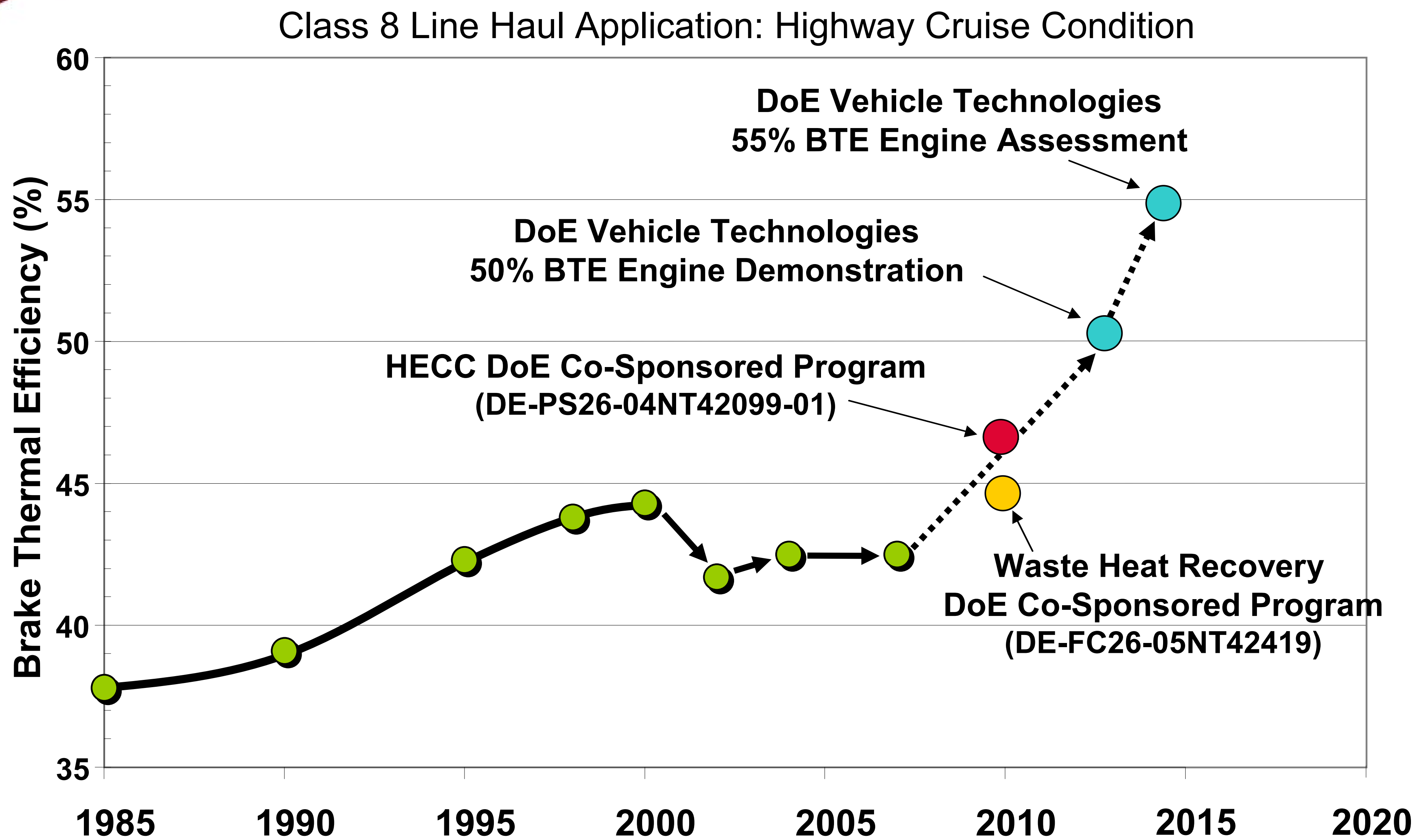
Technology Development for High Efficiency Clean Diesel Engines and a Pathway to 50% Thermal Efficiency

Donald Stanton
Research & Technology

August 5, 2009

Evolution of Heavy Duty Diesel Engine Efficiency



ISX Technology Roadmap for Efficiency Improvement

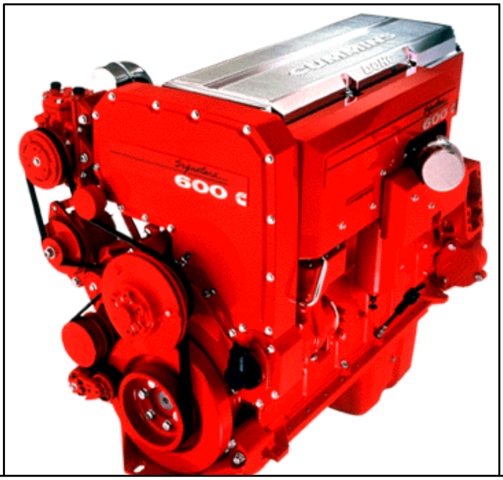
Black – Enabling Technology for HECC Program Phase 3

