Light-Duty Engine Development

SOUTHWEST RESEARCH INSTITUTE®

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Light-Duty Technology Drivers

- EPA Tier 3 standards (phased-in 2017 through 2025)
- CARB LEV III standards (phased-in 2015 through 2028)
- EPA & CARB greenhouse gas emission standards
- NHTSA fuel economy standards

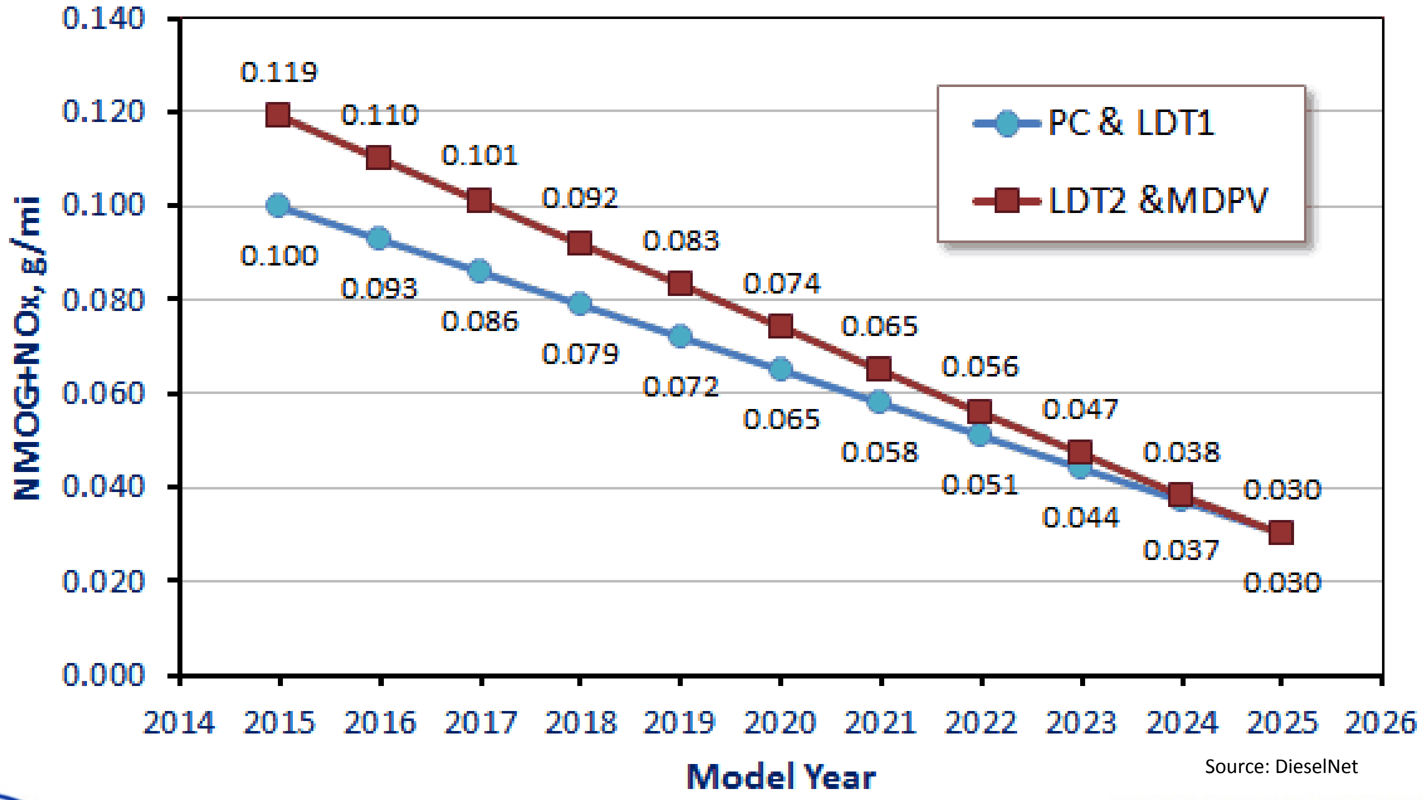
Tier 3 / LEV III Light-Duty Vehicle Emission Standards

Tier 3 / LEV III Light-Duty Vehicle Standards (Useful life = 15 yrs, 150,000 miles)

Bin	NMOG+NOx	PM*	CO	HCHO
	mg/mi	*mg/mi*	*g/mi*	*mg/mi*
Tier 2 Bin 5 (for reference)	160	10	4.2	18
Bin 160 / LEV160	160	3	4.2	4
Bin 125 / ULEV125	125	3	2.1	4
Bin 70 / ULEV70	70	3	1.7	4
Bin 50 / ULEV50	50	3	1.7	4
Bin 30 / SULEV30	30	3	1.0	4
Bin 20 / SULEV20	20	3	1.0	4
Bin 0 / ZEV	0	0	0	0
The 3 mg/mi PM standard is phased in from 2017-2021: 10% of fleet in 2017, 20% in 2018, 40% in 2019, 70% in 2020, 100% in 2021				

Source: DieselNet

Fleet Average NMOG + NOx Standards



Source: DieselNet

CARB LEV III Particulate Matter Phase-In

Model Year	Passenger Car, Light-Duty Truck, Medium-Duty Passenger Vehicles (% of fleet)		
	PM = 10 mg/mi	PM = 3 mg/mi	PM = 1 mg/mi
2017	90	10	0
2018	80	20	0
2019	60	40	0
2020	30	70	0
2021	0	100	0
2022	0	100	0
2023	0	100	0
2024	0	100	0
2025	0	75	25
2026	0	50	50
2027	0	25	75
2028	0	0	100

Tier 3 Gasoline Standards

- Effective January 1, 2017
  - January 1, 2020 for small volume refiners
- Annual average sulfur must be ≤ 10 ppm
- Max sulfur per gallon
  - 80 ppm at the refinery gate
  - 95 ppm downstream
- Lower sulfur level supports 150,000 useful life and lean-burn catalyst technology

