Overview

- Introduce HEV fundamentals, design, control, modeling, and special topics.

- Cover vehicle dynamics, energy sources, electric propulsion systems, regenerative braking, parallel and series HEV design, and practical design considerations.
Outline

– Part 1: Introduction to Hybrid Electric Vehicles
– Part 2: HEV Fundamentals
– Part 3: HEV Modeling and Simulation
– Part 4: Energy Storage for HEV Applications
– Part 5: Series HEV Design and Modeling
– Part 6: Parallel HEV Design and Modeling
– Part 7: A Look into the Current Hybrids
– Part 8: Look at some novel topologies

Part 1:

Introduction to
Hybrid Electric Vehicles
Photo Gallery of EV/HEV

Chrysler Epic Minivan

![Image of Chrysler Epic Minivan]
Electric bus

Ford Electric Ranger
**Nissan Altra EV**

- ZEV certified (zero emission vehicle)
- Front-wheel Drive
- 2-Passenger
- Top Speed: 56 mph
- Range: 53 miles

**TH!NK Neighbor**

- ZEV certified
- Meets new U.S./Canadian federal standards for low speed vehicles
- Seats 2 or 4
- 4 wheel independent suspension
- Top Speed: 25 mph/Range: 30 miles
- Charges 110 AC in 6-hours

**TH!NK City**

- ZEV certified (zero emission vehicle)
- Front-wheel Drive
- 2-Passenger
- Top Speed: 56 mph
- Range: 53 miles
Toyota E-Com

Toyota RAV4
Toyota RAV4 EV

GM ATV
Honda EV PLUS

Solectria Corporation
Toyota Prius (1997)

Toyota Prius’ 03

_ how far will you go to save the planet?
about 566 miles per tank.*
Toyota Prius’ 05

Toyota Highlander
Toyota HEV Minivan’ 03

Ford Escape
Mercury Mariner

Focus Fuel Cell Vehicle (FCV).

Focus Fuel Cell vehicles available in 2004
Ford FCEV Vehicle Programs

1999
P2000 FCEV
Gaseous Hydrogen

2000
California Demo
Ford Focus
Gaseous Hydrogen

2001
Japan Demo
Mazda Premacy
Methanol

2002
Ford Focus
FCEV Hybrid
Gaseous Hydrogen

Honda Civic HEV
Honda Insight

Honda Accord HEV
Chrysler ESX2 HEV

Chrysler ESX3 HEV
HEV

• What is HEV
• Types of HEV
• Why HEV
• Key Advantage of HEV
• Up to Date Sales and Predictions of HEV
• Environmental Impacts of HEV
• Interdisciplinary Nature of HEV

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
  – 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

Current Status of HEV
Global Auto Market Production

In millions, source PriceWaterHouseCoopers, www.autofacts.com

Toyota HEV Program

Market Leader
### Current Hybrid Sales and Predictions in U. S.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Models</th>
<th>Units Sold</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>4</td>
<td>88,000</td>
</tr>
<tr>
<td>2005</td>
<td>10</td>
<td>200,000</td>
</tr>
<tr>
<td>2006</td>
<td>18</td>
<td>260,000</td>
</tr>
<tr>
<td>2010</td>
<td>30</td>
<td>500,000</td>
</tr>
</tbody>
</table>

Source: J. D. Power and Associates

### Toyota Hybrid Sales

Best-ever sales month in 48 years of business in the United States with total July sales of 216,417 vehicles, an increase of 12.3 percent (August 05)

<table>
<thead>
<tr>
<th>Date</th>
<th>Prius</th>
<th>Highlander</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/2005</td>
<td>7,889</td>
<td>2,353</td>
</tr>
<tr>
<td>1-7/2005</td>
<td>62,999</td>
<td></td>
</tr>
<tr>
<td>1-7/2004</td>
<td>27,103</td>
<td></td>
</tr>
<tr>
<td>07/2005</td>
<td>9,691</td>
<td>2,564</td>
</tr>
<tr>
<td>07/2004</td>
<td>5,230</td>
<td></td>
</tr>
<tr>
<td>2004 total</td>
<td>53,991</td>
<td></td>
</tr>
<tr>
<td>2003 total</td>
<td>24,627</td>
<td></td>
</tr>
</tbody>
</table>
Hybrids as Percentage of Total Light-Duty Vehicle Sales, July 2005

<table>
<thead>
<tr>
<th>Automaker</th>
<th>Hybrid</th>
<th>Total LDV</th>
<th>% Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota</td>
<td>14,157</td>
<td>216,417</td>
<td>6.7</td>
</tr>
<tr>
<td>Honda</td>
<td>3,773</td>
<td>143,217</td>
<td>2.6</td>
</tr>
<tr>
<td>Ford</td>
<td>1,138</td>
<td>365,410</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Hybrids as Percentage of Model Sales for July 2005

<table>
<thead>
<tr>
<th>Model</th>
<th>Hybrids</th>
<th>Full model</th>
<th>% hybrids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota Highlander</td>
<td>2,564</td>
<td>14,223</td>
<td>18</td>
</tr>
<tr>
<td>Toyota Rx400h</td>
<td>2,262</td>
<td>9,065</td>
<td>25</td>
</tr>
<tr>
<td>Honda Civic</td>
<td>2,329</td>
<td>28,008</td>
<td>8.3</td>
</tr>
<tr>
<td>Honda Accord</td>
<td>1,370</td>
<td>36,129</td>
<td>3.8</td>
</tr>
<tr>
<td>Ford Escape</td>
<td>1,138</td>
<td>18,245</td>
<td>6.2</td>
</tr>
</tbody>
</table>
Current Market Models in the US.

- Toyota Highlander Hybrid 4x4, V6, $34,430: 31/27 mpg (conventional model: $31,580, 18/24 mpg)

- Toyota Prius, 1.5L, $20,975, 60/51 mpg.

- Ford Escape, SUV, 2.3L, 33/29 mpg 4X4, 36/31 mpg 4X2 (Conventional model: 19/22 mpg 4X4, 24/29 4X2)

Current Market Models in the US.

Continued …

- Honda Civic Hybrid, 1.3L, MT: $19,900, 46/51 mpg, CVT: $20,900, 48/47 mpg (conventional model, AT, $18,310, 1.7L I4, 31/38)

- Honda Insight, 5-spd MT, $19,330, 1.0L, 60/66 mpg, CVT: $21,530, 57/56 mpg
### Fuel Economy Improvements of Current Passenger Hybrid Vehicles

<table>
<thead>
<tr>
<th>Model</th>
<th>City FE Gain</th>
<th>Hwy FE Gain</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honda Civic</td>
<td>66%</td>
<td>24%</td>
<td>EPA Cycle</td>
</tr>
<tr>
<td>Honda Accord</td>
<td>43%</td>
<td>23%</td>
<td>EPA MPG</td>
</tr>
<tr>
<td>Toyota Prius</td>
<td>100%</td>
<td>34%</td>
<td>Compared w/ Corolla</td>
</tr>
<tr>
<td>Ford Escape</td>
<td>80%</td>
<td>24%</td>
<td>EPA MPG</td>
</tr>
<tr>
<td>GM Silverado</td>
<td>10~15%</td>
<td>10~15%</td>
<td>Cycle unknown</td>
</tr>
</tbody>
</table>

### Fuel Economy of Hybrid Trucks

<table>
<thead>
<tr>
<th>Model</th>
<th>FE Gain</th>
<th>Emissions</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hino Ranger</td>
<td>20%</td>
<td>PM 85%; NO\textsubscript{x} 50%; CO\textsubscript{2} 17%</td>
<td>Japan Cycle, advertised</td>
</tr>
<tr>
<td>FedEx W700</td>
<td>50%</td>
<td>PM 93%; NO\textsubscript{x} 54%; CO 60%</td>
<td>FedEx Cycle, Dyno</td>
</tr>
<tr>
<td>UPS P100</td>
<td>36%</td>
<td>Field test</td>
<td></td>
</tr>
<tr>
<td>Coke 4400</td>
<td>34%</td>
<td>Field test</td>
<td></td>
</tr>
<tr>
<td>HTUF Utility</td>
<td>35%</td>
<td>CILCC Cycle, simulation</td>
<td></td>
</tr>
</tbody>
</table>
Environmental Impacts of HEVs

- Reduced air pollution including Nitrogen oxides, Carbon monoxide, Unburned hydrocarbons, and Sulfur oxides due to less fuel needed in HEVs
- Reduce global warming effect by burning less fuel and emitting less carbon oxides
- Reduce oil dependence on foreign oil and leave room for the future

Interdisciplinary Nature of HEV

- Vehicle Dynamics
- Energy Storage
- Vehicle Design
- Power Electronics & Electric Machines
- Vehicle Modeling Simulation
- Emerging Technology
- Control & Power Management
- Regenerative Braking
State-of-the-Art HEV

Toyota Prius

- **Engine**: 1.5 L 4-cylinders DOHC 76 HP / 82 lb-ft
- **Motor**: DC Brushless 500 V 50 kW / 400 Nm

**Engine**
- 4-cyl. Gas
- 1.5 L 4-cylinders DOHC
- 76 HP / 82 lb-ft

**EM**
- 50 kW PM

**Reduction Gearing**
- Planetary Gear set

**Generator**
- 28 kW PM

**Inverter**
- 50 kW PM

**Battery**
- 202 V NiMH 6.5 Ah 21 kW (Panasonic)

**Planetary Gear set**
- Inverter

**Inverter**
- 202 V NiMH 6.5 Ah 21 kW (Panasonic)

**Front Wheels**

**Table**

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

Engine: 2.4 L 4-cylinders DOHC
131 HP / lb-ft
APG: 1.5 kW 100V
Brake: Electronic controlled

<table>
<thead>
<tr>
<th></th>
<th>AWD BL</th>
<th>HEV</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1015 MPG</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1015 Kn/l</td>
<td>18.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UK BL MPG</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPA City</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPA HWY</td>
<td>24</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Sienna Engine: 2.4L 133 ~ 160 HP
Trans: 5-Speed AT

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

<table>
<thead>
<tr>
<th></th>
<th>AT BL</th>
<th>CVT HEV</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>City</td>
<td>29</td>
<td>48</td>
<td>66</td>
</tr>
<tr>
<td>Highway</td>
<td>38</td>
<td>47</td>
<td>24</td>
</tr>
</tbody>
</table>

Note: Civic Engine: 1.7L 115 HP/110lb-ft
Trans: 4-Speed AT
IMA ---- Integrated Motor Assist
Honda Accord

