Automotive Technologies and Fuel Economy Policy

Don MacKenzie
MIT Engineering Systems Division
Sloan Automotive Laboratory
November 18, 2010
Outline

• Technology overview

• Policy overview
Technologies for Higher Fuel Economy

Credit for slides: Irene Berry
SM Mechanical Engineering / Technology and Policy, 2010
We frame vehicle design in terms of range and performance goals.

**Range**

Over a Standard Drive Cycle

**Performance**

0-60 mph Acceleration Time

Energy Specification

Power Specification

11/18/10
Range depends on the energy required at the wheels and vehicle efficiency.

2005 3.0-L Toyota Camry over UDDS drive cycle

Fuel Tank: 100%

Engine

Engine Loss: 76%

Driveline

Driveline Losses: 3%

Standby: 8%

Rolling: 4%

Braking: 6%

Aero: 3%

16% 13%

770% 100%

vehicle efficiency over UDDS cycle: 13%

~ 165 Wh/km
Performance depends on the peak power of the vehicle

Limited region of high efficiency

Power with wide open throttle

bsfc (g/kWh) (efficiency)

500 (14.3%) 600 (14.3%) 700 (12.2%) 800 (10.7%) 1000 (8.57%)

Engine map of spark ignition (SI) internal combustion engine (ICE)

Lowest efficiency is at low loads and high speeds

Typical operating conditions on UDDS drive cycle

Engine speed (rpm)

Engine power (kW)

Peak power

So, we want to increase efficiency while meeting design goals

1. Reduce load (energy required at the wheels)

2. Increase powertrain efficiency
   1. Increase efficiency of engine
   2. Shift engine operating points
   3. Use smaller engine (downsize)

---

Reducing the load at the wheels reduces fuel consumption

- Reduce weight
- Reduce aerodynamic drag
- Reduce accessory loads

These reductions also allow for downsizing

Diesel engines are more efficient, but heavier and more expensive

Compression Ignition (vs. Spark Ignition)
- Only air is compressed
  - Higher compression ratio
- Fuel is injected into the compressed air and self-ignites
  - Direct injection

Diesel (vs. Gasoline) Fuel
- Higher energy content
- Higher emissions from combustion
These engine technologies increase engine efficiency and/or power

<table>
<thead>
<tr>
<th>Technology</th>
<th>Mechanism</th>
<th>Efficiency gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable valve timing</td>
<td>Optimizes efficiency for both high and low engine speeds</td>
<td>5%</td>
</tr>
<tr>
<td>Cylinder deactivation</td>
<td>Increases low load efficiency</td>
<td>7.5%</td>
</tr>
<tr>
<td>Turbo- or super-charge</td>
<td>Increases engine power per size: allows downsizing</td>
<td>7.5%</td>
</tr>
<tr>
<td>Direct Injection</td>
<td>More efficient fuel delivery and combustion</td>
<td>5-10%</td>
</tr>
<tr>
<td>Advanced after-treatment</td>
<td>Allows engine to produce more emissions</td>
<td>N/A</td>
</tr>
</tbody>
</table>
These transmission technologies allow better control of engine speed

<table>
<thead>
<tr>
<th>Technology</th>
<th>Mechanism</th>
<th>Efficiency gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV transmission</td>
<td>Optimize engine speed</td>
<td>6%</td>
</tr>
<tr>
<td>Dual-clutch transmission</td>
<td>Optimize engine speed</td>
<td>7%</td>
</tr>
</tbody>
</table>
Different combustion cycles also offer efficiency improvements

<table>
<thead>
<tr>
<th>Technology</th>
<th>Mechanism</th>
<th>Efficiency gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miller cycle</td>
<td>Trade power for efficiency</td>
<td>5%</td>
</tr>
<tr>
<td>Atkinson cycle</td>
<td>Trade power for efficiency</td>
<td>5%</td>
</tr>
<tr>
<td>HCCI</td>
<td>More efficient at low load</td>
<td>7.5%</td>
</tr>
</tbody>
</table>
There are additional opportunities for energy savings through hybridization.