Other Tier 3 Provisions

- E10 fuel is used for tailpipe and evaporative emission testing
- EPA adopted CARB OBD rules effective model year 2017
- Limited relief for emission testing at high altitude for Bins 125 and lower
- EPA evaporative emission standards more stringent
  - Note: CARB has "zero" evaporative standard under LEV III
- Enrichment for spark-ignition vehicles limited in frequency and magnitude

Fuel Economy / Greenhouse Gas Standards

Footprint Based Fuel Economy Standards

Passenger Cars

- https://www.nap.edu/openbook/21744/xhtml/images/img-310.jpg

Light-Duty Trucks

- https://www.nap.edu/openbook/21744/xhtml/images/img-311.jpg

Source: National Research Council, *Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles,* 2015, DOI 10.17226/21744

Dual Fuel Incentive Phase-Out

- Dual fuel CAFE benefit currently provided by E85 flex fuel vehicles phases-out in 2020

Model Year	Maximum CAFE increase
Through 2014	1.2 mpg
2015	1.0 mpg
2016	0.8 mpg
2017	0.6 mpg
2018	0.4 mpg
2019	0.2 mpg
2020 and later	0.0 mpg

Ref: 49 USC 32906, 40 CFR 600.510-12(h)

Statutory CAFE Credits for Gaseous Fuels

49 USC 32904(c):

(c) GASEOUS FUEL DEDICATED AUTOMOBILES.—For any model of gaseous fuel dedicated automobile manufactured by a manufacturer after model year 1992, the Administrator shall measure the fuel economy for that model based on the fuel content of the gaseous fuel used to operate the automobile. One hundred cubic feet of natural gas is deemed to contain .823 gallon equivalent of natural gas. The Secretary of Transportation shall determine the appropriate gallon equivalent of other gaseous fuels. A gallon equivalent of gaseous fuel is deemed to have a fuel content of .15 gallon of fuel.

Example: A dedicated propane-fueled pickup getting 18 MPGe would count as 120 MPG for CAFE

Defined Gasoline Gallon Equivalents 49 CFR 538.8

TABLE I—GALLON EQUIVALENT MEASUREMENTS FOR GASEOUS FUELS PER 100 STANDARD CUBIC FEET

Fuel	Gallon equivalent measurement
Compressed Natural Gas	0.823
Liquefied Natural Gas	0.823
Liquefied Petroleum Gas (Grade HD–5)*	0.726
Hydrogen	0.259
Hythane (Hy5)	0.741

* Per gallon unit of measure.

Natural Gas Vehicle CAFE/GHG Incentives in 2017-2025 Final Rule

▪ 0.15 CAFE divisor	Yes
▪ 0.15 GHG multiplier	No
▪ CNG vehicle multiplier incentive	
– MY2017-2019	1.6
– MY2020	1.45
– MY2021	1.3

CAFE Calculations Assuming 25 MPGe Vehicle

- Dedicated: 25 MPGe / 0.15 = 166.7 MPGe
- Dual fuel through MY2019:

  $MPGe = ((0.5/MPG\ gasoline) + (0.5/MPGe\ CNG))^{-1}$

  $MPGe = (0.5/25) + (0.5/166.7))^{-1} = 43.5\ MPGe$
- Dual fuel MY2020 and later:

$$MPG = \left(\frac{UF}{MPG_{CNG}} + \frac{(1 - UF)}{MPG_G}\right)^{-1}$$

Where UF = utility factor based on CNG range

Utility Factor for MY2020 and later Natural Gas Vehicles

- To qualify for UF > 0.5:

  (1) The driving range using natural gas must be at least two times the driving range using gasoline.

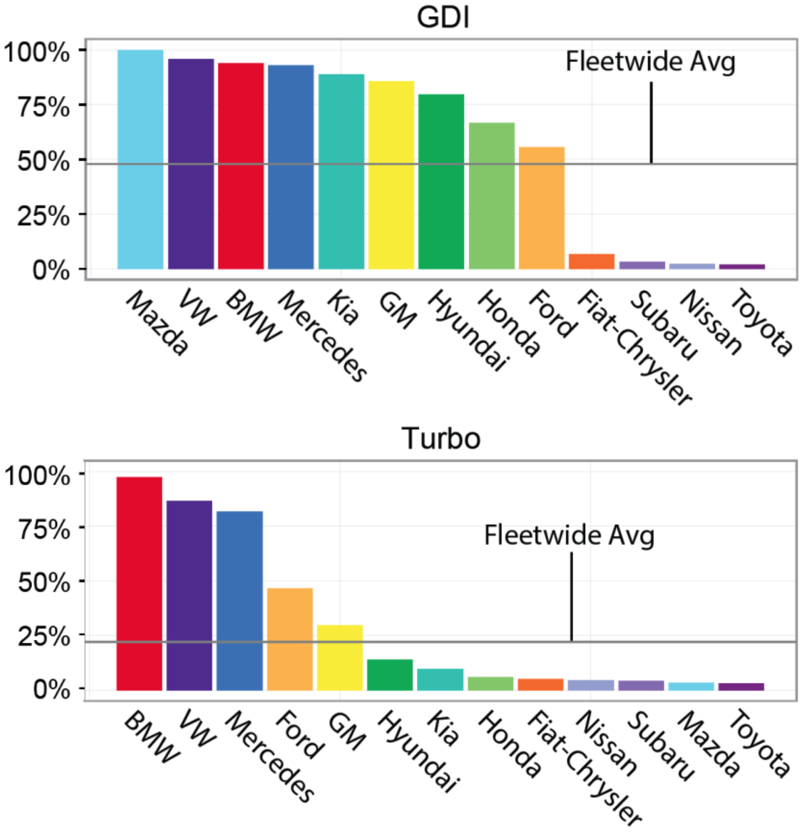
  (2) The natural gas dual fuel vehicle must be designed such that gasoline is used only when the natural gas tank is effectively empty, except for limited use of gasoline that may be required to initiate combustion.

