ATP-LD; Cummins Next Generation Tier 2 Bin 2 Diesel Engine

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Changing the Climate
on Climate Change

Project ID:ACE061

Next Generation T2B2 Diesel Engine Overview

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Timeline

Start: 10/1/2010

End: 9/31/2014

Complete: 60%

Budget

Total Project:
- $15M DoE
- $15M Cummins

Total Spend to date:
- $9.6M DoE
- $9.6M Cummins

Barriers

GHG Requirements of 28 MPG CAFE in ½ ton pickup truck

Low emission – Tier2 Bin2

Cost effective solution

Partners

Nissan Motors Light Truck

Johnson Matthey Inc

Next Generation T2B2 Diesel Engine Objectives

- Engine design and development program to achieve:
  - 40% Fuel Economy improvement over current gasoline V8 powered half-ton pickup truck
  - Tailpipe requirements: US T2B2 new vehicle standards
- FE increase in light trucks and SUVs of 40% would reduce US oil consumption by 1.5M bbl/day
  - Lower oil imports and trade deficits
  - GHG emissions reduction of 0.5 MMT/day
  - Enable OEM ability to continue to offer products as capable as those in commerce today.

Next Generation T2B2 Diesel Engine Objectives

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	Baseline * vehicle data	DoE Program Target **	
FTP – 75 “city”	15.6 570	21.8 462	mpg g/mi CO_2
HFET “Highway”	24.5 363	34.3 292	mpg g/mi CO_2
CAFE	18.6 476	26.0 *** 385	mpg g/mi CO_2

* Baseline data from 2010 EPA database for new vehicle certification for Nissan Titan 2WD at 5500 lb test weight

** DoE program targets base on MPG values at 40% greater than base

*** 26 mpg CAFE does not meet 2015 GHG requirement of 28 mpg

2013 Milestones

	% Complete	2013 Milestones
Mar 2013	100	New engine torque curve demonstration
July 2013	30	T2B5 Demonstration on engine dynamometer
Aug 2013	0	T2B2 Development Engine start up
Sept 2013	10	T2B5 Vehicle installation (DEER display)
Dec 2013	0	T2B5 Vehicle demonstration
Dec 2013	0	Complete T2B2 engine side development

Future Milestones

2014	
March 2014	T2B2 Aftertreatment integrated in dynamometer environment
June 2014	Convert Vehicle to T2B2 configuration
May 2014	Demonstration of FTP on engine dyno at T2B2 tailpipe
Sept 2014	Demonstration of FTP on chassis at T2B2

Technical Approach

- Replace aluminium V8 gasoline engine and emission control system with smaller diesel and its emission control system (ECS) without a weight penalty
- Extensive use of aluminium as well as space saving design features for new engine weight control
- Down Sized Engine with high power density
- Integration of learning from LTD and LDECC programs to utilize PCCI and high charge flow operation
- Reduce FE penalty due to emission controls
  - Low pressure EGR, Cold Start Concept (CSC™) catalyst for cold start NOx & HC mitigation, NH3 gas System for immediate reductant delivery, and a small engine running higher loads resulting in faster warm-up

Technical Accomplishments and Progress; New Engine

- Cummins has successfully designed and procured an all Aluminium 2.8L engine
  - 362 lb (production 2.8L = 480 lb)
- Gasoline engine w/ECS
  - 514 lb

- 152 lb weight allowance for diesel ECS and application
  - Exhaust (with catalysts)
  - Reductant and delivery system
  - Added cooling circuit

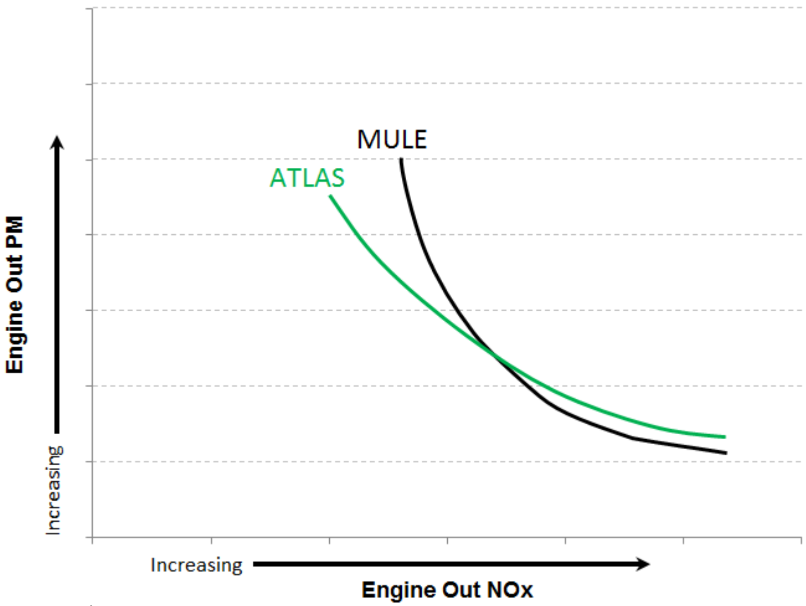
Technical Accomplishments and Progress; New Engine

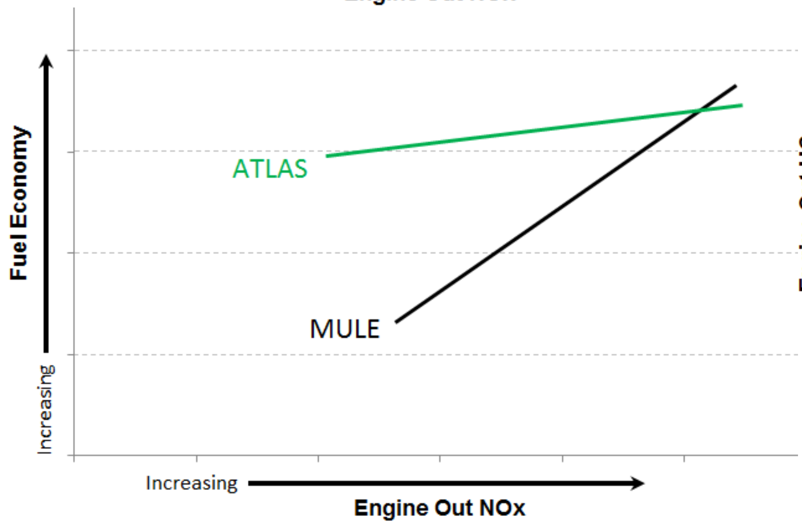
- New engine first fire Dec 2012
- New engine torque curve Jan 2013
  - 350 Ft-lb at 2000 RPM
  - 210 Hp at 3200-3600 RPM
- New engine modal emission demo Feb 2013
  - T2B5 Trim (HP EGR only)

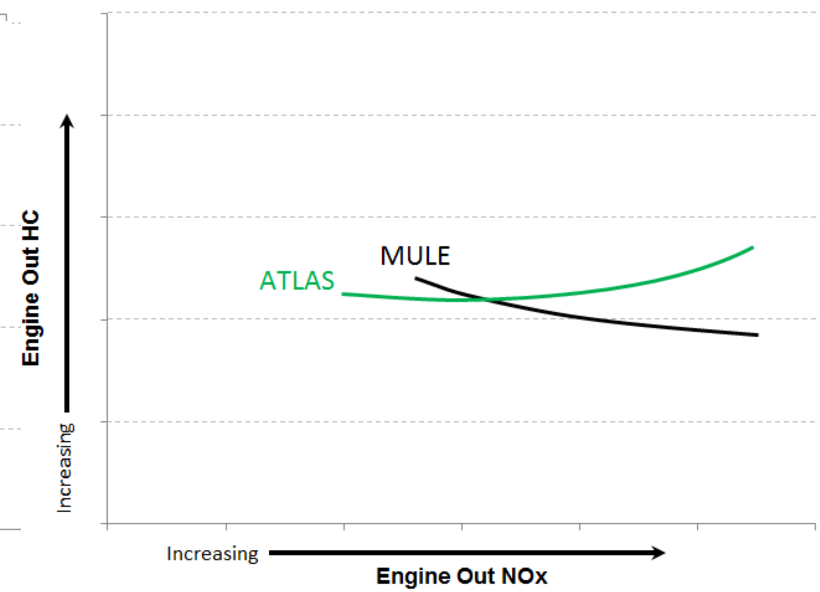
	NOx g/mi	**PM** g/mi	**FE** MPG
ATLAS	0.69	0.09	26.1
Mule	0.63	0.09	25.2

Technical Accomplishments and Progress; New Engine

- Initial set of test data
  - EGR sweeps
  - All high pressure EGR
- Trends display advantage of new engine design