Variable Valve Actuation

Fuel System
- High Injection Pressure
- Piston Bowl/Nozzle
- Multiple injections

Advanced LTC
- Enhanced PCCI
- Mixed Mode Combustion

Variable Intake Swirl



Controls
- Charge Air Manager
- MAF
- Closed Loop Combustion

EGR Loop
- Lower Pressure Drop
- Alternative Cooling

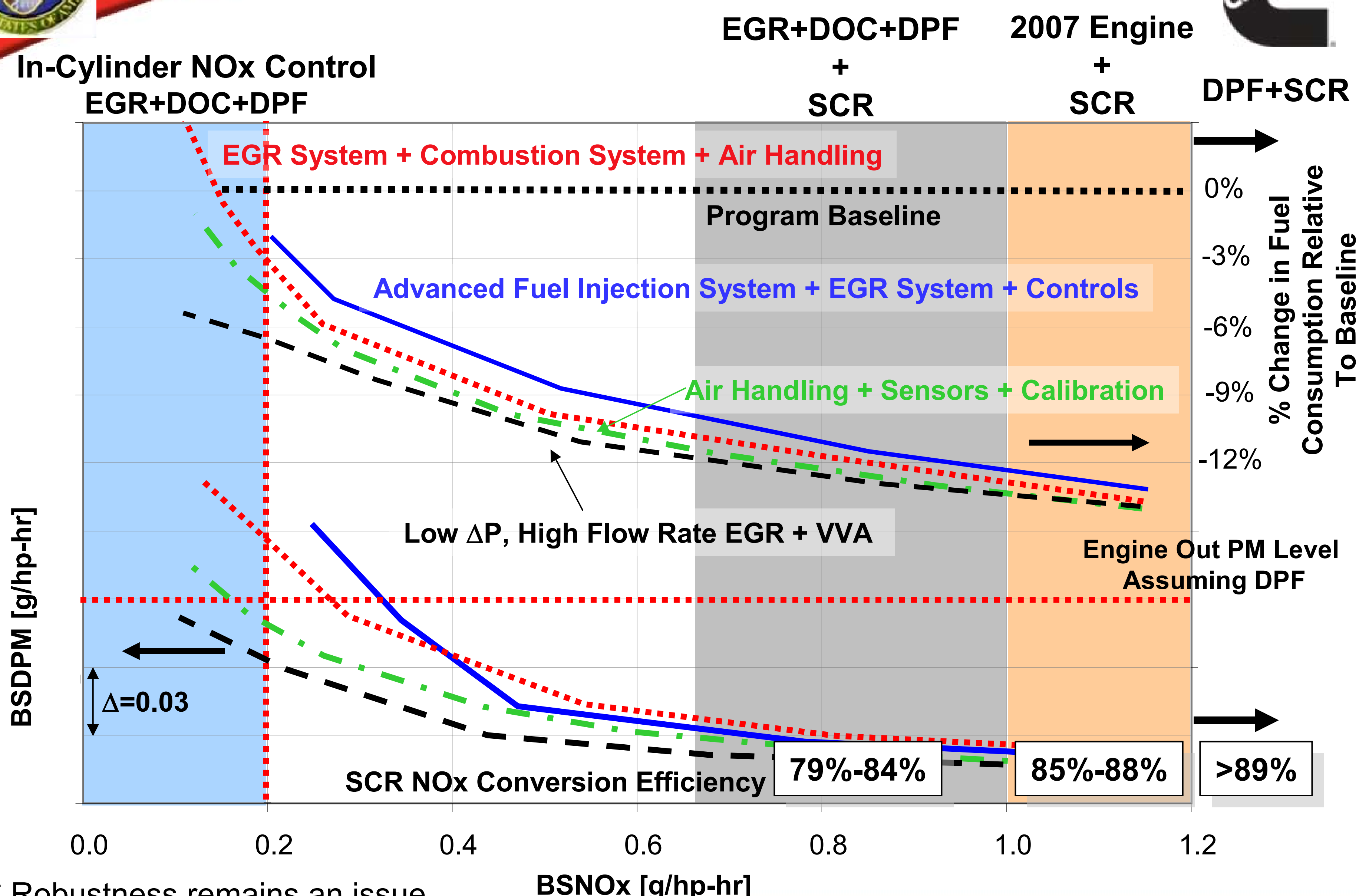
Phase 3: 2008 - 2009

Electrically Driven Components

Turbo Technology
- Electrically Assisted
- 2-Stage

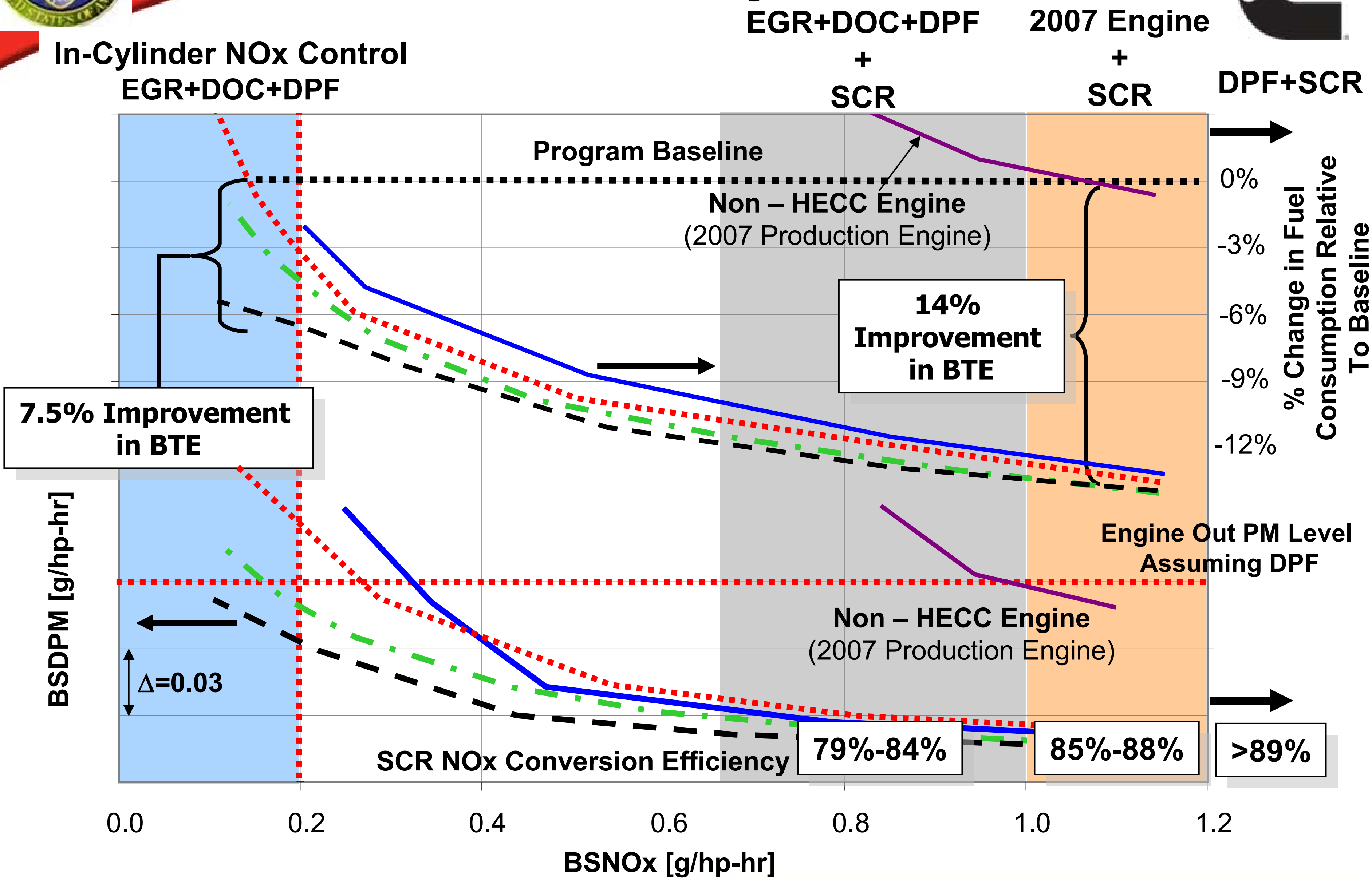
Aftertreatment
- DOC
- DPF
- SCR
- Sensors

