Passenger Car Fuel Economy Standards Globally

Solid markers and solid lines: historical performance
Solid markers and dashed lines: final standard
Hollow markers and dotted lines: proposal or target under study

[1] China’s target reflects gasoline vehicles only. The target may be higher after new energy vehicles are considered.
[3] Mexico does not include early action credits for MYs 2012 and 2013 but does include full application of other credits.
Role of Fuel Economy Standards in Managing Performance – Fuel Consumption Tradeoff: US Example


Phase III (1987-2006): Performance gains take priority over fuel consumption reduction

Phase IV (2007-?): Fuel consumption reduction takes priority over performance again

Data from EPA 2013 Fuel Economy Trends Report
Technology Deployment Spurred by Fuel Economy Standards
Opportunities for Vehicle Efficiency Improvements

- Fuel Tank: 100%
- Standby: 6%
- Engine Loss: 74%
- Driveline Losses: 4%
- Aero: 4%
- Rolling: 5%
- Braking: 7%

Urban Drive Cycle, 2005 2.5L Toyota Camry
The Real Technology Breakthrough

Computers

- Computer design, computer simulations, and on-vehicle computer controls are revolutionizing vehicles and powertrains
- Especially important for lightweight materials
  - Optimize hundreds of parts – size and material
  - Capture secondary weight – and cost – reductions
- The high losses in the internal combustion engine are an opportunity for improvement
- Also reducing size and cost of hybrid system
A broad suite of cost-effective technology packages are available to meet upcoming efficiency standards

- Assessment of US 2012-2025 standards indicates the standards can be met with:
  - Gasoline direct injection (GDI)
  - Turbocharged/downsized engines
  - Advanced transmissions (6-speed/8-speed automatic or dual-clutch transmissions and high efficiency gear box)
  - Vehicle mass reduction
  - Lower tire rolling resistance
  - Improved aerodynamics
  - Friction reduction
  - More efficient vehicle accessories
  - Engine start-stop systems
  - …
  - …
  - …
  - Some increased hybrids, EVs, PHEVs

- No penetration of diesels or hybrid vehicles necessary to meet US 2016 standards.

EPA/NHTSA project that MY2025 vehicles will be 90% advanced gasoline, 9% hybrids, and 1% EV/PHEVs
Accelerating Technology Introduction in the U.S. is driven by Fuel Economy Regulation

<table>
<thead>
<tr>
<th>Year</th>
<th>GDI</th>
<th>Turbo</th>
<th>VVT</th>
<th>6 speed</th>
<th>7+ speed</th>
<th>CVT</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>-</td>
<td>4%</td>
<td>43.7%</td>
<td>5%</td>
<td>0.4%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>2005</td>
<td>-</td>
<td>2%</td>
<td>49.4%</td>
<td>6%</td>
<td>0.4%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>2006</td>
<td>-</td>
<td>3%</td>
<td>58.2%</td>
<td>12%</td>
<td>2%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>2007</td>
<td>-</td>
<td>4%</td>
<td>63.3%</td>
<td>16%</td>
<td>2%</td>
<td>10%</td>
<td>3%</td>
</tr>
<tr>
<td>2008</td>
<td>3%</td>
<td>4%</td>
<td>62.7%</td>
<td>19%</td>
<td>3%</td>
<td>11%</td>
<td>3%</td>
</tr>
<tr>
<td>2009</td>
<td>4%</td>
<td>4%</td>
<td>79.1%</td>
<td>19%</td>
<td>3%</td>
<td>11%</td>
<td>3%</td>
</tr>
<tr>
<td>2010</td>
<td>9%</td>
<td>4%</td>
<td>91.8%</td>
<td>33%</td>
<td>3%</td>
<td>14%</td>
<td>5%</td>
</tr>
<tr>
<td>2011</td>
<td>18%</td>
<td>8%</td>
<td>94.9%</td>
<td>54%</td>
<td>5%</td>
<td>12%</td>
<td>3%</td>
</tr>
<tr>
<td>2012</td>
<td>28%</td>
<td>10%</td>
<td>97.7%</td>
<td>58%</td>
<td>6%</td>
<td>15%</td>
<td>5%</td>
</tr>
<tr>
<td>2013</td>
<td>38%</td>
<td>16%</td>
<td>98.0%</td>
<td>61%</td>
<td>8%</td>
<td>17%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Source: 2013 EPA Fuel Economy Trends Report – Cars only
GDI: Gasoline Direct Injection
CVT: Continuously Variable Transmission
VVT: Variable Valve Timing
Example of Technology Upgrade: High-Selling Passenger Cars 2010 to 2014