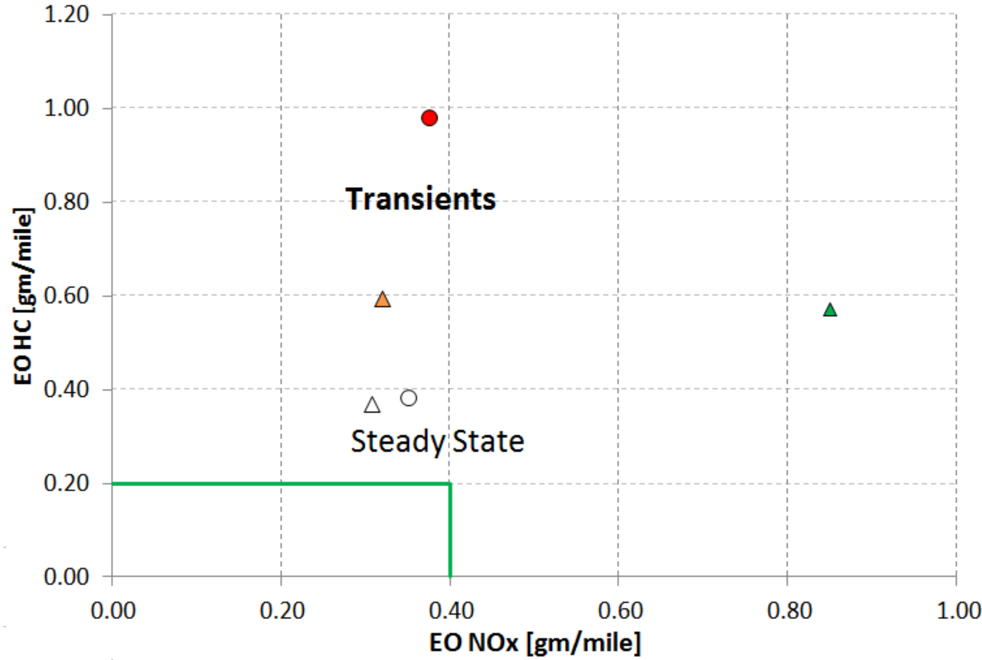


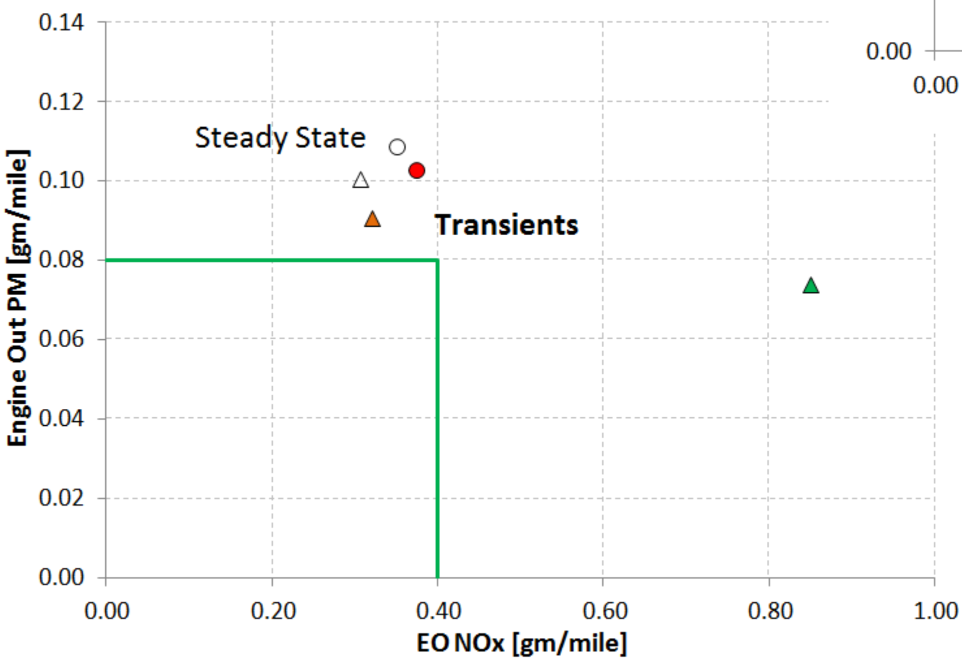
Technical Accomplishments and Progress; Controls

- Concluded work with Rose-Hulman on NOx Sensor
  - Will not use “observability” technique to control SCR
  - Insufficient time/capability for T2B2 requirement
  - Plan to use Cummins SCR control technology
- Air Handling System plan to use Model Predictive Controller (MPC)
  - Physical model linearized about discrete conditions, utilizing empirical data to calibrate transfer functions
  - Ability to rapidly change target control parameters (air flow, charge flow, etc) and hardware configurations
  - Great start for OBD development

Technical Accomplishments and Progress; Controls

- Mule engine test data
  - Dual loop EGR
  - VGT
  - MPC Targeting Test





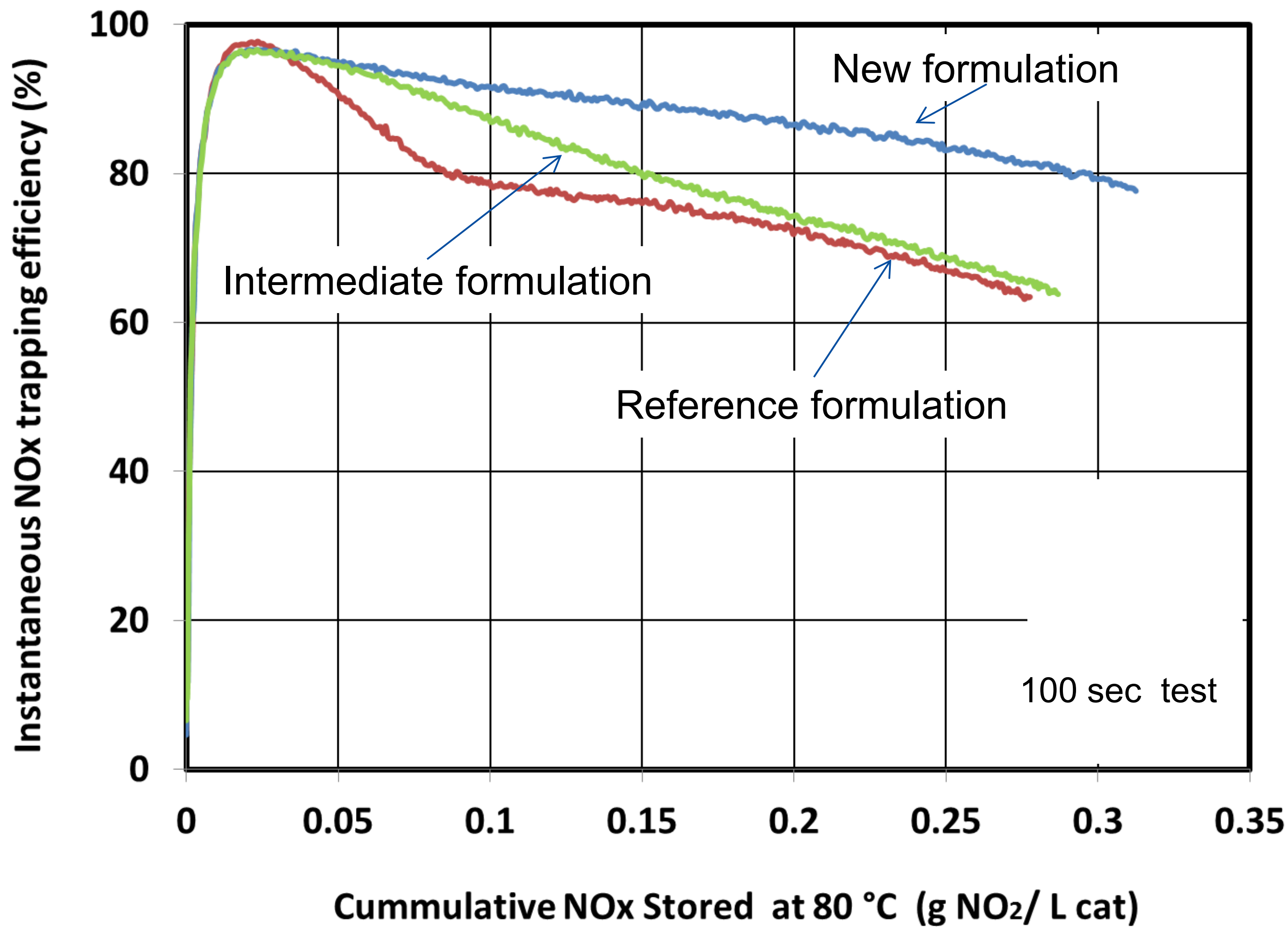
- Response to target parameter
  - NOx & PM show little response to change in target parameter
  - Large HC response