Driving Range (miles)	UF	Driving Range (miles)	UF
10	0.228	160	0.932
20	0.397	170	0.939
30	0.523	180	0.944
40	0.617	190	0.949
50	0.689	200	0.954
60	0.743	210	0.958
70	0.785	220	0.962
80	0.818	230	0.965
90	0.844	240	0.968
100	0.865	250	0.971
110	0.882	260	0.973
120	0.896	270	0.976
130	0.907	280	0.978
140	0.917	290	0.980
150	0.925	300	0.981

Trend toward Direct Injected Turbo Engines

Direct Injection / Turbo Market Share

- Direct injection is approaching 50% market share in U.S. gasoline vehicles
- Some manufacturers are nearly 100% direct injection
- Turbocharged engines are approaching 25% market share



Source: U.S. EPA, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends:1975 Through 2016*

Downsized Engines Need Higher Octane Fuel

- U.S. DRIVE = United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability
- Partnership consisting of:
  - Department of Energy
  - USCAR (FCA, Ford, GM)
  - Five energy companies (BP, Chevron, ExxonMobil, Phillips, Shell)
  - Two utilities (SoCal Edison & DTE Energy)
  - Electric Power Research Institute (EPRI)
- Propane already meets most of the requirements

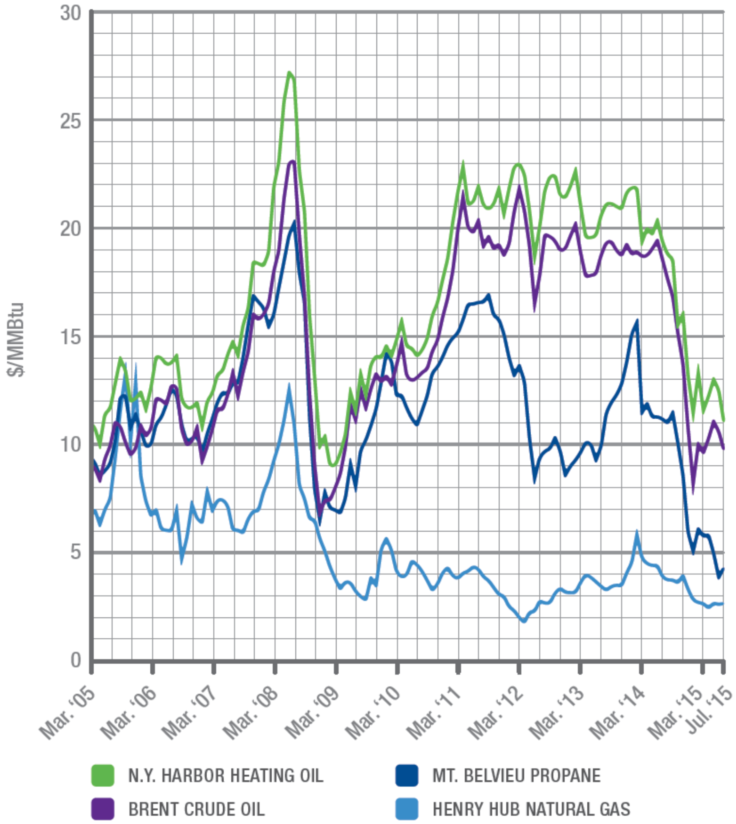
Property	U.S. DRIVE Targets	Propane
RON	> 100	110[1]
Sensitivity	> 12	14[1]
Sulfur	10 ppm max	37 ppm avg[2]
PM Index	< 1.5	very low
Volatility	reduced variation in drivability index	readily vaporizes down to -40C

Sources:
[1] Morganti, et. al, *The Research and Motor octane numbers of Liquefied Petroleum Gas (LPG)*
[2] PERC U.S. LPG Fuel Survey

Displacement of Foreign Oil

Propane Price

- Hydraulic fracturing caused LPG price to decouple from crude oil after 2010
- Mont Belvieu spot price was $0.608 per gallon on May 5, 2017 (EIA)



Source: ICF International, *2016 Propane Market Outlook*, based on U.S. Energy Information Administration (EIA) data

Target Markets / Number of Propane Vehicles Supported by Propane Supply

- Target Markets
  - Applications that use a significant amount of fuel
  - High mileage applications
    - Fleet trucks
    - Taxis

- Based on current production rates, 10 billion gallons per year of propane can be made available for U.S. vehicles
- 1100 gal/yr/vehicle @ 18 mpg, 20k miles per year
- = 9 million propane vehicles

