Impact of PCCI on LNT performance

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May 13, 2008

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U.S. Department of Energy, Office of Vehicle Technologies

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This work is undertaken to investigate the potential synergies of an advanced combustion technique (HECC) and a lean engine catalyst technology (LNT)

- **Advanced combustion technologies enable lowering of engine out emissions**
  - Premixed Charge Compression Ignition (PCCI) creates homogeneous fuel and air mixture; thus, lowering NOx and PM emissions
    - High Efficiency Clean Combustion (HECC) is a PCCI-type combustion mode used in this study
  - Exhaust after-treatment may still be needed to keep emissions at regulatory levels
- **Catalyst technologies enable further reduction of emissions to regulated levels**
  - To reduce NOx to regulatory levels
  - To control higher CO and HC emissions associated with HECC
  - To control emissions at operating conditions where HECC is not feasible in practice

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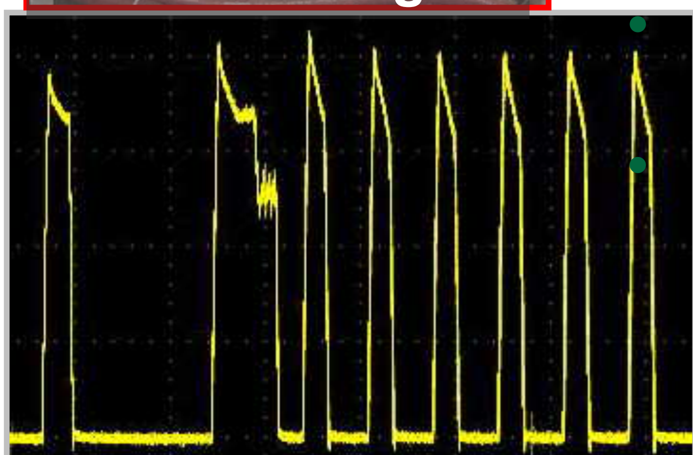
Approach: operate multi-cylinder diesel engine in multi-modes and study synergies of LNT with multimode operation

Hardware Modifications:

- Variable Geometry Turbo
- Custom Exhaust Header
- 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

Engine Control

- Model-Based Full-Pass Control System (Ricardo, VEMPS)
  - unlimited software flexibility
- Advanced Fuel Injection Capabilities
  - high pressure common rail
  - up to 8 injections per combustion event
  - no injection timing window limitations

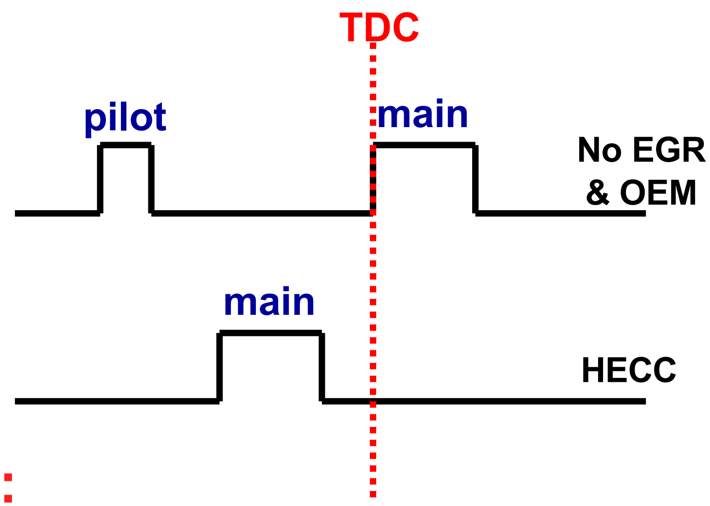


Approach: operate multi-cylinder diesel engine in multi-modes and study synergies of LNT with multimode operation

- **LNT was supplied by Manufacturers of Emissions Control Association (MECA)**
  - 400 cpsi catalyst coated substrate (proprietary formulation)
  - LNT volume = 2.47 liters
- **DPF was installed upstream of LNT**
  - Production catalyzed SiC-based wall-flow filter (stock component on a Mercedes A180 CDI vehicle which is certified to the EU4 emission standard)

Experiments were conducted by operating engine in two conventional and one advanced lean modes

- **No EGR:**
  - Contained a pilot injection pulse prior to top dead center (TDC) and a main fuel pulse near TDC
  - low PM and CO/HCs, high NOx
- **OEM (EGR):**
  - Same injection timing as in No EGR mode
  - OEM EGR level (10-30%)
  - moderate PM, NOx, and CO/HCs



- **High Efficiency Clean Combustion (HECC):**
  - No pilot pulse, main injection pulse is advanced to 8-10º before TDC, increased fuel rail pressure
  - high EGR level (40-50%)
  - low PM and NOx, high CO/HCs
  - HECC efficiency closer to OEM than Low Temperature Combustion (LTC)

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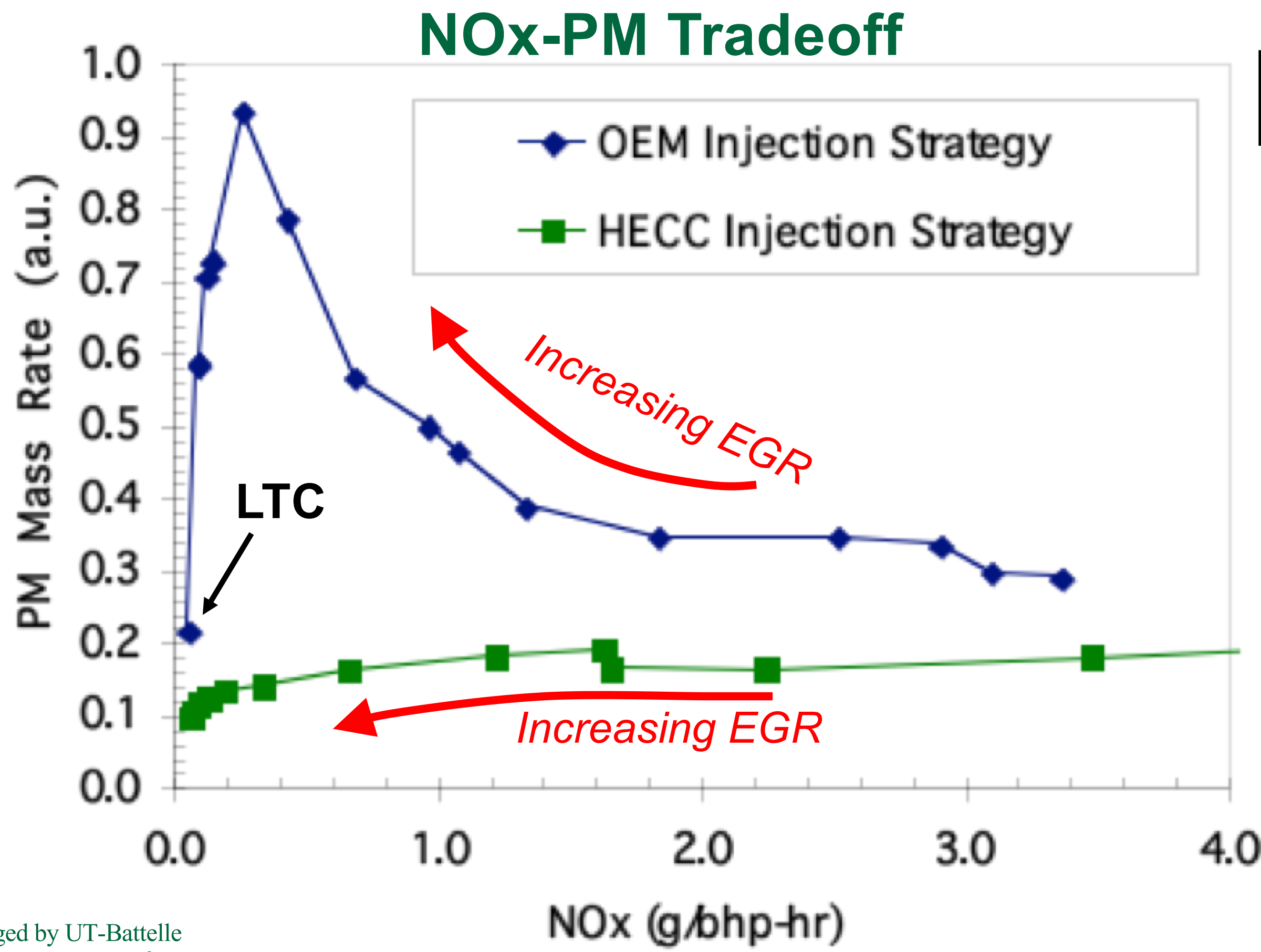
HECC Enables Low PM and NOx