Micro+ Hybrids Eliminates

- Standby: 8%
- Engine Loss: 76%
- Driveline Losses: 3%
- Fuel Tank: 100%
- Engine
- 16%
- Driveline
- 13%
- Aero: 3%
- Rolling: 4%
- Braking: 6%

Full Hybrid Reduces via engine downsizing shifts engine operating

Regenerative Braking Reduces
Hybrid optimization shifts the engine operating points to higher efficiency

Hybrids and electric vehicles are classified by degree of electrification

- **Full Hybrid Electric Vehicle (PHEV)**: Can plug-in to recharge
- **Battery Electric Vehicle (BEV)**: Can have “electric only” range
- **Mild Hybrid**: Can operate in hybrid mode
- **Micro Hybrid**: Can run in electric mode

**Electric Power** (kW of motor power)

**Electric Energy** (watt-hours of battery capacity)
Hybrids achieve fuel savings through multiple efficiency mechanisms.

Data from: An et al 2001

- 40% lower fuel consumption
  - 2001 Honda Insight: 46 MPG
  - 2001 Toyota Prius (US): 38 MPG

- 35% lower fuel consumption
  - 2001 Honda Insight: 13, 7, 11 MPG
  - 2001 Toyota Prius (US): 3, 8, 9 MPG
Battery electric vehicles are fully electric, which has both pros and cons.

### Advantages
- Electricity
  - Any energy source
  - Potentially less emissions
  - Single emissions source
- Electric drive
  - More energy efficient
  - Higher low-speed torque
  - Lower operating costs
  - Less maintenance

### Disadvantages
- Batteries
  - Long charge times
  - High cost
  - Low energy content relative to gasoline
- Limited range
- Concerns over life
- Electric drive
  - Different operating and driving feel
To compare different fuels, consider well-to-wheels energy and emissions.

**Well-to-Tank**
- ~30% Efficient
- ~24% Efficient
- ~16% Efficient
- ~80% Efficient

**Tank-to-Wheel**
- ~80% Efficient
- ~20% Efficient


[http://www.nesea.org/]
Automotive Fuel Economy Policy in the U.S.
Overview of Institutions and Policies

Federal
- DOT: Fuel Economy Standards
- EPA: GHG Standards
- IRS: Fuel Taxes
- IRS: Gas Guzzler Tax

State
- CARB: GHG Standards
- State Governments: Fuel Taxes

Cap & Trade
Feebates

11/18/10
Corporate Average Fuel Economy

- Administered by National Highway Traffic Safety Administration (NHTSA, part of the DOT)

- Sets minimum **average** level of fuel economy that new light-duty* vehicles sold by each manufacturer must meet each year

\[
CAFE = \frac{\sum_i Sales_i}{\sum_i \frac{Sales_i}{MPG_i}}
\]

- Fuel economy is based on a test procedure from the 1970s
  - ~30% higher than real-world values or “window sticker” estimates
- * Light-Duty means a gross vehicle weight rating ≤ 8,500 lbs.

* [External Image](http://www.cornerstonemcm.org/Cafe_Outdoor_Light_Box.jpg)
Corporate Average Fuel Economy

- Separate standards & calculations for cars and “light trucks”

**Fuel Economy (MPG)**

- 2020 Mandate EISA 2007
- 2025 Proposed Range

**Timeline:**

**2025 Proposed Range:**
- Federal Fuel Economy Standards
- EISA: QMR Standards
- IRS: Fuel Taxes
- IRS: Gas Guzzler Tax
- State Governmental Fuel Taxes
The MPG Distortion

- MPG is inverse of metric that matters: fuel consumption

**Fuel Consumption (Gal/100mi)**

- 2020 Mandate
  - EISA 2007
- 2025 Proposed Range
  - 1.7-2.2 gal/100mi
Corporate Average Fuel Economy

**Some Details**

- Electric Vehicle Credited MPG = (Energy-Equivalent MPG) / 0.15
- Credits for overcompliance can be “banked” from past 5 years or “borrowed” from next 3 years
- Flexible-fuel and bi-fuel vehicles capable of using alternative fuels earn ~60% bonus credit on fuel economy rating
  - Total benefit capped at 1.2 mpg each year
- Penalty for noncompliance = $55/mpg/vehicle

Corporate Average Fuel Economy

Recent Changes

- NHTSA now required to set *attribute-based standards*
  - Different standards for each manufacturer, based on product mix
  - Intended to reduce equity issues of regulatory cost
  - Effectively negates downsizing as a compliance strategy

