Advanced Engine Technology
- Near-Zero Emissions -

Ben Knight
V.P. Honda R&D Americas
November 5, 2003, Chattanooga, Tennessee
Key Energy & Emission Issues

- **Energy (Sustainability)**
- **Climate Change (Greenhouse Gas, CO₂)**
- **Air Pollution (Emissions: VOCs, NOx, CO, PM, Toxics)**

Social Concern

- 1990
- 1995
- 2000
- 2005
- 2010
- 2015
- 2020
Honda’s Power Plant Roadmap

- Improvement of Internal Combustion Engines
- Hydrogen fueled FCV
- Hybrids
- Increase Engine Efficiency

Timeline:
- 1990
- 2000
- 2010
- 2020
Clean
Internal Combustion Engine
Power Plants
<table>
<thead>
<tr>
<th>Points</th>
<th>Emissions Rating</th>
<th>Emission Level &amp; Class (note: Tier 2 standards apply to all classes)</th>
<th>Smog Forming Pollutants, g/mi NOx + NMOG</th>
<th>Pounds of Smog Forming Pollution NOx + NMOG per 15,000 mi.</th>
</tr>
</thead>
<tbody>
<tr>
<td>“10”</td>
<td>10</td>
<td>ZEV (Zero Emission Vehicle)</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>“10”</td>
<td>10</td>
<td>CA SULEV II</td>
<td>0.03</td>
<td>1.0</td>
</tr>
<tr>
<td>“10”</td>
<td>10</td>
<td>EPA Tier 2 Bin 2</td>
<td>0.03</td>
<td>1.0</td>
</tr>
<tr>
<td>“9”</td>
<td>9</td>
<td>Tier 2 Bin 3</td>
<td>0.08</td>
<td>2.8</td>
</tr>
<tr>
<td>“9”</td>
<td>9</td>
<td>Tier 2 Bin 4</td>
<td>0.11</td>
<td>3.6</td>
</tr>
<tr>
<td>“9”</td>
<td>9</td>
<td>Light Duty ULEV II</td>
<td>0.12</td>
<td>4.1</td>
</tr>
<tr>
<td>“8”</td>
<td>8</td>
<td>Tier 2 Bin 5 (&amp; LEV II)</td>
<td>0.16</td>
<td>5.3</td>
</tr>
<tr>
<td>“8”</td>
<td>8</td>
<td>Tier 2 Bin 6 (&amp; LEV II)</td>
<td>0.19</td>
<td>6.3</td>
</tr>
<tr>
<td>“7”</td>
<td>7</td>
<td>Tier 2 Bin 7</td>
<td>0.24</td>
<td>7.9</td>
</tr>
<tr>
<td>“7”</td>
<td>7</td>
<td>Tier 2 Bin 8a</td>
<td>0.32</td>
<td>10.7</td>
</tr>
<tr>
<td>“7”</td>
<td>7</td>
<td>Car and Small Truck ULEV</td>
<td>0.36</td>
<td>11.7</td>
</tr>
<tr>
<td>“0”</td>
<td>0</td>
<td>Largest Truck Tier 1</td>
<td>2.11</td>
<td>69.8</td>
</tr>
<tr>
<td>“0”</td>
<td>0</td>
<td>Largest Truck Tier 1 CA</td>
<td>3.66</td>
<td>121.1</td>
</tr>
<tr>
<td>CARB (LEV 1 and 2)</td>
<td>EPA (Tier 2)</td>
<td>EPA 10-Pt scale</td>
<td>Pounds SMOG-Forming Pollution In 15,000 miles</td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------</td>
<td>-----------------</td>
<td>---------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>ZEV</td>
<td>bin 1</td>
<td>“10”</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>SULEV-2 / PZEV</td>
<td>bin 2</td>
<td>“9”</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>ULEV-2</td>
<td>bin 3, 4</td>
<td>“9”</td>
<td>2.8 - 4.1</td>
<td></td>
</tr>
<tr>
<td>LEV-2</td>
<td>bin 5, 6</td>
<td>“8”</td>
<td>5.3 - 6.6</td>
<td></td>
</tr>
<tr>
<td>ULEV-1 Car</td>
<td>bin 7- 8b</td>
<td>“7”</td>
<td>7.9 – 11.8</td>
<td></td>
</tr>
<tr>
<td>LEV-1 Car</td>
<td>bin 9a</td>
<td>“6”</td>
<td>12.3 – 14.2</td>
<td></td>
</tr>
<tr>
<td>ULEV-1 Med. Truck</td>
<td>bin 9b</td>
<td>“5”</td>
<td>15.1 – 19.8</td>
<td></td>
</tr>
<tr>
<td>LEV-1 Med. Truck</td>
<td>bin 10a</td>
<td>“4”</td>
<td>20.8 - 26.8</td>
<td></td>
</tr>
</tbody>
</table>
“Near-Zero” Emission Vehicles

