Ultra-Low Carbon Powertrain Program (ETHOS)

Sep 20, 2016

Innovation You Can Depend On

ETHOS – Program Overview

Project Motivation

- "Ultra-Low Carbon Powertrain Program" (CEC)
  - CEC seeks to fund projects which reduce fossil fuel burning impacts on California
    - Alternative fuels, engine technology for lower emissions, improved vehicle technology
    - ~$100M / year in funding
  - Carbon intensity of E85 significantly less than diesel and gasoline on a well-to-wheels basis from certain fuel pathways

Engine – baseline vs. new

- Baseline vehicle was powered with:
  - Cummins Diesel 6.7l; or
  - GM Gasoline 6.0l

- Significant engine downsizing
  - 2.8l – 610 Nm and 250 hp

Project requirements

- High Power Density - enables increased drive cycle thermal efficiency
  - BMEP 2x higher than Diesel
  - BMEP 2.5x higher than Gasoline

- Because of the high power density
  - High PCP requirement (200 bar) vs. typical 90-130 bar on gasoline engines
  - Good reason to share the diesel engine design

Challenges

- Engine knock at low speeds
  - Use of Al head allowing better heat transfer, avoiding knock
    - Heat transfer by itself reduces efficiency, but higher compression ratio and advanced timing overweigh the heat transfer losses

- Turbine Inlet Temperature, especially at high speeds

Powertrain design

- Shared with diesel requirements
  - Cast Al cylinder head for better heat transfer
  - Cast Al cylinder block with steel liner inserts to maintain durability
  - Dual overhead cam valve train for variable valve timing
    - Independent phasing control
    - Dual lift profile on each camshaft
  - Six speed Allison automatic transmission

