Heavy Duty Truck Engine

2007 Emissions with Excellent Fuel Economy

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Presentation Agenda

- Combustion/Performance/Emissions Tuning
- Engine Thermal Management for Aftertreatment Optimization
- Cold Weather Testing Experience
- Conclusions
- Questions

Background - Program Goals and Timing

Phase I

- Demonstrate
  - **45%** BTE
  - **2002** Emissions
    - 2.5 gm BSNOx
    - 0.1 gm BSPM

Complete

Phase IIA

- Demonstrate
  - **45%** BTE
  - **2007** Emissions
    - 1.2 gm BSNOx
    - 0.01 gm BSPM

Complete

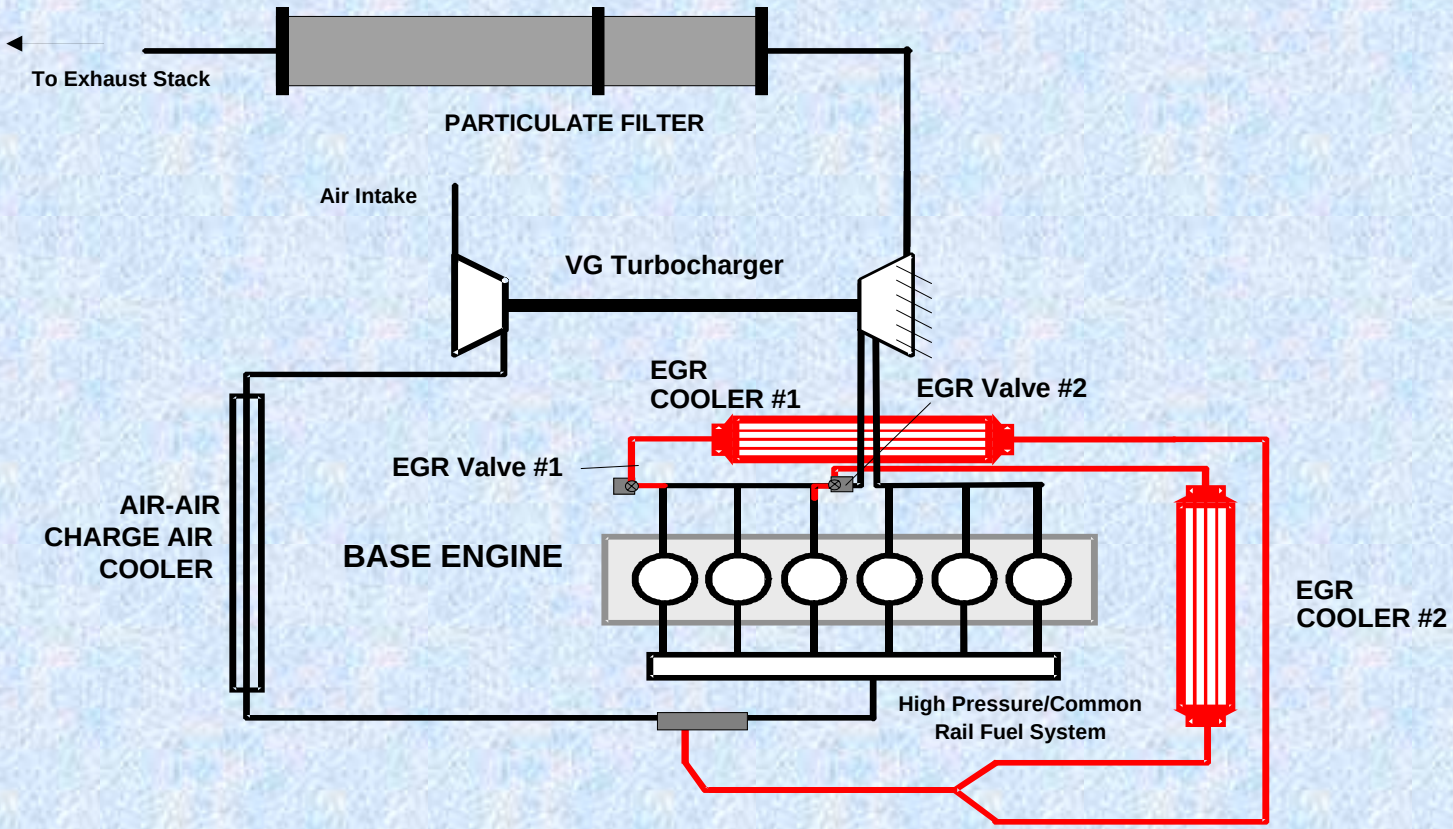
Phase IIB

- Demonstrate
  - **50%** BTE
  - **2010** Emissions
    - 0.2 gm BSNOx
    - 0.01 gm BSPM

In-Progress

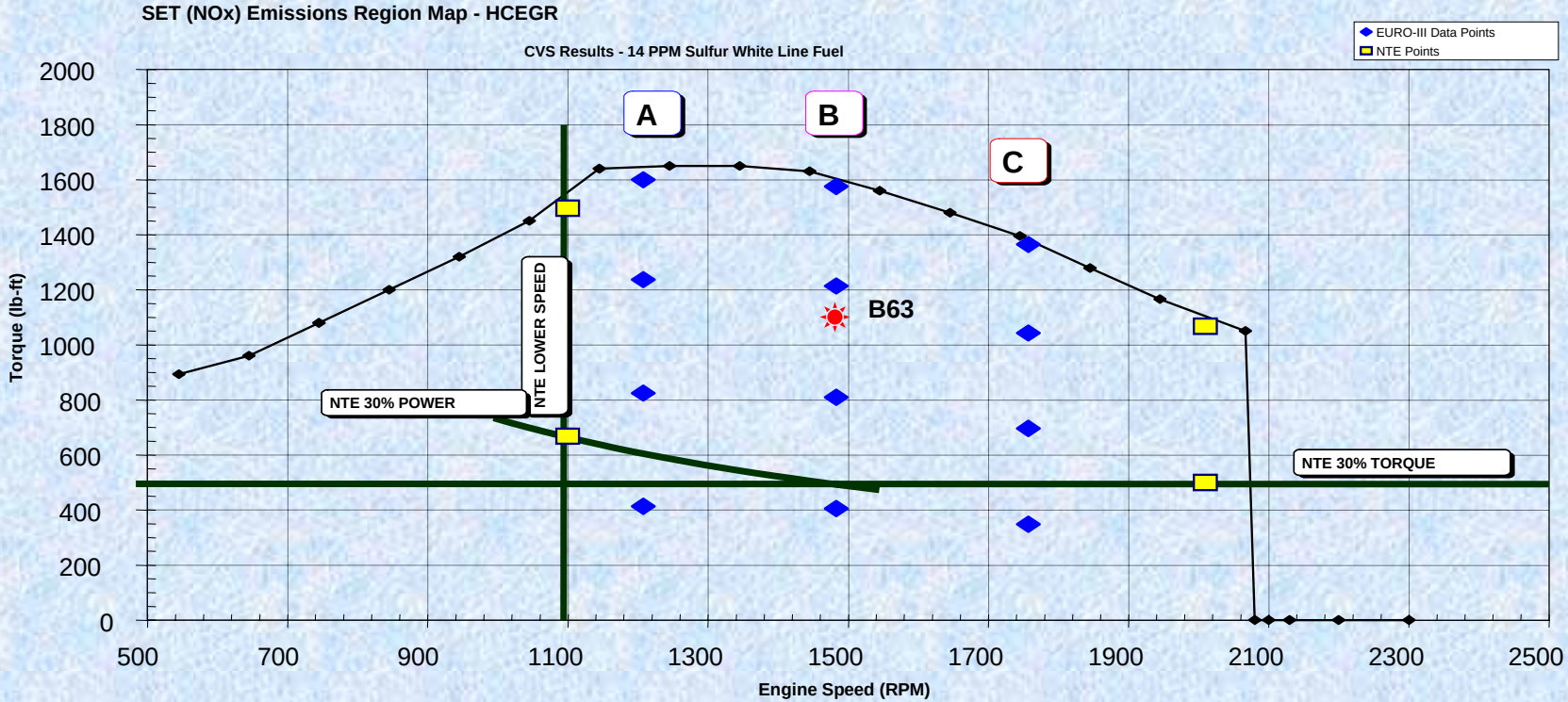
Concept ISX: Dual EGR Valves / EGR Coolers Engine System Configuration

