Emerging Technologies of Hybrid Electric Vehicles

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Presentation Outline

• Introduction to HEV
• Popular HEV designs
• Planetary gear architecture and its power split principle
• More complex HEV involves planetary gears
• Speed and torque coupling principle
• Energy storage challenges
• Power electronics challenges
• Other Challenges and Opportunities
  – Plug-in HEV and what it means
  – Diesel vehicle and diesel HEV
  – Emerging issues in HEV
  – New opportunities in HEV related fields
Part I

Introduction to Hybrid Electric Vehicles

What Hybrids Are Available in 2007?

- Honda Accord Hybrid
- Honda Civic Hybrid
- Ford Escape Hybrid
- GMC Silverado Hybrid
- GMC Sierra Hybrid
- Toyota Prius
- Toyota Highlander Hybrid
- Lexus 400h
- Mazda Tribute Hybrid
- Mercury Mariner Hybrid
- Lexus GS 450h
- Saturn VUE Green Line
2006 Hybrid Sales Figure

- Honda Accord: 5,598
- Honda Civic: 31,253
- Honda Insight: 722
- Ford Escape Hybrid: 19,228
- Mercury Mariner Hybrid: 3,375
- Toyota Camry Hybrid: 27,336 (excludes December 2006 sales; on sale April 2006)
- Toyota Prius: 106,971
- Toyota Highlander: 31,485
- Lexus RX 400h: 20,16
- Lexus GS 450h: 513 (Excludes October-December 2006 sales; on sale April 2006)
- TOTAL: 246,642*

http://www.electricdrive.org/index.php?tg=articles&idx=Print&topics=7&article=692

2007 Hybrid Sales Figure (through March)

- Honda Accord: 945
- Honda Civic: 6,520
- Lexus RX400h: 3,965
- Toyota Camry: 11,277
- Toyota Highlander: 4,393
- Toyota Prius: 39,682
- Total for the vehicles above: 66,782
- 2000: 9,367
- 2001: 20,287
- 2002: 35,961
- 2003: 47,525
- 2004: 83,153
- 2005: 209,711
- 2006: 246,642

http://www.electricdrive.org/index.php?tg=articles&idx=Print&topics=7&article=692
2007 HEV Sales (Through August)

- Ford Escape: 11,444 (through June 2007)
- Honda Accord: 2,579
- Honda Civic: 21,736
- Honda Insight: 3
- Lexus RX400h: 11,214
- Nissan Altima: 1,984 (through June 2007)
- Mercury Mariner: 868 (May and June 2007 sales only)
- Saturn VUE: 3,969 (through May 2007 only)
- Toyota Camry: 36,683
- Toyota Highlander: 13,707 (through July 2007)
- Toyota Prius: 124,620
- Total for the vehicles above: 228,807

What is HEV

- HEV – Stands for Hybrid Electric Vehicle
- An HEV is a vehicle which involves multiple sources of propulsions
  - An EV is an electric vehicle, battery (or ultra capacitor, fly wheels) operated only. Sole propulsion by electric motor
  - A fuel cell vehicle is a series hybrid vehicle
  - A traditional vehicle has sole propulsion by ICE or diesel engine
  - Energy source can be gas, natural gas, battery, ultra capacitor, fly wheel, solar panel, etc.
Types of HEV

• According to the method the energy sources are arranged
  – Parallel HEV: multiple propulsion sources can be combined, or drive the vehicle alone with one of the energy sources
  – Series HEV: sole propulsion by electric motor, but the electric energy comes from another on board energy source, such as ICE

Types of HEV

• Continued …
  – Simple HEV, such as diesel electric locomotive, energy consumption is not optimized; are only designed to improve performance (acceleration etc.)
  – Complex HEV: can possess more than two electric motors, energy consumption and performance are optimized, multimode operation capability
  – Heavy hybrids – trucks, locomotives, diesel hybrids, etc.
Types of HEV

- According to the onboard energy sources
  - ICE hybrids
  - Diesel hybrids
  - Fuel cell hybrids
  - Solar hybrids (race cars, for example)
  - Natural gas hybrids
  - Hybrid locomotive
  - Heavy hybrids

Why HEV?
To Overcome the Disadvantage of Pure EV and Conventional Vehicles

Key Drawbacks of Battery EVs

- High Initial Cost
  - Many times that of conventional vehicles

- Short Driving Range
  - Less miles during each recharge
  - People need a vehicle not only for commuting (city driving), but also for pleasure (long distance highway driving)
Key Drawbacks of Battery EVs

• Recharging takes much longer time than refueling gasoline
  – unless infrastructure for instantly replaceable battery cartridges are available (something like home BBQ propane tank replacing)

• Battery pack takes space and weight of the vehicle which otherwise is available to the customer

Key Drawbacks of ICE Vehicles

• High energy consumption: resources, independent of foreign oil

• High emission, air pollution, global warming

• High maintenance cost

• Environmental hazards

• Noisy
Key Advantages of HEV’s

- Optimize the fuel economy
  - Optimize the operating point of ICE
  - Stop the ICE if not needed (ultra low speed and stops)
  - Recover the kinetic energy at braking
  - Reduce the size (hp and volume) of ICE

- Reduce emissions
  - Minimize the emissions when ICE is optimized in operation
  - Stop the ICE when it’s not needed
  - Reduced size of ICE means less emissions

Key Advantages of HEVs - continued

- Quiet Operation
  - Ultra low noise at low speed because ICE is stopped
  - Quiet motor, motor is stopped when vehicle comes to a stop, with engine already stopped
Key Advantages of HEVs - continued

• Reduced maintenance because ICE operation is optimized, less hazardous material, Less maintenance cost
  – fewer tune ups, longer life cycle of ICE
  – fewer spark-plug changes
  – fewer oil changes
  – fewer fuel filters, antifreeze, radiator flushes or water pumps
  – fewer exhaust repairs or muffler changes

