ROLE OF LIGHT-DUTY DIESEL IN MEETING 2025 CAFE REQUIREMENTS

Livermore, CA, 2016-11-03

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FEV North America Inc., USA
LEV II diesel powertrains are marching ahead with over 30% higher fuel economy and 14% lower CO₂ over comparable gasoline powertrain.

**2017-2015 CAFE average fleet targets for LDT & PC**
- **Passenger cars:** 40% increase 40 → 56 mpg
- **Light-Duty Trucks:** 37% increase 29.4 → 40.3 mpg
- **Cars and trucks combined:** 40.5% increase 35.3 → 49.6 mpg

**2017-2015 GHG average fleet targets for LDT & PC**
- **Passenger cars:** 31.2% reduction 212 → 143 g/mi
- **Light-Duty Trucks:** 32% reduction 295 → 203 g/mi
- **Cars and Trucks combined:** 33% reduction 243 → 163 g/mi

Source: EPA
Upcoming SULEV 30 fleet average by 2025 demands a holistic approach, Shrinking OBD limits demands synergistic powertrain configuration

### TAILPIPE AND OBD EMISSION DEMANDS

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>PM limit (mg/mi)</th>
<th>Phase-in period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Cars, Light Duty Trucks, MDPVs</td>
<td>3</td>
<td>2017-2021</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2025-2028</td>
</tr>
</tbody>
</table>

**Requirements for DPF Filtering Performance Monitor:**
- Absolute PM threshold of 17.5 mg/mi for LEV III vehicles certified to 0.01 g/mi PM standard

**Addition of PM and CO thresholds for aftertreatment monitors** (NMHC Catalyst, NOx Catalyst, Catalyzed PM Filter NMHC Conversion, NOx Adsorber)

- LEV III bins are the sum of LEV II NMOG+NOx
- More bins throughout the lower NMOG+NOx emission levels to provide greater flexibility in complying with standards
- FUL of 150k miles
- SULEV30: 70% NMOG + NOX reduction from 2015

**Source:** CARB
Current forecasts indicate Diesel powertrains will have a measurable market share by 2025.

- Diesel micro hybrid share is expected to grow.
- 2016 CAFE report as of September 2016 (U of M) shows fuel economy gains slowing down.
- Big opportunity for new key technology introduction to further increase the fuel economy.
- More diesel engines can help increase the average sales-weighted fuel economy.

* based on analysis of 7 automakers accounting for 75% of US light duty vehicle market
Source: FEV
Source: University of Michigan
With consumers attracted to drive bigger and high power vehicles, Diesel powertrains can help OE gain on CAFE numbers.

**USE DIESEL LOW END TORQUE AS A KEY ADVANTAGE TO MEET CONSUMER DEMANDS**

- Fuel economy and cost of ownership is key for consumers
- However with low fuel prices fun to drive has taken precedence
- Diesel powertrains offering good low end torque can enable OE’s to fill the void
- Significant opportunity for power delivery systems such as transmissions and driveline to maximize this benefit

Source: FEV

2nd CRC Advanced Fuels and Engine Efficiency Workshop
Over 10% improvement in overall powertrain losses shall be achieved to surpass the 2025 fuel economy targets

MID-SIZED DIESEL SEDAN PASSENGER CAR – CAFE 2025 REQUIREMENT

<table>
<thead>
<tr>
<th>Efficiency balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy needed during a FTP-75 cycle: 7-8 MJ</td>
</tr>
<tr>
<td>Energy in 1 gallon of Diesel fuel: 141.57 MJ</td>
</tr>
<tr>
<td>2025 CAFE limit: 56 mi/gallon (Weighted result) → 47.6 mi/gallon (@FTP-75)</td>
</tr>
<tr>
<td>Required Drive power efficiency: 23.5%</td>
</tr>
<tr>
<td>Current Drive power efficiency: 10-15%</td>
</tr>
<tr>
<td>Required overall loss reduction: 8.5 - 13.5%</td>
</tr>
</tbody>
</table>

If losses cannot be compensated, the powertrain will need additional, emission free power sources

Source: IKA Aachen

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Most of today’s diesel engines use conventional technologies

WIDELY USED ENGINE TECHNOLOGIES IN CURRENT MARKET

Engine Mechanical
- Single looped EGR
- Conventional Fixed Valve Timing
- Single Stage VNT
- Aluminum piston

