Synergies of High-Efficiency Clean Combustion and Lean NOx Trap Catalysts

Jim Parks, Shean Huff, Mike Kass, and Vitaly Prikhodko

Oak Ridge National Laboratory

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Gurpreet Singh, Ken Howden, and Steve Goguen
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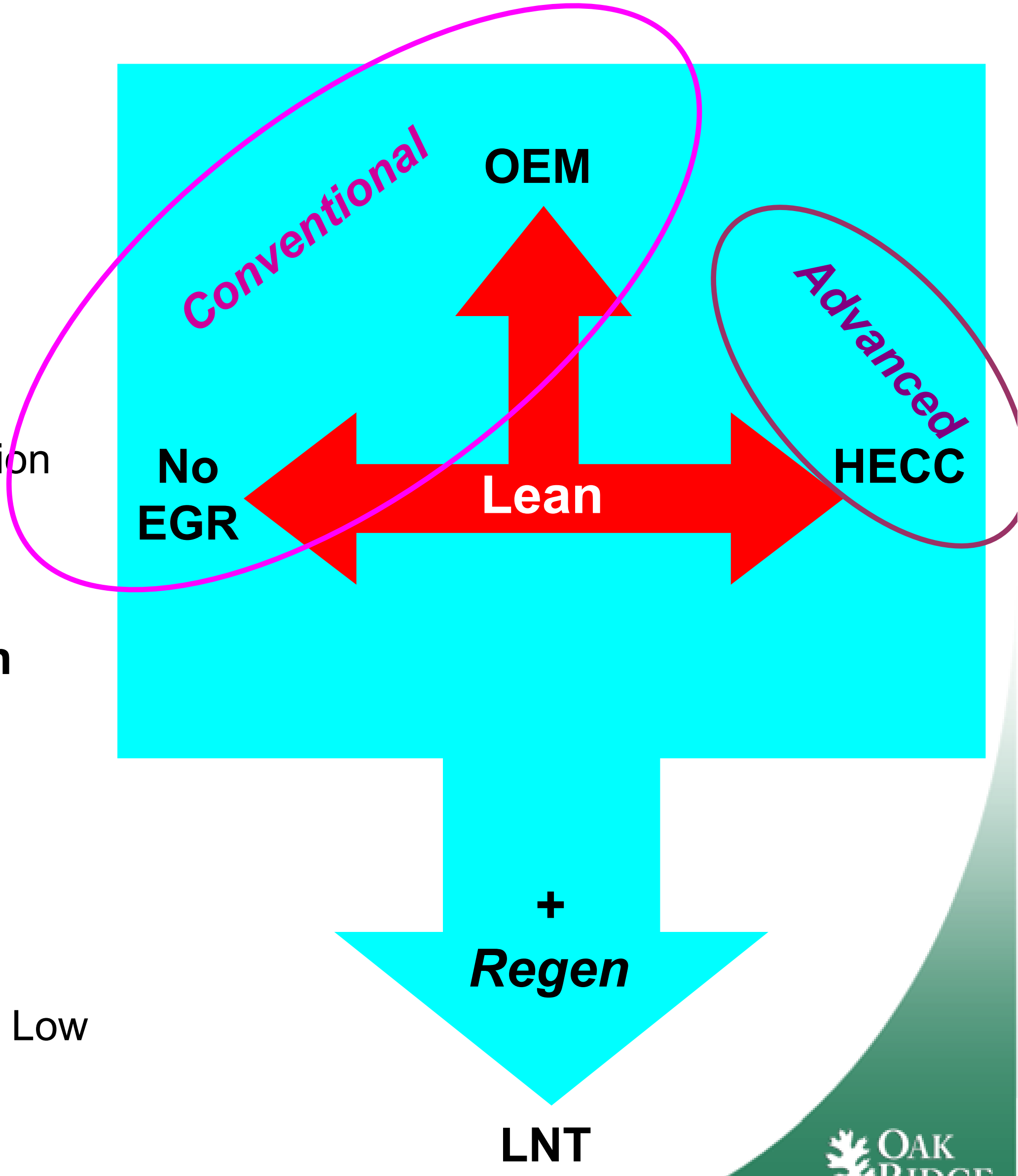
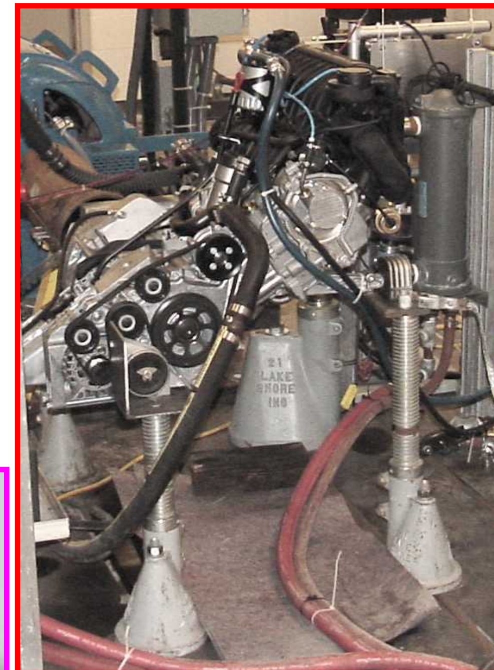
What are synergies between HECC combustion and lean aftertreatment?

<u>**Lean Combustion Modes:**</u>

- **No EGR:**
  - no EGR, lean combustion
  - low PM and CO/HCs, high NOx
- **OEM (EGR):**
  - OEM EGR level (10-30%) and injection timing
  - moderate PM, NOx, and CO/HCs
- **High Efficiency Clean Combustion (HECC):**
  - PCCI-type combustion
  - high EGR level (40-50%), advanced timing, higher fuel rail pressure
  - low PM and NOx, high CO/HCs
  - HECC efficiency closer to OEM than Low Temperature Combustion (LTC)

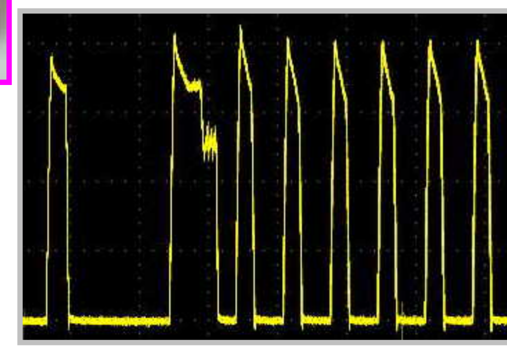


Experimental Setup



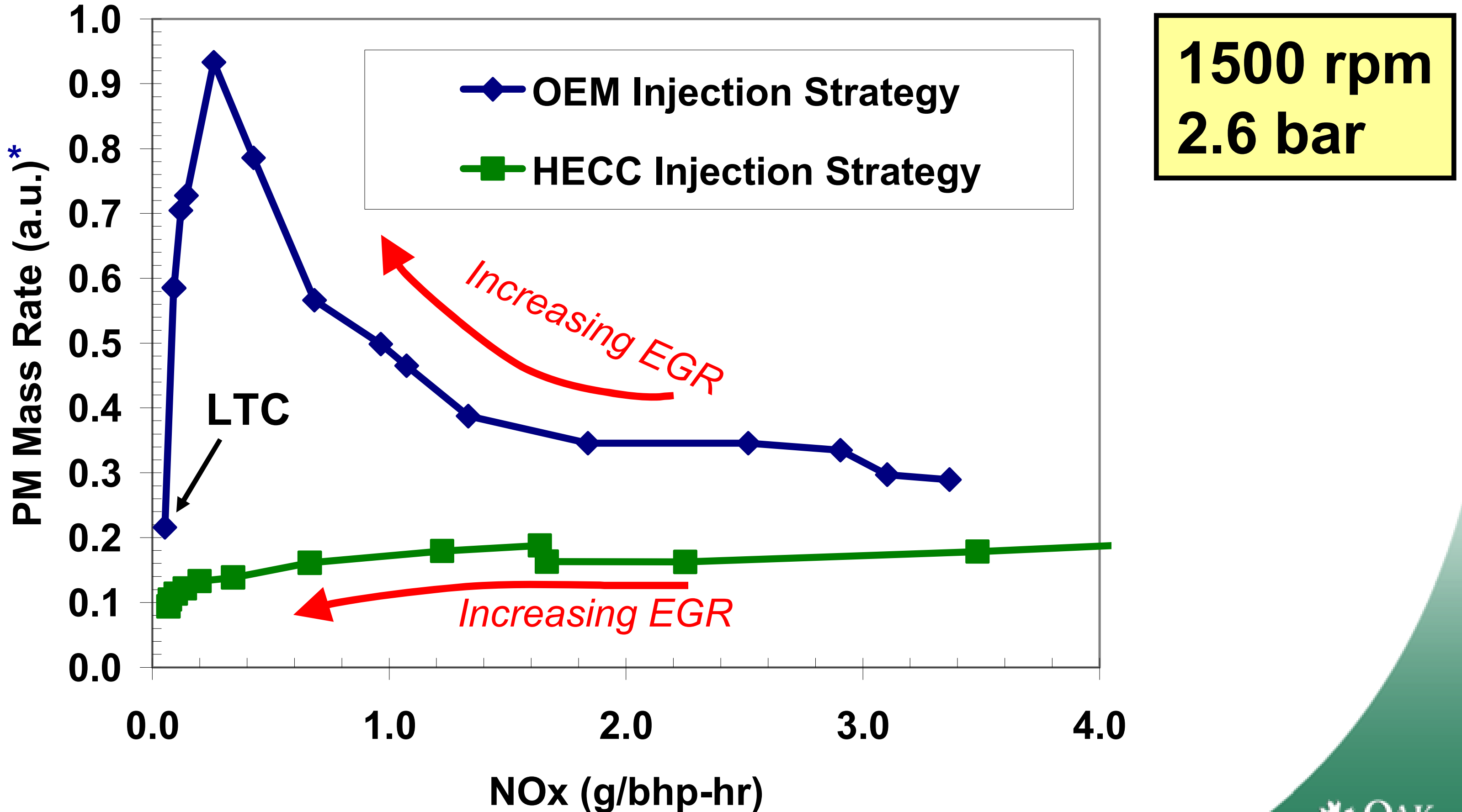
- **Engine:**
  - 1.7-liter, 4-cylinder
  - Variable Geometry Turbo
  - Upgraded Exhaust Header
  - Model-Based Full-Pass Control System
  - Advanced Fuel Injection Capabilities
  - Electronic Intake Throttling Valve
  - Electronic Solenoid Controlled EGR

