Future Transportation Trends and Challenges

SASHTO Partnering Conference

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Toyota Motor North America, Inc
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Scope of Presentation

1. **Drivers of change**
2. Technology options
3. Consumer adoption factors
4. Other considerations
5. Conclusions & recommendations
Issues Driving Future Powertrain Development

Air Pollution

Declining Resources

Climate Change

Traffic Congestion

Energy Security

Regulations
Diversification of Fuels & Powertrains

Primary Energy
- Oil
- Natural gas
- Coal
- Plant
- Uranium
  - Hydro, solar, geothermal power

Automotive fuel
- Gasoline
- Diesel
- Gas fuels
- Synthetic liquid fuels
- Bio-fuel
- Electricity
- Hydrogen

Powertrain
- Internal combustion engine
  - Conventional vehicle & HV
- PHV
- EV
- FCV

Core Technology
Pursue Maximum Efficiency

Oil Reduction
Diversification of Fuels & Powertrains

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Core Technology
- Oil Reduction

Advanced Technology
- Oil Alternatives
Scope of Presentation

① Drivers of change

② Technology Options

③ Consumer adoption factors

④ Other considerations

⑤ Conclusions & recommendations
Advanced Technology Options

- Battery Electric Vehicle (BEV) [ RAV4-EV ]
- Fuel Cell Hybrid Electric Vehicle [ FCHV-adv ]
- Hybrid Electric Vehicle (HEV) [ Prius ]
- Plug-in Hybrid Electric Vehicle (PHEV) [ Prius PHEV ]
- Battery Electric Vehicle (BEV) [ FT-EV ]
Hybrid is the Foundation

Potential Gains from Hybridization

- Engine idle stop
- Regenerative braking
- Atkinson cycle (Engine efficiency improvement)
- EV drive (Optimization of engine use)
- PHEV (Ability to recharge from the grid)

Optimization of hybrid characteristics key to maximizing efficiency
Hybrid Evolution

*All fuel economy numbers of US spec vehicles based on current EPA rating system
Japan spec vehicle based on previous EPA system

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<td>50 mpg</td>
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<td>12.5 sec</td>
<td>10.5 sec</td>
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<td>10.5 sec</td>
<td>9.8 sec</td>
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<td>SULEV</td>
<td>AT-PZEV</td>
<td>AT-PZEV</td>
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<td>Size Class</td>
<td>Sub-Compact</td>
<td>Compact</td>
<td>Mid-Size</td>
<td>Mid-Size</td>
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</table>

Future evolution will balance cost reduction with performance improvement
Expansion of Toyota Hybrid Technology

**Past**

- Toyota
  - Prius
  - Camry Hybrid
  - Highlander

- Lexus
  - RX400h

**Present**

- Toyota
  - Prius
  - Camry Hybrid
  - Highlander

- Lexus
  - CT200h
  - RX450h
  - HS250h
  - GS450h
  - LS600h

**Future**

- Toyota
  - Prius V

- Lexus
  - LF-Gh Concept

- Prius C
Hybrid is the Foundation

PHV

EV (Battery EV)

FCHV (Hydrogen FCEV)

Issues

Cruising range Charging time Infrastructure Cost Battery durability

Zero CO₂ emissions during driving

Zero CO₂ emissions during inner city driving

Cost Battery durability

Infrastructure Cost Stack durability

Energy saving (Fuel economy improvement)
PHEV

- Battery Electric Vehicle (BEV) [ RAV4-EV ]
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Energy Density Comparison

Energy density of electricity is approx. 1/50 of gasoline
Prius PHEV

- 600 Vehicle global demonstration program
  - Gauge consumer acceptance and use patterns in various markets
- Consumer version available in 2012

**Minimum System Change from HV**

2 Main Modifications
- High Power Lithium-Ion Battery
- 13 mile AER
- 100V/240V Charger

<table>
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<tr>
<th></th>
<th>Base HV</th>
<th>PHV</th>
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<tbody>
<tr>
<td>Engine</td>
<td>1.8L Atkinson &amp; Cooled EGR</td>
<td>73kW ←</td>
</tr>
<tr>
<td>Motor</td>
<td>AC Synchro. + Boost Converter + Reduction Gear</td>
<td>60kW ←</td>
</tr>
<tr>
<td>Battery</td>
<td>Ni-MH</td>
<td>1.3kWh</td>
</tr>
</tbody>
</table>

