Hybrid Vehicles
Powertrain Architectures and Controls

Glenn R. Bower  Engine Research Center
Wisconsin Automotive Excellence
International Collegiate Championships

1998 – Hybrid Vehicle Team
1999 – Hybrid Vehicle Team
2000 – Baja SAE
2001 – Baja SAE
2001 – Hybrid Vehicle Team
2002 – Hybrid Vehicle Team
2003 – Hybrid Vehicle Team
2004 – Hybrid Vehicle Team
2004 – SAE Clean Snowmobile
2006 – SAE Clean Snowmobile
2007 – Formula SAE
2007 – Hybrid Vehicle Team
2008 – Formula SAE
2008 – SAE Clean Snowmobile - Electric
2009 – SAE Clean Snowmobile - Electric
2009 – SAE Clean Snowmobile – Flex Fuel

16 International Championships!
32 Top 5 Finishes in the Last 11 Years!
OUTLINE

• Vehicle Losses
• Battery Technology
• Motor Technology
• Hybrid Architectures
• Load Leveling & Hybrid Control
• Summary
Conventional Vehicle Losses

Vehicle Energy Use

Conventional Vehicle, Urban Cycle

Transmission Losses = 6
Idling Losses = 11

Fuel Used = 100
Power to Wheels = 66

Accessory Load = 2
Engine Losses = 65
Hybrid Vehicle Losses

Vehicle Energy Use
Hybrid Vehicle, Urban Cycle

Fuel Used
50
(50% Savings)

Accessory Load = 2
Regenerative Braking = +4

Engine Losses = 30
Idling Losses = 0

Electric Propulsion &
Transmission Losses = 6

Power to Wheels 16
Key Parameters to Increasing Fuel Economy

1. Mass
2. Aerodynamics
3. Tires
4. Accessories
Lowering Accessory Loads

2010 Toyota Prius – Solar Panels Power Cabin Air Fan
Energy Storage Systems

- Batteries
- Hydraulic
- Flywheels
- Ultra-Capacitors
Battery Evolution

- Lead Acid
- Nickel Cadmium
- Nickel Metal Hydride
- Lithium Ion
- Electric Vehicles - Energy Dense Cells
- Hybrid Vehicles - Power Dense Cells
- PHEV’s – Power & Energy
Energy Comparison

- Gasoline
  - 120 MJ/Gal
    - 33.3 kWh
      - 8.325 kWh/Kg - Battery Equiv.
      - 5 kWh/Kg
        - 1.25 kWh/Kg - Battery Equiv.
  
- Electricity
  - 0.07 – 0.1 kWh/Kg
Energy Price Comparison

• **Gasoline** – Gallon of Fuel
  - $2.00

• **Electricity** (Assume 10 kWh = 1 gallon gas)
  - $1.10 - $1.50
# Battery Selection

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Voltage per Cell</th>
<th>Number of Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel Metal Hydride</td>
<td>1.25 V/Cell</td>
<td>10 Cells</td>
</tr>
<tr>
<td>Lead Acid</td>
<td>2.12 V/Cell</td>
<td>6 Cells</td>
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<tr>
<td>Lithium-Ion</td>
<td>4.00 V/Cell</td>
<td>3 Cells</td>
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</table>

12.0 V → 3 Cells
PHEV Battery Specifications

- ~10 kWh battery pack
  - 300 to 400 Volt, 40 to 50 amp-hrs
  - 200 to 250 Volt, 60 to 70 amp-hrs
- > 20 miles range electric
- ~70% Depth of Discharge
Cylindrical Cells
Prismatic Cells

- Interconnect Cover
- Laser Welded Bus Bar
- Control Electronics
- Electronics Cover Plate
- Compression Band
- Pressure Plate
- Heatsink Plates
- Lithium Ion Prismatic Cell
Battery Management

Estimate state-of-charge (SOC)

- Battery terminal voltage model
  - Voltage source
  - Series resistance
    - $R$ based on temperature
  - Series RC element
    - $\tau, R$ based on temperature

- Estimate SOC based on
  - $V_{\text{terminal}}$
  - $I_{\text{instantaneous}}, I_{\text{LPF}}$
  - Battery temperature

- Outputs
  - SOC, DTE indications
  - Warn rider at 10%
  - Terminate operation at 3%
Cold Performance

Rated by manufacturer at -10°C

Nearly full capacity available
Electric Motors

- AC to DC: AC-DC Inverter Module
- DC to AC: Energy Storage Box
- Energy flow from AC Motor/Generator to AC-DC Inverter Module to Energy Storage Box
AC Induction

Delphi EV1 Motor

105 kW continuous  ≥ 90% efficient
AC Permanent Magnet
Hybrids

- Accessories
- Energy Management & System Controls
- Body Chassis
- Fuel Tank
- Thermal Management System
- Hybrid Power Unit
- Traction Motor
- Energy Storage Unit
Series or PHEV Hybrid

- Battery powers the traction motor
- Traction motor powers the vehicle
- Engine charges the battery through a generator

Traction motor must meet maximum vehicle power requirements.