- **Catalyzed Diesel Particulate Filter:**
  - SiC Substrate, Catalyzed
  - OEM stock component (Euro vehicle)
- **Lean NOx Trap Catalyst:**
  - Supplied by Manufacturers of Emission Controls Association (MECA)
  - ~100 g/ft3 PGM, 2.47 liters (1.5 ESV)



HECC Enables Low PM and NOx

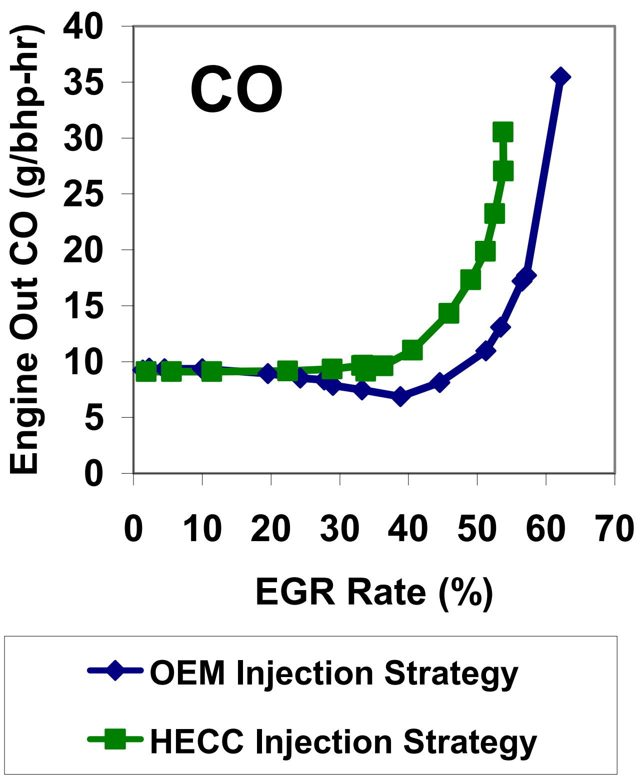
- EGR sweep conducted with OEM and HECC injection parameters
  - NOx-PM tradeoff curve shown
- HECC enables low PM emissions across span of EGR rates
- Less sensitivity of PM emissions to EGR rate for HECC is an advantage for PM control



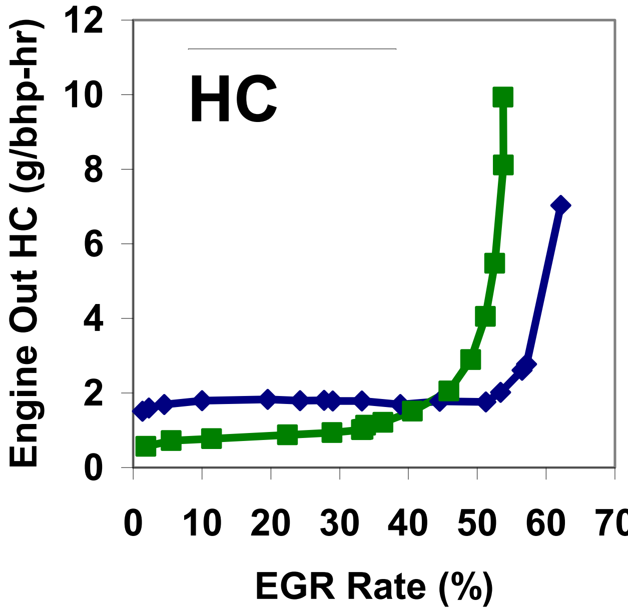
PM measurement is opacity-based

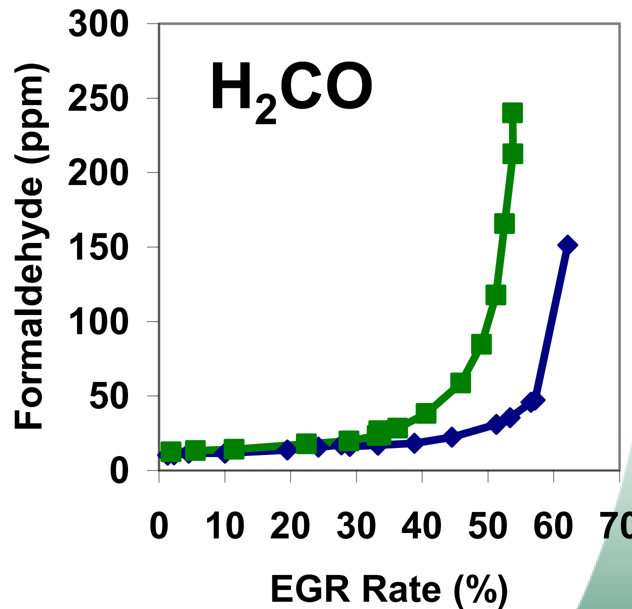
Downside of HECC is Higher HC and CO Emissions

- 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 SAE 2008-01-2431
- Catalytic oxidation of these emissions dependent on temperature



