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

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Changing the Climate on Climate Change

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Cummins Inc

13 May 2011

Project ID:ACE061

Next Generation T2B2 Diesel Engine Overview

Timeline

Start: 10/1/2010

End: 9/31/2014

Complete: <10%

Barriers addressed

High efficiency - 28 MPG CAFE in ½ ton pickup truck

Low emission – Tier2 Bin2

Cost effective solution

Budget

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

Total Spend to date:
- $0.5M DoE
- $0.5M Cummins

Partners

Nissan Motors Light Truck

NxtGen Emissions Solution

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

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Next Generation T2B2 Diesel Engine Objectives

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

Milestones

	% Complete	2011 Milestones
Dec 2010	100%	Vehicle baseline testing – Fuel Economy, Emissions and Performance
Apr 2011	75%	Engine baseline testing – Fuel Economy and Emissions
May 2011	40%	A/T system model available for exercise
Jun 2011	50%	Readied for test, combustion mule engine
Jul 2011	10%	A/T system readied for test
Sep 2011	50%	Mule vehicle complete
Dec 2011	10%	Major reviews complete for new engine design (long lead time items)

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Program Milestones

2012 - 2014	
Mar 2012	Demonstration of LA-4 on engine dyno with Engine Out Emissions at target level
Jul 2012	A/T system architecture is defined, include sensor plan and OBD plan
Sep 2012	New engine assembly complete
May 2013	Demonstration of FTP on engine dyno at T2B5 tailpipe
Nov 2013	New engine operational in vehicle with full A/T system
Dec 2013	Demonstration of FTP on chassis at T2B5
May 2014	Demonstration of FTP on engine dyno at T2B2 tailpipe
Sept 2014	Demonstration of FTP on chassis at T2B2

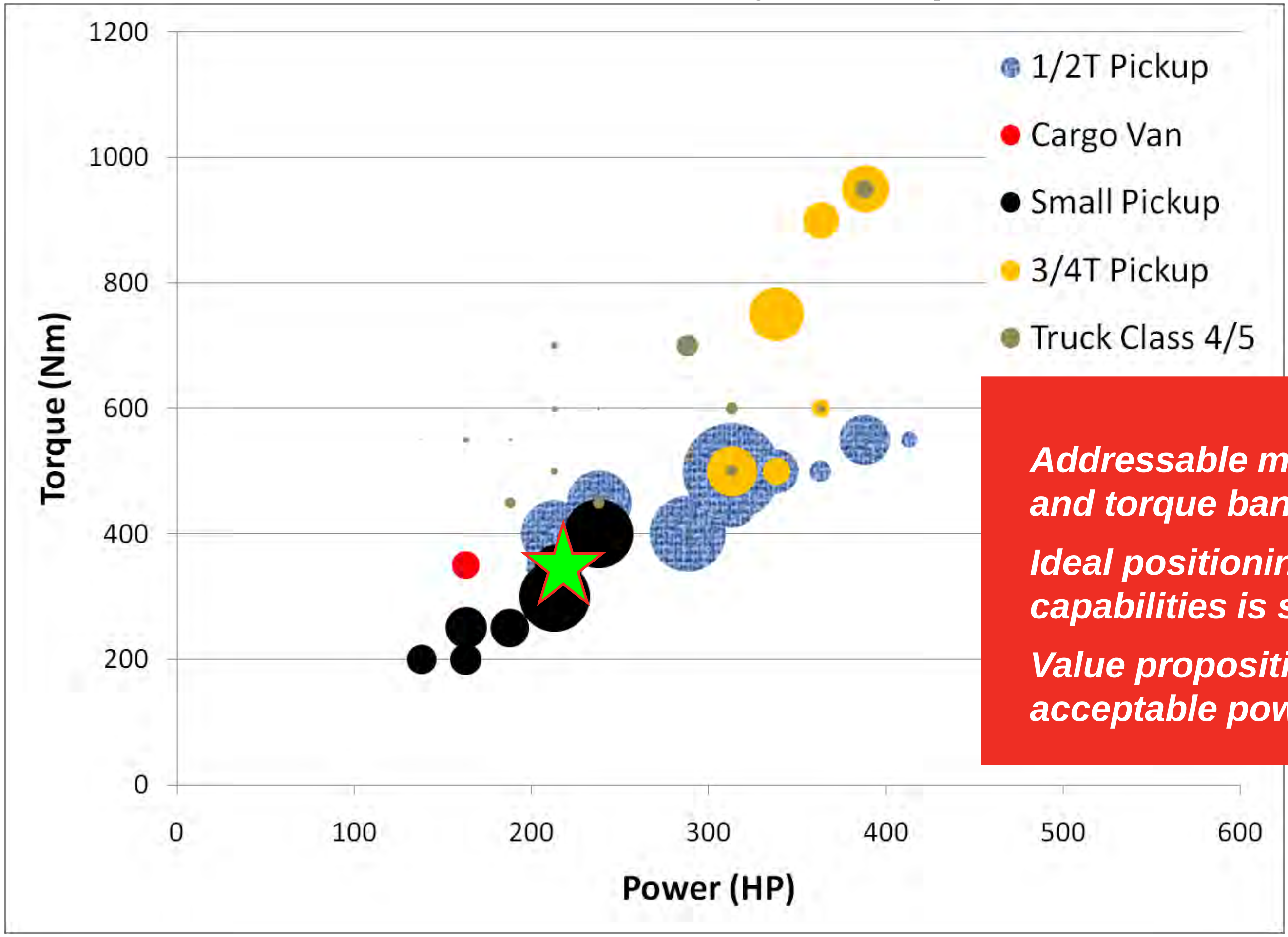
Technical Approach – High Efficiency

- **Learning from LDECC program**
  - **High charge flow improves NOx/PM potential via extended PCCI operating range**
  - **High charge flow reduces energy available for A/T**
- Appropriate sized engine
  - Displacement for power, thermal management, fuel economy
- Reduce FE penalty due to emission controls
  - Low pressure EGR to reduce EGR pumping work
  - Fast exhaust warm up via design features
- Diesel application weight control
  - Engine weight control via design features

