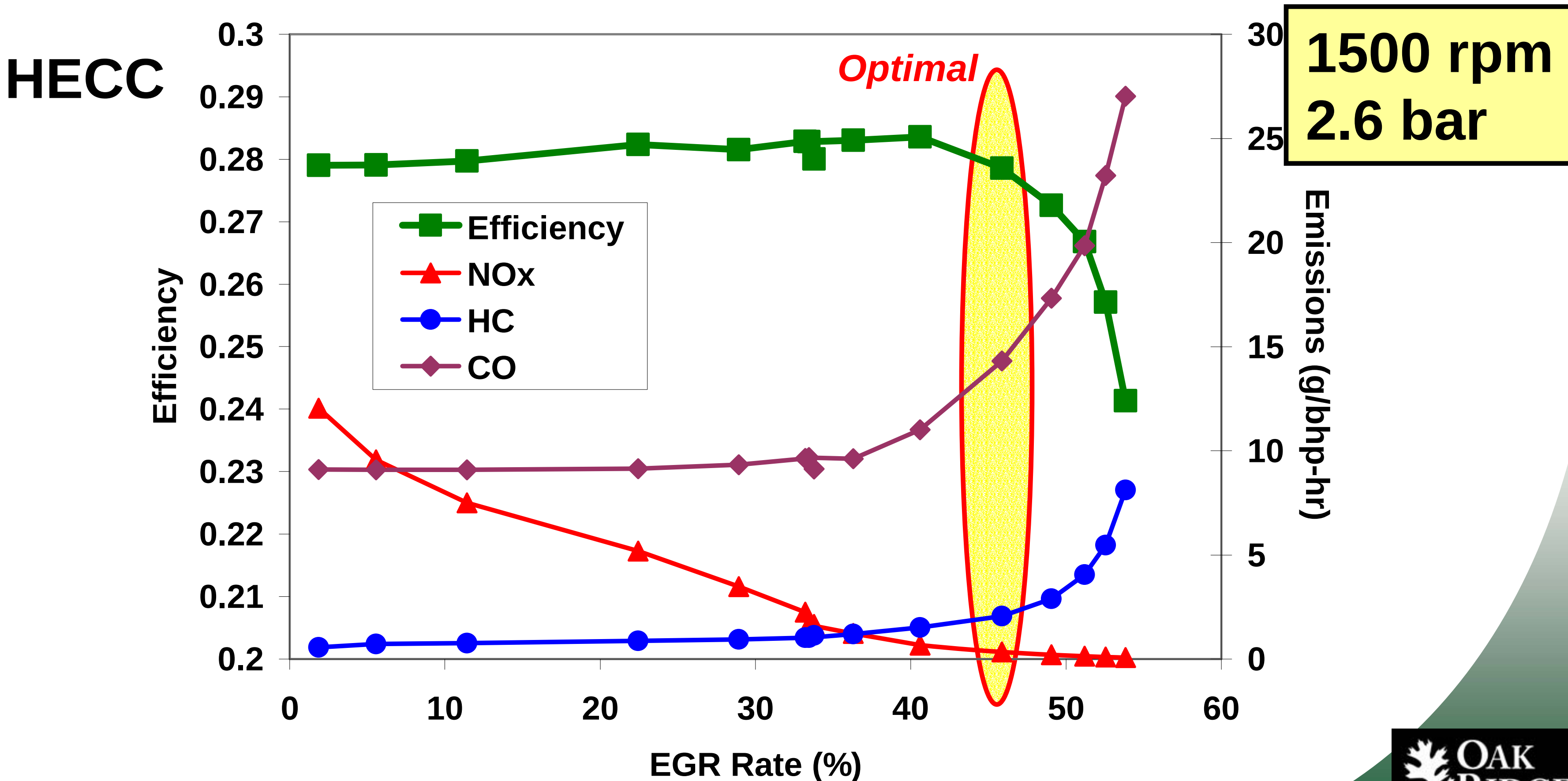






Optimization of HECC combustion is Trade-Off between Efficiency and Emissions

- **As EGR rate increases, NOx emissions continue to drop, but …**
- **Ultimately, efficiency will drop at the highest EGR rates as combustion becomes less stable**
- **Optimal HECC operating parameters determined by varying EGR rate and injection timing**



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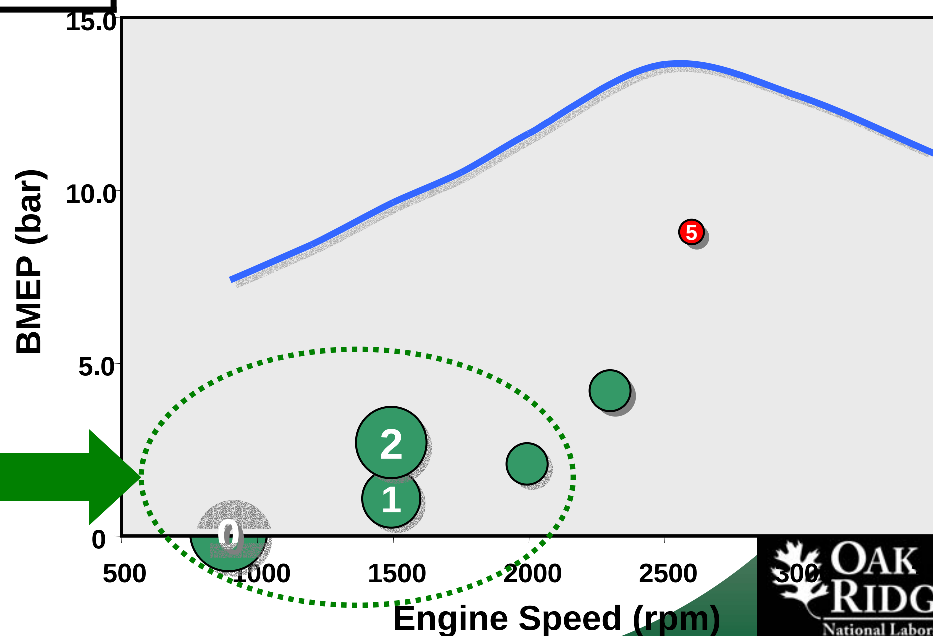
Experiments made use of engine conditions developed by Ad Hoc Working Group

Point	Speed / Load	Weight Factor	Description
0	900 rpm / 0.1 bar	700	Idle
1	1500 rpm / 1.0 bar	400	Catalyst transition temperature
2	1500 rpm / 2.6 bar	600	Low speed cruise
3	2000 rpm / 2.0 bar	200	Low speed cruise w slight acceleration
4	2300 rpm / 4.2 bar	200	Moderate acceleration
5	2600 rpm / 8.8 bar	75	Hard acceleration

- **Considered representative speed-load points for light-duty diesel engines.**
- **Does not include cold-start or other transient phenomena.**
- **Represents method for estimating magnitude of drive-cycle emissions.**

- **HECC operation achieved for Modes 0 to 4 using high levels of dilution on ORNL combustion project engine**
  - Reference: Sluder and Wagner, SAE 2006-01-3311
- **HECC operation achieved for Modes 0 to 3 with ORNL emissions engine (different EGR)**

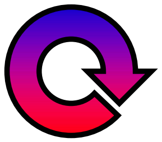


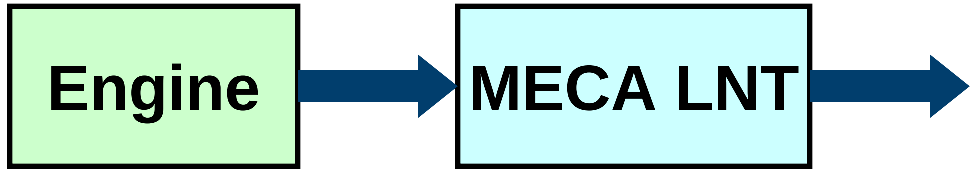
Regeneration Performed with Combination of O_2 Reduction and Fuel Enrichment Techniques

O_2 Reduction:

- **Throttle**

- **EGR**

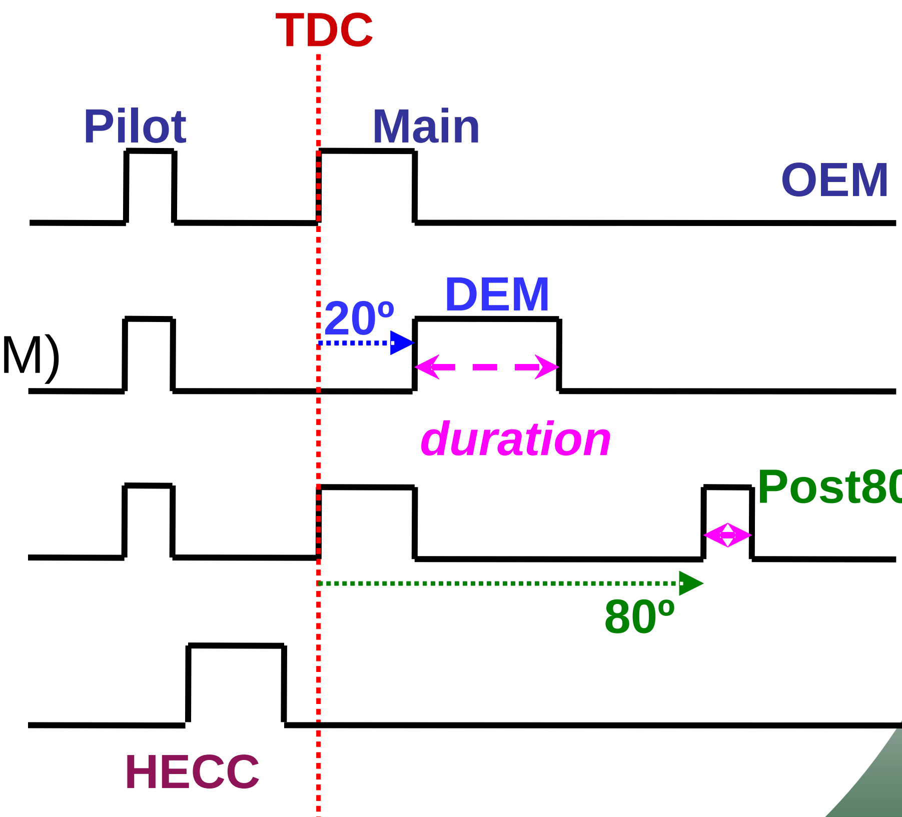




MECA LNT: ~100 g/ft3 PGM, 2.47 liters (1.5 ESV)

