survey of vehicle mass-reduction technology trends and prospects

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el monte, california
may 18th, 2010
Outline

- **Introduction:** CO\(_2\) reduction technologies
- **Vehicle mass-reduction technology**
  - Mass-reduction techniques
    - Background, advanced materials, components, designs
  - Potential for future designs
    - Prototypes, concepts
- **Objective**
  - Highlight emerging mass-reduction technology trends
  - Examine the technology potential for the 2025 timeframe

This a presentation based on the following report:
http://pubs.its.ucdavis.edu/publication_detail.php?id=1390
**Vehicle GHG emissions**

**Carbon dioxide (CO₂)**

- Engine
- Transmission
- A/C compressor
- Auto exhaust emission control catalyst
- Nitrous oxide
- Methane
- Black carbon

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### GHG-Reduction Technologies

- There are many promising CO₂-reduction technologies for vehicles
- Vehicle design and electric-drive technologies could be increasingly critical

<table>
<thead>
<tr>
<th>Area</th>
<th>Technology or mechanism for CO₂ reduction</th>
<th>Potential CO₂ reduction *</th>
<th>U.S. adoption in 2008 fleet #</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Engine</strong></td>
<td>Variable valve timing or lift</td>
<td>2-8%</td>
<td>53%</td>
</tr>
<tr>
<td></td>
<td>Cylinder deactivation</td>
<td>3-6%</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>Turbocharging</td>
<td>2-5%</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Gasoline direct injection</td>
<td>8-15%</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>Compression ignition diesel</td>
<td>15-40%</td>
<td>0.1%</td>
</tr>
<tr>
<td><strong>Powertrain</strong></td>
<td>Digital valve actuation</td>
<td>5-10%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>Homogeneous charge compress. ignition</td>
<td>15-20%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>6+ speed</td>
<td>3-5%</td>
<td>21%</td>
</tr>
<tr>
<td><strong>Transmission</strong></td>
<td>Continuously variable</td>
<td>4-6%</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>Dual-clutch, automated manual</td>
<td>4-8%</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Aerodynamics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-8%</td>
<td>-</td>
</tr>
<tr>
<td><strong>Tire rolling resistance</strong></td>
<td></td>
<td>2-8%</td>
<td>-</td>
</tr>
<tr>
<td><strong>Vehicle</strong></td>
<td>Advanced material component</td>
<td>5-10%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Integrated vehicle design</td>
<td>10-20%</td>
<td>-</td>
</tr>
<tr>
<td><strong>Hybrid systems</strong></td>
<td>Stop-start mild hybrid</td>
<td>5-10%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td></td>
<td>Full hybrid electric system</td>
<td>20-50%</td>
<td>2%</td>
</tr>
<tr>
<td><strong>Electric-drive</strong></td>
<td>Plug-in capable electric vehicles</td>
<td>30-75%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>Fuel cell vehicles</td>
<td>30-75%</td>
<td>0%</td>
</tr>
</tbody>
</table>

* Many technologies can be combined, but percents are not strictly additive;
Estimations are based primarily on US EPA/NHTSA, 2010; # From US EPA, 2009
Background: Mass and CO$_2$ emissions

- Vehicle mass is fundamental part of vehicle CO$_2$ emissions
  - Efficiency is the ability of a powertrain to convert energy into vehicle propulsion
  - The ultimate vehicle “road load” is tied directly to the vehicle mass
  - Reduction in mass $\rightarrow$ reduction in required energy $\rightarrow$ reduction in CO$_2$ emissions

Approximately based on U.S. city and highway drive cycles (Kromer and Heywood, 2008); in addition to inertial mass and rolling resistance hill-climbing is also directly linked to vehicle mass, percent vehicle energy use and loss vary greatly according to vehicle technology and drive cycle.
Background: Mass and CO$_2$ emissions

- Mass has a large effect on vehicle CO$_2$ emissions
  - With vehicle mass-reduction technology, CO$_2$ emissions are decreased due to reduced vehicle road loads (i.e., inertial acceleration, rolling resistance, grade)
  - For constant performance, 20% mass-reduction $\rightarrow$ ~12-16% CO$_2$/mi decrease

Sources: Casadei and Broda, 2008; Bandivadekar et al, 2008; FKA, 2007; Pagerit et al, 2006. Effects differ by drive cycle (greater effect in city/urban, lesser effect in highway conditions)
Use of Mass-Reduction Technology

- **Today’s vehicles use different amounts of mass-reduction technology**
  - For a given size and functionality, some models are heavy (by over 40%)
  - Models with more mass-reduction technology can be 20-25% lighter (for a given size)
  - Some automakers use far more mass-reduction technology across all their models

![Graph showing vehicle curb weight vs. vehicle footprint](image.png)