Minimal vehicle modifications and small battery **reduce cost → High Volumes**
PHEV Systems

- **Reduced Cost** while achieving required vehicle performance
- Potential loss of performance when battery is depleted
- High cost and weight
- Required vehicle performance

*AER: All Electric Range*
PHEV Demo Program

- ~160 Prius PHEV prototypes are being used by the public in test fleets around the US
- Toyota is posting on the web a summary of the collected data at http://www.toyota.com/esq/#

Time in EV vs. HV Mode

Mileage per Trip

Charging Time
BEVs

Battery Electric Vehicle (BEV) [ RAV4-EV ]

Hybrid Electric Vehicle (HEV) [ Prius ]

Plug-in Hybrid Electric Vehicle (PHEV) [ Prius PHEV ]

Fuel Cell Hybrid Electric Vehicle [ FCHV-adv ]

Battery Electric Vehicle (BEV) [ FT-EV ]
Battery Electric Vehicles – RAV4-EV Experience

- Offered 1998 – 2003 in CA and AZ
- Over 1200 deployed
- 75-95 mile real-world range
- Most leased to fleet customers
- Only OEM to actually sell EVs
- ~300 still in operation
- Per vehicle marketing cost 15x Prius
- Conclusions (2006)
  - High consumer awareness
  - Small pent-up demand when introduced
  - Low sales, not increasing over time

Little evidence to indicate EV demand has grown significantly in last decade
Toyota BEVs

**IQ EV** - Concept
- Small urban commuter EV
- Range of ~50 miles
- Charging time: ~2.5 hrs / 7.5 hrs (220V / 110V)

**RAV4 EV**
- Based on current RAV4 ICE
- +100 mile target range
- Powertrain from Tesla
- 2012 Introduction

Range, recharge time & cost limit the market for BEVs
Battery Electric Vehicle (BEV) [ RAV4-EV ]

Fuel Cell Hybrid Electric Vehicle [ FCHV-adv ]

Hybrid Electric Vehicle (HEV) [ Prius ]

Plug-in Hybrid Electric Vehicle (PHEV) [ Prius PHEV ]

Battery Electric Vehicle (BEV) [ FT-EV ]
WTW Powertrain Efficiency for Natural Gas

Toyota estimation

<table>
<thead>
<tr>
<th>Process</th>
<th>Fuel efficiency</th>
<th>Vehicle Efficiency</th>
<th>Total efficiency</th>
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<tbody>
<tr>
<td>Mining/Liquefaction/Transportation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No processing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Refueling</td>
<td>CNG 82%</td>
<td>CNG HV 34%</td>
<td>28%</td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refueling</td>
<td>Hydrogen 60%</td>
<td></td>
<td>36%</td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refueling</td>
<td>Electricity 30%</td>
<td>EV 81%</td>
<td>24%</td>
</tr>
</tbody>
</table>

Hydrogen fuel cell vehicles have the best WTW efficiency
How a Polymer Electrolyte Fuel Cell Works

Theoretical efficiency of a fuel cell $DG/DH = 83\%$ (Hydrogen)
Fuel Cell Structure

- Spreading catalyst
- Polymer electrolyte membrane
- MEA: Membrane Electrode Assembly
- Separator
- Assembling
- Single cell
- Stacking cells
- FC Stack
- Stack
FCHV System Components

- Power control unit
- Motor
- Battery
- TOYOTA FC Stack
- High pressure hydrogen tank
- Fuel Cell System Technology
Major Technical Challenges for FC Vehicles

Issues to be solved

Established technology

Balance cost vs. compactness & performance vs. durability

Cruising range

Cold start / Driving performance
Cold Start / Driving Capability Verified

Timmins, Canada

Ambient Air Temperature at Timmins

(degC) Ambient Air Temp.