Fuel Enrichment

- OEM Injection Timing
- Delayed and Extended Main (DEM)
- Post-80º Enrichment (Post80)
- HECC Enrichment



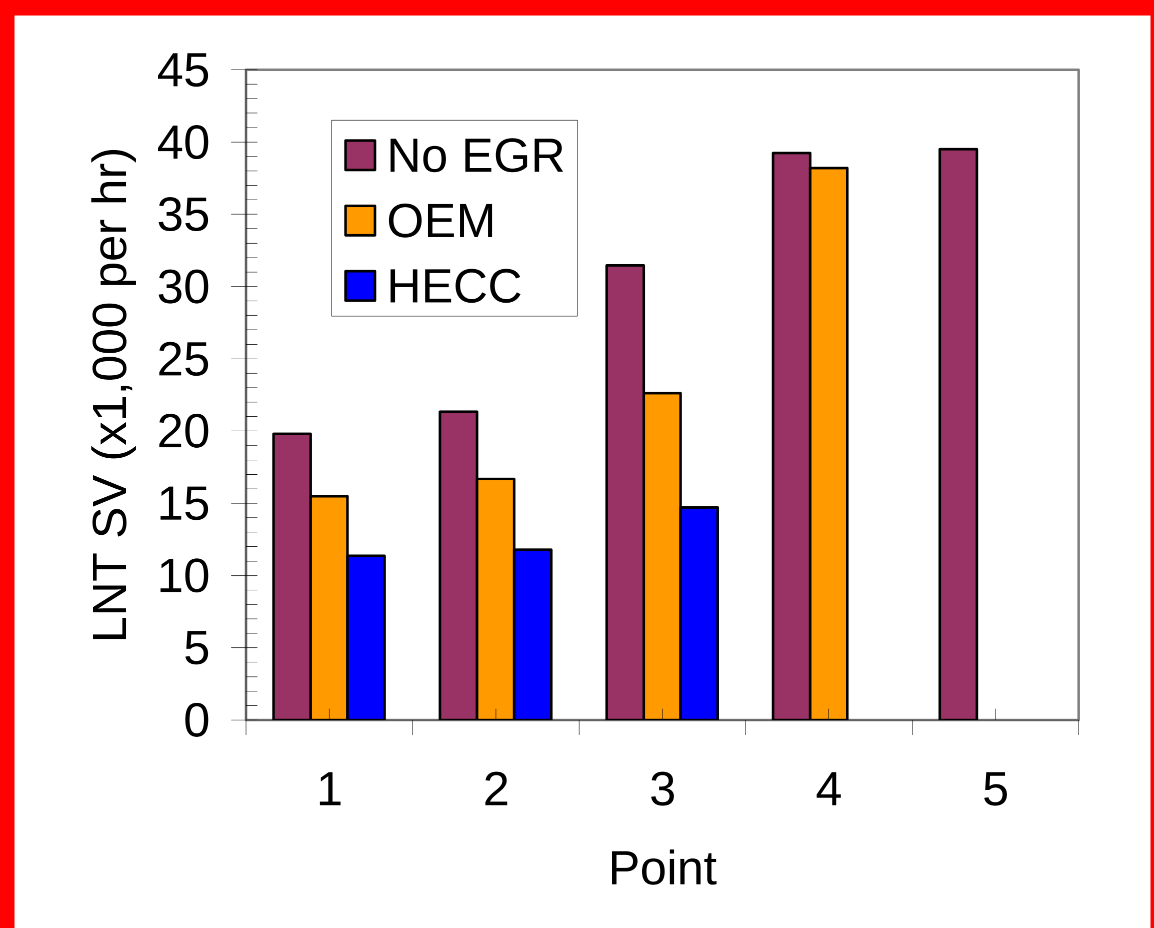
Regeneration Approach for SS Conditions

Point	Speed / Load	SV (/hr)	LNT Temperature (ºC)	Modes	Regeneration Technique
1	1500 rpm / 1.0 bar	11,400-19,800	128-142	Lean, OEM, HECC	EGR and Throttle w/ HECC and DEM Enrichment
2	1500 rpm / 2.6 bar	11,800-21,300	244-258	Lean, OEM, HECC	EGR and Throttle w/ HECC Enrichment
3	2000 rpm / 2.0 bar	14,700-31,500	242-282	Lean, OEM, HECC	EGR and Throttle w/ HECC Enrichment
4	2300 rpm / 4.2 bar	38,200-39,200	354-366	Lean, OEM	Throttle w/ DEM Enrichment
5	2600 rpm / 8.8 bar	39,500	485	Lean	Throttle w/ Post80 Enrichment

- **LNT temperatures challenging for conditions #1 and #2**
- **Steady-state modes not truly representative of LNT temperature during transient operation, large temperature and SV variations observed in matrix**

Regeneration Approach for SS Conditions

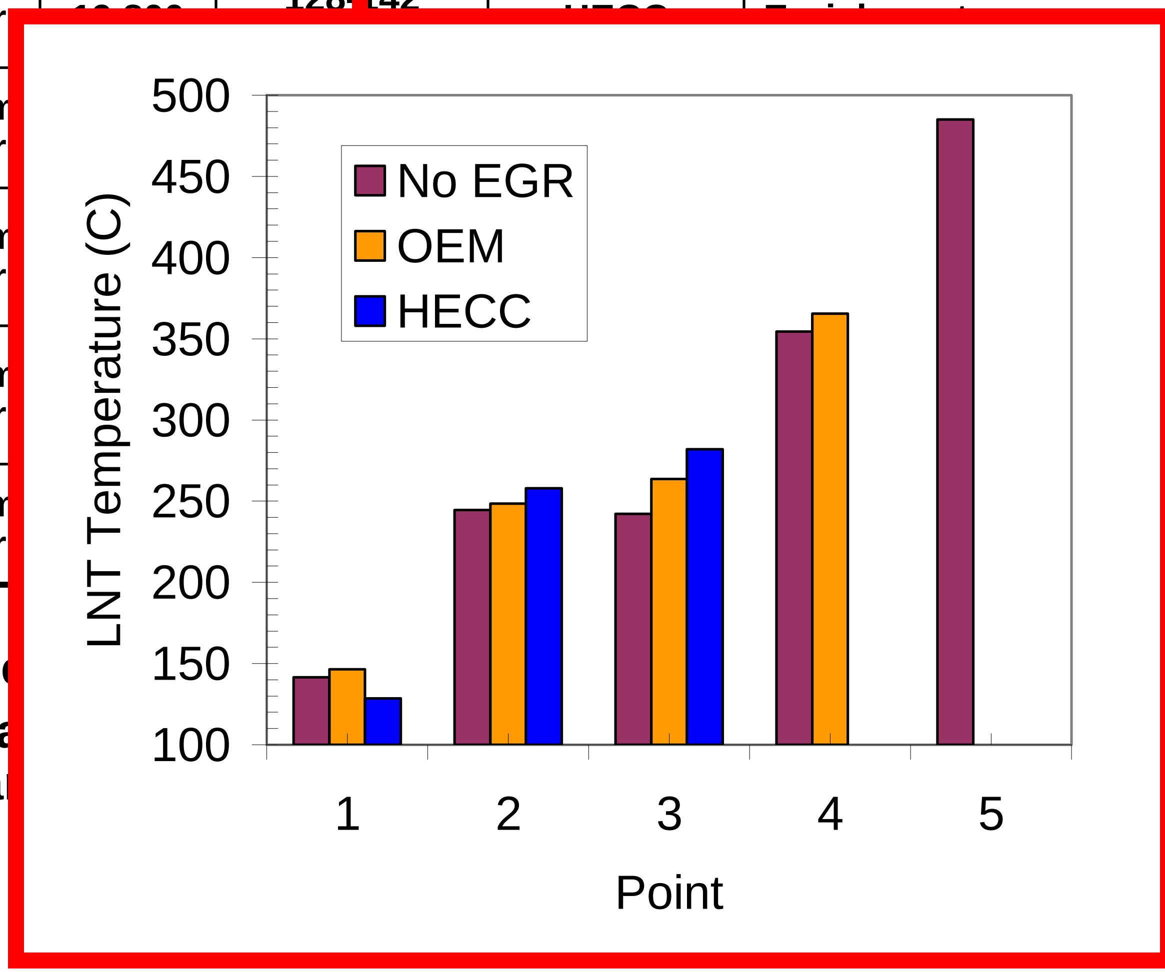
Point	Speed / Load	SV (/hr)	LNT Temperature (ºC)	Modes	Regeneration Technique
1					rottle w/ HECC and DEM
2					rottle w/ HECC Enrichment
3					rottle w/ HECC Enrichment
4					EM Enrichment
5					ost80 Enrichment