- Engine: 3.0 L VTEC V6
  - 240 hp / 217 lb-ft
  - w/ Variable Cylinder Management (VCM) system
- Trans: New 5-Speed AT
- Motor: DC Brushless
  - 12 kW / 74 Nm Assist
  - 14 kW / 123 Nm Regen

---

Nissan Tino – 2004 Production Model

- Engine: 1.8 L 4-cylinders DOHC
  - 98 HP / lb-ft
- Motor: DC Brushless
  - 350 V
  - 17 kW / Nm

---

EPA MPG

<table>
<thead>
<tr>
<th></th>
<th>AT</th>
<th>BL</th>
<th>HEV</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>City</td>
<td>21</td>
<td>20</td>
<td>30</td>
<td>43</td>
</tr>
<tr>
<td>Highway</td>
<td>30</td>
<td>37</td>
<td>37</td>
<td>23</td>
</tr>
</tbody>
</table>

Note: AT/BL Engine: 3.0L 240 HP/212 lb-ft

IMA ---- Integrated Motor Assist


http://www.nissan.com/nissan/vehicle/index.cfm?id=12925
Ford Escape – 2004 Production Model

Engine: 2.3 L Inline 4-Cylinder
133 hp / 129 lb-ft
Motor: PM 330 V
70 kW / xx Nm

<table>
<thead>
<tr>
<th>EPA</th>
<th>MPG</th>
<th>3.0 L</th>
<th>AT</th>
<th>HEV</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>City</td>
<td>20</td>
<td>36</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highway</td>
<td>25</td>
<td>31</td>
<td>24</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BL1 3.0L 200 HP 4-speed AT
BL2 2.3L 153 HP 4-speed AT
22/25 City/Highway MPG

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>908 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

<table>
<thead>
<tr>
<th>Performance</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPG*</td>
<td>~ 60%</td>
</tr>
<tr>
<td>PM</td>
<td>~ 90%</td>
</tr>
<tr>
<td>NOx</td>
<td>~ 50%</td>
</tr>
<tr>
<td>HC</td>
<td>~ 90%</td>
</tr>
<tr>
<td>CO</td>
<td>~ 90%</td>
</tr>
</tbody>
</table>

* Advertised Numbers —— Over CBD14 Cycle

Application of Allison’s E\textsuperscript{V} Drive\textsuperscript{TM}

* 20 New Flyers 40’ buses w/E* 40 are being tested in 26 locales: Philadelphia 12, Salt Lake City 3, OC 2, Hartford 2, Seattle 1.

Transit Bus

Suburban Coach

E\textsuperscript{V} Drive\textsuperscript{TM}
Eaton Hybrid System for Commercial Trucks

Engine: 4.3 L 4-cylinders Diesel
170 HP / 420 lb-ft
Motor: PM DC 340 V
44 kW / 420 Nm

Battery: 340 V Li-Ion
7.2 Ah
(Shin-Kobe)

Engine 4-cyl. Diesel
EM 44 kW PM
6-Speed AMT
Rear Wheels

Inverter

Engine: 4.3 L 4-cylinders Diesel
170 HP / 420 lb-ft
Motor: PM DC 340 V
44 kW / 420 Nm

Battery: 340 V Li-Ion
7.2 Ah
(Shin-Kobe)

Engine 4-cyl. Diesel
EM 44 kW PM
6-Speed AMT
Rear Wheels

Inverter

Hino 4T Ranger HEV Announced in 2004

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

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
Nissan Condorr 2003 Prototype

Vehicle: Wheelbase 172 in; Curb 10100 lbs; Payload 7000 lbs w/Engine stop/start; Cost $123,000

Engine: 6.93 L 6-Cylinders Diesel
204 HP @ 3000 / 369 lb-ft 2 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 Change

<table>
<thead>
<tr>
<th>Performance</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

Hybrid Architecture
Architectures of HEV

Series hybrid

Fuel tank

IC engine

Generator

Power converter

Electric motor

Battery

Series-parallel hybrid

Fuel tank

IC engine

Generator

Power converter

Electric motor

Battery

Series-parallel hybrid

Fuel tank

IC engine

Generator

Power converter

Electric motor

Battery

Parallel hybrid

Fuel tank

IC engine

Transmission

Battery

Power converter

Electric motor

Parallel hybrid

Fuel tank

IC engine

Transmission

Battery

Power converter

Electric motor

Complex hybrid

Fuel tank

IC engine

Electric motor

Battery

Power converter

Electric motor

Complex hybrid

Fuel tank

IC engine

Transmission

Battery

Power converter

Electric motor

Series Architecture

Fuel tank

Engine

Generator

Rectifier

Motor controller

Traction motor

Battery charger

Traction

Engine operating region

Speed

Torque

Tractive Effort

Vehicle speed

Speed

Engine operating region

Battery charge
**Operation Mode of Series Architecture**

- Battery alone mode: engine is off, vehicle is powered by the battery only
- Engine alone mode: power from ICE/G
- Combined mode: both ICE/G set and battery provides power to the traction motor
- Power split mode: ICE/G power split to drive the vehicle and charge the battery
- Stationary charging mode
- Regenerative braking mode

**Advantages of Series Architecture**

- ICE operation can be optimized, and ICE itself can be redesigned to satisfy the needs
- Smaller engine possible
- High speed engine possible
- Single gear box. No transmission needed. Multiple motors or wheel motors are possible
- Simple control strategy
Disadvantages of Series Architecture

- Energy converter twice (ICE/G then Motor), plus battery
- Additional weight/cost due to increased components
- Traction motor, generator, ICE are full sized to meet the vehicle performance needs

Parallel Architecture

- Two energy converters
- Engine and motor mechanically coupled
- Different configurations possible
Operation Mode of Parallel Architecture

- Motor alone mode: engine is off, vehicle is powered by the battery/motor only
- Engine alone mode: ICE drive the vehicle alone
- Combined mode: both ICE and motor provide power to drive the vehicle
- Power split mode: ICE power split to drive the vehicle and charge the battery
- Stationary charging mode
- Regenerative braking mode (include hybrid braking mode)

Advantages of Parallel Architecture

- ICE operation can be optimized, with motor assist or share the power from the ICE
- Flexible in configurations and gives room for optimization of fuel economy and emissions
- Reduced engine size
- Possible plug-in hybrid for further improved fuel economy and emission reduction
Disadvantage of Parallel Architecture

- Complicated control strategy
- Complex transmission

Current Hybrid Designs

Clutch-MG-Transmission Configuration

Source: Eaton Corporation

MG: Motor/Generator
AC: Automatic Clutch

Advantage: Simple structure and adaptability for truck transmissions
Parallel Hybrid Configuration

Advantage: Compact, Simple Structure, Optimized Engine performance
Disadvantage: Two Motors, No engine direct mode, double energy conversion

Operation Modes:
- Motor Alone
- Combined
- Electric CVT
- Regenerative Braking

Vehicle Models: Toyota Prius

GM Hybrid Configuration_DCT AMT Based

Electric Machines
Dual Clutches
Planetary Trains
Solid Shaft
Hollow Shaft
Engine
Great minds for a great future!

Pros and Cons

• Generally increases MPG
• People like hybrids
• Engine will be on all the time when heat or air conditioning is needed – MPG will be much lower
  – The hybrids fell as much as 40 percent below the EPA mileage figures for combined city and highway driving during a recent test, which covered a mix of Detroit-area roads. *Detroit Free Press, TOP STORIES, Thursday, February 03, 2005*
• Benefits may not pay back the cost increase
Toyota, Shell and JR Tokai Bus Launch World’s First Trial of GTL-Fueled Diesel Hybrid Bus

August 10, 2005

A group of partners in Japan have launched the first trial of a diesel-hybrid bus fueled with synthetic Gas-to-Liquids (GTL) diesel. The bus, which will operate for two months, will carry visitors to the 2005 World Exposition at Aichi, as well as commuters in Seto City and Kasugai City.

Source: http://www.greencarcongress.com/hybrids/

The Future of HEV and Opportunities

• More efficient diesel hybrids

• Plug in hybrids

• Fuel cell and plug in vehicles

• Powering your house/business with your fuel cell/hybrid cars

• And more
4.5 Million by 2013?

• The Cleveland market research firm Freedonia Group Inc. said recently that the worldwide market for light hybrids is forecast to advance rapidly, reaching 4.5 million units in 2013. They’re expected to reach 6 percent of total vehicles that year, due to rising energy costs and increased emissions regulations. That should help cut the current cost disparities between hybrids and conventional vehicles, currently $600 to $4,000 per vehicle, the study said. – Matt Roush, The Great Lakes IT Report.

Honda

• Honda forecasts surge in U.S. hybrid sales: AutoBeat Daily reported Monday that Honda Motor Co. expects the new hybrid version of its core Accord sedan to push its hybrid vehicle sales above 45,000 in the U.S. next year. Honda expects to sell about 20,000 hybrid Accords and a combined 25,000 more of its hybrid Insight and Civic cars in the U.S. next year. The company is aiming the hybrid Accord, which debuts in December, at customers who are affluent, middle-aged and well educated. Priced at about $30,000, the car will be about $3,500 costlier but more powerful and fuel efficient than a conventional high-end Accord. Honda says the hybrid Accord will be rated at 30 mpg in the city and 37 mpg on the highway vs. 21/31 mpg for a conventional model with V-6 engine. – Matt Roush, The Great Lakes IT Report, October 12, 2004
GM

- **GM to build Malibu 'mild hybrid' in Kansas City:** Speaking of hybrids, AutoTech Daily reported that General Motors Corp. says it will build the previously announced Chevrolet Malibu with an integrated starter-alternator at its Fairfax plant in Kansas City starting in 2007. The facility currently makes the traditionally powered Malibu and Malibu Maxx. The Malibu's mild-hybrid system operates at speeds of less than 6 mph. Under those conditions, an electrohydraulic starter-alternator takes over for the Malibu's 2.4-liter four-cylinder engine. It also will power accessories when the vehicle is stopped in traffic. The system is expected to yield a 10 to 15 percent gain in fuel efficiency vs. a standard Malibu. – Matt Roush, *The Great Lakes IT Report*, October 12, 2004

Energy Department and USCAR Invest $195 Million

- To Help Develop Energy-Efficient Vehicles
- To develop advanced high-performance batteries for electric, hybrid electric and fuel cell vehicle applications $125M
- To develop lightweight, high-strength materials that increase fuel efficiency through a reduction of vehicle weight $70M