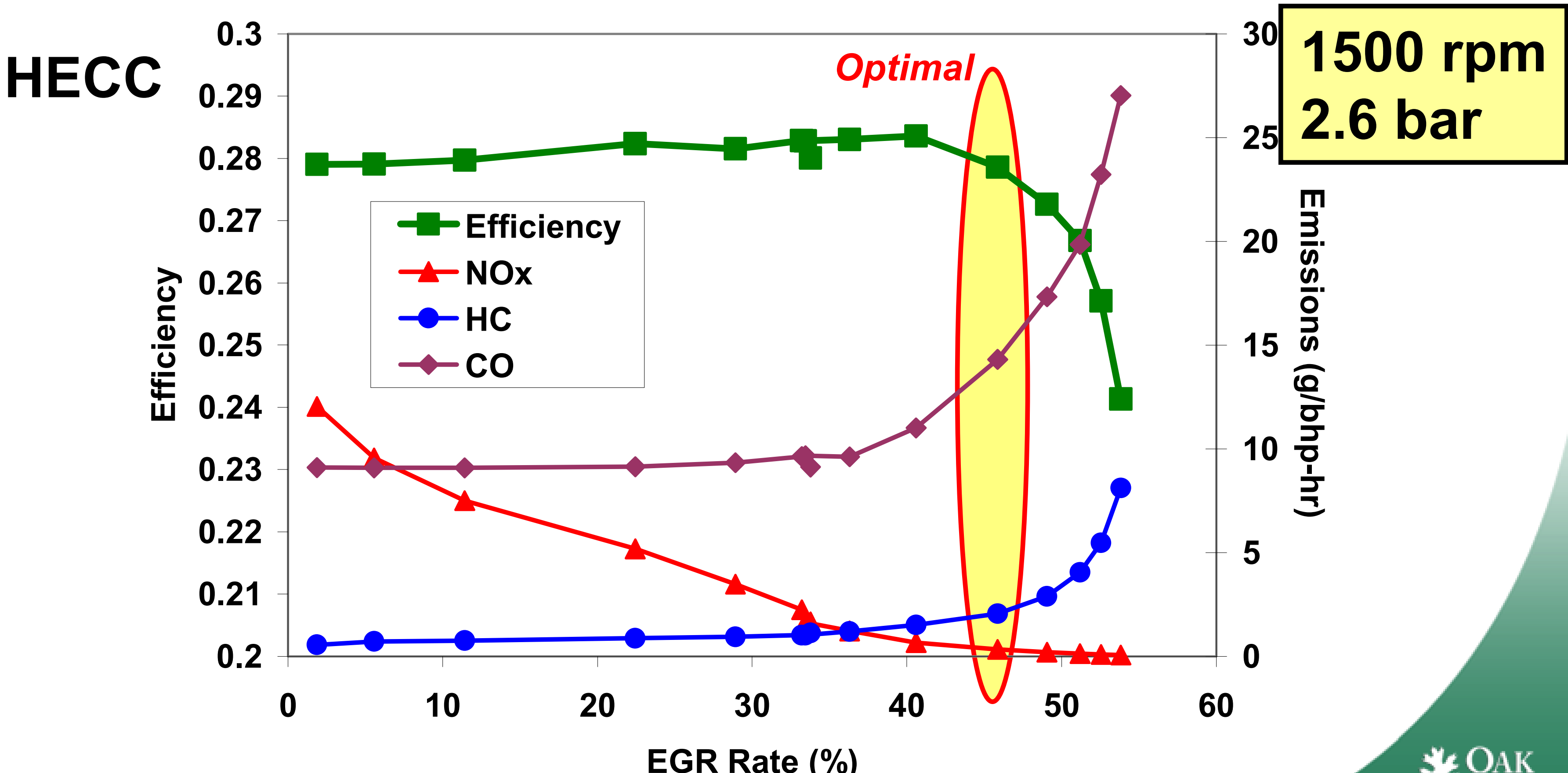
1500 rpm
2.6 bar





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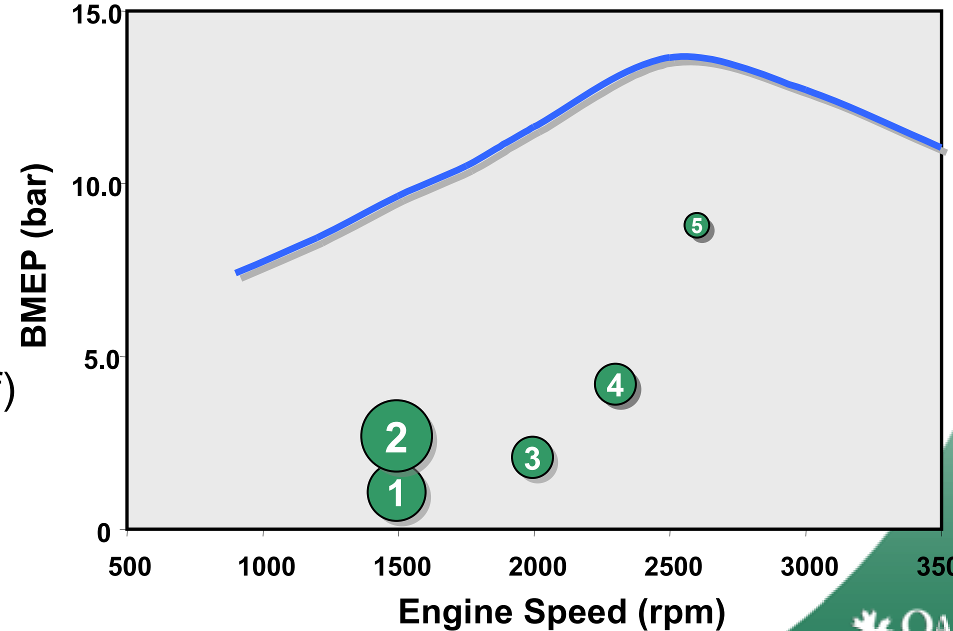
Experiments made use of engine conditions developed by Ad Hoc Working Group

Point	Speed / Load	Weight Factor	Description
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.**



References:

- SAE 1999-01-3475 (Kenney)
- SAE 2001-01-0148 (Szymkowicz, French, Crellin)
- SAE 2001-01-0151 (Kenney *etal*.)
- SAE 2001-01-0650 (Hilden, Eckstrom, Wolf)
- SAE 2002-01-2884 (Natarajan *etal*.)
- SAE 2006-01-3249 (Amann)
- SAE 2006-01-3311 (Sluder, Wagner)

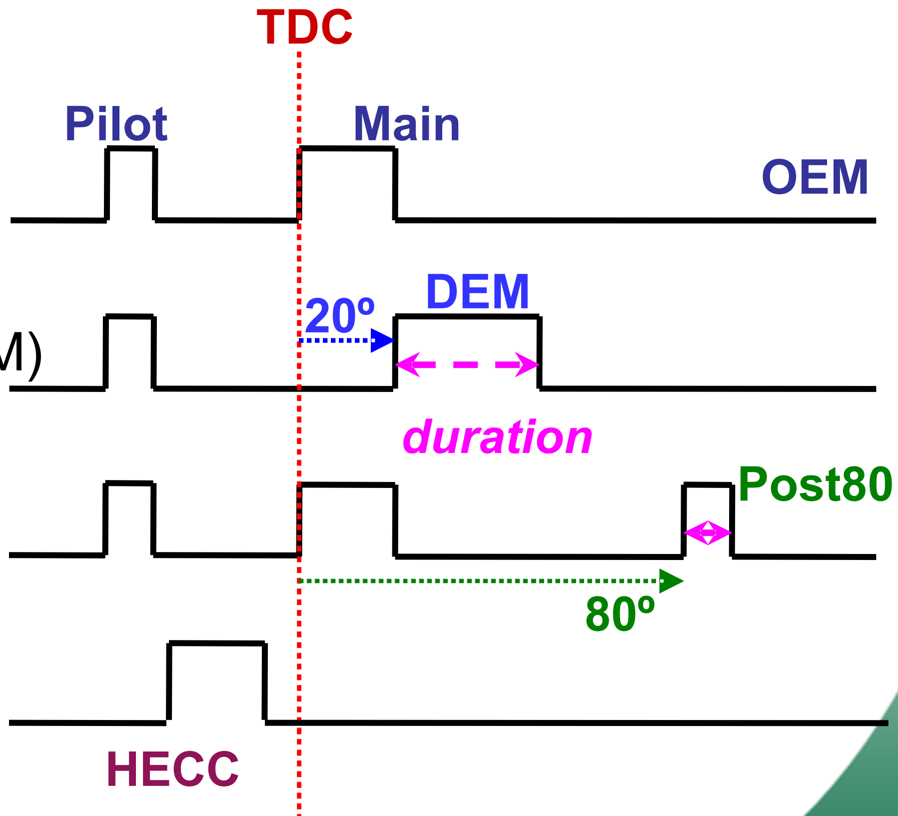
Regeneration Performed with Combination of O_2 Reduction and Fuel Enrichment Techniques

O_2 Reduction:

- **Throttle**
- **EGR**

Fuel Enrichment

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

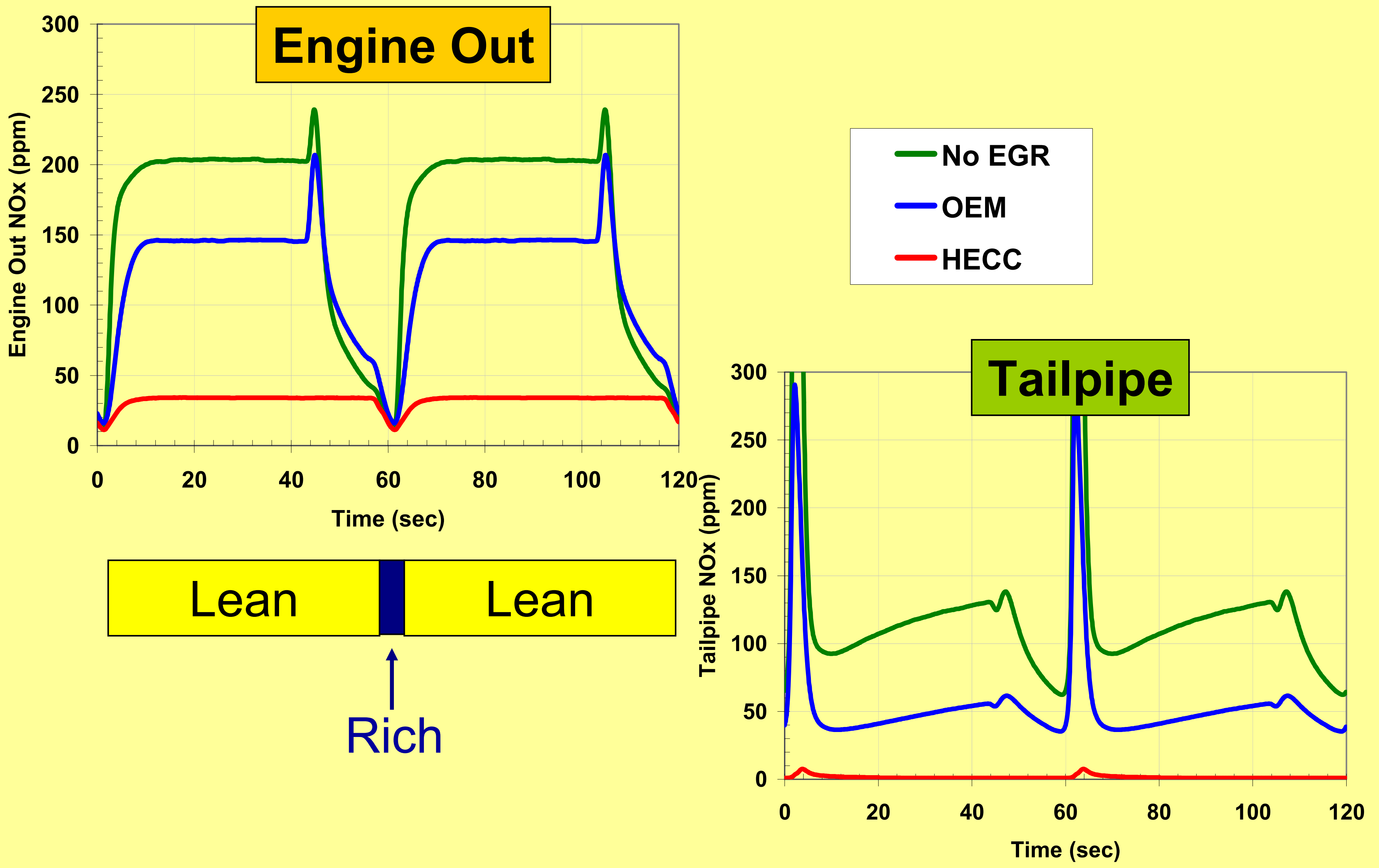


Regeneration Approach for SS Conditions

Point	Speed / Load	SV (/hr)	LNT Temperature (°C)	Modes	Regeneration Technique
1	1500 rpm / 1.0 bar	11,400-19,800	128-142	No EGR, OEM, HECC	EGR and Throttle w/ HECC and DEM Enrichment
2	1500 rpm / 2.6 bar	11,800-21,300	244-258	No EGR, OEM, HECC	EGR and Throttle w/ HECC Enrichment
3	2000 rpm / 2.0 bar	14,700-31,500	242-282	No EGR, OEM, HECC	EGR and Throttle w/ HECC Enrichment
4	2300 rpm / 4.2 bar	38,200-39,200	354-366	No EGR, OEM	Throttle w/ DEM Enrichment
5	2600 rpm / 8.8 bar	39,500	485	No EGR	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



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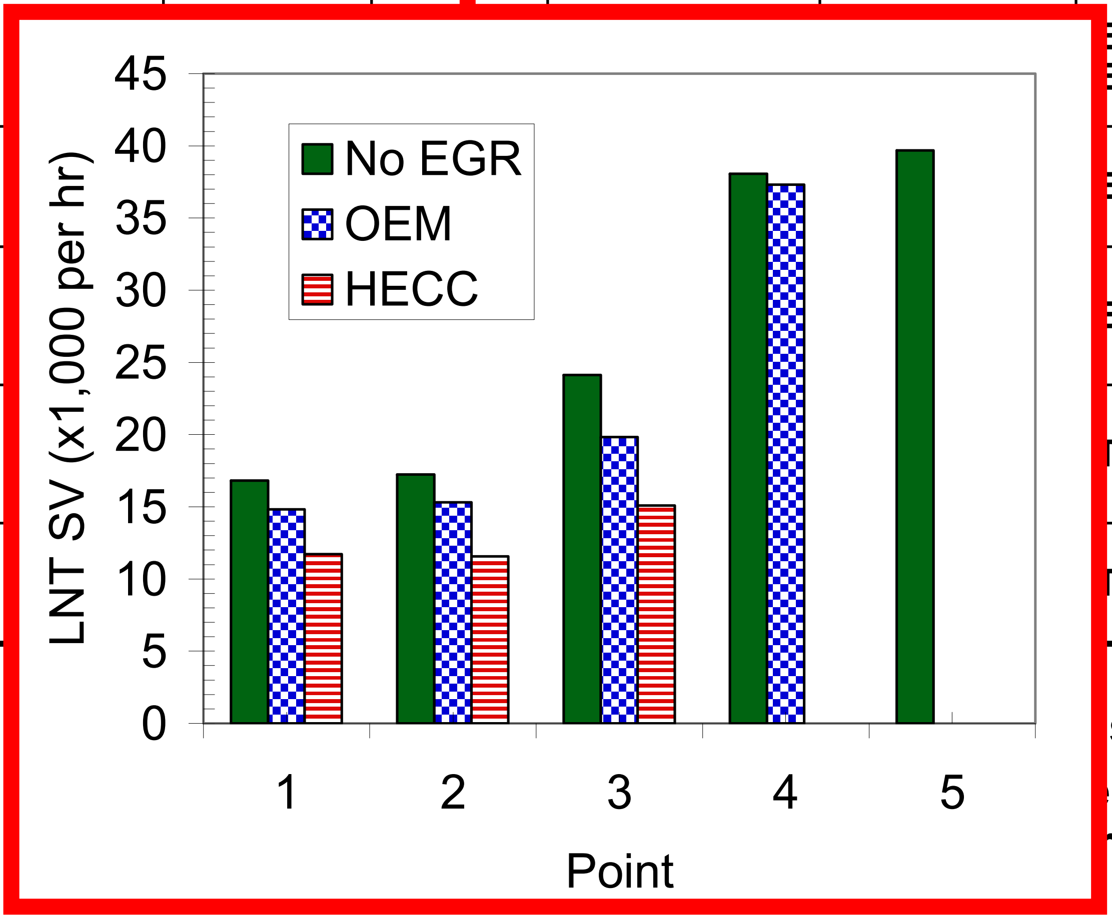