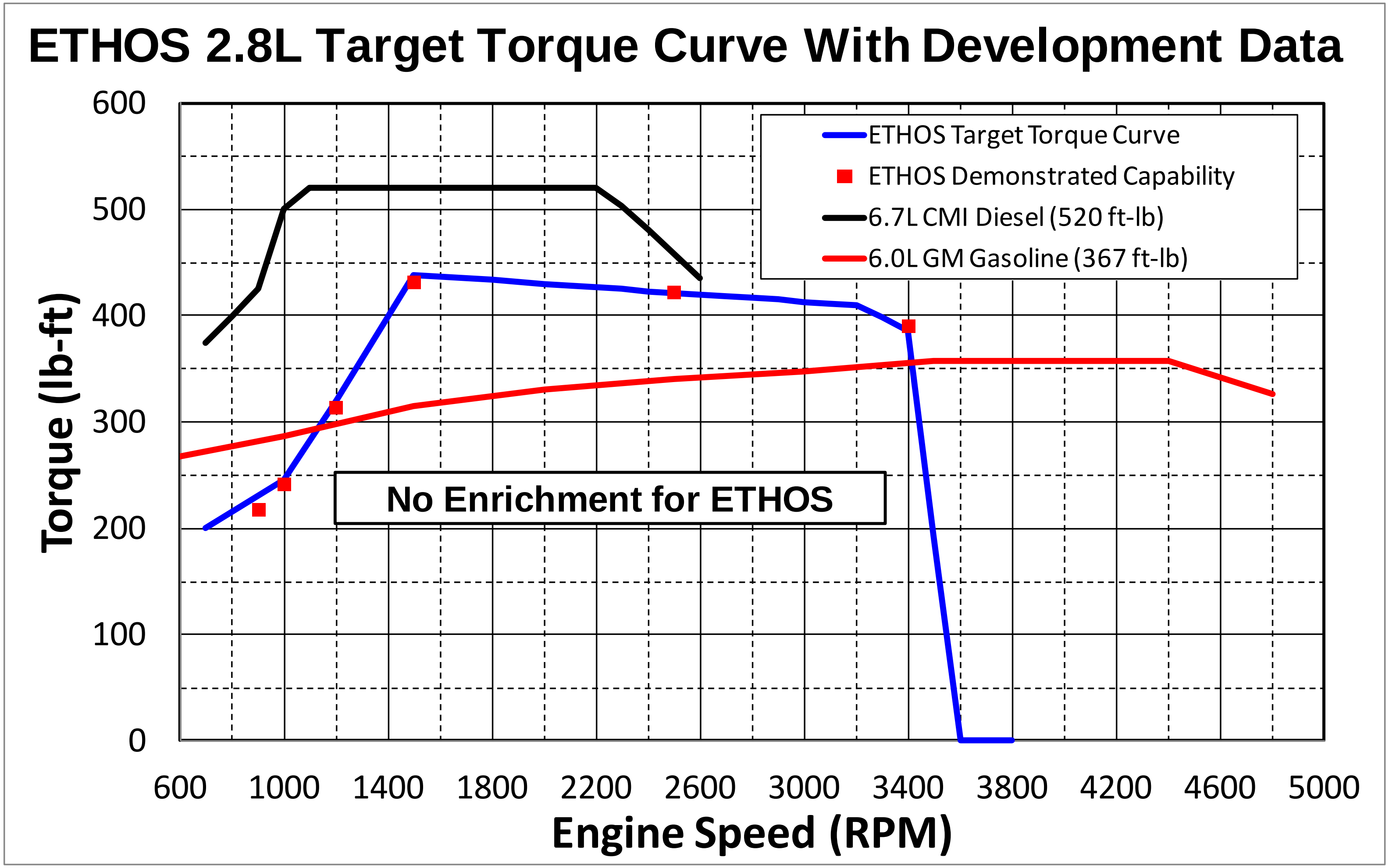
Engine design

- Specific to E85
  - Fuel system
    - High pressure DI – common rail of 200 bar – high charge cooling capability and avoid knock
  - Spark ignition system
    - Iridium spark plugs
  - Compression ratio
    - 12:1 – between 10-14 to maximize BMEP and avoid knock
  - Cylinder head
    - Intake port design – designed to create the optimum in-cylinder charge motion
    - Center mounted spark plug