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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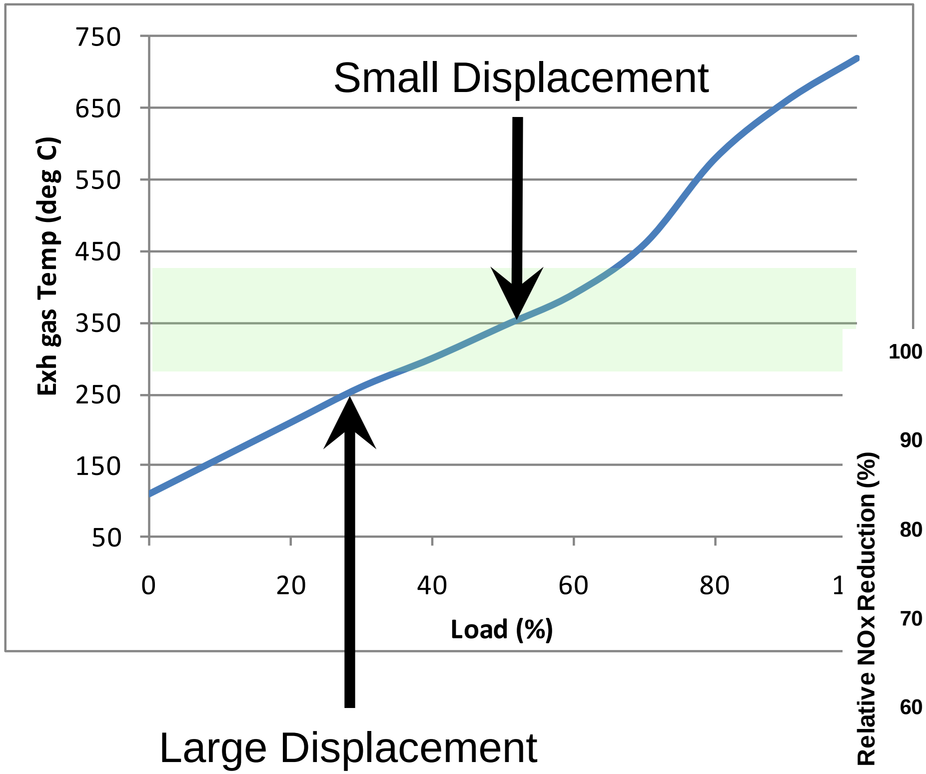
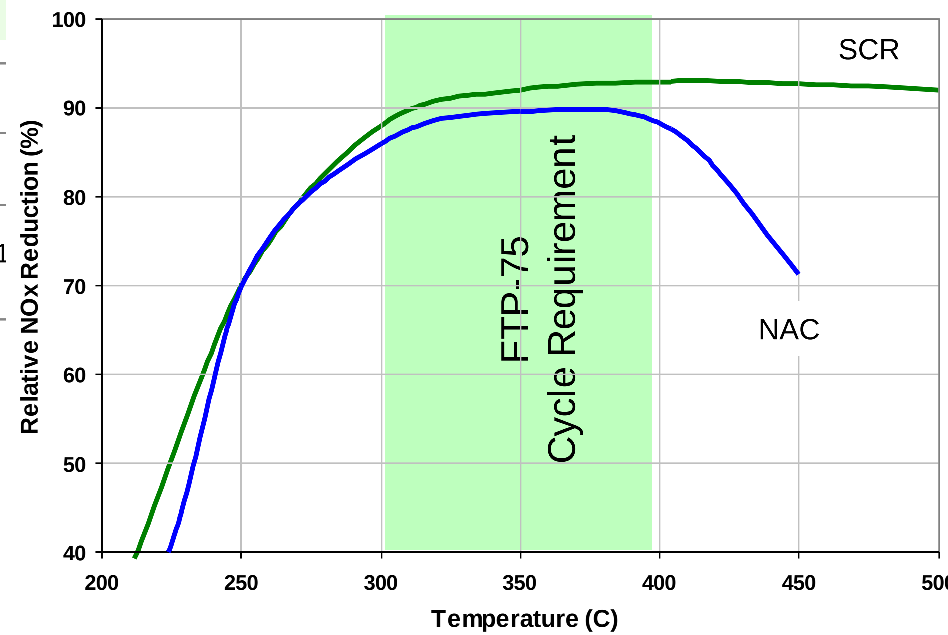
Technical Approach – High Efficiency