Best Efficiency during City (Stop/Start) Driving

Engineer Peak Efficiency of Engine/Generator to Coincide
Parallel Hybrid

- Engine can drive the vehicle and/or charge the battery
- Traction motor can charge battery or ‘boost’ vehicle power
- Both traction motor and engine can power the vehicle together

Down Size Engine approximately 25 to 30%
Size Traction System to Deliver 40 to 50% of Engine Power
INCREASES FUEL ECONOMY & ACCELERATION
Power Splits

Single Continuously-Variable gear ratio within the EVT
One Mode Power Split

* Input Split *
Output Split
Compound Split
Two Mode Powertrain
Two Mode Integrated into ‘Conventional’ RWD Transmission Case
Two Mode Power Split

- Power From ICE to Input Internal Gear 1
- Electric Motor/Generator A to Input Internal Gear 2
- Electric motors and ICE can operate independently through the multiple gearsets.
- Electric Motor/Generator B to Output Sun Gears
- Grounded (Stationary) to Transmission Case
- Multiple Disc Clutch

Mechanical Component Connections

- Power From Final Drive to Carrier 3
- Multiple Disc Clutch

Energy Storage Box (ESB)

- Input Planetary Gear Set
- Reaction Planetary Gear Set
- Output Planetary Gear Set

Final Drive

- Internal Combustion Engine (ICE)
- Electric Motor/Generator A
- Electric Motor/Generator B
- Multiple Disc Clutch
Ranking of Current Powertrain Technologies

• Efficiency
  – DI Diesel > Gasoline Direct Injection > Homogeneous Spark Ignition

• Emission Technologies
  – Homogeneous Spark Ignition > Gasoline Direct Injection > DI Diesel

• Cost
  – DI Diesel > Gasoline Direct Injection > Homogeneous Spark Ignition
Fuel Cells – Cool Combustion

• Think of a fuel cell as the reverse of electrolysis

• Catalyst separates electrons from hydrogen

• Hydrogen ion - proton - diffuses through the membrane

• Electrons flow through the circuit
Hydrogen Engines
Hybrid System Efficiency

- Each Component Efficiency must be accounted for:
- Regenerative Braking
  - Tires, Motor, Controller, Battery
  - Total Input Efficiency up to 80%
- Same Efficiencies Apply to Assist
  - Total Output Efficiency up to 80%
- Max Throughput % = $0.8^2 = 0.64\%$
  - Realistically, use 40 to 50%
Load Leveling

- Increasing or Decreasing the Engine Load and/or Speed to ‘Force’ it into a Higher/Highest Fuel Efficiency Regime
- Traditionally, Electric Traction System has been Used as Load Leveler
- HV Battery acts as Energy Capacitor
- Engine will be Shut Off Sometime during the Load Leveling Process
- Also Can be Used to Minimize Engine-out Emissions
Load Leveling

- SI
- CI ↓

Fuel Consumption Map [g/kW-Hr]

B. Georgi, et al., SAE972686 (1997)

Baseline 2 Valve Engine Map
Controlling a Hybrid

- Torque Request From Driver Through Pedals
- Calculate % of Torque Request to be Supplied by Each Device (i.e. Motor & Engine)
- Account for Current Status of All Device – SOC, Temp, Wheel Slip, Speed
- Make It Drive Seamlessly – Like a Conventional Vehicle
Solar Panels ???