<table>
<thead>
<tr>
<th>Year</th>
<th>2010 4-cylinder sedans</th>
<th>2014 4-cylinder sedans</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fuel economy (km/l)

Vehicle footprint (m²)
Technology Costs Dropping Rapidly

Technology availability increases - and its costs decrease - over time

- Incremental vehicle costs and percent improvements versus MY2008 baseline
- Data from EPA/NHTSA 2012-2016 rulemaking and EPA/NHTSA/CARB TAR for 2020
Examples of new/future Technologies
Next-generation Gasoline Engines

Fiat MultiAir
Digital Valve Actuation

Improvement in fuel economy: 30%

Honda Prototype Engine Base
( Electro-magnetic valve )

Heat release rate
Crank angle [ATDC deg]

Requires increasing the self-ignition region

Conventional

Negative valve overlap

EX
IN
NOL

HCCI Engine

EX
IN

Turbo Dedicated EGR Engines

- Highly dilute, low temperature combustion
- ~1% \( \text{H}_2 \) by volume in the intake
- Advanced ignition systems required
- ~40% brake thermal efficiency (similar to diesel)
- PSA 2018 introduction
Lightweight Materials:
Costs are dropping rapidly
Vehicle Lightweight Research in 2017-25 Rule

- Technical assessments on mass-reduction involve major studies by national US laboratories, OEM steel suppliers, OEMs with universities
  - Each data point represents a different material/design approach to mass reduction
  - Studies vary in technical rigor, transparency, comprehensiveness, crashworthiness validation
  - EPA projected average vehicle mass would decrease by 7% by 2025

![Graph showing incremental mass reduction cost and percent vehicle curb weight reduction with data points representing different studies.](chart.png)

- Data from research literature (confidential industry data not shown)
- EPA/NHTSA ($4.33/lb/%)
- CARB evaluation ($2.3/lb/%)
Major New Mass-Reduction Work

- Lotus Engineering (CARB) – Toyota Venza
  - Continuation of 2010 study (-33% mass Toyota Venza)
  - Cost-effective 18-32% mass reduction at < $0/vehicle
  - Includes crashworthiness safety (NHTSA FMVSS) validation

- FEV (US EPA) – Toyota Venza
  - Technical assessment of -18% mass at < $0/vehicle
  - Includes crashworthiness safety (NHTSA FMVSS) validation and detailed tear-down cost assessments

- EDAG / Electricore (NHTSA) – Honda Accord
  - Technical assessment of -22% mass at $319/vehicle
  - Includes crashworthiness safety (NHTSA FMVSS) validation

- EDAG WorldAutoSteel “Future Steel Vehicle”
  - 12-18% mass reduction, no additional cost, with only using steels

- George Washington University (NHTSA) – Chevy Silverado
  - 19% mass reduction with advanced plastics, composites
  
Vehicle lightweighting is highly cost-effective

- Major new state-of-the-art studies examine advanced materials, parts integration, system-level holistic vehicle redesign
  - High lightweighting potential, crashworthy designs, and diverse highly cost-effective approaches
  - EDAG, FEV, Lotus, and FSV lightweighting cost results are shown below

![Graph showing incremental cost vs. percent vehicle curb weight reduction with data from older and recent studies.](image)
Weight Reduction in 2015 Ford F150

Vanguard of a truly radical transformation in how vehicles are designed and built

The largest selling vehicle in the US

Weight reduction: 318 kg, 14%
Engine downsize: 3.5L to 2.7L

First use of aluminum body in high volume production vehicle

95% of body– Aluminum
77% of frame– HSS

Source: http://www.ford.com/trucks/f150/2015/
# Examples of vehicles in production