Technical Accomplishments and Progress; Aftertreatment

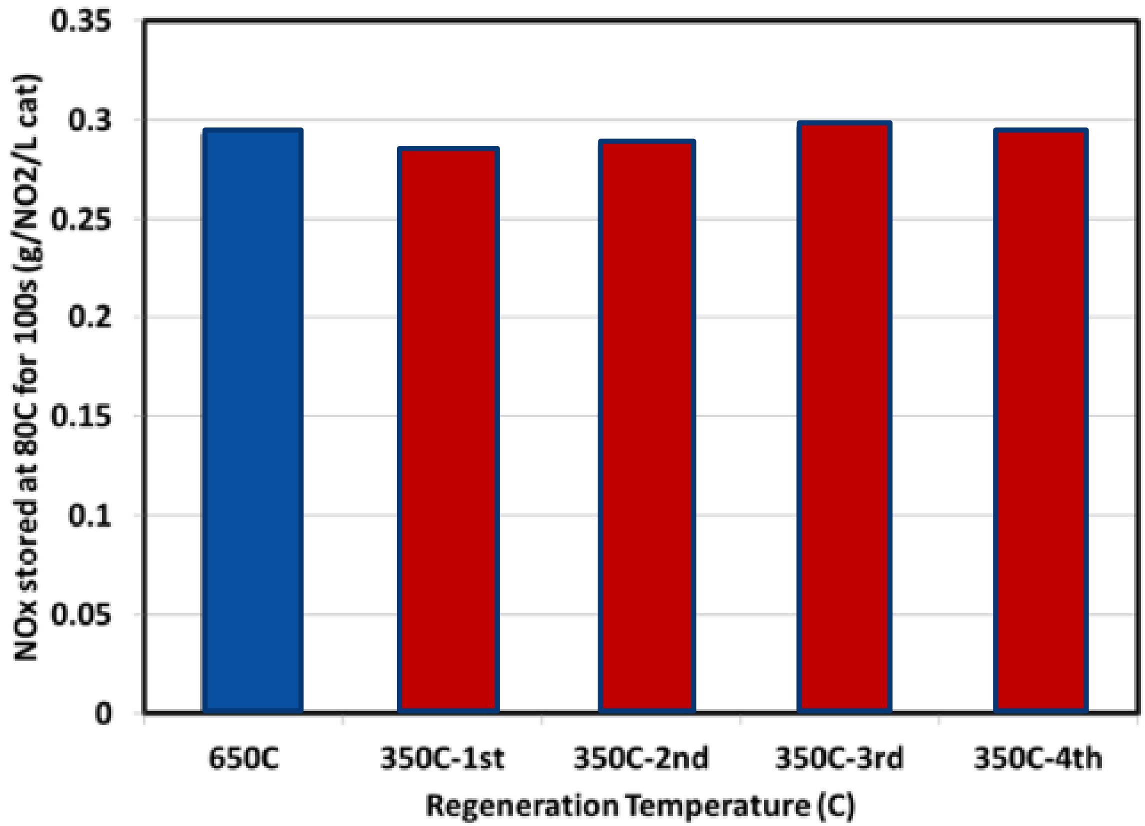
- Continued development work on Cold Start Concept (CSC™)* Catalyst Technology
  - CSC™ is an advancement beyond passive NOx adsorber
  - Improved NOx holding capacity
  - Repeatable loading and complete release at 350°C
  - Optimizing PGM loading for performance
    - NO_2/NO split and HC conversion
- SCR on Filter formulation advances
  - Showing improved effectiveness both degreened as well as fully aged
  - Very high performance under warm conditions

*CSC™ is a trademark owned by JM

New CSC™ formulation has significantly higher instantaneous NOx trapping efficiency at 80°C



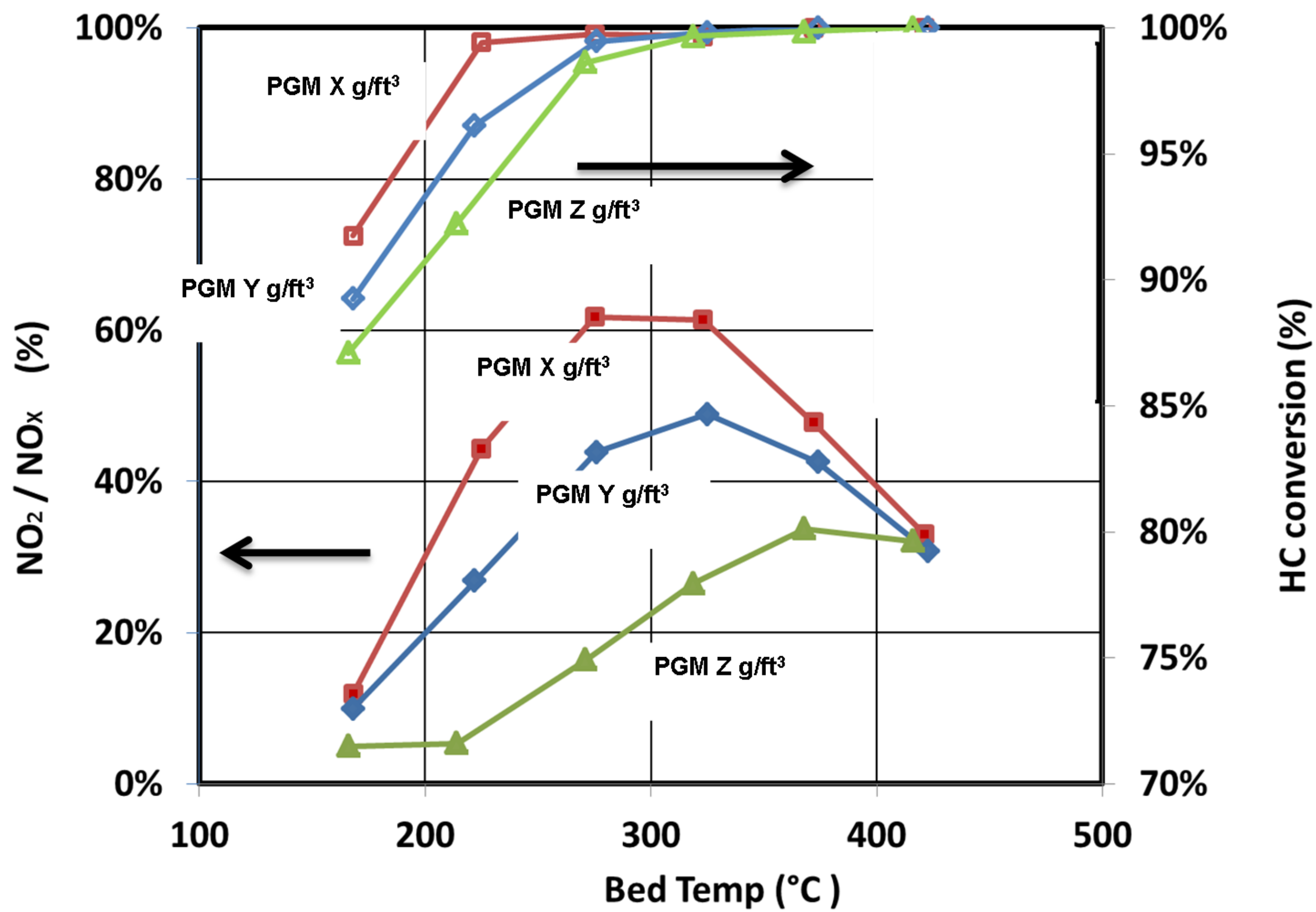
New CSC^{TM} can be fully regenerated by thermal exposure to 350^{o}C under lean conditions



Cumulative NOx stored on the CSC^{TM} for the first 100 seconds at 80^{o}C after regeneration at 650^{o}C (blue bar) and subsequently after each repeated regenerations at 350^{o}C (red bars)