2010 Toyota Prius
Solar Energy 101

- Ideal Solar Load
  - 1340 Watts per SQUARE METER
- Current Photovoltaic Efficiency
  - 15 to 20%
- 2010 Toyota Prius ~ 0.5 m²
  - 134 Watts
  - Time to Charge 10 kWh pack
  - 74.6 Hours !!!!!!
A GOOD START

DOWNSIZE YOUR VEHICLE

Suburban: 15 mpg  21 mpg

Malibu: 24 mpg  34 mpg

Equinox: 19 mpg  26 mpg

Vue Greenline:
27 mpg  32 mpg
Questions
Hybrid & Electric Vehicle Issues

- Battery Life
- Service
- Cost
- Safety
- Recycling
- Temperature Extremes
- Public Acceptance
- Driving Range
Electric Vehicles

- GM’s EV1 - 1st Ground-up Electric Vehicle
EV1 Battery

- Generation 1
  - 26 Lead Acid Modules
    - 60 Amp-Hr @ 312 volts
      - 18.7 kWh

- Generation 2
  - Nickel Metal Hydride
    - 77 Amp-Hr @ 343 volts
      - 26.4 kWh
Johnson Controls NiMH Batteries

Specifications:

- NiMH
- 44 Module, 317 V Nominal

<table>
<thead>
<tr>
<th></th>
<th>JCI</th>
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</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
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</tr>
<tr>
<td>Capacity (Ah)</td>
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<tr>
<td>Specific Power (W/kg)</td>
<td>1350</td>
</tr>
<tr>
<td>Specific Energy (Wh/kg)</td>
<td>47</td>
</tr>
<tr>
<td>Weight (g)</td>
<td>1200</td>
</tr>
<tr>
<td>Internal Resistance (mΩ)</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Current Hybrid Battery of Choice
The Real Driver to Fuel Efficient Vehicle - Cost


Relative Price of Gasoline
United States Energy Sources

- **Petroleum**: 40.4%
- **Natural Gas**: 22.7%
- **Coal**: 22.6%
- **GeoThermal**: 0.3%
- **Solar**: 0.1%
- **Wind**: 0.2%
- **Hydroelectric**: 2.7%
- **Nuclear**: 8.1%
- **BioMass**: 2.9%

Biomass is 70% Wood, 20% Waste & 10% Alcohol Fuels
US Electrical Production

- Petroleum: 3.0%
- Natural Gas: 18.7%
- Renewables: 2.3%
- Nuclear: 19.3%
- Hydroelectric: 6.5%
- Coal: 49.7%
- Other Gas: 0.4%
- Other: 0.1%
Converting to Electricity

• Replacing Gasoline with Electricity
• 390 Million Gallons per Day
  – ~13,000,000 MWh of Energy
• 11,388,342 MWh produced in US Daily
• 24,000,000 MWh System Capacity @ Plant

Would Need to Double PowerPlant Capacity
Grid Power Peaking

- Use Smart Charges to Power Grid during Power Spikes

- Charge Car During Power Lull
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Charging Issues

• 10 kWh Pack Charge Time for:
  – 50 amp, 240 Volt Outlet  15 amp, 110 Volt Outlet
  – 90% Charging Efficiency

• ~ 1 Hour  ~ 6 Hours

• Battery Limits Process
  – Thermal Limits
  – Hydrogen Out-gassing Precautions
Hydrogen

- Zero Carbon Energy Carrier
- Can Resolve Local Emission Issues
- May Increase Overall Global Greenhouse Gas Emissions
- Ultimately, as GM quotes – “We want to remove the automobile from the energy equation”
- Ultimately, Hydrogen has to be from Renewable Energy
Issues with Hybrid Powertrains

- Must pay for two powertrains
  - incremental cost is not offset by increased fuel economy - even at $3.00 per gallon
- There is added complexity, weight, serviceability and volume with hybrid
- Powertrain must be optimized for a particular driving cycle - may lend itself to known fleet use
- Operator needs to be more engaged in understanding the powertrain limitations
Fuel Cell Vehicles

• Heavy
  – Fuel Cell Constructed of Metal Grids
• Noisy
  – Need to Humidify Air
  – Compressors & Fans to Feed Fuel Stack
• Expensive
  – Currently > $1000 per Horsepower
Issues with Fuel Cell Vehicles

- The local exhaust emission can be very low

- Two modes of getting hydrogen on the vehicle
  - Direct on board storage
    - Issues: range, safety - may not be a problem with fleet operation
  - On board reforming of HC fuel
    - Infrastructure exists and no range problem
    - Extremely complicated system.
Issues with Fuel Cells

- They are expensive - currently a factor of 5
  - Tremendous progress is being made in cost reduction
- You need hydrogen
  - Most readily available hydrogen in attached to carbon - HC fuels - oil and gas
- Need a technology to generate hydrogen from HC fuels - reforming of HC to \( \text{H}_2 \)
  - Need for “wells to wheels” analysis