Benefits of Propane with Direct Injected Turbo Engines

Experimental Setup

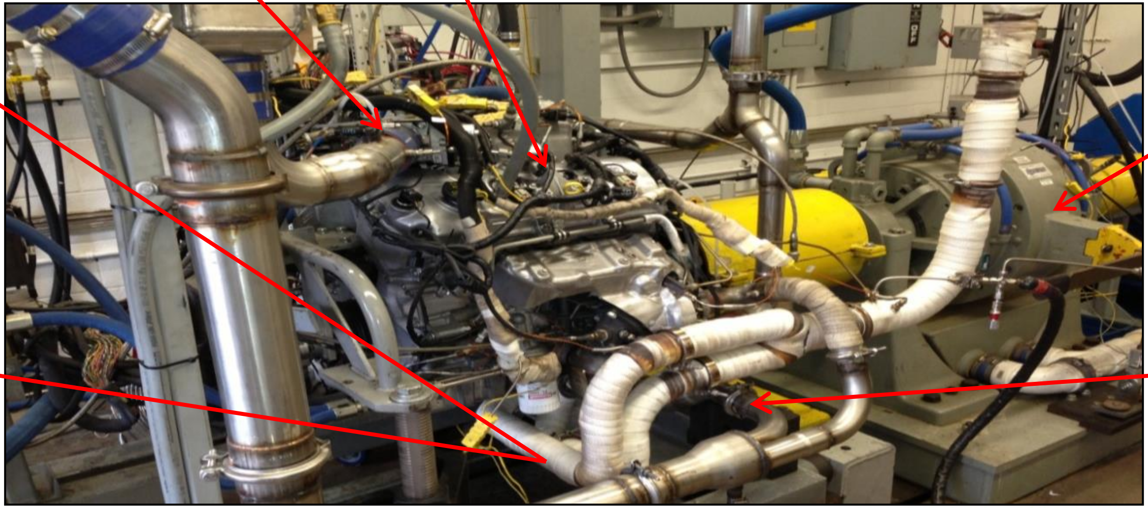
Horiba MEXA

AVL MicroSoot Sensor

Suite of temperatures and pressures

OEM GDI Pump

Clean Fuels USA tank and pump system



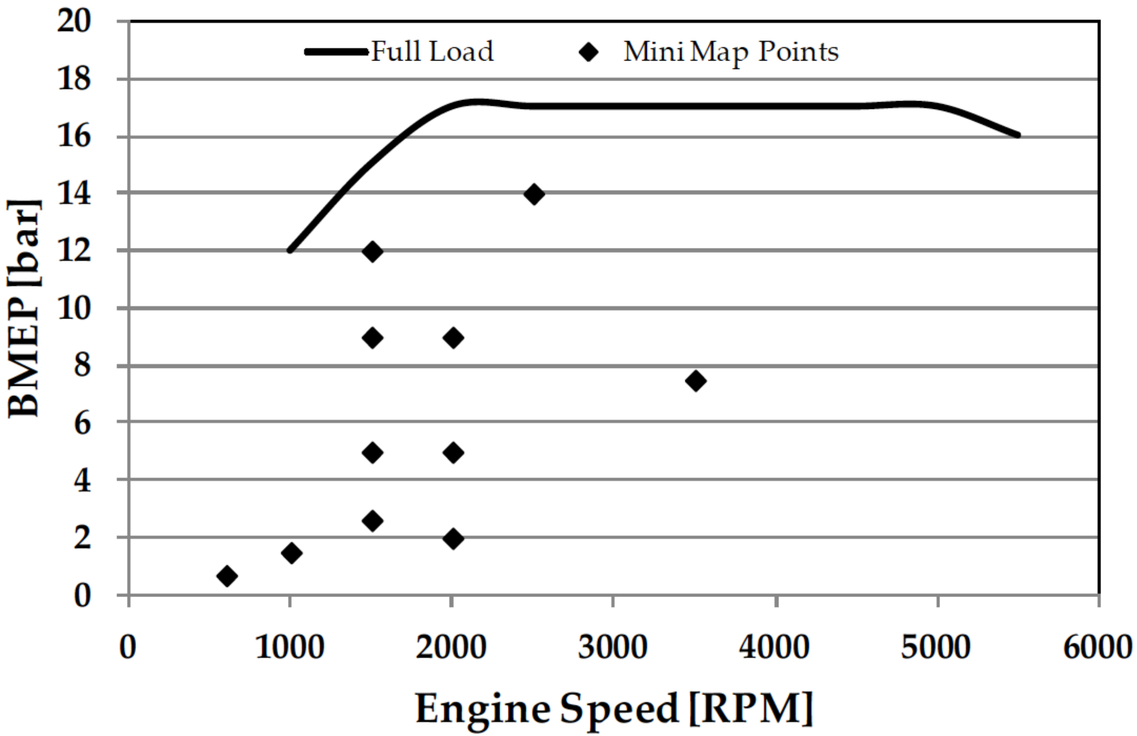
Engine Dyno

OEM Catalyst

2010 Ford 3.5L V6 TGDI Engine

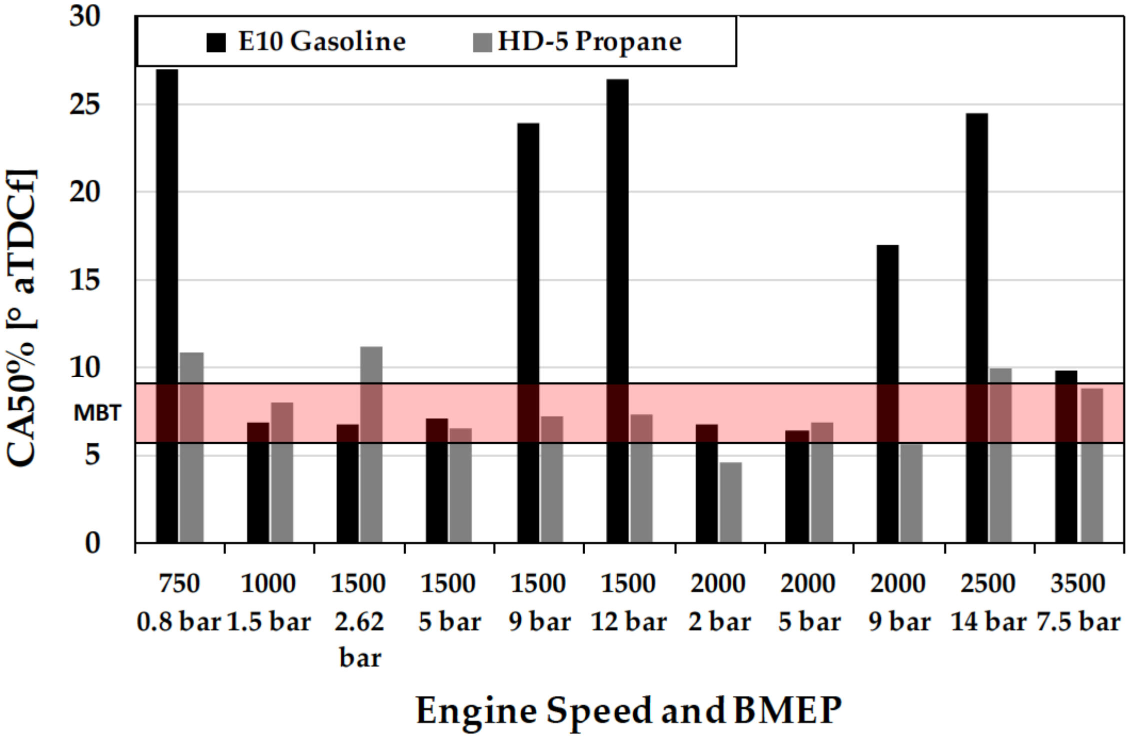
Mini-Map Points

- Mini-map representative of typical in-use LDV operation
- Used to evaluate part load performance and emissions
- Ignition timing and injection timing optimized at each point



