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## Hybrid Electric Vehicles into the Future: Opportunities and Challenges

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### Outline

- Motivation for Hybrid Electric Vehicle Research
- Introduction to Basic and Advanced HEV Topologies
- Hybrid Electric Vehicle Energy Storage Systems (Batteries, Ultra Capacitors, and Fuel Cells)
- Advanced Motors and Power Electronics for HEV Applications
- Simulation Results for Advanced HEV Drive Train Topologies
- Practical HEV Vehicles and Commercial Status
- Future Development Work and Conclusions

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### Motivation for Hybrid Electric Vehicle Studies

**Oil Production Versus Oil Usage**

**Percent of Total Pollution Caused By Transportation**

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### Motivation for Hybrid Electric Vehicle Studies

**Percentage Distribution of Vehicles in The United States**

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### Motivation for Hybrid Electric Vehicle Studies

- Corporate Average Fuel Economy (CAFE) standards were set for passenger cars and light trucks in 1978.
- Currently, the standards for light trucks and passenger cars are 20.7 miles/gallon and 27.5 miles/gallon, respectively.
- Between 1997 and 2001, the average fuel efficiency dropped from 22 miles/gallon to 20.4 miles/gallon.

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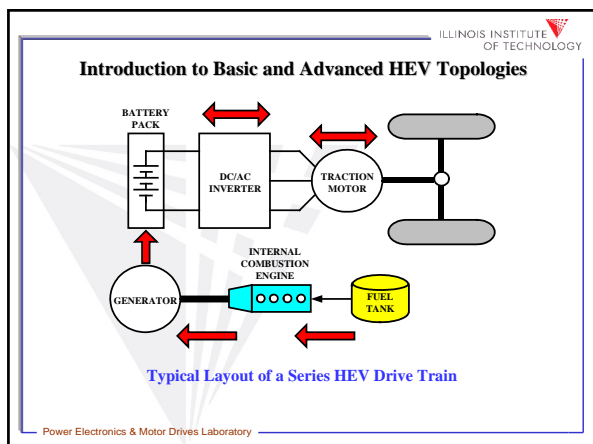
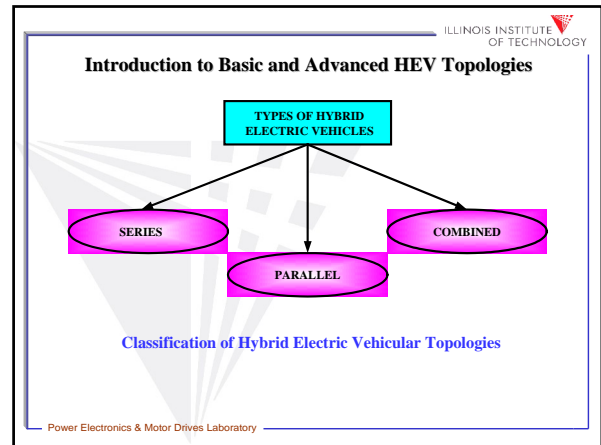
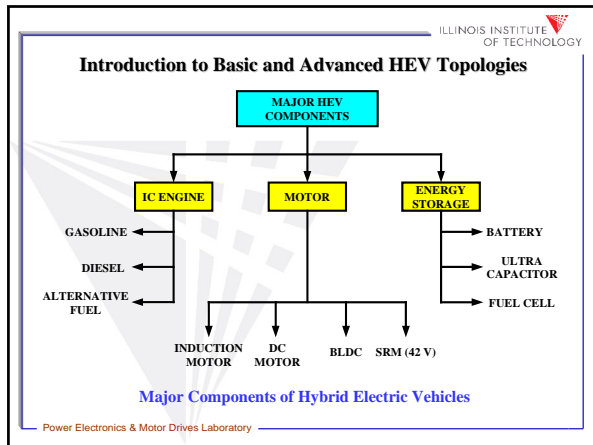
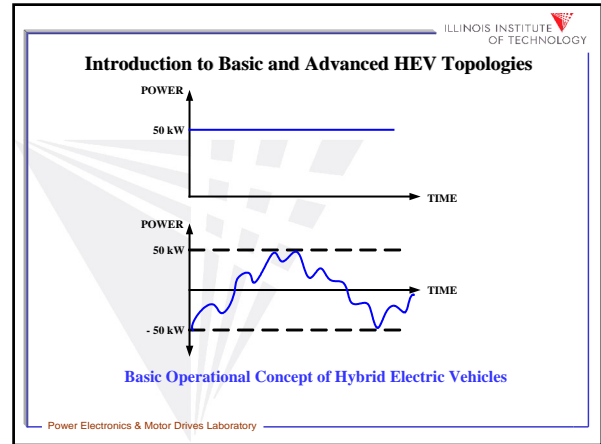
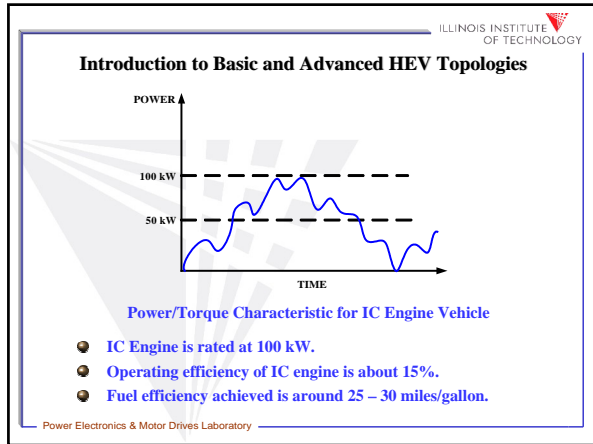
### Motivation for Hybrid Electric Vehicle Studies