Appropriate sized engine

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





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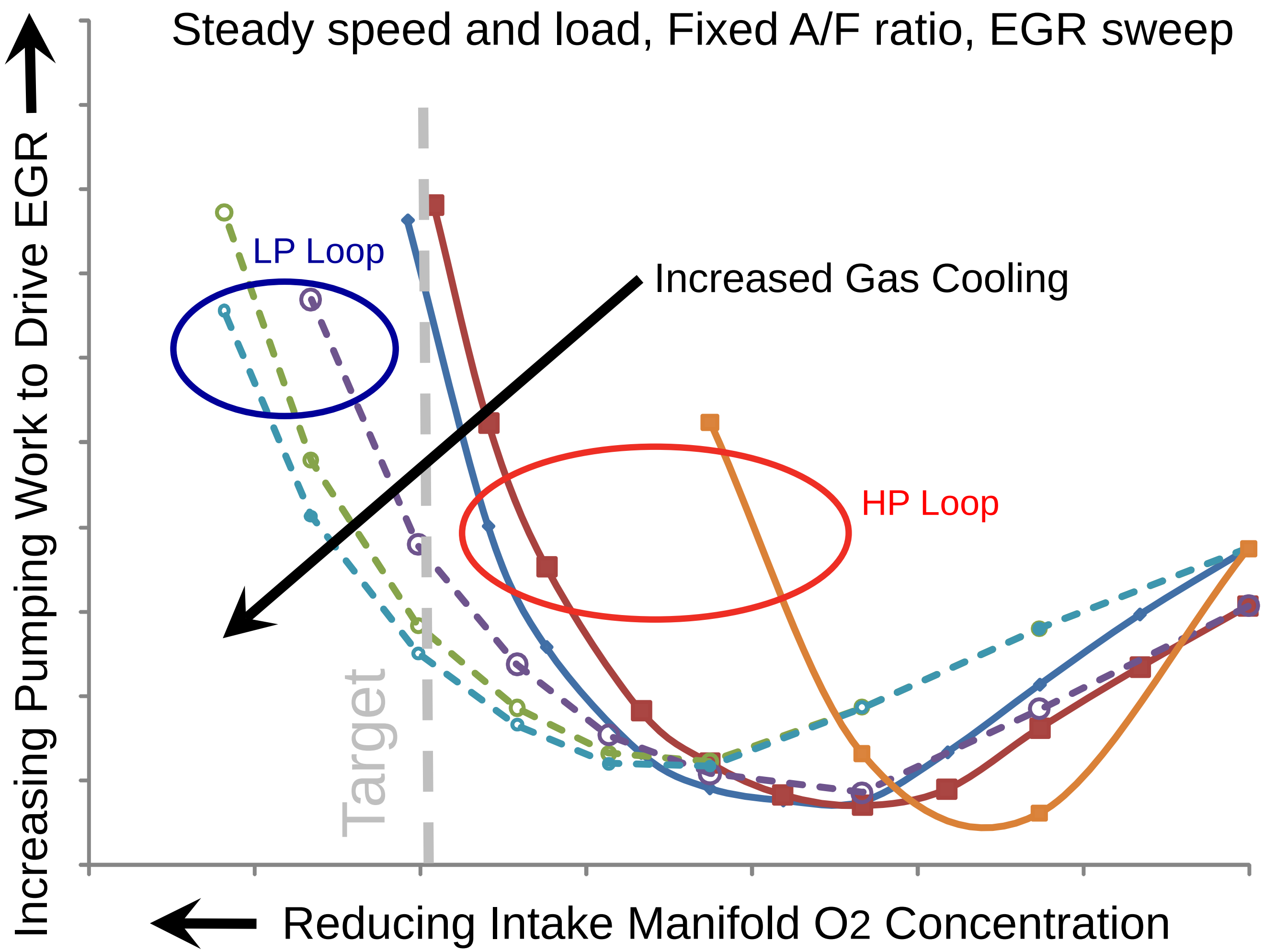
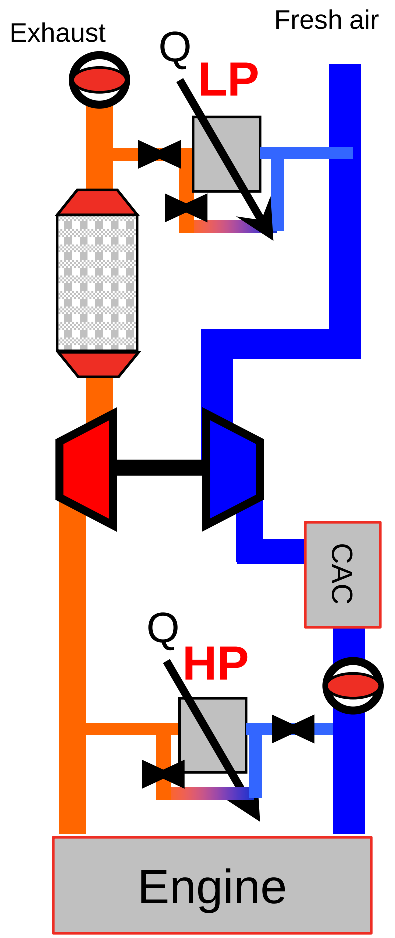
Technical Approach – High Efficiency

Reduce FE penalty due to emission controls

- Low pressure EGR to reduce pumping work

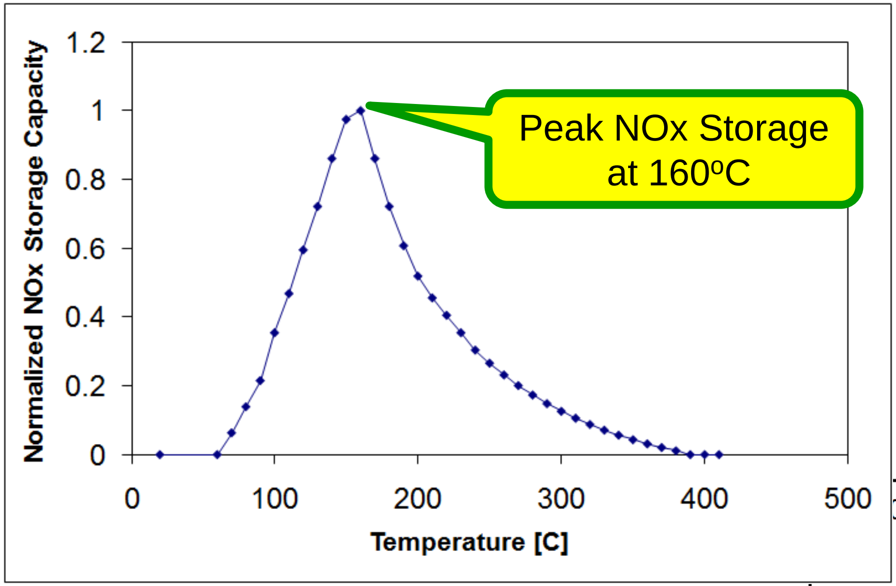




Technical Approach – High Efficiency

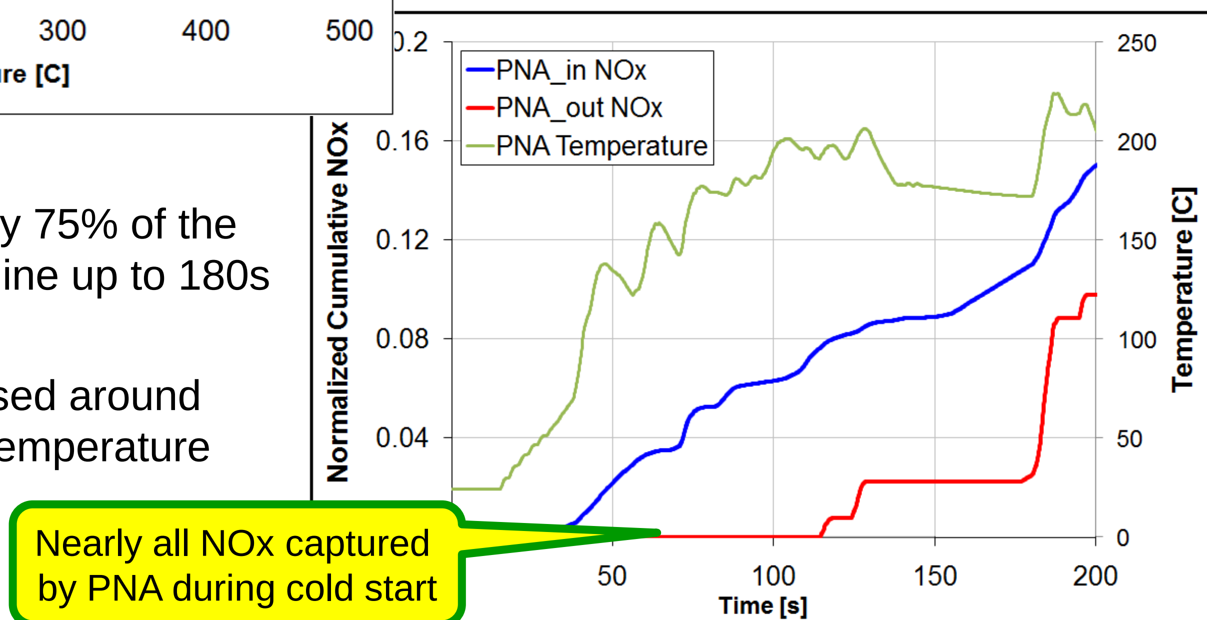
Reduce FE penalty due to emission controls