- **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**

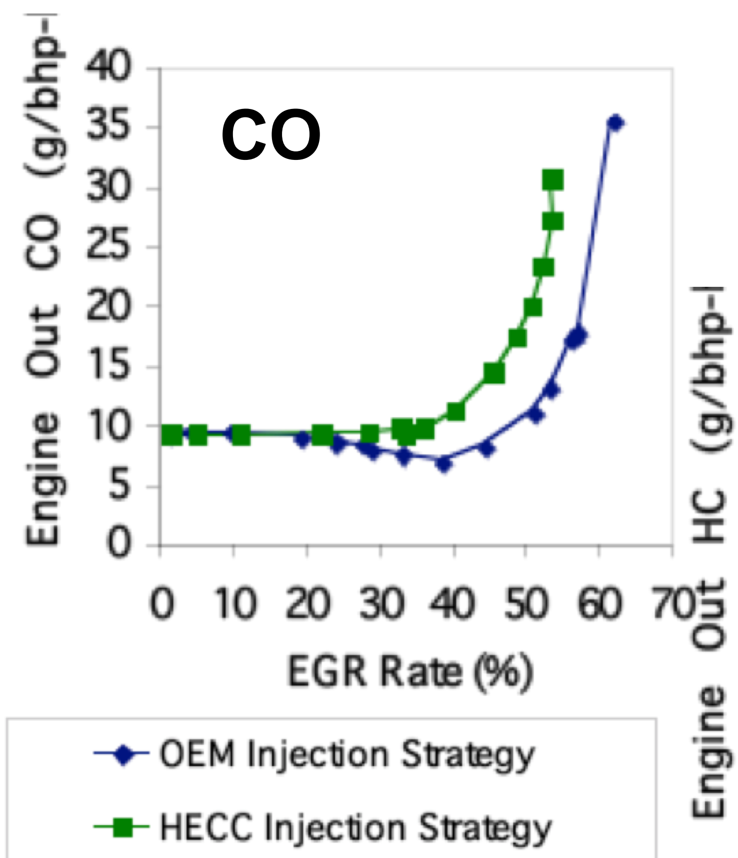


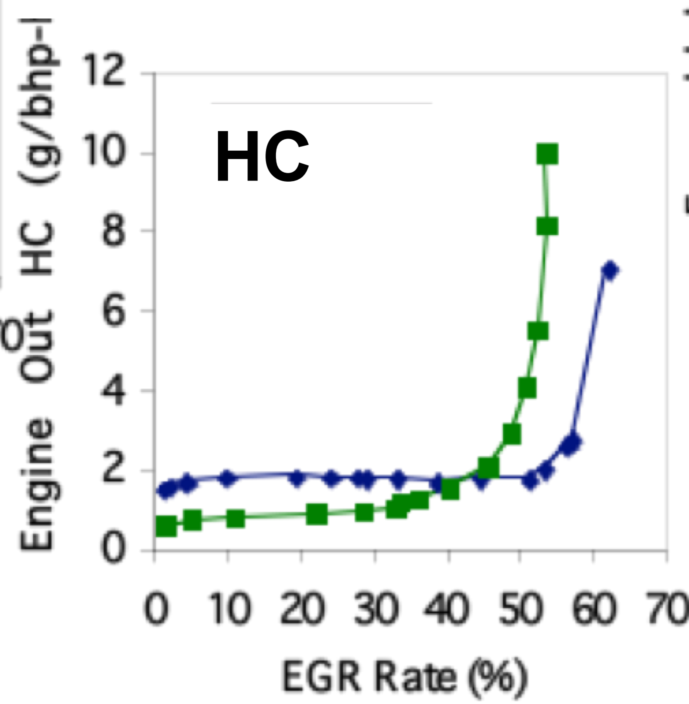
1500 rpm, 2.6 bar

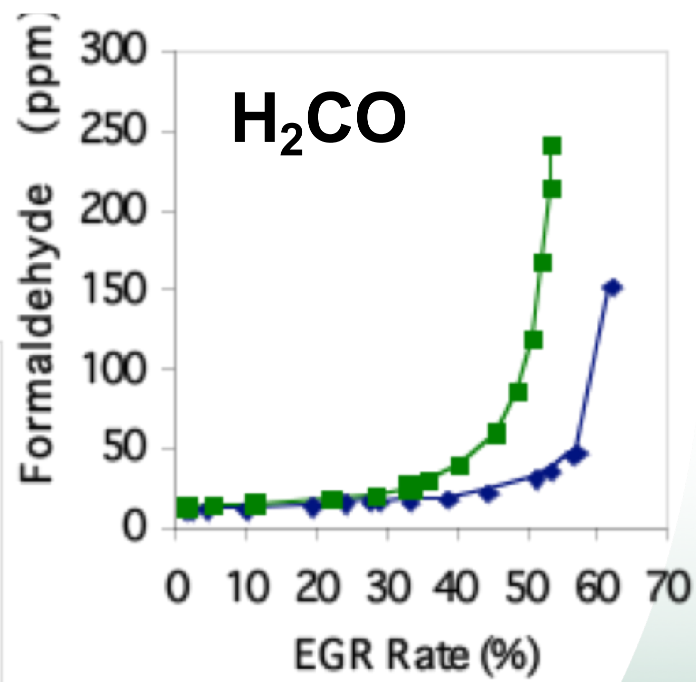
Downside of HECC is Higher HC and CO Emissions

- 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
- Catalytic oxidation of these emissions dependent on temperature