Key Concerns of HEVs

• High initial cost
  – Increased components such as battery, electric machines, motor controller, etc.
• Reliability concern
  – Increased components, especially power system, electronics, sensors
• Warranty issues
  – Issues on major electric components
  – Dealership and repair shop not familiar with new components
• Safety: high voltage system employed in HEV
• EMC Vulnerability
Architectures of HEV

Series hybrid
- Fuel tank
- IC engine
- Generator
- Power converter
- Electric motor
- Battery
- Transmission

Parallel hybrid
- Fuel tank
- IC engine
- Transmission
- Battery
- Power converter
- Electric motor

Series-parallel hybrid
- Fuel tank
- IC engine
- Generator
- Power converter
- Electric motor
- Battery
- Transmission

Complex hybrid
- Fuel tank
- IC engine
- Transmission
- Electric motor
- Battery
- Power converter

Electrical link
Hydraulic link
Mechanical link

Series Architecture

Fuel tank
- Engine
- Generator
- Rectifier
- Motor controller
- Traction motor
- DC/DC
- Battery
- Battery charger

Vehicle speed
Traction
Engine operating region
Power
Speed
Vehicle speed
Traction
Battery charge
Parallel Architecture

- Two energy converters
- Engine and motor mechanically coupled
- Different configurations possible

Part II

Popular HEV Designs
### Toyota Prius (2005)

**Engine:** 1.5 L 4-cylinders DOHC
57 kW / 110 Nm

**Motor:** DC Brushless 500 V
50 kW / 400 Nm

<table>
<thead>
<tr>
<th>EPA MPG</th>
<th>1.8L AT Corolla</th>
<th>HEV</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>City</td>
<td>30</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Highway</td>
<td>38</td>
<td>51</td>
<td>34</td>
</tr>
</tbody>
</table>

**Note**
- Corolla 1.8L 130 HP 4-speed AT
- Echo 1.5L 108 HP 4-speed AT
- 33/39 City/Highway MPG

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### Toyota Highlander

**Engine:** 3.3 L 6-cylinders DOHC
155 HP(5600rpm)
283Nm (4400rpm)

**Motor:** PM 123kW@4500rpm (MG2)
330Nm @0-1500rpm front
50 kW@5120rpm Rear
650V

<table>
<thead>
<tr>
<th>EPA MPG</th>
<th>Conventional</th>
<th>HEV</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>City</td>
<td>18</td>
<td>31</td>
<td>72%</td>
</tr>
<tr>
<td>Highway</td>
<td>24</td>
<td>27</td>
<td>12.5</td>
</tr>
</tbody>
</table>

**Note**
- Conventional comparison base is, V6 and 4X4,
- 215hp @5600rpm, 222lb.ft @3600rpm
- V4 MPG 2WD is 22/27, engine 155hp HEV 2WD, MPG is 33/28
Honda Civic

Engine: 1.34L 85 HP (63 kW) / 119 Nm
Motor: PM DC Brushless
10 kW / 62 Nm Assist
12.6 kW / 108 Nm Regen

EPA MPG AT BL CVT HEV Gain (%)
City 29 48 66
Highway 38 47 24

Honda Accord

Engine: 3.0 L VTEC V6
179kW / 290Nm
w/ Variable Cylinder Management (VCM) system
Trans: New 5-Speed AT
Motor: DC Brushless
12 kW / 74 Nm Assist
14 kW / 123 Nm Regen

EPA MPG AT BL AT HEV Gain (%)
City 21 30 43
Highway 30 37 23

Note BL Engine: 1.7L 115 HP/110lb-ft
Trans: 4-Speed AT
IMA ---- Integrated Motor Assist
Motor start/stop engine, 12V start for jump start


Nissan Tino – 2004 Production Model

Engine: 1.8 L 4-cylinders DOHC
73kW
Motor: DC Brushless 350 V
17 kW / Nm

<table>
<thead>
<tr>
<th>BL</th>
<th>HEV</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1015 MPG</td>
<td>23km/l</td>
<td></td>
</tr>
</tbody>
</table>

Ford Escape

Engine: 2.3 L Inline 4-Cylinder
99kW / 172Nm
Motor: PM 330 V
70 kW

EPA MPG
<table>
<thead>
<tr>
<th>BL 1</th>
<th>AT HEV</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22/25 City/Highway MPG</td>
<td>22/25 City/Highway MPG</td>
<td></td>
</tr>
</tbody>
</table>

Note
BL 1 3.0L 200 HP 4-speed AT
BL 2 2.3L 153 HP 4-speed AT

http://www.fordvehicles.com/suvs/escapehybrid/features/specs/
GM Hybrid Vehicles

GM Hybrid Portfolio Evolution

Offering a new, scalable strong hybrid architecture

<table>
<thead>
<tr>
<th>Year</th>
<th>Vehicle</th>
<th>Fuel Economy Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>GM Allison Hybrid Bus System</td>
<td>up to 60%</td>
</tr>
<tr>
<td>2003/2004</td>
<td>FAS Full-size truck</td>
<td>10-12%</td>
</tr>
<tr>
<td>2006</td>
<td>BAS/CVT VUE</td>
<td>12-15%</td>
</tr>
<tr>
<td>2007</td>
<td>BAS/CVT Malibu</td>
<td>12-15%</td>
</tr>
<tr>
<td>2007</td>
<td>AHS II Full-size SUV</td>
<td>25-35%</td>
</tr>
<tr>
<td>2008</td>
<td>AHS II Full-size truck</td>
<td>25-35%</td>
</tr>
</tbody>
</table>