Among the distinguishing underlying factors on relative vehicle weight are the use of advanced materials (e.g., high-strength steels, aluminum) and mass-optimized designs.
Mass-Reduction: Automaker Plans

- Major efforts to reduce vehicle mass are underway

<table>
<thead>
<tr>
<th>Company</th>
<th>Quote, statement, or commitment</th>
</tr>
</thead>
</table>
| Ford       | • From 2011 to 2020: “Full implementation of known technology… weight reduction of 250-750 lbs”  
• “The use of advanced materials such as magnesium, aluminum and ultra high-strength boron steel offers automakers structural strength at a reduced weight to help improve fuel economy and meet safety and durability requirements” |
| Toyota     | • 10-30% weight reduction for small to mid-size vehicles                                                                                                                                                                           |
| Volkswagen | • “Automotive light weight solutions are necessary more than ever to reduce CO$_2$ emissions”  
• “Multi-Material Concepts promise cost effective light weight solutions”                                                                                                 |
| GM         | • “We… are likely to use more lightweight materials in the future”  
• “One trend is clear - vehicles will consist of a more balanced use of many materials in the future, incorporating more lightweight materials such as nanocomposites and aluminum and magnesium.” |
| Mazda      | • Reduce each model by 220 lb by 2015; another 220 lb by 2020                                                                                                                                                                       |
| Nissan     | • Average 15% weight reduction by 2015  
• “We are... expanding the use of aluminum and other lightweight materials, and reducing vehicle weight by rationalizing vehicle body structure”                                                                 |
| BMW        | • “Lightweight construction is a core aspect for sustainable mobility improving both fuel consumption and CO$_2$ emissions”                                                                                                           |
| Renault    | • “To meet commitments on CO$_2$ emission levels, it is important that we stabilize vehicle weight as from now, and then start bringing it down.”                                                                                               |
Use of Mass-Reduction Technology

• One example: the 2011 Porsche Cayenne
  – The model year 2011 offers a 10% weight reduction from mass-reduction technology
  – 550-lb reduction (with 154 lb of added amenities) → 396 lb net reduction
  – And actually slightly larger size than 2010; also Porsche’s first hybrid offering

Vehicle Mass and Body Mass

- **The vehicle body or “body-in-white”**
  - Core structure and frame of the vehicle; roughly one-quarter of vehicle mass
  - Fundamental to the core structure and integrity of the vehicle
  - Often the critical part of the vehicle that is designed in mass-reduction concepts

<table>
<thead>
<tr>
<th>System</th>
<th>Major components in system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body-in-white</td>
<td>Passenger compartment frame, cross and side beams, roof structure, front-end structure, underbody floor structure, panels</td>
</tr>
<tr>
<td>Powertrain</td>
<td>Engine, transmission, exhaust system, fuel tank</td>
</tr>
<tr>
<td>Chassis</td>
<td>Chassis, suspension, tires, wheels, steering, brakes</td>
</tr>
<tr>
<td>Interior</td>
<td>Seats, instrument panel, insulation, trim, airbags</td>
</tr>
<tr>
<td>Closures</td>
<td>Front and rear doors, hood, lift gate</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Electrical, lighting, thermal, windows, glazing</td>
</tr>
</tbody>
</table>
Vehicle Body Mass Reduction

- Major reductions from production vehicles, prototypes, design concepts
  - Many designs with 20%, 30%, 40%+ reduction of vehicle body mass
Vehicle Mass Reduction: Strategies

- **Major reductions from different approaches**
  - Steel-intensive design
    - 15-40% reduction
    - Many OEMs, ThyssenKrupp, Porsche, Auto/Steel, EDAG, Ford, Lotus, VW
  - Aluminum-intensive design
    - 30-45% reduction
    - Audi, GM, Honda, Jaguar, Ford
  - Multi-material design
    - 30-50% reduction
    - VW/Superlight car, Lotus, DCX
  - Carbon-intensive design
    - 40-60% reduction
    - Dodge, RMI
Vehicle Mass Reduction: Materials

- **Material composition:** a continuation of past trends
  - From 1995 to 2007
    - Magnesium: +100%
    - Aluminum: +22%
    - Plastics/composites: +25%
    - High-strength steels: +45%
  - Lotus baseline to Low Development
    - Magnesium: 3x
    - High-strength steels: 1.6x
  - Lotus baseline to High Development
    - Magnesium: 26x
    - Aluminum: 2x
    - Plastics/composites: +20%
Overall Vehicle Mass Reduction

- Materials and designs can offer promising vehicle mass reduction
  - Lotus (2010) designs use some similar techniques, materials of the PNGV (~2000) models
  - Both show range of approaches with 20-33%+ vehicle mass reduction
  - But now many new low-cost techniques are proven in existing vehicles

Sources:

Mass-Reduction: Costs

- Some of the mass-reduction projects also estimate costs
  - Near-term incremental approaches - up to 20% - have minimal costs
  - More advanced technologies (~30% mass reduction) could have more substantial vehicle manufacturing cost increases.