- Built on existing 2002 Platform technology



Combustion Performance and Emissions Tuning (for Phase IIA)

BSNOx/PM SET Emissions with Concept ISX Engine



BSNOx SET comp. 1.07 g/hp-hr

BSPM SET comp. 0.002 g/hp-hr

Conclusion : SET BSNOx and BSPM are well below the 2007 targets

Target FTP Tailpipe Out Emissions

BSNOx: 1.149 g/hp-hr

BSPM: 0.0149 g/hp-hr

NMHC: 0.1450 g/hp-hr

Actual FTP Tailpipe Out Emissions

BSNOx: 1.295 g/hp-hr

BSPM: 0.001 g/hp-hr

NMHC: 0.03 g/hp-hr

Note: FTP NOx measured values did not meet our targets due to transient control issues with the dual EGR valves. Cummins viewed this as being acceptable given that composite SET NOx values were well within limits.

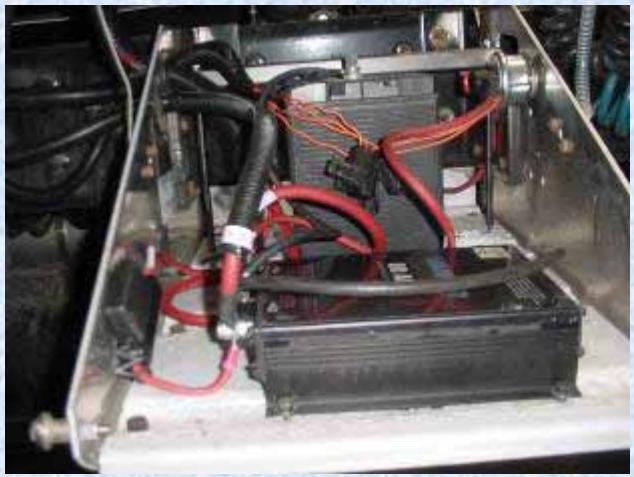
Parasitic Load Reduction (for Phase IIA)

Parasitic Reduction

- Two approaches to Parasitic Load Reduction were investigated for Phase IIA
  - *An Electric Water Pump*
    - The Mechanical Water Pump was replaced with an Electrical Pump
    - Coolant Flow could be tailored to specific engine need
  - *A Variable Flow Lube Pump*
    - Data was collected on a 'Variable Flow' pump design at required flowrates and pressures to support ISX operation.

Electric Water Pump

- **EMP (Engineered Machine Products) Designed and Controlled**
- **42 VDC Powered Unit**
- **Leece-Neville 42VDC, 90Amp Alternator**



Actual Electric Water Pump Performance

- **Efficiency Improvement at Cruise Point (1480 rpm, 63% load)**

  0.3% BTE Improvement

  Baseline (Mechanical Water Pump) BSFC = 0.324 (+/- 0.004)

  Electric Water Pump BSFC = 0.321 (+/- 0.004)