- LI … #2
- St … emperature du … variations ol …

Regeneration Approach for SS Conditions

Point	Speed / Load	SV (/hr)	LNT Temperature (ºC)	Modes	Regeneration Technique
1	1500 rpm / 1.0 bar	11,400-	128-142	Lean, OEM,	EGR and Throttle w/ HECC and DEM
2	1500 rpm / 2.6 bar				CC Enrichment
3	2000 rpm / 2.0 bar				CC Enrichment
4	2300 rpm / 4.2 bar				ment
5	2600 rpm / 8.8 bar				chment



- LNT tempe
- Steady-sta ure during tra ns observed

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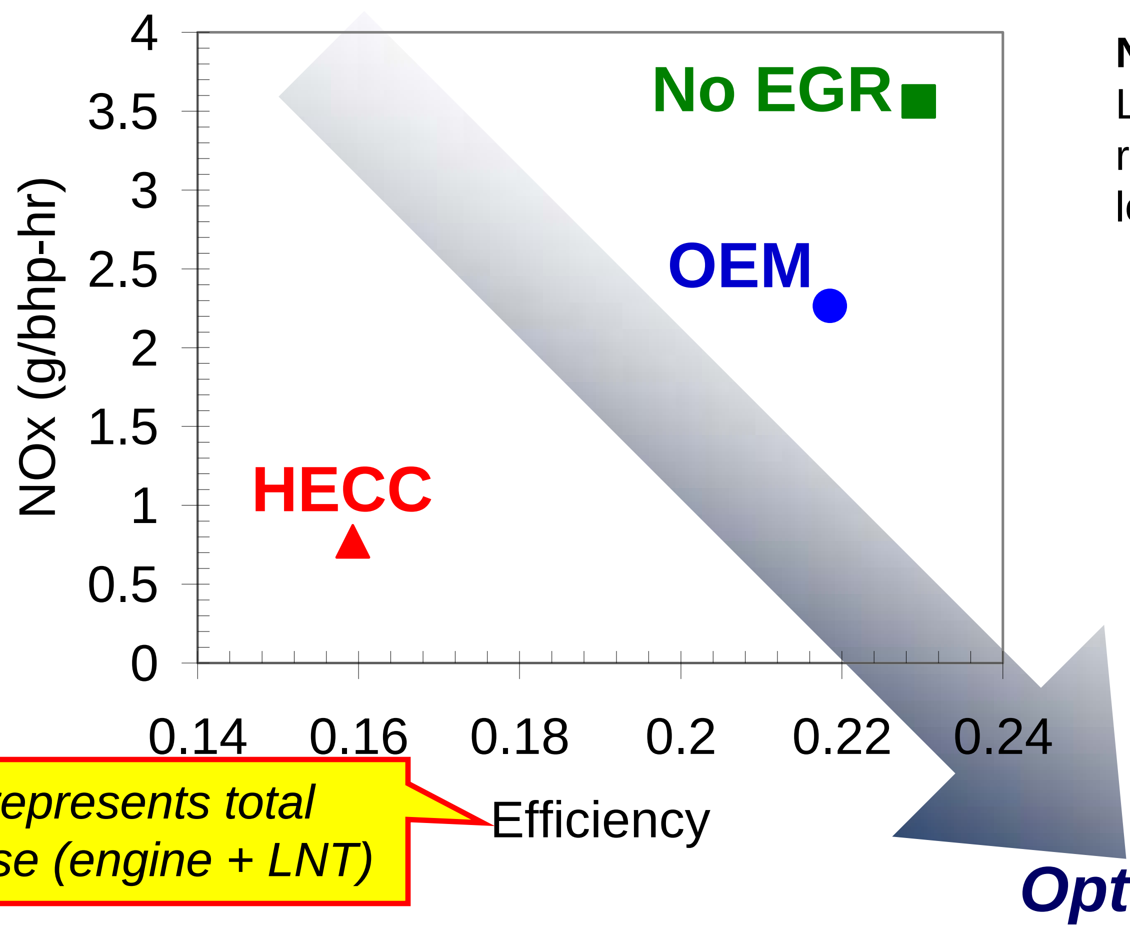
Point #1: 1500 rpm / 1.0 bar (Catalyst transition temperature)

- **No NOx reduction observed by catalyst**
- **Temperature (<150 C) is too low**
- **Reductants generated pass through LNT**
- **HECC is lowest NOx option**

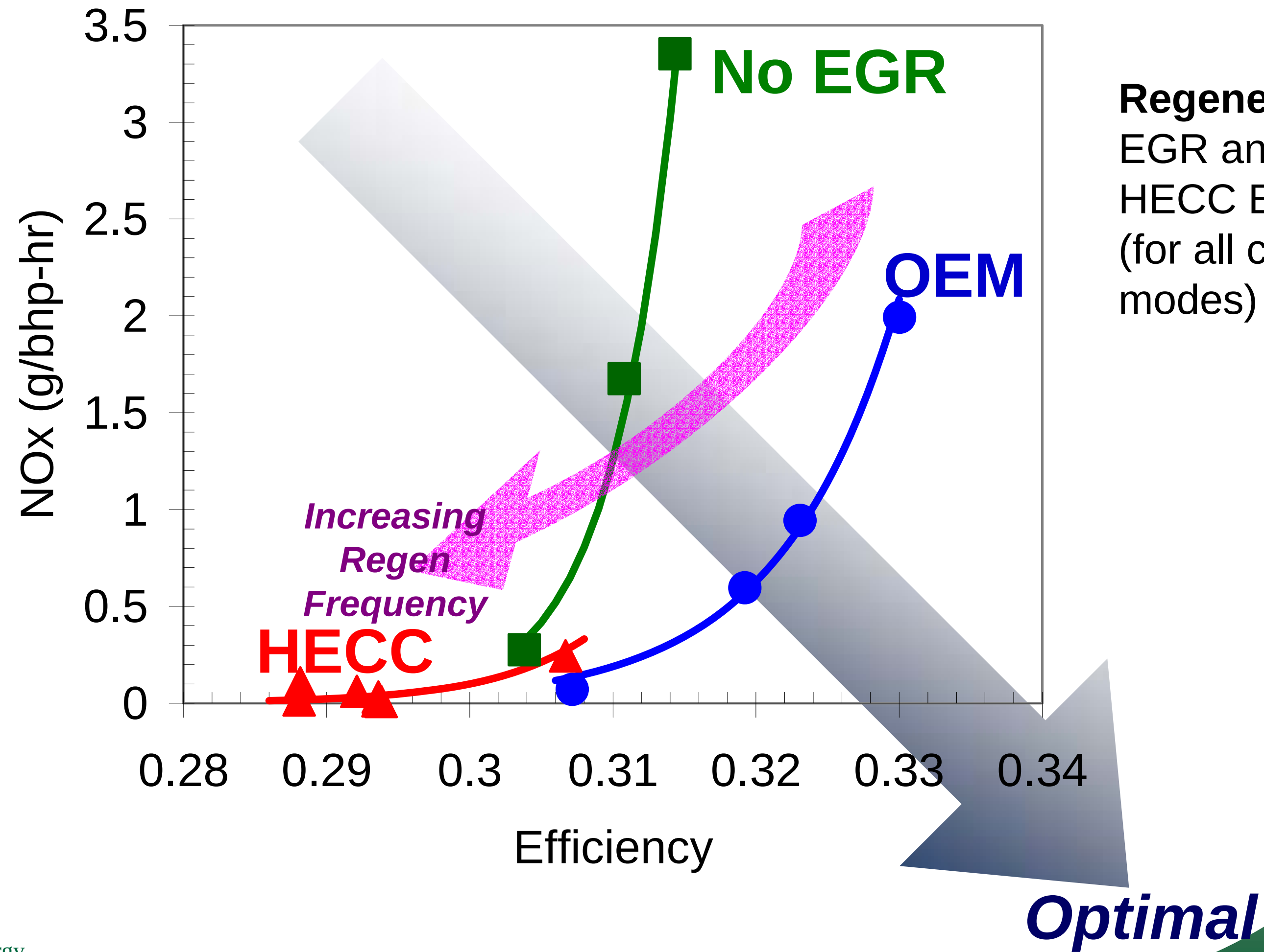


No Regeneration: LNT not capable of regeneration due to low temperatures

Efficiency represents total system fuel use (engine + LNT)

Point #2: 1500 rpm / 2.6 bar (Low speed cruise)