(degF)

2/8 2/10 2/12 2/14 2/16 2/18

Date

-40 -30 -20 -10 0 10

-50 -32 -20 0 20 32

-40 -37degC

-37degC
Real World Driving Range

**System Efficiency Improvement**
- FCHV-adv: improved FC system efficiency at all loads
- Increased regenerative energy
- Improved vehicle efficiency (fuel economy)

**Range Improvement (Image)**
- Fuel economy + 23%
- On-board H2 + 94%

**Rush Hour in Los Angeles**
- 2 FCHVs
- Over 400 miles / tank
- 68.3 miles/kg of H2

**Fairbanks to Vancouver**
- 2300 miles
- Over 300 miles / tank
- No mechanical problems
Durability

Durability improving, but must advance further before introduction
Cost Reduction

The cost of new FC system is ~1/10 of current FCHV-adv. An additional 50% reduction is targeted for early commercialization.
EV and FCV System Cost Comparison

For longer driving ranges, FCVs are a less costly option.

Toyota Estimation around 2020
**Business Model for Hydrogen Station** (Toyota Estimation)

**Profit Factor**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Sales</th>
<th>Variable Costs</th>
<th>Fixed Costs</th>
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</thead>
<tbody>
<tr>
<td><strong>Sales</strong></td>
<td>FCHV, FC BUS</td>
<td>H$_2$ Cost / Tax, Labor Cost, Maintenance Cost</td>
<td>Facility Cost, Construction Cost</td>
</tr>
<tr>
<td><strong>Variable Costs</strong></td>
<td></td>
<td>- Cost Analysis of H$_2$, Development of highly durable station</td>
<td></td>
</tr>
<tr>
<td><strong>Fixed Costs</strong></td>
<td></td>
<td></td>
<td>Development of low cost station</td>
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- **Break-Even-Point**: Income / Expense
- **Early Turnaround**

Subsidies or incentives required to minimize losses

Hydrogen infrastructure is the greatest hurdle for FCV adoption
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Technology Penetration Takes Time

- 10 years to reach 1 million hybrid sales
- Hybrids currently ~ 2% of US market

Cumulative Hybrid Sales Thru 2010

- Hybrids continue to sell at niche market volumes
Willingness to Spend for “Green” Vehicle

Q: Think about the vehicle that you would most likely consider purchasing next. If the manufacturer of that vehicle came out with a version of it that was identical in every respect in terms of styling, acceleration, safety, reliability, etc. to the original, except that it was significantly better for the environment, how much extra, if anything, would you be willing to pay for it?

Source: Synovate, Feb 2010

Consumers continue to be unwilling to pay significantly more for a “green” vehicle as the median difference remains constant at a $2K premium.
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Comprehensive Measures are Needed

LDV efficiency is only part of the solution. An “Integrated Approach” to GHG reduction in the transport sector is needed.

Alt & bio fuels
Traffic congestion
Traveling miles
Vehicle volume
Vehicle efficiency

Road Transportation

Other transportation

US CO₂ Emissions for Fuel Combustion

- Transportation 31%
- Power Generation 43%
- Industry 16%
- Residential/Service and others 10%

US Total in 2007: 5769 MtCO₂


- LDVs consume ~45% of US petroleum (Current focus gasoline, not petroleum reduction)
- LDVs generate ~19% of US CO₂ emission
Petroleum & GHG Reduction Potential

• GHG benefits vary greatly with fuel source
• PHEVs require clean electricity to reduce GHGs (relative to a HEV)

WTW GHG reduction more challenging than petroleum reduction
Shifting Vehicle Size Based on Need

No single powertrain/fuel is optimum of all applications
Conclusions & Recommendations

• Hybridization is the 1\textsuperscript{st} step toward fuel/vehicle diversification

• New technologies and fuels are coming to market today, but will likely take decades to have a major impact

• Petroleum and CO\textsubscript{2} reduction strategies may not be synergistic

• GHG and petroleum reduction policy/regulation must include:
  – All economic sectors
  – All petroleum products, i.e. gasoline, diesel, jet
  – Fuel availability along with vehicle technology, i.e. hydrogen for FCVs
  – Integrated Approach to complement vehicle improvements, i.e. ITS

• Employ stable technology neutral policies and regulations

• Consumers, not policymakers, select the winning technology