1500 rpm, 2.6 bar



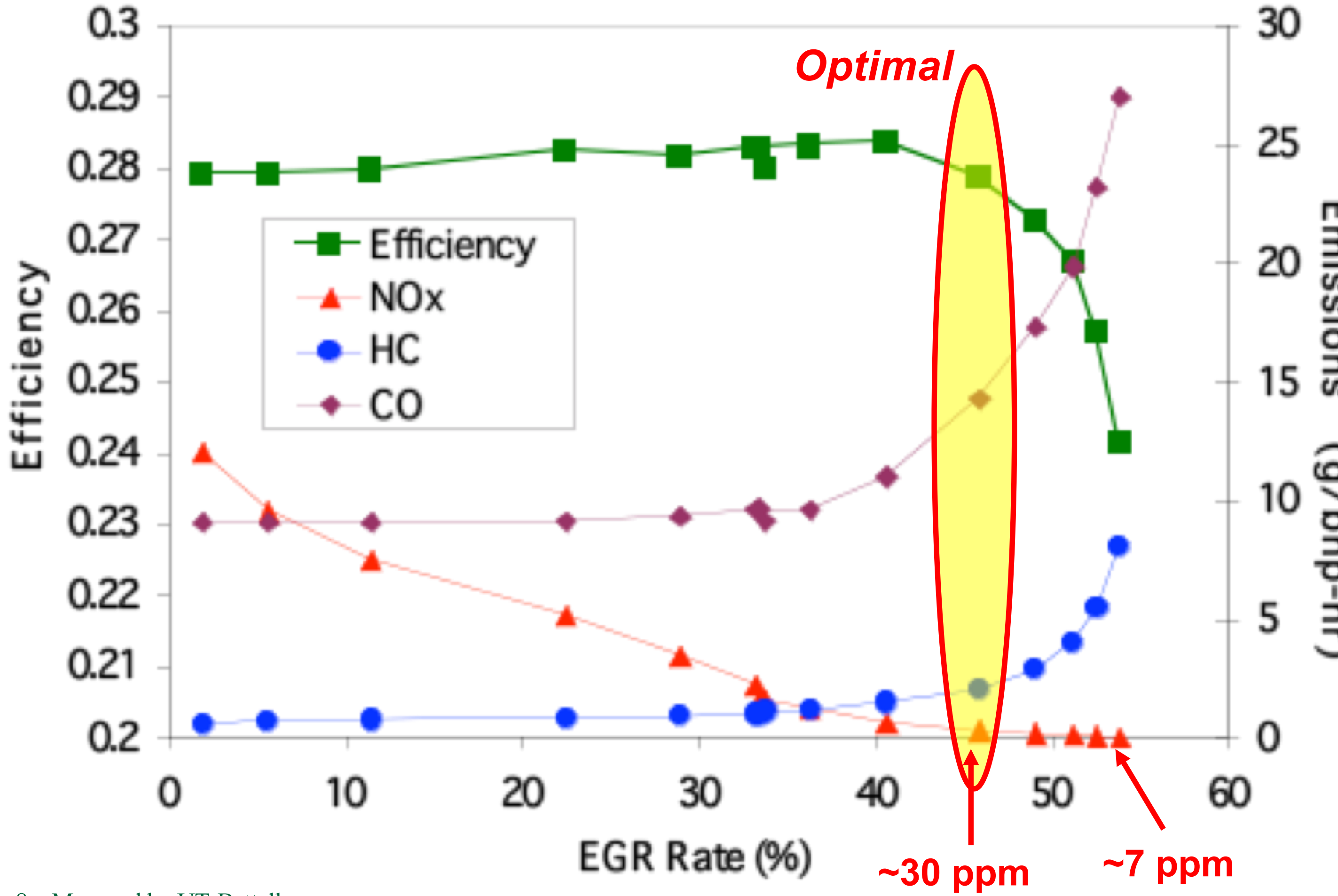




Optimization of HECC combustion is Trade-Off between Efficiency and Emissions

- **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**

1500 rpm, 2.6 bar



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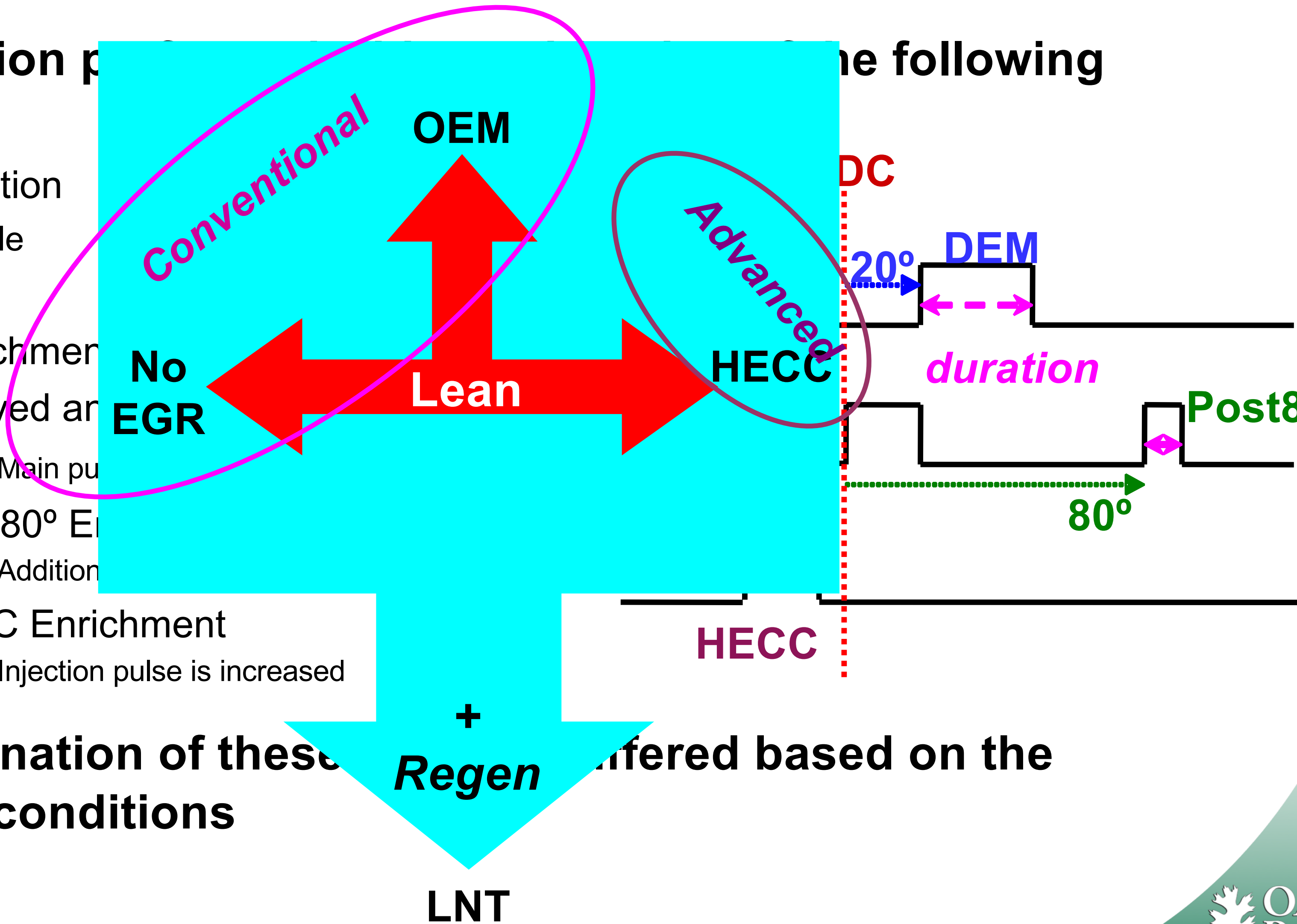
What are synergies between HECC combustion and lean NOx trap?

- **Periodically, after operating under lean conditions, LNT requires rich conditions to reduce stored NOx to N_2**
- **Regeneration p... ...he following controls**
  - O_2 Reduction
    - Throttle
    - EGR
  - Fuel Enrichmen...
    - Delayed ar...
      - Main pu...
    - Post-80º E...
      - Addition...
    - HECC Enrichment
      - Injection pulse is increased
- **The combination of these ... ...fered based on the operation conditions**



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Operating points within each mode made use of engine conditions developed by Ad Hoc Working Group

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2	CC
3	CC
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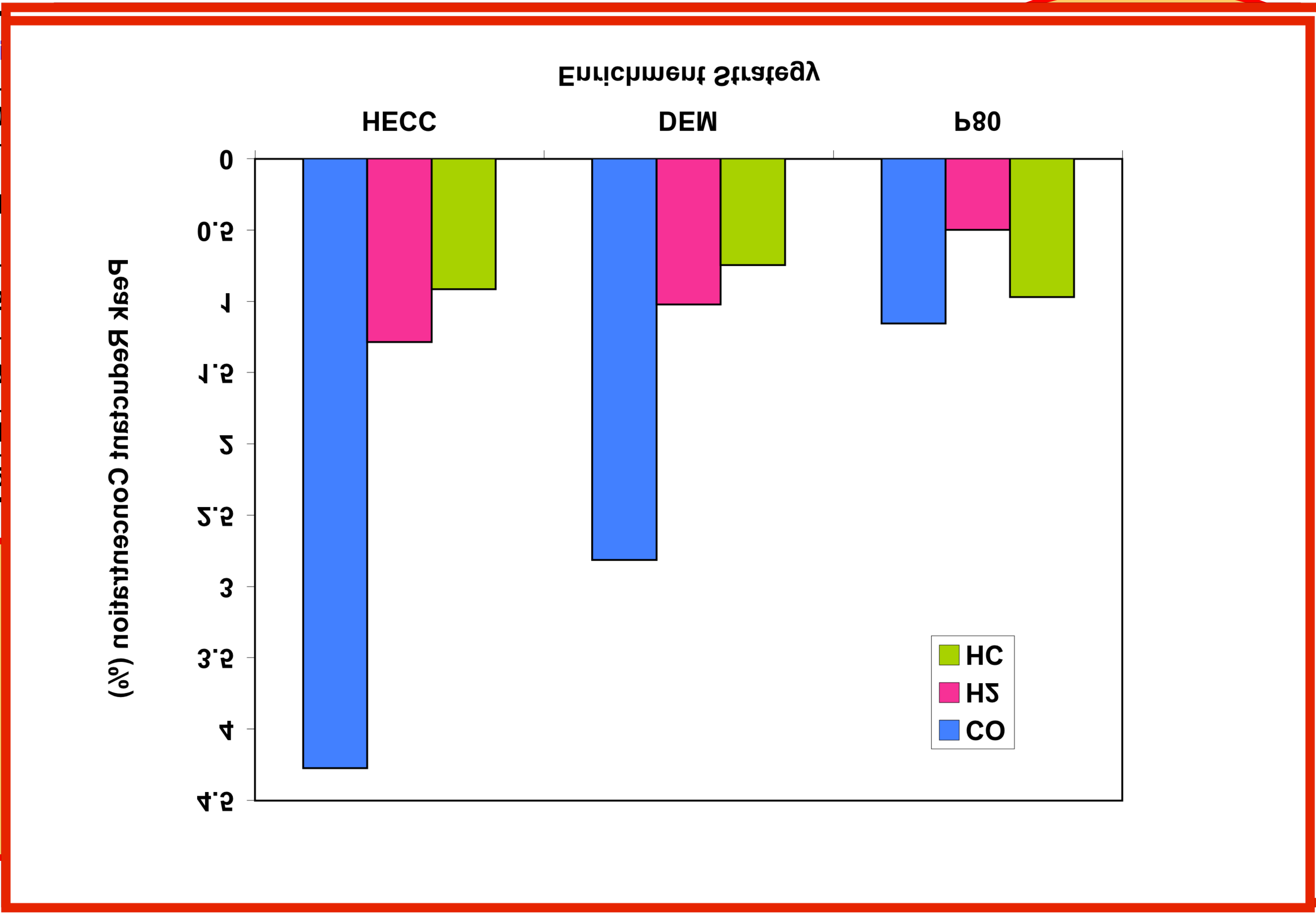