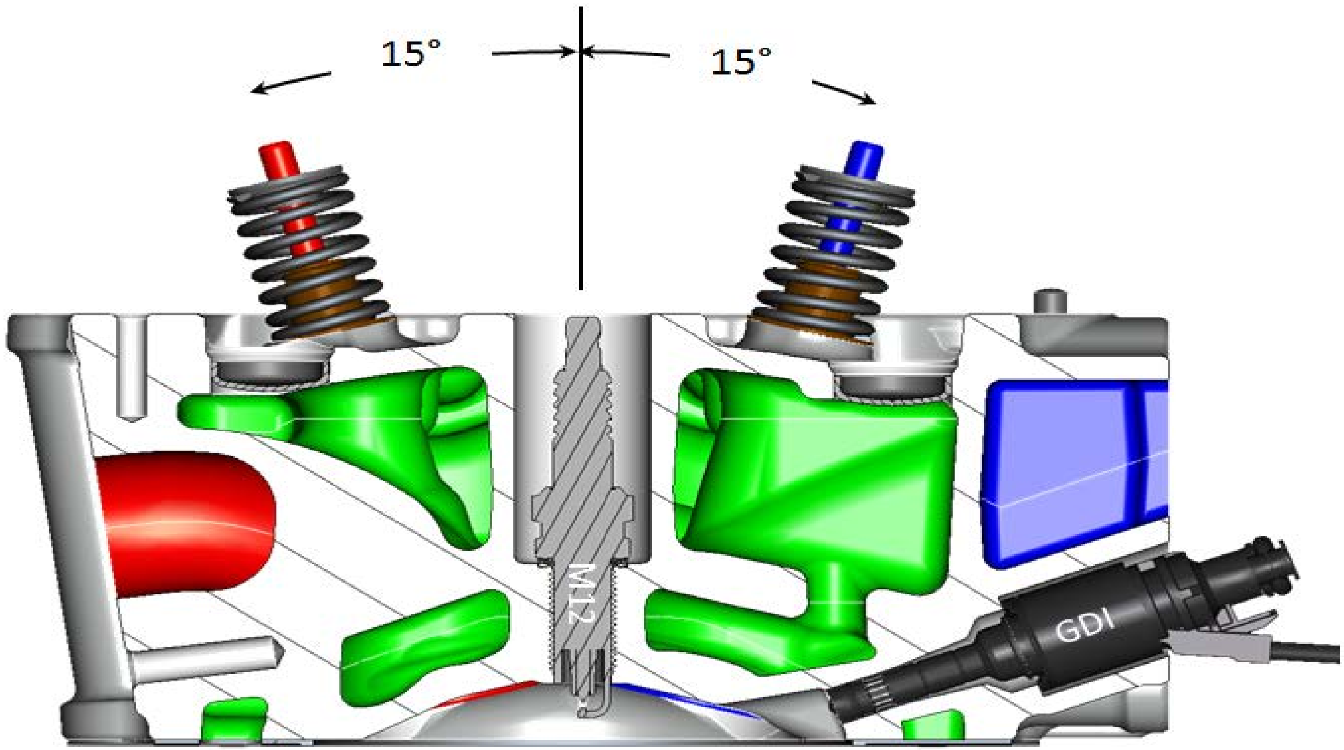
Engine design

- Specific to E85
  - Piston
    - Aluminum and gallery cooled to improve heat transfer; as the cylinder head
  - Intake throttle for full map Stoichiometric Combustion
    - Use of three way catalyst
  - Closed couple catalyst
  - Lean at light loads and stoichiometric at high loads represent an opportunity for further improvement