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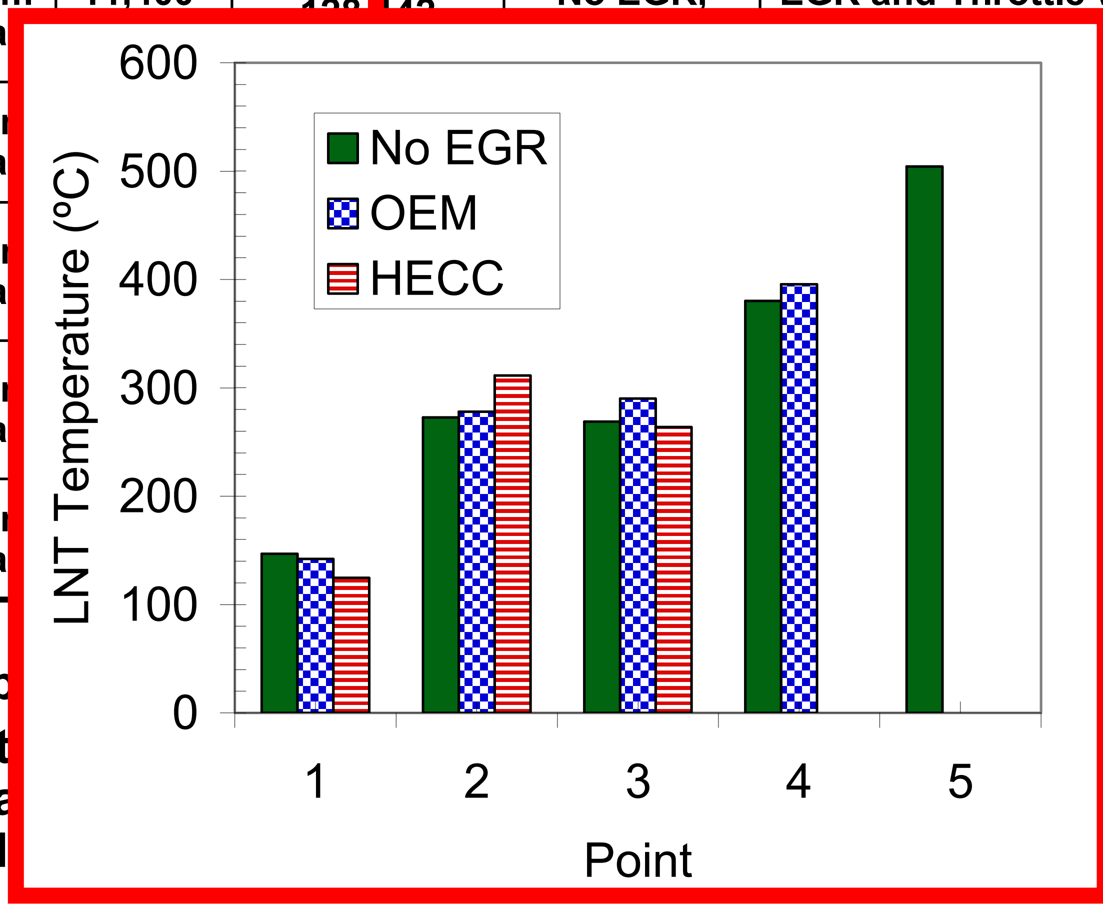
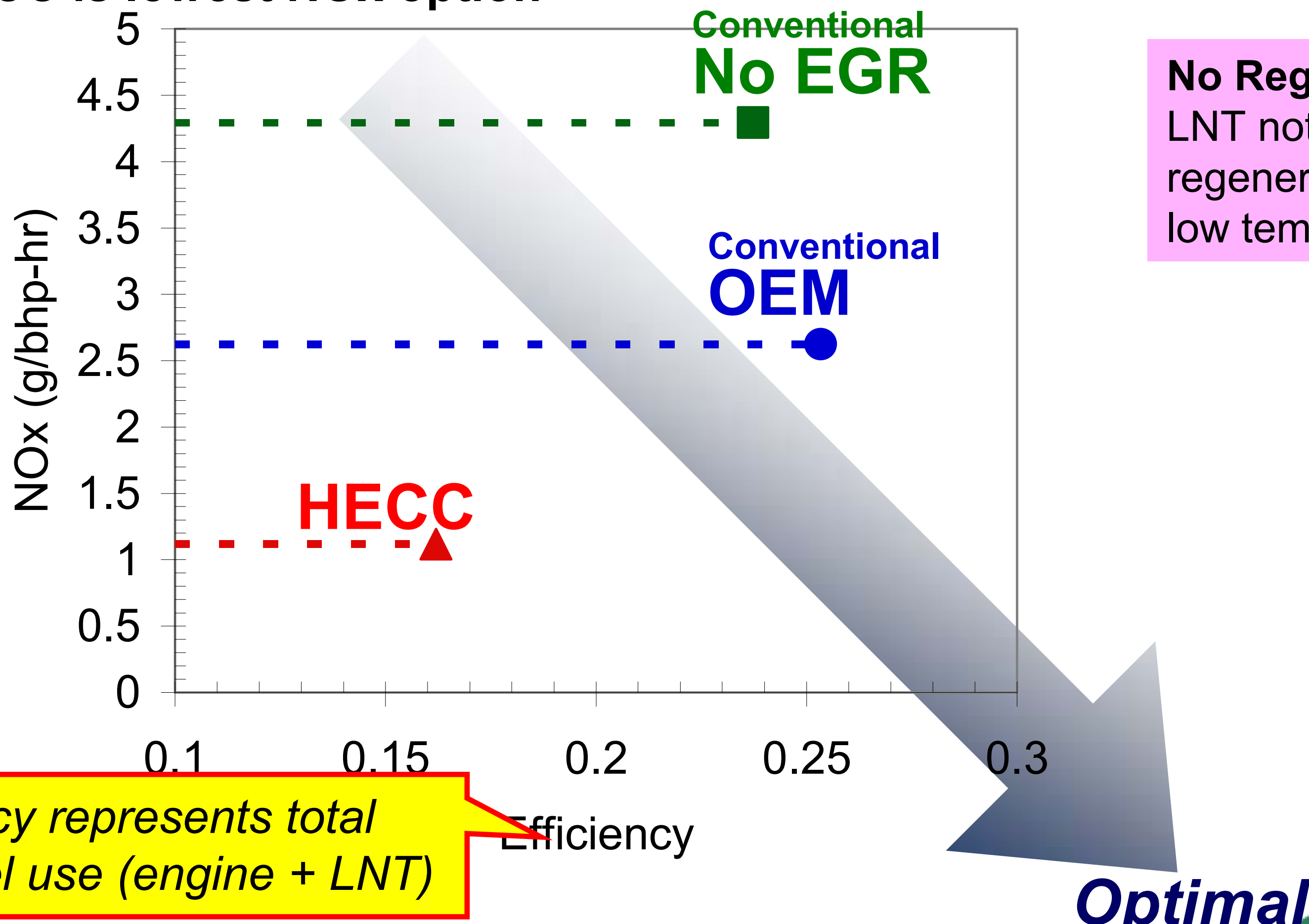
5	2600 rp / 8.8 ba				Enrichment



- LNT temp
- Steady-st ... rature during tra ... ations observed

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

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

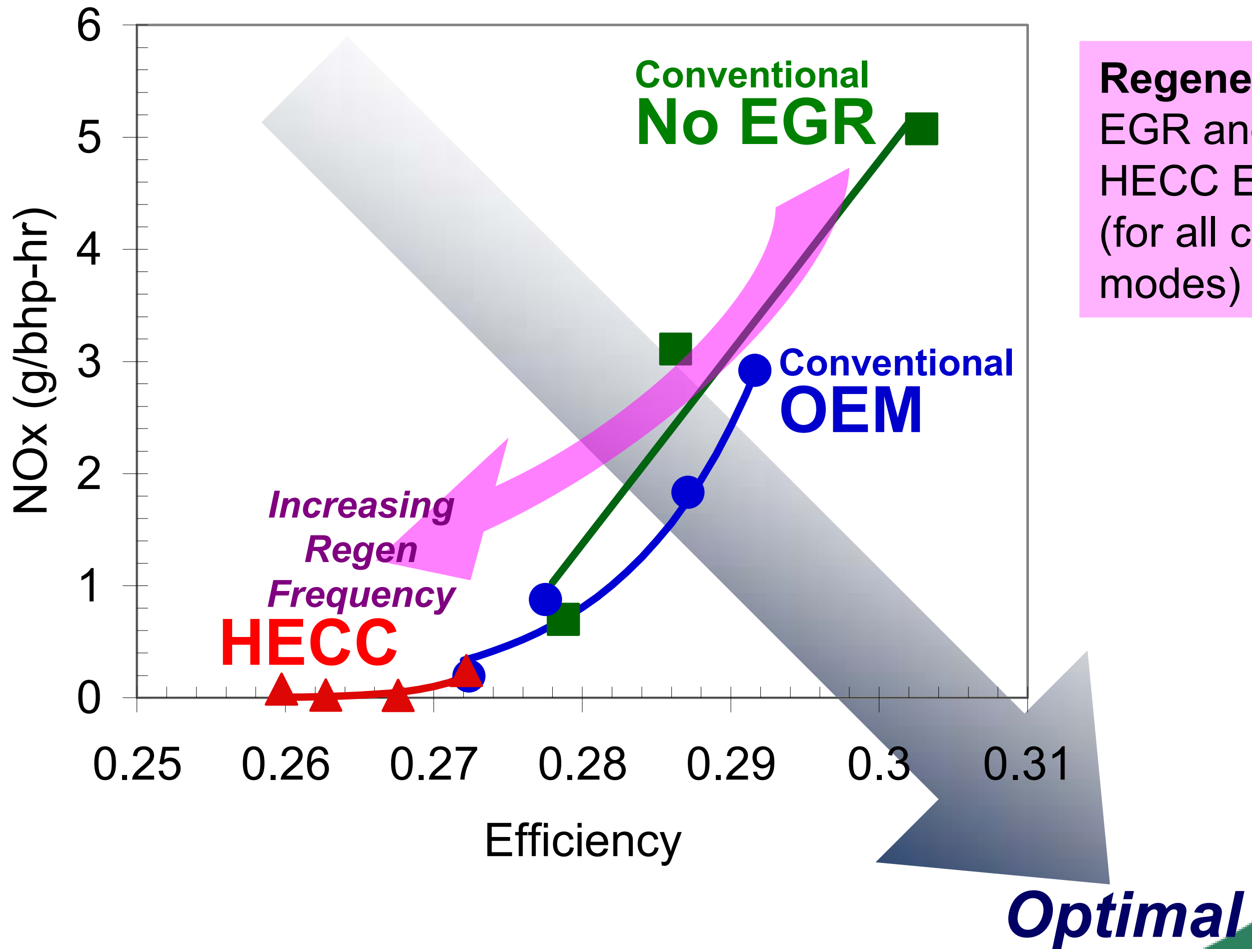


No Regeneration: LNT not capable of regeneration due to low temperatures

Efficiency represents total system fuel use (engine + LNT)