**HYBRID ELECTRIC VEHICLE GOALS**

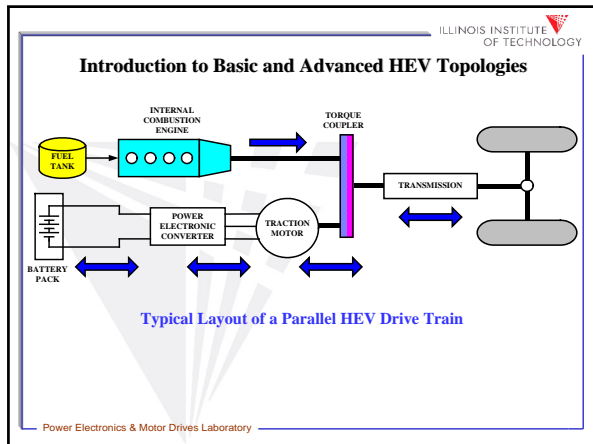
- 50 - 60 % FUEL ECONOMY IMPROVEMENT
- UP TO 40 % REDUCTION IN CO<sub>2</sub> EMISSIONS
- GREATER DRIVING RANGE
- LOAD LEVELING AND REGENERATIVE BRAKING

**Critical Goals of Hybrid Electric Vehicular Technology**

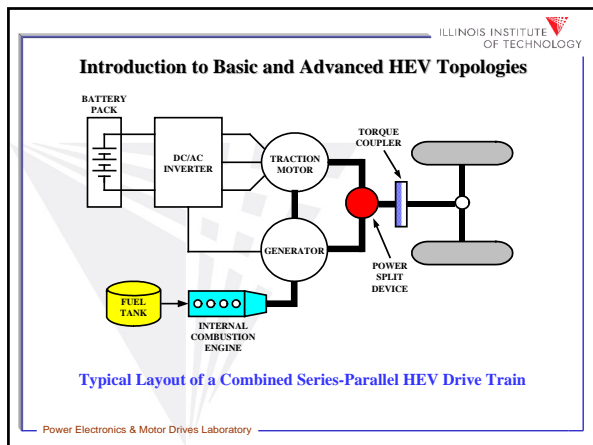
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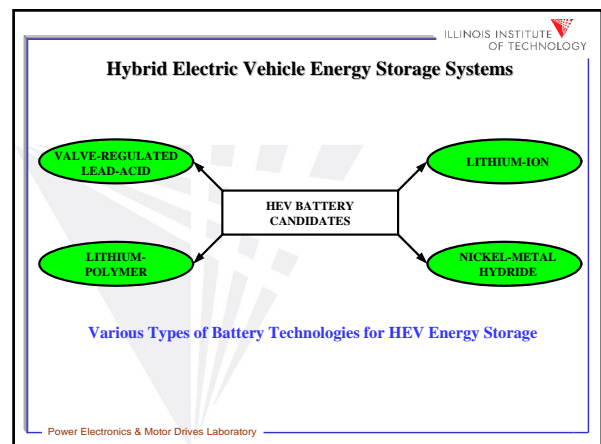
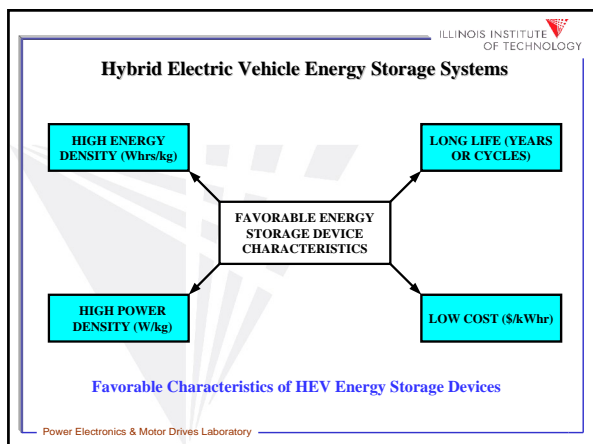
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- ### Introduction to Basic and Advanced HEV Topologies
- A series hybrid vehicle is primarily an electric vehicle with an on-board battery charger.
  - An ICE is generally run at an optimal efficiency point to drive the generator and charge the propulsion batteries on-board the vehicle.
  - When the state of charge (SOC) of the battery is at a predetermined minimum, the ICE is turned on to charge the battery.
  - The ICE turns off again when the battery has reached a desirable maximum SOC.
  - It must be noted that, in a series HEV, there is no mechanical connection between the ICE and the wheels.
  - Some energy is lost because of the two-stage power conversion process. A series hybrid vehicle is more applicable in city driving.
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- ### Introduction to Basic and Advanced HEV Topologies
- Parallel HEVs have both the ICE and the traction motor mechanically connected to the transmission.
  - The vehicle can be driven with the ICE, or the electric motor, or both at the same time.
  - Therefore, it is possible to choose the combination freely to feed the required amount of torque at any given time.
  - The most widely used strategy is to use the motor alone at low speeds, since it is more efficient than the ICE, and then let the ICE work alone at higher speeds.
  - When only the ICE is in use, the traction motor can function as a generator and charge the battery.
  - Using CVTs, it is possible to choose the most efficient operating points for the ICE at given torque demands freely and continuously.
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- ### Introduction to Basic and Advanced HEV Topologies
- There is an additional mechanical link between the generator and the electric motor, compared to the series configuration, and an additional generator compared to the parallel hybrid.
  - With this design, it is possible to combine the advantages of both the series and parallel HEV configurations.
  - It must be highlighted here that the series-parallel HEV is also relatively more complicated and expensive.
  - There are 2 major combinations of the ICE and motor; electric-intensive and engine-intensive.
  - A common operative characteristic for both types of series-parallel HEV systems is that the electric motor is used alone at start with ICE turned off/idling.
  - This is the system used in the *Toyota Prius* and the *Toyota Estima* hybrids.
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## Hybrid Electric Vehicle Energy Storage Systems