ETHOS Torque Curve

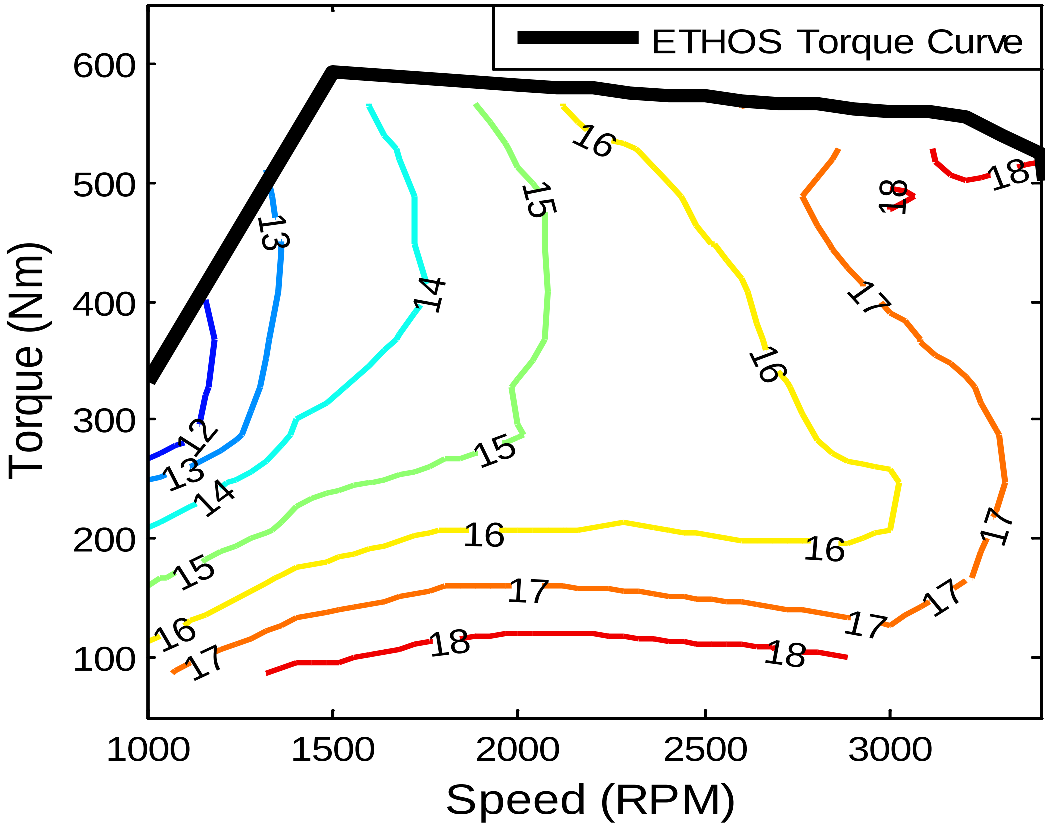


Combustion System Design



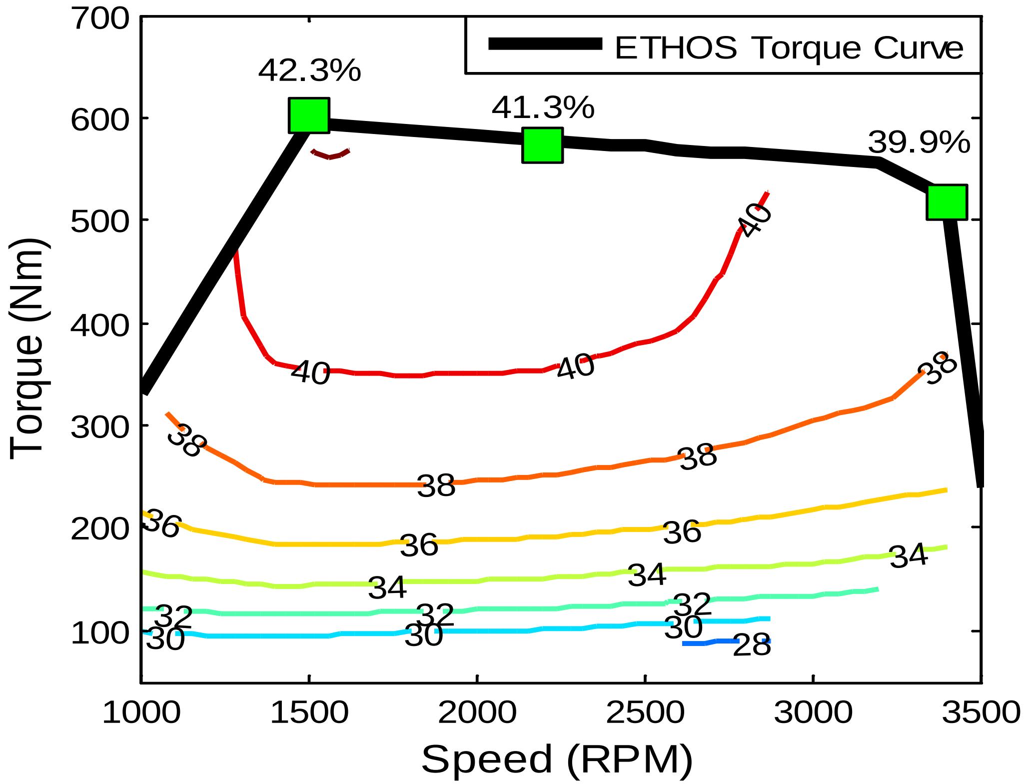
- Pent roof combustion chamber with flat piston
- High tumble charge motion to mix larger quantities of fuel due to low LHV of E85
- Direct injection for high charge cooling

Combustion Burn Duration (Degrees)