<table>
<thead>
<tr>
<th>Vehicle make</th>
<th>Model year</th>
<th>Weight reduction (kg)*</th>
<th>Weight reduction (%)*</th>
<th>Designed market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford F150</td>
<td>2015</td>
<td>318</td>
<td>14%</td>
<td>US</td>
</tr>
<tr>
<td>Acura MDX</td>
<td>2014</td>
<td>111</td>
<td>5%</td>
<td>US</td>
</tr>
<tr>
<td>GM Cadillac CTS</td>
<td>2014</td>
<td>111</td>
<td>6%</td>
<td>US</td>
</tr>
<tr>
<td>Peugeot 308 SW Blue Hdi</td>
<td>2014</td>
<td>140</td>
<td>9%</td>
<td>EU</td>
</tr>
<tr>
<td>VW Golf TDI</td>
<td>2015</td>
<td>49</td>
<td>4%</td>
<td>EU</td>
</tr>
<tr>
<td>Audi Q7</td>
<td>2014</td>
<td>363</td>
<td>15%</td>
<td>US, EU</td>
</tr>
<tr>
<td>BMW i3 EV</td>
<td>2014</td>
<td>249</td>
<td>17%</td>
<td>US, EU</td>
</tr>
<tr>
<td>Land Rover Range Rover</td>
<td>2014</td>
<td>350</td>
<td>14%</td>
<td>US, EU</td>
</tr>
<tr>
<td>Porsche Cayenne</td>
<td>2012</td>
<td>181</td>
<td>8%</td>
<td>US, EU</td>
</tr>
<tr>
<td>Audi A8</td>
<td>2014</td>
<td>145</td>
<td>7%</td>
<td>US, EU</td>
</tr>
<tr>
<td>Audi A3</td>
<td>2014</td>
<td>80</td>
<td>6%</td>
<td>US, EU</td>
</tr>
<tr>
<td>Nissan Leaf</td>
<td>2012</td>
<td>80</td>
<td>5%</td>
<td>US, EU</td>
</tr>
<tr>
<td>Lamborghini Huracan</td>
<td>2015</td>
<td>78</td>
<td>5%</td>
<td>US, EU</td>
</tr>
<tr>
<td>Audi TT 3rd gen 2.0 TDI</td>
<td>2015</td>
<td>50</td>
<td>4%</td>
<td>US, EU</td>
</tr>
</tbody>
</table>

* The weight of new models are compared to its predecessors, except for BMW i3 EV, which is compared to the conventional steel structure.
Technology Tear-Down: Robust and Transparent Cost Estimates
Significantly improved method to assess CO$_2$ reduction potential and costs of technologies.

**US EPA / CARB / ICCT**
- Vehicle computer simulation
  RICARDO (Detroit)
- Tear-down cost assessment
  FEV (Detroit)

**ICCT**
- Vehicle computer simulation
  RICARDO (Shoreham + Detroit)
- Tear-down cost assessment
  FEV (Aachen + Detroit)
Significantly improved method to assess CO$_2$ reduction potential and costs of technologies.
Data sources

FEV and Lotus Mass Reduction Analyses

Ricardo CO$_2$ reduction analysis on behalf of ICCT

FEV cost analysis on behalf of ICCT

EPA / NHTSA 2017-25 rulemaking

only where no EU information available

CO$_2$ reduction cost curves for EU vehicle segments
(ICCT, Meszler Engineering Services)
Methodology

The Final Result

- C-segment gasoline
Comparison of Vehicles in US versus Mexico
F:

High Altitude Impacts

- Fuel economy is BETTER at high altitude:
  - Air density is lower, decreasing aerodynamic drag and reducing pumping losses.
- There is a loss of power if the engine is naturally aspirated:
  - If a manufacturer designs the vehicle for high altitude, they will need to install a larger engine.
  - However, engines in Mexico are still smaller and have less power than engines in the US, making it easier for Mexican vehicles to meet the standards.
- Turbocharging will eliminate the power loss at high altitude - while preserving the pumping loss improvements:
  "All EcoBoost V-6 engines maintain peak torque capability at well over 5,000 feet above sea level, making EcoBoost-equipped vehicles ideal for high-altitude operation."
  [http://media.ford.com/article_display.cfm?article_id=30651](http://media.ford.com/article_display.cfm?article_id=30651)
Wide-Range Transmission Gears

- Older 4- and 5-speed transmissions have a gear range of about 4.5 (ratio of shortest gear to tallest gear). It cannot cover all driving from highway cruising to high-altitude grades. Thus, some low-powered vehicles may need to have shorter gears for Mexico.

- Current 6+ speed transmissions have wider gear ranges, of 6.0 or more. This provides proper gearing for both highway cruising and high-altitude grades, without the need to change gearing.