Achieving a Wide Range of Engine Out NOx Capability



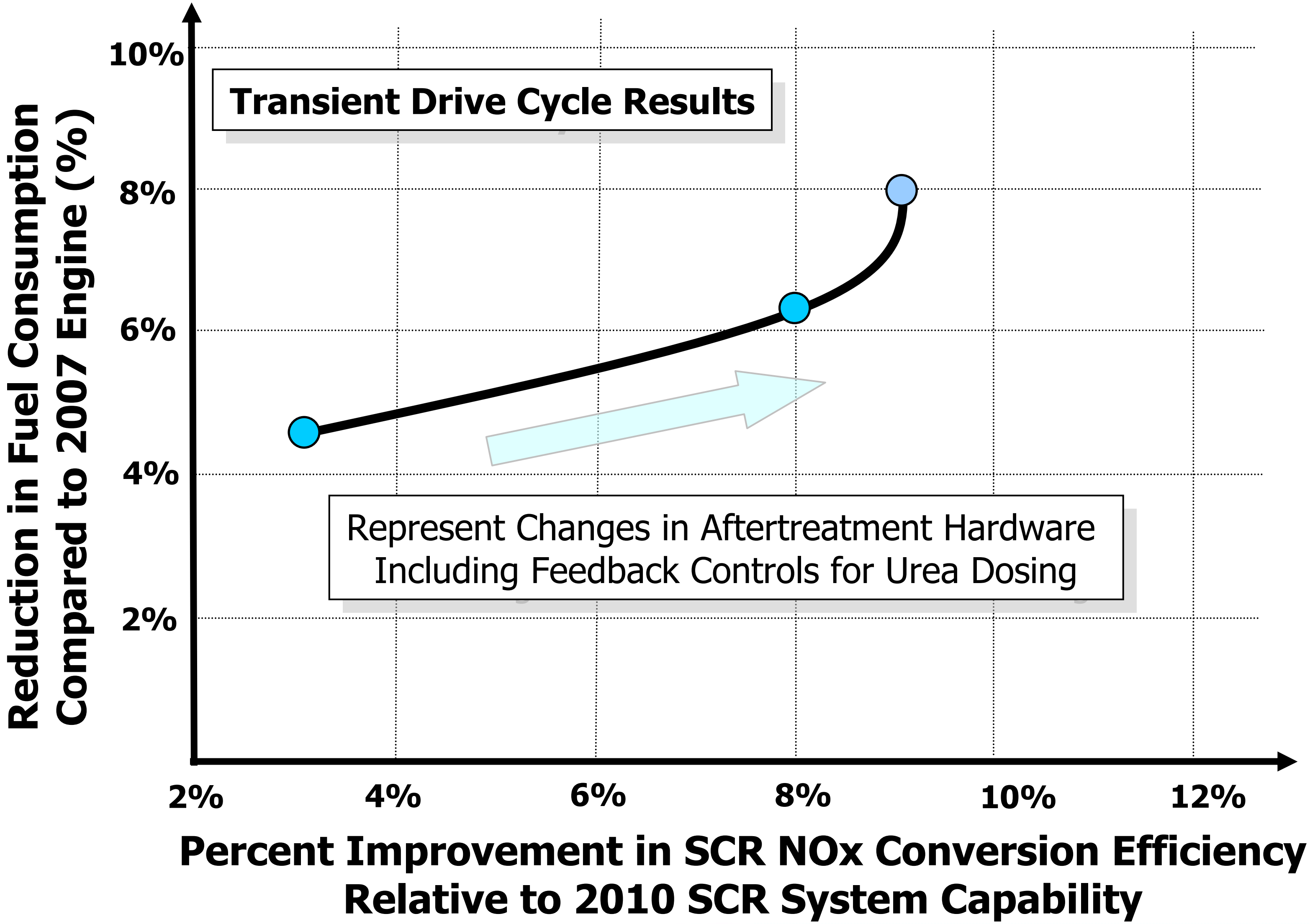
* Robustness remains an issue for In-Cylinder NOx Control

Fuel Consumption Comparison of the In-Cylinder vs SCR NOx Control Engine Architectures