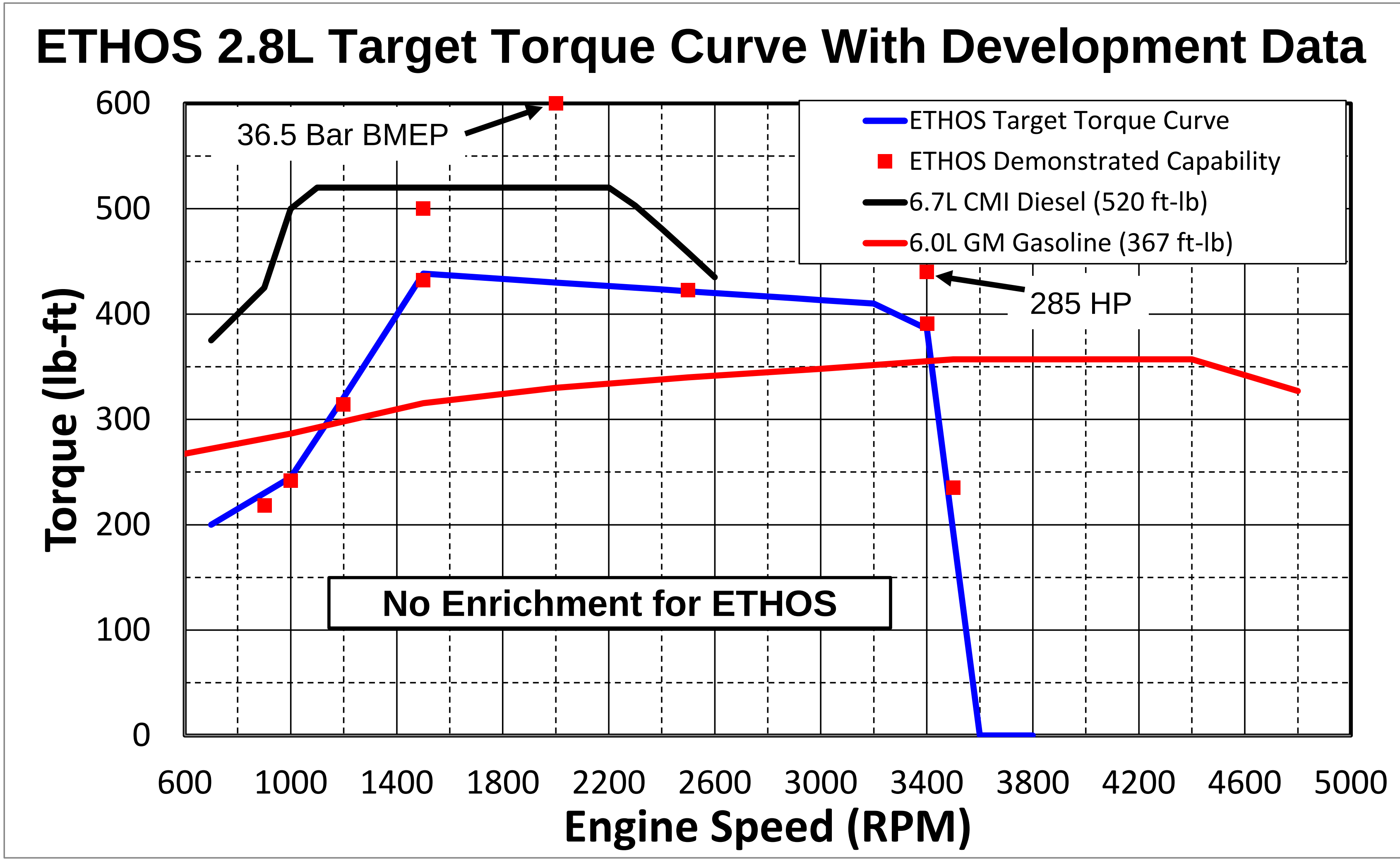
- Fast burn rates resulting in short combustion duration across the operating space

Engine Brake Thermal Efficiency (%)