### Typical Specifications of VRLA Batteries

State of Charge	Voltage	Temperature (deg. C)	Charging Voltage
100%	2.13 V	0	2.35 V
70%	2.09 V	10	2.28 V
50%	2.06 V	20	2.23 V
20%	2.02 V	30	2.20 V
		35	2.17 V

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## Hybrid Electric Vehicle Energy Storage Systems

- **Nickel-Metal Hydride (Ni-MH) batteries** offer reasonable specific energy and specific power capabilities.
- They have a much longer life cycle than lead acid batteries and are safe and abuse-tolerant.
- They are constructed using rare earth or nickel alloy negative electrode and a sintered-type positive electrode.
- The main challenges with nickel-metal hydride batteries are their high cost, high self-discharge, and excessive heat generation at high temperatures.
- Furthermore, controlling the loss of hydrogen is a major issue, which eventually contributes to low cell efficiency.
- Although Nickel-Cadmium (Ni-Cd) batteries have higher specific energy and better life cycle than lead acid batteries, they do not deliver sufficient power, and are not considered for HEV applications.

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## Hybrid Electric Vehicle Energy Storage Systems

Nominal Voltage

→ Similar (1.25 V)

Discharge Capacity

→ Ni-MH up to 40% greater than Ni-Cd

High-Temperature Discharge Capacity

→ Ni-MH slightly better than Ni-Cd

Operating Temperature Limits

→ Ni-MH better at cold temperatures (Overall Similar)

Environmental Issues

→ Reduced with Ni-MH

**Significant Comparative Points Between Ni-MH and Ni-Cd Batteries**

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## Hybrid Electric Vehicle Energy Storage Systems

- **Lithium-Ion** batteries are rapidly entering laptop and cell-phone markets because of their high specific energy.
- In addition, they also have high specific power, high energy efficiency, good high-temperature performance, and low self-discharge.
- These characteristics make Lithium-Ion batteries suitable for HEV applications.
- However, to make them commercially viable for HEVs, further development is needed, similar to those for the EV-design versions.
- Issues that need to be looked at include, calendar and cycle life, higher degree of cell and battery safety, abuse tolerance, and acceptable cost.
- **Lithium polymer** batteries with high specific energy, initially developed for EV applications, also have the potential to provide high specific power for HEV applications.

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## Hybrid Electric Vehicle Energy Storage Systems

### Typical Specifications of Lithium-Ion Batteries

- 72 V = 20 Cells.
- Maximum Power = 22 kW.
- Weight = 60 kg.
- Cycle Life > 500.
- Life > 25,000 miles.
- Cost = \$2000 (Small Quantity).

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## Hybrid Electric Vehicle Energy Storage Systems

BATTERY MANAGEMENT ISSUES

PROTECTION ←

CONTROL ←

CHARGE MANAGEMENT ←

DATA RECORDING CAPABILITIES ←

LIFE TIME/CYCLE LIFE PREDICTION ←

→ BATTERY FUEL GAUGE

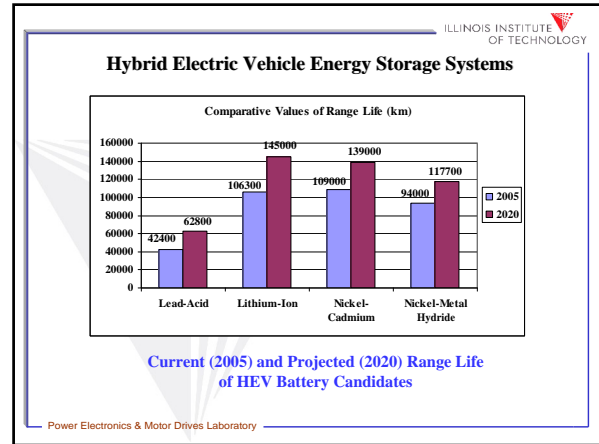
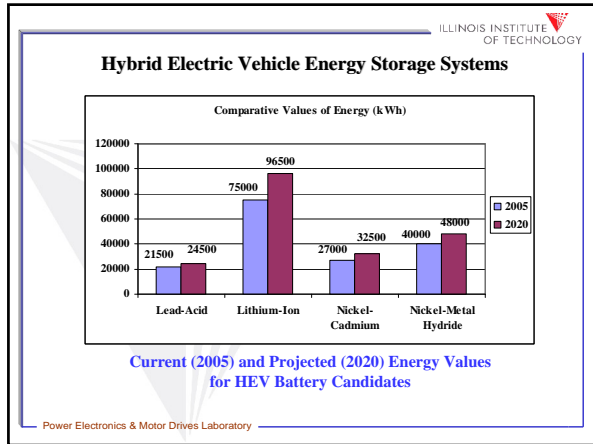
→ STATE OF FUNCTION