- **OEM and HECC effective at achieving low NOx levels**

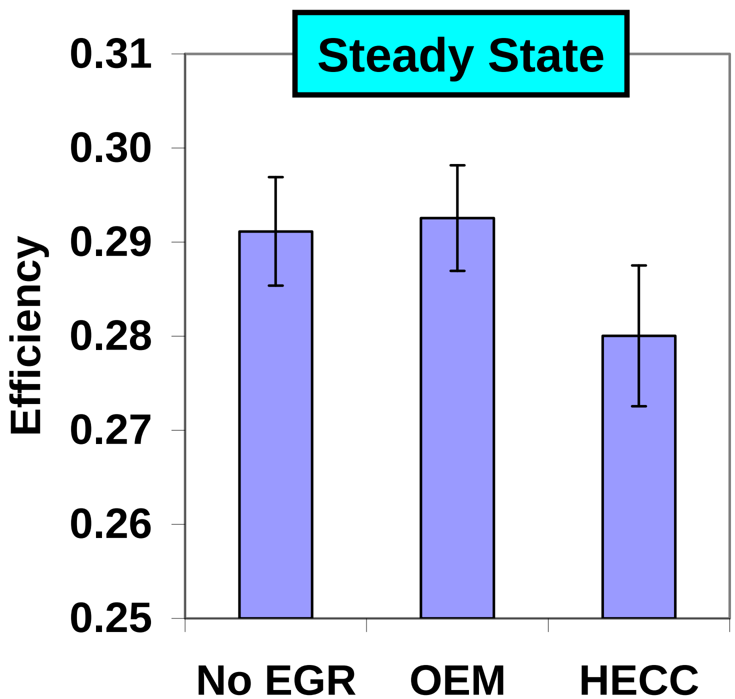


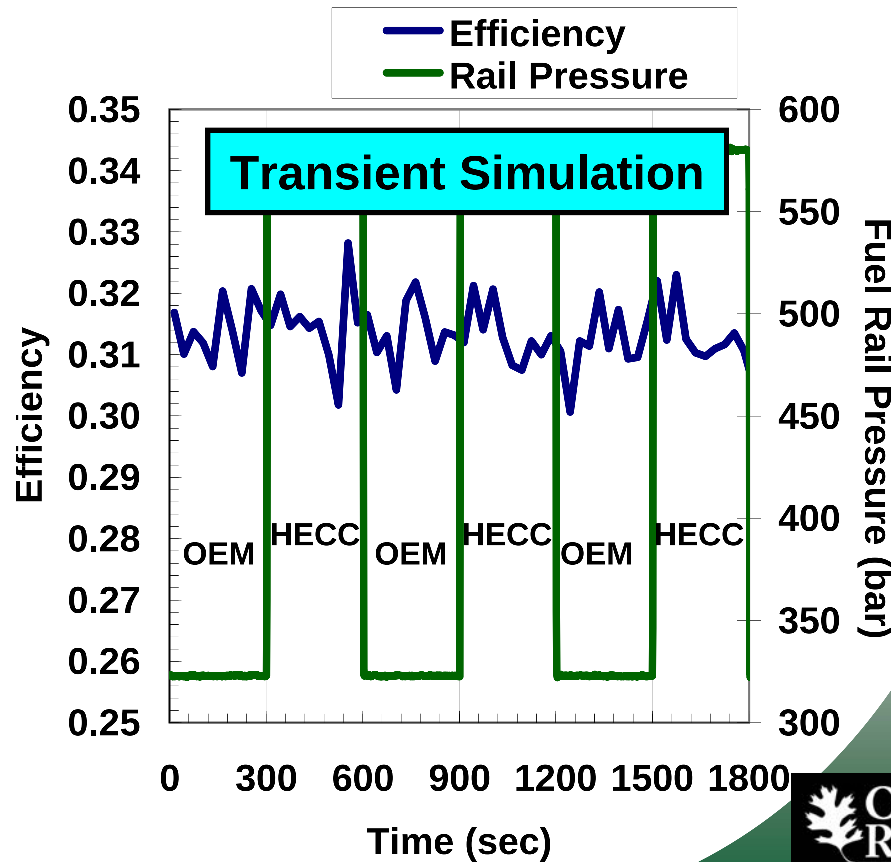
Regeneration:
EGR and Throttle w/ HECC Enrichment (for all combustion modes)

Transient Operation Avoids System Cooling Effects Responsible for Drop in HECC Efficiency

- **At steady-state conditions, HECC efficiency can drop due to system cooling issues at some conditions**
- **For transient operation, switching between combustion modes helps to preserve HECC efficiency to OEM levels**
  - **Experiment shows maintaining efficiency during switching from OEM to HECC modes every five minutes**

1500 rpm
2.6 bar





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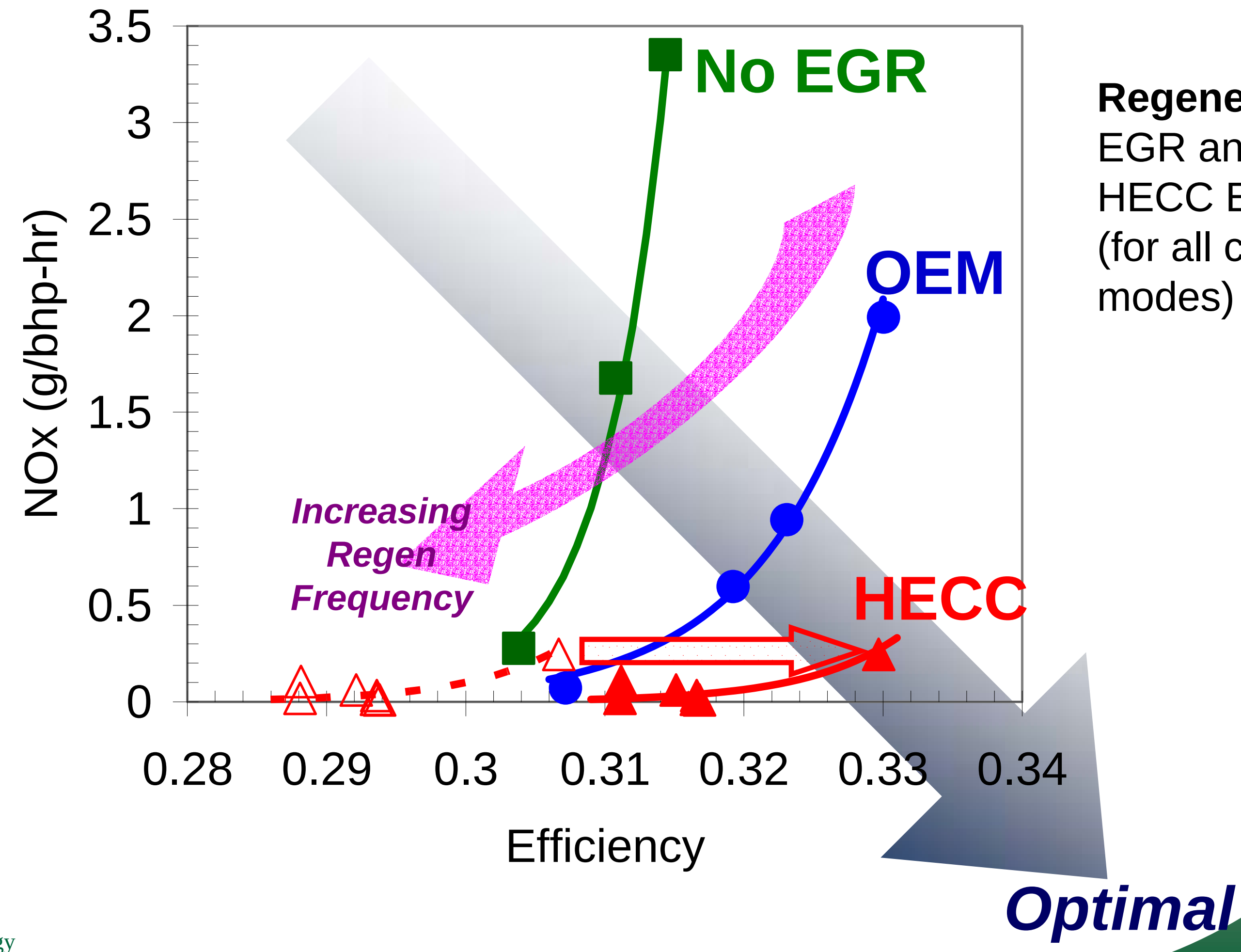
Point #2: 1500 rpm / 2.6 bar (Low speed cruise)