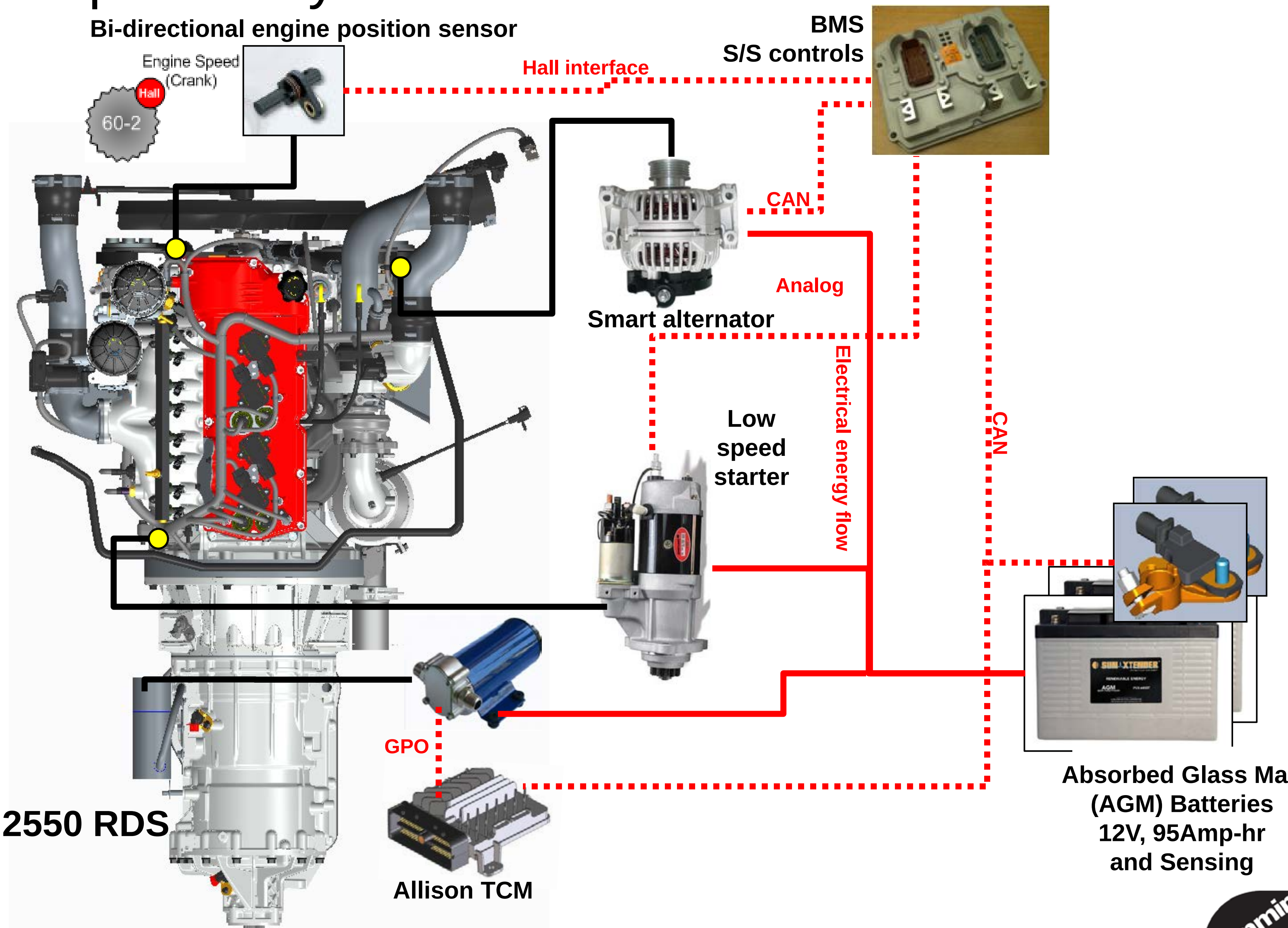
- Excellent thermal efficiency across a broad operating space
- BTE ~= GITE at peak efficiency due to positive PMEP and low FMEP

