Feedback Controlled Brushless DC Motor: Personal Electric Vehicle Application

Summary Lecture

Problem Review

Alternative transportation means needed that is not reliant on fossil fuels

Solution methods

- Personal electric vehicles can replace many automobile applications
  - Energy efficient transport
  - Reduced carbon dioxide emissions
  - Possibility for independence from fossil fuel
  - Less material-intensive manufacture

Solution trade-offs

- Weather inconvenience
- Two-wheel vehicle barrier?
- Paradigm shift from multi-passenger to single passenger vehicles
- Longer distance trips (>60km) not addressed

Solution trade-offs

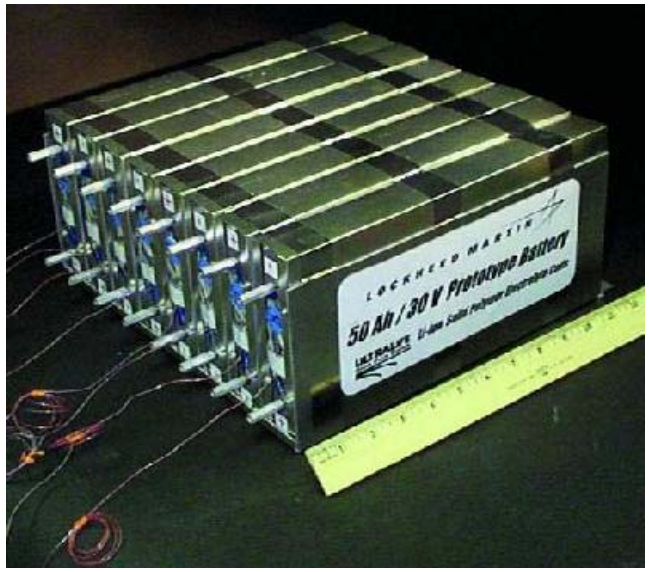
- Short range per charge (20 to 40 miles, advanced PEV's up to 125 miles)
- Time-consuming recharge (2 hours min.)
- Hazardous materials in battery life-cycle
- Reliance on rare earth magnets

Characteristics of US Driving

- **How We Travel**
  - 87 percent of daily trips take place in personal vehicles
  - 91 percent of people commuting to work use personal vehicles
- **How Many Trips We Take Every Day**
  - Americans take 1.1 billion trips a day — four for every person in the U.S
  - U.S. daily travel averages 11 billion miles a day — almost 40 miles per person per day
- **How Many Trips We Take in a Year**
  - Americans take 411 billion daily trips a year or about 1,500 trips per person
  - U.S. daily travel totals about 4 trillion miles — 14,500 miles per person
- **Why We Travel**
  - 45 percent of daily trips are taken for shopping and errands
  - 27 percent of daily trips are social and recreational, such as visiting a friend
  - 15 percent of daily trips are taken for commuting

Factors favoring PEV's

- Battery technology has improved
  - Lead acid
  - Nickel cadmium
  - Nickel metal hydride
  - Lithium ion
  - Lithium polymer



- Motor technology has improved
  - Brushed DC motor
  - Brushless DC motor

Battery Technology

	Mass energy density (Wh/kg)	Volumetric energy density (Wh/l)	Mass power density (W/kg)	Energy cost (US$/Wh)	Cycle durability	Charge-discharge efficiency
Lead acid	30-40	60-75	180	<1.0	200-500	80
NiCad	40-60	50-150	150	1.2	2000	80
NiMH	30-80	140-300	250-1000	2.8	500-1000	66
Lithium ion	160	270	1800	2.0-5.0	~1200	99
Lithium polymer	130-200	300	~2800	2.3-5.0	>1000	99

How does a BLDC motor make a difference in PEV's?

- Higher power to weight ratio
  - BLDC: 2000 W/kg
  - Brushed DC: 1000 W/kg
- Higher efficiency in converting electric energy to rotating mechanical energy
  - BLDC: >90%
  - Brushed DC: 75%

How does a BLDC motor make a difference in PEV's?

