Automotive Powertrain Technologies through 2016 and 2025

University of Michigan Transportation Research Institute Conference. Marketing New Powertrain Technologies: Strategies in Transition
February 15, 2012

Mark Kuhn
Ricardo Strategic Consulting
Agenda

- Introduction to Ricardo
- Technology Roadmaps
- Passenger Car Fuel Economy Improvement and Greenhouse Gas Reduction Potential
Ricardo Strategic Consulting

Introduction to Ricardo Strategic Consulting

Ricardo is one of the world's leading automotive consulting companies

Established Success Factors

- Focused on value-adding services
- Solving key industry issues
- Program delivery as a core competence
- Investment in people and technology
- Critical mass with revenues exceeding $330M and over 1500 people
- Independent and long established (1908)

Value-Adding Capabilities

International Presence

Global Client Base (selection)
Agenda

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Future Trends in Vehicle Technology

- Regulation is driving new technology & innovation to higher efficiency
  - Accelerating the rate of technology introduction to passenger cars
  - Trend is now continuing into the commercial vehicle space in US, Japan and Europe

- Passenger car efficiency dominated by ICE technologies in the short/med term
  - There is no “silver bullet” - we will need a range of technologies to meet targets
  - A better understanding of life cycle emissions will enable more informed choices
  - Electrification is a longer term trend but we need a breakthrough in batteries

- Both evolutionary and disruptive technologies are likely to be successful
  - Intelligent Electrification is a key approach to enable more radical ICE technology
  - Mechanical Hybrids could offer substantial cost reductions over electric systems
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Transportation sector is 33% of total CO₂ contribution. Nearly 65% comes from gasoline engines for personal vehicles.

**CO₂ Emissions from Fossil Fuel Combustion by Fuel Consuming End-Use Sector**

- Commercial
- Residential
- Industrial
- Transportation

65% from gasoline engines, in personal transportation

The growth of both regulation and targets for Low Carbon Vehicles sets a major challenge for the road transport sector.


**Regulatory Framework**

- **USA, EU, Canada, Australia, China & Japan** – Legislation / agreements for fuel economy or CO₂
  - USA has proposed target of
    - 35.5 mpg by 2016
    - 54.5 mpg by 2025
    - Implemented over entire country by EPA
  - EU Proposal for Vans
    - 175 g/km from 2014-16
    - 135 g/km by 2020

- **Challenging Targets:**
  - US 4.7% pa to 2025
  - EU 3.9% pa to 2020

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[1] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.

Regulation will continue to drive lower toxic emissions with additional fuel economy and CO$_2$ legislation likely

### Passenger car and light commercial vehicle tailpipe emission targets

<table>
<thead>
<tr>
<th>Region</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC: 140 g/km CO$_2$</td>
<td>PC: 120 g/km CO$_2$</td>
<td>PC: 100 g/km CO$_2$</td>
<td>PC: 120 g/km CO$_2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LT: 175 g/km CO$_2$</td>
<td>LT: 175 g/km CO$_2$</td>
<td>LT: 175 g/km CO$_2$</td>
<td>LT: 175 g/km CO$_2$</td>
<td></td>
</tr>
</tbody>
</table>

#### US (49 states)

- **Tier 2 (phase in 04-09)**
  - PC: 27.5 mpg
  - LT: 23.5 mpg
  - PC+LT combined average in 2016: 34.1 mpg
  - PC+LT combined average, 2015 target: 37.8 mpg
  - PC+LT combined average, 2016 target: 47 - 62 mpg
  - PROPOSALS FOR PC+LT COMBINED AVERAGE IN 2025

#### California

- **LEV II (2004)**
  - PC: 43.6 mpg equivalent
  - LT: 36.8 mpg equivalent
  - LT2a, 2015 target: 47 - 62 mpg
  - Proposals for PC+LT combined average in 2025

- **LEV III**
  - Regulated and CO$_2$ emissions combined from 2009
  - Under discussion; dates are uncertain

#### China

- **Euro 3 and 4**
  - Stages 2 and 3 (2008): 18 - 45 mpg equivalent (dependent upon weight class)
  - Stage 4 (proposal; dates uncertain): 24 - 50 mpg equivalent (dependent upon weight class)

#### Japan

- **Stage A**
  - PC: 0.05 NOx, 0.05 NIMIC, 1.15 CO
  - LT: 0.05 NOx, 0.05 NIMIC, 4.02 CO
  - PC: 30.5 mpg equivalent
  - LT: 35.6 mpg equivalent