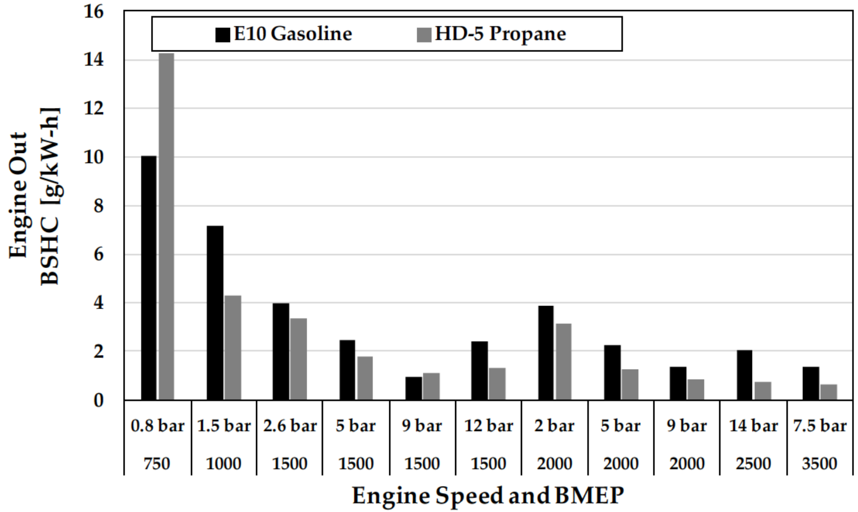
Mini-Map Combustion Phasing

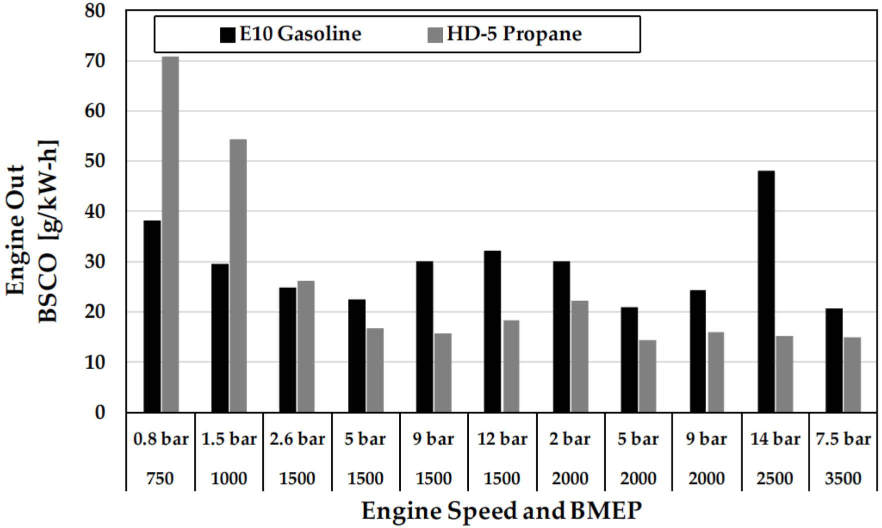
Combustion phasing improves with propane at 9 bar and higher brake mean effective pressure (BMEP)



Mini-Map Engine Out HC and CO

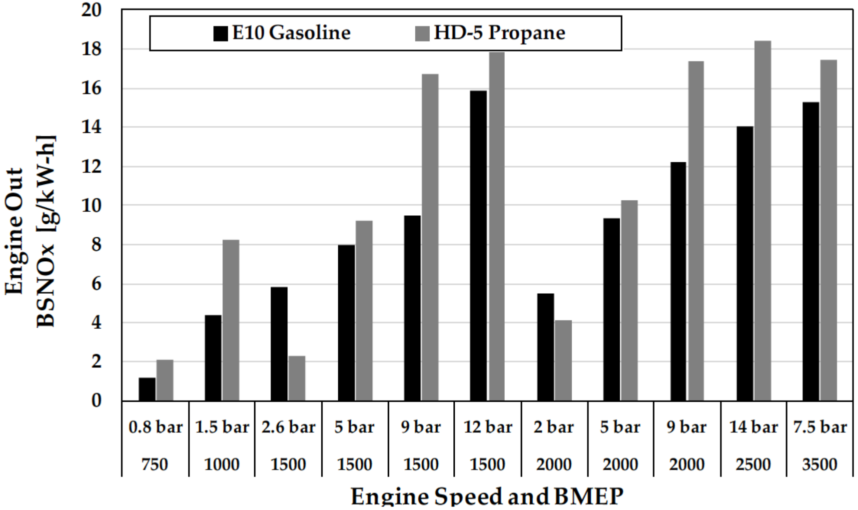
- Lower HC with propane except at idle
- Lower CO with propane at 5 bar and higher BMEP points
- Increases in HC and CO at low speed and load may be solved by adding return line to DI pump