ETHOS Final Torque Capability



- 43% Peak Brake Thermal Efficiency

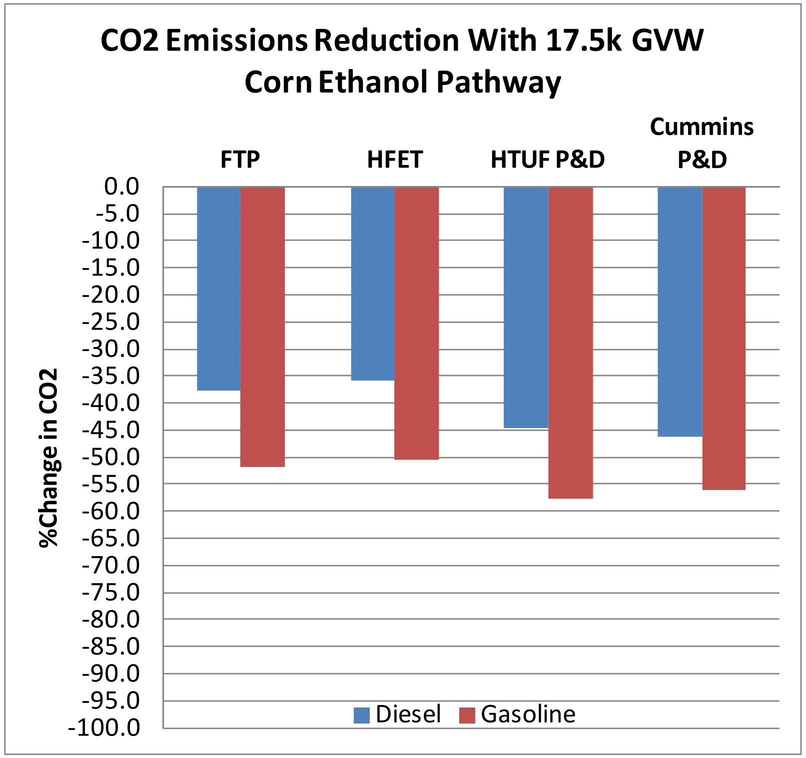
Stop/Start System

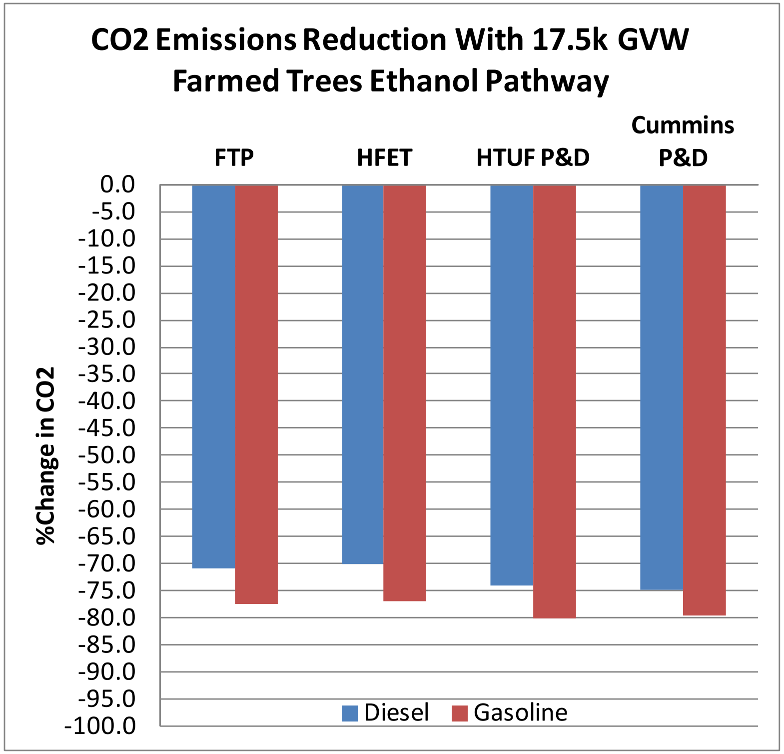


Vehicle Benchmarking

- FCCC MT45 step van tested in both gasoline and diesel powertrains
- Multiple test weights to cover class 4-6 vehicles
  - 15k, 17.5k, 20k, and 23k lbs
- 4 drive cycles studied to cover various duty cycles
  - FTP75, Highway Fuel Economy, HTUF P&D, Cummins P&D
- CO_2 targets established for comparison to both fuels