Aftertreatment
- Diesel Oxidation Catalyst
- Diesel Particulate Filter
- Selective Catalytic Reduction
- Conventional low pressure DEF dosing system

Miscellaneous
- Air to Air Charge Air Cooler
- Chain Driven Oil Pump/Coolant Pump
- Conventional Powertrain
- Solenoid Injectors (up to 2000 bar)

Source: FEV
Today’s Diesel engines have tremendous opportunity to reduce friction losses

There are several high yield solutions to minimize frictional losses that can be incorporated in future high volume diesel engines:

- Downsizing
- Steel pistons
- Electrical accessories
- Tailored engine oils
- Roller bearings on cam
- Cylinder wall finish and coating
- Offset crank
- VCR

Source: FEV
Over 2.5% improvement in BSFC is achievable in part load operation with the use of Variable Compression Ratio (VCR)

### Highlights

- In part load operating points a compression ratio of 17:1 improves the fuel economy by approximately 2.5% compared to a compression ratio of 14:1.
- At the same time the HC and CO emissions (not shown) are significantly reduced.
- Drop of exhaust temperature has to be taken into account for the layout of the aftertreatment system.
- VCR for engines with high specific power additionally improves fuel economy due to lower peak firing pressure and possibility to use small bearings and 0W20 oil.
CHOOSING THE RIGHT AFTERTREATMENT IS KEY

LEV III proposals

- Aftertreatment architectures shall consider
  - Minimize cold start emissions spread
  - Avoid continuous thermal management
  - Minimize DPF regeneration intervals
  - Minimize Desulphurization events
    - Combine with DPF regeneration
- Powertrain duty cycle consideration while designing the aftertreatment layout is crucial to maximize the emission benefit and minimize the penalty on fuel economy (fluid economy)

Consideration to minimize cold start emissions slip and avoid continuous thermal management will improve fluid economy and emissions robustness.

Source: FEV
An approximately 40% emissions spread reduction opportunity exists in optimum handling of gas exchange across engine Control system architecture is a key.

**CONTROL AND EMISSION SPREAD REDUCTION**

Fuel economy can also profit from more defined controls.

Source: FEV

2nd CRC Advanced Fuels and Engine Efficiency Workshop
E-charger can help stabilizing gas exchange across engine to improve fuel economy during transient torque demands

**LOAD STEP AT 2000 RPM**

<table>
<thead>
<tr>
<th>Fuel economy</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph showing fuel economy" /></td>
<td>▪ Shorter time to full load</td>
</tr>
<tr>
<td><img src="image2.png" alt="Graph showing torque and pressure" /></td>
<td>▪ Lower pressure difference over the engine</td>
</tr>
<tr>
<td><img src="image3.png" alt="Graph showing cumulated fuel mass" /></td>
<td>▪ Faster acceleration of the turbocharger</td>
</tr>
<tr>
<td><img src="image4.png" alt="Graph showing energy at crankshaft" /></td>
<td>▪ Reduction of the cumulated fuel mass burned</td>
</tr>
<tr>
<td><img src="image5.png" alt="Graph showing cumulated soot" /></td>
<td>▪ With the higher air-fuel-ratio, the peak in the soot can be reduced drastically, resulting in a 50% in cumulated soot</td>
</tr>
</tbody>
</table>

Source: FEV

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Variable valve train controls will benefit from optimum volumetric efficiency management throughout the engine operation and aid in exhaust heat up.
Minimize incidental events such as DPF regeneration, future diesel engines require engine out soot levels below 30 mg/mile

FUTURE DIESEL ENGINE EMISSIONS TARGET

- Low PM combustion systems are critical
  - Fuel atomization, mixing, lambda distribution
  - Cylinder set strategy (Bowl, head, fuel spray)
- Enable improved EGR control strategies
- Mild-Hybrid system (48V) can offer advanced functionalities like engine-off sailing and early start/stop
  - Take advantage of transient torque boosting

Source: FEV
Effective torque damping and smooth power delivery is critical to surpass consumer demands and efficiency needs.

**Highlights**

- Downsizing with high power density increases the torsional vibrations
- Efficient damping systems are crucial especially for Diesel engines
- Diesel specific tailored transmission to take benefit of low speed torque for smooth launch performance

**Source:** FEV

2nd CRC Advanced Fuels and Engine Efficiency Workshop
Fuel economy can be improved through combustion control to CA50; this also help attain robust combustion with wide variety of fuels.