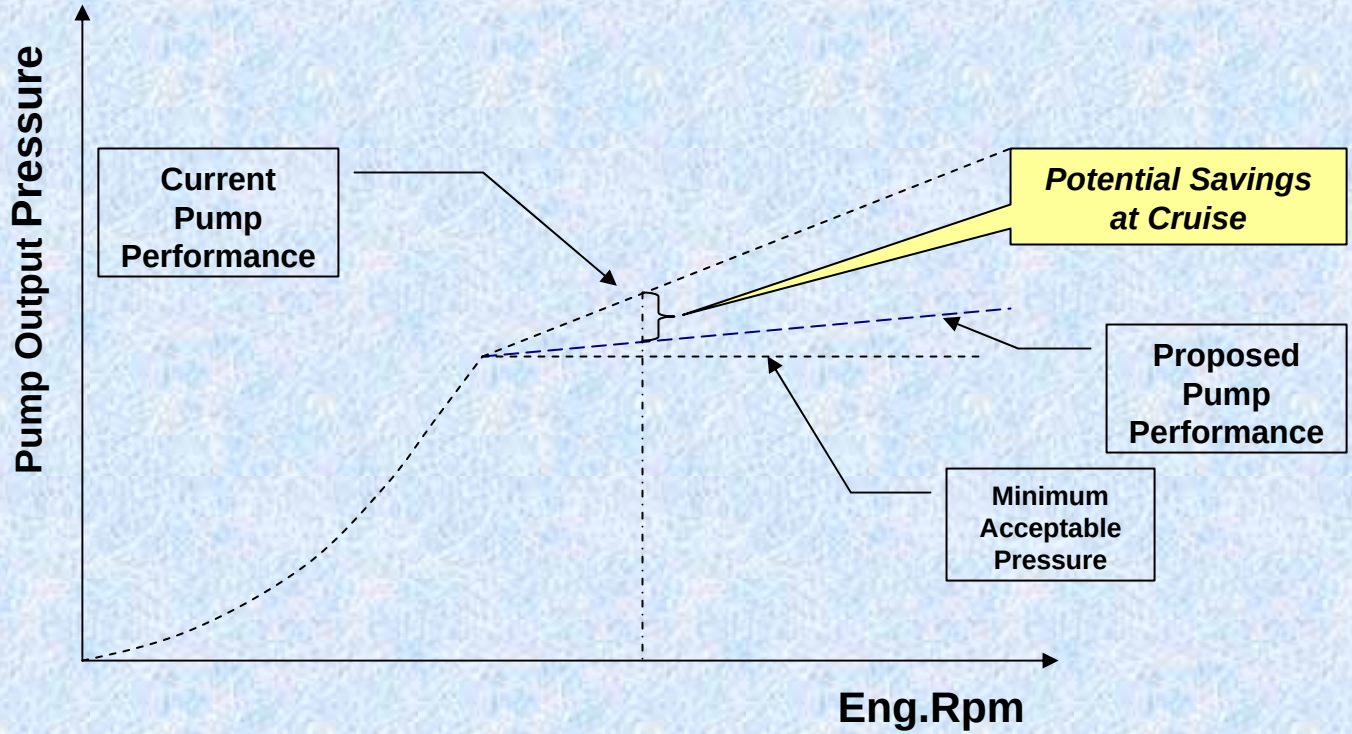
Variable Flow Lube Pump

- Proposed replacement for current Fixed-Gear pump
  - Adjustable rotor – flowrate controlled by pump output pressure.
  - Sought to minimize flow while maintaining system pressure.
- Would provide adequate flow and pressure for engine operation
- Pressure/flow/power consumption performance data collected from a Supplier prototype (similarly sized to the ISX pump)

Variable Flow Lube Pump

Variable Output Lube Pump

Proposed Performance vs. Current Product



Variable Flow Lube Pump

- Data applied to engine and vehicle simulations and produced a 0.2% BTE improvement – a 0.002 point BSFC improvement at the cruise point.

- Vehicle drive-cycle simulations showed very little MPG improvement. The amount of time spent at higher speed points didn't contribute much to the overall MPG.