Se ... **nes**

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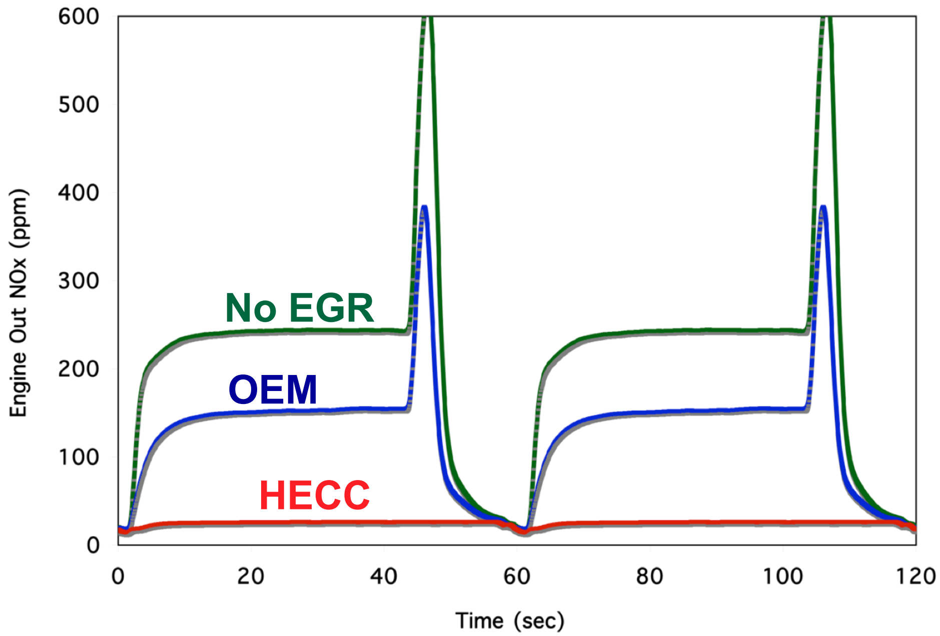
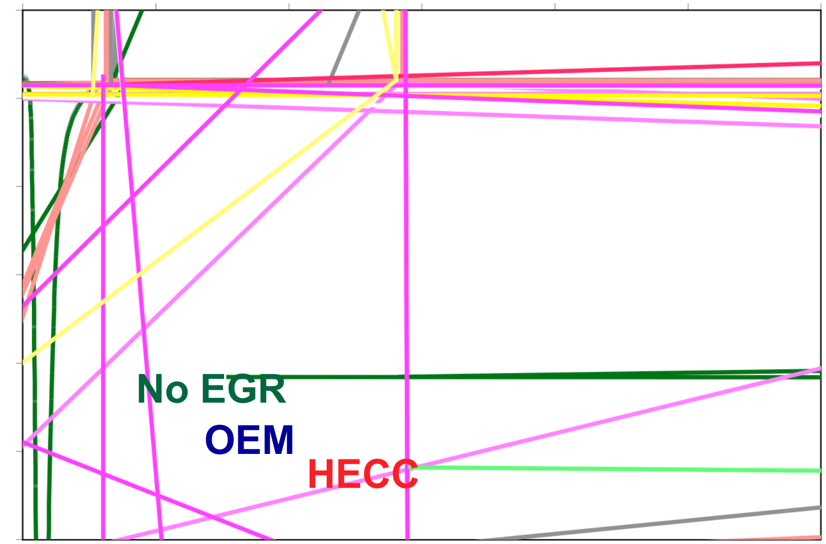
Typical set of engine out and tailpipe NOx emission data

1500 rpm, 2.6 bar (Ad Hoc 2: low speed cruise), 60s cycle with 3s regen

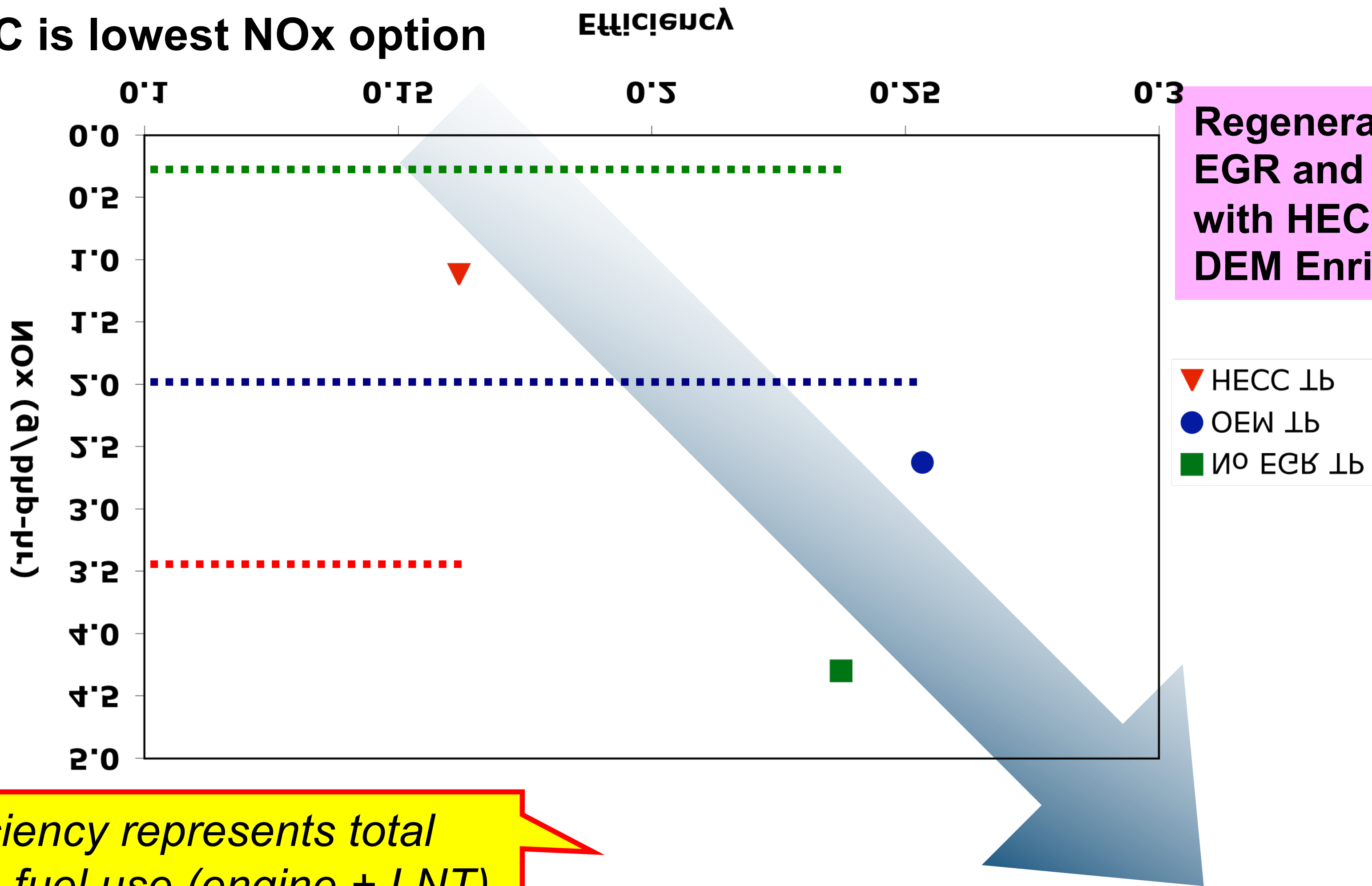




- **Rich period was 3 seconds but transition into the rich state lasted 10-15 sec**
  - **Transitioning involved throttling and/or EGR rate changing to dilute exhaust**
- **Lean time between regeneration events was varied to build NOx emission vs. fuel efficiency data curves**