**Combustion Control Around CA50; Impact on Emissions and Fuel Economy Tested on US06**

<table>
<thead>
<tr>
<th>Engine out gaseous emissions [g/mile]</th>
<th>Fuel economy [mpg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>THC</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>3.5</td>
<td>4</td>
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</table>

Source: FEV

2nd CRC Advanced Fuels and Engine Efficiency Workshop

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2025 Diesel powertrain still finds competitive position over alternate options, Diesel fuel price influences total cost of ownership (TCO) greatly

### Diesel Powertrain with Advancements to Engine, Aftertreatment with Hybrid Technology

#### Energy price based on 2025 EIA forecast:
- Gasoline (92 Ron) = 3.33 $/gallon
- Diesel price (High) = 4.00 $/gallon
- Diesel price (Low) = 3.00 $/gallon
- Electricity price = 12 $-cent/kWh

#### Compliance target

1: TCO model assumptions: Driver annual mileage = 16,500 miles, Holder period = 5 years, Utility factor (PHEV) = 47%, Interest rate: 1.0%
2: 4-cylinder inline, rated power = 136 kW, displacement = 2.5l, naturally aspirated, dual variable valve timing, port fuel injection, three-way catalyst, automatic 6-speed transmission

#### Technology strategies

<table>
<thead>
<tr>
<th>#</th>
<th>Technology strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mild downsizing &amp; Miller &amp; AT8</td>
</tr>
<tr>
<td>2</td>
<td>Strong downsizing &amp; EGR &amp; AT8</td>
</tr>
<tr>
<td>3</td>
<td>Mild downsizing &amp; Lean combustion &amp; AT8</td>
</tr>
<tr>
<td>4</td>
<td>Strong downsizing &amp; Miller &amp; VVL &amp; VCR</td>
</tr>
<tr>
<td>5</td>
<td>Strong downsizing &amp; Miller &amp; VVL &amp; EGR</td>
</tr>
<tr>
<td>6</td>
<td>Strong downsizing &amp; Miller &amp; VVL &amp; EGR &amp; VCR &amp; Cylinder deactivation</td>
</tr>
<tr>
<td>7</td>
<td>Atkinson &amp; VVL &amp; Cylinder deactivation &amp; AT8</td>
</tr>
<tr>
<td>8</td>
<td>AT9/10 &amp; Mild downsizing &amp; Miller</td>
</tr>
<tr>
<td>9</td>
<td>CVT &amp; Mild downsizing &amp; Miller</td>
</tr>
<tr>
<td>10</td>
<td>MHEV-P2 &amp; Mild downsizing &amp; VVL &amp; Miller</td>
</tr>
<tr>
<td>11</td>
<td>HEV-Powersplit &amp; VVL &amp; AT8</td>
</tr>
<tr>
<td>12</td>
<td>HEV-Powersplit &amp; Mild downsizing &amp; Miller</td>
</tr>
<tr>
<td>13</td>
<td>PHEV-P2 (&quot;x&quot; kWh) &amp; Atkinson</td>
</tr>
<tr>
<td>14</td>
<td>PHEV-P2 (&quot;2x&quot; kWh) &amp; Atkinson</td>
</tr>
<tr>
<td>15</td>
<td>2nd level vehicle measures &amp; Mild downsizing &amp; Miller &amp; AT9/10</td>
</tr>
<tr>
<td>16</td>
<td>3rd level vehicle measures &amp; Mild downsizing &amp; Miller</td>
</tr>
<tr>
<td>17</td>
<td>2025 Diesel Midsize Car (Adv Cmb, Adv ATS, AT8)</td>
</tr>
</tbody>
</table>

AT8 = automatic 8 speed transmission  
EGR = Exhaust Gas Recirculation  
VVL = Var. Valve Lift  
VCR = Var. Compression Ratio  
ATS = Aftertreatment system

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Diesel engines can play a major role in 2025 fuel economy targets while maintaining emissions compliance using proven technologies.

Current Diesel powertrain show significant fuel economy and CO2 emissions benefit over alternate powertrain configurations.

Diesels still look competitive in 2025.

With 48V hybrid systems the gains in GHG and fuel economy can be further enhanced.

Widespread use of BioDiesel derived from non-food source feedstock is also one of the enablers for Diesel usage for overall CO2 reduction.

Thank You