Source: www.doe.gov
Toyota Initiatives

• Toyota is going to build more hybrid models in Japan

• Build Camry HEV in the US

• Plan to build a HEV plant in China

Toyota to Launch 10 hybrids

• Ten new hybrids on tap for Toyota: Toyota Motor Corp. is developing 10 gasoline-electric hybrid vehicles to launch worldwide within the next four or five years, Jim Press, who heads the automaker's U.S. sales operations, told AutoTech Daily. Not all of the vehicles will necessarily be sold in the U.S., but Press expects hybrids to eventually account for 25 percent of Toyota's U.S. sales. The automaker previously targeted sales of 1 million hybrids worldwide by 2010. The list of new hybrids being developed includes previously announced gasoline-electric versions of the Lexus GS and Toyota Camry due next year. Toyota's current hybrid lineup in the U.S. includes the Prius and recently introduced Highlander and Lexus RH 400 SUVs. A hybrid pickup likely will be one of the new models, Press says, noting that a gasoline-electric version of the Tundra is being studied. In such large vehicles, he adds, consumers may be able to choose between optimizing fuel economy and increasing power by flipping a switch. Press envisions overall demand in the U.S. for hybrids to continue to grow in coming years, with the potential for such vehicles to account for up to 15 percent of the total market by the start of the next decade. Hybrid sales totaled just over 83,000 vehicles last year in the U.S., led by the Prius with nearly 54,000 new registrations. Matt Roush – The Michigan Energy Report, August 31, 2005
GM, DCX to Develop Gasoline-Electric Hybrid System

- General Motors Corp. and DaimlerChrysler AG will jointly develop a gasoline-electric power system to catch Toyota Motor Corp. and Honda Motor Co. in the technology that saves fuel and cuts tailpipe emissions, said people familiar with the plans. 12/24/2004

http://www.freep.com/money/autonews/hybrid13e_200412213.htm

BMW to join GM/DCX Hybrid Co-Operative

- Three weeks after GM and DaimlerChrysler finalized their agreement on Aug. 22 to co-operate on the design of hybrid gas-electric powertrains, BMW signed on to the program as an equal partner in the venture.
- The three companies will share development costs for at least two hybrid power plants, including one for trucks and SUVs designed by GM, with the second for luxury vehicles.

http://www.theglobeandmail.com
September 15, 2005
Ford, Honda Unveil Latest Hybrids

- Three major automakers unveiled their latest hybrid cars and technology at an environmental conference, promoting their most fuel efficient vehicles as gas prices soar in the aftermath of Hurricane Katrina.
- Ford Motor Co., Honda Motor Co. and Toyota Motor Corp. brought their hybrid vehicles.
- The latest hybrid sports utility vehicle - the 2006 Mercury Mariner Hybrid. The compact, four-wheel-drive SUV can get 33 miles per gallon in the city and 29 miles per gallon on highways.
- Honda unveiled its latest hybrid offering - the 2006 Civic Hybrid, which can get 50 miles per gallon on highways and city streets.

The Great Lakes IT Report 9/12/2005

Toyota Could Go All-Hybrid

- Toyota Motor Corp. says all its vehicles will one day be hybrid-powered, according to a Bloomberg News report cited by AutoBeat Daily. The news service attributes the claim to Kazuo Okamoto, Toyota's executive vice president for research and development and design, who didn't offer a timetable for such an ambitious goal. Earlier this year Jim Press, Toyota's top U.S. executive, predicted that virtually all cars sold in America would have a hybrid powertrain of some sort by 2045.

- Toyota expects to sell about 250,000 hybrids this year, or roughly 3 percent of its total current unit volume. It aims to produce up to 400,000 hybrids next year and has said it expects hybrids to reach 1 million annual sales by about the beginning of the next decade.

The Great Lakes IT Report 9/15/2005
Reference Books

- Miller, “Propulsion Systems for Hybrid Vehicles,” IEE, 2004

Useful Websites

- http://www.greencarcongress.com/hybrids/
- http://www.hevprogress.com/
- http://www.autofacts.com
- http://www.toyota.com
- http://www.honda.com
National, State and Regional Government Programs

- FreedomCAR (U.S. Office of Advanced Automotive Technologies):
  http://www.eere.energy.gov/vehiclesandfuels/
- Hybrid Electric Vehicle Program (U.S. Department of Energy):
  http://www.ott.doe.gov/hev/
  http://www.eere.energy.gov/hydrogenandfuelcells/

Summary

- EV/HEVs have been in existence since the last century
  - Issues concerning cost and driving range have limited the use of EVs
  - More stringent fuel economy requirements and environmental concerns have pushed the development and acceptance of HEVs
- Architectures of HEVs include parallel, series, and complex configurations
- Various HEVs have been developed and made available to the general public.
- Diesel vehicles are competing with HEVs, but diesel HEVs may be a better choice
- HEVs are likely to dominate the auto industry for the next 10 years to come
Questions
Hybrid Electric Vehicles: Control, Design, and Applications

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Part 2
HEV Fundamentals
Outline

- Vehicle Resistance
- Traction and Slip Model
- Vehicle Dynamics
- Transmission
- Vehicle Performance
- Fuel Economy and Improvements
- Braking Performance
- Power Management
- Vehicle Control

Forces Acting on a Vehicle

- Tractive force
- Aerodynamic
- Gravitational
- Rolling
Grading Resistance - Gravitational

• The gravitational force, $F_g$ depends on the slope of the roadway; it is positive when climbing a grade and is negative when descending a downgrade roadway. Where $\alpha$ is the grade angle with respect to the horizon, $m$ is the total mass of the vehicle, $g$ is the gravitational acceleration constant.

$$F_g = mg \sin \alpha$$

Rolling Resistance

• On hard road surfaces
  – Caused by hysteresis of tire material
  – Deflection of the carcass while the tire is rolling
  – The hysteresis causes asymmetric distribution of ground reaction
  – The pressure in the leading half is larger than the trailing half of the contact surface
  – Results in ground force shifting forward
Rolling Resistance

• On soft road surfaces
  – Caused by the deformation of the ground surface
  – The ground reaction force almost completely shifts to the leading half

\[
F_r = \begin{cases} 
\text{sgn}(V)mg(C_0 + C_1V_0^2) & \text{if } V \neq 0 \\
F_{TR} - F_g & \text{if } V = 0 \text{ and } |F_{TR} - F_g| \leq C_0mg \\
\text{sgn}(F_{TR} - F_g)(C_0mg) & \text{if } V = 0 \text{ and } |F_{TR} - F_g| > C_0mg
\end{cases}
\]

\[
\text{sgn}(V) = \begin{cases} 
1 & V > 0 \\
-1 & V < 0
\end{cases}
\]

--where \( V \) is vehicle speed, \( F_{TR} \) is the total tractive force, \( C_0 \) and \( C_1 \) are rolling coefficients
**Typical Rolling Coefficient**

- $C_0$ is the maximum rolling resistance at standstill
- $0.004 < C_0 < 0.02$ (unitless)
- $C_1 << C_0$ ($S^2/m^2$)
- Approximation

\[
C_0 = 0.01 \\
C_1 = C_0 \frac{V}{100}
\]

<table>
<thead>
<tr>
<th>Condition</th>
<th>Rolling coefficient $C_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car tire on concrete or asphalt</td>
<td>0.013</td>
</tr>
<tr>
<td>Rolled gravel</td>
<td>0.02</td>
</tr>
<tr>
<td>Unpaved road</td>
<td>0.05</td>
</tr>
<tr>
<td>Field</td>
<td>0.1-0.35</td>
</tr>
<tr>
<td>Truck tires on concrete of asphalt</td>
<td>0.006-0.01</td>
</tr>
<tr>
<td>Wheels on rails</td>
<td>0.001-0.002</td>
</tr>
</tbody>
</table>

**Aerodynamic Drag Force**

Diagram showing high pressure and low pressure areas around a moving vehicle, indicating the direction of movement.
Aerodynamic Drag Force $F_{AD}$

- The aerodynamic drag force, $F_{AD}$ is the viscous resistance of the air against the motion.
  - $\rho$: Air density
  - $C_D$: Aerodynamic drag coefficient
  - $A_F$: Equivalent frontal area of the vehicle
  - $V_{\omega}$: Head-wind velocity

$$F_{AD} = \text{sgn}[V] \{0.5 \rho C_D A_F (V + V_{\omega})^2\}$$

Typical Drag Coefficients

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Coefficient of Aerodynamic Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open convertible</td>
<td>0.5...0.7</td>
</tr>
<tr>
<td>Van body</td>
<td>0.5...0.7</td>
</tr>
<tr>
<td>Pontoon body</td>
<td>0.4...0.55</td>
</tr>
<tr>
<td>Wedge-shaped body; headlamps and bumpers are integrated into the body, covered underbody, optimized cooling air flow.</td>
<td>0.3...0.4</td>
</tr>
<tr>
<td>Headlamp and all wheels inside body, covered underbody</td>
<td>0.2...0.25</td>
</tr>
<tr>
<td>K-shaped (small breakway section)</td>
<td>0.23</td>
</tr>
<tr>
<td>Optimum streamlined design</td>
<td>0.15...0.20</td>
</tr>
<tr>
<td>Trucks, road trains</td>
<td>0.8...1.5</td>
</tr>
<tr>
<td>Buses</td>
<td>0.6...0.7</td>
</tr>
<tr>
<td>Streamlined buses</td>
<td>0.2...0.4</td>
</tr>
<tr>
<td>Motorcycles</td>
<td>0.6...0.7</td>
</tr>
</tbody>
</table>
Traction and Tire Slip Ratio Model

- Tractive force is introduced due to “slip” between the wheel and the vehicle linear speed
- Slip is defined as the relative difference of wheel speed and vehicle speed
- Braking force is generated by negative slip ratio
- Tractive force is proportional to adhesive coefficient
- There is a maximum tractive effect; beyond that the wheel will spin on the ground

\[ \lambda = \frac{V_{ao} - V}{V_{ao}} \quad \text{for traction} \]
\[ \lambda = \frac{V_{ao} - V}{V} \quad \text{for braking} \]

Typical Traction (adhesive) Coefficient

- Traction effort coefficient
  - Longitudinal
  - Lateral
- Slip range: 0% to 100%
- Example values:
  - Slip: 15~20 µ
  - Traction coeff: 500 ~ 100%
Adhesive Coefficient for Different Road Conditions

- For almost all road conditions, braking force reaches maximum around 0.15-0.20 slip ratio.
- For traction, we need to control the torque not to exceed the maximum limited by the tire ground cohesion.
- For braking, we need to control the braking torque so that slip ratio is maintained at optimum, therefore, maximum braking effect can be achieved.