- Lower maintenance
  - BLDC: no regular maintenance
  - Brushed DC: replace brushes
- Lower gear-ratio transmission
  - BLDC: 5:1@2500rpm, typically single-stage
  - Brushed DC: 20:1 @10,000rpm, typically two-stage

Drawbacks to BLDC versus Brushed DC

- Higher acquisition cost
  - BLDC with electronic controller about 50% higher for 1.5hp
- High magnetic field strength permanent magnets on rotor

Carbon Dioxide Emissions

- Gasoline use in engines used for transportation accounts for about 18% of US CO_2 emissions
- Cars and motorcycles account for over 90% of the gasoline use

Cars and motorcycles account for over 16% of US CO_2 emissions

How much CO2 is emitted annually by the average US driver?

- Average US passenger vehicle (2005):
  - 12,400 miles per year
  - 22.9 miles per gallon
  - 541 gallons
  - 10,800 lbs CO2

How much CO2 is emitted annually in the US by cars and motorcycles?

- 136,568,000 US passenger vehicles (2005):
  - 1.690e12 miles travelled
  - 73.87e9 gallons
  - 1.478e12 lbs CO2

Davis, S.C. and Diegel, S.W., “Transportation Energy Data Book,” edition 26, Oak Ridge National Laboratory publication number ORNL-6978, United States Department of Energy, 2007

Calculate the mileage of a Segway

- Specifications:
  - 16 to 24 mile range per charge
  - Two 73.6V, 5.3Ah battery packs
- Calculations
  - Charge energy = (73.6)(5.3)(2) = 0.780kWh
  - Mileage = 0.780kWh / 20miles = 0.039kWh/mile
- Comparison
  - Segway white paper quotes 0.052kWh/mile

How significant is the CO2 reduction with PEVs?

- 1.690e12 miles travelled (2005)
- 1.478e12 lbs (670 million metric tons) CO2

- If 10% of the miles travelled were replaced by a 0.052kWh/mile PEV:

$$\left(1.690\cdot 10^{11}\text{miles}\right)\left(0.052\frac{\text{kWh}}{\text{mile}}\right)=8.79\cdot 10^{9}\text{kWh}$$

$$\left(1.477\cdot 10^{12}\text{lbsCO2}\right)\left(0.1\right)-\left(8.79\cdot 10^{9}\text{kWh}\right)\left(1.55\frac{\text{lbs}}{\text{kWh}}\right)$$

$$\left(1.477\cdot 10^{12}\text{lbsCO2}\right)\left(0.1\right)-13.62\cdot 10^{9}\text{lbsCO2}=134.1\cdot 10^{9}\text{lbsCO2}$$

=60.8 million metric tons reduction in CO2 emissions

How significant is the CO2 reduction with PEVs?

- For a 0.052kWh/mile PEV, assuming the current US electric generation fuel mix (1.55 lbsCO2/kWh):

$$\left(0.052\frac{\text{kWh}}{\text{mile}}\right)\left(1.55\frac{\text{lbsCO2}}{\text{kWh}}\right)=0.0806\frac{\text{lbsCO2}}{\text{mile}}$$

- For a 22.9 mpg auto:

$$\left(\frac{\text{gallon}}{22.9\text{mile}}\right)\left(20\frac{\text{lbsCO2}}{\text{gallon}}\right)=0.873\frac{\text{lbsCO2}}{\text{mile}}$$

91% reduction in CO2 emissions

What about PEV cost?

- Acquisition cost:
  - Segway (2 wheel) US$5,500
  - NMG (3 wheel enclosed) US$36,000
  - Enertia (electric motorcycle) US$12,000
  - Zero electric motorcycle US$8000




What about PEV cost?

- Energy operating cost:
  - Segway 0.61 US$/100miles
  - NMG 2.00 US$/100miles
  - Enertia 1.00 US$/100miles
  - Zero 0.70 US$/100miles




Conclusions: PEV's, BLDC's and society

- PEV's are technically feasible
- Motor and battery technology is mature
  - Future efficiency gains above 90% small
  - Mass density improvement
  - Geometric configurations for direct drive
- Fuel cost and government regulation will open PEV markets
- Challenge: Understand trade-offs among cost, weight, range, comfort, capacity