- 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 75% 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

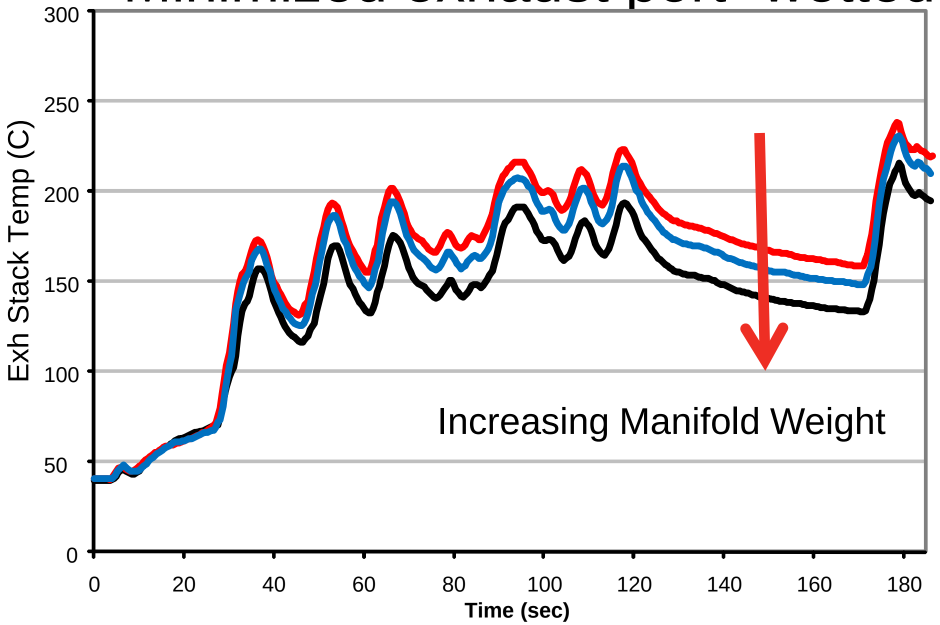


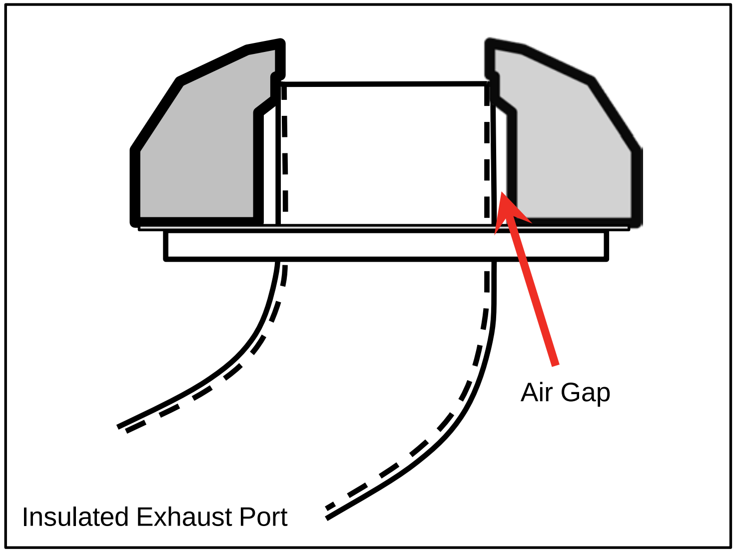
Technical Approach – High Efficiency

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



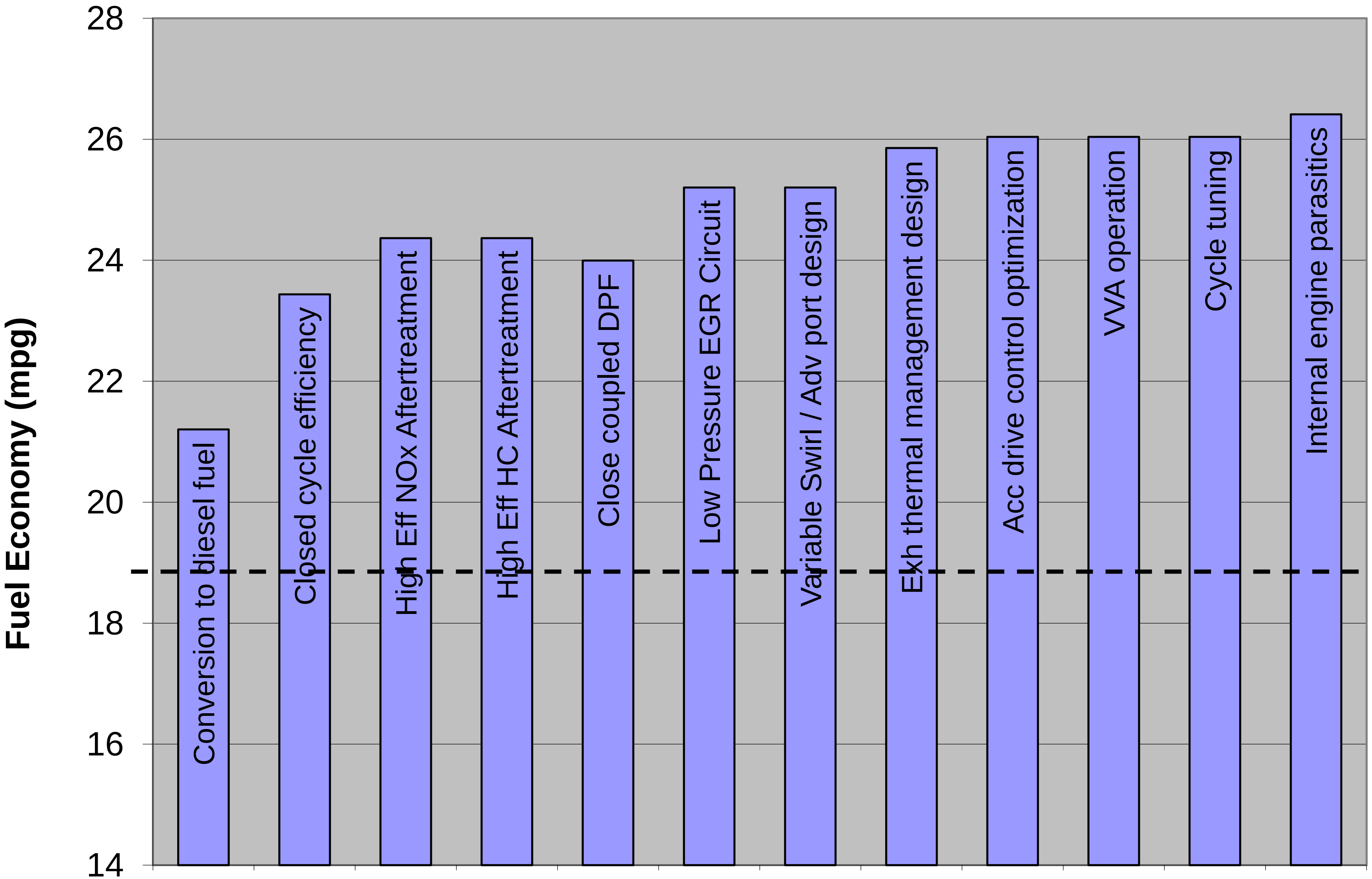


Technical Approach – Engine weight control via design features

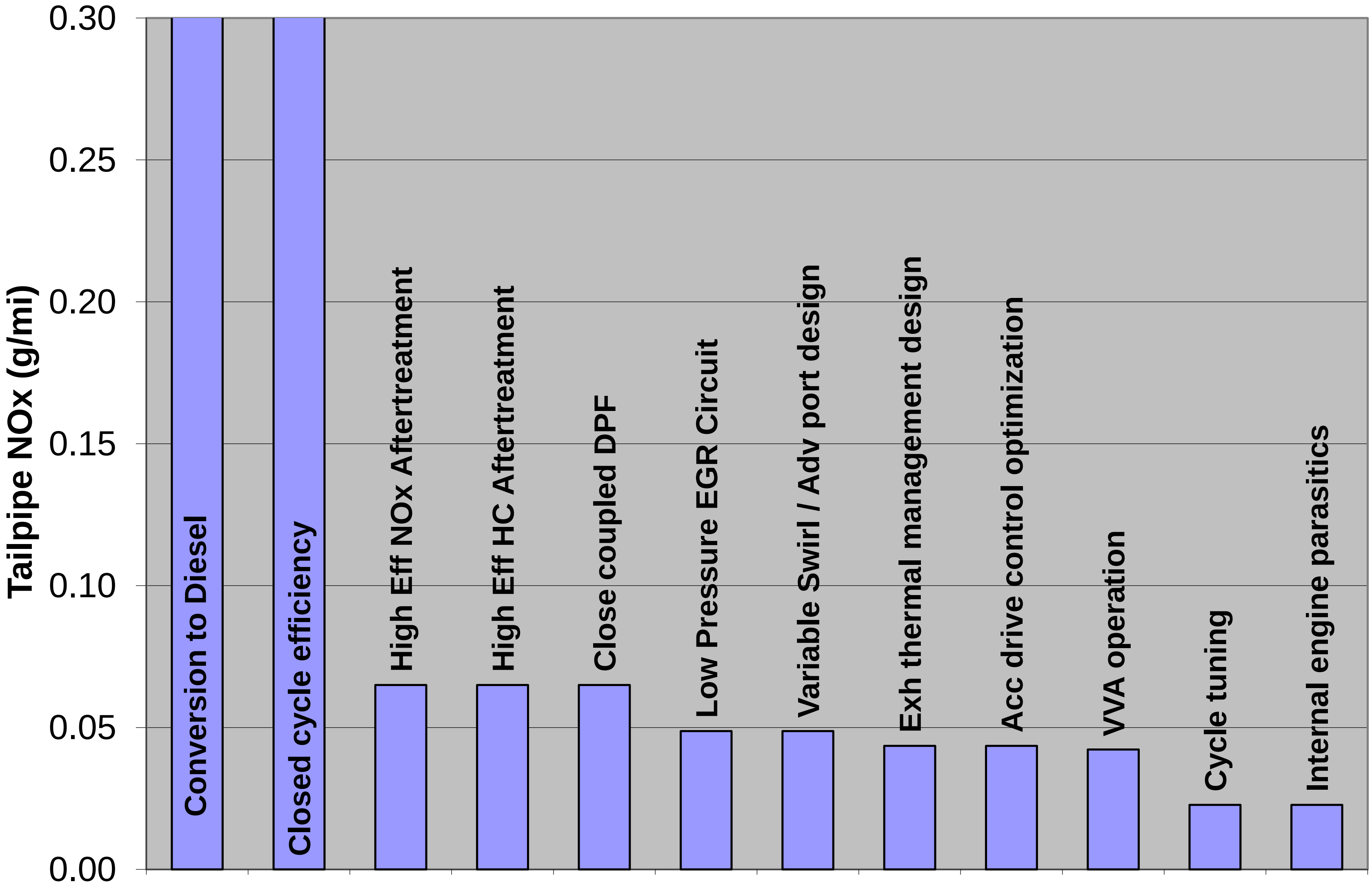
<u>Goal: equivalent application weight as baseline engine</u>

- Light weight steel piston for reduced friction & compression height with increased power density
  - Reduce deck height, reduced cylinder block weight
- Aluminum cylinder head for weight and size optimization
  - Reduced development time and cost to program
  - Make common with LDD V8 (previous DoE program engine)
- Fabricated manifold for rapid exhaust warm up
  - Reduced weight vs standard cast iron
- Forged crankshaft with smaller (than cast) journals and increased strength for power density
  - Smaller and lighter vs standard cast iron

APT LD CAFE Fuel Economy Plan



APT Light Duty Tailpipe NOx Strategy



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Technical Accomplishments and Progress

- Baseline engine performance testing complete and correlated to GT-Power model
  – Included FE response to oil viscosity testing
- Baseline vehicle performance testing complete
  – Basis for front end of vehicle model
- Combustion Mule Engine
  – Design and procurement of variable swirl system
  – Design and procurement of Generation 3 Piezo FIE adapted to engine
  – Design and procurement of HP/LP EGR system
- Mule Vehicle for drive train optimization
  – Build complete, first fire in April 2011
  – Development of shift strategy, acc load management, etc..