Dynamics of Vehicle Motion: Quarter Vehicle Model

- The dynamic equation of motion in the tangential direction, neglecting weight shift, is

\[ K_m m \frac{dV}{dt} = F_{TR} - F_r \]

- where \( K_m \) is the rotational inertia coefficient to compensate for the apparent increase in the vehicle’s mass due to the onboard rotating mass.

- Typically, \( 1.08 < K_m < 1.1 \)
Propulsion Power

- Torque at the vehicle wheels is obtained from the power relation
  \[ P = T_\omega \omega = F_t V \]
  where
  \( T_\omega \) is the tractive torque in N-m,
  \( \omega \) is the angular velocity in rads/sec,
  \( F_t \) is in N

- The angular velocity and the vehicle speed is related by
  \[ V = \omega r_d \]

In Steady State

\[
F_T = mg[\sin \alpha + C_0 \text{sgn}(V)] + \text{sgn}(V)[mgC_1 + \frac{\rho}{2} C_D A_F V^2]
\]
The tractive force vs. steady-state velocity characteristics can be obtained from the equation of motion, with zero acceleration:

\[
\frac{dF_T}{dV} = 2V \text{sgn}(V)(\frac{DC_aA_l}{2} + mgC_l) > 0 \quad \forall V
\]

\[\lim_{V \to 0^+} F_T \neq \lim_{V \to 0^-} F_T \quad \Rightarrow \text{Slope of } F_T \text{ is always positive}
\]

\[\Rightarrow \text{Discontinuity at zero velocity is due to rolling resistance}\]

With Zero Acceleration (steady state)

Maximum Gradeability

- The maximum grade that a vehicle will be able to overcome with the maximum force available from the propulsion unit is an important design criterion as well as performance measure.
Maximum Gradeability

• Continued …
– The vehicle is expected to move forward very slowly when climbing a steep slope, and hence, the following assumptions for maximum gradeability are made:
  • The vehicle moves very slowly \( v \leq 0 \)
  • \( F_{AD}, \ F_r \) are negligible
  • The vehicle is not accelerating, i.e. \( \frac{dv}{dt} = 0 \)
  • \( F_{TR} \) is the maximum tractive force delivered by motor at or near zero speed

\[
F_T = mg \sin \alpha
\]

\[
\text{max % grade} = \frac{100F_T}{\sqrt{(mg)^2 - F_T^2}}
\]

FDB to determine maximum gradeability

Maximum Gradeability

With the assumptions, at near stall conditions

\[
\sum F = 0 \Rightarrow F_T - F_g = 0 \Rightarrow F_T = mg \sin \alpha
\]

The maximum percent grade is

\[
\text{max % grade} = 100 \tan \alpha
\]

Forces & grade
Velocity and Acceleration

• The vehicles are typically designed with a certain objective, such as maximum acceleration on a given roadway slope on a typical weather condition.

• Energy required from propulsion unit depends on acceleration and road load force.

Velocity and Acceleration

continued …

• Maximum acceleration is limited by maximum tractive power and roadway condition.

• Road load condition is unknown in a real-world scenario.

• However, significant insight about vehicle velocity profile and energy requirement can be obtained by considering simplified scenarios.
**Scenario I: Constant $F_T$, Level Road**

- The level road condition implies that grade $\alpha (s)=0$
- EV is assumed to be at rest initially; also the initial $F_{TR}$ is assumed to be capable of overcoming the initial rolling resistance

\[
\begin{align*}
\text{At } t>0 & \Rightarrow \sum F = m \frac{dV}{dt} \Rightarrow F_T - F_{fr} - F_{gr} - F_{ds} = m \frac{dV}{dt} \\
F_T - mg[sin\alpha + C_s \text{sgn}(V)] - \text{sgn}(V)[mgC_1 + \frac{p}{2m}C_oA_r]V^2 = m \frac{dV}{dt}
\end{align*}
\]

**The Velocity Profile for Constant $F_T$**

Assume zero grade and solving for acceleration, $dv/dt$

\[
\frac{dV}{dt} = K_1 - K_2 V^2
\]

where

\[
K_1 = \frac{F_i}{m} - gC_o, \quad K_2 = \frac{p}{2m}C_oA_r + gC_1
\]

The velocity profile:

\[
V(t) = \sqrt{\frac{K_1}{K_2}} \tanh(\sqrt{K_1K_2} t)
\]
Distance and Terminal Velocity

**Terminal Velocity:**

\[
V_T = \lim_{t \to \infty} v(t) = \sqrt{\frac{K_1}{K_2}}
\]

**Distance Traversed:**

\[
s(t) = \int v(t) \, dt = \frac{1}{K_2} \ln(\cosh K_2 V_f t)
\]

Desired Velocity and Power Consumption

**The time to reach a desired velocity** \(V_f\),

\[
t_f = \sqrt{\frac{1}{K_1 K_2}} \tanh^{-1}\left(\sqrt{\frac{K_2}{K_1}} V_f \right)
\]

**Tractive power:** The instantaneous tractive power delivered by the propulsion unit is \(P_T(t) = F_T v(t)\).

\[
P_T(t) = F_T V_f \tanh(\sqrt{K_1 K_2} \ t)
\]
Mean Tractive Power

The mean tractive power over the acceleration interval $\Delta t$ is

$$\bar{P}_T = \frac{1}{t_f} \int P_r(t)dt = \frac{F_r V_f}{t_f} \frac{1}{\sqrt{K_1 K_2}} \ln[\cosh(\sqrt{K_1 K_2} t)]$$

Energy required during an interval of the vehicle can be obtained from the integration of the instantaneous power equation as

$$\Delta e_T = \int_0^t P_r(t)dt = t_f \bar{P}_T = F_r V_f \frac{1}{\sqrt{K_1 K_2}} \ln[\cosh(\sqrt{K_1 K_2} t)]$$

Example 1

- An electric vehicle has the following parameter values:
  - $m=692\text{kg}$, $C_D = 0.2$, $A_F = 2\text{m}^2$, $C_0 = 0.009$, $C_1 = 1.75\times10^{-6}$ $\text{s}^2/\text{m}^2$, $\rho = 1.18 \text{kg/m}^3$, $g = 9.81 \text{m/s}^2$
  - The vehicle is going to accelerate with constant tractive force. Maximum force that can be provided by the vehicle drive line is 1500N.
    - (a) find terminal velocity as a function of $F_T$ and plot it
    - (b) if $F_T = 500\text{N}$, find $V_T$, plot $v(t)$, and calculate the time required to accelerate to 60mph
    - (c) Calculate the instantaneous and average power corresponding to $0.98 V_T$. 

Example 2

- An electric vehicle has the following parameter values:
  - \( m = 800 \text{kg} \), \( C_D = 0.2 \), \( A_F = 2.2 \text{m}^2 \), \( C_0 = 0.008 \), \( C_1 = 1.6 \times 10^{-6} \text{s}^2/\text{m}^2 \), density of air \( \rho = 1.18 \text{kg/m}^3 \), and acceleration due to gravity \( g = 9.81 \text{m/s}^2 \)
  - The vehicle is on level road. It accelerates from 0 to 65mph in 10 s such that its velocity profile is given by
    - (a) Calculate \( F_{TR}(t) \) for \( 0 < t < 10 \text{s} \)
    - (b) Calculate \( P_{TR}(t) \) for \( 0 < t < 10 \text{s} \)
    - (c) Calculate the energy loss due to non conservative forces \( E_{\text{loss}} \)
    - (d) Calculate \( \Delta e_{TR} \).

\[
\nu(t) = 0.29055 t^2 \quad 0 \leq t \leq 10 \text{s}
\]

Scenario II: Non-constant \( F_T \), General Acceleration

If an arbitrary velocity profile or acceleration profile is known, then the tractive force can be determined:

\[
\sum F = m \frac{dV}{dt} \quad F_T = m \frac{dV}{dt} + mg[sin \alpha + C_s \text{sgn}(V)] - \text{sgn}(V)[mgC_i + \frac{\rho}{2} C_o A_v V^2]
\]
Scenario II: continued

The instantaneous tractive power $P_T(t)$ is

$$P_T(t) = F_T(t)v(t)$$

$$= mV \frac{dV}{dt} + mg[\sin \alpha + C_o \text{sgn}(V)]V - \text{sgn}(V)[mgC_1 + \frac{P}{2}C_o A_F]V^3$$

The change in tractive energy during an interval

$$\Delta e_T = \int_{t_1}^{t_2} P_T(t) \, dt$$

The total energy consists of kinetic and potential energy; as well as the energy needed to overcome the non-constructive forces including the rolling resistance and the aerodynamic drag force. These two are known as loss term.

Powertrain Rating

- The powertrain of an EV provides force to:
  - Accelerate from zero speed to a certain speed within a required time limit
  - Overcome wind force
  - Overcome rolling resistance
  - Overcome aerodynamic force
  - Provide hill climbing force
Units

• Mass
  – SI units, kg
  – Imperial units, pound or lbm
  – 1 kg = 2.2 lbm

• Force (weight)
  – SI, Newton, 1 N = m * g = 9.8 kg m/s²
  – Imperial, pound or lbf, 1 lbf = 32.2 lbm ft / second²
  – 1 lbf = 4.455 N

• Speed
  – SI, m/s, km/h
  – Imperial, ft/s, or mile/hour
  – 1 m/s = 3.281 ft/s, 1 mile/hour = 1.609344 km/h

Units

• Power
  – SI units, Watts
  – Imperial units, hp (motor) Watts (generator)
  – 1 hp = 745.6999 W

• Energy
  – kW.h
  – Joule
  – 1 kW.h = 3 600 000 joules
  – 1 watt = 1 joule / second
Weight and Mass

• Everyday we ask
  – “What’s the weight?”
  – “How much do you weigh?” “I am 70kg, I am 154 lb”

• We really mean
  – “What’s the mass?”
  – “What’s your mass” – My mass is 70kg or 154 lbm

• Your real weight
  – I weigh 637N or 4959 lbm ft / second^2 on earth

What’s the easiest way to lose weight?
Go to the moon!

