Technology trends and developments towards 2022-25 MidTerm Review

Resources for the Future
Identifying Research Priorities for the Midterm Review

John German, Senior Fellow
International Council on Clean Transportation
December 17, 2013
Pace of change is quickening

Lightweight Materials
Engine downsizing
Direct Injection
Hybrids
Joint-Agency TAR: Technology Packages

- Major CO\textsubscript{2}-reduction potential from emerging technologies by 2025
  - US EPA’s OMEGA used many technology packages, 19 vehicle classes
  - Increasing costs from incremental efficiency, to hybrid, and to electric technology

Price in figure refers to the incremental cost to the consumer due to the new technology packages; technology packages include many different technologies; technology labels are approximate for illustration; grid electricity applies US EPA assumptions and accounting method for US electric grid (558 gCO\textsubscript{2}e/kWh) for electric and plug-in hybrids.
Technology Costs Dropping

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
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
Compliance with US GHG standards is projected to primarily result from increased adoption of advanced gasoline efficiency technologies:

- Federal and California rulemakings utilize same underlying technical assumptions
- California’s ZEV program also includes electric-drive vehicle requirements

### Projected Technology Adoption

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Engine</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline Direct Injection (GDI)</td>
<td>65%</td>
<td>94%</td>
<td></td>
</tr>
<tr>
<td>Turbocharged GDI (all)</td>
<td>64%</td>
<td>93%</td>
<td>51%</td>
</tr>
<tr>
<td>Cooled EGR, turbocharged GDI (24 bar)</td>
<td>15%</td>
<td>64%</td>
<td>14%</td>
</tr>
<tr>
<td>Boosted EGR, turbocharged GDI (27 bar)</td>
<td>3%</td>
<td>6%</td>
<td></td>
</tr>
<tr>
<td><strong>Driveline</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7+ speed or CVT</td>
<td>72%</td>
<td>91%</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>Dual-clutch, automated manual or CVT</td>
<td>54%</td>
<td>56%</td>
<td>56%</td>
</tr>
<tr>
<td><strong>Load reduction</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass reduction (fleet average)*</td>
<td>5%</td>
<td>7%</td>
<td>8%</td>
</tr>
<tr>
<td>Low RR tires</td>
<td>73%</td>
<td>97%</td>
<td>&gt;95%</td>
</tr>
<tr>
<td><strong>Advanced</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid electric (strong + mild)</td>
<td>11%</td>
<td>31%</td>
<td>6%</td>
</tr>
<tr>
<td>Plug-in hybrid + electric + fuel cell</td>
<td>1%</td>
<td>2%</td>
<td>15%</td>
</tr>
</tbody>
</table>

*Mass reduction is fleet average (not percent new vehicle technology share, like other technologies listed)*

2008 and 2013 from 2013 EPA FE Trends Report (cars and light trucks)
2021 and 2025 from CARB GHG regulation and US EPA/NHTSA 2017-2025 rulemaking documents
# Accelerating Technology Introduction

<table>
<thead>
<tr>
<th>Year</th>
<th>GDI</th>
<th>Turbo</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>5%</td>
<td>0.4%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>2005</td>
<td>-</td>
<td>2%</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>12%</td>
<td>2%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>2007</td>
<td>-</td>
<td>4%</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>19%</td>
<td>3%</td>
<td>11%</td>
<td>3%</td>
</tr>
<tr>
<td>2009</td>
<td>4%</td>
<td>4%</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>33%</td>
<td>3%</td>
<td>14%</td>
<td>5%</td>
</tr>
<tr>
<td>2011</td>
<td>18%</td>
<td>8%</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>58%</td>
<td>6%</td>
<td>15%</td>
<td>5%</td>
</tr>
<tr>
<td>2013</td>
<td>38%</td>
<td>16%</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
Pace of Technology Innovation is Accelerating

<table>
<thead>
<tr>
<th>Technology</th>
<th>Source</th>
<th>Benefit</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo-charging and downsizing</td>
<td>2001 NRC Report</td>
<td>5-7%</td>
<td>$250-$400</td>
</tr>
<tr>
<td>(no cyl. reduction)</td>
<td>Draft RIA – 18 bar</td>
<td>12-15%</td>
<td>$342</td>
</tr>
<tr>
<td></td>
<td>Draft RIA – 24 bar</td>
<td>16-20%</td>
<td>$550</td>
</tr>
<tr>
<td></td>
<td>Draft RIA – w/</td>
<td>20-25%</td>
<td>$967</td>
</tr>
<tr>
<td></td>
<td>boosted EGR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4- to 6-speed automatic</td>
<td>2001 NRC Report</td>
<td>3-4%</td>
<td>$150-$300</td>
</tr>
<tr>
<td></td>
<td>Draft RIA</td>
<td>3-4%</td>
<td>($ 15)</td>
</tr>
<tr>
<td>Automatic to DCT</td>
<td>Draft RIA</td>
<td>4-6%</td>
<td>($154-$223)</td>
</tr>
</tbody>
</table>

- **Cost** is direct manufacturing cost
- **NRC Report** is Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, 2002
- **Draft RIA** is for NHTSA/EPA proposed standards for 2017-25 light-duty vehicles: 23% 18 bar, 64% 24 bar; 6% boosted EGR

- New technology: x 2 efficiency again
- New technology: more efficient and cheaper
- From cost increase to decrease
Next-generation Gasoline Engines

