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)

<table>
<thead>
<tr>
<th>Bin</th>
<th>NMOG+NOx (mg/mi)</th>
<th>PM* (mg/mi)</th>
<th>CO (g/mi)</th>
<th>HCHO (mg/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tier 2 Bin 5 (for reference)</td>
<td>160</td>
<td>10</td>
<td>4.2</td>
<td>18</td>
</tr>
<tr>
<td>Bin 160 / LEV160</td>
<td>160</td>
<td>3</td>
<td>4.2</td>
<td>4</td>
</tr>
<tr>
<td>Bin 125 / ULEV125</td>
<td>125</td>
<td>3</td>
<td>2.1</td>
<td>4</td>
</tr>
<tr>
<td>Bin 70 / ULEV70</td>
<td>70</td>
<td>3</td>
<td>1.7</td>
<td>4</td>
</tr>
<tr>
<td>Bin 50 / ULEV50</td>
<td>50</td>
<td>3</td>
<td>1.7</td>
<td>4</td>
</tr>
<tr>
<td>Bin 30 / SULEV30</td>
<td>30</td>
<td>3</td>
<td>1.0</td>
<td>4</td>
</tr>
<tr>
<td>Bin 20 / SULEV20</td>
<td>20</td>
<td>3</td>
<td>1.0</td>
<td>4</td>
</tr>
<tr>
<td>Bin 0 / ZEV</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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
<table>
<thead>
<tr>
<th>Model Year</th>
<th>Passenger Car, Light-Duty Truck, Medium-Duty Passenger Vehicles (% of fleet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM = 10 mg/mi</td>
</tr>
<tr>
<td>2017</td>
<td>90</td>
</tr>
<tr>
<td>2018</td>
<td>80</td>
</tr>
<tr>
<td>2019</td>
<td>60</td>
</tr>
<tr>
<td>2020</td>
<td>30</td>
</tr>
<tr>
<td>2021</td>
<td>0</td>
</tr>
<tr>
<td>2022</td>
<td>0</td>
</tr>
<tr>
<td>2023</td>
<td>0</td>
</tr>
<tr>
<td>2024</td>
<td>0</td>
</tr>
<tr>
<td>2025</td>
<td>0</td>
</tr>
<tr>
<td>2026</td>
<td>0</td>
</tr>
<tr>
<td>2027</td>
<td>0</td>
</tr>
<tr>
<td>2028</td>
<td>0</td>
</tr>
</tbody>
</table>
Tier 3 Gasoline Standards

- Effective January 1, 2017
  - January 1, 2020 for small volume refiners
- Annual average sulfur must be $\leq 10$ 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

### Dual Fuel Incentive Phase-Out

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

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Maximum CAFE increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through 2014</td>
<td>1.2 mpg</td>
</tr>
<tr>
<td>2015</td>
<td>1.0 mpg</td>
</tr>
<tr>
<td>2016</td>
<td>0.8 mpg</td>
</tr>
<tr>
<td>2017</td>
<td>0.6 mpg</td>
</tr>
<tr>
<td>2018</td>
<td>0.4 mpg</td>
</tr>
<tr>
<td>2019</td>
<td>0.2 mpg</td>
</tr>
<tr>
<td>2020 and later</td>
<td>0.0 mpg</td>
</tr>
</tbody>
</table>

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**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Gallon equivalent measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed Natural Gas</td>
<td>0.823</td>
</tr>
<tr>
<td>Liquefied Natural Gas</td>
<td>0.823</td>
</tr>
<tr>
<td>Liquefied Petroleum Gas (Grade HD–5)*</td>
<td>0.726</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.259</td>
</tr>
<tr>
<td>Hythane (Hy5)</td>
<td>0.741</td>
</tr>
</tbody>
</table>

*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: $25 \text{ MPGe} / 0.15 = 166.7 \text{ MPGe}$
- Dual fuel through MY2019:
  \[
  \text{MPGe} = \left(\frac{0.5}{\text{MPG gasoline}} + \frac{0.5}{\text{MPGe CNG}}\right)^{-1}
  \]
  \[
  \text{MPGe} = \left(\frac{0.5}{25} + \frac{0.5}{166.7}\right)^{-1} = 43.5 \text{ MPGe}
  \]
- Dual fuel MY2020 and later:
  \[
  \text{MPG} = \left(\frac{UF}{\text{MPG}_{CNG}} + \frac{1 - UF}{\text{MPG}_G}\right)^{-1}
  \]
  Where $UF = \text{utility factor based on CNG range}$
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.

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

<table>
<thead>
<tr>
<th>Property</th>
<th>U.S. DRIVE Targets</th>
<th>Propane</th>
</tr>
</thead>
<tbody>
<tr>
<td>RON</td>
<td>&gt; 100</td>
<td>110[1]</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>&gt; 12</td>
<td>14[1]</td>
</tr>
<tr>
<td>Sulfur</td>
<td>10 ppm max</td>
<td>37 ppm avg[2]</td>
</tr>
<tr>
<td>PM Index</td>
<td>&lt; 1.5</td>
<td>very low</td>
</tr>
<tr>
<td>Volatility</td>
<td>reduced variation in drivability index</td>
<td>readily vaporizes down to -40°C</td>
</tr>
</tbody>
</table>

Sources:
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)
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
  - $1100 \text{ gal/yr/vehicle} \times 18 \text{ mpg, 20k miles per year}$
  - $= 9 \text{ million propane vehicles}$
Benefits of Propane with Direct Injected Turbo Engines
Experimental Setup

- Horiba MEXA
- AVL MicroSoot Sensor
- OEM GDI Pump
- Clean Fuels USA tank and pump system
- Engine Dyno
- OEM Catalyst
- Suite of temperatures and pressures
- 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

Gasoline

Propane
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

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