Peak Brake Thermal Efficiency Summary

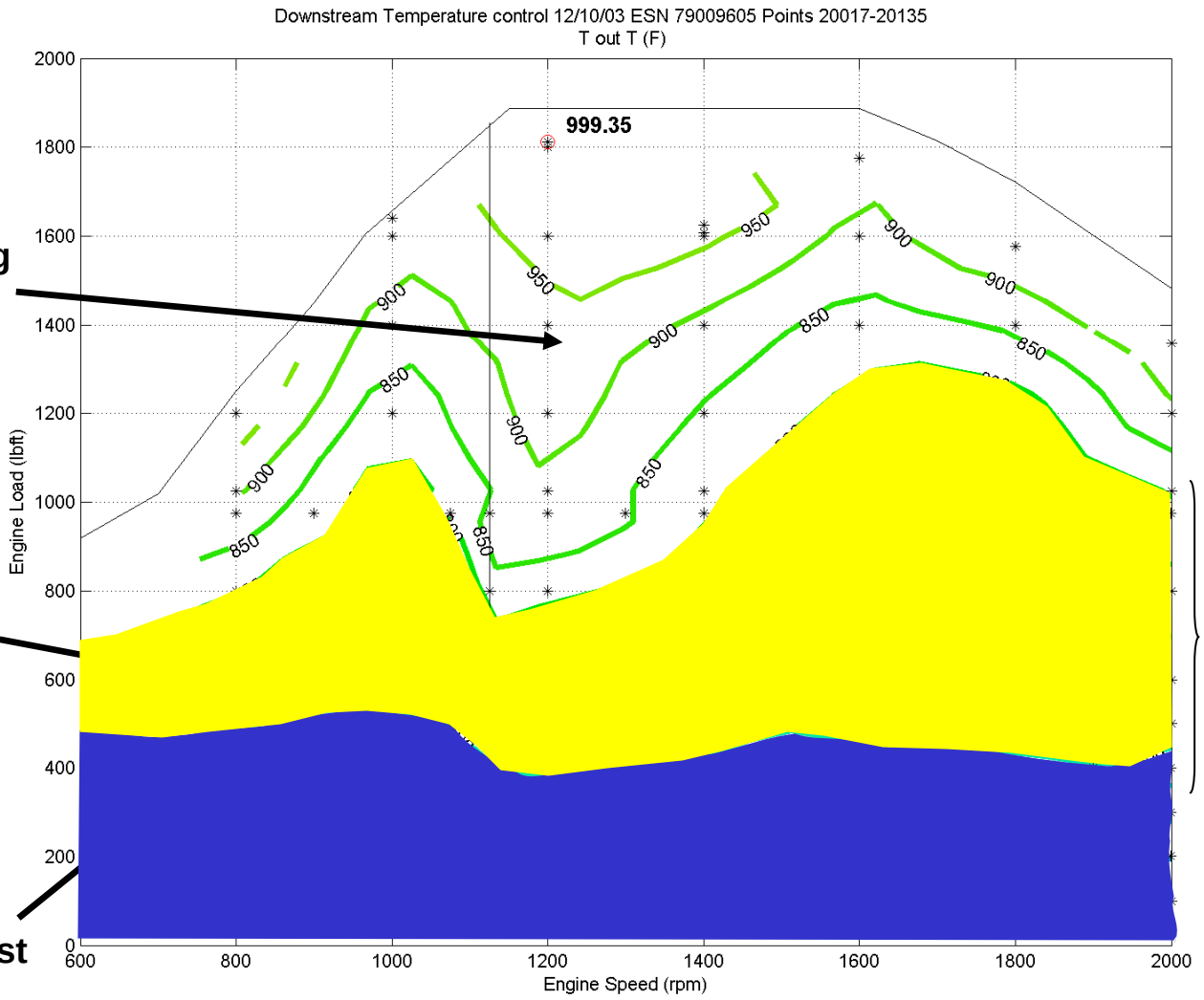
- Maximum BTE from the base engine at cruise was 43.2% while meeting 2007 emissions
- Additional BTE was shown to be available from Parasitic Reductions -
  - Electric Water Pump (engine data) – 0.3%
  - Variable Flow Lube Pump (simulation) – 0.2%
- With the additional benefits of the parasitic load reductions, a peak efficiency of 44% was achieved at the 2007 emissions level.