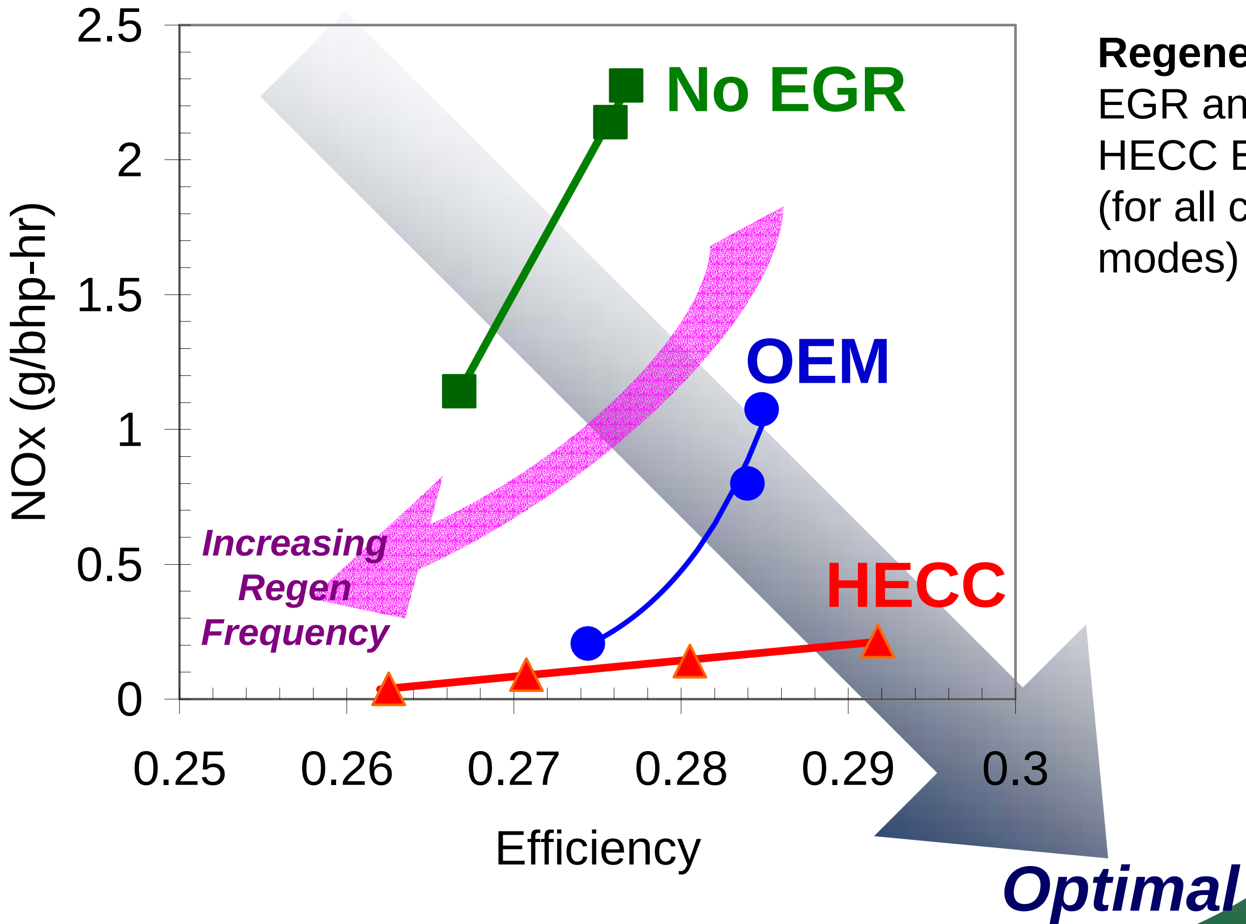
- **HECC preferred if transient operation maintains equivalent efficiency to OEM**



Regeneration:
EGR and Throttle w/ HECC Enrichment (for all combustion modes)

Point #3: 2000 rpm / 2.0 bar (Low speed cruise w/ slight acceleration)

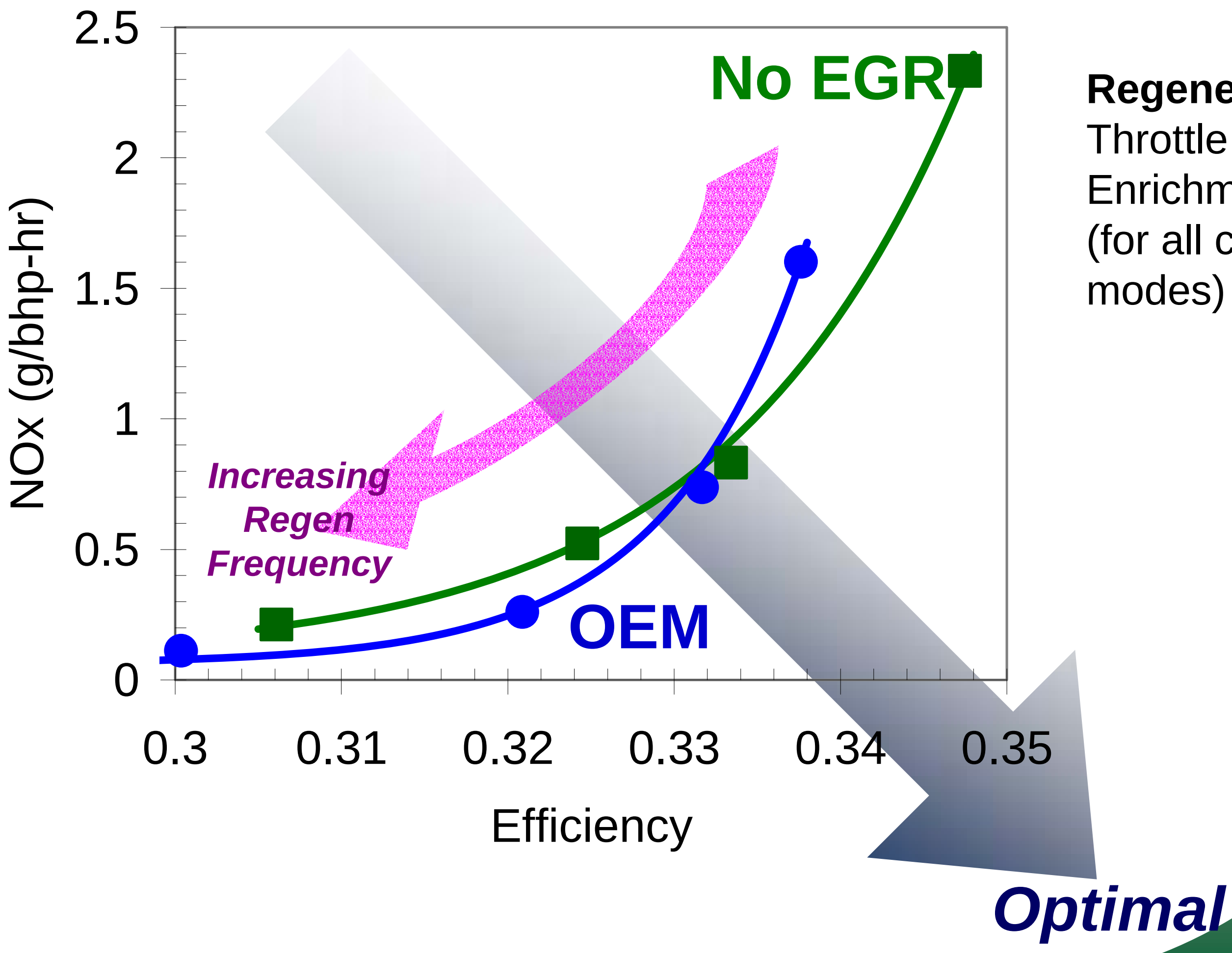
- **HECC shows optimal results; OEM also good with frequent regen**
- **HECC benefits from higher LNT temperature and lower SV**
- **Efficiency of HECC remains high at steady state as exhaust temperatures are more stable**



Regeneration:
EGR and Throttle w/ HECC Enrichment (for all combustion modes)

Point #4: 2300 rpm / 4.2 bar (Moderate Acceleration)

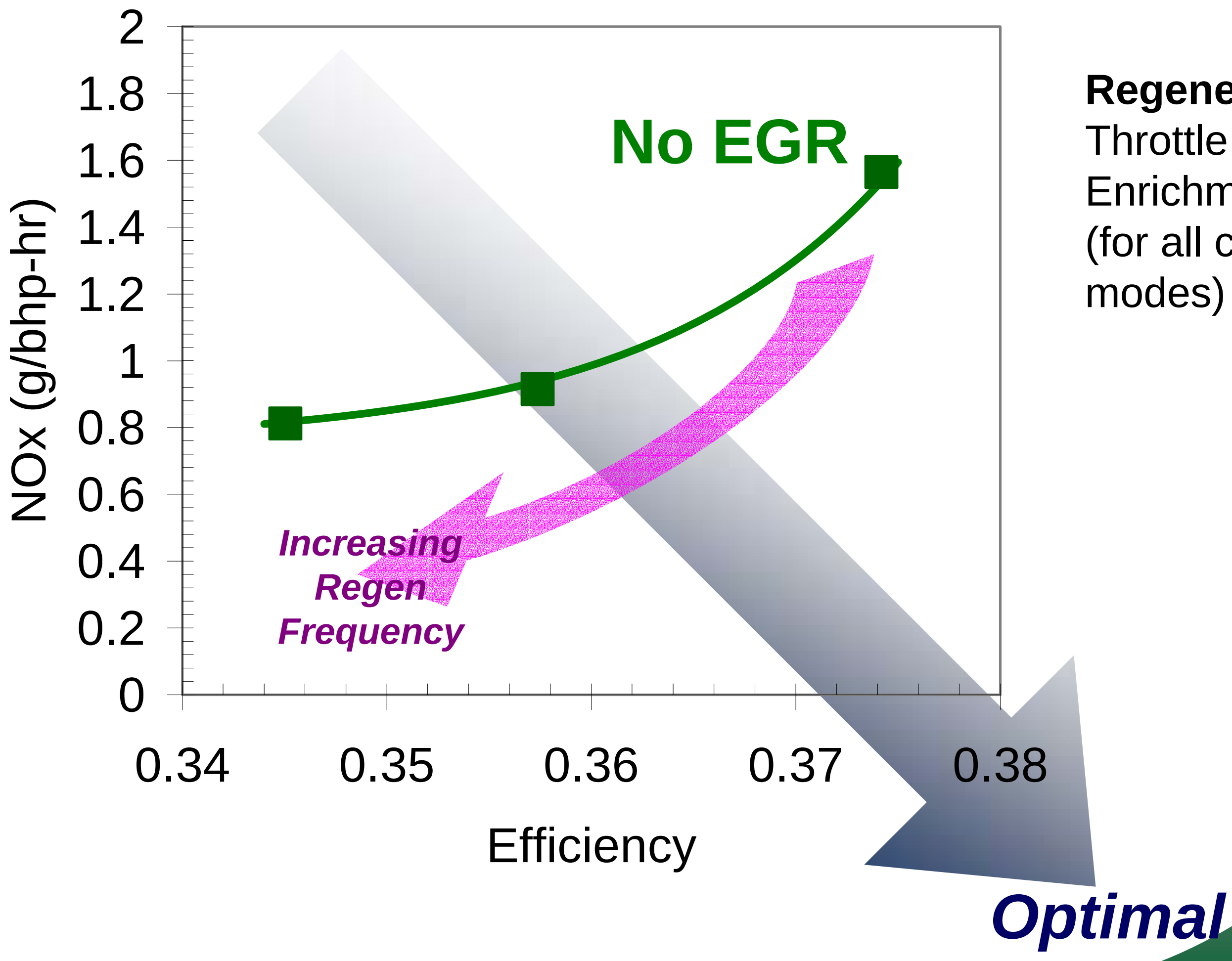
- **OEM (EGR) more efficient than "No EGR" mode at low NOx levels**
- **HECC not attained at condition #4**