CARB recognized ‘near-zero’ vehicles:

- SULEV-2 (LEV-2 std.) (= EPA bin 2)
- PZEV (= EPA bin 2)

PZEV definition:

- SULEV-2 exhaust emissions
- 15 year / 150k mile emissions warranty
- ‘zero-evaporative’ fuel system
**Near-Zero Emission Vehicles Today**

10 OEMs, 16+ model series in ’04 MY:

<table>
<thead>
<tr>
<th>Car Manufacturer</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW</td>
<td>325i, 325ci, 325i Sport Wagon PZEVs</td>
</tr>
<tr>
<td>Ford</td>
<td>Focus, Focus Wagon PZEVs</td>
</tr>
<tr>
<td>Honda</td>
<td>Accord PZEV, Civic Hybrid AT PZEV, Insight CVT SULEV, Civic Nat. Gas AT PZEV</td>
</tr>
<tr>
<td>Hyundai</td>
<td>Elantra PZEV</td>
</tr>
<tr>
<td>Mazda</td>
<td>Mazda 3 PZEV</td>
</tr>
<tr>
<td>Mitsubishi</td>
<td>Galant PZEV</td>
</tr>
<tr>
<td>Nissan</td>
<td>Sentra PZEV, Altima PZEV</td>
</tr>
<tr>
<td>Subaru</td>
<td>Legacy AWD, Wagon, Outback PZEVs</td>
</tr>
<tr>
<td>Toyota</td>
<td>Prius AT PZEV, Camry PZEV</td>
</tr>
<tr>
<td>VW</td>
<td>Jetta PZEV</td>
</tr>
</tbody>
</table>
Needed to achieve the goal:

- Cold Start Emissions Solutions
- Catalyst Efficiency Approaching 100 percent
- Robust Real World Control
- Durable at high mileage
- Clean burning, low sulfur fuel
Cold Start Emission Solutions

Example: Accord PZEV (SULEV)

- Non-rich combustion after cold startup, prior to catalyst activation
- Catalyst activation in seconds

SAE Paper # 2000-01-0551
**Effective New Catalysts**

**Example: Accord PZEV (SULEV)**

- **Fast Activation**
  - New structure and formulation

- **High Efficiency**
  - Catalyst efficiency approaching 100%

Almost 100% of Smog Forming Compounds Removed

SAE Paper # 2000-01-0936 and 2000-01-0551
Effective New Catalysts Structure
(High Cell Density – short path length to an active site)

Past
e.g. Tier 0, Tier-1

Today
e.g. Tier-2, LEVs, ULEVs, NLEVs, Near-Zero (bin-2, SULEVs, PZEVs)

- Catalyst efficiency approaching 100%

SAE Paper # 2000-01-0936 and 2000-01-0551
Durable, High Efficiency Catalysts

(Example: Accord PZEV (SULEV))

Catalysts demonstrating practically no deterioration in performance:

- Catalyst maintains O2 storage without “breakout”
- Operates in “sweet spot” over lifetime (effective catalyst O2 performance is maintained)

SAE Paper # 2001-01-0264
Reliable & Durable Emission Performance

- No spark plug wires ("direct ignition")
- No points to set, no timing to adjust
- Durable spark plug materials (100,000+ mile life)
- Clean burning fuel (e.g. CA spec, Federal spec in 2006)
- Fuel injection, O₂ sensors with adaptive control
Near-Zero Emissions Achieved?

- Robust ‘Real-World’ Control
- Durable
- Cold Start Solutions

SULEV
SUPER ULTRA LOW EMISSION VEHICLE

HONDA
New gas engines rated nearly pollution-free

Sentra, Accord use a low-sulfur fuel

By James R. Healey
USA TODAY

Gasoline engines now in production can be nearly pollution-free, a California university engineering laboratory reports after three years of study.