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

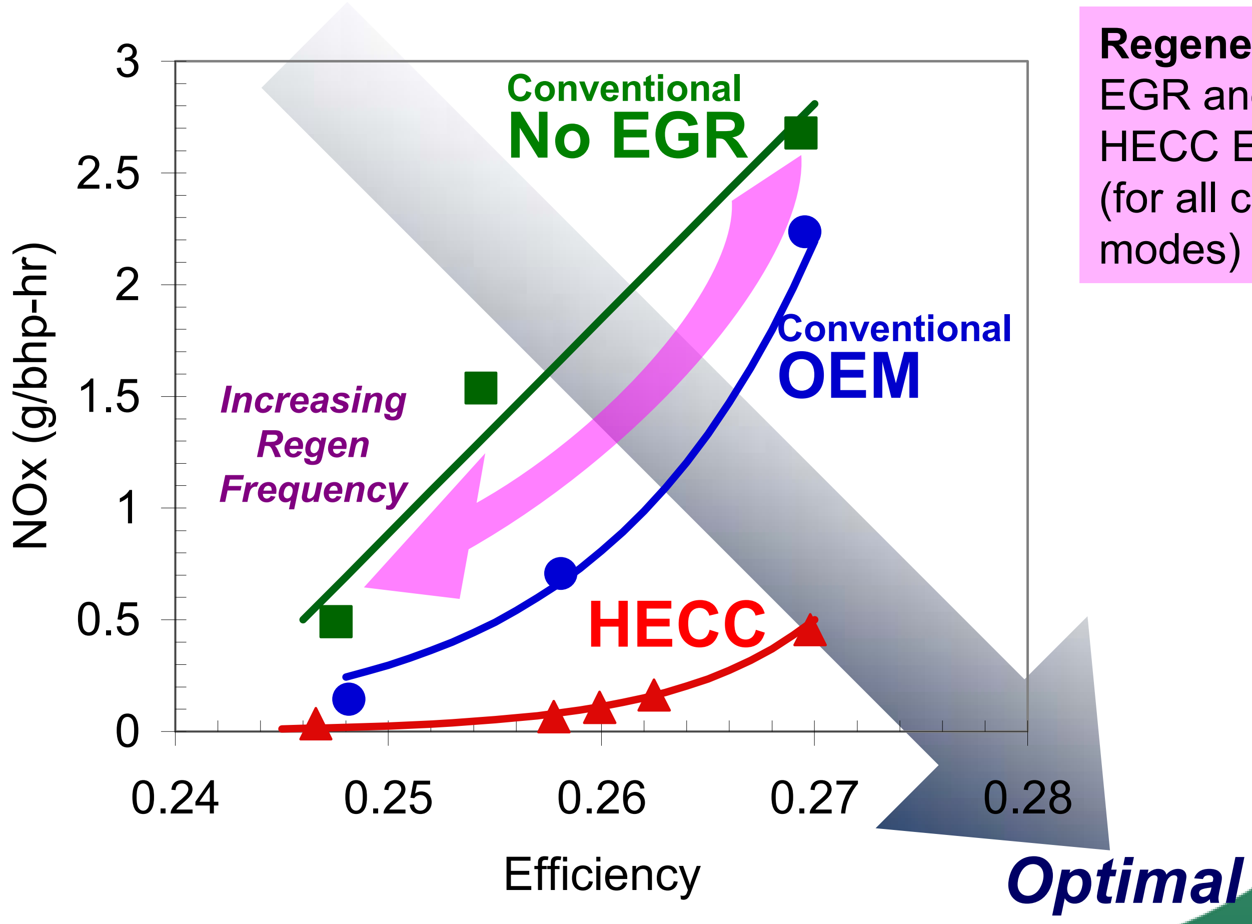
- **OEM and HECC effective at achieving low NOx levels**



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

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

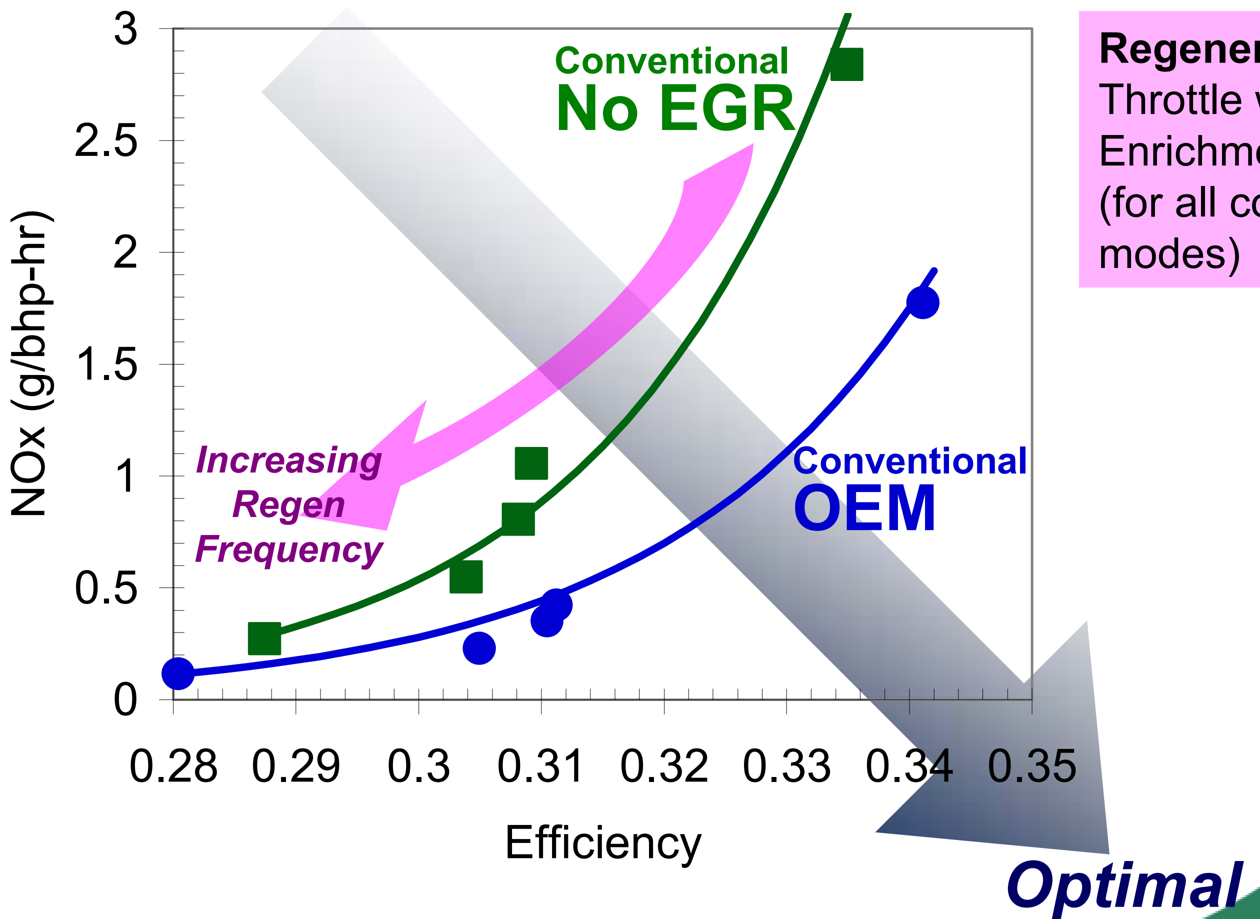
- HECC shows optimal results; OEM also good with frequent regen
- HECC benefits from higher LNT temperature and lower SV
- Efficiency of HECC remains high at steady state as exhaust temperatures are more stable