NET: Three hybrid systems
12 models
Potential for one million vehicles by 2007

The Allison Hybrid Powertrain System

<table>
<thead>
<tr>
<th>Model</th>
<th>E*40</th>
<th>E*50</th>
<th>E*60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Transit Bus</td>
<td>Sub. Coach</td>
<td>Articulated Bus</td>
</tr>
<tr>
<td>DPIM</td>
<td>430-900 VDC 160 kW 3-phase AC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>968 lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Pwr</td>
<td>280 hp</td>
<td>330 hp</td>
<td>330 hp</td>
</tr>
<tr>
<td>Max In Trq</td>
<td>910 lb-ft</td>
<td>1050 lb-ft</td>
<td>1050 lb-ft</td>
</tr>
<tr>
<td>Rated In Spd</td>
<td>2300 rpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accel Power</td>
<td>350 hp</td>
<td>400 hp</td>
<td>400 hp</td>
</tr>
<tr>
<td>Battery</td>
<td>NiMH 330V (Panasonic)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controller</td>
<td>Two AT1000/2000/2400 controller</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Performance Change

- MPG*: ~ 60%
- PM: ~ 90%
- NOx: ~ 50%
- HC: ~ 90%
- CO: ~ 90%

* Advertised Numbers — Over CBD14 Cycle
Series ISE Hybrid

Eaton Hybrid System for Commercial Trucks

<table>
<thead>
<tr>
<th></th>
<th>BL</th>
<th>HEV</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPG*</td>
<td>9.3</td>
<td>13.42</td>
<td>45%</td>
</tr>
<tr>
<td>PM</td>
<td>0.158</td>
<td>0.0112</td>
<td>93%</td>
</tr>
<tr>
<td>NOx</td>
<td>12.9</td>
<td>5.8984</td>
<td>54%</td>
</tr>
<tr>
<td>HC</td>
<td>0.02</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>CO2</td>
<td>1103</td>
<td>758</td>
<td>31%</td>
</tr>
<tr>
<td>CO</td>
<td>1.89</td>
<td>0.7352</td>
<td>60%</td>
</tr>
<tr>
<td>0–60</td>
<td>32.2</td>
<td>30</td>
<td>7%</td>
</tr>
<tr>
<td>Grade</td>
<td>4%</td>
<td>5.1%</td>
<td>28%</td>
</tr>
</tbody>
</table>

* Over the FedEx cycle, a modified FTP cycle

Engine: 4.3 L 4-cylinders Diesel
        127kW / 560Nm
Motor: PM DC 340 V
       44 kW / 420 Nm
**Hino 4T Ranger HEV**

- **Engine**: J05D-TI<JS-JA> 4.73 L 4-cyl. Diesel
  - 177 HP (132 kW) / 340 lb-ft (461 Nm)
- **Motor**: Induction AC 23 kW
- **Battery**: 274V NiMH 6.5 Ah

**Performance Change**

<table>
<thead>
<tr>
<th></th>
<th>BL</th>
<th>HEV</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPG</td>
<td></td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>PM</td>
<td></td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td>NOx</td>
<td></td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td></td>
<td>17%</td>
<td></td>
</tr>
</tbody>
</table>

**Note**

- BL Engines
  - 199 kW / 797 Nm, 177 kW / 716 Nm
  - 165 kW / 657 Nm, 162 kW / 574 Nm
  - 154 kW / 588 Nm, 132 kW / 490 Nm

**HIMR ---- Hybrid Inverter Controlled Motor & Retarder System**

The HIMR system has already been installed in more than 100 vehicles (trucks and buses) operated mainly in major cities and state parks.

http://www.hino.co.jp/e/info/news/ne_20040421.html

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**Nissan Condorr 2003 Prototype**

- **Vehicle**: Wheelbase 172 in; Curb 10100 lbs; Payload 7000 lbs
- **Engine**: 6.93 L 6-Cylinders Diesel
  - 152kW @ 3000 / 493Nm @ 1400 rpm
- **Motor**: PM AC
  - 55 kW @ 4060 ~ 9000 rpm / 130 N @ 1400 rpm
- **Ultracap**: 346 V 60kW 583 Wh 384-cell 6.3 Wh/kg
  - 1105 x 505 x 470 mm from Okamura Laboratory

**Performance**

<table>
<thead>
<tr>
<th></th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPG*</td>
<td>50%</td>
</tr>
<tr>
<td>CO₂</td>
<td>33%</td>
</tr>
</tbody>
</table>

* Cycle unknown

http://www.sae.org/automag/globalvehicles/12-2002
Saturn VUE Green Line Hybrid System

Part III

Planetary Gear and Its Power Split and e-CVT Principle
Planetary Gear Train

• Speed relationship
  – Number of teeth of sun gear $N_s$
  – Number of teeth of ring gear $N_r$
  – Angular speed $\omega_s$, $\omega_r$, $\omega_c$
  – (c-carrier, r-ring gear, s-sun gear)

\[
\omega_c = \frac{N_r}{N_r + N_s} \omega_r + \frac{N_s}{N_r + N_s} \omega_s
\]

Planetary Gear Train

• Torque relationship
  – Neglect losses
  – $P = T \omega$
  – Use $T_c$, $T_r$ and $T_s$
  – (c-carrier, r-ring gear, s-sun gear)

\[
T_c \omega_c = T_s \omega_s + T_c \omega_s
\]

\[
T_c = \frac{N_r}{N_r + N_s} T_c
\]

and

\[
T_s = \frac{N_s}{N_r + N_s} T_c
\]

• Therefore fixed torque split between sun gear and ring gear,
  – Neglect losses
Planetary Gear Train

- Tc: Carrier input torque
  - \(\omega_s\) can be controlled

\[
T_c \omega_c = T_r \omega_r + T_s \omega_s \\
\text{or}
\]

\[
P_c = P_r + P_s \\
\therefore P_r = \frac{N_r}{N_r + N_s} \omega_s T_c \\
\text{and}
\]

\[
P_s = \frac{N_s}{N_r + N_s} \omega_s T_c
\]