Approximate Rating of Powertrain

- To determine the forces needed for a 3000lb vehicle to accelerate at 10mph/second; assume aerodynamic, rolling and hill-climbing force counts extra 10% of the forces needed.

\[
\text{Force} = 1.1 \times \text{mass} \times \text{acceleration} \\
= 1.1 \times 3000\text{lb} \times 10\text{mph/second} \times \frac{5280\text{ft}}{3600\text{second}} \\
= 48400 \text{lbf} = 1503 \text{lbf}
\]

\[
\text{Force} = 1.1 \times \text{mass} \times \text{acceleration} \\
= 1.1 \times 3000\text{lb} \times 2.2 \times 10\text{mph/s} \times \frac{1609\text{ft}}{3600\text{second}} \\
= 6704 \text{N}
\]
Rating of Powertrain

- Determine the average power needed to accelerate the vehicle from zero speed to 60mph

\[
\text{energy} = \text{mass} \times V \times V / 2 \\
= 3000\text{lb}/2.2 \times [60\text{mph} \times 1609/3600\text{second}]^2 / 2 \\
= 490318 \text{ joules}
\]

\[
\text{time} = v / a \\
v = at \\
= [60\text{mph} \times 1609/3600] / [10\text{mph/second} \times 1609/3600] \\
= [26.8 \text{ m/s}] / [4.47\text{m/s}^2] \\
= 6 \text{ seconds}
\]

Average power = force \times \text{distance/seconds} = \text{energy} / \text{time} \\
= 81.7 \text{ kW} \quad \text{(peak power } p_{\text{max}}=FV=180\text{kW)}

Approximate Rating of Powertrain

- Alternatively, determine the forces needed for a 3000lb vehicle to accelerate to 60mph in 10 seconds; assume aerodynamic, rolling and hill-climbing force counts extra 10% of the forces needed, and a constant acceleration

- Final speed \( V = 60\text{mph} \times 1609/3600 = 26.8 \text{ m/second} \)
- Acceleration \( a = V / t = 26.8 / 10 = 2.68 \text{ m/S}^2 \)
- Force \( F = m^*a = 3000/2.2 \times 2.68 \text{ m/S}^2 = 3657 \text{ N} \)
- Power \( = FV = 3657 \times 26.8 = 98 \text{ kW} \) (at 60mph speed)
Rating of Powertrain

- The above assumed a constant acceleration. In real life, the acceleration near 60mph will be greatly reduced. Therefore, the actual power needed to accelerate the vehicle is much less than 90kW

  Average power = Final power / 2 = 49 kW

Rating of Motor

- Assume the effective tire radius is R

- Torque at wheel is
  \[ Tw = FR \]
  \[ T_{motor} = \frac{Tw}{rg} \]
  Where \( rg \) is gear ratio

- Alternatively, motor torque is
  \[ T = \frac{P}{\omega_m} \]
  Where \( \omega_m \) is motor angular speed
Size of Drive Train

• Motor size is determined by

\[ D^2 l = \frac{6.1 \times 10^8}{C} \cdot \frac{P}{AB} \cdot \frac{1}{n} \]

Where:
- \( P \) is motor input power, in kW, \( P = \frac{P_{\text{max}}}{\text{efficiency}} \)
- \( A \) is airgap current density
- \( B \) is airgap magnetic flux density
- \( C \) is a constant, between 0.5 and 0.9
- \( n \) is motor speed in rpm

- \( D \) is inner diameter of stator or inner diameter of rotor
- \( L \) is effective length of stator/rotor

Size of Motor

• Note that the power required to cruise a vehicle on highway at 60mph is only 6% of the power needed to accelerate the vehicle from 0 to 60mph in 10 seconds.

• Since most motors can be designed to overload for a short time, a motor can be designed at much lower ratings. Example:
  - 30kW rated power (13.8kW dragging at 60mph, 1/3 rated)
  - 2 times overload for 60 seconds (60 kW)
  - 3 times overload for 30 seconds (90 kW)
  - 4 times overload for 20 seconds (120 kW)
  - 5 times overload for 10 seconds (150 kW)
Efficiency

• Note also that a motor can have efficiency (including controller) of over 90%, while an engine only has efficiency less than 30%

• An ICE does not have the overload capability as that of a motor. That’s why the rated power of ICE is usually much higher than required for highway cruising

Vehicle Power Plant Characteristics

• Ideal characteristics
• Constant power over all speed ranges
• Constant torque at low speeds to provide high tractive effort where acceleration and hill climbing capability are high
Engine Performance at Full Throttle

- Operating smoothly at idle speed
- Maximum torque is reached at intermediate speed
- Torque declines as speed increases further
- There is a maximum fuel efficiency point in the speed range

Motor Performance at Full Load

- Constant torque below base speed
- Constant power above base speed – field weakening region
- Only single gear or fixed gear is needed in motor transmission
Tractive Effort of Internal Combustion Engine

- In order to increase tractive effort, a multi gear transmission is needed in ICE vehicles.
- Manual gear transmission consists of clutch, gear box, final drive, and drive shaft.
- Highest gear (smallest ratio): max vehicle speed
- Lowest gear (maximum ratio): maximum tractive effort

Tractive Effort of EV with Single Gear
Continuously Variable Transmissions (CVT)

- Provide infinite gear ratios
- Virtually matching any engine speed with vehicle speed

Vehicle Performance – Speed and Gradeability of ICEV

- Engine alone
- Gradeability is reduced at higher speed
- Gear provides wider range of speed/gradeability
Vehicle Performance – Speed and Gradeability of EV

- One gear
- More gradeability than ICEV
**Fuel Economy of ICE**

- ICE has optimum operating point for best fuel economy
- Ways to increase fuel economy include:
  - Optimum vehicle design
  - Improving engine efficiency
  - Properly matching transmission
  - Advanced hybrid technology

**Braking Performance**

- Energy wasted during braking in conventional vehicles
- Can be partially recovered in EV and HEV
- ABS performance can be improved in HEV/EV
- Traction control is easier to achieve in HEV/EV
Braking Example

- Determine the energy expected when bringing a 3000lb vehicle to a halt from a speed of 60mph in 10 seconds

\[
\text{Energy} = \frac{1}{2} \times \text{mass} \times V^2 = \frac{1}{2} \times 3000/2.2 \times (26.8 \text{ m/s})^2 \\
= 489709 \text{ joules} = 0.136 \text{ kW h}
\]

Using average speed of 30mph, the vehicle will travel 44 ft/second or 440 ft in 10 seconds,
Assume an average drag force of 100 lbf, drag loss is
\[
=100 \times 4.455 \times 440 / 3.28 = 59762 \text{ joules} = 0.0166 \text{ kW.h}
\]

Energy can be recovered is 0.136 - 0.0166 = 0.1194
Power (in 10 seconds) = 43kW

HEV Propulsion System Design

- The design requirements related to vehicle power typically specified by a customer are:
  - the initial acceleration
  - rated velocity on a given slope
  - maximum % grade
  - maximum steady state velocity
- The complete design is a complex issue involving numerous variables, constraints, considerations and judgment, which is beyond the scope of this course.
HEV Design Steps

- Power and energy requirement from the propulsion unit is determined from a given set of vehicle cruising and acceleration specifications.

- Component level design:
  - Electrical and Mechanical engineers design the electric motor for EV or the combination of electric motor and internal combustion engine for HEVs.
  - Power electronics engineers design the power conversion unit which links the energy source with the electric motor.
  - Controls engineer working in conjunction with the power electronics engineer develops the propulsion control system.
  - Electrochemists and Chemical engineers design the energy source based on the energy requirement and guidelines of the vehicle manufacturer.

- Vehicle design is an iterative process; several designers have to interact with each other to meet the design goals.

Summary

- Vehicular forces include rolling resistance, gravitation, aerodynamic and traction force.
- Traction and braking are achieved due to slip ratio on the wheel.
- Vehicle dynamics can be derived from its kinetic motion.
- Vehicle performance can be mathematically calculated with given traction force, or demanded traction force can be determined if a desired vehicle velocity profile is given.
- HEV powertrain can be generally smaller due to the nature of electric motor used. The power splitting or combining is managed by vehicle control to maximize fuel economy and performance.
- Rating of a powertrain can be determined using the vehicle data and design requirements.
Solutions to Example 1

\[ V_r(F_{ia}) = \frac{K_1}{\sqrt{K_2}} = 53.2\sqrt{1.45\times10^{-1} F_{ia} - 0.0883} \]

\[ K_1 = \frac{F_{ia}}{m} - gC_0 \quad K_2 = \frac{\rho}{2m} C_v A_v + gC_i \]

\[ V_r = 42.45 \text{ m/s, } V_f = 60 \text{ mph} = 27 \text{ m/s, } t_f = \frac{1}{\sqrt{K_1 K_2}} \tan^{-1}(v_f \sqrt{K_1 / K_2}) \]

\[ v(t) = 42.45 \tanh(1.22 \times 10^{-2} t) \]

\[ P_f(t) = F_f V_r \tanh(\sqrt{K_1 K_2} t) \]

\[ \overline{P_f} = \frac{1}{t_f} \left[ P_f(t) dt = \frac{F_f V_r}{t_f} \frac{1}{\sqrt{K_1 K_2}} \ln[\cosh(\sqrt{K_1 K_2} t)] \right] \]

Solutions to Example 2

- (a) From the force balance equation, the tractive force is:
  \[ F_{ia} - F_{a0} - F_{oa} = m \frac{dv}{dt} \]
  \[ \Rightarrow F_{ia}(t) = m \frac{dv}{dt} + \frac{\rho}{2} C_v A_v v^2 + mg(C_v + C_s v) \]
  \[ = 464.88t + .02192t^4 + 62.78N. \]

- (b) The instantaneous power is
  \[ P_{ia}(t) = F_{ia}(t) \cdot v(t) \]
  \[ = 135.07t^2 + .00637t^6 + 18.24t^3W. \]

- (c) The energy lost due to non-conservative forces
  \[ E_{loss} = \int_0^t v(F_{ia} + F_{oa}) dt = \int_0^t 0.29055t(0.0219t^4 + 62.78) dt \]
  \[ = 15,180J. \]

- (d) The kinetic energy of the vehicle is
  \[ \Delta KE = \frac{1}{2} m \left[ v(10)^2 - v(0)^2 \right] = 337,677J \]

- Therefore, the change in tractive energy is
  \[ \Delta e_{TR} = 15,180 + 337,677 \]
  \[ = 352,857J. \]
Hybrid Electric Vehicles: Control, Design, and Applications

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Part 3

HEV Modeling and Simulation
Outline

- Vehicle Dynamics
- Modeling Basics
- Vehicle Performance
- Modeling Examples
- Modeling using Simplorer

Objectives

- After completing this session, you will be able to
  - Write vehicle dynamic equations
  - Setup simulation models using the dynamic equations
  - Simulate vehicle performance for constant tractive force
  - Simulate required tractive force for a desired vehicle velocity profile or gradeability
  - Perform simulation using Ansoft Simplorer or related tool, using block diagrams
Forces Acting on a Vehicle