→ STATE OF HEALTH

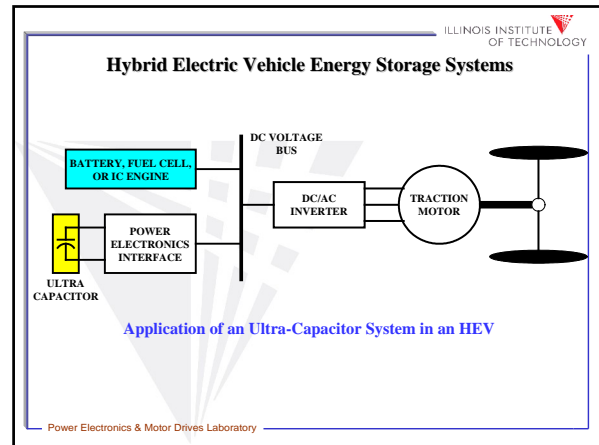
→ CELL EQUALISATION

→ TEMPERATURE MANAGEMENT

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- ### Hybrid Electric Vehicle Energy Storage Systems
- **Ultra-capacitors** are the most recent promising technology for improving HEV energy storage capabilities.
  - Also known as super-capacitors, pseudo-capacitors, and double-layer capacitors, ultra-capacitors are essentially powerful, high-cycle life, high energy capacitors.
  - Ultra-capacitors are currently available on the market with capacitance ranges up to 2,700 farads, and are capable of releasing that energy at a high or low rate.
  - Ultra-capacitors can deliver up to 10–20 times more power (joules or watts) than batteries.
  - They also offer 10–100 times the energy density (Wh/kg) of conventional capacitors.
  - For HEV applications, ultra-capacitors are being proposed as the secondary power source and are sized for short-duration load leveling.
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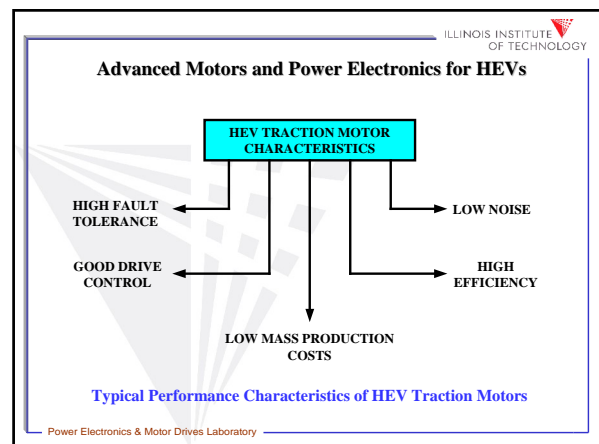
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### Hybrid Electric Vehicle Energy Storage Systems

Performance Comparison Between Lead-Acid Battery, Ultra-Capacitor, and Conventional Capacitor Storage Systems

Performance Parameter	Lead-Acid Battery	Ultra-Capacitor	Conventional Capacitor
Charge Time	1 - 5 hours	0.3 - 30 s	10 ms - 10 us
Discharge Time	0.3 - 3 hours	0.3 - 30 s	10 ms - 10 us
Energy (Wh/kg)	10 - 100	1 - 10	< 0.1
Cycle Life	1000	> 500,000	> 500,000
Specific Power (W/kg)	< 1000	< 10,000	< 100,000
Charge/Discharge Efficiency	0.7 - 0.85	0.85 - 0.98	> 0.95

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## Advanced Motors and Power Electronics for HEVs

### Considerations for Design of Electric Traction Motor for HEVs

- Using suitable driving schedule (drive cycle) to find most critical speed and torque regions.
- Optimize motor design in proper torque-speed regions, resulting in a high-speed design that cuts size and weight significantly.

One Drive Cycle of The Urban Dynamometer Driving Schedule (UDDS)

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## Advanced Motors and Power Electronics for HEVs

**FRONT-RUNNING HYBRID ELECTRIC VEHICLE TRACTION MOTOR CANDIDATES**

Various Hybrid Electric Vehicle Traction Motor Candidates

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## Advanced Motors and Power Electronics for HEVs

### Comparative Summary of Electric Traction Motors Advantages

MOTOR PARAMETER	IM	PMSM	SRM	DCM	SM
SIZE		●			
HIGH SPEED	●	●	●		
ENDURANCE	●		●		
EFFICIENCY		●			
CONTROLLER SIZE				●	
CONTROLLABILITY	●	●		●	
POWER CKT. SIZE			●	●	
RELIABILITY					
OVERALL	BETTER	BEST	GOOD	—	—

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## Advanced Motors and Power Electronics for HEVs

Integrated Starter-Alternator (ISA) System for Mild HEVs (42 V)

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## Simulation of Advanced HEV Topologies

### A. Conventional Vehicle

- A **conventional drive train** was selected using the already existing physical parameters of the *Honda Insight*.
- Engine size was selected to be 100 kW, with a maximum efficiency of 34%.
- It was run through the “Urban Dynamometer Driving Schedule (UDDS),” in order to simulate city conditions.
- For simulating the highway driving schedule, the vehicle was run on the “US06HWY” highway drive cycle.
- Each of the simulations were carried out using 5 complete drive cycles of each type.