- Varying speed of sun gear will change the power split between the two gears
- For example,
  - if \(\omega_s=0\), then \(P_r=P_c\)
  - Where \(\omega_s\) is controlled through other device

The Toyota Prius Hybrid System

[Diagram of the Toyota Prius Hybrid System]

Planetary gear set (power split device)

- Four-cylinder engine
- Drive train
- Ring gear (motor and output axle)
- Sun gear (generator)
- Planetary carrier (engine)
Example

- Engine (carrier), provides 100kW, at 2000rpm optimum operating point
- Ring gear 72 teeth, sun gear 30 teeth
- Vehicle speed 45 mph or 20.6m/s ring gear (motor, through final drive ratio 3.7865, and wheel radius 0.283m) speed of 45*58.5=2632rpm
- Therefore, sun gear (generator) speed needs to be 482rpm

\[
\omega_c = \frac{N_r}{N_r + N_s} \omega_r + \frac{N_s}{N_r + N_s} \omega_s
\]

\[
= \frac{72}{72 + 30} \omega_r + \frac{30}{72 + 30} \omega_s
\]

\[
= 0.706\omega_r + 0.294\omega_s
\]

\[
\omega_s = (\omega_r - 0.706\omega_c) / 0.294
\]

\[
= (2000 - 0.706 * 2632) / 0.294
\]

\[
= 482\text{rpm}
\]
Example

- Torque:
  - Engine (carrier):
  - Ring gear:
  - Generator (sun gear)

- Power:
  - Engine (carrier):
  - Ring gear:
  - Generator (sun gear)

\[
T_e(\text{engine}) = \frac{P_{\text{engine}}}{\omega_{\text{engine(carrier)}}} = 477 \text{ Nm}
\]

\[
T_e(\text{Ring gear}) = \frac{N_s}{N_s + N_r} \cdot T_c = 0.706 \times 477 = 337 \text{ Nm}
\]

\[
T_e(\text{generator}) = \frac{N_s}{N_s + N_r} \cdot T_c = 0.294 \times 477 = 140 \text{ Nm}
\]

\[
P_e(\text{engine}) = 100 kW
\]

\[
P_e(\text{Ring gear}) = T_e \cdot \omega_c = 337 \times 2 \times \pi \times 2632 / 60 = 92.9 kW
\]

\[
P_e(\text{generator}) = T_e \cdot \omega_c = 140 \times 2 \times \pi \times 482 / 60 = 7.1 kW
\]

\[
P_e(\text{engine}) = P_e(\text{ring gear}) + P_e(\text{generator})
\]

Further

- If vehicle needs 120kW of power, then motor power is \( P_{\text{veh}} - P_{\text{ring}} = 120 - 92.9 = 27.1 \text{kW} \)
- \( P_{\text{bat}} = P_{\text{motor}} - P_{\text{generator}} = 27.1 - 7.1 = 20 \text{kW} \)

- You can see here \( P_{\text{engine}} + P_{\text{bat}} = P_{\text{vehicle}} \)
Power Flow

• Starting and low speeds (up to 20mph)
  - ICE off
  - Motor drives the vehicle
  - Battery supplies the needed power

Power Flow

• Sudden Acceleration
Power Flow

- Normal Driving
  - ICE power is split
  - CVT is achieved
  - Parallel and series functions
- Parallel paths
  - ICE → final drive
  - Motor → final drive
- Series path:
  - ICE → G → Motor

Power Flow

- Braking
  - ICE is off
Power Flow

- Stationary Charging

2004 Prius Powertrain
Generator Rotor

Motor Assembly
Power Converter

![Power Converter Image]

Power Converter Packaging

![Power Converter Packaging Diagram]
2006 Mercury Mariner Hybrid

- I4 Gasoline Engine w/ Atkinson Cycle
- Nickel-Metal Hydride Battery
- Electric Transaxle
- Vehicle System Controller (VSC)
- Super Ultra Low Emissions (AT-PZEV)
- Electric Power Assisted Steering (EPAS)
- Series Regenerative Braking

MARINER HYBRID POWER FLOW
ATKINSON CYCLE ENGINE

- **2.3L I4 Gasoline Engine**
  - Atkinson Cycle to Improve Thermal Efficiency
  - 12.3 Compression Ratio
  - 99 Kw (133 HP) @ 6000 RPM
  - 168 Nm (124 ft-lb) @ 4250 RPM

- **Electronic Throttle Control**

- **Advance EVAP & Tailpipe Emission Control Systems**
  - Meets AT-PZEV emissions in California
  - Meets T2B3 Federally

---

**OTTO VS. ATKINSON ENGINE**

*Otto Cycle*

*Atkinson Cycle*

[Diagram showing Otto Cycle and Atkinson Cycle with labeled components: Compression, Expansion, Late Intake Valve closure]
PV COMPARISON

Expansion

Compression

LIVC

Otto Cycle

Atkinson Cycle

Log P

Log V

TORQUE COMPARISON

Engine Speed (RPM)

Engine Torque (Nm)

Otto Cycle

Atkinson Cycle
POWER SPLIT TRANSMISSION

- **Electro-Mechanical CVT with Electric Drive Capability**
  - 45 kW Permanent Magnet AC Generator/Motor
  - 70 kW Permanent Magnet AC Traction Motor
  - Planetary Gear and Final Drive Gears
  - Integrated Power Electronics/Voltage Inverter

- **Capable of Front-Wheel & All-Wheel Drive**

THE VSC (BRAIN) COORDINATES THE SYSTEM RESPONSE
POWER SOURCES FOR ACCELERATION

ACCELERATION CURVE COMPARISON
The 2007 Camry Hybrid

- Inverter
- Hybrid Battery
- 12V Battery
- Hybrid Transaxle
- Vapor-Containment Fuel Tank