- Tractive force
- Aerodynamic
- Gravitational
- Rolling

Dynamics of Vehicle Motion: Quarter Vehicle Model

- The dynamic equation of motion in the tangential direction, neglecting weight shift, is

\[ K_m m \frac{dV}{dt} = F_{TR} - F_r \]

- where \( K_m \) is the rotational inertia coefficient to compensate for the apparent increase in the vehicle’s mass due to the onboard rotating mass

- Typically, 1.08 < \( K_m \) < 1.1
Start the Modeling Process (Using Simulink or Simplorer)

- The integration of $dv/dt$ is speed
- The integration of $v$ is distance

To Get $dv/dt$

- Use the vehicle dynamic equations to derive $dv/dt$

\[ K_m m \frac{dV}{dt} = F_{rr} - F_r \]

\[ \Rightarrow \]

\[ \frac{dV}{dt} = \frac{(F_{rr} - F_r)}{(K_m m)} \]
To Get Total Resistive Force $F_r$

- \[ F_r = F_g + F_{roll} + F_a \]
- While all forces are functions of speed

For Constant Tractive Force
Vehicle Dynamics Simulation Model

• Inputs to the simulation model:
  – Roadway slope $\alpha$
  – Propulsion Force $F_t$
  – Road Load Force $F_r$

• Outputs:
  – Vehicle velocity $V$
  – Distance traversed $s$

The Speed Profile with constant tractive force

- Velocity (m/s)
- Time (s)
With 1800Nm Tractive Force

Driving Cycles
Giving Speed Profile

• Solve for forces needed for given velocity profiles, such as UDDS and SAE driving cycles

Example 1

• An electric vehicle has the following parameter values:
  • m = 692 kg, \( C_D = 0.2 \), \( A_F = 2 m^2 \), \( C_0 = 0.009 \),
  • \( C_1 = 1.75 \times 10^{-6} \) s²/m², \( \rho = 1.18 \) kg/m³, \( g = 9.81 \) m/s²
  • The vehicle is going to accelerate with constant tractive force. Maximum force that can be provided by the vehicle drive line is 1500N.
    – (a) find terminal velocity as a function of \( F_T \) and plot it
    – (b) if \( F_T = 500 \) N, find \( V_T \), plot \( v(t) \), and calculate the time required to accelerate to 60mph
    – (c) Calculate the instantaneous and average power corresponding to 0.98 \( V_T \). 

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Example 2

- An electric vehicle has the following parameter values:
  - $m = 800 \text{kg}$, $C_D = 0.2$, $A_F = 2.2 \text{m}^2$, $C_0 = 0.008$,
  - $C_1 = 1.6 \times 10^{-6} \text{ s}^2/\text{m}^2$, density of air $\rho = 1.18 \text{ kg/m}^3$, and acceleration due to gravity $g = 9.81 \text{ m/s}^2$
- The vehicle is on level road. It accelerates from 0 to 65mph in 10 s such that its velocity profile is given by
  \[ v(t) = 0.29055t^2 \quad 0 \leq t \leq 10 \text{s} \]

- (a) Calculate $F_{TR}(t)$ for $0 < t < 10 \text{ s}$
- (b) Calculate $P_{TR}(t)$ for $0 < t < 10 \text{ s}$
- (c) Calculate the energy loss due to non conservative forces $E_{loss}$
- (d) Calculate $\Delta e_{TR}$. 
Summary

- Vehicle performance can be simulated using simulation tools such as Simplorer or Simulink, based on vehicle dynamic equations
- Vehicle performance can include
  - Simulating vehicle speed, acceleration, and gradeability for given traction force
  - Simulating vehicle performance for a given velocity profile by controlling the traction force
  - Determine the required traction effort for a given velocity profile (driving cycles), acceleration and gradeability requirement
Hybrid Electric Vehicles: Control, Design, and Applications

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Part 4

Energy Sources and Energy Storage
Contents

- Comparison of energy sources
- Onboard energy storage
- Energy converters
- Battery
- Fuel cell
- Ultra-capacitors
- Flywheels
- Other renewable energy sources

Energy Source, Energy Converter, and Energy Storage

- Energy refers to a source of energy, such as gasoline, hydrogen, natural gas, coal, etc.
- 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>

### Why Battery

- **Batteries**
  - Popular choice of energy source for EV/HEVs
  - Desirable characteristics of batteries are:
    - High-peak power
    - High specific energy at pulse power
    - High charge acceptance
    - Long calendar and cycle life
  - Extensive research on batteries
    - There is no current battery that can deliver an acceptable combination of power, energy and life cycle for high-volume production vehicles
Battery Basics

- Constructed of unit cells containing chemical energy that can be converted to electrical energy
- Cells can be grouped together and are called a battery module
- Battery modules can be grouped together in a parallel or serial combination to yield desired voltage/current output and are referred to as a battery pack.

Battery Cell Components

- Positive Electrode
  - oxide or sulfide or some other compound that is capable of being reduced during cell discharge
- Negative Electrode
  - a metal or an alloy that is capable of being oxidized during cell discharge
  - Generates Electrons in the external circuit during discharge
- Electrolyte
  - medium that permits ionic conduction between positive and negative electrodes of a cell
  - must have high and selective conductivity for the ions that take part in electrode reactions
  - must be a non-conductor for electrons in order to avoid self-discharge of batteries.
Battery Cell Components

- Separator
  - Is a layer of electrically insulating material, which physically separates electrodes of opposite polarity.
  - Separators must be permeable to the ions of the electrolyte and may also have the function of storing or immobilizing the electrolyte.

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.
### Batteries: In Depth

<table>
<thead>
<tr>
<th>Battery</th>
<th>Energy Density (Wh/kg) Theoretical</th>
<th>Energy Density (Wh/kg) Practical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid</td>
<td>108</td>
<td>50</td>
</tr>
<tr>
<td>Nickel-cadmium</td>
<td>-</td>
<td>20-30</td>
</tr>
<tr>
<td>Nickel-zinc</td>
<td>-</td>
<td>90</td>
</tr>
<tr>
<td>Nickel-iron</td>
<td>-</td>
<td>60</td>
</tr>
<tr>
<td>Zinc-chlorine</td>
<td>-</td>
<td>90</td>
</tr>
<tr>
<td>Silver-zinc</td>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>Lithium metal sulphide</td>
<td>-</td>
<td>170</td>
</tr>
<tr>
<td>Sodium-sulfur</td>
<td>770</td>
<td>150-300</td>
</tr>
<tr>
<td>Aluminum-air</td>
<td>-</td>
<td>300</td>
</tr>
</tbody>
</table>

- **Lead Acid Battery**
  - First lead acid battery produced in 1859
  - In the early 1980’s, over 100 million lead acid batteries produced per year
  - Long Existence due to:
    - Relatively low cost
    - Availability of raw materials (lead, sulfur)
    - Ease of manufacture
    - Favorable electrochemical characteristics
Cell Discharging

- Positive Electrode Equation
  - PbO$_2$ + 4H$^+$ + SO$_4^{2-}$ → PbSO$_4$ + 2H$_2$O + 2e
- Negative Electrode Equation
  - Pb + SO$_4^{2-}$ → PbSO$_4$ + 2e
- Overall Equation
  - Pb + PbO$_2$ + 2H$_2$SO$_4$ → 2PbSO$_4$ + 2H$_2$O

WATER
2H$_2$O

- Electron Flow

RL
Cell Charging

- **Positive Electrode Equation**
  - \( \text{PbSO}_4 + 2\text{H}_2\text{O} \rightarrow \text{PbO}_2 + 4\text{H}^+ + \text{SO}_4^{2-} + 2e^- \)

- **Negative Electrode Equation**
  - \( \text{PbSO}_4 + 2e^- \rightarrow \text{Pb} + \text{SO}_4^{2-} \)

- **Overall Equation**
  - \( 2\text{PbSO}_4 + 2\text{H}_2\text{O} \rightarrow \text{Pb} + \text{PbO}_2 + 2\text{H}_2\text{SO}_4 \)
Battery Parameters

- **Battery Capacity**
  - The amount of free charge generated by the active material at the negative electrode and consumed by the positive electrode
  - Capacity is measured in Ah (1Ah=3,600 C or Coulomb, where 1 C is the charge transferred in 1 sec by 1A current in the MKS unit of charge).
  - Theoretical capacity of a battery
    - $Q_T = x n F$
    - $x =$ number of moles of limiting reactant associated with complete discharge of battery
    - $n =$ number of electrons produced by the negative electrode discharge reaction
    - $L$ is the number of molecules or atoms in a mole (known as Avogadro constant) and $e_0$ is the electron charge, $F$ is the Faraday constant and $F=Le_0$

- **Discharge Rate**
  - is the current at which a battery is discharged. The rate is expressed as $Q/h$ rate, where $Q$ is rated battery capacity and $h$ is discharge time in hours

- **State Of Charge**
  - is the present capacity of the battery. It is the amount of capacity that remains after discharge from a top-of-charge condition

$$SoC_T(t) = Q_T - \int_{t_o}^{t} i(\tau) d\tau$$
Battery Parameters

- State of Discharge
  - A measure of the charge that has been drawn from a battery
  \[
  SoD_f(t) = \Delta q = \int_{t_0}^{t_f} i(\tau) d\tau
  \]

- Depth of Discharge
  - the percentage of battery capacity (rated capacity) to which a battery is discharged
  \[
  DoD(t) = \frac{Q_T - SoC_T(t)}{Q_T} \times 100\%
  \]

Technical Characteristics

- Battery can be represented with
  - Internal voltage \( E_v \)
  - Series Resistance \( R_i \)

\[\text{Diagram: Battery circuit diagram with labels} \]

\[\text{Diagram: Battery discharge characteristics} \]
Technical Characteristics

- Practical Capacity
  - Practical capacity $Q_P$ of battery is always much lower compared to the theoretical capacity $Q_T$ due to practical limitations. The practical capacity of a battery is given as

  $$Q_P = \int_{t_i}^{t_{cut}} i(t) \, dt$$

- Capacity Redefined
  - The practical capacity of a battery is defined in the industry by a convenient and approximate approach of Ah instead of Coulomb under constant discharge current characteristics

Technical Characteristics

- Practical Capacity
  - Capacity depends on magnitude of discharge current

- Battery Energy
  - The energy of a battery is measured in terms of the capacity and the discharge voltage
Battery Energy