- Credits can now be traded between fleets and between manufacturers
  - Subject to certain restrictions
Corporate Average Fuel Economy

Size-Based Standards

\[
\text{Standard} = \frac{\sum \text{Sales}_i}{\sum \text{Sales}_i + f(\text{footprint})}
\]

Figure 1.D.3-1 Final MY 2011 and Proposed MY 2012-2016 Passenger Car Fuel Economy Targets

Federal Register / Vol. 74, No. 186 / Monday, September 28, 2009 / Proposed Rules
Corporate Average Fuel Economy

Size-Based Standards

\[
\text{Standard} = \frac{\sum \text{Sales}_i}{\sum f(\text{footprint}_i)}
\]

Figure I.D.3-2. Final MY 2011 and Proposed MY 2012-2016 Light Truck Fuel Economy Targets

Federal Register / Vol. 74, No. 186 / Monday, September 28, 2009 / Proposed Rules
Corporate Average Fuel Economy

**How Standards are Set**

- Cost-benefit analysis including discounted lifetime fuel expenses, estimated technology costs, monetized values of non-financial costs and benefits
- Applies efficiency-enhancing technologies in order of cost effectiveness, subject to judgment-based constraints
- Equalizes marginal cost of more technology with marginal benefit

*World’s biggest black box?*
Vehicle GHG Standards

- **(2002)** “Pavley” GHG standards required by California Assembly Bill 1493, to be implemented by California Air Resources Board
  - 13 other states opt in to California’s standards under Clean Air Act provisions

- **(2004)** Auto manufacturers, trade associations, dealers sue, citing principle that GHG regulation is tantamount to fuel economy regulation, explicitly preempted by CAFE law

- **(2007)** Supreme Court rules in Massachusetts v EPA that GHGs are pollutants under the Clean Air Act

- **(2007)** Bush Administration denies California “waiver” from federal preemption (waiver needed to implement regulations)

- **(2009)** Obama administration grants waiver, brokers truce between manufacturers and states, announces harmonized state & federal standards. Dealers continue to sue.
Electric vehicles assumed to have zero emissions, up to first 200,000-300,000 produced.
Gasoline Taxes

- 10% increase in fuel price → 3.3% increase in MPG (long term)
- To go from 26 → 35 MPG:
  - Need gas to go from $2/gal to ~$5/gal
  - Annual gasoline bill increases by ~$1000/year for new cars
  - Annual gasoline bill increases by ~$1800/year for older cars

http://www.gaspricewatch.com/usgastaxes.asp
Gas Guzzler Tax

- Applies only to cars, not light trucks
Other Policies

- **Feebates**
  - Fee + Rebate, purchase incentive system
  - Greater cost certainty, less emissions certainty relative to CAFE
  - Recently adopted in France, initial results promising

- **Cap & Trade**
  - Would effectively be a gas tax
  - $10 / tonne CO$_2$ ~ $0.10 / gallon

- **Cash for Clunkers**
  - Not energy/carbon policy
    - $200+ per ton of avoided emissions (Knittel, 2009)
  - More effective if goals are criteria pollutant emissions
  - *Maybe* effective as economic stimulus

---

## Advantages and Disadvantages of Policies

<table>
<thead>
<tr>
<th></th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| Standards           | +Emissions certainty +Well-established                  | -Rebound effect takes back ~10% of benefits, increases other externalities  
|                     |                                                        | -Uncertain costs                                                    |
|                     |                                                        | -No incentive to exceed standard                                   |
|                     |                                                        | -Disparate impact on manufacturers                                  |
| Incentives          | +Cost certainty +Stimulates continuous improvement      | -Little experience                                                 |
|                     |                                                        | -Reduced operating cost → rebound effect                            |
| Fuel Taxes          | +Drives reductions throughout system                    | -Hits consumers hardest, especially w/ older vehicles              |
|                     |                                                        | -Politically difficult                                              |
Current Issues...

...being dealt with
- How to include electric vehicles & plug-in hybrids
- State versus Federal regulation

... and not being dealt with
- How to sustain increases in fuel economy over the long term
- Cost to manufacturers of meeting regulations