2AZ-FXE 2.4L 4-cylinder

- Intake Camshaft
- Exhaust Manifold
- Piston
- Belt Layout*

* No belt-drive for PS pump or A/C compressor
2AZ-FXE Atkinson Engine

- Variant of std Camry 2.4L 2AZ-FE
  - Expansion Ratio - 12.5:1 / Compression Ratio - 9.6:1
  - Revised piston, exhaust manifold, serpentine belt layout
  - Atkinson combustion cycle increases efficiency
  - Revised intake camshaft
  - Reduced pumping losses compared to Otto cycle
- Output = 147 Hp (110 KW)

Hybrid Transaxle P311
Hybrid Transaxle

-1” (25mm)

Two Planetary System
Hybrid System Components

- **Two motor/generators**
  - MG1 (blue) is connected to ICE
    - acts primarily as a generator
    - also as a motor for speed control, engine starting
    - driven by 3-phase current up to 650VAC
    - speeds up to 13,000 rpm
    - water/oil-cooled permanent magnet
  - MG2 (red) connects directly to final drive
    - acts primarily as a motor
    - also as a generator for regenerative braking
    - driven by 3-phase current up to 650VAC
    - Peak speed = 14,500 rpm
    - water/oil-cooled permanent magnet
- **No clutches, bands, valves, or hydraulics**

- **Power Split Planetary Gear Set**
  - Sun gear connected to MG1 (Generator)
  - Planet carrier connected directly to engine
  - Ring gear connected to counter gear
  - 72/28% ring/sun engine torque split
- **Speed Reduction Planetary Gear Set**
  - Sun gear connected to MG2 (Motor)
  - Carrier grounded
  - Ring gear connected to counter gear
  - Speed reduction/torque increase: 2.478:1

- **Multifunction Gear**
  - Combines power split planetary gear set ring & speed reduction planetary gear set ring
  - Incorporates parking gear and counter drive gear

---

**Inverter**
Inverter Ratings

- **Inverter**
  - Next generation inverter
  - More compact & lighter than Prius or Hybrid SUV inverter
  - Converts High-Voltage DC to AC
  - Located under the hood, drivers side
  - Converts DC to 3-phase AC to drive MG1 and MG2
  - Controlled by Hybrid ECU
  - Boost converter raises 244V DC up to 650V DC
  - MG ECU is packaged within inverter assembly
  - Reduced mass: ~40%
  - Reduced volume: ~60%

Battery Pack Assembly

- 34 Ni-MH (Nickel Metal Hydride) modules
  - Each module is 7.2V DC (1.2V X 6 cells)
  - Total 244V DC
  - Total power: 30kW
- Includes battery, battery ECU, SMRs & service plug
- DC-DC converter moved to the battery pack
- DC/DC converter transforms 244V DC to 12V DC for auxiliary items and to charge the auxiliary battery
Power Delivery – Conventional

30-50 Acceleration

Acceleration

Time

Gas
Power Delivery - Hybrid

30-50 Acceleration

Fast Start

Smooth

Hybrid Gas

Acceleration

Time

Hybrid Synergy Drive

Diagram showing the components of a hybrid synergy drive system.
Part IV

More Complex HEV Involves Planetary Gears

Dual Clutch AMT Based HEV Powertrain
GM Two Mode Hybrid

GM Two-Mode Hybrid Variation
A More Complex Parallel Hybrid Drivetrain

1. Sun of both PGT
2. Carrier of input PGT
3. Final Drive
4. Output ring
5. Final Drive
6. Output carrier
7. Input ring

- Please read reference by Tsai

More Complex Parallel Hybrid

- Please read reference by Zhang, etc.
Torque and Speed Coupled Parallel Hybrid

Timken Two-Mode HEV Variation

Read more, HEV book by Ehsani
Renault HEV Powertrain

Toyota Highlander – The Toyota e-Four System

**Engine:** 3.3 L 6-cylinders DOHC
155 HP (5600rpm)
283Nm (4400rpm)

**Motor:** PM 123kW@4500rpm (MG2)
330Nm @0-1500rpm front
50 kW@5120rpm Rear
650V

<table>
<thead>
<tr>
<th>EPA MPG</th>
<th>Conventional</th>
<th>HEV</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>City</td>
<td>18</td>
<td>31</td>
<td>72%</td>
</tr>
<tr>
<td>Highway</td>
<td>24</td>
<td>27</td>
<td>12.5</td>
</tr>
</tbody>
</table>

*Note: Conventional comparison base is, V6 and 4X4, 215hp @5600rpm, 222lb.ft @3600rpm
V4 MPG 2WD is 22/27, engine 155hp HEV 2WD, MPG is 33/28*
To Read on Complex HEV


References (continued)

Part V

Speed and Torque Coupling Principle

Torque Coupling

- Splits engine torque
- Or combine engine torque and motor torque
- Regenerative braking

\[ T_{\text{out}} = k_1 T_1 + k_2 T_2 \]

\[ \omega_{\text{out}} = \frac{\omega_1}{k_1} = \frac{\omega_2}{k_2} \]
## Commonly Used Torque Coupling

<table>
<thead>
<tr>
<th>Gear Box</th>
<th>Pulley or chain assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{in}} = \frac{\omega_{\text{in}}}{\omega_{\text{out}}}$</td>
<td>$T_{\text{in}} = \frac{\omega_{\text{in}}}{\omega_{\text{out}}}$</td>
</tr>
<tr>
<td>$T_{\text{rot}} = \frac{\omega_{\text{rot}}}{\omega_{\text{rot}}}$</td>
<td>$T_{\text{rot}} = \frac{\omega_{\text{rot}}}{\omega_{\text{rot}}}$</td>
</tr>
<tr>
<td>$k_i = \frac{z_i}{z_i}$, $k_j = \frac{z_j}{z_j}$</td>
<td>$k_i = \frac{z_i}{z_i}$, $k_j = \frac{z_j}{z_j}$</td>
</tr>
<tr>
<td>$z_p, z_s, z_r$—Tooth number of the gears</td>
<td>$z_p, z_s, z_r$—Tooth number of the gears</td>
</tr>
</tbody>
</table>