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

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

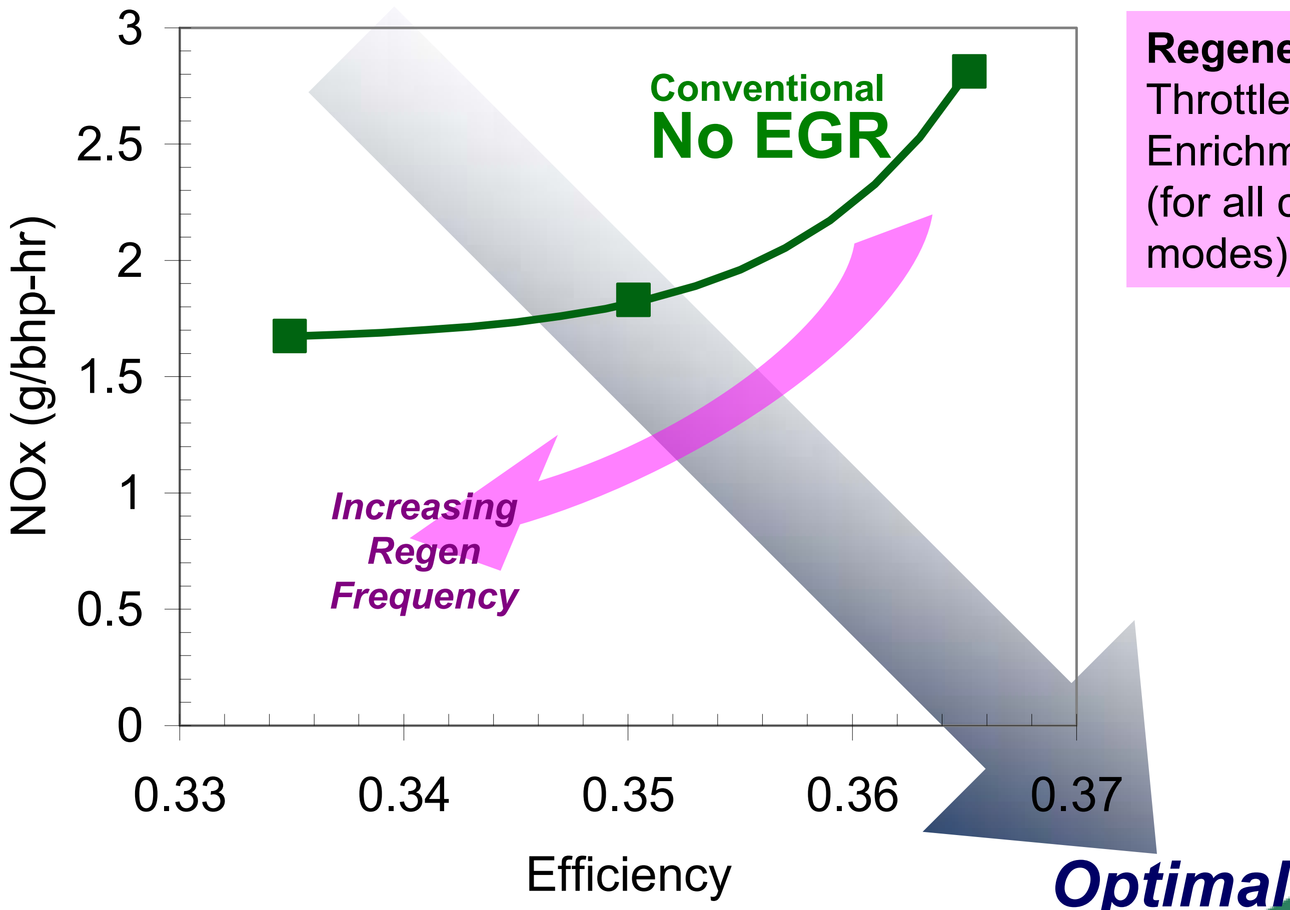
- **OEM (EGR) more efficient than "No EGR" mode at low NOx levels**
- **HECC not attained at condition #4**



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

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

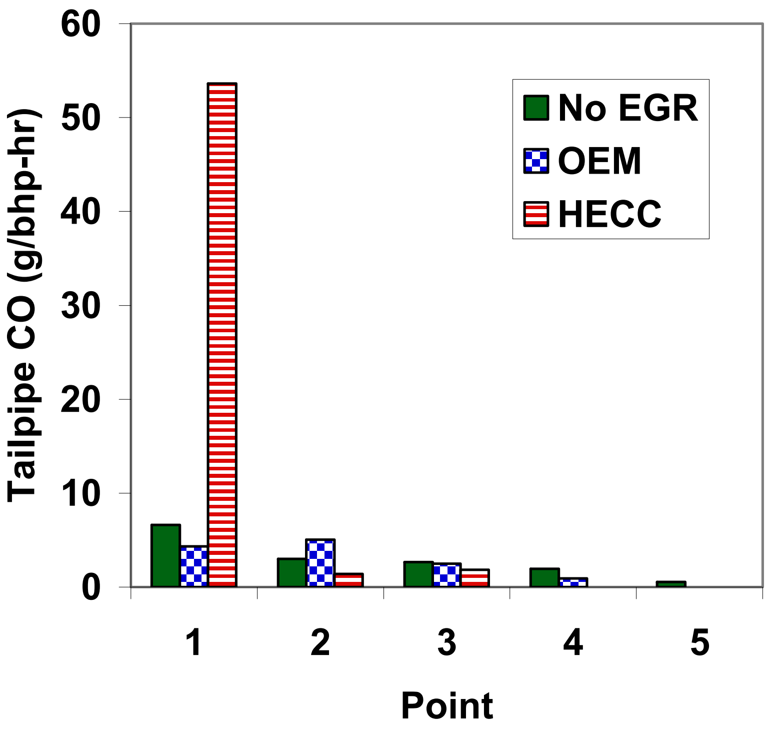
- **No EGR mode is only option explored at higher load**
- **Optimization occurs at midpoint of curve**

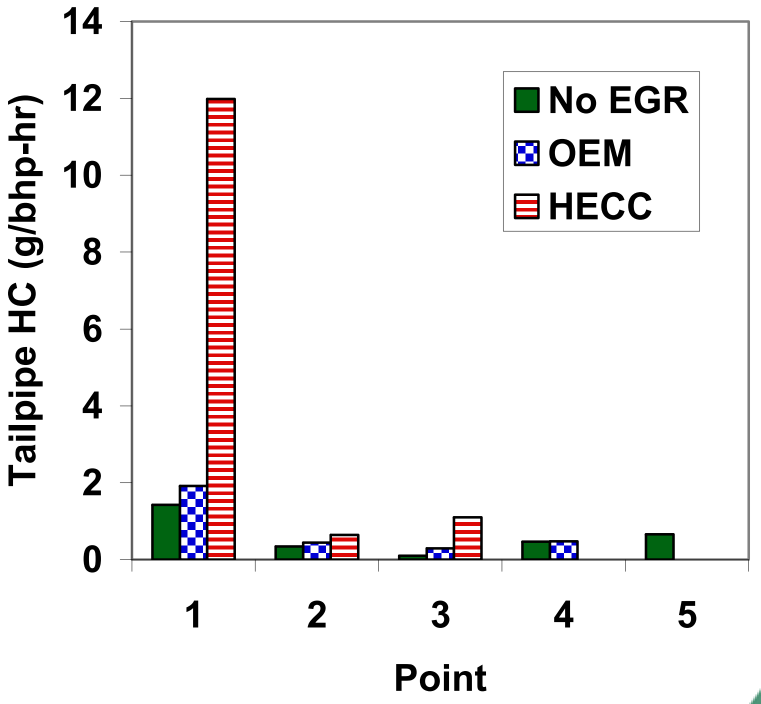


Regeneration:
Throttle w/ Post80 Enrichment
(for all combustion modes)