Regeneration:
Throttle w/ DEM Enrichment
(for all combustion modes)

Point #5: 2600 rpm / 8.8 bar (Hard Acceleration)

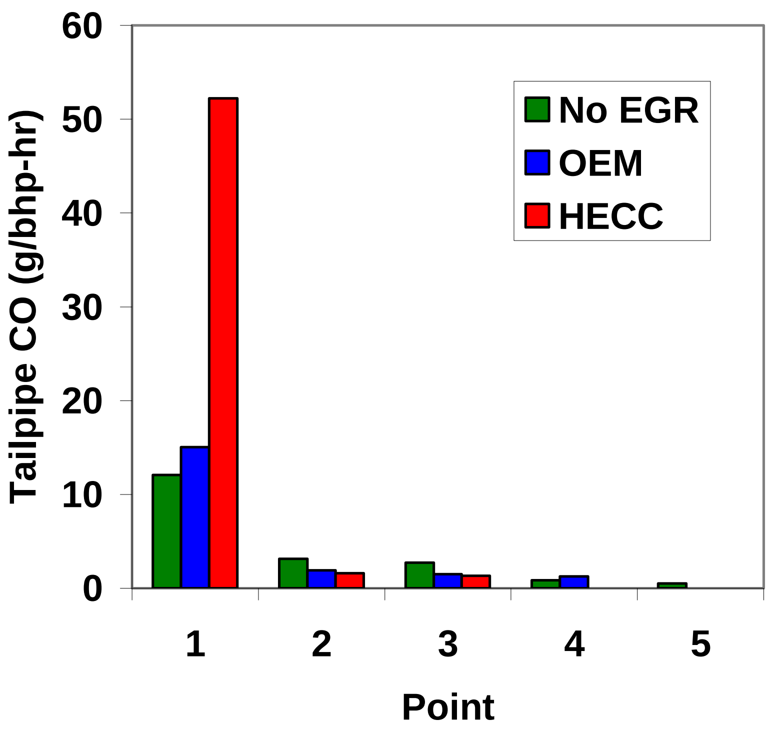
- **No EGR mode is only option explored at higher load**
- **Optimization occurs at midpoint of curve**

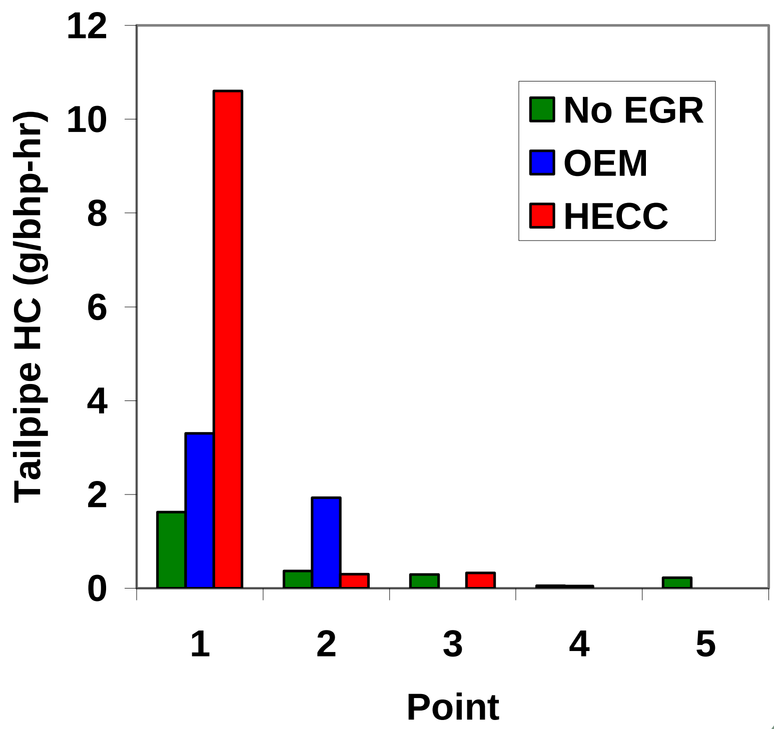


Regeneration:
Throttle w/ Post80 Enrichment
(for all combustion modes)

CO and HC Emissions Problematic at Point #1

- **Tailpipe CO and HC emissions for no regeneration case at each speed/load point**
- **Point #1 is below light-off temperature of LNT**
- **Low temperature oxidation catalyst needed**





Bad EGR Chemistry Detriment to System

- **High EGR rate combined with heavy hydrocarbons and soot in cool system lead to problematic deposits in EGR system**
- **Multiple cases of EGR valve failure and EGR loop fouling observed during experiments**
- **Especially problematic at lowest exhaust temperatures**

Tar-like deposits removed from EGR system

HECC and LNT Technology Synergistic at Some Conditions

- **NOx reduction from the combination of HECC combustion and LNT aftertreatment is excellent at low temperatures**
  - **Efficiency can be optimal in transient conditions where combustion switches between HECC and OEM operation**
- **CO, HC, and MSAT emissions from HECC are controlled by LNT at higher temperatures but are not controlled at lower temperatures**
- **High EGR rate and HC chemistry are bad mixture at low temperatures**
  - **System durability issues are biggest hurdle to overcome**

Point	Speed / Load	LNT Temperature (ºC)	Comments
1	1500 rpm / 1.0 bar	128-142	OEM and HECC optimal, but CO and HC Emissions Problematic
2	1500 rpm / 2.6 bar	244-258	HECC optimal, but HECC efficiency drops off for long term operation
3	2000 rpm / 2.0 bar	242-282	HECC optimal
4	2300 rpm / 4.2 bar	354-366	OEM optimal (HECC not achieved)
5	2600 rpm / 8.8 bar	485	No EGR optimal