- Gear box
- Chain assembly
- Shaft

## Two Transmission Design

- Flexibility in design
- Complex two transmissions
Two Shaft Design – torque before transmission

- One transmission design

Separated Axle Configuration
Speed Coupling

- Splits engine torque
- Combines engine speed and motor speed
- Regenerative braking

\[ \omega_{\text{out}} = k_1 \omega_1 + k_2 \omega_2 \]

\[ T_{\text{out}} = \frac{T_1}{k_1} = \frac{T_2}{k_2} \]
Reference

Part VI

Energy Storage Challenges

Energy Source, Energy Converter, and Energy Storage

• Energy source refers to a source of energy, such as gasoline, hydrogen, natural gas, coal, etc. (sometimes called energy carrier)
• Renewable energy source refers to solar, wind, and geothermal, etc.
• Energy converter refers to converting energy from one form of energy source to another form, such as electric generator, gasoline/diesel engine, fuel cell, wind turbine, solar panel, etc.
• Energy storage refers to intermediate devices for temporary energy storing, such as battery, water tower, ultra-capacitor, and flywheel.
Comparison of Energy Sources/storage

<table>
<thead>
<tr>
<th>Energy source/storage</th>
<th>Nominal Energy Density (Wh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>12,300</td>
</tr>
<tr>
<td>Natural gas</td>
<td>9,350</td>
</tr>
<tr>
<td>Methanol</td>
<td>6,200</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>28,000</td>
</tr>
<tr>
<td>Coal (bituminous)</td>
<td>8,200</td>
</tr>
<tr>
<td>Lead-acid battery</td>
<td>35</td>
</tr>
<tr>
<td>Sodium-sulfur battery</td>
<td>150-300</td>
</tr>
<tr>
<td>Flywheel (steel)</td>
<td>12-30</td>
</tr>
</tbody>
</table>

Battery Types

- Primary Battery
  - Cannot be recharged. Designed for a single discharge
- Secondary Battery
  - Batteries that can be recharged by flowing current in the direction opposite of discharge
    - Lead-acid (Pb-acid)
    - Nickel-cadmium (NiCd)
    - Nickel-metal-hydride (NiMH)
    - Lithium-ion (Li-ion)
    - Lithium-polymer (Li-poly)
    - Sodium-sulfur
    - Zinc-air (Zn-Air)

Secondary batteries are primary topic for HEV/EV’s
### A Comparison of Batteries

<table>
<thead>
<tr>
<th>System</th>
<th>Specific energy (Wh/kg)</th>
<th>Peak power (W/kg)</th>
<th>Energy efficiency (%)</th>
<th>Cycle life</th>
<th>Self-discharge (% per 48h)</th>
<th>Cost (US$/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acidic aqueous solution</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead/acid</td>
<td>35-50</td>
<td>150-400</td>
<td>&gt;80</td>
<td>500-1000</td>
<td>0.6</td>
<td>120-150</td>
</tr>
<tr>
<td><strong>Alkaline aqueous solution</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel/cadmium</td>
<td>50-60</td>
<td>80-150</td>
<td>75</td>
<td>800</td>
<td>1</td>
<td>250-350</td>
</tr>
<tr>
<td>Nickel/iron</td>
<td>50-60</td>
<td>80-150</td>
<td>75</td>
<td>1500-2000</td>
<td>3</td>
<td>200-400</td>
</tr>
<tr>
<td>Nickel/zinc</td>
<td>55-75</td>
<td>170-260</td>
<td>65</td>
<td>300</td>
<td>1.6</td>
<td>100-300</td>
</tr>
<tr>
<td>Nickel/Metal Hydride</td>
<td>70-95</td>
<td>200-300</td>
<td>70</td>
<td>750-1200+</td>
<td>6</td>
<td>200-350</td>
</tr>
<tr>
<td>Aluminum/air</td>
<td>200-300</td>
<td>160</td>
<td>&lt;50</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Iron/air</td>
<td>80-120</td>
<td>90</td>
<td>60</td>
<td>500+</td>
<td>?</td>
<td>50</td>
</tr>
<tr>
<td>Zinc/air</td>
<td>100-220</td>
<td>50.80</td>
<td>60</td>
<td>600+</td>
<td>?</td>
<td>90-120</td>
</tr>
<tr>
<td><strong>Flow</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc/bromine</td>
<td>70-85</td>
<td>90-110</td>
<td>65-70</td>
<td>500-2000</td>
<td>?</td>
<td>200-250</td>
</tr>
<tr>
<td>Vanadium redox</td>
<td>20-30</td>
<td>110</td>
<td>75-85</td>
<td>-</td>
<td>-</td>
<td>400-450</td>
</tr>
<tr>
<td><strong>Molten salt</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium/sulfur</td>
<td>150-240</td>
<td>230</td>
<td>80</td>
<td>800+</td>
<td>0*</td>
<td>250-450</td>
</tr>
<tr>
<td>Sodium/Nickel chloride</td>
<td>90-120</td>
<td>130-160</td>
<td>80</td>
<td>1200+</td>
<td>0*</td>
<td>230-345</td>
</tr>
<tr>
<td>Lithium/iron</td>
<td>100-130</td>
<td>150-250</td>
<td>80</td>
<td>1000+</td>
<td>?</td>
<td>110</td>
</tr>
<tr>
<td>Sulfide (FeS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Organic/Lithium</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithium-ion</td>
<td>80-130</td>
<td>200-300</td>
<td>&gt;95</td>
<td>1000+</td>
<td>0.7</td>
<td>200</td>
</tr>
</tbody>
</table>