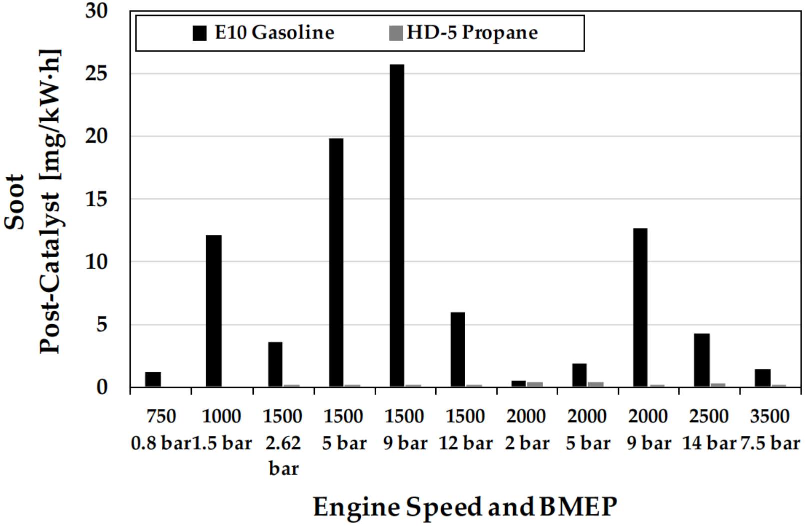




Mini-Map Engine Out NOx and Soot

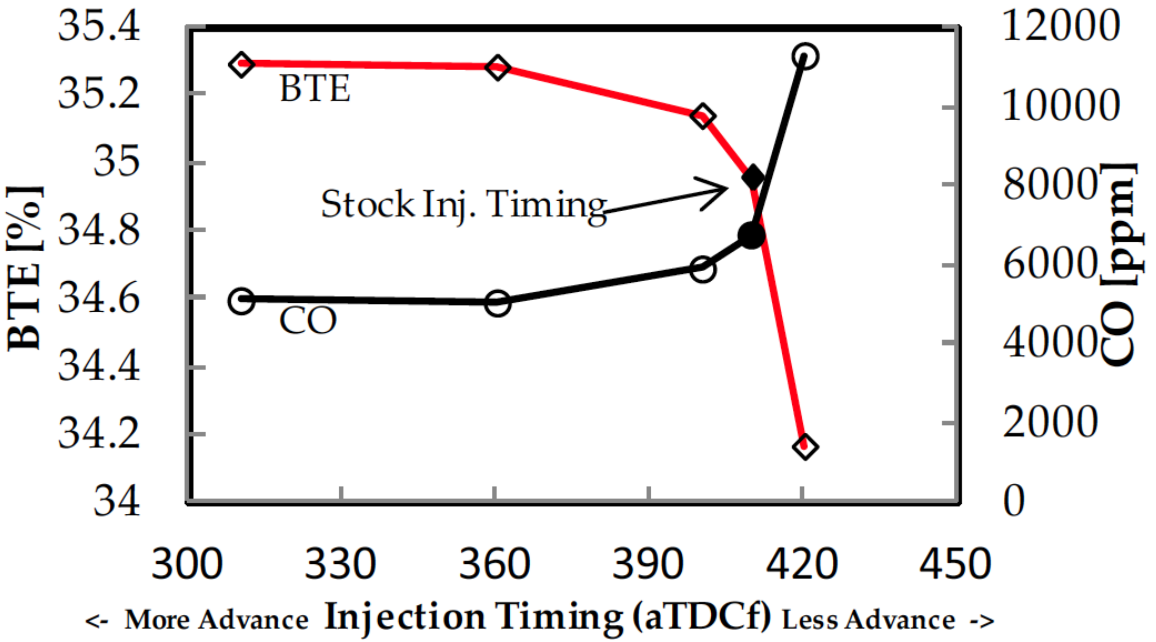
- Higher NOx at high load due to more advance combustion phasing
- Soot with propane is nearly zero at all points



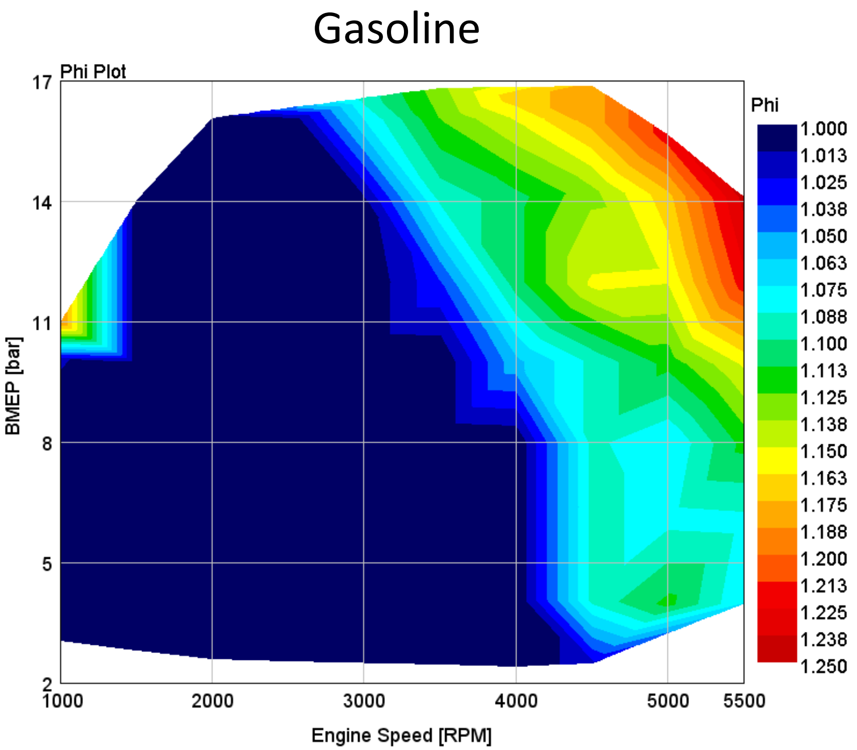


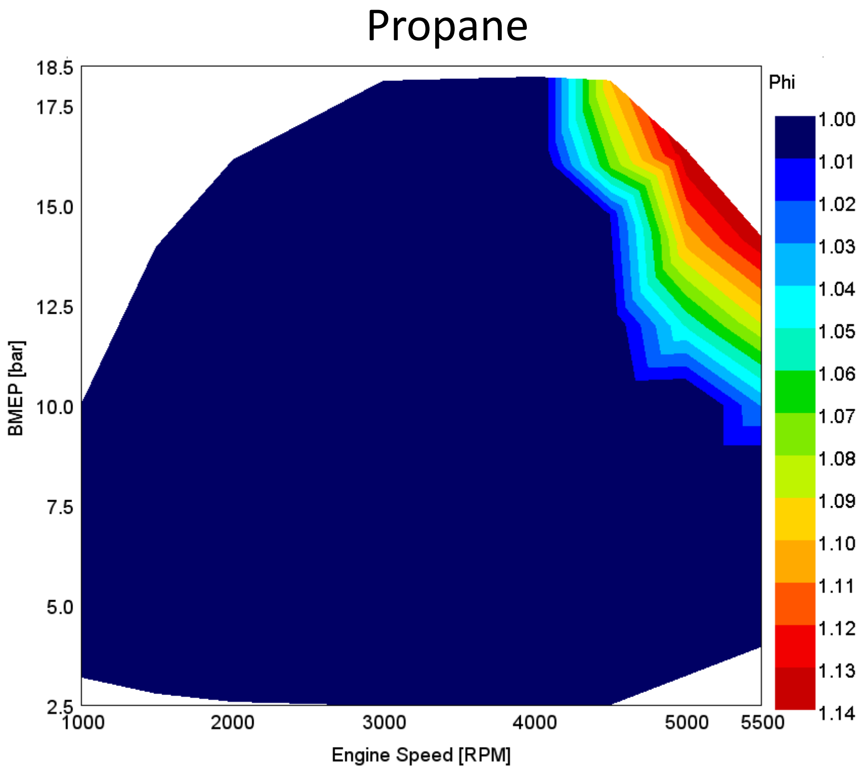
Injection Timing Effects with Propane

- More advanced injection timing was needed with LPG
- Brake thermal efficiency (BTE) and carbon monoxide (CO) improved with advanced injection timing