Technical Accomplishments and Progress

- Base engine
  - crank analysis completed for new mat'l, main and pin sizes – design included low viscosity oil properties
  - power cylinder kit designed for short comp height and low friction ring pack
  - detailed GT model (capable of coupling with vehicle and A/T)
- Control system
  - Completed first order HP/LP operational model
  - Designed and implemented mule vehicle control network
- Aftertreatment modeling
  - New A/T technology first order model (PNA)
  - Full model for A/T options (SCR vs NAC)
  - Detailed model for target development of 0-180 sec
- Vehicle model
  - Baseline for mule development underway

Collaborations

- Partners
  - **Johnson-Matthey** –(industry, subcontractor) Advanced aftertreatment formulations and architecture
    - Passive NOx adsorbers for cold start NOx emission mitigation
    - Close coupled SCR on filter for improved cost and effectiveness
  - **Nissan** (industry, partner) – Vehicle integration and guidance on engine technical profile.
  - **NxtGen** – (industry, subcontractor) exhaust thermal enhancer via syngas generation

- Other involvement
  - **Rose-Hulman** – (institution, contract) Control system development to reduce sensor needs and improve robustness of controls
  - **ORNL** – (Nat'l Lab, association) working with light weight CRADA team to integrate advanced material process into base engine components

Future Work

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- 2011: Complete combustion mule development in order to specify technical design requirements for;
  - HP/LP EGR and air handling system (control, cooling, restrictions, etc)
  - Fuel injection system (Nozzle specs, operational specs, etc..)
  - Variable swirl system and base cylinder head specifications
  - Aftertreatment system architecture and materials
- 2011: Complete single cylinder engine work to investigate variable valve motion (VVA and VVT)
- 2011: Complete mule vehicle development in order to specify technical design requirements for;
  - Drive train (Shift conditions, warm up methods, rear axle, acc drive…)
- 2012: Procure and build new engine based on mule development and technical specifications
  - Testing of new engine planned for September 2012

Summary

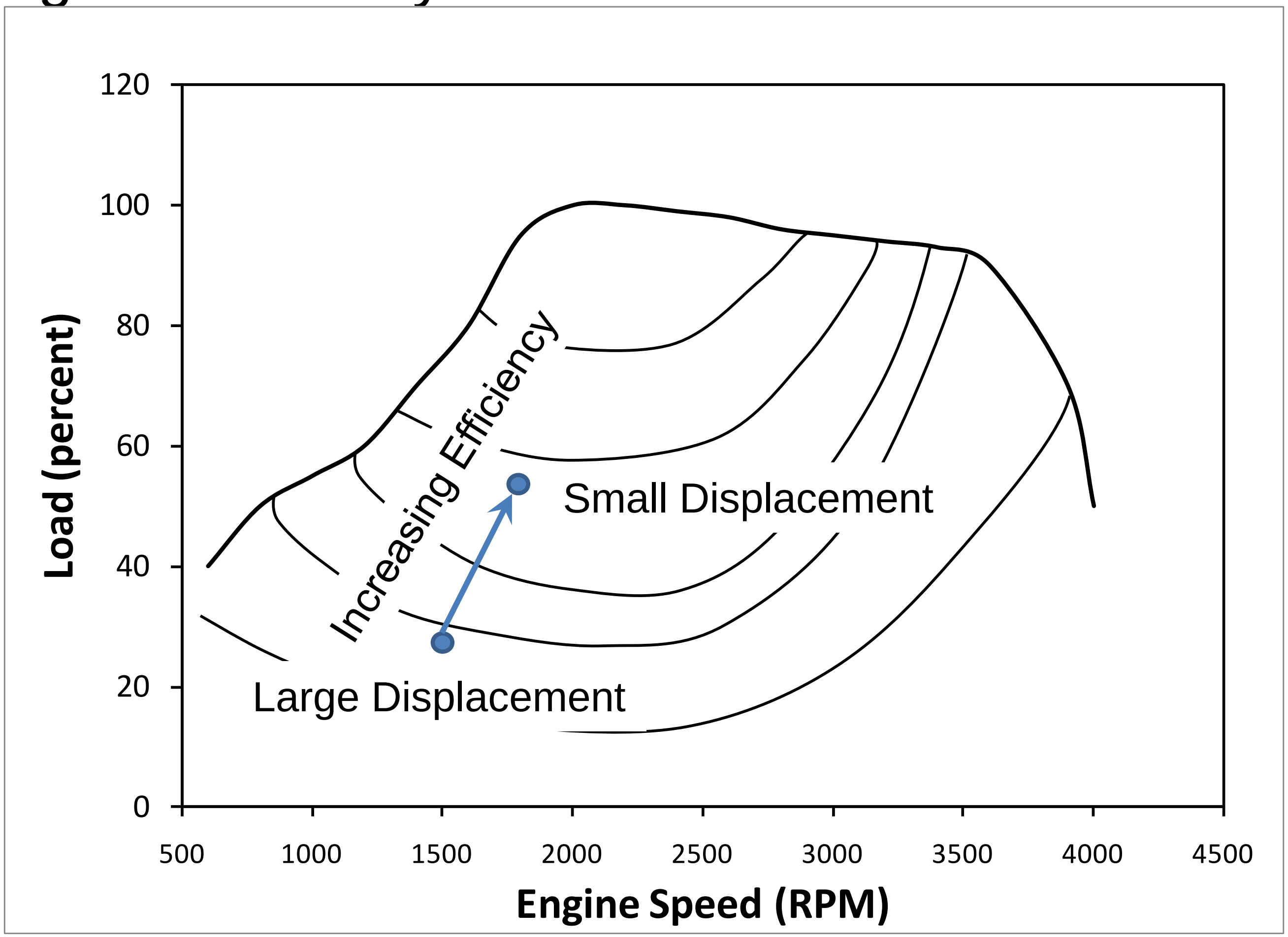
- Sound technical strategy to achieve 40% FE improvement and T2B2 tailpipe emissions.
- Program built on previous program (LDECC) learnings:
  - High charge flow, low O2 combustion scheme
  - Push premixed combustion zone to higher loads
- Collaboration with OEM to ensure the application is designed with minimum impact on vehicle systems and interface.
  - Package majority of emission control system on engine (charge air cooler, Urea doser, DOC/DPF and LP EGR)
- Evaluation of technology based on:
  - Value (performance vs cost)
  - Weight – effect on FE and vehicle impact (component change)
- Cummins will work within current manufacturing strategy to improve commercial opportunities.
  - Minimize impact of new engine on capital investment and supply base