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## Simulation of Advanced HEV Topologies

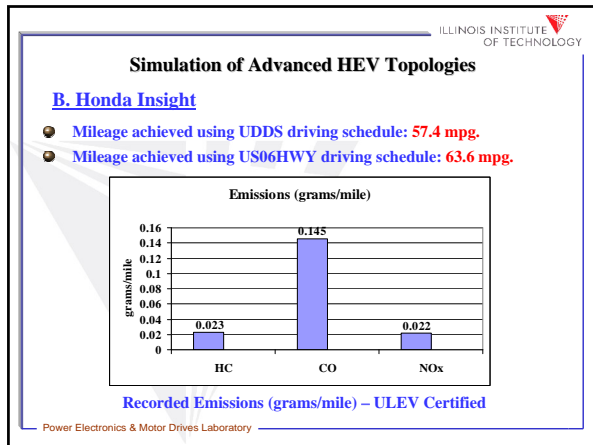
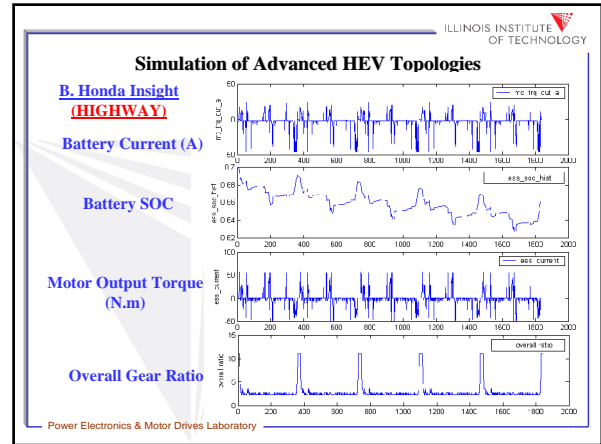
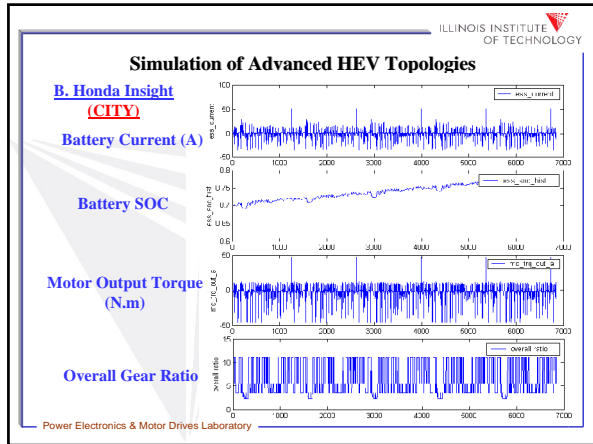
### A. Conventional Vehicle