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

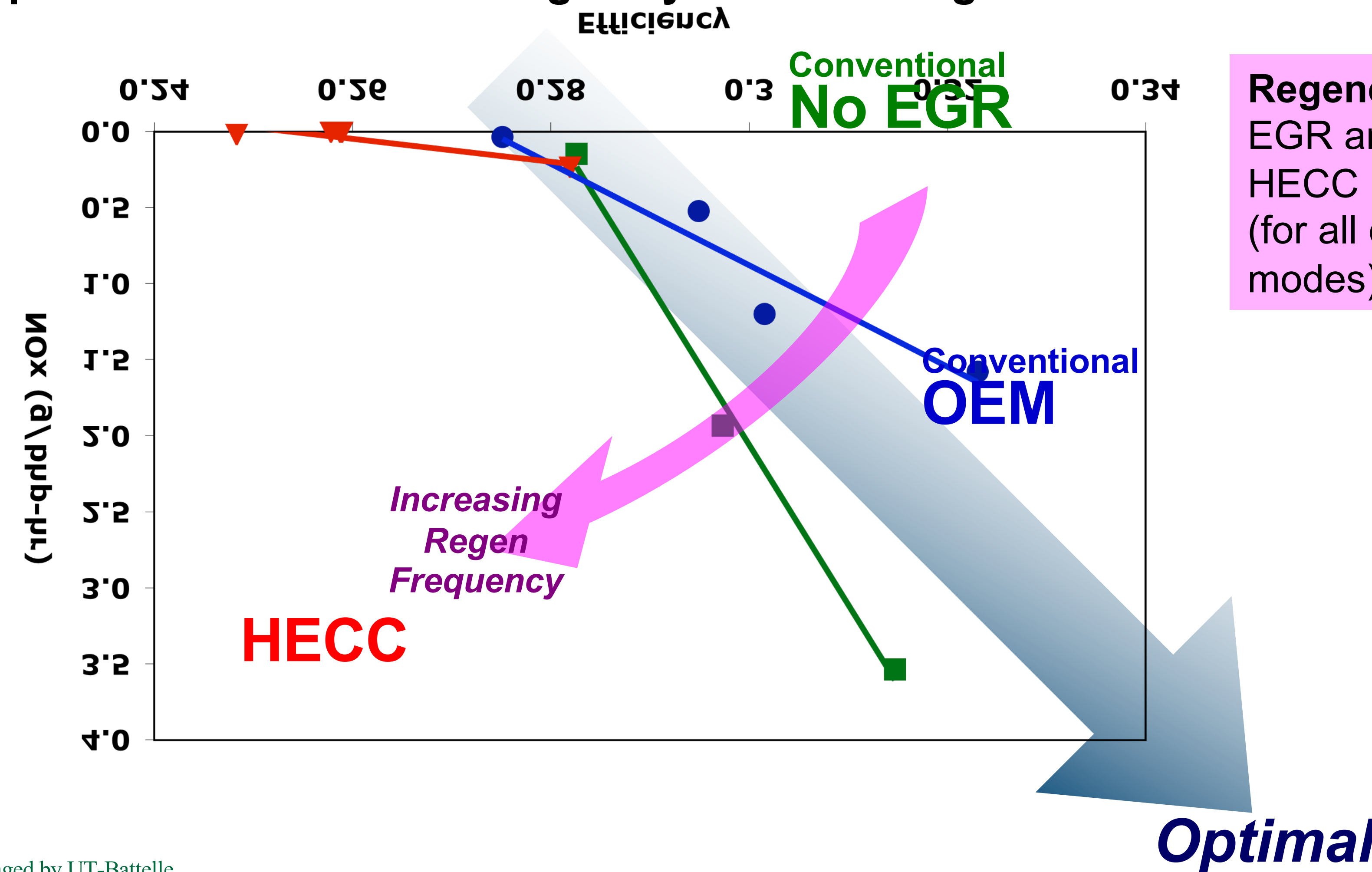


Regeneration: EGR and Throttle with HECC and DEM Enrichment

Efficiency represents total system fuel use (engine + LNT)

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

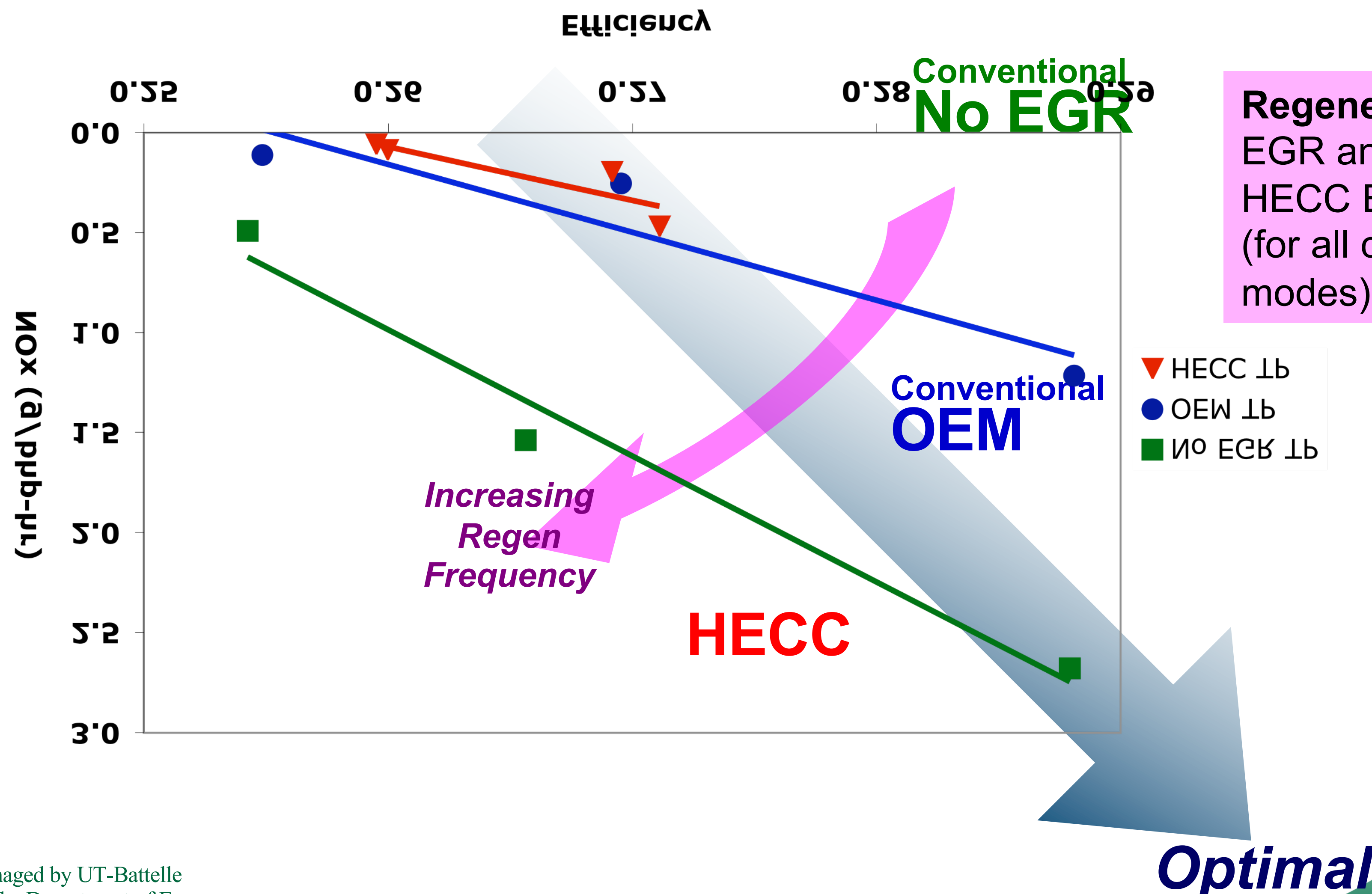
- **OEM and HECC effective at achieving low NOx levels**
- **Lower thermal efficiency in HECC as compared to OEM (normally HECC gives equivalent thermal efficiency of OEM) is due to the extended time of operation in HECC resulting in cylinder cooling**