Source: Ricardo, National government sources, Arbuthnot Securities estimates
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There are three interlinked phases of change required to current light duty powertrain technology and strategy

<table>
<thead>
<tr>
<th>SHORT TERM: ~2015</th>
<th>MEDIUM TERM: ~2025</th>
<th>LONG TERM: ~2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boosting &amp; downsizing</td>
<td>High Efficiency Advanced Combustion:</td>
<td>Plug-in/Hybrid electric systems dominate</td>
</tr>
<tr>
<td>– Turbocharging</td>
<td>– Lean Stratified SI</td>
<td>– Very high specific power ICE’s</td>
</tr>
<tr>
<td>– Supercharging</td>
<td>– Low temperature combustion</td>
<td>Range of application specific low carbon fuels</td>
</tr>
<tr>
<td>Low speed torque enhancements</td>
<td>Combined turbo/supercharging systems</td>
<td>Exhaust &amp; Coolant energy recovery</td>
</tr>
<tr>
<td>Stop/Start &amp; low cost Micro Hybrid technology</td>
<td>Advanced low carbon fuel formulations</td>
<td>Advanced thermodynamic Cycles</td>
</tr>
<tr>
<td>Friction reduction</td>
<td>PHEV’s in premium &amp; performance products</td>
<td>– Split Cycle?</td>
</tr>
<tr>
<td>Advanced thermal systems</td>
<td>EV’s for city vehicles</td>
<td>– Heat Pumps?</td>
</tr>
<tr>
<td>Niche Hybrid, PHEV’s and Electric Vehicles</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Ricardo Technology Roadmaps, Ricardo Analysis
Mass market roadmap developed by Ricardo shows that range of technologies will be required to meet regulatory targets

- **US GHG and CAFE (mpg)**: 27.3, 35.0, 54.5
- **EU Fleet Average CO₂ Targets (g/km)**: 130, 95, TBD

Road Transport Energy Vectors 2050 Ricardo projection

- **Hydrogen**
- **Electricity**
- **NG/Biogas**
- **Liquid Bio**
- **Liquid Fossil**

Energy Storage Breakthrough

**IC Engine & Transmission innovations** (gasoline/diesel/renewables)

**Vehicle Weight and Drag Reduction**

**Regulation Basis:**
- Tailpipe CO₂ or Vehicle fuel efficiency
- Well to Wheels CO₂ & efficiency
- Life Cycle Analysis

Source: Ultra Low Carbon Vehicles in the UK – BERR/DfT; Ricardo roadmaps and technology planning; Shell Energy Scenarios to 2050 (2008)
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Ricardo HyBoost concept features “Intelligent Electrification” - downsizing, e-Boost & brake energy recovery/stop/start

Fuel Economy Improvement/CO₂ Emissions Reduction:
Base vehicle (Ford Focus 2.0 litre Gasoline) 107 kW:
50% downsized 1 litre, Boosted DI, low friction 105 kW
Add stop-start and 6kW re-generation during deceleration
Add cooled EGR and revised turbo match via e-supercharger
High torque enables taller gear ratios + gearshift advisor
HyBoost vehicle CO₂ emissions

<table>
<thead>
<tr>
<th>Description</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base vehicle (Ford Focus 2.0 litre Gasoline) 107 kW:</td>
<td>169g/km</td>
</tr>
<tr>
<td>50% downsized 1 litre, Boosted DI, low friction 105 kW</td>
<td>-25%</td>
</tr>
<tr>
<td>Add stop-start and 6kW re-generation during deceleration</td>
<td>-10%</td>
</tr>
<tr>
<td>Add cooled EGR and revised turbo match via e-supercharger</td>
<td>-6%</td>
</tr>
<tr>
<td>High torque enables taller gear ratios + gearshift advisor</td>
<td>-7%</td>
</tr>
<tr>
<td>HyBoost vehicle CO₂ emissions</td>
<td>99.7g/km</td>
</tr>
</tbody>
</table>

40% Impr
Disruptive lower cost hybrid technologies possible via high speed flywheel technology – Ricardo “kinergy”

- Primary USP of Flywheel technology is very high “round trip” energy efficiency
- Project to apply Torotrak & Kinergy® technology on a PSV (Optare bus)
- Reduces CO$_2$ emission by around 20 percent during urban stop-start operation.
- Partners: Torotrak, Ricardo, Optare, Allison