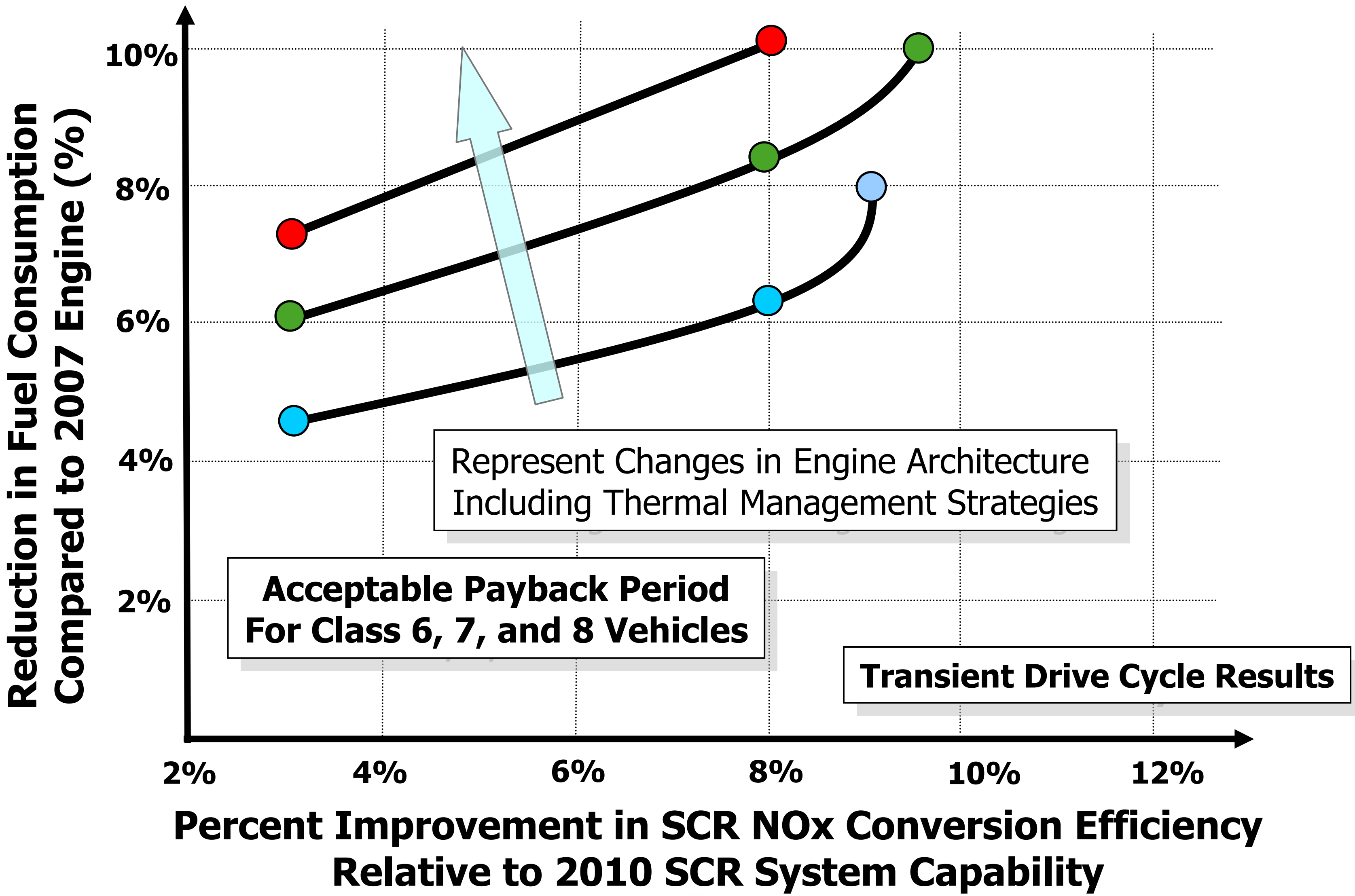
Evolution of High Efficiency SCR

Does Not Include DEF Usage

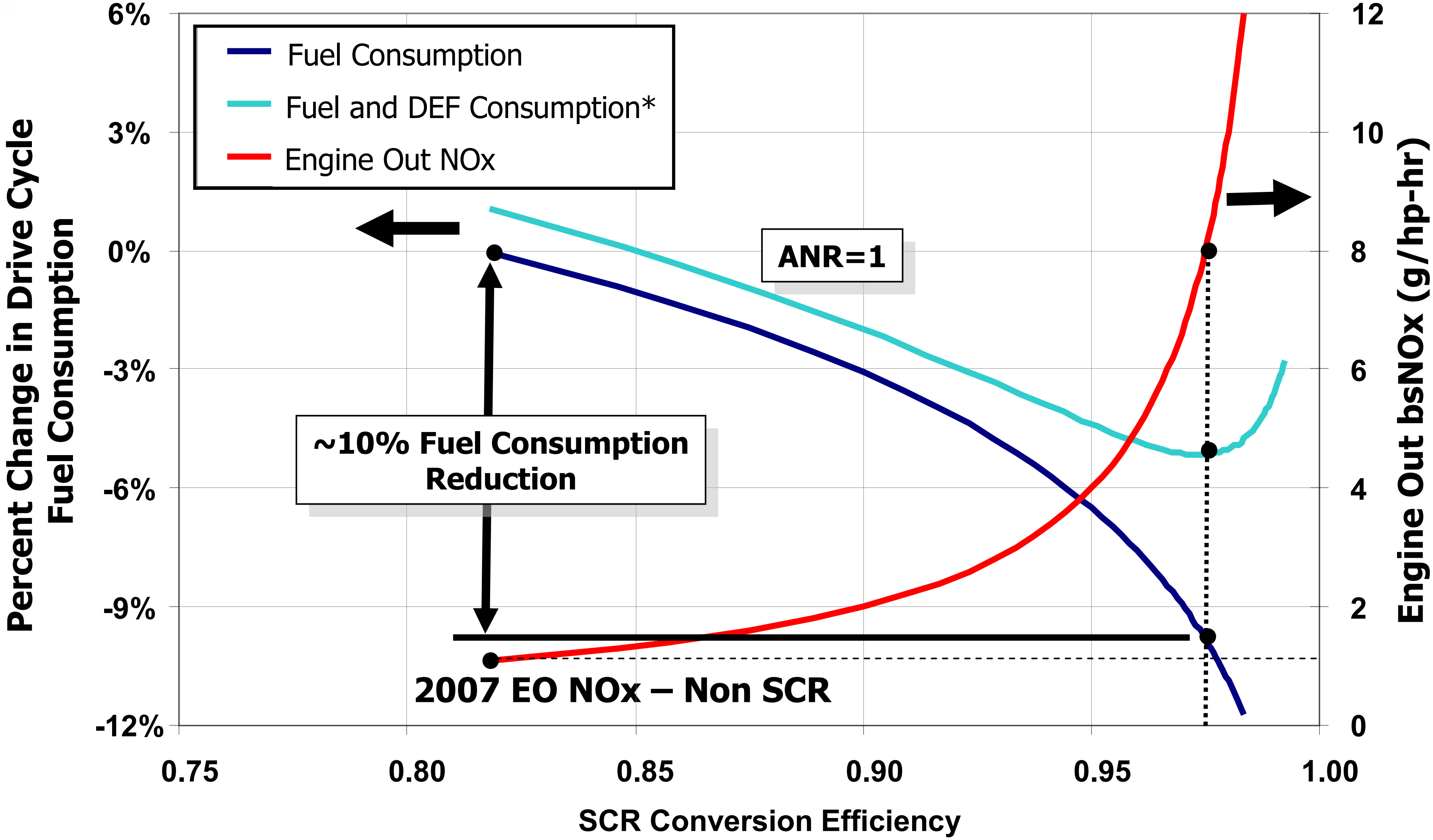


Evolution of High Efficiency SCR

Does Not Include DEF Usage

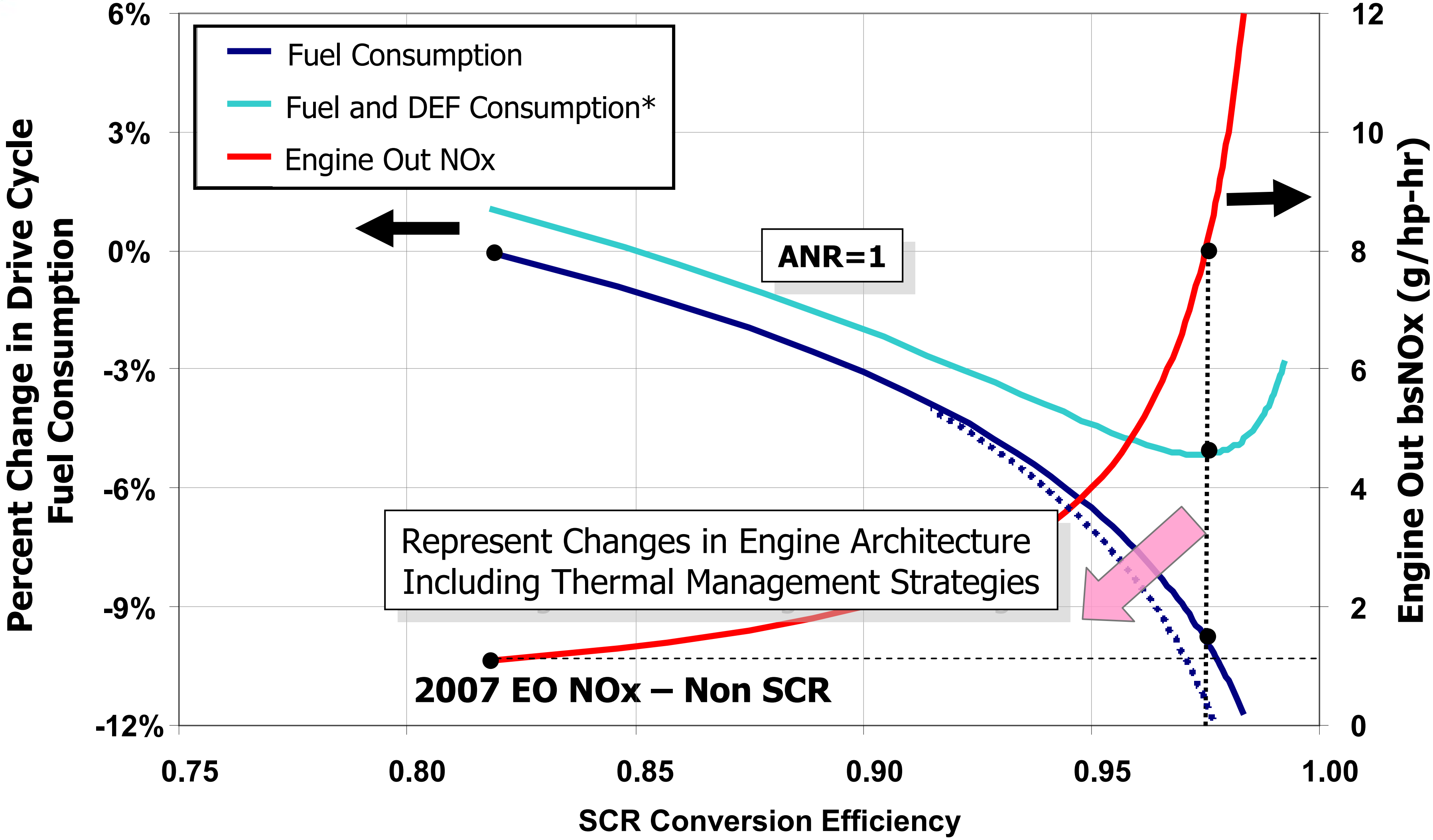


Potential Fuel Consumption Benefit of Higher SCR NOx Conversion Efficiency



* Assumes DEF cost = diesel fuel cost/2

Potential Fuel Consumption Benefit of Higher SCR NOx Conversion Efficiency



* Assumes DEF cost = diesel fuel cost/2

Technical Barriers with Possible Solutions

<u>In-Cylinder NOx Control</u>

- Vehicle heat rejection
  - Low temperature radiator configuration (multiple options considered)
- Power density limitations
  - Increased vehicle heat rejection capability
  - Cylinder pressure capability
- Robustness
  - Reduce charge flow and fuel flow variation
    - Control algorithms
    - Sensor technology
    - EGR cylinder to cylinder distribution
- Transient response
  - 2-stage turbo
  - Electrically assisted boost
  - CAC bypass

