NEW TECHNOLOGIES TO MEET 2025 CAFE STANDARDS AND THEIR IMPACT ON FUELS

CRC Advanced Fuel and Engine Efficiency Workshop
H-D Systems
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GHG Standards and Corporate Average Fuel Economy Standards for 2017-2025

- EPA and the Department of Transportation (NHTSA) are regulating the fleet of cars and light duty trucks to an EPA estimated combined car + light truck average of 54.5 mpg or 163 g/mi of CO2
  - EPA: criteria pollutants and GHGs under the Clean Air Act (CAA)
  - NHTSA: CAFE standards equivalent to EPA’s GHG standards
  - California’s Air Resources Board (CARB) is working with EPA on the GHG standards
- NHTSA will carry out a review, in 2017, of the 2022-2025 standards
  - NHTSA can only set standards for five years
  - The three agencies will cooperate on the technical assessment
EPA and NHTSA standards are defined by “footprint curves,” which assign a specific CO₂ or MPG target for each possible vehicle footprint.

- Passenger cars and light trucks have separate footprint curves.
- Each manufacturer has a unique car fleet average standard and a unique light truck fleet average standard.

Standards for each manufacturer are derived from footprint curves, based on the sales-weighted distribution of vehicles.

There are a number of credits available for “off-cycle” technologies and early introduction of fuel efficient vehicles that reduce the stringency of the standard substantially from 54.5 mpg.
# Estimates of Actual 2025 Requirements

<table>
<thead>
<tr>
<th>Description</th>
<th>GHG emissions g/mi</th>
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<tr>
<td>EPA 2025 Standard</td>
<td>163.0 (54.5 mpg)</td>
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<tr>
<td>Air Conditioner Improvements</td>
<td>21.3</td>
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<tr>
<td>Off Cycle Technology Credits (at cap)</td>
<td>10.0</td>
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<td>High Efficiency Pickup truck Credit</td>
<td>0.4</td>
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<tr>
<td>EV/PHEV zero g/mi credit at 5% penetration</td>
<td>4.5</td>
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<tr>
<td>Over-estimate of car market share</td>
<td>4.8</td>
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<tr>
<td>Increased wheelbases for all vehicles</td>
<td>4.0 +</td>
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<tr>
<td>Net Total</td>
<td>205+ g/mi (&lt;43.4 mpg)</td>
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New Technology

- New technology information obtained from literature, SAE meetings, product plans and direct meetings with auto-manufacturers and suppliers.
- Information shows that different manufacturers have surprisingly different views on engine technology and somewhat different views on transmission technology.
- Product plans, which are firm to 2018 (and soon to 2019) show manufacturer strategic directions for 2020/2025 compliance.
- Combining information gives a good fleet-wide view of technology penetration to 2020 and direction to 2025.
- Importance of Engine downsize/GDI – Turbo, emphasized by EPA, is not accepted by Japanese manufacturers.
Gasoline Engine Pathways

- +High Compression Ratio
  - DI
  - cooled EGR
  - var. eff. compress.
  - knock rest. fuels

- +Lean Combustion
  - SGDI
  - HCCI

- Downsizeing
  - CDA
  - VVT
  - T/C
  - DI
  - VVL

- Downspeeding
  - VVT
  - Gears+
  - CVT
  - (DI)

Barriers/Limits
- Friction reduction
- Thermal management
- Mass reduction

- Pre-Ignition
- Knocking
- Ignition
- De-throttling potential
- Emissions (NOx)
- Controllability (HCCI)
- NVH
- Drivability (Turbolag)
- Displacement per cyl.
- NVH, drivability
- No. of shifting operations
- Mass, friction, hydraulic
Europe is firmly committed to the GDI – Turbo – Downsize path and VW and BMW have already converted most engines, with Mercedes catching up rapidly.

The majority of GDI – turbo engines in the US market boost to 17-19 bar BMEP but new engines for 2013 from BMW, Porsche and GM are at 22-23 bar. In general, the higher boost is enabled either by a reduction of CR from 10 to 9, or by requiring premium gasoline. No one is using cooled EGR yet.

While suppliers talk about boosting to 27 - 30 bar with extreme engine downsizing and cooled EGR, manufacturers suggest that 22-24 bar may be the highest for this decade. Intake deposits with cooled EGR, and EGR thermal management are major issues.