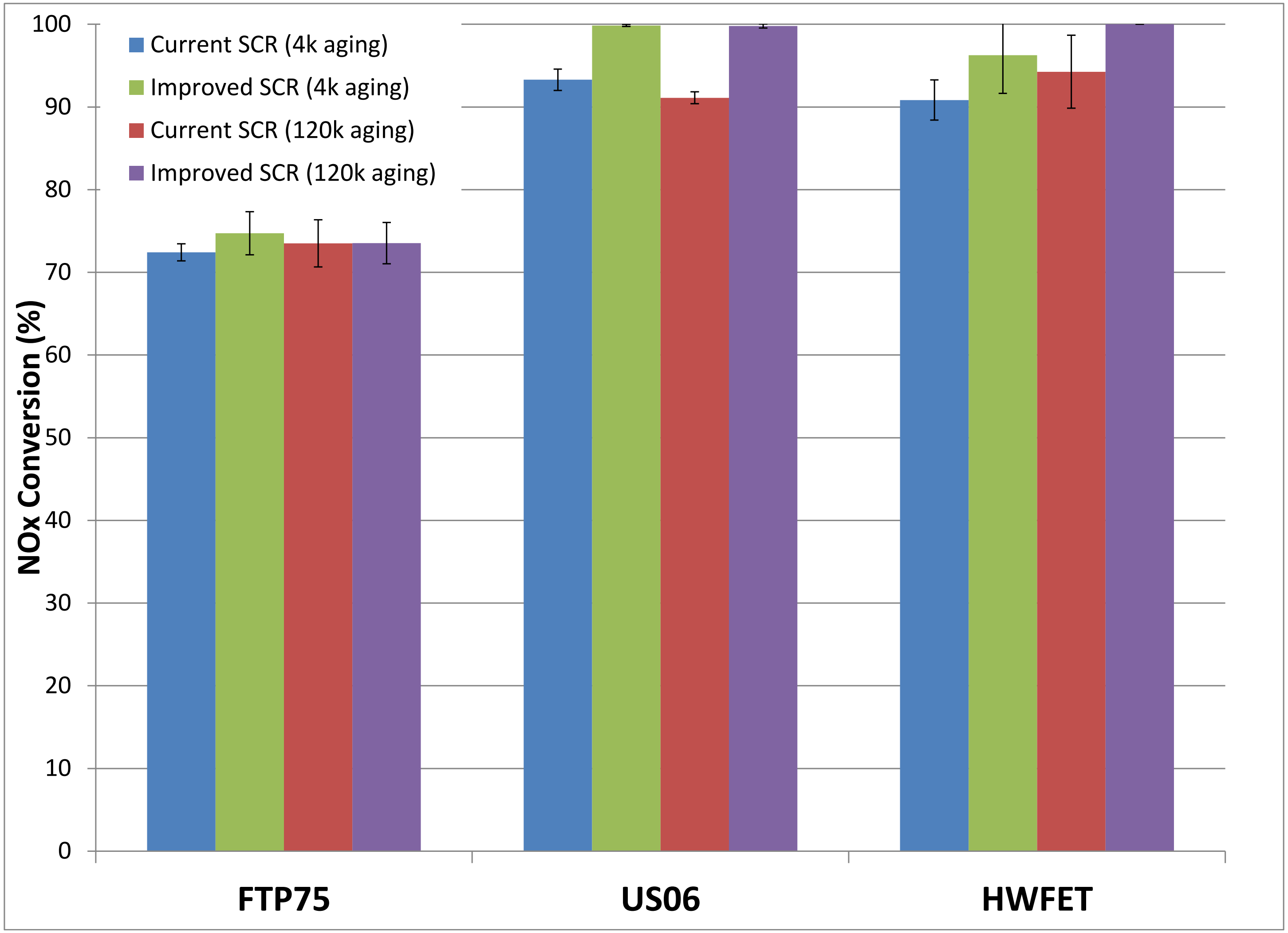
Catalyst optimization for optimal NO_2/NOx & HC conversion varying PGM load on CSC™ parts

PGM loading increases as X>Y>Z g/ft^3



NOx conversion for current and improved SCR technologies, degreened and engine aged

(same technology to be applied to SCRF)



Collaborations

- Partners
  - **Johnson Matthey** –(industry, subcontractor) Advanced aftertreatment formulations and architecture
    - CSC™ for cold start NOx and HC emission mitigation
    - Close coupled SCR on filter for improved cost and effectiveness
    - *Mule engine hardware transferred to JMI for on engine development*
  - **Nissan** (industry, partner) – Vehicle integration and guidance on engine technical profile.

- Other involvement
  - **Rose-Hulman** – (institutio[illegible]act) Control system development to reduce sensor needs [illegible]iprove robustness of controls CONCLUDED
  - **ORNL** – (Nat'l Lab, association) working with light weight CRADA team to integrate advanced material process into base engine components
    - Additional work on fast exhaust gas measurement to ID individual cylinder performance work is being planned

Future Work

- 2013: Move all Cummins development from mule to new engine
  - Second round of castings in process to fix material specification problems as well as design and machining fixes
  - Document individual cylinder performance via ORNL CO2 measurements
  - Procure hardware and begin T2B2 development (New engine LP-EGR)
- 2013: Mule hardware will go to JM for catalyst system development
  - System integration work for on engine testing
  - Formulation optimization and tuning as a system test bed
- 2013: Control network refinement
  - Integrate engine and aftertreatment control systems into on control module
  - Move MPC from controls rapid prototype tool to control module
  - Develop electrical load management for cold start
    - Glow system, starter motor, NH3 storage system heater

Summary

- Cummins is on plan to deliver fuel economy 40% improved over that of the baseline gasoline power train while also meeting the requirements of Tier2Bin2 tail pipe emissions.
- Technical focus over the past year have been centered on transferring work from mule to new engine
  - Planned march to achieve T2B5 followed up by T2B2 demo
- The new engine is showing fuel economy improvement at similar NOx and PM as mule in a packaging friendly design
- Cummins and our partners are developing technology to improve the overall engine package;
  - JM – Delivering materials for low temperature emission mitigation
  - ORNL – Leveraging light weight materials and measurement techniques for general engine development
  - Nissan – Guiding hardware updates to vehicle systems for up to date technology improvements

Technical Backup Slides

Technical Approach – High Efficiency

- Learning from LDECC program
  - High charge flow for extended PCCI operating range
  - High charge flow reduces energy available for A/T
- Appropriate sized engine
  - Down sized engine =>Increased power density => Maintain vehicle drivability & Improved FE
  - Down sized engine => increased loads => higher exhaust gas temperature => Improved A/T performance
- Reduce FE penalty due to emission controls
  - Low pressure EGR to reduce pumping work
  - CSC™ to control NOx & HC under cold start w/o FE penalty
  - Direct Ammonia Delivery System (DADS) for immediate reductant delivery without need for thermal enhancement

Technical Approach – High Efficiency Engine weight control via design features

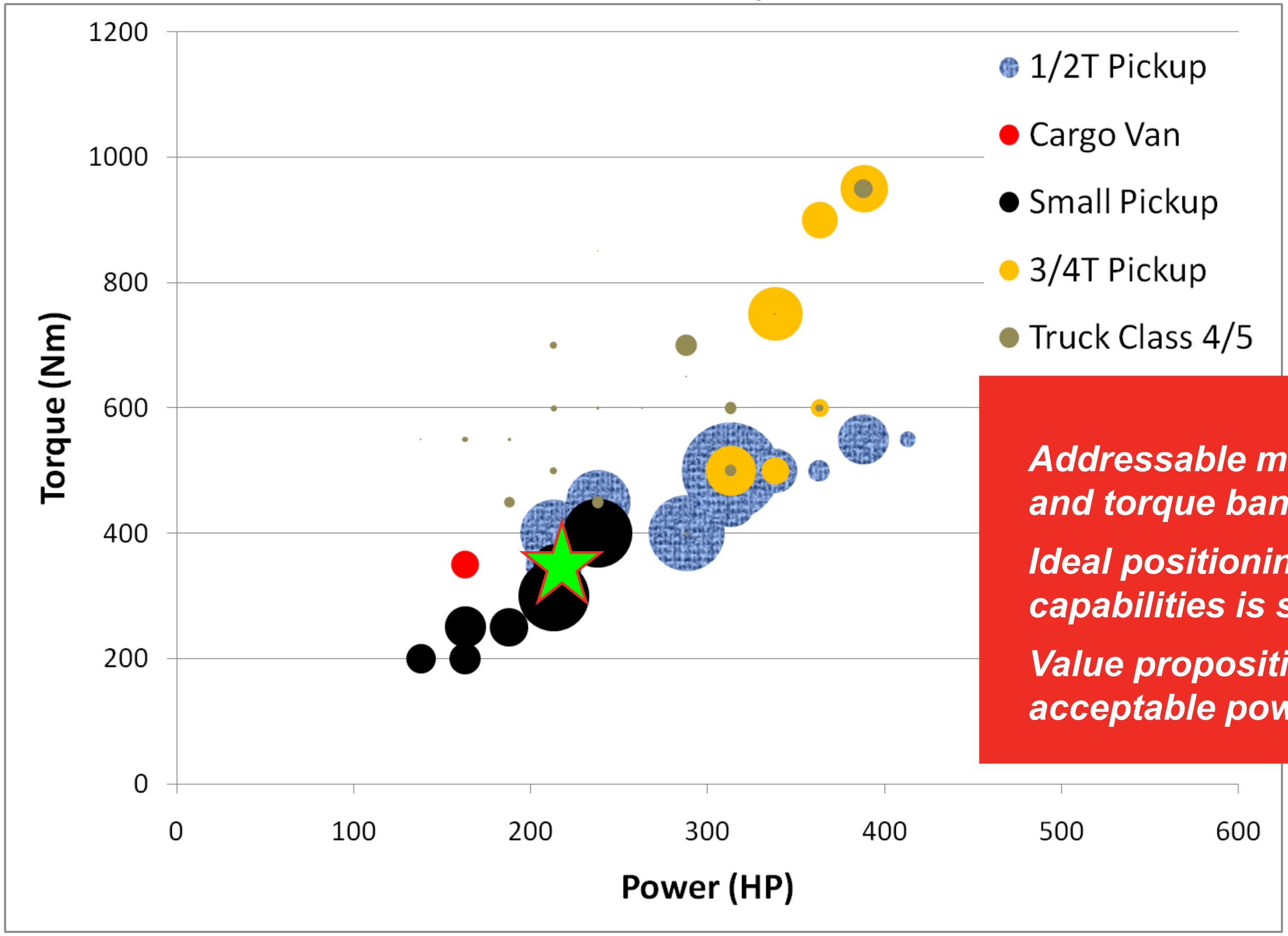
Goal: equivalent application weight as baseline engine