Well – To – Wheels Carbon Emissions

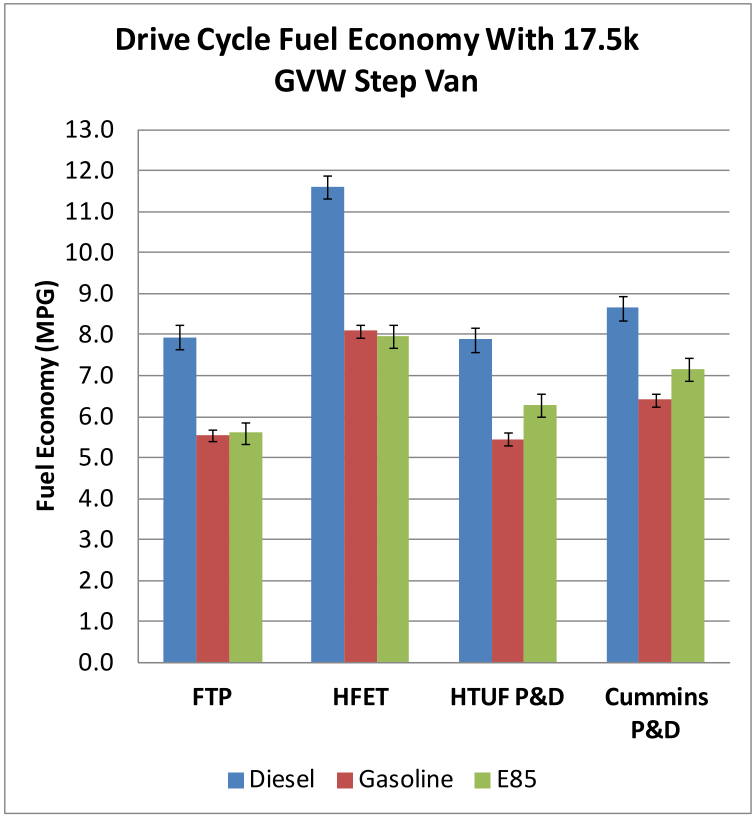


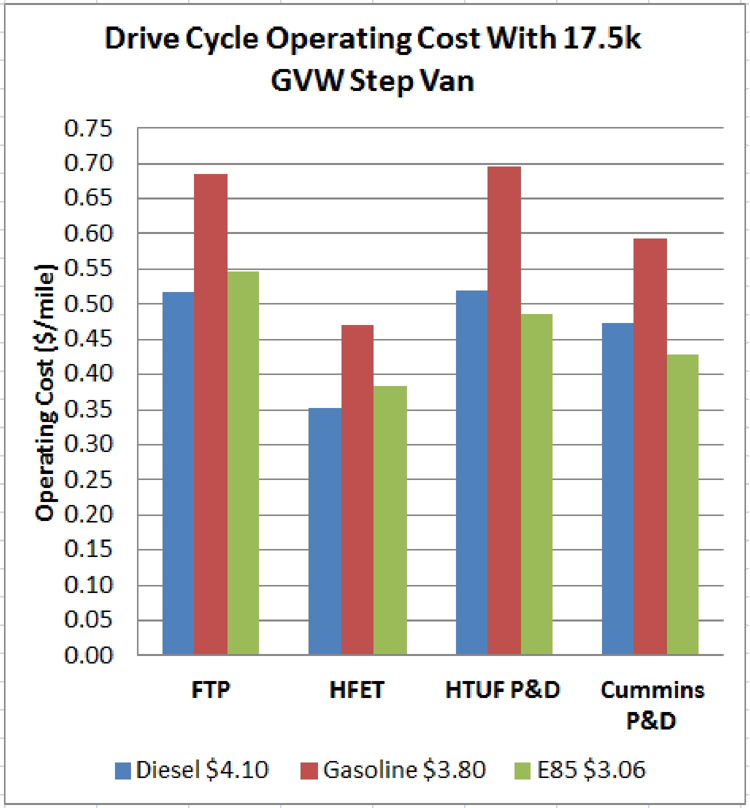


Fuel	Elemental Carbon	Well to Tank Carbon
	g CO2/ MJ	g CO2/ MJ
California Reformulated Gasoline	72.90	98.95
California Ultra-Low Sulfur Diesel	74.10	98.03
Corn Ethanol	71.02	65.66
Cellulosic Ethanol from Farmed Trees	71.02	21.40
California E85 - Corn	71.34	70.65
California E85 - Farmed Trees	71.34	33.03

- 35%-80% CO_2 reduction potential
  - Fuel and pathway dependant

Vehicle Operating Cost Comparison





- Equal MPG to gasoline vehicle
- Equal operating cost to diesel vehicle

Conclusions

- Optimization for E85 fuel properties enables
  - High efficiency operation
  - High BMEP and downsizing capability at diesel like torque curves
  - Equal MPG to a baseline gasoline powertrain
  - Equal operating cost to a baseline diesel engine
  - System cost reduction relative to a diesel powertrain
  - Significant well-to-wheels CO_2 reduction