In actual practice, fuel economy benefit of this route has lagged expectations.
Supplier View of Potential

- MAHLE Downsize 2-Stage Turbo
- MAHLE Downsize Single Turbo
- VW 1.4l SC / TC
- Ford 2.0l EcoBoost
- Fiat 1.8 TGDI
- Audi 2l TFSI AVS
- Audi 1.8 TFSI
- Audi 1.8T

Specific Power Output (kW/l)

Peak BMEP (bar)
Current FE Benefits of GDI-Turbo

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<tbody>
<tr>
<td>Ford F-150</td>
<td>Auto-6</td>
<td>5.0L V8</td>
<td>20.47</td>
<td>3.5L V6 T</td>
<td>22.15</td>
<td>8.2%</td>
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<tr>
<td>Ford Fusion</td>
<td>Auto-6</td>
<td>2.5L I-4</td>
<td>34.56</td>
<td>1.6L I4 T</td>
<td>37.70</td>
<td>9.1%</td>
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<tr>
<td>VW Jetta</td>
<td>Auto-6</td>
<td>2.5L I4</td>
<td>33.11</td>
<td>2.0L I4 T</td>
<td>34.95</td>
<td>5.5%</td>
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<tr>
<td>GM Sonic</td>
<td>Auto-6</td>
<td>1.8L I4</td>
<td>37.79</td>
<td>1.4L I4 T</td>
<td>41.36</td>
<td>9.4%</td>
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Mercedes has introduced a new lean burn engine for the EU in 2013. Engine features include:

- Central piezo injector with conical spray
- Spray guided charge stratification
- Ultra-lean combustion at light loads to 4 bar BMEP
- Intermediate stage “homogenous-stratified” lean combustion to 7 bar
- Stoichiometric combustion from 7 bar to full load

Engine uses a lean NOx adsorber to meet emissions standards and is planned for US introduction in MY 2016 with the advent of 10ppm sulfur fuel.

Mercedes introduced a turbo-downsized engine in 2014 with lean burn in the EU and will extend lean operation to 12 bar BMEP, with stoichiometric operation to 23 bar.
Lean Burn Fuel Consumption

be = 290 g/kWh

Δ 10%
Δ 17.1%
Δ 6%
Δ 12.4%
Δ 4%
Δ 8.9%
Δ 3%
Δ 7.9%
Δ 2%
Δ 6.5%
Δ 1%

specific fuel consumption for 2000 l/min
- stratified combustion
- HOS
- variable valve lift, Lambda 1
Japanese manufacturers are more wary of GDI/Turbo with engine downsizing as a strategy for the US and Japanese markets as they perceive greater risk and cost. Instead, the strategy appears to be evolving to higher CR in combination with the Miller or Atkinson cycle. The power loss associated with the Atkinson cycle has been overcome with improved combustion and better scavenging. Mazda’s first generation high CR engine (13:1) employs all of these techniques but the quoted 15% FE improvement is from other sources as well. Only about 5% is due to the high CR with an additional 3% from the Atkinson cycle, 4% from friction reduction and 3% from idle speed reduction and improved thermal management.
Honda has introduced a 13 CR engine with the Atkinson cycle and uses cooled EGR to improve detonation resistance. The engine is used only in the Accord hybrid due to a 10% power loss. The engine has attained the lowest BSFC of any gasoline engine at 213 g/kWh, about 7% lower than 11 CR engines.

The Honda engine uses PFI, possibly due to concerns about intake deposits with cooled EGR.

Nissan has also introduced a 13CR 3-cylinder engine in the EU with DI and Miller cycle, with the supercharger used to bring power back to typical naturally aspirated engine level. The vehicle shows a 20% fuel consumption reduction relative to the same vehicle with a 1.2L PGI engine.

Toyota, Nissan and Honda have discussed this strategy for the next generation of engines.
The next step in the high CR strategy is to combine with lean burn. Mazda is planning to introduce a HCCI system with the new high CR engine later in this decade, possibly 2017-18. Mazda claims that the high CR – Atkinson cycle – Lean Burn strategy will raise efficiency to that of a diesel, suggesting that fuel economy improvement of another 15% is possible. While some existing studies suggest that HCCI engines do not need high octane fuel, Mazda insists that RON of fuel will continue to be important. Other Japanese manufacturers are more skeptical about the robustness of HCCI combustion, but suggest that it could emerge after 2020 with more development.
Newer third generation DI diesels with sequential turbo-chargers have been introduced by BMW and Mercedes. The new engines have very good low RPM torque and offer about 75 to 80 HP/L specific output.

Like turbo-gasoline engines, the new engines allow engine downsizing and down-speeding and provide 7 to 9% better FE than earlier engines. This has maintained the 30% diesel FE advantage over gasoline, but at higher costs.

Due to higher engine and fuel costs, diesels have not been very successful in the car market with the exception of the VW Jetta and Passat. However, the diesel has been relatively successful in SUVs with a take rate of 25 to 30% in most models, suggesting a possible future for diesels in light trucks.
Three major directions are being explored in future transmission developments – 8 to 10 speed conventional automatics, dual clutch automated manual (DCT) transmissions and continuously variable transmission (CVT).

On a theoretical basis, the CVT should provide the highest benefit but higher internal friction and drive ‘feel’ have held back market penetration. The newer generation of CVT models have reduced internal friction and offer better driver response.

New developments in gear sets and clutches have reduced the cost and improved the efficiency of multi-speed automatics and have made them attractive as they offer the best drivability. Stop-start capability has been integrated into some transmissions.