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





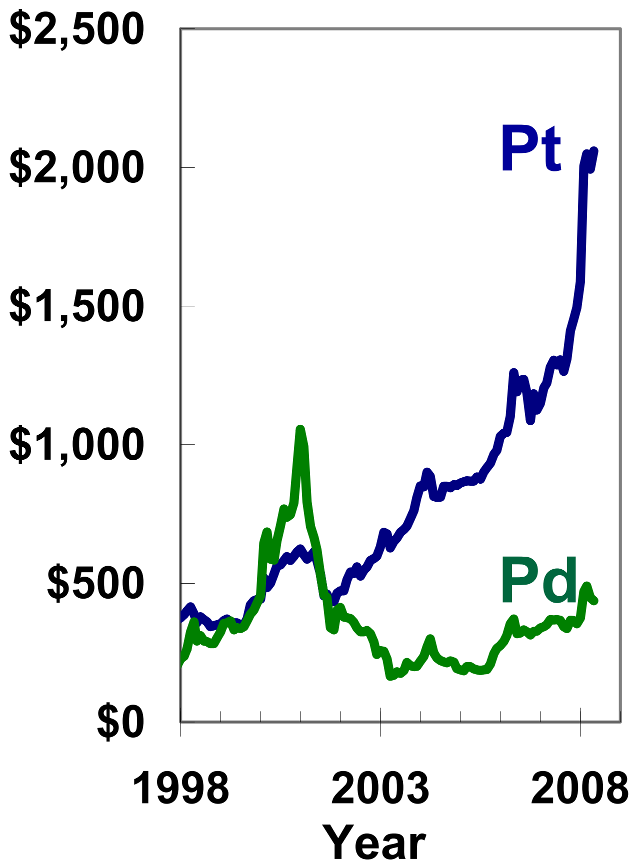
Bad EGR Chemistry Detriment to System

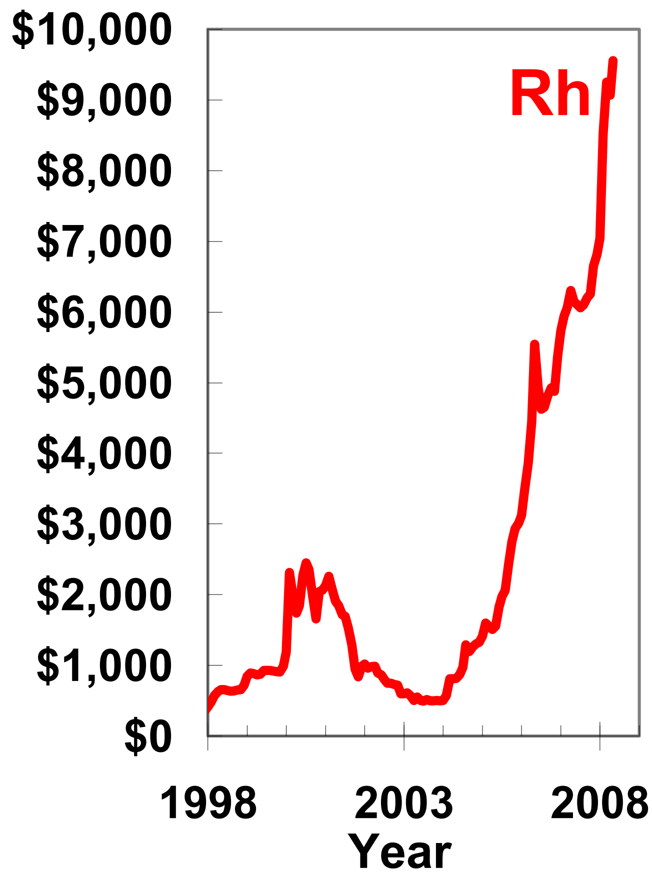
- **High EGR rate combined with heavy hydrocarbons and soot in cool system lead to problematic deposits in EGR system**
- **Multiple cases of EGR valve failure and EGR loop fouling observed during experiments**
- **Especially problematic at lowest exhaust temperatures**

Tar-like deposits removed from EGR system

PGM Costs: HECC May Mitigate Impact

Historic cost per Troy Ounce from www.platinum.matthey.com (JohnsonMatthey)

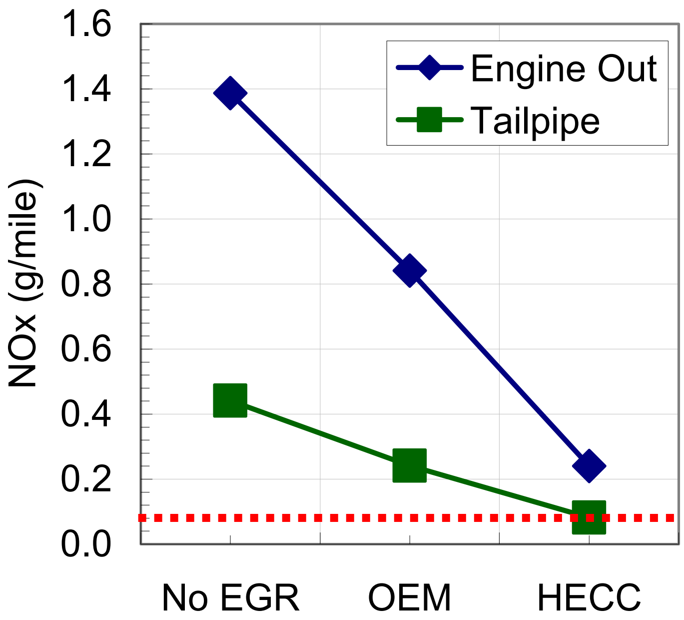




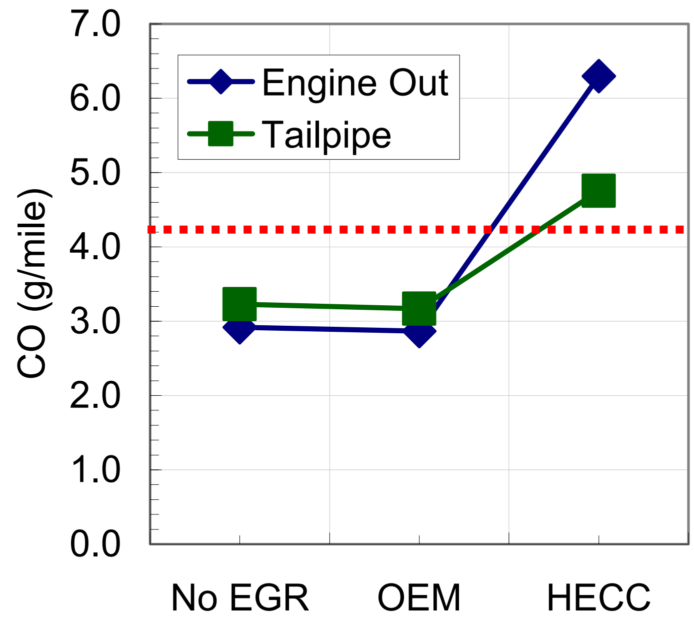
- **Platinum Group Metal (PGM) costs have risen dramatically in last 10 years**
  - **Pt is ~5x 1998 value**
  - **Rh is ~10x 1998 value**

- **HECC may mitigate impact of rising PGM costs by alleviating performance impacts on LNT catalyst**
  - **But, higher CO and HC emissions must still be controlled**

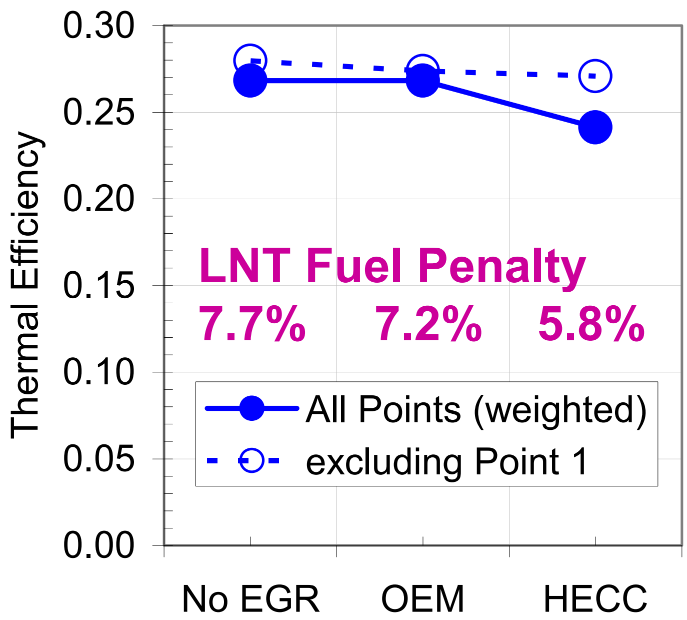
HECC Enables Lowest NOx Emissions and Reduces LNT Impact on Fuel Efficiency



Tier 2 Bin 5 Level in Red



- **HECC lowers NOx level, but CO level increased**
- **Weighted efficiency for HECC drops slightly due to lowest load point**



All Results from Weighted Average To Estimate FTP Emissions

HECC and LNT Technology Synergies: Summary

- NOx reduction from the combination of HECC combustion and LNT aftertreatment is excellent at low temperatures
- 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
- HECC adds option of shifting emission reduction burden to engine (from catalyst system) to reduce catalyst costs

Thank You for Your Attention!