- Light weight steel piston for reduced friction & compression height with increased power density
  - Reduce deck height=> reduced cylinder block weight
- Aluminum cylinder head and block
  - Reduced weight and physical size
  - Create a weight allowance for emission control devices
- Low thermal mass exhaust manifold for rapid warm up
  - Reduced mass & thermal load vs standard cast iron construction
- Forged crankshaft with smaller (than cast) journals and increased strength for power density
  - Smaller and lighter vs standard cast iron

Technical Approach – High Efficiency

Appropriate sized engine

- Down sized engine =>Increased power density => Maintain vehicle drivability & Improved FE



Addressable market based on power and torque band in base offerings.

Ideal positioning given current capabilities is shown with a 'star'.

Value proposition is 'high FE' with acceptable power/torque.

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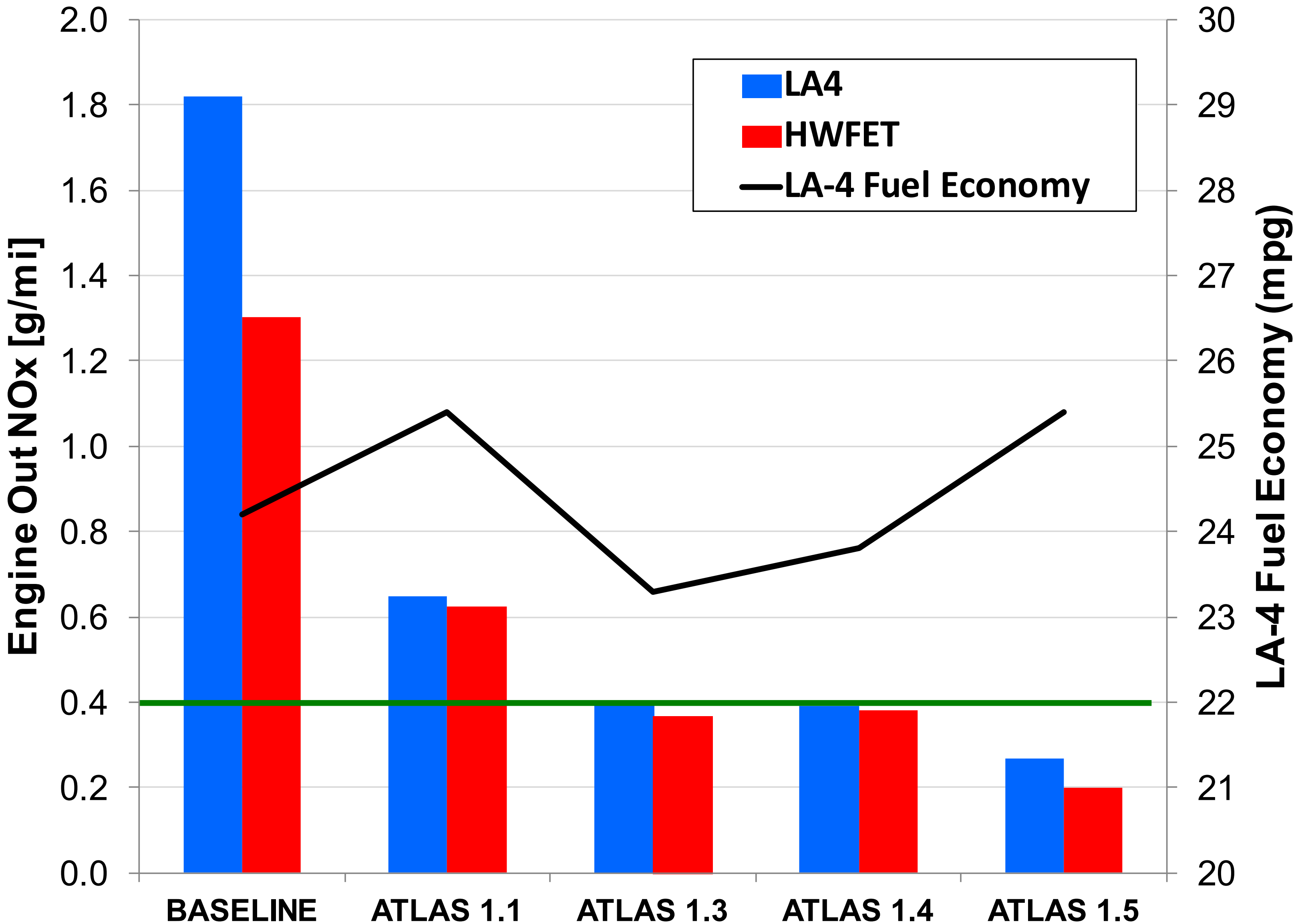
Technical Accomplishments and Progress
Engine Out Emissions and Fuel Economy