DCTs are popular in Europe and have low internal friction but US customers are not satisfied with early models’ shift quality.
Transmission Tradeoffs - Nissan

The broken lines mean equal fuel consumption @ US Comb. mode.

Future Ultimate Transmission

CVT
Reduce Friction
Wide R/C

Future

AT
Multiple gear
JG(6AT)

DCT
Dry-7DCT
Wet-6DCT

NISSAN
Other Company

Transmission Efficiency
Weight Reduction

- New studies on weight reduction show costs are coming down with advancements is HS steel, Aluminum and improved design and manufacturing.
- Many new body designs now have HSS content of 55 to 60% compared to only 20% in mid-2005. This is attributed to new dual phase steel with better formability and weld-ability.
- Importance of cost reduction from secondary weight reduction in the engine, suspension and brakes is being more fully recognized in cost analysis.
- Aluminum castings have largely replaced iron, and aluminum closures will likely take over luxury car market. The Ford F-150 Aluminum truck is an exciting new development.
- BMW is pushing hard on automotive grade low cost carbon fiber and will introduce it in many high load structures.
Total Cost Of Weight Reduction – Mid Size Car with 3400 lb. Base Weight
Hybrid Technology

- Hybrid technology has evolved into 3 separate approaches. The Belt Alternator Starter (BAS) is the simplest and is being pushed by GM. However, the GM system has relatively high cost and small benefit, with poor market acceptance.
- The Prius type design with 2 electric motors has been successful in the market. Although cost is high, FE benefit and drivability are very good. Toyota, Ford and now Honda, have adopted the system which accounts for 80% of US hybrid sales.
- The 1 motor 2 clutch (1M2C) system provides about 80% of the FE benefit of the Prius system at 50% of the cost, but the engine restart problem leads to occasionally poor driving. The system is also less well suited to PHEV conversion. Market acceptance has been poor, except for the Hyundai model which also uses a BAS system to solve the restart problem.
- Improved part load engine efficiency suggests future direction will be towards smaller electrical systems.
Engine Efficiency – Motor Requirement Interaction

Driven by motor

Drive motor by regenerative braking

Driven by Engine

Generate electricity and drive motor at the highest efficiency point of engine

Motor

Engine

BSFC

BMEP

Current Engine

2nd Step Engine

Best FE point

Best FE point
Overall assessment of fuel and lubricant issues with new technology shows only modest impacts.

Impacts investigated include:
- GDI injector fouling and fuel coking due to higher tip temperature.
- Intake valve deposits with GDI
- Lubricant dilution from fuel spray impingement from GDI
- Fuel octane and composition issues with GDI/Turbo
- Lubricant requirements for GDI/Turbo
- Fuel Issues with high CR engines
- Impact of fuel properties on PM emissions
- Low RPM pre-ignition on highly turbocharged engines
Both the EU and US have set standards for PM with weight in the US and particle number in the EU at approximately similar levels. GDI combustion creates more PM than PFI.

Manufacturers seem a little divided on fuel effects on PM emissions. Japanese manufacturers suggest significant effect, while European manufacturers suggest spray pattern and timing are more important although this may be due to the centrally mounted high cost piezo injectors being employed by Mercedes and BMW.

Directionally, Europeans agree with the Honda analysis of fuel effects. Honda has found PM emissions are proportional to the C9+ aromatics and the final boiling point of the fuel.
GDI Turbo Issues

- Turbo operating temperatures are generally higher and result in somewhat more severe requirements for fuels and lubes.
- All manufacturers agree that octane benefits for FE and performance are relatively small with about 2 to 3% change in both for 4 octane points. EU Turbo vehicle customers perceive a larger performance benefit.
- VW suggested that engines are set up for the lowest quality fuel in the region (foe eastern Europe in EU cars) so that the “full” benefits of higher octane in the EU are not seen.
- Only some manufacturers are interested in a E25 fuel with 98+RON for GDI/Turbo but all agree that more ethanol and higher octane are preferable with higher boost. Honda chart shows why 24/27 bar boost is unlikely for the US without cold EGR and attendant intake deposit and thermal management problems.
Optimal Octane Requirement
The phenomenon of low RPM high torque auto-ignition in GDI engines has received a lot of attention lately and is being researched by an auto-oil coalition. This type of auto-ignition does not occur on each cycle but randomly.

Toyota has outlined the different types of abnormal combustion phenomena and has traced low speed auto-ignition (LSPI) to oil droplets ejected occasionally into the combustion chamber from crevices.

Toyota found good correlation of the LSPI frequency of occurrence to the oil’s auto-ignition temperature, suggesting oil components need to have this temperature above 280°C.

Other manufacturers believe that auto-ignition may be due to both fuel and oil properties and this is being investigated.
Abnormal Combustion Modes

[Diagram showing different modes of abnormal combustion, such as low speed pre-ignition, high speed pre-ignition, knocking, natural aspirated engine, and turbocharged engine, plotted against engine speed and torque.]