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

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

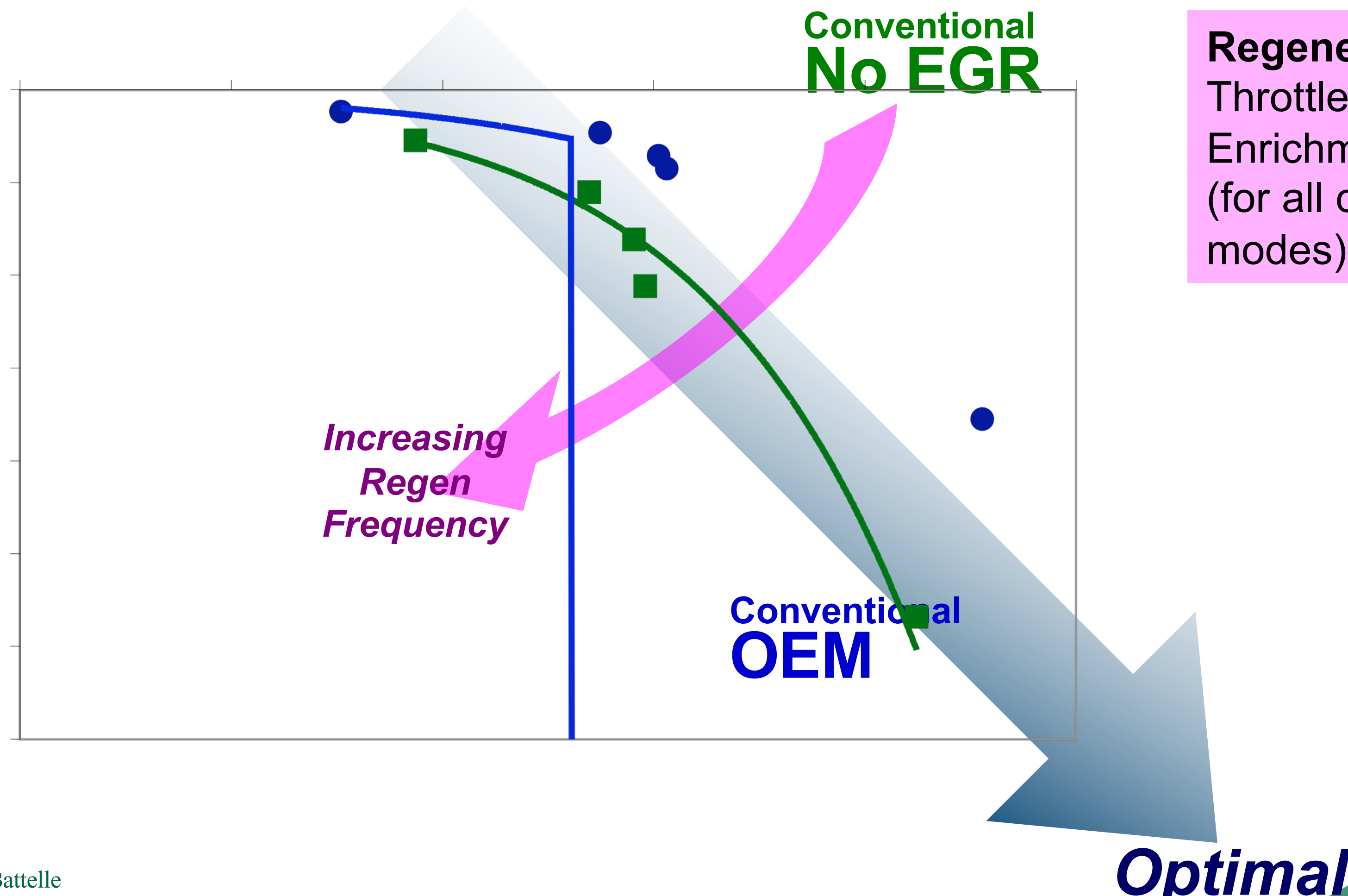
- **HECC and OEM show optimal results**
- **Efficiency during HECC is maintained at a level comparable to the OEM case**



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

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

- OEM is more efficient than "No EGR" mode for all NOx levels
- HECC not attained at this point due to limitations of the EGR rates



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

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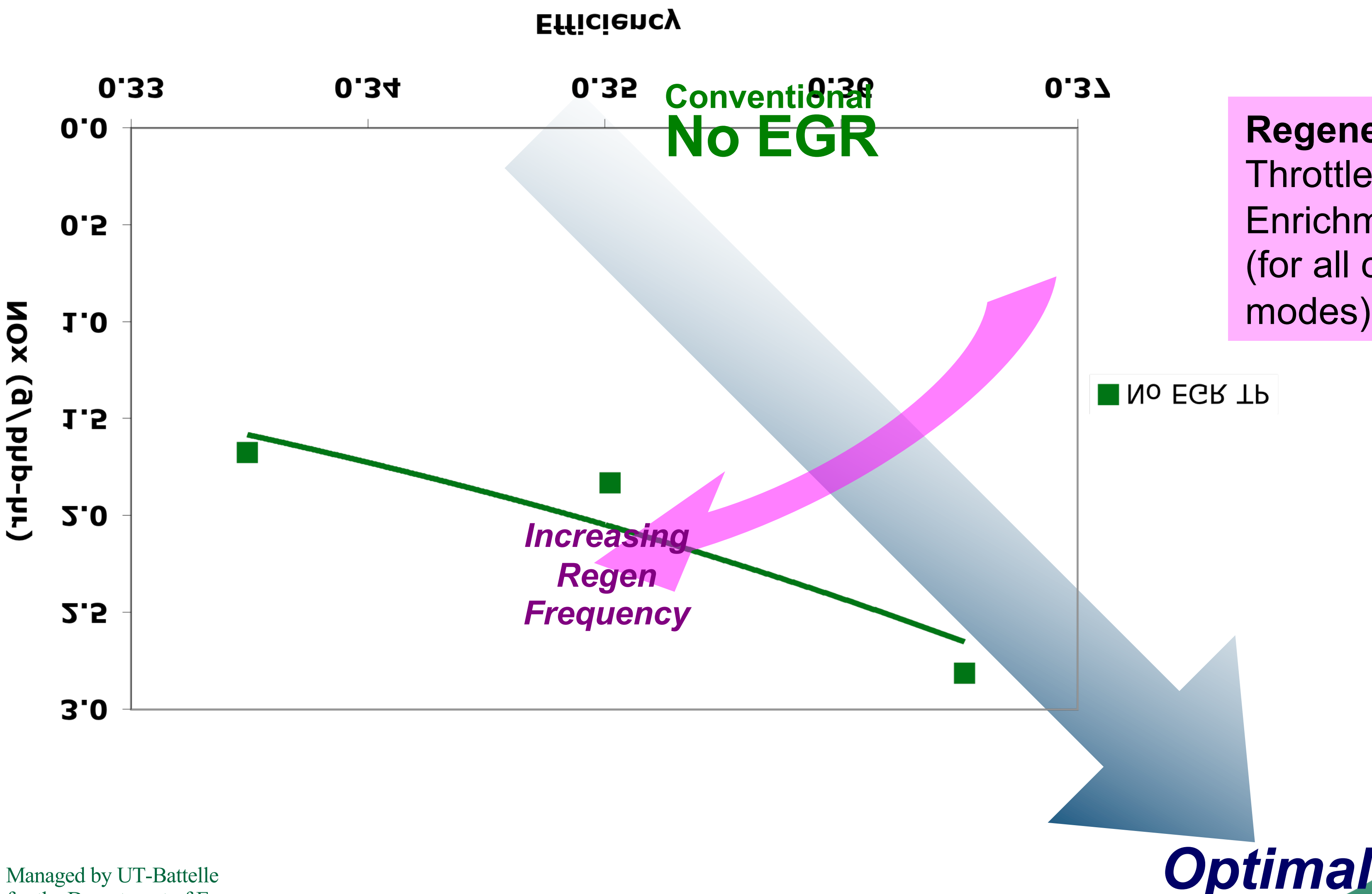
Point #5: 2600 rpm / 8.8 bar (Hard Acceleration)

- **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)