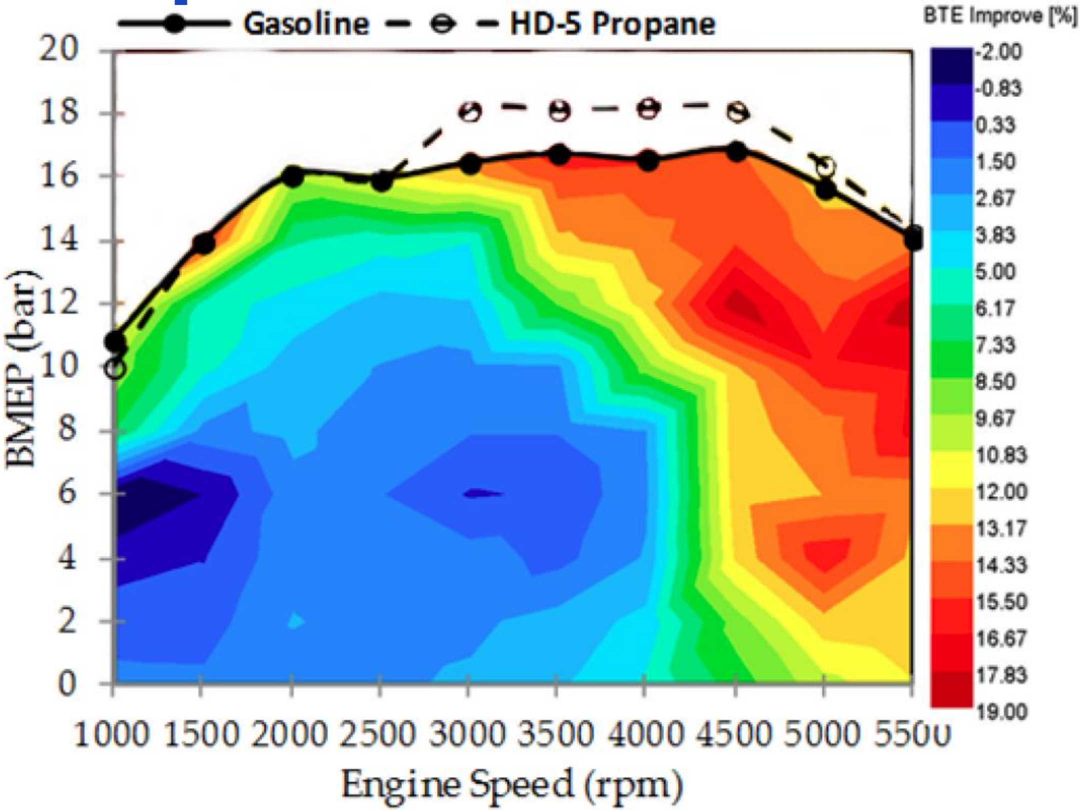
Enrichment Maps





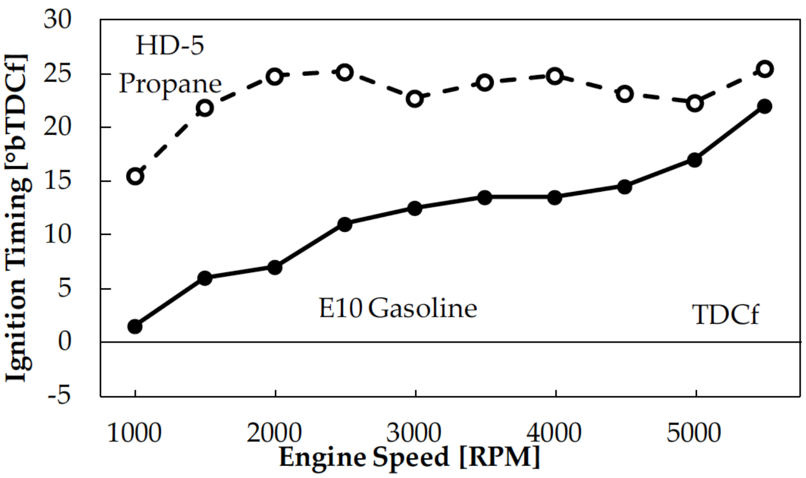
Fully Optimized Brake Thermal Efficiency Improvement for Propane vs. Gasoline

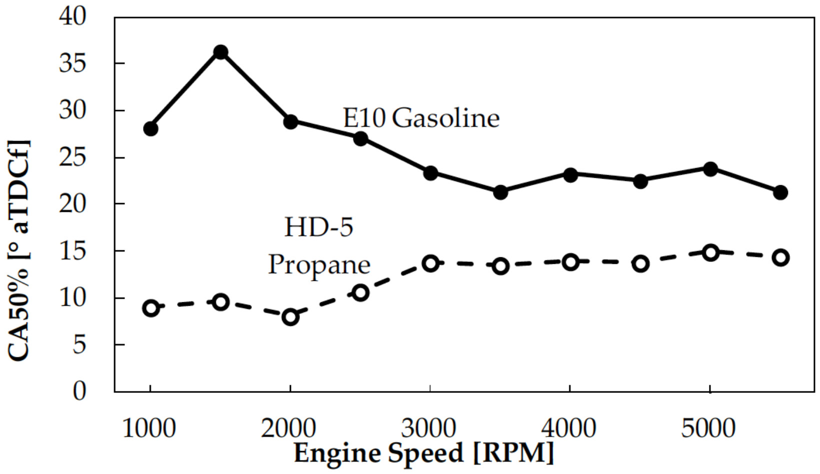
- Fully Optimized Map
  - ✓ Injection timing
  - ✓ Ignition timing
  - ✓ Fueling