Camless Valve Actuation

- Lift sensor
- Upper spring
- Coil
- Armature
- Yoke
- Hydraulic tappet
- Lower spring

Honda Prototype Engine Base
( Electro-magnetic valve )

Improvement in fuel economy: 30%

Heat release rate

<table>
<thead>
<tr>
<th>Crank angle [ATDC deg]</th>
<th>dQ/dθ [J/deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>0</td>
</tr>
<tr>
<td>-20</td>
<td>5</td>
</tr>
<tr>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
</tr>
</tbody>
</table>

HCCI Engine

Requires increasing the self-ignition region
Turbo-Boosted EGR Engines

- Highly dilute combustion – considerable efficiency improvement
- Advanced ignition systems required
- 6% penetration for 2025 forecasted by EPA/NHTSA

Terry Alger, Southwest Research Institute, “Clean and Cool”, Technology Today, Summer 2010
Turbo Dedicated EGR Engines

- Highly dilute, low temperature combustion
- Advanced ignition systems required
- > 42% indicated efficiency (Alger)
- PSA 2018 introduction

Terry Alger and Barrett Mangold, SwRI, Dedicated EGR, SAE 2009-01-0694
Hybrid System Cost Reduction

- Advanced P2 hybrid system: single motor, two clutches
  - Small, relatively inexpensive motor
  - Next step is to integrate motor into transmission
    - Reduces costs for case, clutches, lubrication, and cooling
    - Although high capital costs to redesign transmission

- New higher-power Li-ion batteries: smaller, lighter, lower cost

- Improved on-board computer controls will increase efficiency

Nissan will launch the first integrated one-motor two-clutch CVT hybrid system for FWD and AWD in 2014
Major New Mass-Reduction Work

- Lotus Engineering (CARB)
  - Continuation of 2010 study (-20%, -33% mass Toyota Venza)
  - Includes crashworthiness safety (NHTSA FMVSS) validation
  - Demonstrates cost-effective 30% mass reduction at < $0/vehicle

- EDAG / Electricore (NHTSA)
  - Technical assessment of -22% mass Honda Accord 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

- FEV (US EPA)
  - Technical assessment of -18% mass Toyota Venza at no cost
  - Includes crashworthiness safety (NHTSA FMVSS) validation
Vehicle Mass-Reduction Cost

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- FSV and FEV studies indicate 12-18% weight reductions at zero cost
- EDAG and Lotus studies indicate larger mass reductions at costs on the CARB cost trend line

![Graph showing mass reduction costs and weight reductions.](image-url)
Computers Transforming Body Design

Percent of Nameplates Achieving IIHS Top Safety Pick

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford</td>
<td>52%</td>
<td>75%</td>
<td>93%</td>
</tr>
<tr>
<td>Toyota</td>
<td>52%</td>
<td>65%</td>
<td>77%</td>
</tr>
<tr>
<td>GM</td>
<td>54%</td>
<td>74%</td>
<td>78%</td>
</tr>
</tbody>
</table>

http://corporate.ford.com/microsites/sustainability-report-2012-13/vehicle-data#b

2014 Acura MDX\(^1\)
- 55% high strength steel, some aluminum and magnesium parts
- 6% weight reduction (275 pounds)
- Improved crash results
- Improved NVH (noise, vibration, harshness)

\(^1\) AEI-Online.org, "2014 MDX re-engineered to pass IIHS test, reduce NVH". July 2, 2013, pages 36-38.

2007 Acura MDX\(^2\)
- 56% high strength steel

No Consumer Tradeoffs

New technologies are better
Advanced Technologies are Better

- Turbocharged engines have much higher low-end torque and less vibration (don’t rev as high)
- 6+ speed transmissions improve acceleration and are smoother (smaller gear steps)
- High-strength steel and aluminum have better crash properties, plus vehicle handles better (changes direction easier)
- Better aerodynamics reduce wind noise

The tradeoff is simply higher cost
Technology is Paid by the Fuel Savings

- Decrease in amount paid for fuel is larger than the increase in monthly vehicle payments
- The average customer winds up with more money in their pocket

The fuel producers are the ones who pay for the benefits, not consumers
Consumers are, in general, LOSS AVERSE

2002 Nobel Prize for Economics
(Tversky & Kahnemann, J. Risk & Uncertainty 1992)

- **Uncertainty** about future fuel savings makes paying for more technology a risky bet
  - What MPG will I get (your mileage may vary)?
  - How long will my car last?
  - How much driving will I do?
  - What will gasoline cost?
  - What will I give up or pay to get better MPG?

Causes the market to produce less fuel economy than is economically efficient

“A bird in the hand is worth two in the bush.”
Mid-Term Review Plans

- ICCT is paying FEV to update hybrid costs
- Otherwise, no firm plans yet – will be coordinating with NGOs, CARB, EPA, and NHTSA
  - Will push for an efficiency assessment of the dedicated EGR engine and updated cost assessments
Summary

- Computers are transforming technology – and the pace is accelerating
  - Accelerating introduction of technologies into the market
  - Top engine technology in 2025 rule already obsolete
  - Hybrid costs are dropping
  - 2014 MDX almost meets 2025 weight reduction target – with modest material changes and improved safety and NVH
- New technologies are better in other ways as well – only tradeoff is cost
Thank You