- Battery Energy
  - To calculate the energy, the capacity of the battery must be expressed in coulombs
  - In general, the theoretical stored energy is
    \[ E_T = V_{bat} Q_T \]
  - The practical available energy is
    \[ E_P = \int_{t_0}^{t_{cut}} v_i \, dt \]

Battery Power

- Specific Energy
  - \[ SE = \frac{\text{Discharge Energy}}{\text{Total Battery Mass}} = \frac{E}{M_b} \]
  - The theoretical specific energy of a battery is
    \[ SE_T = 9.65 \times 10^7 \times \frac{n^2 V_{bat} M_B}{M_M M_B} \]

- Battery Power
  - The instantaneous battery terminal power is
    \[ p(t) = V_i \]
Battery Power

- Battery Power
  - The maximum power is
    \[ P_{\text{max}} = \frac{E^2}{4R_i} \]

- Specific Power
  - The specific power of a battery is
    \[ SP = \frac{P}{M_B} \] (units: W/kg)

---

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>Acidic aqueous solution</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>Alkaline aqueous solution</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>
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<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>
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<tr>
<td>Nickel/Metal</td>
<td>70-95</td>
<td>200-300</td>
<td>70</td>
<td>750-1200+</td>
<td>6</td>
<td>200-350</td>
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<tr>
<td>Hydride</td>
<td>200-300</td>
<td>160</td>
<td>&lt;50</td>
<td>?</td>
<td>?</td>
<td>?</td>
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<tr>
<td>Anode/air</td>
<td>80-120</td>
<td>90</td>
<td>60</td>
<td>500+</td>
<td>?</td>
<td>50</td>
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<tr>
<td>Zinc/air</td>
<td>100-220</td>
<td>30-80</td>
<td>60</td>
<td>600+</td>
<td>?</td>
<td>90-120</td>
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<tr>
<td>Flow</td>
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<td></td>
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<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>
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<td>Vanadium redox</td>
<td>20-30</td>
<td>110</td>
<td>75-85</td>
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<td>400-450</td>
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<tr>
<td>Molten salt</td>
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<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>Organic/Lithium</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, but some energy loss by cooling
US Advanced Battery Consortium (USABC)

- Oversees the development of power sources for EVs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mid-term</th>
<th>Commercialization</th>
<th>Long-term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Energy (Wh/kg) (C/3 discharge rate)</td>
<td>80-100</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Energy Density (Wh/liter) (C/3 discharge rate)</td>
<td>135</td>
<td>230</td>
<td>300</td>
</tr>
<tr>
<td>Specific Power (W/kg) (80% DoD per 30 s)</td>
<td>150-200</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Specific Power (W/kg), Regen. (20% DoD per 10 s)</td>
<td>75</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Power Density (W/liter)</td>
<td>250</td>
<td>460</td>
<td>600</td>
</tr>
<tr>
<td>Recharge time, h (20% → 100% SoC)</td>
<td>&lt;6</td>
<td>4-6</td>
<td>3-6</td>
</tr>
<tr>
<td>Fast Recharge Time, min</td>
<td>&lt;15</td>
<td>&lt;30</td>
<td>&lt;15</td>
</tr>
<tr>
<td>Calendar life, years</td>
<td>5</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Life, cycles</td>
<td>600 @80% DoD</td>
<td>1000 @80% DoD</td>
<td>1000 @80% DoD</td>
</tr>
<tr>
<td>Lifetime Urban Range, mile</td>
<td>100,000</td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Operating environment, °C</td>
<td>-30 to +65</td>
<td>-40 to +50</td>
<td>-40 to +65</td>
</tr>
<tr>
<td>Cost, US$/kWh</td>
<td>&lt;150</td>
<td>&lt;150</td>
<td>&lt;150</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>75</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

Battery Model

- Can be represented by a capacitor in series with an internal resistor

Battery model in Simplorer: a capacitor is series with an internal resistor
**Fuel Cells**

- Generates electricity through electrochemical reaction that combines hydrogen with ambient air.

- Function is similar to a battery, but consumes hydrogen and air instead of producing electricity from stored chemical energy.

- Difference from battery: Fuel Cell produces electricity as long as fuel is supplied, while battery requires frequent recharging.

**Fuel Cells**

- Being used in space application, but has characteristics desirable to EV applications.

- Tremendous interest in vehicle and stationary applications.

- Research focus:
  - Higher power cells
  - Develop FC that can internally reform hydrocarbons.
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: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$
Fuel Cell Demo

- http://www.plugpower.com/technology/works.cfm

Demo Fuel Cells
The First System

- In the world that uses an SOFC fuel cell coupled with a gas turbine was developed at Siemens Westinghouse in Pittsburgh, Pennsylvania. The 220-kW power plant converts nearly 60% of the energy contained in natural gas into electric power.
Useful links

- NYSERDA
- Electric Power Research Institute
- U.S. Environmental Protection Agency
- Fuel Cells 2000
- National Fuel Cell Research Center
- U.S. Department of Energy
- U.S. Fuel Cell Council
- The Hydrogen & Fuel Cell Investor's Newsletter
- National Hydrogen Association

Fuel Cell Applications

- Vehicle Applications: Require low temperature operation
- Stationary Applications: Rapid operation and cogeneration is desired
- Research: new materials for electrodes and electrolytes
Fuel Cell Characteristics

- Fuel cell theoretically operates isothermally
  - => all free energy in a chemical reaction should convert to electrical energy

- H fuel does not burn, bypassing thermal to mechanical conversion
  - => direct electrochemical converter

- Isothermal operation: Not subject to limitations of Car, not subject to cycle efficiency imposed on heat engines.

Fuel Cell Characteristics

- Voltage/Current Output of a hydrogen/oxygen fuel cell.

- 1V is the theoretical Prediction, but not achievable in a practical cell
Fuel Cell Characteristics

- Working voltage falls with increasing current
- Several cells are stacked in series to get desired voltage
- Major advantage: Lower sensitivity to scaling (system efficiency similar from kW to MW range).

Fuel Cell Types

- Six Major Fuel Cell Types:
  - Alkaline Fuel Cell (AFC)
  - Proton Exchange Membrane (PEM)
  - Direct Methanol Fuel Cell (DMFC)
  - Phosphoric Acid Fuel Cell (PAFC)
  - Molten Carbonate Fuel Cell (MCFC)
  - Solid Oxide Fuel Cell (SOFC, ITSOFC)
## 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 (~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 (~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>

## Hydrogen Storage

- Hydrogen is not very dense at atmospheric pressure
- Can be stored as compressed or liquefied gas
  - Lot of energy required to compress the gas
  - Generation of liquid hydrogen requires further compression
**Fuel Cell Controller**

- Fuel cell characteristics as a function of flow rate

**Fuel Cell Operation**

- Fuel Cell Operation
  - Low Voltage/High Current make it sensitive to load variations
  - Fuel Cell Controller regulates flow of hydrogen into fuel cell to maximize performance while minimizing excess hydrogen venting
  - Pulling too much power without compensation in hydrogen flow may damage fuel cell membrane
  - Controller avoids operation in current limit mode to maintain a decent efficiency
Fuel Cell Operation

- Fuel Cell Operation
  - Due to slow response characteristics a reserve of energy is kept to ensure uninterrupted operation
  - At 100% hydrogen usage, Fuel Cell goes into current limited mode due to internal losses
  - By-product of Fuel Cell is water and (steam) and excess H
  - Steam can be used for heating in the vehicle, but excess hydrogen is wasted

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
Ultra-Capacitors

- More suitable for HEVs
- Can provide power assist during acceleration and hill climbing, and for recovery of regenerative energy
- Can provide load leveling power to chemical batteries
- Current aim is to develop ultra capacitors with capabilities of 4000 W/kg and 15Whr/kg.

How an Ultra-Capacitor Works

Energy = \( \frac{1}{2} CV^2 \)
Equivalent Circuit

- Three major components:
  - Capacitance
  - Series resistance
  - Dielectric leakage resistance

\[ V_i = V_c - Ri \]
\[ C \frac{dV_c}{dt} = -i_c = i_L + i \]
\[ i_L = \frac{V_c}{R_L} \]

Typical Discharging of Ultra-capacitor

- 2600F capacitance
- 2.5V cell voltage
Useful Energy and SOC

Useful Energy: \( E_u = \frac{1}{2} C(V_{CR}^2 - V_{Cb}^2) \)

\[ SOC = \frac{0.5CV_{Cr}^2}{0.5CV_{Cr}^2} = \frac{V_{Ch}^2}{V_{Cr}^2} \]

- Efficiency, when neglecting \( i_L \)
  \[ \eta_c = \frac{I_cV_C}{I_lV_t} = \frac{V_C}{V_t} \]
- Charging:
  \[ \eta_d = \frac{I_lV_c}{I_cV_C} = \frac{V_l}{V_C} \]
- Discharging

Technical Specifications

<table>
<thead>
<tr>
<th>Capacitance (Farads, -20% /+20%)</th>
<th>BCAP0010 (Cell)</th>
<th>BMOD0115 (Module)</th>
<th>BMOD0117 (Module)</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum series resistance ESR at 25°C (m Ω)</td>
<td>2600</td>
<td>145</td>
<td>435</td>
</tr>
<tr>
<td>Voltage, (V) Continuous (peak)</td>
<td>2.5 (2.8)</td>
<td>42 (50)</td>
<td>14 (17)</td>
</tr>
<tr>
<td>Specific power at rated voltage (W/kg)</td>
<td>4300</td>
<td>2900</td>
<td>1900</td>
</tr>
<tr>
<td>Specific energy at rated voltage (Wh/kg)</td>
<td>4.3</td>
<td>2.22</td>
<td>1.82</td>
</tr>
<tr>
<td>Maximum current (A)</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Dimensions (mm) (reference only)</td>
<td>60×172 (Cylinder)</td>
<td>195 ×65×415 (Box)</td>
<td>195×265×415 (Box)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>0.525</td>
<td>16</td>
<td>6.5</td>
</tr>
<tr>
<td>Volume (Liter)</td>
<td>0.42</td>
<td>22</td>
<td>7.5</td>
</tr>
<tr>
<td>Operating temperature* (°C)</td>
<td>-35 to +65</td>
<td>-35 to +65</td>
<td>-35 to +65</td>
</tr>
<tr>
<td>Storage temperature (°C)</td>
<td>-35 to +65</td>
<td>-35 to +65</td>
<td>-35 to +65</td>
</tr>
<tr>
<td>leakage current (mA) 12 hours, 25°C</td>
<td>5</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

* Steady state case temperature
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

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
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
Two Topologies of Hybridization