* No self-discharge, may some energy loss by cooling

### Fuel Cells

- **Fuel**: hydrogen and oxygen
- **Concept**: Opposite of electrolysis
- **A catalyst speeds the reactions**
- **An electrolyte allows the hydrogen to move to cathode**
- **Flow of electrons from anode to cathode in the external circuit produces electricity**
- **Oxygen or air is passed over cathode**
Fuel Cell Reaction

- Anode: \[ H_2 \rightarrow 2H^+ + 2e^- \]
- Cathode: \[ 2e^- + 2H^+ + \frac{1}{2}(O_2) \rightarrow H_2O \]
- Cell: \[ H_2 + \frac{1}{2}O_2 \rightarrow H_2O \]

A fuel cell
## Fuel Cell Comparison

<table>
<thead>
<tr>
<th>Fuel Cell Variety</th>
<th>Fuel</th>
<th>Electrolyte</th>
<th>Operating Temperature</th>
<th>Efficiency</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphoric Acid</td>
<td>H₂, reformate (LNG, methanol)</td>
<td>Phosphoric acid</td>
<td>~200°C</td>
<td>40-50%</td>
<td>Stationary (&gt;250kW)</td>
</tr>
<tr>
<td>Alkaline</td>
<td>H₂</td>
<td>Potassium hydroxide solution</td>
<td>~80°C</td>
<td>40-50%</td>
<td>Mobile</td>
</tr>
<tr>
<td>Proton Exchange Membrane</td>
<td>H₂, reformate (LNG, methanol)</td>
<td>Polymer ion exchange film</td>
<td>~80°C</td>
<td>40-50%</td>
<td>EV/HEV, Industrial up to ~80kW</td>
</tr>
<tr>
<td>Direct Methanol</td>
<td>Methanol, ethanol</td>
<td>Solid polymer</td>
<td>90-100°C</td>
<td>~30%</td>
<td>EV/HEVs, small portable devices (1W-70kW)</td>
</tr>
<tr>
<td>Molten Carbonate</td>
<td>H₂, CO (coal gas, LNG, methanol)</td>
<td>Carbonate</td>
<td>600-700°C</td>
<td>50-60%</td>
<td>Stationary (&gt;250kW)</td>
</tr>
<tr>
<td>Solid Oxide</td>
<td>H₂, CO (coal gas, LNG, methanol)</td>
<td>Yttria-stabilized zirconia</td>
<td>~1000°C</td>
<td>50-65%</td>
<td>Stationary</td>
</tr>
</tbody>
</table>

## Ultra-Capacitors

- Electrochemical energy storage systems
- Devices that store energy as an electrostatic charge
- Higher specific energy and power versions of electrolytic capacitors
- Stores energy in polarized liquid layer at the interface between ionically conducting electrolyte and electrode
How an Ultra-Capacitor Works

Flywheels

- Electromechanical energy storage device
- Stores kinetic energy in a rapidly spinning wheel-like rotor or disk
- Has potential to store energies comparable to batteries
- All IC Engine vehicles use flywheels to deliver smooth power from power pulses of the engine
- Modern flywheels use high-strength composite rotor that rotates in vacuum

Energy = \frac{1}{2} CV^2
Flywheels

- A motor/generator connected to rotor shaft spins the rotor up to speed for charging and to convert kinetic energy to electrical energy during discharging.
- Drawbacks are: very complex, heavy and large for personal vehicles.
- There are safety concerns for a device that spins mass at high speeds.

Basic Structure

\[ \text{Energy} = \frac{1}{2} J \omega^2 \]
High Speed Flywheel Example

- High Speed Flywheel, 36,000 RPM
- High strength hub material, 4340 steel
- 1.25 kW-hr of Energy Storage
- 13.3 Wh/kg of energy to weight ratio
- 105 kW-hr/m³ of energy to volume ratio
- Bi-directional Power Electronics
- High efficiency, 92% includes electronics

Hybridization of Energy Storage

- Use multiple sources of storage
- Tackle high demand and rapid charging capability
- One typical example is to combine battery and ultracap in parallel

![Diagram of hybrid energy storage system](image)
Two Topologies of Hybridization

- Direct parallel connection
- Or through two quadrant chopper for better power management

Current Issues with NMH Batteries

- Efficiency
- Self Discharge
Current Issues with Lithium Battery

- **Cost**
  - Cost is above FreedomCAR targets
  - Raw materials & materials processing
  - Cell and module packaging
  - Electrical and mechanical safety devices

- **Abuse tolerance**
  - Overcharge
  - Crush
  - Short circuits

- **Life**
  - Calendar life

Part VII

Power Electronics Challenges
Emerging Issues

- Power losses and efficiency
- Reliability
- Novel thermal management technology
- Cost reduction with better power bus regulation
- EMC concerns
- Emerging and new semiconductor devices
- EMC due to power electronics switching and transmission
- Increased use of microcontrollers
- Increased of sensors
- Reliability
Power loss and conversion efficiency

- Power loss of semiconductor devices, especially switching power circuits, is a serious issue in the conversion efficiency, and thermal management is key design issue for many automotive electronics applications.
- New circuit topologies, such as cascade circuits, multilevel converters, soft switching, can significantly reduce the loss.
- Selecting the right switching devices is a complex trade-off.
- Peak vs. normal power operation dilemma: load leveling may help the design.

Non-ideal switching

- Creates switching loss.
- Creates EMC issue.
- Blanking time needed.