UDDS Drive Cycle

US06HWY Drive Cycle

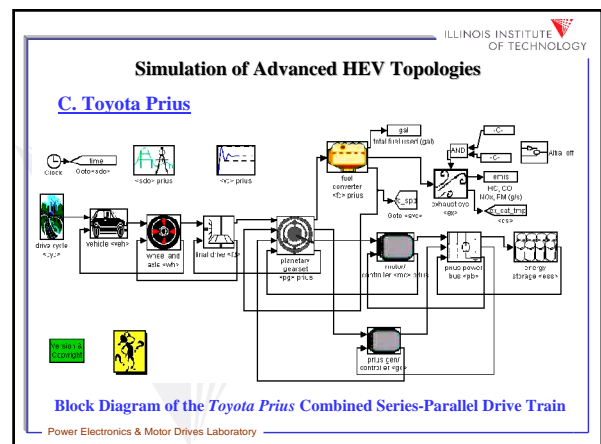
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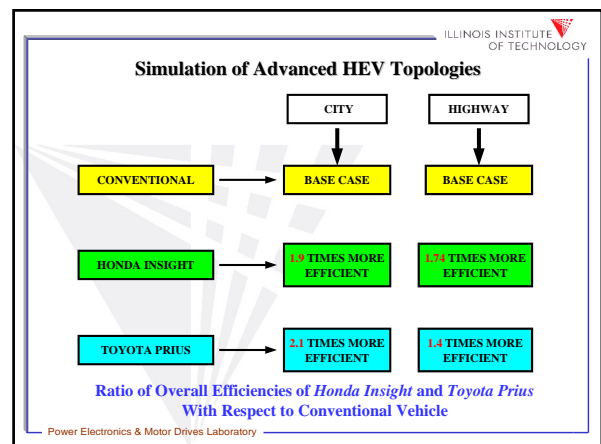
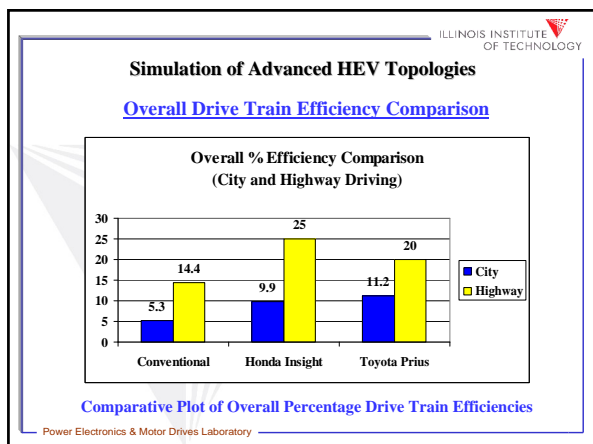
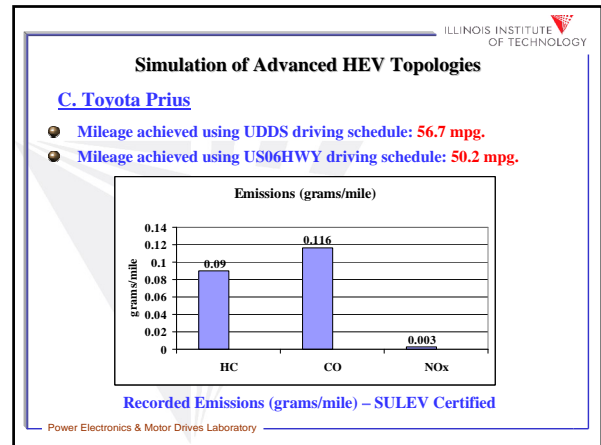
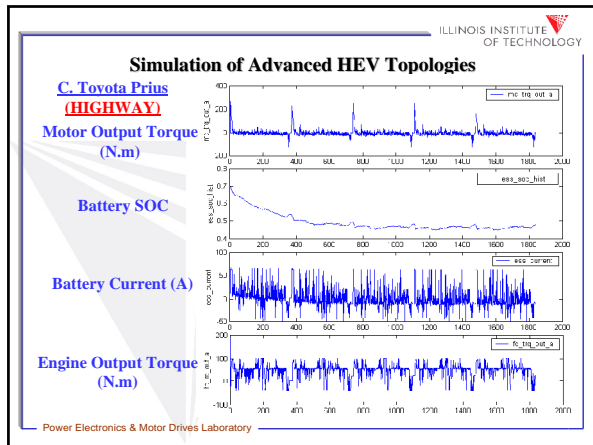
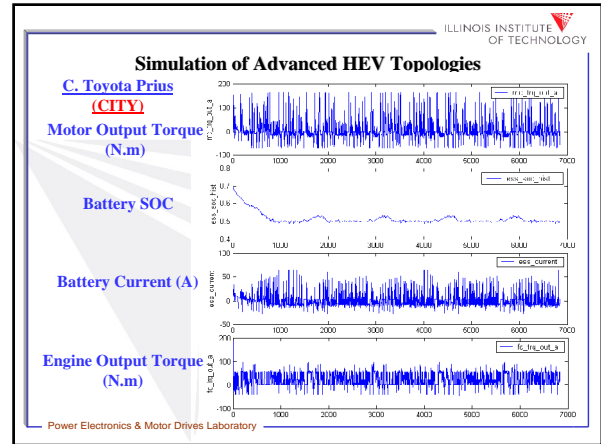
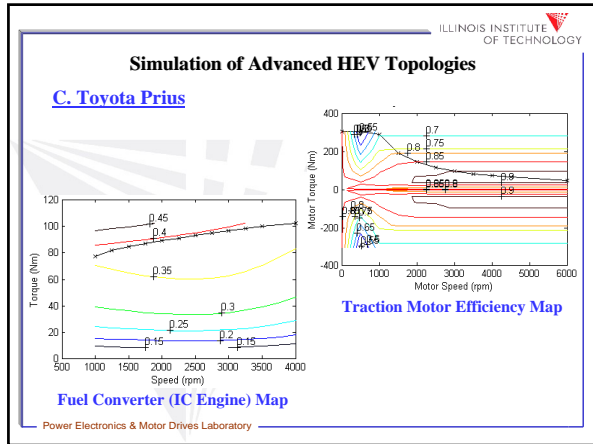