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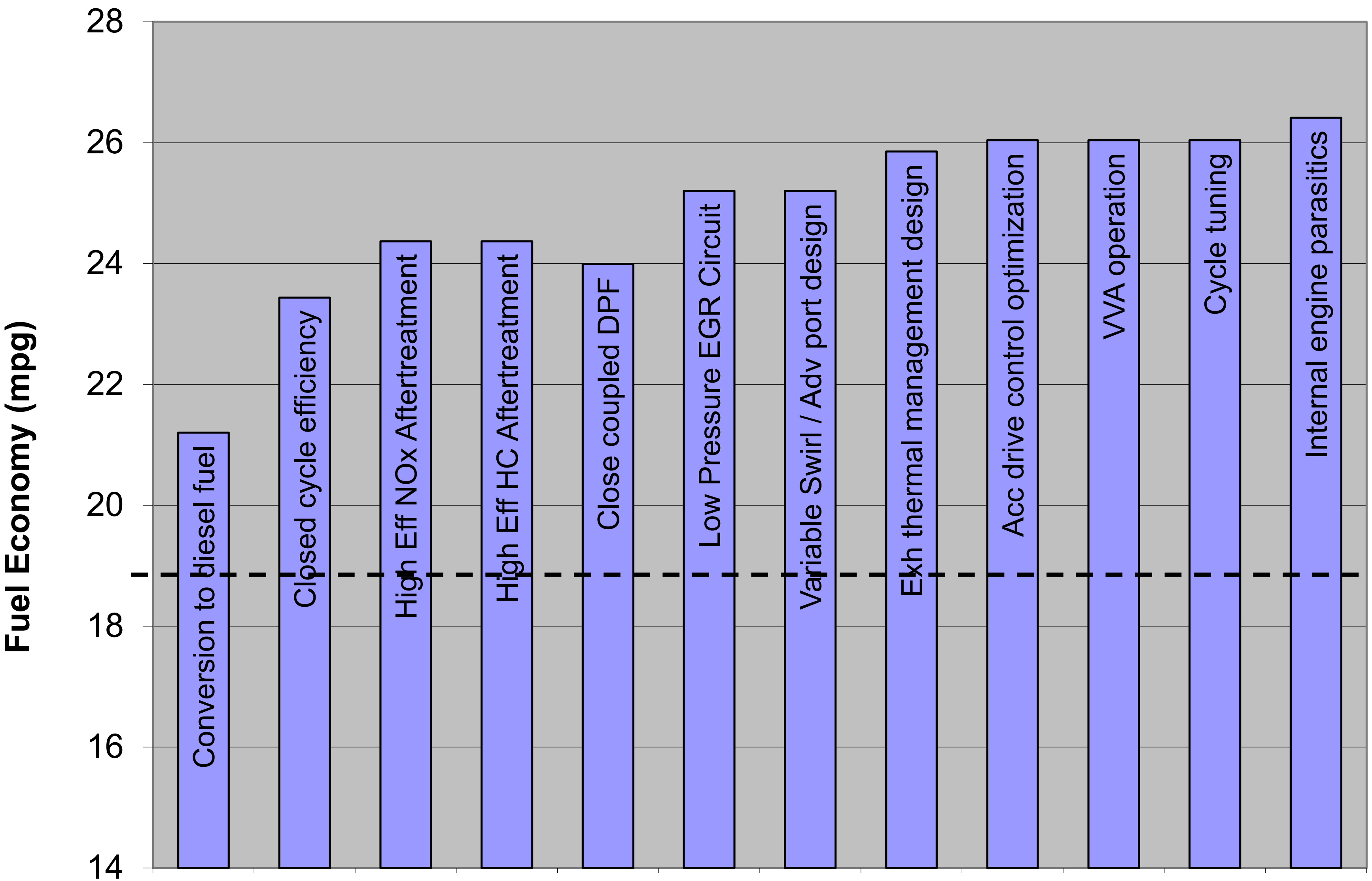
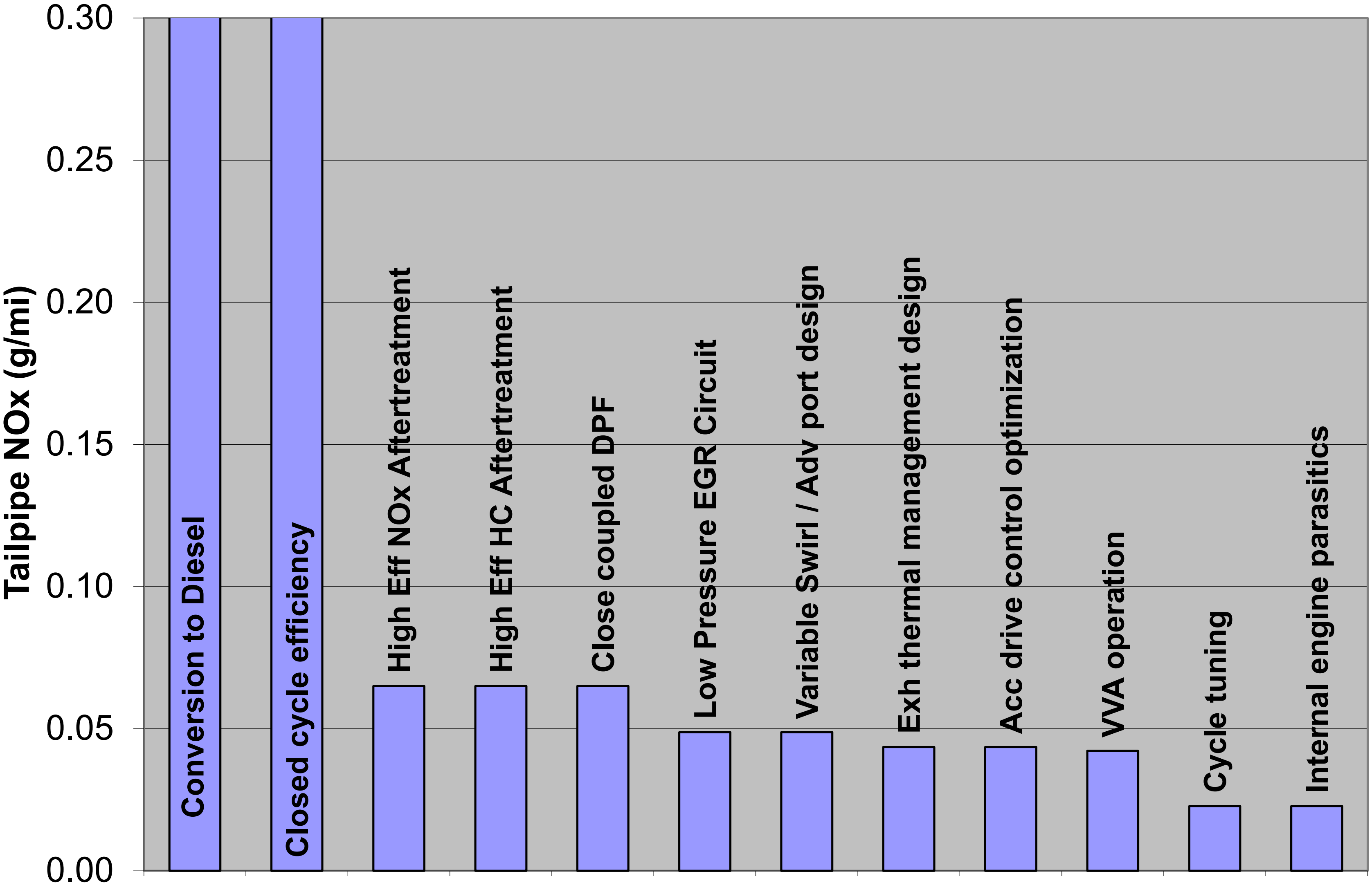
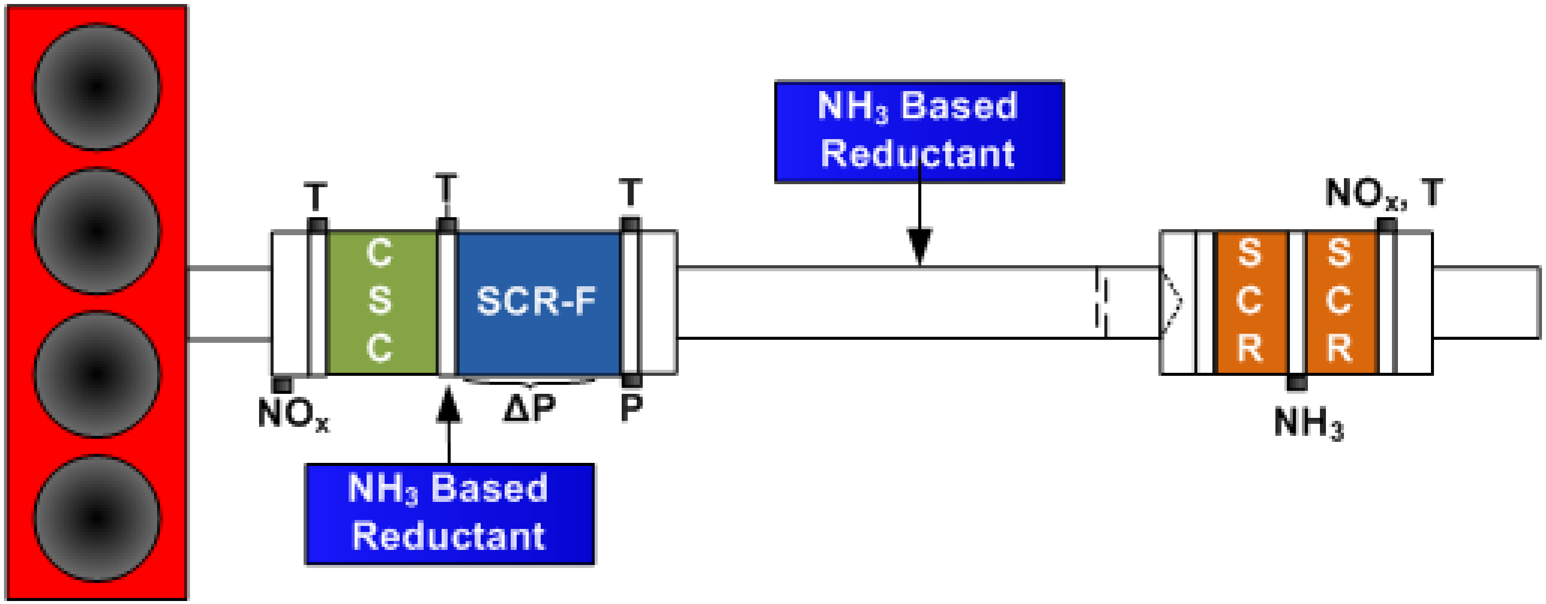
APT LD Fuel Economy Plan