Full Load Combustion Phasing

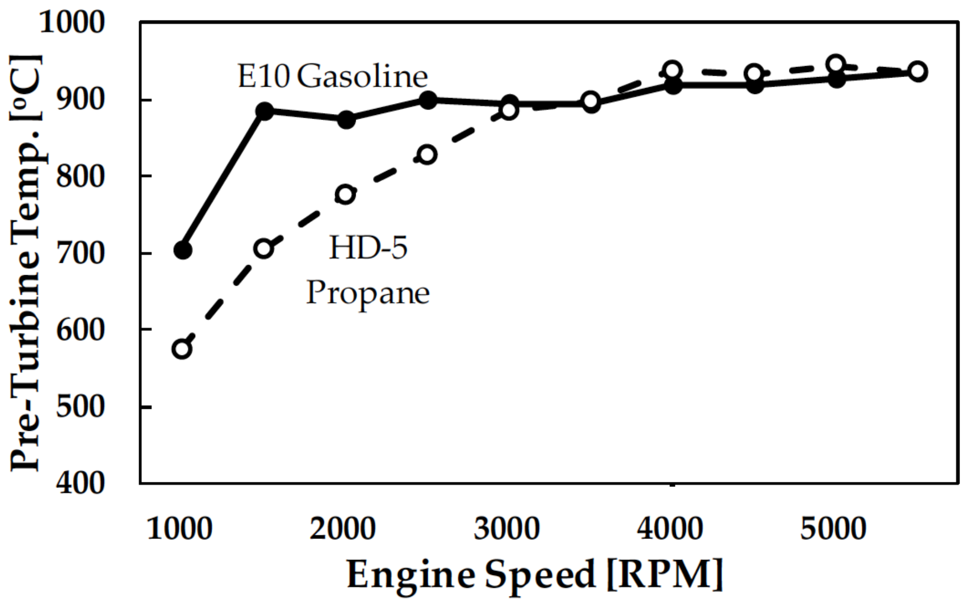
- Gasoline combustion phasing is retarded to suppress knock
- Propane allows near maximum brake torque combustion phasing





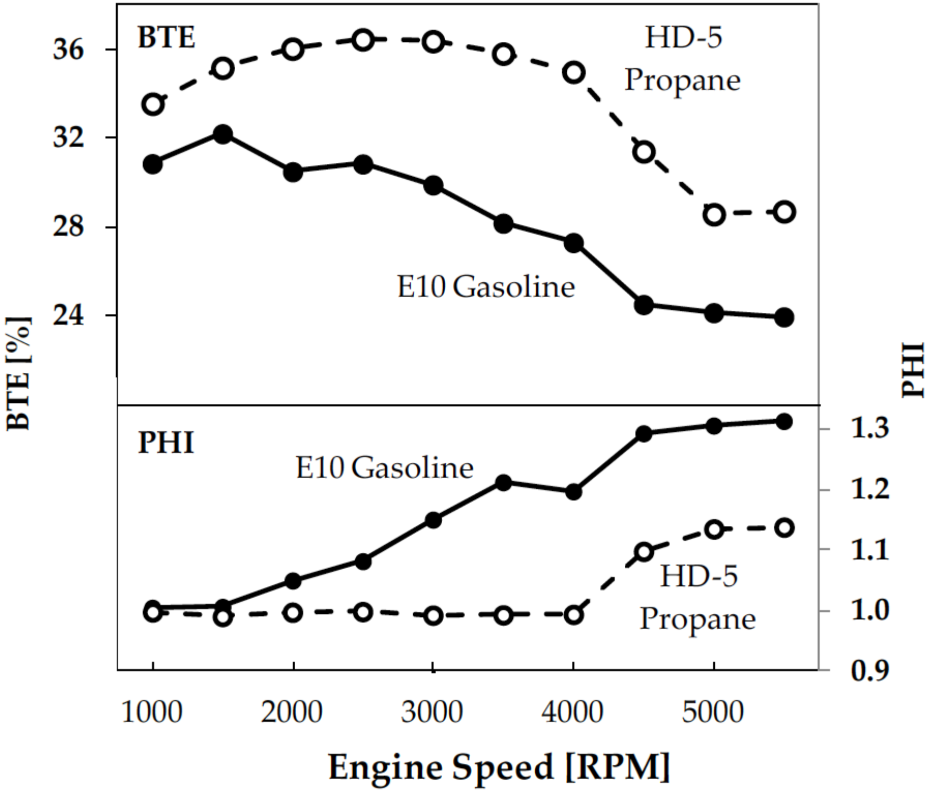
Full Load Turbine Inlet Temperature

- Improved combustion phasing with propane reduces turbine inlet temperature
- Lower exhaust temperature while operating at stoichiometry
- Enrichment is only required above 4000 RPM



Full Load Brake Thermal Efficiency (BTE) and Fuel / Air Equivalence Ratio (phi)

- Propane significantly improves full load BTE
- Stoichiometric operation possible up to 4000 RPM
- Less enrichment to control exhaust temperature above 4000 RPM



Research & Development Needs for LPG Direct Injection

R&D Needs for LPG Direct Injection (LPG-DI)

- LPG-DI spray modeling
- DI pump and injector durability testing
- Evaluation of LPG-DI engine deposits
  - Injectors, ports, and combustion chamber
- Impact of LPG-DI on engine lubrication
  - Fuel dilution, soot, need for special additive package
- LPG fuel supply system design
  - In-tank fuel pump, recirculation/purge/starting, need for fuel cooling

Applications for Propane Direct Injection

Higher Efficiency

1. **Naturally aspirated GDI engines**
   - Low cost solution for OEM propane fleet applications
   - Limited efficiency benefits unless compression ratio is increased
2. **Boosted GDI engines**
   - Propane enables further downsizing without penalizing real-world fuel economy
3. **Diesel derived engines**
   - High cylinder pressure capability enables high BMEP
   - Optimized spark-ignition head design
   - Diesel equivalent torque with less cost and complexity
   - Ultra-low emissions with simple three-way catalyst

Lower Cost

Questions?

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