We all share the goal of maximizing fuel economy and emissions of transportation vehicles.
Case Study: EPA CO₂ Impact Study

Program Objectives
- Ricardo work commissioned by the EPA to support future Vehicle GHG Rulemaking
- EPA’s desired outcomes:
  • Provide a Peer-Reviewed report that characterizes individual and combined vehicle technology efficiency improvement potentials
  • Use a robust, science-based “full vehicle simulation” analysis to characterize consequences of combining multiple technologies for efficiency gains

Program Approach
- Physical model of total vehicle to accurately simulate EPA specified packages
- Used millisecond-millisecond simulation that satisfies an energy balance and included performance
- Provided accurate input data from our proprietary database and subject matter experts which were peer reviewed by EPA
- Total vehicle system analysis -- ensured compatibility of technologies in a package

Results and Benefits
- Full vehicle simulation analysis to characterize impacts of 26 technology packages on CO2 and performance estimated for 5 different vehicle classes including
  • How individual technologies and their combinations provide different levels of vehicle efficiency improvement in different vehicle classes
  • Impact of synergies vs. One at a time technologies
- Final report has been issued to the EPA and into the public domain

Total Vehicle Fuel Economy Process

Vehicle Systems Approach
- Propulsion System
- Ancillaries
- Drivetrain
- Rolling Resistance
- Aerodynamic Drag

Scientific Simulation Methodologies
- Fuel Economy (MPG)
- Vehicle Speed (MPH)
Introduction to Ricardo

Ricardo was selected because it is one of the world's leading transportation engineering & management consulting firms – with total vehicle and PT capability

Value-Adding Capabilities

- Product Engineering
  - Engine (Gas & Diesel)
  - Transmission & Driveline
  - Controls and Electronics
  - Vehicle Engineering
- Niche Manufacturing
- Strategic Consulting

International Presence

- UK
- Germany
- USA
- India
- Korea
- Japan

Success Indicators

- Independent and long established (1908)
- Analysis foundation approach
- Core competence in turn-key program delivery
- Significant Investment in people and advanced technology
- Global critical mass with 1800 people and $320 million revenue

Global Client Base

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www.totalvehiclefueleconomy.com
Ricardo has developed a total vehicle fuel economy simulation model that enables full vehicle attribute trade-off's to be assessed.

Every design parameter can be accessed by the optimizer.

- **Friction**
  - Crankshaft Friction
  - Balancer Drive Friction
  - Power Cell Friction
  - Camshaft Friction
  - Valve train Friction
  - Front End Drive Friction
  - Oil Pump Friction
  - Water Pump Friction
  - Accessory Drive Friction
  - Other Technology Effects

- **BSFC maps**
  - Databases
    - I4, V6, V8, etc...
    - Diverse fuel, NA, Turbo
  - Technology Modifier maps
    - Coefficient maps to apply to base BSFC map or additional maps to integrate advance technology: VVT, VVA, Turbocompound, etc...
    - Database, Papers, WAVE

- **Transmission**
  - Type of gears
  - Number/type of seals
  - Number/type of bearings
  - Number/type of clutches
  - Wet/Dry Sump, etc...

- **Vehicle**
  - Tire / Rolling Resistance
  - Drag Reduction
  - Cooling System
  - Interior Feature
  - Exterior Features, etc...

- **Core Vehicle Model**
  - Driveability Assessment and Rating Tool
  - Database Simulation [AMESim, Flowmaster] Papers
  - Papers

- **Test Results**
  - Trade Off Analysis
    - Fuel Economy
    - Acceleration & Performance
    - Gradeability
    - Hybrid Post-Processor
    - Start/Stop, Regen Capacity
    - Driveability

- **Excel/Test**
  - MT
  - AT
  - CVT
  - DCT
  - etc T...

- **Look Up Map**
  - [FEAD, etc...]

- **Custom Fuel Maps**
Report shows that up to 27% (“car”) - 34% (“truck”) fuel economy improvement is possible using this subset of “conventional” or “nearer-term” technologies, without altering weight.
Recommendations for further study

- Study CAFE impact with more/different vehicle classifications
- Evaluate more technologies, particularly Hybrids and emerging Tier 1 technologies
- Define and evaluate weight saving technologies and weight impact of PT technologies
- Critically examine non-powertrain assumptions (aero, rolling resistance, friction)
- Simulate Performance vs Fuel Economy tradeoffs
- Integrated cost and technology impact study

Report available on www.totalvehiclefueleconomy.com
Where does the remaining 25% come from? Fuel economy improvements must be accomplished with minimum tradeoffs

- Consumer
  + Purchase Drivers

- Environment
  + Energy Security
  - CO2
  + MPG

- Achieving maximum fuel efficiency at minimum cost requires a holistic, total vehicle approach including all powertrain and vehicle systems

- No silver bullet
- Multiple technologies
- OEMs have limited capital & engineering resources
Ricardo's R&D portfolio is focused on advanced technology for fuel economy, emissions & vehicle electrification.

**Technology Portfolio**

- **Hybrids & Fuel Cells**
- **Advanced Gasoline Engines**
- **Clean Diesels**
- **Efficient Transmissions**
- **Controls and Electronics**
- **Alternative Fuels**

**Example Ricardo Solutions**

- **Pass Car T2B2 Diesel Adv Tech Demo Vehicle**
- **2-Stroke/ 4-Stroke Engine**
- **Ethanol Boosted DI Engine “EBDI”**
- **Hydrogen-Powered Vehicle Concept**
- **Torque Vectoring - Active Steer with Safety Critical Software**
- **Optimized E85 Powertrain**
- **Hybrid Transmission Design**
- **Vehicle-to-Vehicle or Infrastructure Communication**
- **Advanced electronic controllers**
- **WAVE-RT for Full Model Based Control in ECU**
The Key Question:

How will you implement the right combinations of discrete technologies to increase vehicle efficiency in the most cost-effective manner?
A traditional view of FE roadmaps will lead to very expensive solutions

Without a total systems approach, FE achievements will be below expectations or at uncompetitive costs
Ricardo has a proven process and analytical tools to solve vehicle fuel economy challenges.