APT Light Duty Tailpipe NOx Strategy



Technical Approach - Exhaust System Configuration

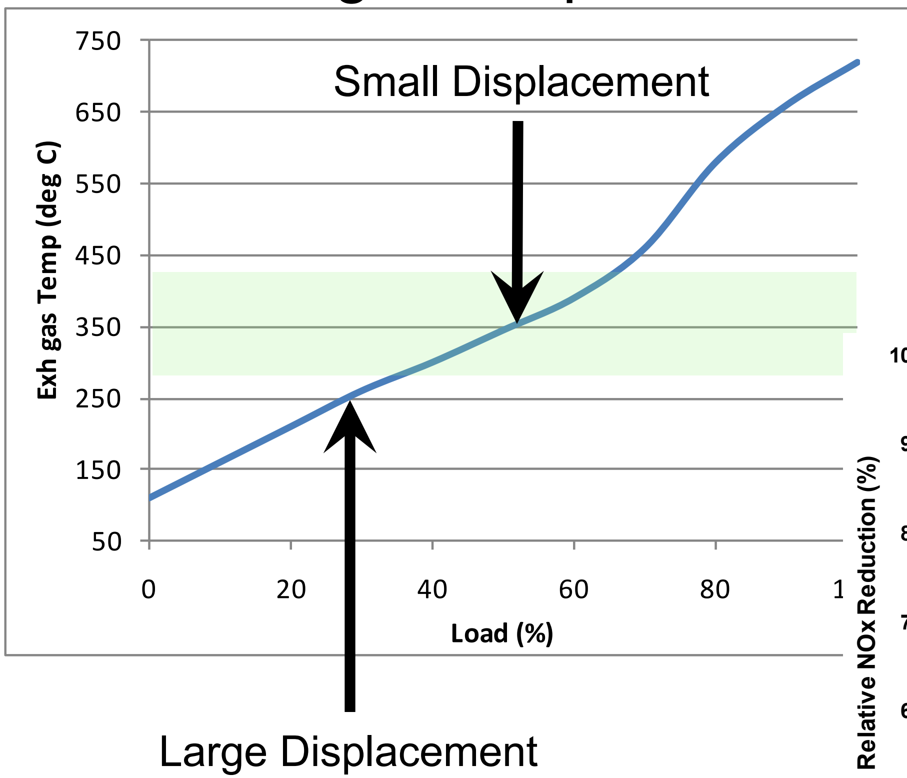


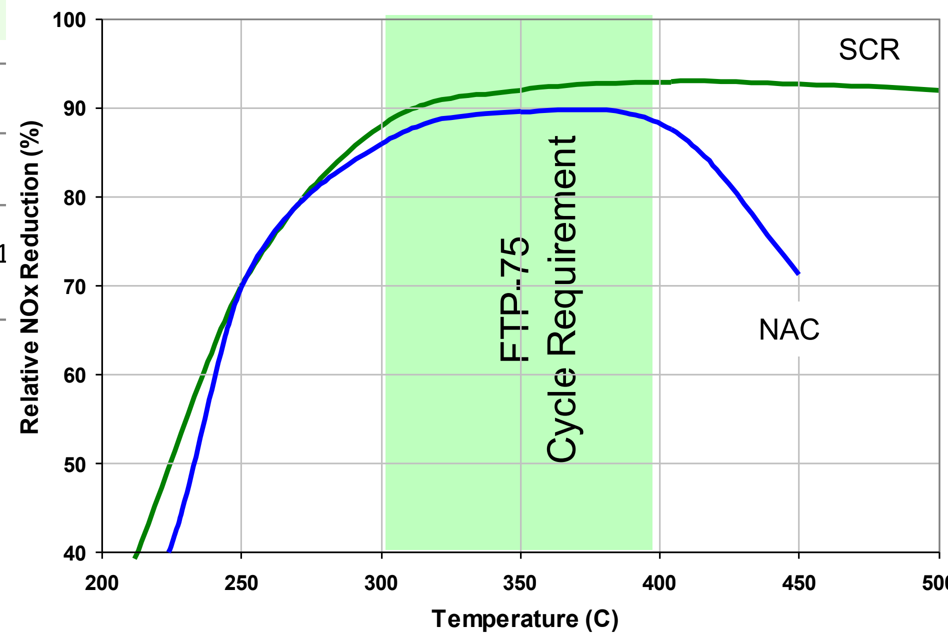
- Close coupled filter system to enable low pressure EGR
- SCR coated on filter (SCR-F) allows for close coupling of SCR function for fast light off
- Use of a direct ammonia delivery system (DADS) can further improve NOx conversion performance by reducing the time delay before NH_3 introduction after cold start
- DADS also allows for multiple NH_3 dosing locations, which allows for the integration of additional under-floor SCR elements to mitigate IRAF

Technical Approach – High Efficiency

Appropriate sized engine

- Down sized engine => increased loads => higher exhaust gas temperature => Improved A/T performance