The finding suggests Americans can enjoy much cleaner air without the high price of electric cars.

“You won’t get to zero (emissions), but you will get pretty close,” says Joseph Norbeck, director of the facility that performed the challenging tests at the University of California-Riverside.

For now, the promising technology is limited to California because to work right, the engines require low-sulfur gasoline that is widely available only there.

It probably will take a federal mandate for the clean fuel to become available across the USA, opening the door to cleaner-burning engines everywhere.

Environmentalists saluted the report, though it paints the gasoline internal-combustion engine as less a villain than they prefer.

“You have to be practical. The internal-combustion engine is going to be around 20 or 30 years, so you need to address air quality problems,” says David Friedman, engineer and senior analyst at the Union of Concerned Scientists, which favors hydrogen power. “It’s a significant finding.”

“It’s good news and shows that the auto industry, when it uses advanced technology, can do better than the law requires,” says Dan Becker, spokesman for the Sierra Club, an environmental group.

UC tested the two cars with four-cylinder engines that meet California’s strictest anti-pollution standards for gasoline engines; Nissan Sentra and Honda Accord.

The engines have been sold in small numbers, but starting with 2003 models, the Honda engine is standard in California-market Accord sedans with automatic transmissions, and the Nissan engine is standard in California Sentras.

Honda and ChevronTexaco helped pay for the UC research. Other money came from state and federal agencies.

“If auto companies and oil companies are commissioning a report that shows they can use technology to improve things, I’m not troubled at all,” Becker says.
Michelin Bibendum Challenge Sept. 2003

Photo credit: Wieck Media Services
In the background, the Acura MDX and Honda Element wait their turn.

EPA (Jane Armstrong) loading the real-time emission analyzer into the PZEV Accord.
Insight Hybrid ready for on-board emission measurement

Sample line
Flow meter (hot-wire anemometer)
Research themes

- Develop instrumentation for on-road measurement of emissions of extremely low emitting vehicles (ULEV, SULEV, PZEV)
- Develop emission models
- Assess air quality impact

Research Sponsors:
- CARB
- EPA
- Honda
- Chevron Texaco
- MECA (Mfg Emission Controls Assn.)
Real World Emission Measurement

SAE Papers # 2000-01-1140 and 2000-01-1140

Touch-screen data display, modal mass emission data (combined data)

FTIR Spectrometers

Accurate, real-time measurements at ambient and SULEV (near-zero) levels
Results: Examples of Measurements

CE-CERT on-road measurements under actual operating conditions – warmed up only

<table>
<thead>
<tr>
<th>Average speed</th>
<th>Route*</th>
<th>NMHC g/mi</th>
<th>CH4 g/mi</th>
<th>NOx g/mi</th>
<th>CO g/mi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning rush hour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>64.4 mph</td>
<td>1</td>
<td>0.00011</td>
<td>0.00003</td>
<td>0.0082</td>
<td>0.184</td>
</tr>
<tr>
<td>25.4 mph</td>
<td>2</td>
<td>0.00007</td>
<td>0.00009</td>
<td>0.0085</td>
<td>0.230</td>
</tr>
<tr>
<td>Light traffic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65.3 mph</td>
<td>1</td>
<td>0.00014</td>
<td>0.00002</td>
<td>0.0065</td>
<td>0.188</td>
</tr>
<tr>
<td>59.6 mph</td>
<td>2</td>
<td>0.00018</td>
<td>0.00008</td>
<td>0.0025</td>
<td>0.111</td>
</tr>
</tbody>
</table>

*Data was obtained from traveling a section of Highway 91 at median speeds with the designated warmed vehicle. Route 1 = westbound. Route 2 = eastbound.
On-Road Data  City Drive

NMHC

Time

ppm.C

Honda Exhaust

Intake (ambient)

Ambient (intake air)

Honda Exhaust
On-Road Data  One-Hour City Drive

NOx

- Intake (ambient)
- Honda Exhaust

Time: 1 Hour

ppm

0 1 2 3 4 5 6 7 8 9 10
Cost of Near Zero Emission?

New Hardware / Redesign Required

Examples of cost-up:
- Cold start solutions
- Advanced catalysts
- New fuel system materials
- Tight tolerances
- Extended Warranty (PZEV)

Any side benefits?
- Know-how for more cost-effective LEV-2, ULEV-2, bin 3-6 vehicles.
- Greater attention to durability, reliability (customer satisfaction)?