1. Assessment of baseline vehicle/ portfolio status and competitor benchmarks
2. Construction of simulation model and correlation to measured data
3. Analysis of energy balance, prioritization of focus area
4. Improvement opportunities characterized (simulated)
5. Optimization conducted through design of experiments
6. Optimization refined through real cost/benefit ranking
7. Implementation to hardware

Maximum fuel economy at minimum cost
TVFE is applicable to optimization of portfolios of vehicles and individual vehicles.
Case Study

For an Asian vehicle manufacturer, Ricardo was responsible for identifying and validating a real world fuel economy improvement of 13% on their highway bus project.

**Situation and Objective**
- Desire to improve fuel consumption competitiveness of their Highway Bus product
- System approach with combined development of engine, transmission and vehicle systems required
- Targeting fuel consumption improvement over real-world customer drive cycle

**Ricardo Responsibilities**
- On-site support for vehicle data acquisition
- Engine test bed development of calibration maps and turbocharger matching
- Simulation of vehicle over selected drive cycles
- Energy analysis to define Fuel Consumption critical components / systems. Confirm effect of system developments
- Engineering of development specifications
- Implementation support of developed systems and vehicle confirmation testing

**Results and Benefits**
- 13% fuel consumption improvement identified:
  - 2.0% from engine re-calibration
  - 2.5% from transmission and driveline
  - 8.5% from cooling system and thermal management strategy
- Cost/benefit analysis completed to enable the OEM to make an informed decision on what changes to implement in production
A systems approach identifies and integrates opportunities across the entire vehicle – selected Ricardo favorites

<table>
<thead>
<tr>
<th>Propulsion System</th>
<th>Parasitic Loads</th>
<th>Drivetrain</th>
<th>Vehicle Systems</th>
<th>Exterior/ Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>• T2B2 diesel solutions (SULEV) enabling reduced NOx aftertreatment</td>
<td>• Electrified accessories</td>
<td>• Advanced transmissions</td>
<td>• Calibration optimization</td>
<td>• Exterior Design (e.g. Styling)</td>
</tr>
<tr>
<td>• Ethanol Boosted Direct Injection for extreme downsizing</td>
<td>• Reduced alternator loads through optimization</td>
<td>• Optimized PT matching &amp; shifting strategies</td>
<td>• Tire Technology</td>
<td>• Underbody Aerodynamics</td>
</tr>
<tr>
<td>• EGR Boost for downsizing with full flex fuel capability</td>
<td>• PT Cooling Strategy &amp; optimization</td>
<td>• Gear Ratio’s</td>
<td>• PT &amp; Vehicle thermal optimization</td>
<td>• Impact of Drive Cycle(s)</td>
</tr>
<tr>
<td></td>
<td>• EPAS</td>
<td>• Drivetrain Efficiency</td>
<td>• Vehicle Weight</td>
<td>• Real time controls</td>
</tr>
</tbody>
</table>

- **The race for improved technologies that address the long-term efficiency challenge must be met with fully integrated solutions that bring multiple systems together efficiently**
Case Study

Optimizing the fuel economy requires a careful analysis of the dominant drive cycles

- Relative merits of Diesel or Hybrid depend on application and drive pattern
- Stop/start and low speed driving favors Hybrid configuration
- Higher speed operation requires high efficiency combustion and transmission
Electrical Load Optimization and Control ➔
Low cost fuel economy improvement

- Many stand alone systems have shown promise to reduce electrical loads (e.g. Smart Alternator and Smart Power Distribution Boxes) but have not been fully integrated.
- A full system approach can yield significant fuel economy benefits through optimized control of these devices and therefore at minimal cost.
- Ricardo is developing a vehicle electrical control system aimed at real world fuel economy gains in conventional powertrain vehicles.

![Typical Alternator Losses Graph]

<table>
<thead>
<tr>
<th>Drive Cycle</th>
<th>Baseline</th>
<th>Results</th>
<th>% Improve</th>
</tr>
</thead>
<tbody>
<tr>
<td>City (FTP75)</td>
<td>21.79</td>
<td>22.21</td>
<td>1.93%</td>
</tr>
<tr>
<td>Highway (HWFET)</td>
<td>32.56</td>
<td>33.23</td>
<td>2.06%</td>
</tr>
<tr>
<td>Metro-Highway (Combined)</td>
<td>26.64</td>
<td>27.17</td>
<td>2.00%</td>
</tr>
</tbody>
</table>

*Opportunity for improvement*
• Co-simulation between cooling system, HVAC and engine performance models to predict system performance, fuel economy and emissions
• Improved system design through holistic vehicle approach leads to reduced cost and significant fuel economy benefits
Summary

- Ricardo report shows that at current volumes, 27-34% of the 40% improvement can be achieved with “conventional technologies”
- Remaining 25% of the gap is turning into a space race for technology
- Technology must be accomplished at the minimum cost
- Occurs only with a systems approach, otherwise results will be too costly
- Ricardo launched TVFE to make such an approach available in a stand alone offering for all customers