Engine Thermal Management for Aftertreatment Optimization

Particulate Filter Aftertreatment

- 2007 emissions levels essentially mandate the use of Particulate Filter aftertreatment
- Soot Loading and resultant performance issues are a key consideration in the application of this technology
  - Trap regeneration/cleaning is a necessity
- Optimized engine thermal management strategies seek to reduce the fuel consumed in A/T regeneration
  - Aftertreatment hydrocarbon/fuel dosing to the Particulate Filter creates regeneration heat
  - Maintaining exhaust gas temperatures high enough to maintain regeneration without extra dosing is the goal

Exhaust Temperature Critical to Filter Operation



Self Supporting Regeneration

Fuel Dosing Region

Inadequate "natural" exhaust temperature

Target Temps Depend Upon A/T Spec and Losses in Exhaust System

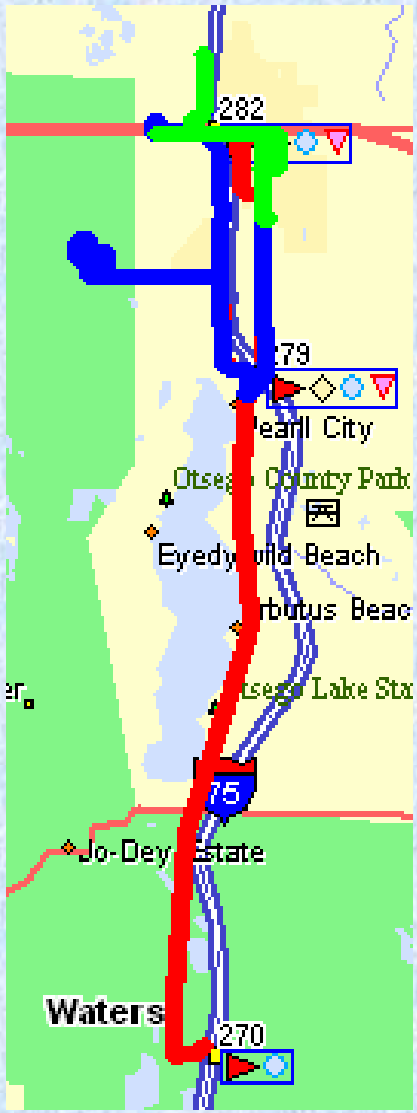
Cold Weather Testing

Cold Weather Test Objectives

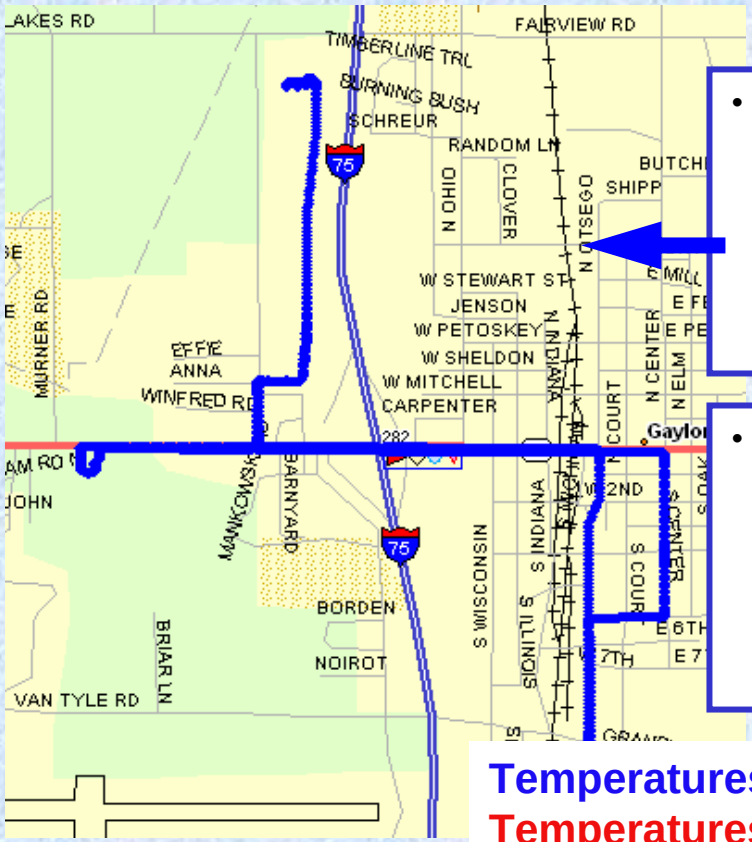
- Cold weather presents special challenges for Particulate Filter system reliability
- Winter test provided a platform for testing of various AT technologies
  - Demonstrate robustness of systems in the presence of noise factors.
  - Demonstrate resolution of previously identified issues.
  - Identify duty cycles & boundary conditions for in-house testing and modeling.
  - Collect data to validate embedded controls models
  - Gain reliability experience in real transient operation
    - Temperature control
    - Diagnostics
    - NOx control
  - Identify unanticipated failure modes.