Any downsides in addition to cost?
- Peak HP same or slightly down?
Market for Near-Zero Emission Vehicles?

Do customers seek low emission cars?
• A few are asking

Dealer / Customer education effort?
• Some efforts made
• Complexity of new stds makes it difficult
  • Gov’t role? (“10-pt” scale? “Near-Zero”?)

Do Automakers charge a premium?
• Generally no charge or a small charge

Do customers perceive benefits?
• Possible association with quality, technology?
• Association with low performance to overcome?
Natural Gas Vehicles?
# AT-PZEV Certified Natural Gas Civic

<table>
<thead>
<tr>
<th>Emissions</th>
<th>AT-PZEV / SULEV / bin 2 150,000 mile Gov’t Standard (g/mile)</th>
<th>Civic NGV 150,000 mi. Test Data* (g/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOG</td>
<td>0.010</td>
<td>0.001</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>0.004</td>
<td>0.000</td>
</tr>
<tr>
<td>CO</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>NOx</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

*Certification data

- Fast Catalyst Warm-up
- Precise Fuel Control
- Dedicated O₂ Sensors
Natural Gas-Specific Oxygen Sensors

Example: Civic GX Natural Gas Vehicle

**Problem:** Typically CH₄ and H₂ Interferes with \( O_2 \) Sensors

**Solution:**

- Primary \( O_2 \) Sensor
  - Hi-Tolerance of \( H_2 \) & \( CH_4 \) for A/F Measurement
    - Catalytic Coating Overcoat
    - Minimization of Impurities in Electrode

- Secondary \( O_2 \) Sensor
  - Inactive to \( CH_4 \) for Catalyst Monitoring
    - by Silver-doping of electrode
Natural Gas Civic: Particulate Matter
Test Results (EUDC) – VTT / IEA

PM flow (particle number)

PM size distribution

Natural Gas Civic Particulate Matter (practically zero)
IEA PM COLD

Total number of particles in different size classes over the European LD emission tests
Can internal combustion vehicles achieve near-zero emissions real world?
Summary

Can I.C.E. vehicles achieve near-zero emissions?

• ‘Near Zero’ truly achieved – 15 years ahead of imagined timeframe
  • Well-to-wheel basis, some CNG and gasoline cars exceeding Electric Vehicle emission and energy benefits in many regions of U.S.
Summary

Can gasoline vehicles achieve near-zero emissions?

• ‘Near Zero’ truly achieved – 15 years ahead of imagined timeframe
  • Well-to-wheel basis, some CNG and gasoline cars rivaling or exceeding Electric Vehicle emission and energy benefits in many regions of U.S.

• Near Zero emission vehicles are now entering the market in volume
  • Customer benefits from development of reliable engine systems
  • Minimal or no performance loss
  • 10 OEMs offering 16 model lines
  • Fuel composition also a key, 2006 available nationwide
Summary

Can gasoline vehicles achieve near-zero emissions?

• ‘Near Zero’ truly achieved – 15 years ahead of imagined timeframe
  • Well-to-wheel basis, superior to EVs in some regions.

• Near Zero emission vehicles are now entering the market in volume
  • Customer benefits from development of reliable engine systems
  • Minimal or no performance loss
  • 10 OEMs offering 16 model lines
  • Fuel composition also a key, 2006 available nationwide

• Gasoline trucks now available nationwide at ULEV-2 / EPA bin-5.
  • Expect outstanding real world emission performance - to be verified.
Summary
Can gasoline vehicles achieve near-zero emissions?

• ‘Near Zero’ truly achieved – 15 years ahead of imagined timeframe
  • Well-to-wheel basis, superior to Evs in some regions of U.S.

• Near Zero emission vehicles are now entering the market
  • Customer benefits from development of reliable engine systems
  • Minimal or no performance loss
  • 10 OEMs offering 16 model lines
  • Fuel composition also a key, 2006 available nationwide

• Gasoline trucks now available nationwide at ULEV-2 / EPA bin-5.
  • Expect outstanding real world emission performance - to be verified.

• Clean gasoline vehicles are the most certain and fastest path to improve the air quality
  • UC Riverside CE-CERT research on performance and impact.
Thanks