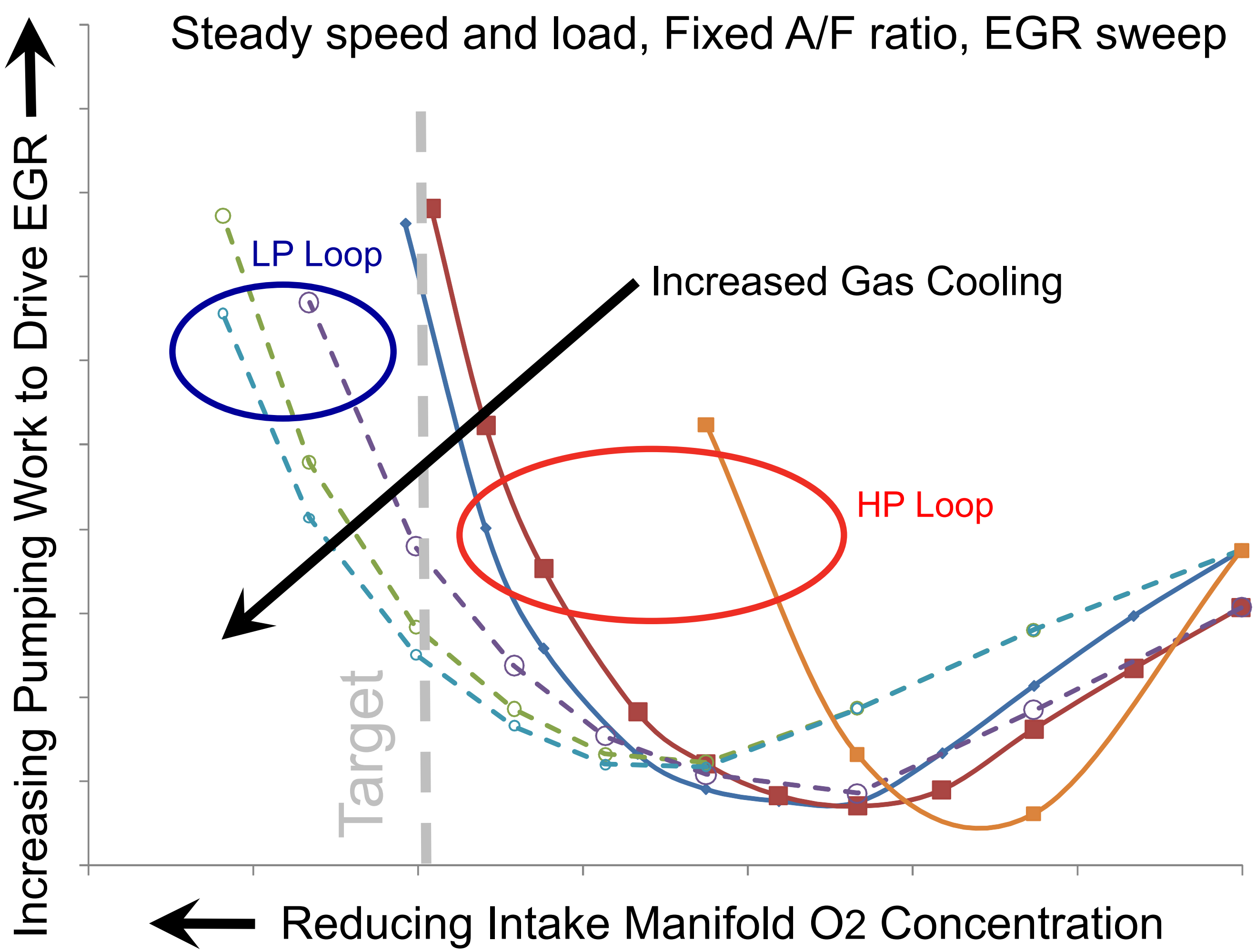


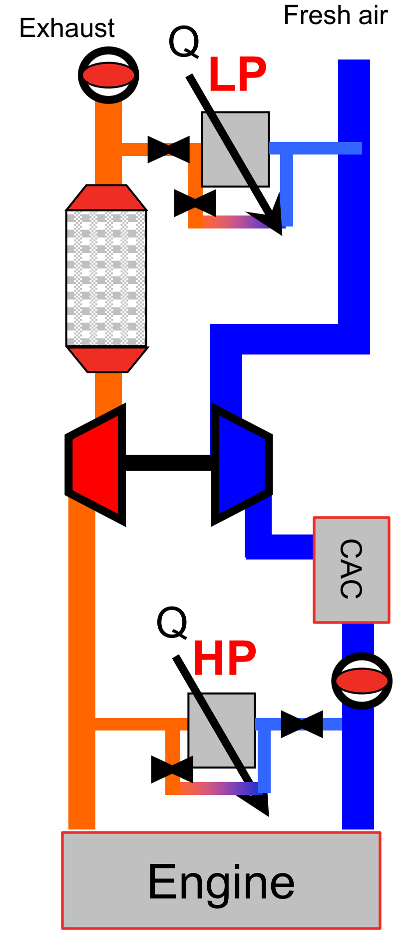


Technical Approach – High Efficiency

Reduce FE penalty due to emission controls

- Low pressure EGR to reduce pumping work

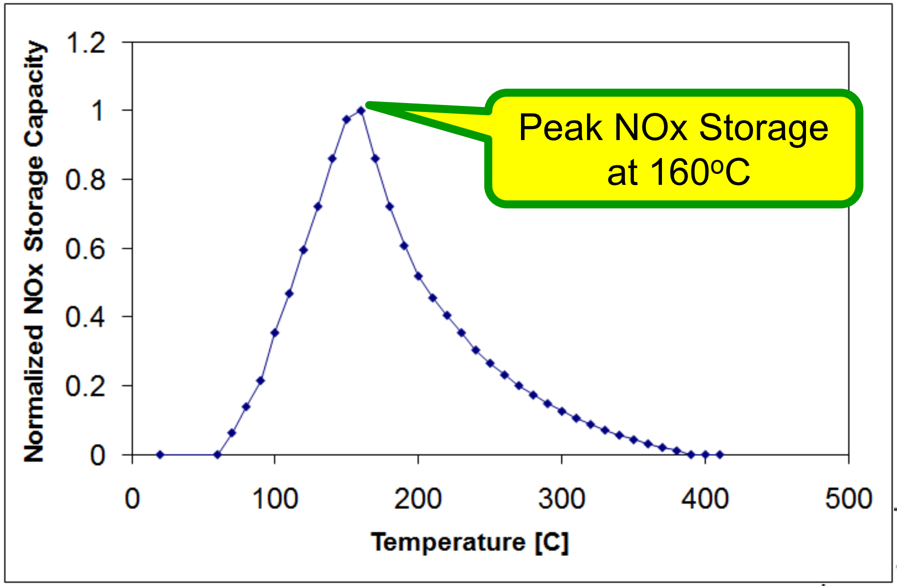




Technical Approach – High Efficiency

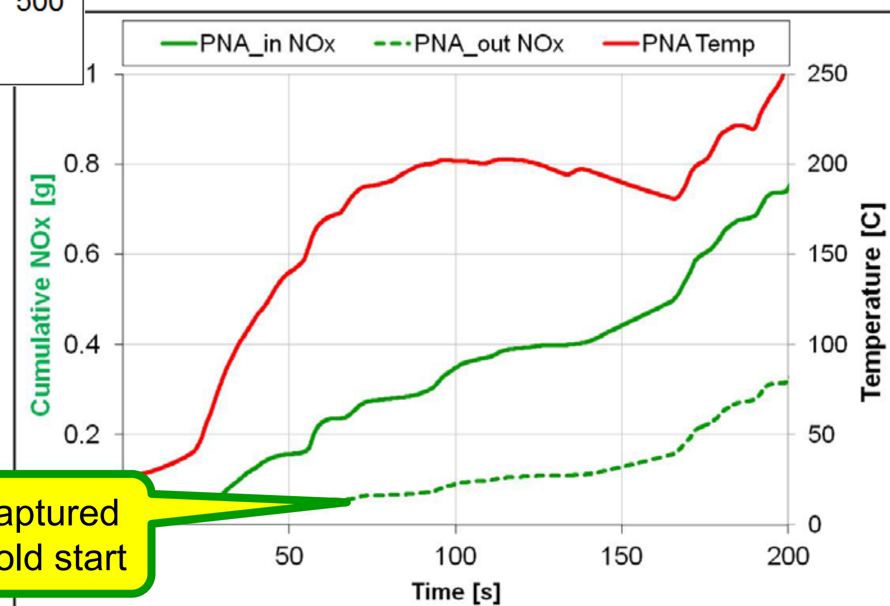
Reduce FE penalty due to emission controls

- PNA to control NOx under cold start w/o FE penalty



- A passive NOx Adsorber (PNA) stores NOx at low temperature and desorbs as the catalyst temperature increases
- With an optimal formulation release of NOx when the SCR reaches operating temperature

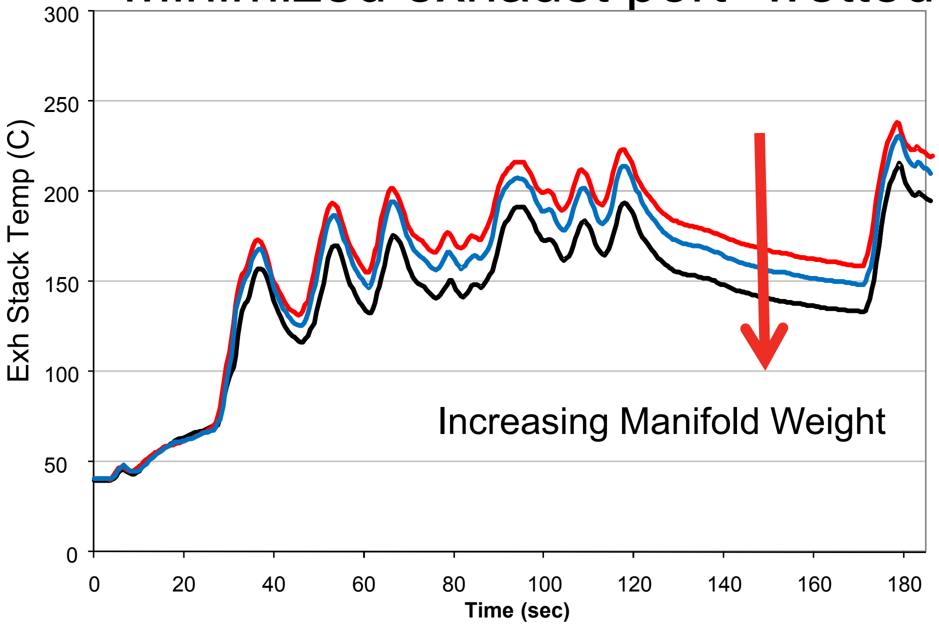
- PNA stores approximately 65% of the NOx released by the engine up to 180s into the cold FTP cycle
- This stored NOx is released around 180s when the exhaust temperature reaches 200°C

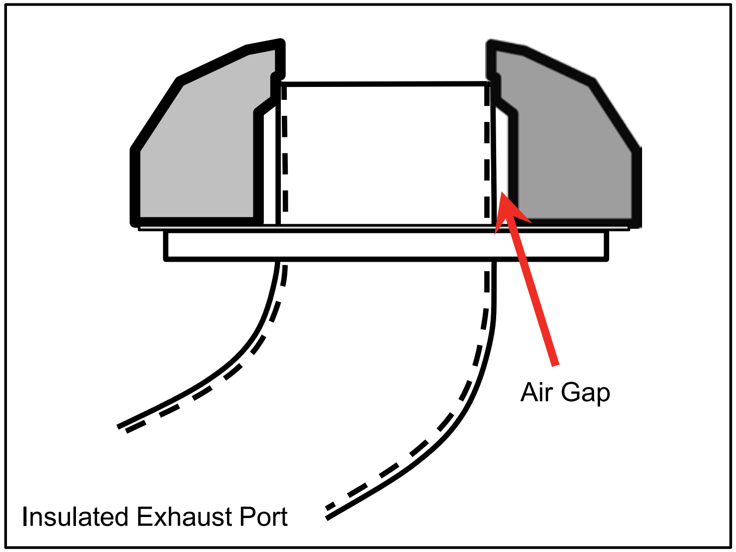


Technical Approach – High Efficiency
Reduce FE penalty due to emission controls

Design features for fast warm up

- Fabricated exhaust manifold instead of cast iron
- Close coupled aftertreatment
  - DOC/DPF assembled onto engine
  - Dual wall exhaust pipe work underbody
- Minimized exhaust port "wetted" area





Technical Accomplishments and Progress
Vehicle Systems

- Mule vehicle build complete
  - Established vehicle communication network
  - Baseline for mule engine fuel economy and emission map
  - Development bed for NVH solutions
- Completed system map for FE accounting
  - Alternator, Vacuum pump, Oil viscosity, etc.

	Base 15W40 Mech Vac	15W40 Elec Vac	5W30 Mech Vac	15W40 Mech Vac No Alt load	
Fuel Economy LA-4	24.2	24.4	25.5	26.9	MPG
Fuel Economy HWFET	33.1	N/A	N/A	N/A	MPG