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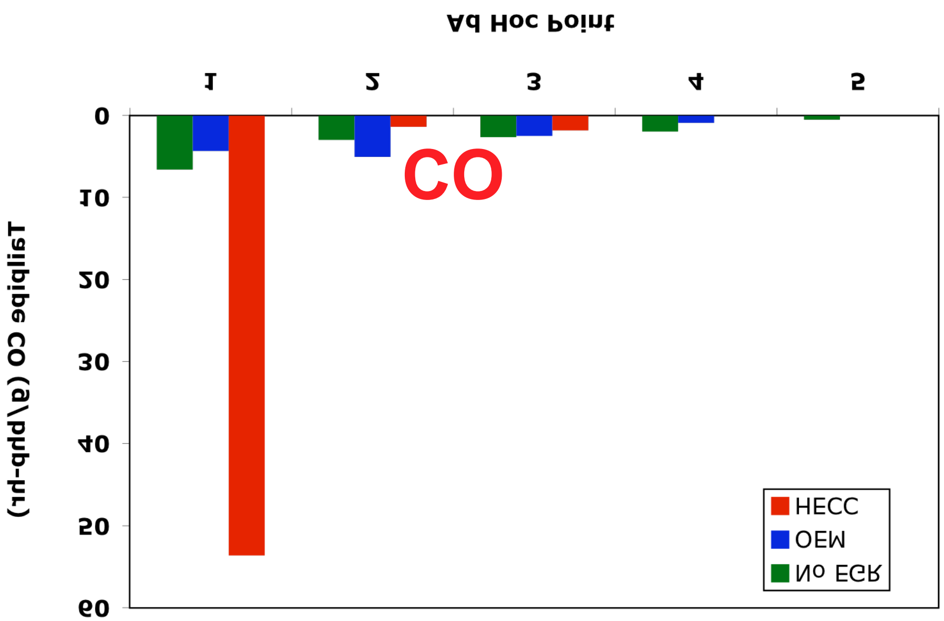
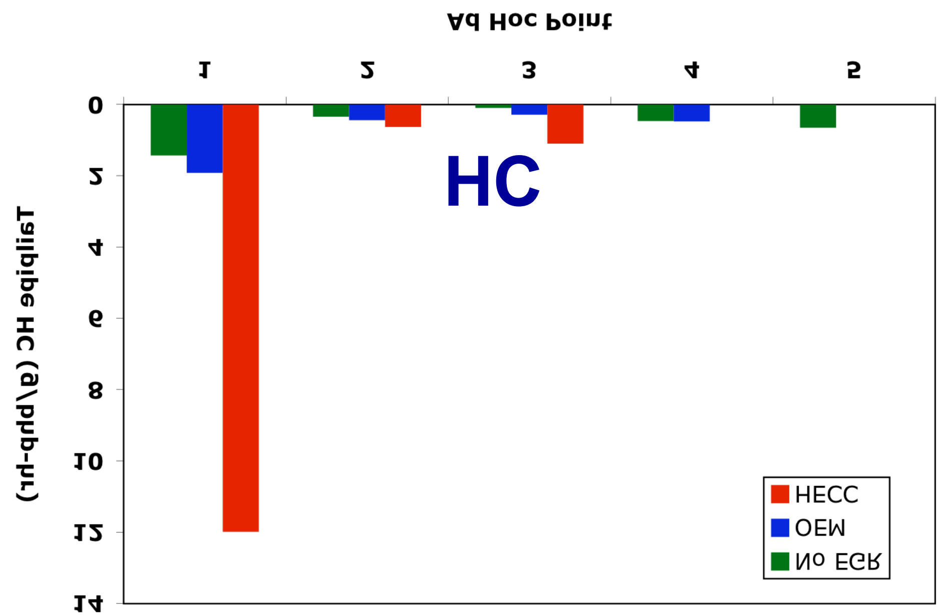
CO and HC Emissions Problematic at Point #1

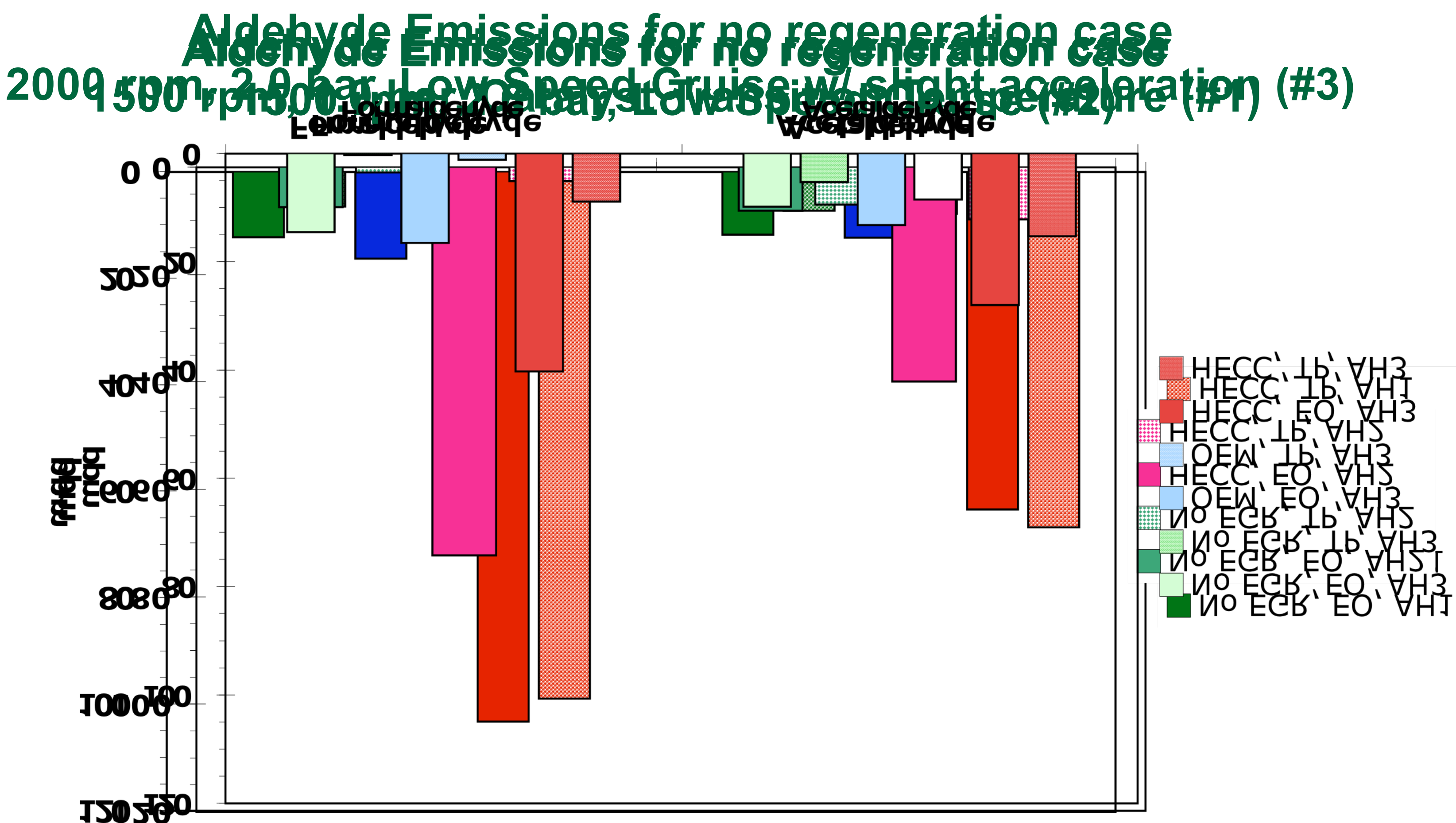
- Tailpipe CO and HC emissions for no regeneration case at each speed/load point
- Point #1 is below light-off temperature of LNT
- Low temperature oxidation catalyst needed





Engine out Mobile Source of Air Toxic (MSAT) emissions increase for HECC mode

- LNT is not effective in removing aldehydes at point #1 due to low temperature
- 75-95% formaldehyde conversion is achieved at points #2 and #3