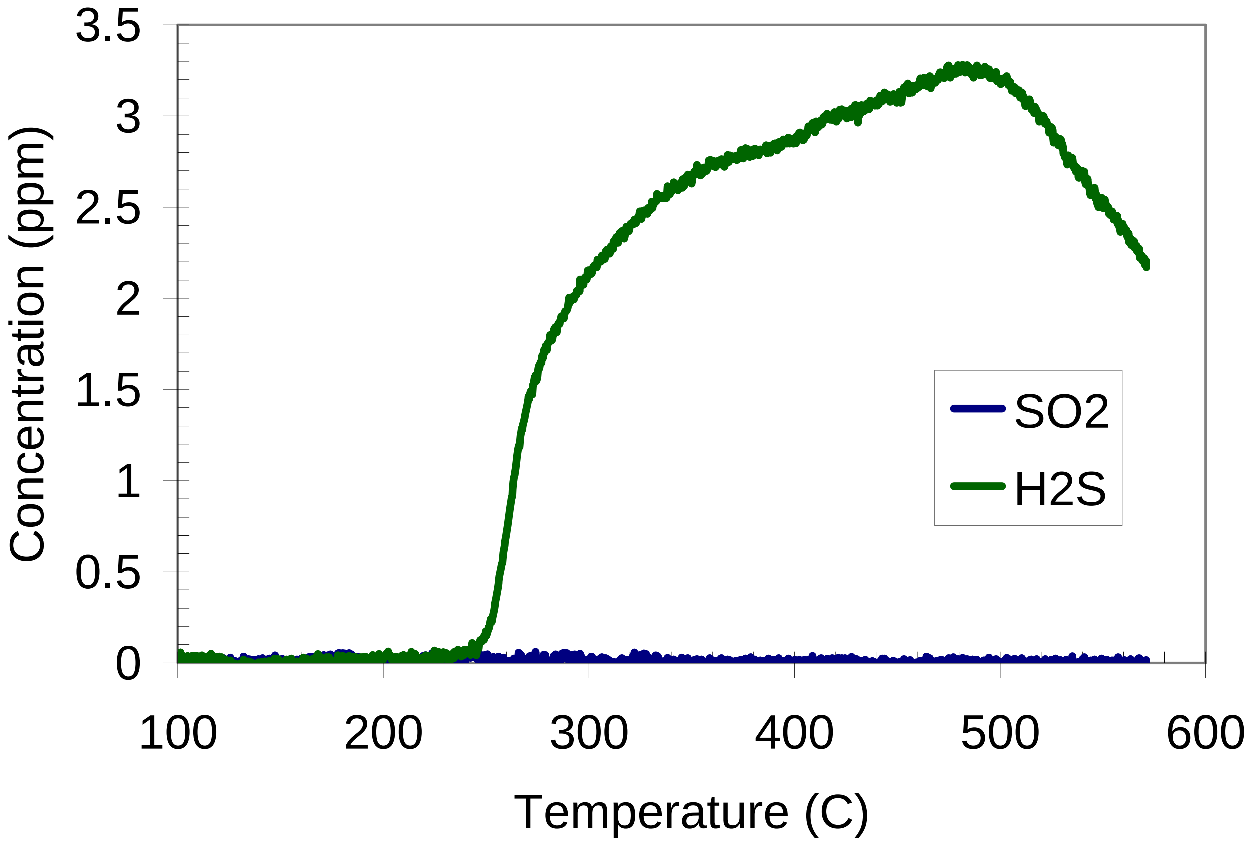
Bench Flow Reactor Characterization of Ce-Based Lean NOx Trap

Are Ce-based LNTs suitable for light-duty diesel engine applications?

- **Honda has studied use of Ce-based LNT for hybrid (LNT + SCR) aftertreatment system for future diesel vehicles**
  - Reference: Naohiro Satoh, Hiroshi Ohno, and Tadao Nakatsuji, *Aachener Kolloquium Fahrzeug- und Motorentechnik 2006*
- **What are advantages of Ce-based LNTs?**
- **Investigated model Ce LNT on bench flow reactor**

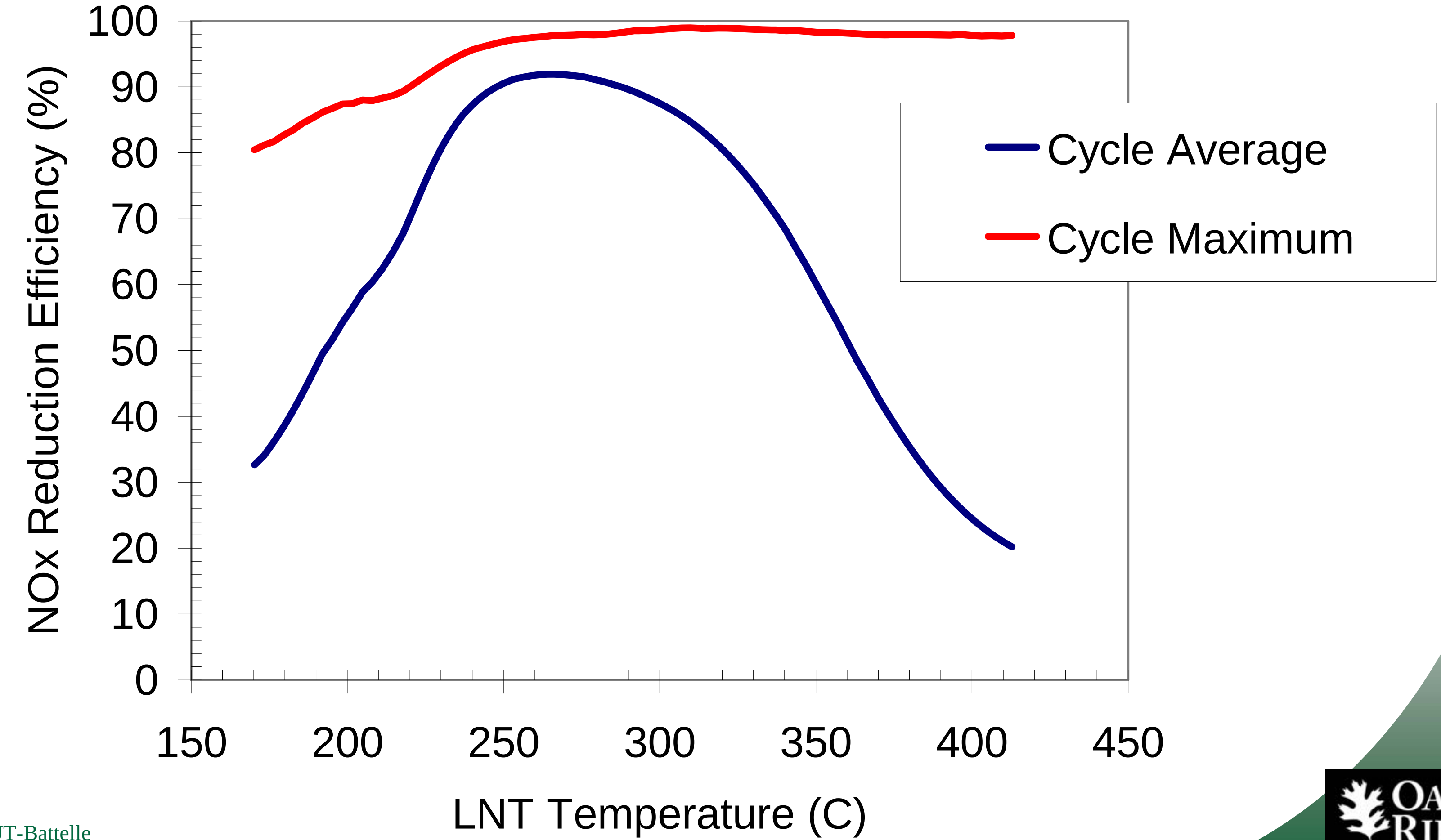
Ce-Based LNT Offers Low deSulfation Temperature

- **Temperature programmed reduction (TPR) of LNT after S exposure with SO_2**
- **Conditions: SV=30k/hr, CO_2=H_2O=6%, 0.5% H_2**
- **Sulfur release (as H_2S) begins at 250 C**



Ce-LNT Peak Efficiency at 250-280 C

- **NOx reduction efficiency peaks between 250 and 280 C**
- **In general, good performance at low temperatures, but poor performance at higher temperatures (>350 C)**
- **Conditions: SV=30k/hr, CO_2=H_2O=6%, O_2=8%, 200 ppm NO, CO and H_2 reductants, lean/rich cycle=55/5 sec**



Ce-Based LNTs Offer Low Temperature Performance

- **Low deSulfation temperature observed**
- **NOx reduction performance is shifted to lower temperatures relative to Ba-based LNTs**

Technology Transfer/Publications and Future Plans

Technology Transfer

- **Interactions with field at …**
  - DEER Conference
  - CLEERS Workshop, Focus Group conference calls, and website (database)
  - SAE Conferences
- **Informal interactions with MECA partners and OEMs**

Publications/Patents

- **Since Last Review (June, 2007):**
  - Jim Parks, Shean Huff, Matt Swartz, and Brian West, "Lean NOx Trap Formulation Effect on Performance with In-Cylinder Regeneration Strategies", *13th Diesel Engine-Efficiency and Emissions Research Conference*, Detroit, MI, August, 2007.
  - Jim Parks, Shean Huff, Mike Kass, and John Storey, "Characterization of In-Cylinder Techniques for Thermal Management of Diesel Aftertreatment", *SAE Technical Paper Series* 2007-01-3997 (2007).
  - Jim Parks, Brian West, Matt Swartz, and Shean Huff, "Characterization of Lean NOx Trap Catalysts with In-Cylinder Regeneration Strategies", *SAE Technical Paper Series* 2008-01-0448 (2008). [*will be presented at SAE Congress 2008*]