<table>
<thead>
<tr>
<th>Automaker</th>
<th>Findings related to vehicle costs of mass-reduction technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford F150 “IMPACT”</td>
<td>• 19% mass reduction at zero net cost</td>
</tr>
<tr>
<td></td>
<td>• 25% mass reduction at $500 increase in variable vehicle cost</td>
</tr>
<tr>
<td>ThyssenKrupp “New Steel Body”</td>
<td>• 24% body mass reduction at 2% manufacturing cost increase</td>
</tr>
<tr>
<td>IBIS aluminum</td>
<td>• 40%+ body mass reduction for $500-600 cost increase (aluminum body)</td>
</tr>
<tr>
<td></td>
<td>• 17% vehicle mass reduction for $100-200 vehicle cost increase</td>
</tr>
<tr>
<td>Volkswagen-led “Super Light Car”</td>
<td>• 22% body mass reduction “multi-material, economic” at &lt;5 €/kg</td>
</tr>
<tr>
<td></td>
<td>• 39% body mass reduction “multi-material, advanced” at &lt;10 €/kg</td>
</tr>
<tr>
<td>Lotus “Low Development”</td>
<td>• 20% vehicle mass decrease causes 2% decrease in cost (~$300/vehicle)</td>
</tr>
<tr>
<td>Lotus “High Development”</td>
<td>• 33% vehicle mass decrease causes 3% increase in cost (~$500/vehicle)</td>
</tr>
</tbody>
</table>
Mass-Reduction: Upstream CO₂

- Some materials have larger upstream energy and CO₂ impacts
  - The vast majority of vehicle’s CO₂ emissions are due their use of energy during driving
    - But manufacturing, end-of-life stages differ by material
    - And more efficient vehicles put increased proportion of energy/CO₂ impacts upstream
  - Materials, like aluminum and magnesium, are used on many mass-reduction designs and warrant further consideration of upstream impacts

Source:
Mass-Reduction: Safety

- Issues of safety is commonly raised with mass-reduction
  - From U.S. EPA and NHTSA:
    “...the likely deleterious safety effects of the MYs 2012-2016 standards may be much lower than originally estimated. They may be close to zero, or possibly beneficial if mass reduction is carefully undertaken in the future”
  - No known impacts from mass-reduced components (aluminum engine, carbon fiber roof, aluminum doors)
  - Many of the above projects found no compromises.
  - The recent studies (Lotus, Super Light Car, Future Steel Vehicle) continue to investigate structure, crashworthiness
  - Many Five-Star safety rated vehicles are no heavier for a given size than others
    - Half of them have lower mass than industry average

Sources:
U.S. EPA and NHTSA. Final rule for MY2012-2016 CO2 and fuel economy standards.
NHTSA 5-star safety ratings (frontal, side driver, side rear), model year 2008 (www.safercar.gov)
Conclusions

- **Mass-reduction technology is a core efficiency technology**
  - It has been, is being, and will continue to be deployed by automakers

- **There is a variety of known approaches for mass-reduction**
  - High-strength steel, aluminum, multi-material designs will all be prominent
  - Many off-the-shelf options for use of advanced materials, components
    - Deploying best-in-class options for components throughout the vehicle
    - Up to 20% mass reduction, minimal costs, near-term ~2015 availability
  - Many emerging concepts are available
    - New manufacturing techniques, greater use of advanced designs
    - Up to ~30-35% mass reduction, additional costs, mid-term ~2020 availability

- **Areas for further study**
  - Full manufacturer costs, crashworthiness, upstream CO₂ impacts, manufacturing phase-in, inclusion with electric-drive technologies.
Vehicle Mass Reduction: Conclusions

• Acknowledgement
  – Study done under contract for California Air Resources Board

• See publication for documentation
Mass-Reduction Technology
(and what it is not)

- Vehicle mass-reduction technology is not “downsizing”

  + **Mass-reduction technology**: the redesign of vehicle models with advanced materials and designs for reduced mass (without compromise in vehicle space, utility)

  - **Downsizing**: referred to generally as a shifts in the fleet toward smaller vehicles
Hybrid Technology: GHG Reduction

- Hybrid vehicle models commercialized in U.S.
  - Span vehicles: compacts, sedans, crossovers, large SUVs, pickups
  - Average 33% CO₂/mi reduction, 50% mpg increase vs. similar non-hybrids
  - Hybrids also put an upward pressures on vehicle mass (~9%)