Technical Backup slides

Technical Approach – High Efficiency

Appropriate sized engine

- Down sized engine =>Small engine => increased loads => higher efficiency



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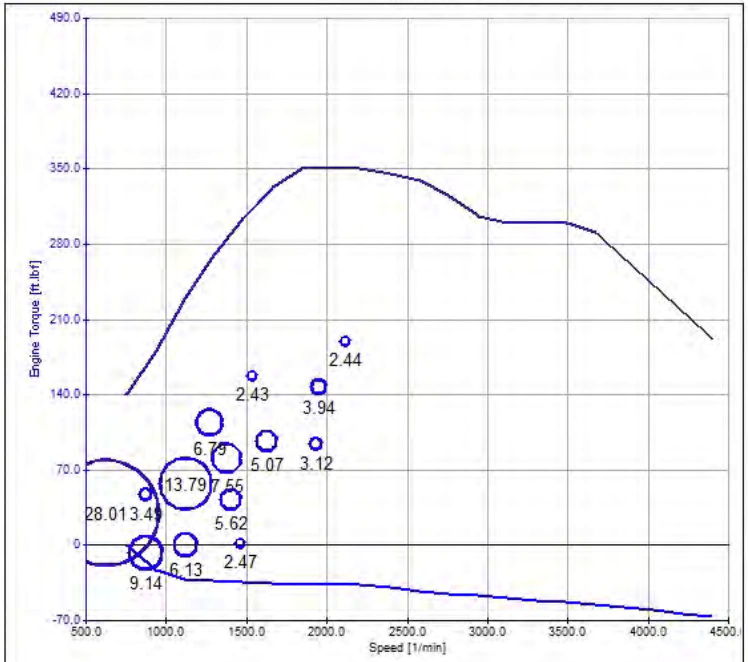
Mule Vehicle Model Development

FTP72 — AVL CRUISE

CHARACTERISTIC DATA		
Curb Weight	<lb.mass>:	5136.8
Vehicle Mass	<lb.mass>:	5302.1
Frontal Area	<sq.in.>:	9360.00
Drag Coefficient	<->:	0.440
Displacement	<cu.in.>:	170.866
Number of Cylinders	<->:	4
Number of Strokes	<->:	4
stat. Roll. Radius	<in.>:	12.008
dyn. Roll. Radius	<in.>:	12.283
Calculation Mode:		Quasi stationary 1
Slip		: Off

Speed [1/min]	Torque [ft.lbf]	Abund. [%]	Abund. [s]
625.0	30.51	28.01	384.27
1125.0	57.28	13.79	189.25
875.0	-6.77	9.14	125.41
1375.0	80.34	7.55	103.59
1268.34	114.05	6.79	93.1
1125.0	0.36	6.13	84.15
1404.51	42.96	5.62	77.16
1625.0	96.31	5.07	69.62
1947.99	147.06	3.94	54.1
875.0	47.47	3.49	47.91
1933.16	94.83	3.12	42.75
1458.56	1.2	2.47	33.95
2116.73	190.01	2.44	33.48
1538.48	157.4	2.43	33.27



FTP72 — AVL CRUISE

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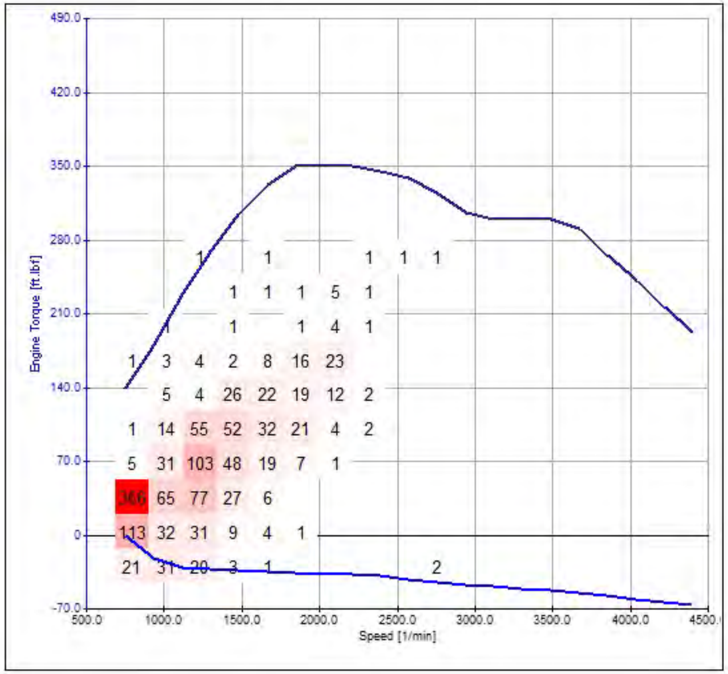