To eliminate the need for vacuum seals a non-penetrative magnetic coupling system is used to transfer kinetic energy through the housing.
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Approach
- Ricardo team identified future technology packages and estimated their effects on fuel consumption
- Created new vehicle classes, implemented hybrid powertrains and controls (P2 and Powersplit), and incorporated new technology packages to define a broad design space
- Ricardo's complex systems modeling approach used to examine the extensive design space

Situation and objective
- EPA wanted objective technical input to support Notice of Proposed Rule Making (NPRM)
- Analysis estimates greenhouse gas emissions of future vehicles based on future technology packages and combinations thereof
- Use a defensible rationale for technology section revisions to rule including new/ revised technology definitions, technology selection logic, vehicle classes, and applicability

Results and benefits
- Broad design space examined hundreds of combinations of technologies, and their synergistic effects
- Predicted MPG reductions of 35% to 62% relative to baseline SI engine
- Technologies included combinations of advanced gasoline, diesel, hybrid, 8 speed transmissions
- Also included weight reduction, aerodynamics and reduced rolling resistance
Ricardo, EPA, ICCT, and Calif ARB identified several LDV technologies for further evaluation by Ricardo SMEs

- Engine technologies and configurations
  - Fuel injection, boost system, valvetrain, combustion, and controls
- Hybrid powertrain technologies and configurations
- Transmission technologies and configurations
  - Advanced automatics, CVT, DCT, launch devices
  - Transmission technologies
- Vehicle technologies
  - Mass reduction, aerodynamic improvements, rolling resistance, accessories
Gasoline engines focus will be on CO₂ reduction as emission legislation remains less challenging, even under LEV III

**Technology Roadmap for Light Duty Gasoline**

<table>
<thead>
<tr>
<th>Emissions</th>
<th>EPA Tier 2 / Calif LEV II</th>
<th>Calif LEV III</th>
</tr>
</thead>
<tbody>
<tr>
<td>US GHG and CAFE (mpg)</td>
<td>27.3</td>
<td>35.5</td>
</tr>
<tr>
<td>Power Density</td>
<td>Reduce CO₂ and increase kW/ℓ</td>
<td></td>
</tr>
</tbody>
</table>

**Engine Concept**
- Engine Downsizing, Downspeeding & Hybridization
- Energy Recovery / Split Cycle

**Engine Design**
- Thermal & Lubrication Systems
- Advanced Structures
- Variable Tumble Intake Ports
- VGT, E-boost, Compounded Boost
- Cylinder Deactivation, CPS, VVL

**Combustion**
- Biofuel
- Homogeneous GDI
- 2nd Generation Stratified GDI
- CAI, WOT, EGR, Lean Boost, Deep Miller Cycle

**Emissions Control**
- TWC – Optimizing Formulation and Substrates
- Lean NOx Trap (for lean SI)
- GPF

Source: Ricardo Analysis. Notes: CPS = camp profile switching, VVL = variable valve lift. GDI = gasoline direct injection. CAI = controlled auto ignition. TWC = 3-way catalyst, GPF = gasoline part. filter

### Emissions
- **2010**: 91 g/km CO₂
- **2015**: 85 g/km CO₂
- **2020**: 75 g/km CO₂
- **2025**: 65 g/km CO₂

### US GHG and CAFE (mpg)
- **2010**: 25 mpg
- **2015**: 30 mpg
- **2020**: 35 mpg
- **2025**: 40 mpg
Incremental improvements are the most cost effective route and make sense in context of CO$_2$/ fuel consumption penalties.

Benchmark Passenger Car: - CO$_2$ Cost Benefit for Powertrain Technologies

- Consumers buy vehicles – not powertrains – technologies must also compete on image, utility and lifestyle requirements and deliver fundamentally Good Cars.

Source: Ricardo Analysis. NEDC = New European Drive Cycle
Technology packages in the 2020–2025 Design Space

- **Engines:**
  - Stoichiometric direct-injection turbocharged (SDIT) SI engine
  - Lean-stoichiometric direct-injection turbocharged (LDIT) SI engine
  - EGR direct-injection turbocharged (EDIT) SI engine
  - Atkinson cycle SI engine with cam-profile switching (CPS)
  - Atkinson cycle SI engine with digital valve actuation (DVA)
  - Advanced European Diesel
  - Advanced U.S. Diesel
  - 2010 Baseline SI engines
  - 2010 Baseline Diesel engines

- **Transmissions:**
  - 2010 baseline six-speed automatic
  - Advanced automatic transmission, eight-speed
  - Dual clutch transmission, eight-speed, dry or wet clutch
  - Powersplit planetary gearbox

Source: Ricardo Analysis.
Fuel economy improvements of 22-47% were predicted for various sized vehicles from standard car to pick-up truck.