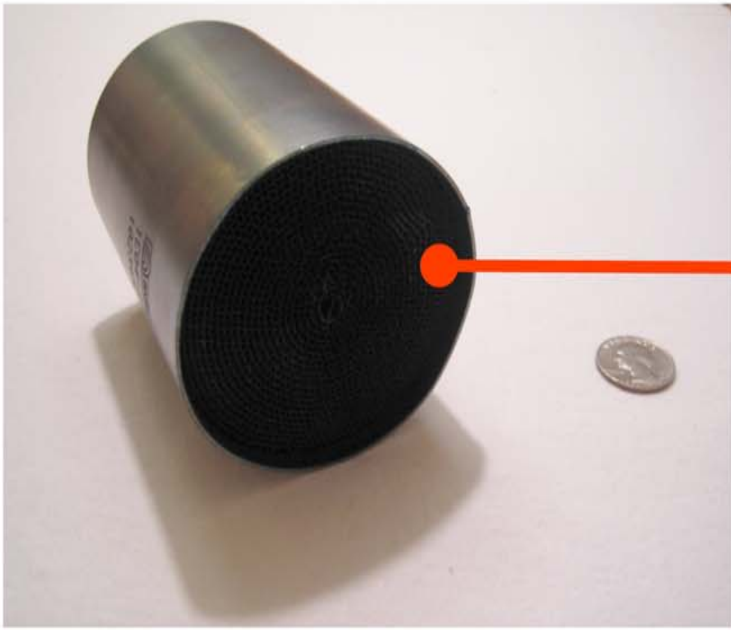
Plans for Rest of FY08 and FY09

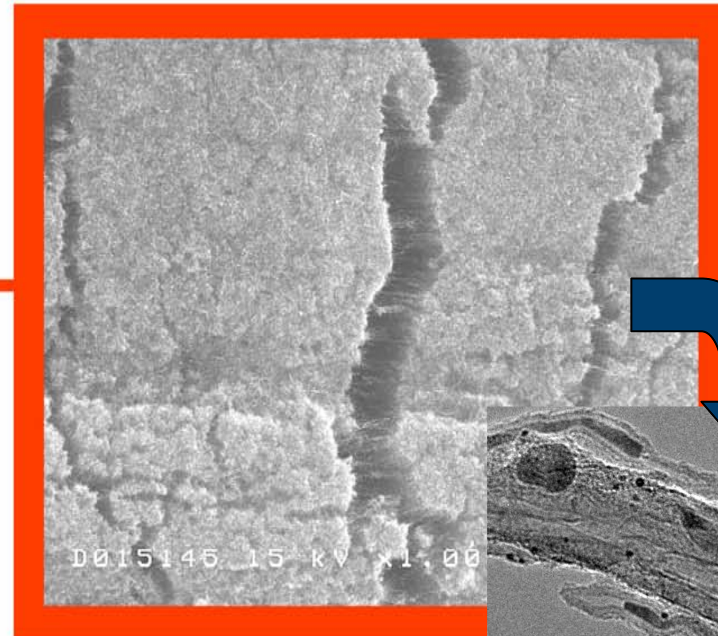
- **Rest of FY08**
  - **Continue multimode study: add SCR and DOC**
  - **Investigate novel HC-SCR catalyst from University of Kentucky (Mark Crocker)**
  - **Continue Ce LNT study and add PGM loading study (1st on bench, then migrate to engine)**
- **FY09**
  - **Migrate to new engine platforms**
    - **GM 1.9-liter diesel (4-cylinder)**
    - **Lean gasoline (still looking for specific engine)**
  - **Study hybrid LNT-SCR systems**

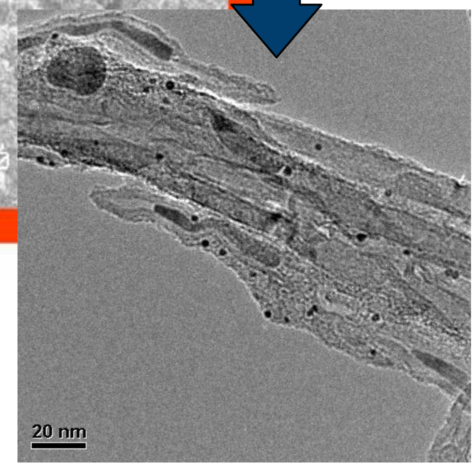
Plans for Univ of Kentucky MWNT HC-SCR

- **Study MWNT HC-SCR catalyst on Mercedes 1.7-liter diesel platform**
  - **In-pipe injection of diesel fuel**
  - **In-cylinder reductant production**
    - **Reductant mixture of H_2, CO, and HCs added to lean exhaust with cylinder indexing approach**
  - **Slipstream exhaust geometry**
- **Goal: Characterize unique HC-SCR catalyst under realistic engine conditions**

Novel HC-SCR Based on C Nanotubes (U of K)

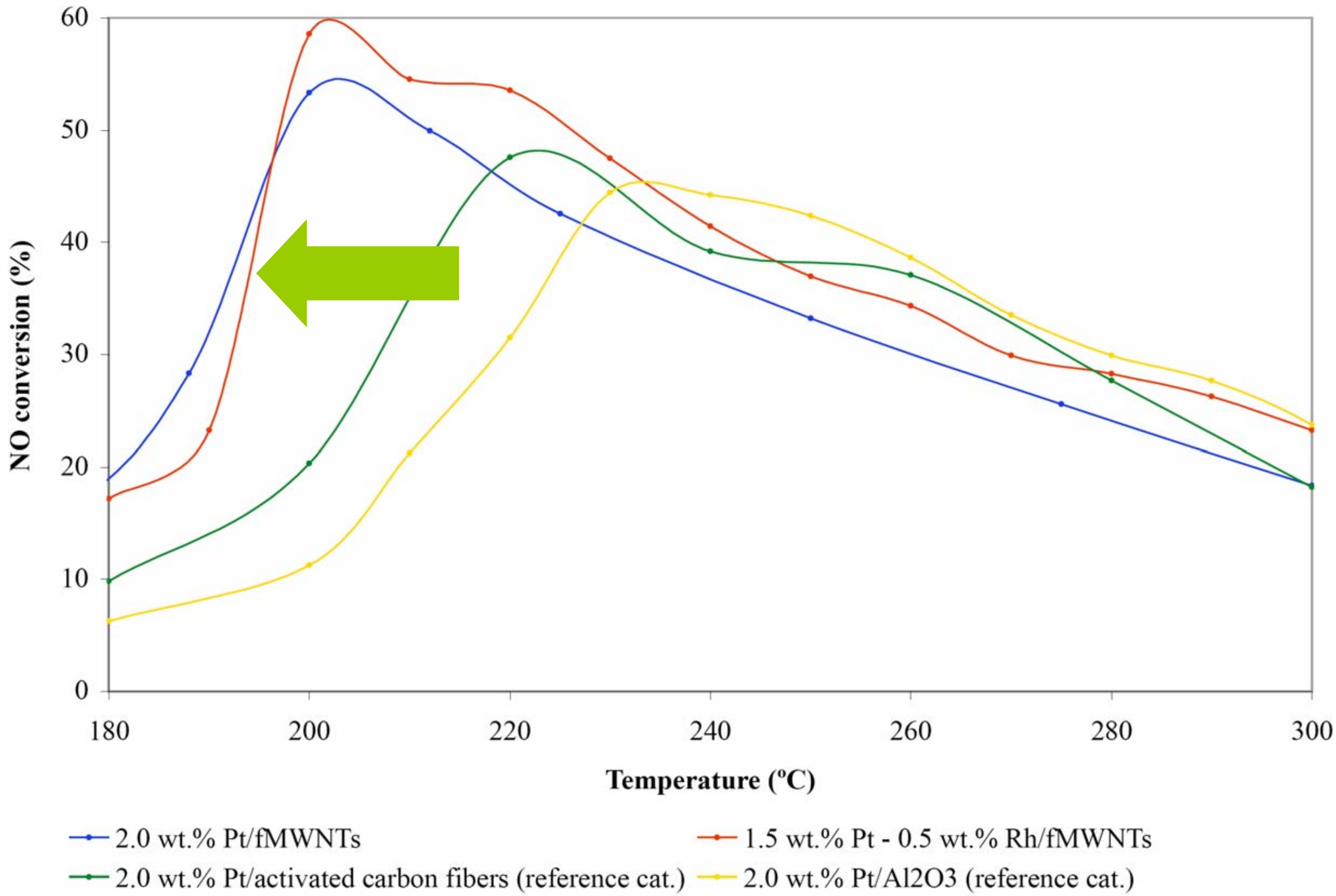






- **Multiwalled carbon nanotubes (MWNTs) for development of lean NOx catalysts (HC-SCR)**
  - **MWNT growth on steel monolith**
  - **Functionalization of the monolith-grown MWNTs prior to precious metal deposition**
- **University of Kentucky (Mark Crocker *et al*)**
  - **Coordinating Research Council (CRC) sponsoring U of K**

MWNTs Offer Improved Low Temp Performance



- **Bench flow reactor results show higher NOx conversion at lower temps**
- **Feed: 500 ppm NO, 500 ppm C_3H_6, 10% O_2, 10% H_2O (SV=50k/hr)**

Engine Platform Evolution

•More modern engine
•Platform for DOE efficiency and combustion studies

Diesel Platform:
GM 1.9-l engine with aftertreatment controls

Current Platform:
Mercedes 1.7-l
with modern components and controls

Lean Gasoline Platform:
Still being defined

•Representative of gasoline engine evolution
•Opportunity for more petroleum savings

Summary

- **Relevance**

  Improved understanding of emission control technologies and their interactions with advanced combustion techniques is critical to enabling greater use of high efficiency lean-burn engines

- **Approach**

  Multi-cylinder engine-based experiments with advanced diagnostic tools, model and MECA-supplied catalysts

- **Accomplishments**
  - **Synergies of LNT and HECC combustion exist for low temperatures where HECC feasible, but CO/HC emissions and EGR fouling issues are a concern**
  - **Ce LNT investigated on bench flow reactor shows low deSulfation temperature**

- **Collaboration**

  Working closely with industry, other labs, and CLEERS LNT focus group.

- **Future Research**
  - **Continue LNT research with Ce-based LNT and PGM loading study**
  - **Study urea SCR, HC-SCR, and DOCs for multimode combustion**

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