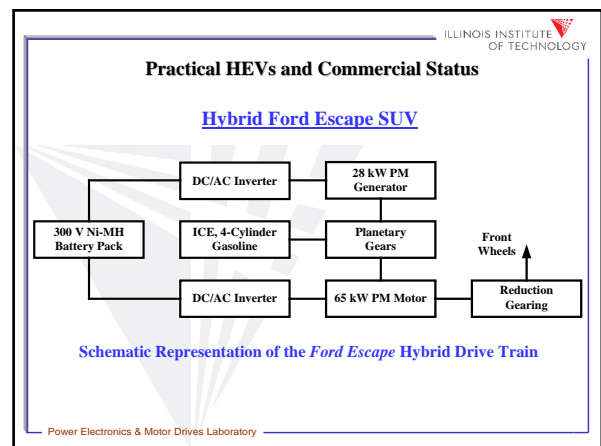
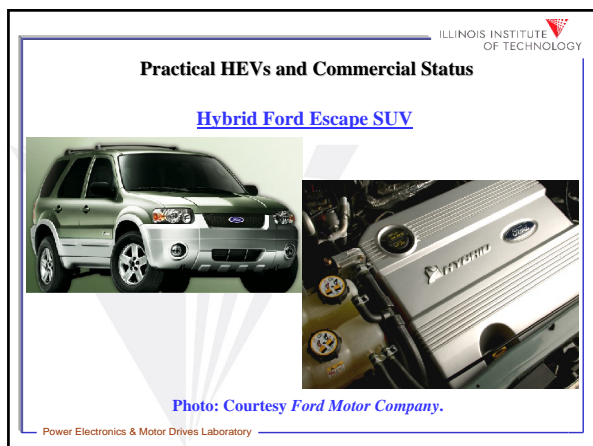
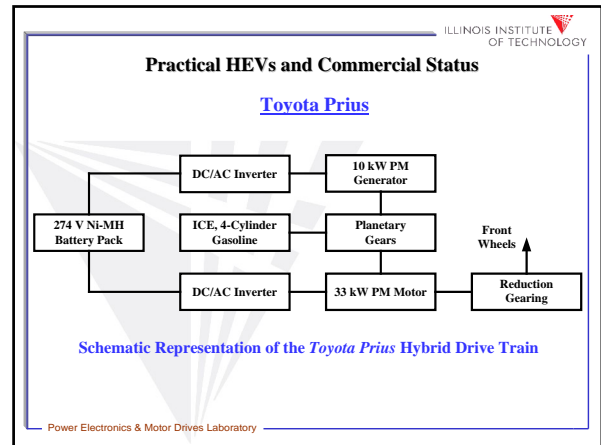
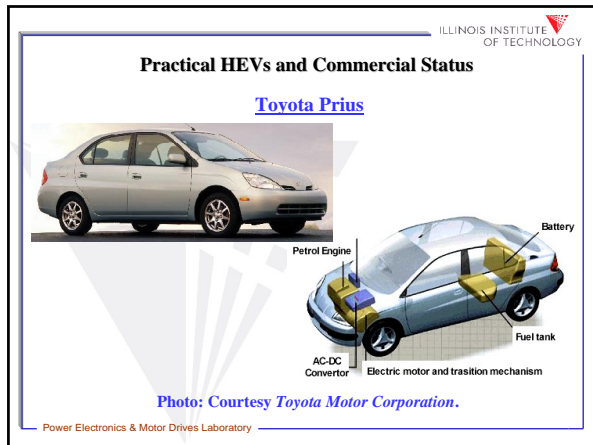
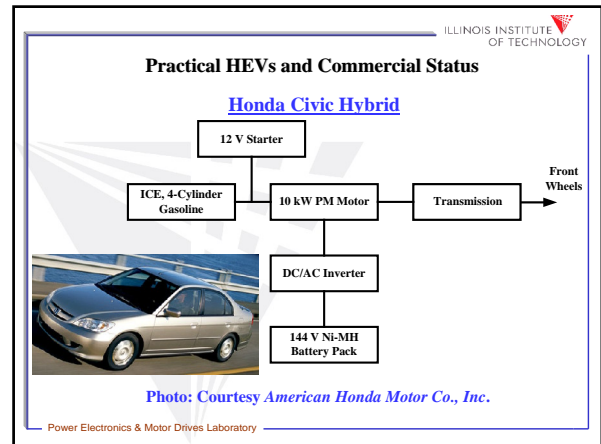
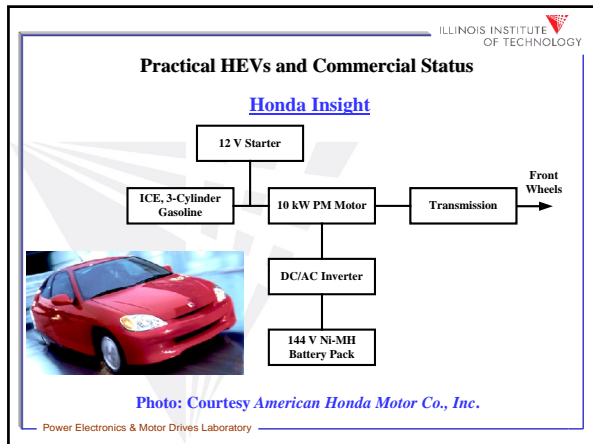


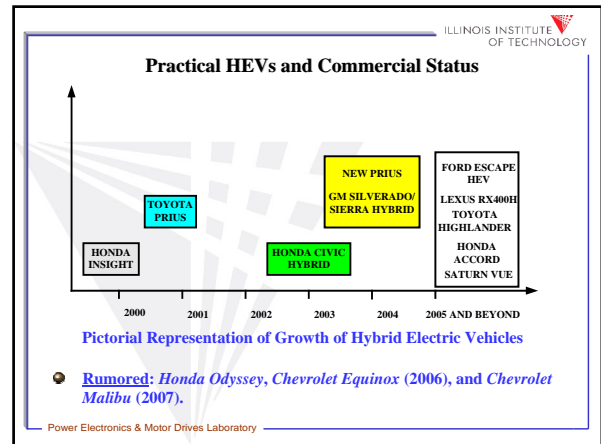
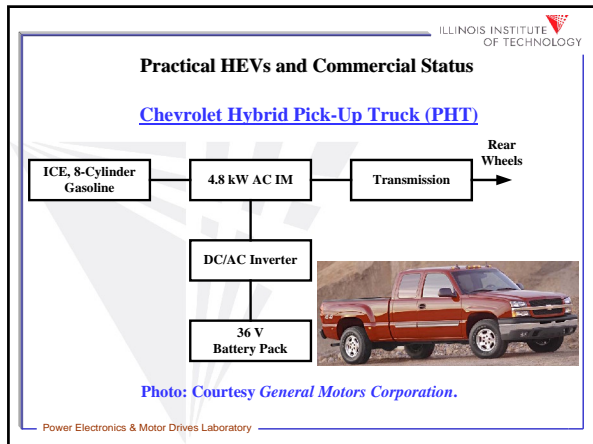
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- ### Simulation of Advanced HEV Topologies
- C. Toyota Prius**
- The vehicle details of the **Toyota Prius** are as described below:
- 4-door, 4-passenger sedan.
  - 2700-lb curb weight.
  - 5.4 kW (7.2 HP) road load @50 mph (80 km/h).
- The ICE details of the **Toyota Prius** are as described below:
- 1.5 L, in-line 4-cylinder.
  - 43 kW @4000 rpm.
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- ### Simulation of Advanced HEV Topologies
- C. Toyota Prius**
- The traction motor details of the **Toyota Prius** are as described below:
- Brush-less permanent magnet DC motor.
  - Generator: 15 kW @4800 rpm.
  - Motor: 30 kW @6000 rpm.
- The battery details of the **Toyota Prius** are as described below:
- Panasonic, Ni-MH, spiral wound cells.
  - 1.8 kWh, 21 kW, 40 kg.
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### Future Development Work and Conclusions