Fuel Economy Improvement*

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Car</td>
<td>32.0</td>
<td>+33%</td>
<td></td>
</tr>
<tr>
<td>Small MPV</td>
<td>28.8</td>
<td>+24%</td>
<td></td>
</tr>
<tr>
<td>Full Size Car</td>
<td>25.5</td>
<td>+22%</td>
<td></td>
</tr>
<tr>
<td>Large MPV</td>
<td>23.1</td>
<td>+26%</td>
<td></td>
</tr>
<tr>
<td>Truck</td>
<td>17.6</td>
<td>+47%</td>
<td></td>
</tr>
</tbody>
</table>

Technologies included:
- Cam phasing
- Variable valve lift
- Gasoline direct injection
- Diesel (for truck)
- Turbocharging
- Dual clutch transmission
- Electric accessories and fast engine warm-up
- Aero drag reduction & low rolling resistance tires
- Final drive ratio
- Oil and friction modifier

*Note 1: 22-47% fuel economy (MPG) improvement = 18-32% fuel consumption (gal/mile) reduction
Note 2: Change from old truck to new std. car reduces fuel consumption by 59%
Hybrid and conventional powertrains can lead to similar GHG emissions; improvements from 25% to 62% reduced CO$_2$

- Various C Class vehicle configurations can achieve similar GHG levels

<table>
<thead>
<tr>
<th>C Class Vehicle Configuration</th>
<th>Vehicle Mass</th>
<th>Rolling Resist.</th>
<th>Aero. Drag</th>
<th>g CO$_2$/km on NEDC</th>
<th>% Reduction from baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline with SI engine</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>165</td>
<td>25%</td>
</tr>
<tr>
<td>Baseline with Diesel engine</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>124</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>107</td>
<td>52%</td>
</tr>
<tr>
<td>Stoich DI Turbo + 8-spd DCT</td>
<td>85%</td>
<td>90%</td>
<td>90%</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70%</td>
<td>80%</td>
<td>80%</td>
<td>83</td>
<td>50%</td>
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<tr>
<td></td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>104</td>
<td></td>
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<tr>
<td>Adv EU Diesel + 8-spd DCT</td>
<td>85%</td>
<td>90%</td>
<td>90%</td>
<td>93</td>
<td>53%</td>
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<td></td>
<td>70%</td>
<td>80%</td>
<td>80%</td>
<td>83</td>
<td></td>
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<tr>
<td></td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Atkinson (CPS) Powersplit Hybrid</td>
<td>85%</td>
<td>90%</td>
<td>90%</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70%</td>
<td>80%</td>
<td>80%</td>
<td>77</td>
<td>62%</td>
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<tr>
<td></td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td>Atkinson (CPS) P2 Hybrid</td>
<td>85%</td>
<td>90%</td>
<td>90%</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70%</td>
<td>80%</td>
<td>80%</td>
<td>62</td>
<td></td>
</tr>
</tbody>
</table>

- All other parameters are at 100% of nominal C Class value

Note: CPS = cam profile switching. P2 hybrid = Inline full hybrid, capable of full engine-off operation at any speed
Conclusions – Aggressive fuel consumption and lower GHG standards will drive innovation in passenger car segments

- Several technology combinations will be pursued in parallel to help meet new fuel economy and GHG emissions standards
  - Mix will include more than just hybrids
  - Downsized engines and advanced transmissions have a role to play
  - Continued development in aerodynamics, lightweighting and reduced rolling resistance

- Trends and product announcements from the industry are consistent with those predicted by Ricardo for this study
  - E.g., 2012 Ford Escape with downsized engine replacing hybrid option

- With eye on 2016 requirements and knowing that tougher rules are coming in the US, EU, and Japan, manufacturers and suppliers have not been sitting idle
  - Several manufacturers implementing advanced valvetrain designs
  - Several manufacturers implementing turbocharging and direct injection to support downsizing engines
  - Hybridization and electrification of vehicles continues
Thank you for your attention…

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