Cold Weather Test Routes

- **City P&D**
  - 35 mph max speed
  - Frequent stops
  - Engine idles during stops
- **Suburban P&D**
  - City P&D + added stops in industrial park
  - Slightly higher average speed
- **Local P&D**
  - Suburban P&D + state highway
- **Highway/Linehaul**
  - Interstate cruise

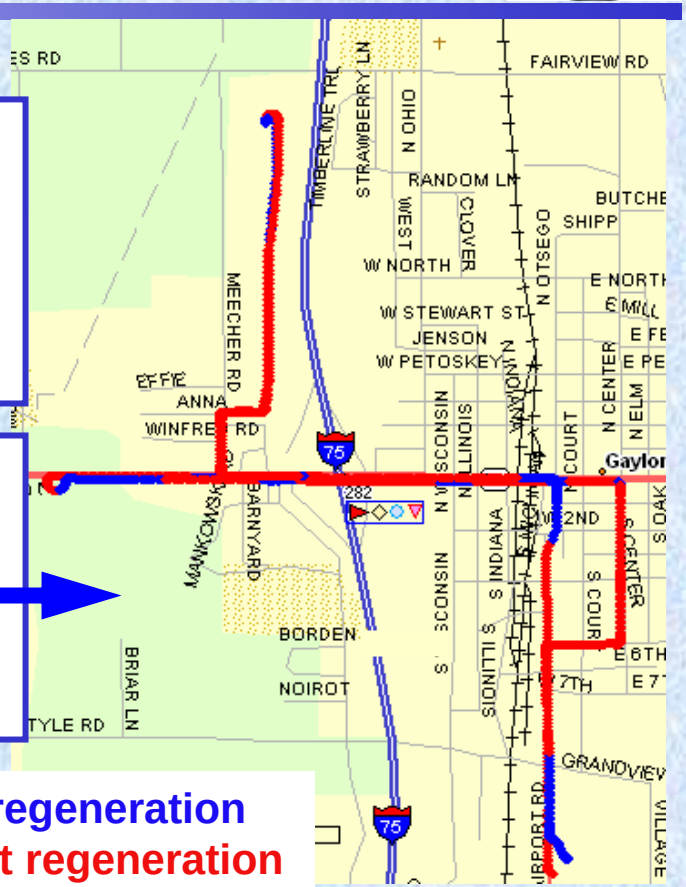


Cold Weather Test Thermal Management Results



- City P&D without thermal management does not provide exhaust temperature profile needed to support active regeneration.

- City P&D with thermal management provides exhaust temperature profile needed to amply support active regeneration.



Temperatures too low to support regeneration
Temperatures adequate to support regeneration

Without thermal management

With thermal management

Thermal Management decreases the amount of dosing required to Maintain the Particulate Filter.

Summary and Conclusions

Key Work Completed to Date

Efficiency

- Transient Performance Tuning to Demonstrate Efficiency Goals
- Vehicle Integration to Demonstrate our Phase IIA System On-Highway performance
- Reduced Parasitics - Analysis and Testing

Emissions

- Demonstration of a compliant Engine System against 2007 emissions standards
- Aftertreatment Thermal Management Strategy

Reliability

- Cold Weather Operation Test Experience
- Aftertreatment Stress Analysis and Noise Factor Analysis

Program Summary

The HDTE Program is proceeding steadily towards program goals at Cummins

- Demonstration of 44% BTE while operating at 2007 Emissions levels, (Phase IIA), (complete)
- Demonstration of 50% BTE and 2010 emissions is now in progress, (Phase IIB), (in progress)

Thanks to our Sponsors!

Cummins Inc. thanks –

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