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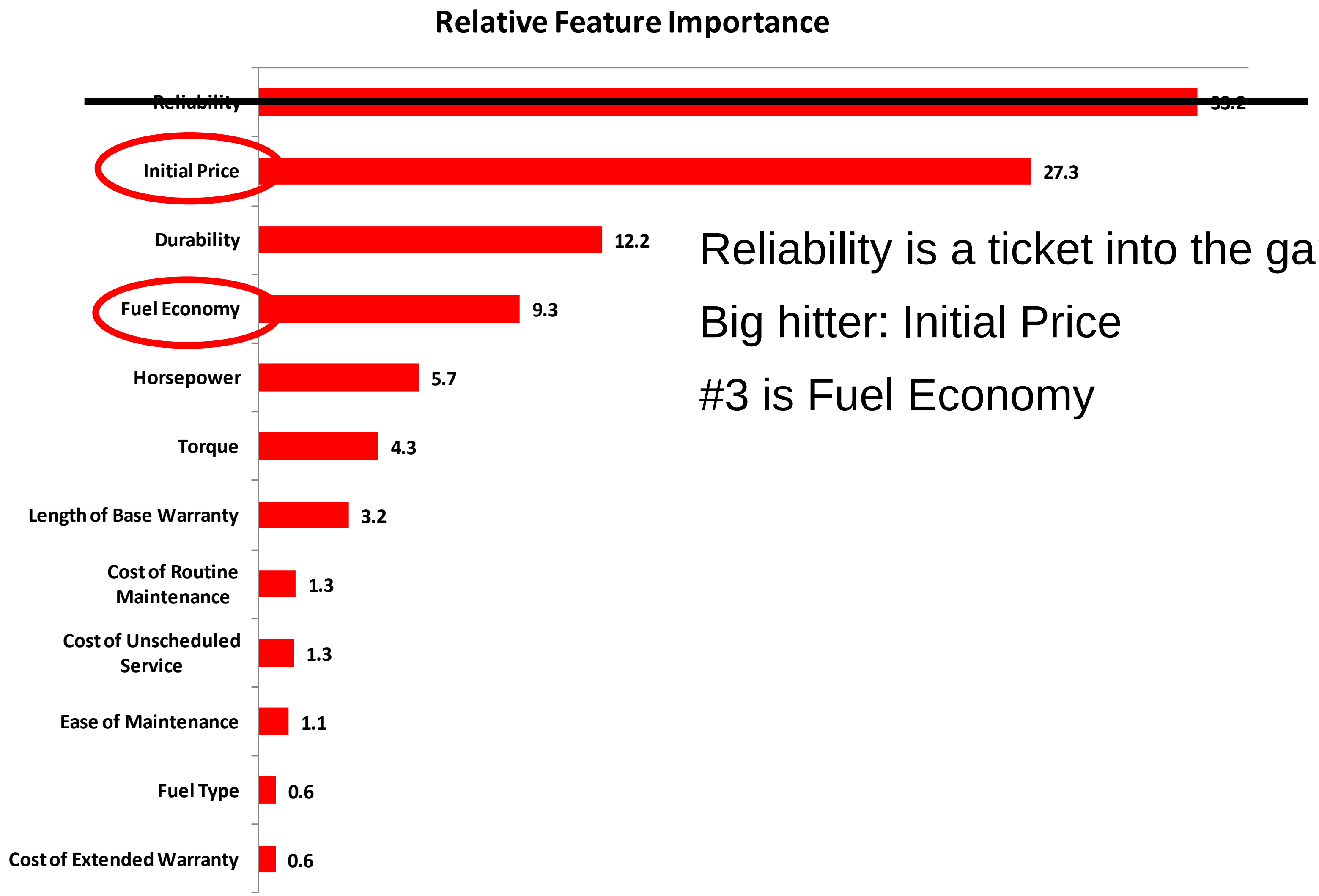
Mule Vehicle Build

Marketing Research Data on ½ Ton P/U Truck Buyers (Morpace Research Group – 2010)



Reliability is a ticket into the game

Big hitter: Initial Price

#3 is Fuel Economy

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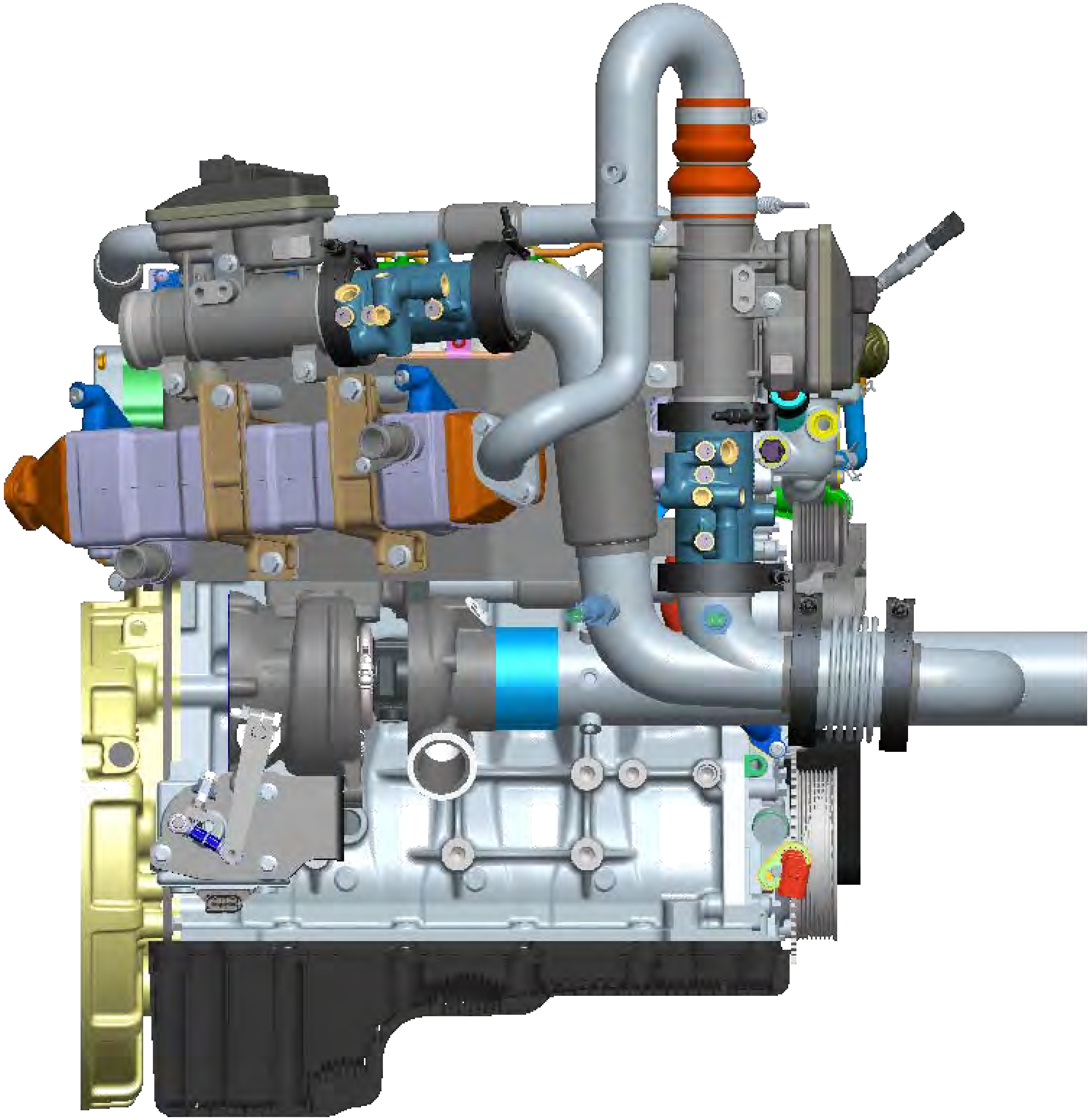
HP/LP EGR on Combustion Mule



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