#### Fuel Saving via Usage of HEV Conversion Kit

Conventional Vehicle	Fuel Consumption	Annual Fuel Cost	25% HEV Improvement	Annual Saving	50% HEV Improvement	Annual Saving
10 mpg	1,200 gallons	\$2,400	12.5 mpg	\$480/year	15.0 mpg	\$800/year
15 mpg	800 gallons	\$1,600	18.75 mpg	\$320/year	22.5 mpg	\$533/year
20 mpg	600 gallons	\$1,200	25.00 mpg	\$240/year	30.0 mpg	\$400/year
25 mpg	480 gallons	\$960	31.25 mpg	\$192/year	37.5 mpg	\$320/year
30 mpg	400 gallons	\$800	37.50 mpg	\$160/year	45.0 mpg	\$266/year
35 mpg	343 gallons	\$686	43.75 mpg	\$137/year	52.5 mpg	\$229/year
40 mpg	300 gallons	\$600	50.0 mpg	\$120/year	60.0 mpg	\$200/year

- Gasoline Price: \$2.00/gallon
- Driving Distance: \$12,000 miles/year

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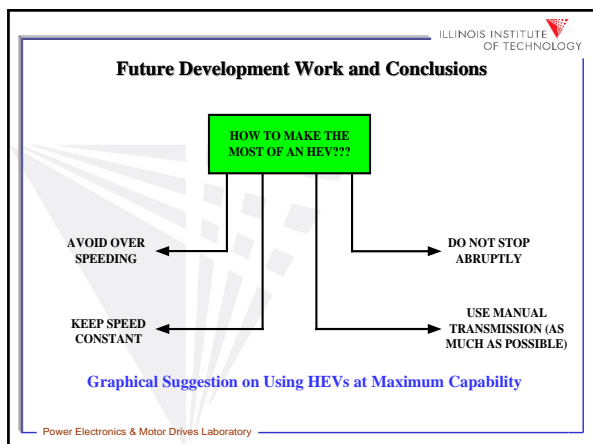
### Future Development Work and Conclusions

#### Fuel Saving via Usage of HEV Conversion Kit

Conventional Vehicle	Fuel Consumption	Annual Fuel Cost	25% HEV Improvement	Annual Saving	50% HEV Improvement	Annual Saving
10 mpg	1,200 gallons	\$4,800	12.5 mpg	\$960/year	15.0 mpg	\$1,600/year
15 mpg	800 gallons	\$3,200	18.75 mpg	\$640/year	22.5 mpg	\$1,066/year
20 mpg	600 gallons	\$2,400	25.00 mpg	\$480/year	30.0 mpg	\$800/year
25 mpg	480 gallons	\$1,920	31.25 mpg	\$384/year	37.5 mpg	\$640/year
30 mpg	400 gallons	\$1,600	37.50 mpg	\$320/year	45.0 mpg	\$532/year
35 mpg	343 gallons	\$1,372	43.75 mpg	\$274/year	52.5 mpg	\$458/year
40 mpg	300 gallons	\$1,200	50.0 mpg	\$240/year	60.0 mpg	\$400/year

- Gasoline Price (Upon Increase): \$4.00/gallon (Doubled)
- Driving Distance: \$12,000 miles/year

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- ### Future Development Work and Conclusions
- Today, around 40,000 vehicles sold in the US annually are hybrids.
  - Of those, nearly 50% comprise of the *Toyota Prius*, 47% of the sale belongs to *Honda Civic Hybrid*, and 3% sales belongs to the *Honda Insight*.
  - It is projected that by the year 2007, the annual sales of HEVs will rise to nearly 500,000.
  - Release of new HEVs, such as the *Ford Escape SUV*, *Lexus RX400H*, *Toyota Highlander*, *Honda Accord*, *Saturn VUE*, and others, constitutes a major portion of the automotive industrial development plan.
  - Between the years 2015 and 2030, it is believed that the auto market will have a stronger influence of HEVs.
  - This time period will also probably see the introduction of all-electric and fuel cell vehicles.
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### Future Development Work and Conclusions



Toyota Prius



Honda Insight

TODAY, HEVs ARE COST EFFECTIVE,  
ENVIRONMENTALLY FRIENDLY, AND  
FUEL EFFICIENT



Ford Escape Hybrid



Honda Civic Hybrid