<u>High NOx Conversion Efficiency SCR</u>

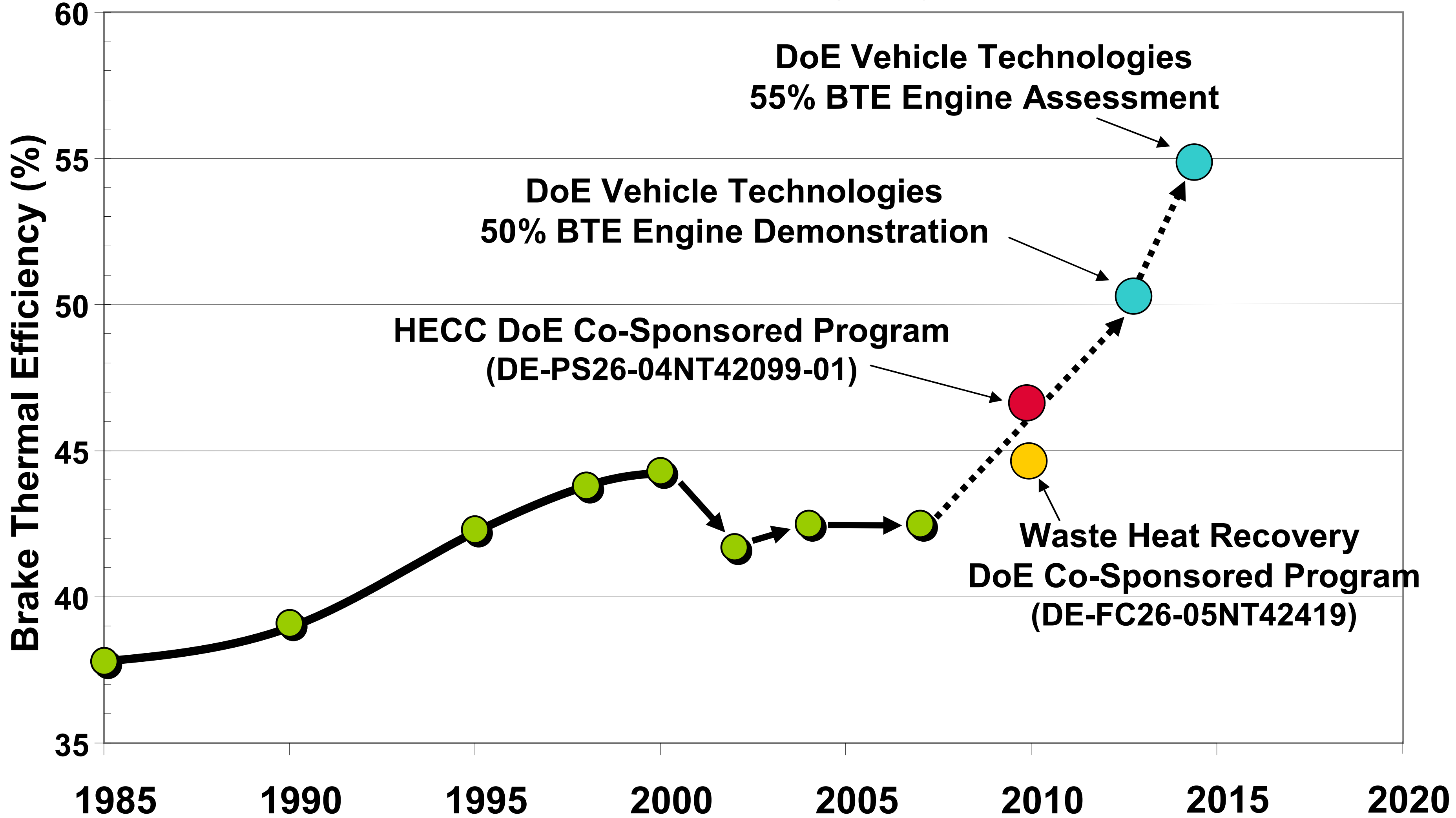
- >97% conversion efficiency over relevant drive cycles
  - Conversion of urea to ammonia (eliminate urea derived deposits)
  - NOx selectivity of the ammonia slip catalyst
- System pressure drop
- Packaging
  - Unique arrangements defined
  - Reduce catalyst size via zone coating
  - New substrate material for smaller size
- Fuel efficient thermal management for transient emissions (FTP)
  - Turbomachinery
  - Injection strategy
  - EGR cooler by-pass
  - Compressor by-pass

Improved Customer Value

- Must significantly reduce the aftertreatment cost
  - Aggressive target should be a 50% reduction in price
- Diesel particulate filter size reduction with lower ΔP and combined SCR functionality
  - As SCR NOx conversion efficiency increases, PM emissions reduced drastically
  - DPF operating in passive regeneration mode
- Eliminate ammonia slip catalyst
- Greater than 50% reduction in precious metal loading of DOC
- Key is system integration with novel control strategies

Evolution of Heavy Duty Diesel Engine Efficiency

Class 8 Line Haul Application: Highway Cruise Condition



ORC Energy Recovery Potential

Greater exhaust stream heat recovery potential with high efficiency SCR system

WHR ~9.5% BTE Benefit

Less EGR stream heat recovery With high efficiency SCR system

- Coolant Heat Recovery +0.5%
- Charge Air Heat Recovery +1.0%
- Exhaust Heat Recovery +3.0%
- EGR Heat Recovery +2.0%
- Vehicle/ Condenser Capacity +1%
- Component Efficiencies +1%
- Working Fluid +1%

Nearly a 10% performance improvement is possible – though with high additional cost and system complexity

Future development must focus on the most promising and realistic potentials energy recovery sources -

Cost Reduction is a Key Area of Emphasis for the Cummins 2nd Generation ORC WHR System

Engine Fuel Energy Balance to Meet 50% BTE