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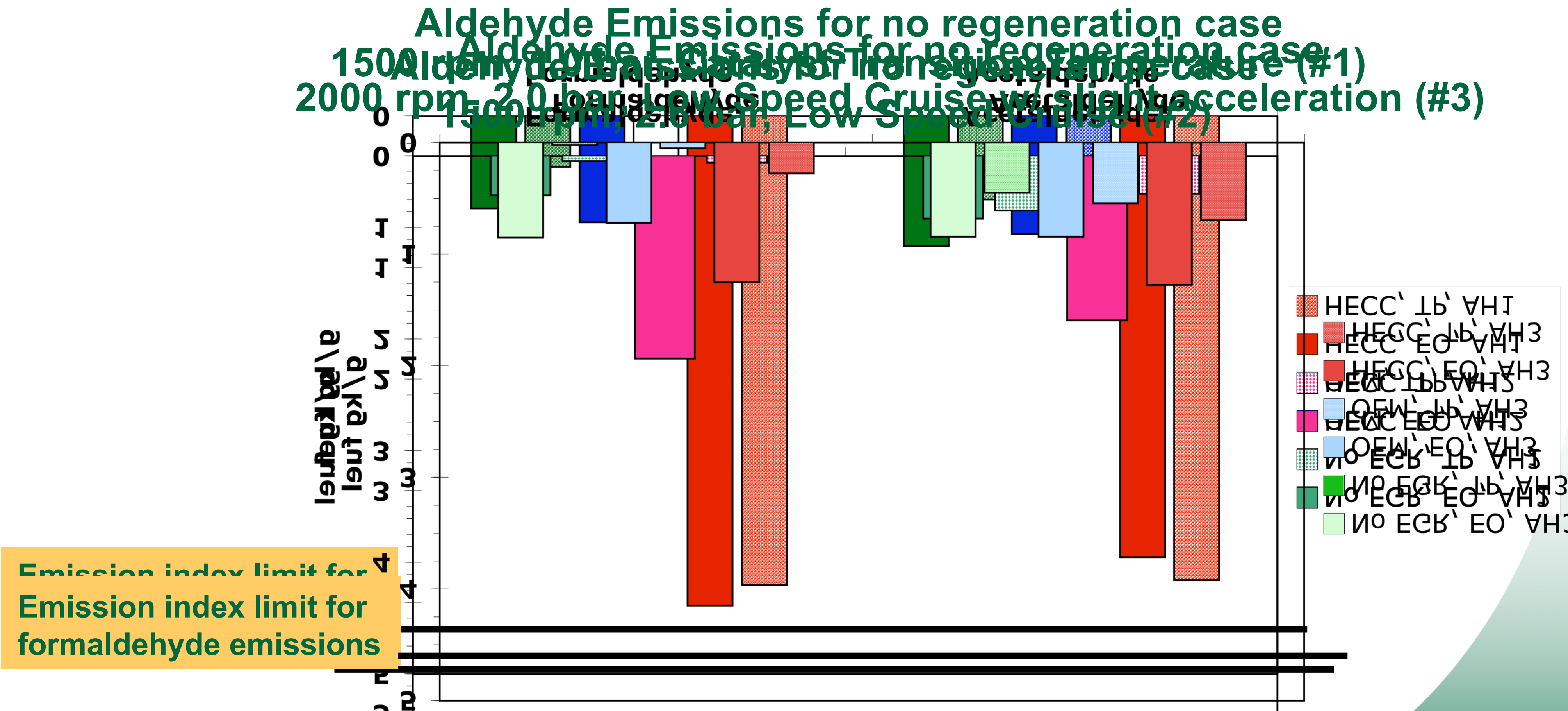
Engine out Mobile Source of Air Toxic (MSAT) emissions increase for HECC mode

- Light-duty emission regulations for formaldehyde are 0.018 g/mile
  - For a vehicle with FTP fuel economy of 45 mpg it is equivalent to 0.25 g/kg fuel
- There are no emission regulations for acetaldehyde
- Regulated level of formaldehyde emissions is not met at point #1



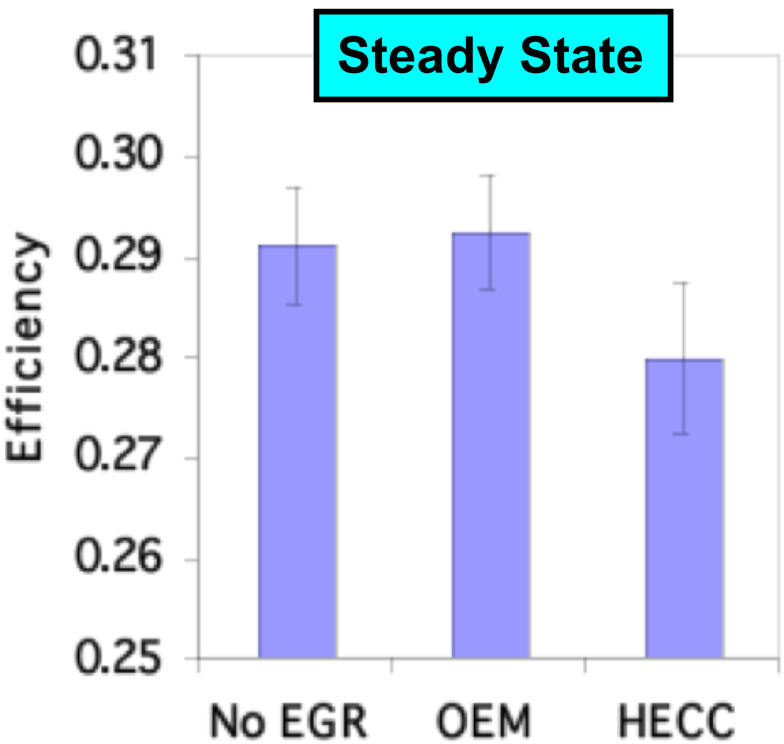
Summary

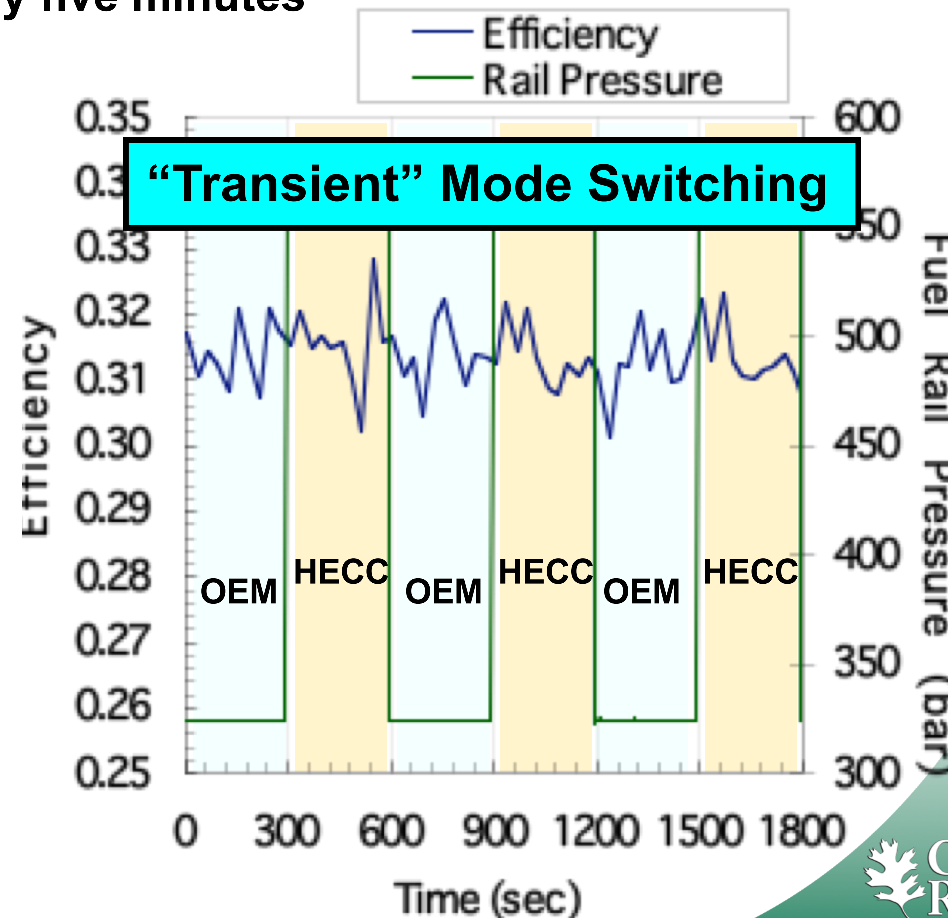
- At low loads (Ad Hoc #1), emission control becomes challenging
  - LNT temperature is too low to enable efficient regeneration
  - OEM and HECC are optimal for NOx emissions, but CO, HC and MSAT emissions are increased
- Medium Loads (Ad Hoc #2 & #3)
  - HECC engine out NOx emissions are lowest enabling lower NOx emissions at tailpipe
  - LNT is effective in removing CO, HC and MSAT emissions
- High Loads (Ad Hoc #4 & #5)
  - Achieving HECC was difficult due to EGR limitations
  - Conventional combustion together with LNT offer acceptable emissions and efficiency

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 over long time frames (>10 minutes)**
- **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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