- Also note that turbocharged engines do not lose performance at high-altitude, further reducing any need for shorter gears.

| Older transmissions | Gear range | Mexico gearing | European gearing | Current US transmissions | Gear range |
Displacement vs. Footprint: All Vehicles

- Regression of engine size versus vehicle footprint is 14% higher in the US than in Mexico
- 2008 data for Mexico and the US, cars and light trucks combined

### Displacement/kg - Mexico versus US vehicles - 2008 data

<table>
<thead>
<tr>
<th></th>
<th>US</th>
<th>Mexico</th>
<th>Mexico vs US</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test weight (kg)</td>
<td>1875</td>
<td>1548</td>
<td>-17%</td>
</tr>
<tr>
<td>Engine size (liter)</td>
<td>3.3</td>
<td>2.4</td>
<td>-27%</td>
</tr>
<tr>
<td>Liters/kg</td>
<td>0.117</td>
<td>0.102</td>
<td>-13%</td>
</tr>
</tbody>
</table>
Regression of engine power (hp) versus vehicle footprint is 12% higher in the US than in Mexico

2008 data for Mexico and the US, cars and light trucks combined

<table>
<thead>
<tr>
<th>Regression</th>
<th>US</th>
<th>Mexico</th>
<th>Mexico vs US</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test weight (kg)</td>
<td>1875</td>
<td>1548</td>
<td>-17%</td>
</tr>
<tr>
<td>Horsepower</td>
<td>220</td>
<td>157</td>
<td>-28%</td>
</tr>
<tr>
<td>HP/kg</td>
<td>0.117</td>
<td>0.102</td>
<td>-13%</td>
</tr>
</tbody>
</table>
Cars 1.0L – 3.5L: Horsepower v Footprint

- Regression of HP versus vehicle footprint is 17% higher in the US
  - 2008 data for Mexico and the US
Cars 1.0L – 3.5L: Horsepower v Test Weight

- Regression of HP versus test weight is 11% higher in the US
  - 2008 data for Mexico and the US
Cars 1.0L – 1.8L: Horsepower v Footprint

- Regression of HP versus vehicle footprint is 3% higher in the US
  - 2008 data for Mexico and the US

![Graph showing regression of HP versus vehicle footprint for US and Mexico MY2008 vehicles.](image-url)
Cars 1.0L – 1.8L: Horsepower v Test Weight

- Regression of HP versus test weight is 2% higher in the US
  - 2008 data for Mexico and the US

### Linear Regression

- **U.S. MY2008 vehicles**
  - $y = 0.0928x$
  - $R^2 = 0.35022$

- **Mexico MY2008 vehicles**
  - $y = 0.0913x$
  - $R^2 = 0.52025$
Heavy-Duty Vehicle Fuel Economy Improvement Opportunities
There are many opportunities to reduce fuel consumption of heavy vehicles (including buses).

- Improve vehicle and trailer aerodynamics
- Reduce rolling resistance
- Improve transmission and drivetrain efficiency
- Reduce auxiliary loads
- Improve engine efficiency
- Optimize driver behavior
- Reduce vehicle weight
U.S. National Academy of Sciences (March 2010) found 35-50% improvement could be achieved in the 2015 to 2020 timeframe.
Conclusion
Summary

• Computer aided design and computer simulations are accelerating technology development.
  • Especially important for lightweight materials.
• Costs are rapidly decreasing.
• Altitude impacts are becoming less important, due to turbocharging and transmissions with a wider range of gears.
• Engines in Mexico are smaller and have less power than in the US, making it easier for them to meet the standards.
For more information…

- ICCT Passenger Vehicles website:
  http://www.theicct.org/passenger-vehicles

- Global Passenger Vehicle Standards Update:

- US CAFE Standards:
  http://www.theicct.org/policies/us-cafe-standards

- EU LDV CO2 Regulation:
  http://www.theicct.org/policies/eu-light-duty-vehicle-co2-regulation

- Review and Comparative Analysis of Fiscal Policies to promote fuel economy:
  http://www.theicct.org/review-and-comparative-analysis-fiscal-policies

- CO2 Standards:
  http://www.theicct.org/issues/co2-standards

Anup Bandivadekar
anup “at” theicct.org

@TheICCT
Thank You