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

Summary

- An energy source is where the energy is converted from. Energy sources include gasoline, diesel, hydrogen, coal, nuclear, solar light, wind, etc.
- An energy storage device is something that holds the energy source, such as a fuel tank or battery
- Energy converters are devices that convert energy from one form to another, such as ICE, motor, turbine, fuel cell, etc.
- Batteries are the most used energy storage device in HEVs, but have limitations, such as weight and energy/power density
- Ultra capacitors and flywheels supplement the HEV application with their performance that batteries do not have, such as rapid charging and discharging
- Fuel cells convert hydrogen to electricity without pollutant. Hydrogen has to be produced somewhere else
- Hybridization of energy storage is likely the solution
Hybrid Electric Vehicles: Control, Design, and Applications

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Fax: (313)583-6336

Part 5
Series HEV Design and Modeling
Concept of Hybrid Powertrain

- Use multiple sources of power so that it will
  - Develop sufficient power to meet the demand of vehicle performance
  - Carry sufficient energy onboard to support sufficient driving range between each refuel
  - High efficiency
  - Emit less pollutants
- HEV may contain more than one energy source (gasoline + electricity) and more than one energy converters (ICE + motor/generator)
Basic Concept of Hybridization

Architectures of HEV
Series Architecture

Operation Mode of Series Architecture

- Battery alone mode: engine is off, vehicle is powered by the battery only
- Engine alone mode: power from ICE/G
- Combined mode: both ICE/G set and battery provides power to the traction motor
- Power split mode: ICE/G power split to drive the vehicle and charge the battery
- Stationary charging mode
- Regenerative braking mode
Advantages of Series Architecture

• ICE operation can be optimized, and ICE itself can be redesigned to satisfy the needs
• Smaller engine possible
• High speed engine possible
• Single gear box. No transmission needed. Multiple motors or wheel motors are possible
• Simple control strategy

Disadvantages of Series Architecture

• Energy converted twice (ICE/G then Motor), plus battery
• Additional weight/cost due to increased components
• Traction motor, generator, ICE are full sized to meet the vehicle performance needs
Typical Control Diagram of Series HEV

Operation Patterns of the ICE
Operation Patterns of the ICE

- Engine is controlled to operate in the optimum region to maintain high efficiency and low emission
- ICE may be smaller as the battery will provide peaking power as needed

Control Objectives

- To meet the power demand of the driver
- To operate each component with optimal efficiency
- To recapture regenerative braking energy
- Maintain the SOC of battery within the preset thresholds
Vehicle Performance

- Acceleration: vehicle must be able to accelerate to certain speed within certain time limits. It is constrained by the traction motor rating and the power from I/G set and battery.
- Gradeability: must be able to climb certain grade
- Maximum cruising speed
- Range

Control Strategy

- A control rule
  - Preset in the vehicle controller
  - Control the operation of each component
  - Receive commands from the driver
  - Receive the feedback from the drivetrain and components
- Many strategies available, typical are:
  - Maximum SOC strategy
  - Thermostat or Engine on-off strategy
Maximum SOC Strategy

- To meet the power demand by the driver and at the mean time, maintain high level SOC
  - Suitable for stop-go driving patterns
  - Military vehicles: carrying out mission is critical
  - Guarantee high performance of vehicle
- Disadvantages
  - When battery fully charged, vehicle enters engine alone mode. Engine will not operate efficiently

Typical Operation Modes
Control Diagram

Thermostat Control (Engine on-off)

- Engine is turned off when SOC reaches preset top limit
- Engine is on when SOC drops below its preset low limit
  - Disadvantage is, if vehicle needs sudden demand but the SOC is at low, there may be a problem
Design of Series HEV

• Design and selection of major components:
  – Traction motor
  – Engine
  – Generator
  – Battery/energy storage

• Verify vehicle performance
  – Acceleration
  – Gradeability
  – Maximum cruising
  – Fuel economy and emissions

Design Example

• Specifications
  – Total mass 1500kg
  – Rolling resistance coefficient 0.01
  – Aerodynamic drag coefficient 0.3
  – Frontal area 2 m$^3$
  – Transmission efficiency 0.9

• Performance
  – Acceleration time (0 to 100km/h) 10 sec
  – Maximum gradeability 30% at low speed and 5% at 100km/h
  – Maximum speed 160km/h
Traction Motor

- Must be able to satisfy all vehicle performances such as acceleration, gradeability, etc.
- Motor power to overcome all resistance + ma
- Designed to be 82.5kW for the example

Gear Ratio

- Vehicle reaches maximum speed when motor reaches maximum speed
  - Motor maximum speed is 5000rpm
  - Vehicle maximum speed is 160km/h or 44.4 m/s
  - Radius is 0.28m
- Then gear ratio is 3.3
  - $5000 \text{rpm}/60 \text{ sec} \times 2 \pi \times 0.28 \text{m} = 44.4 \text{m/s} \times \text{ig}$
Acceleration Performance

Gradeability

- 46.6% at low speeds
- 15% at 100 km/h
Engine/Generator

- Highway driving: long time with constant speed
  - Engine/generator must be able to supply sufficient power to support the speed
- Frequent stop-go pattern
  - Must be able to maintain SOC of battery
- During Acceleration
  - Total power from battery and I/G is needed to support acceleration

Design Example
Required Engine Power

- Constant Speed: on flat road and on 5% grade
- Different driving cycle: average power
- Therefore engine is 32.5kW

Energy Storage System

- Power capacity
  - To fully utilize the motor power capacity
  - \( \text{Ppps} > \text{Pmtor,max} - \frac{\text{Pe}}{\text{g}} \)
  - Example: \( 82.5/0.85 \text{ (eff)} - 32.5 \times 0.9 \text{ eff} = 67.8 \text{kW} \)
- Energy Capacity
  - Support the whole acceleration range when partially discharged
  - 2.5kWh (0.2 SOC change corresponding to 0.5kWh change in PPS energy)
  - In battery alone, with maximum motor capacity, vehicle can run 109 seconds (2.5kWh*3600/82.5kW)
Fuel Consumption

- Engine is operated at 34.3% efficiency
- Fuel economy depends on driving cycle
- Fuel economy depends on control strategy
- Example vehicle:
  - 42.3 mpg FTP75 Urban Driving Cycle
  - 43.5 mpg FTP75 Highway Driving Cycle
Summary

- HEVs can be designed to have series, parallel or complex configurations to overcome the cost/range problem in pure EVs.
- Series HEVs convert energy twice, hence there may be more cost and efficiency disadvantages.
- Series HEVs are suitable for most stop-go applications such as bus, delivery truck, commuter car, yard tractor, etc.
- Series HEVs can be controlled using either maximum battery SOC or thermostat (engine on-off) control.
- The design of series includes sizing the ICE, motor, and energy storage device.
- The performance of series HEVs can be simulated for standard driving cycles, which include maximum speed, acceleration, gradeability, etc.
Hybrid Electric Vehicles: Control, Design, and Applications

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Part 6
Parallel HEV Design and Modeling
Contents

- Parallel hybrid architecture
- Control strategy of series HEV
- Sizing of major components
- Design example
- Modeling of parallel HEV

Parallel Architecture

- Two energy converters
- Engine and motor mechanically coupled
- Different configurations possible
Operation Mode of Parallel Architecture

- Battery alone mode: engine is off, vehicle is powered by the battery only
- Engine alone mode: power from ICE/G
- Combined mode: both ICE/G set and battery provides power to the traction motor
- Power split mode: ICE/G power split to drive the vehicle and charge the battery
- Stationary charging mode
- Regenerative braking mode (include hybrid braking mode)

Advantages of Parallel Architecture

- ICE operation can be optimized, with motor assist or share the power from the ICE
- Flexible in configurations and gives room for optimization of fuel economy and emissions
- Reduced engine size
- Possible plug-in hybrid for further improved fuel economy and emission reduction

Disadvantages
- Complicated control strategy
- Complex transmission
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

- 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

\[ \omega_{\text{out}} = k_1 \omega_1 + k_2 \omega_2 \]
\[ T_{\text{out}} = \frac{T_1}{k_1} = \frac{T_2}{k_2} \]
Speed Coupled HEV

Torque and Speed Coupling
Control Objectives

• Control objectives
  – To satisfy performance requirements including acceleration, gradeability, and maximum cruising speed
  – To achieve overall high efficiency
  – To maintain battery SOC
  – To recover braking energy

Control Strategy

• Categories of the control strategy
  – Supervisory: vehicle controller
  – Component controllers: engine controller, motor controller, battery controller
Control Scheme for Parallel HEV

- Two different modes: propelling and braking
- Vehicle controller gather commands from accelerator and brake pedal
- And gather data from vehicle speed and SOC
- Sends commands to component controller

Control Strategy and Power Management

- Motor alone:
  - Speed $V < V_{low}$
  - SOC > SOC_{low}
- Combined
  - $P > P_{e-opt}$
  - SOC > SOC_{low}
- Power split
  - $P < P_{e-opt}$
  - SOC > SOC_{low}
- Engine alone
  - $P < P_{e-opt}$
  - SOC > SOC_{high}
- Engine off
  - $V < V_{hysteresis}$
  - SOC > SOC_{low}
- Avoid engine on/off too often

- Regen
- Hybrid braking

- Example: $V_{low} = 25$ mph
  - $V_{hysteresis} = 15$ mph
  - SOC_{low} = 0.6
  - SOC_{high} = 0.99
Mild Hybrids

- Reduce size of battery (cost, weight and volume)
- Reduce complexity of drivetrain (reduced cost)
- Reduce energy consumption during engine idle (shut off engine, as well as transmission loss saved)
- Drawbacks
  - Not able to drive vehicle alone using the motors
  - Not be able to recover majority of braking energy

Parallel Mild Hybrid

- Example, Honda Civic: 10kW motor (10 percent of engine)
- Operation Modes
  - Engine alone
  - Motor alone (ultra low speed)
  - Regen mode
  - Combine mode
  - Power split mode
Plug-in Hybrids

- Further increase fuel economy
- Need bigger battery pack
- 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

Summary

- Parallel HEVs can be designed with speed coupling or torque coupling or both
- A parallel HEV is suitable for both city and highway driving
- It can be controlled using thermostat (engine on-off) control, and operated in seven different modes (combine, power split, regenerative braking being the most important ones)
- The design of a parallel HEV includes sizing of the ICE, motor, and energy storage device
- The performance of a series HEV can be simulated for standard driving cycles, which include maximum speed, acceleration, gradeability, etc.
- Mild HEV, and Plug-in HEV may play an important role in the near future