![Diagram of non-ideal switching](image)
Reliability

- A key element toward making electric propulsion more practical is the development of cost-effective, high efficiency, integrated power electronics modules.
- The reliability of these modules will be of paramount importance for the success of various EV/HEV concepts due to the critical safety concerns for drivers/passengers, stringent quality assurance requirements of vehicles and the extreme harsh under hood automotive environments.
- In addition, automotive electric drive train, due to their wide dynamic range of operation and diverse usage profiles, will likely impose a more stringent reliability requirement on the electronics than any other industrial electronics applications.
Failure Mechanism

- Elevated junction temperature (125°C normal operation, 150°C absolute max)
- Thermal mechanical stress and fatigue; wire bond lift off, solder joints crack, Si chip cracks, etc.
- Vibration
- Contamination
- Defects

Novel thermal management

- Dissipate heat from electronics is the most limiting factor for reliability (failure), cost, and compactness of the system
- The disparity between the peak load and average load operation of automotive power electronics severely lowers the hardware utilization and sets a limit on cost reduction and reliability enhancement
- Peak power load is typically several times higher than average load power, but only lasts for a short period of time ranging from a few tens of milliseconds to a few seconds, thus must be handled quickly
Phase changing material

- Transitions between solid, liquid, and gas phases typically involves large amount of energy compared to specific heat. For example, one gram of water absorbs 4 joules of heat to increase its temperature by 1 degree C, but amazingly, one gram of water absorbs 2260 joules of energy when vaporized even without any change in temperature.
- Phase change material can be used as a passive heat moderator in power electronics packages to level the peak load.

EMC Concerns

- EMC compliance is a major challenge for automotive power electronics systems.
- Large common mode inverter currents due to coupling paths to grounds through the motor and housing.
- Large dV/dt and di/dt while minimizing switching losses generated broadband radiated and conducted emissions.
- RF characteristics of power electronics semiconductors devices, especially bipolar types, are neither fully investigated nor considered in the EMC issues.
- Conducted immunity concerns, load dump, negative transients, etc.
Emerging Devices

• SiC
• JFET
• MOS-thristors
• Integrated Circuits
• New Materials

Silicon Carbide (SiC)

• Silicon carbide (SiC) is a ceramic compound of silicon and carbon.
• Wide band semiconductors material (SiC 3.3eV vs 1.12 eV Si)
• High electric Breakdown field (SiC 1.5-4e6V/cm vs Si 2-8e5 V/cm)

An electronvolt (symbol eV, or, rarely and incorrectly, ev) is the amount of kinetic energy gained by a single unbound electron when it passes through an electrostatic potential difference of one volt, in vacuum. The one-word spelling is the modern recommendation although the use of the earlier electron volt still exists.

One electronvolt is a very small amount of energy:

\[ 1 \text{ eV} = 1.602 \, 176 \, 53 \, (14) \times 10^{-19} \, \text{J} \]  
(Source: CODATA 2002 recommended values)

It is a unit of energy, accepted (but not encouraged) for use with SI.
Property of SiC

- High temperature operation
- High switching frequency
- Available devices include
  - Diodes
  - Power mosfets
  - Thyristors
  - BJT
  - IGBTs
  - CMOST devices

Challenges of SiC

- Material: 75-100mm bulk and epi wafers with low defect density at a reasonable price
- Oxide interface quality and reliability
- Ion implantation processes: high temperature implantation and annealing
- Sheet resistance and contact resistance for p-type SiC doping
- Companion Packing technology
Summary of Silicon Power Device Capabilities

New Semiconductor Materials for Power Devices

- Silicon not optimum material for power devices

- Gallium arsenide promising material
  - Higher electron mobilities (factor of about 5-6) - faster switching speeds and lower on-state losses
  - Larger band-gap $E_g$ - higher operating temperatures

- Silicon carbide another promising materials
  - Larger bandgap than silicon or GaAs
  - Mobilities comparable to Si
  - Significantly larger breakdown field strength
  - Larger thermal conductivity than Si or GaAs

- Diamond potentially the best materials for power devices
  - Largest bandgap
  - Largest breakdown field strength
  - Largest thermal conductivity
  - Larger mobilities than silicon but less than GaAs
On-State Resistance Comparison with Different Materials

- Specific drift region resistance of majority carrier device

\[ R_{on} \cdot A = \frac{4 q (B_D)^2}{e_m (B_D)^3} \]

- Normalize to silicon - assume identical areas and breakdown voltages

\[ \frac{R_{on(x)}}{R_{on(Si)}} \cdot A = \text{resistance ratio} = \frac{e_{Si}}{e_{x}} \left[ \frac{B_D, Si}{B_D, x} \right]^3 \]

- Numerical comparison

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1</td>
</tr>
<tr>
<td>GaAs</td>
<td>6.4x10^-2</td>
</tr>
<tr>
<td>SiC</td>
<td>9.6x10^-3</td>
</tr>
<tr>
<td>Diamond</td>
<td>3.7x10^-5</td>
</tr>
</tbody>
</table>

Part VIII

Other Challenges and Opportunities
Plug-in HEV

- With a bigger battery pack, vehicle can be driven on electric only range for 20 to 40 miles
- Further increase fuel economy
- Possible to make a portable battery pack
  - Charged overnight for commute driving (up to 100 miles)
  - Removed for long time driving (just like removable seats)
- Will have remarkable savings
- However, cost of battery will be an issue

Diesel HEV

- **Pros** —
  - Fuel economy
  - Durable
  - Familiar technology
  - Customer satisfaction
  - Less greenhouse gas
- **Cons** —
  - Pollution (NOx, soots)

- Diesel HEV will consist of diesel engine and electric motor
- All topology used for gasoline HEV are applicable to diesel HEV
- **Pros:**
  - Increased fuel economy
  - Reduced emission, particular cold start issues
- **Cons:** incremental cost will be large
Emerging Issues

- Power electronics technology
- Energy storage technology
  - Lithium-ion battery
  - Ultracapacitor
- Cooling technology
- Waste heat recovery
- Increased demand and further increase of oil price will push for high efficiency vehicles
- Global warming become significant

Opportunities

- China, India, and other developing countries, will surfer more from economic development
- Material, battery, power electronics, and associated industry will have impact of $300B market
- Traditional auto manufacturers will have to rethink their business model
  - Huge opportunities for EE engineers
Thank You!

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