
http://media-files.gather.com

What's the Deal with Hybrid and Electric Cars?

Day 1: Introduction to Electric Vehicles

Irene Berry, Mike Khusid, Manolis Kasseris, and Arthur Mak;
MIT Electric Vehicle Team

January 20, 2009
web.mit.edu/evt/iap2009

Outline: *Introduction to Electric Vehicles (EVs) and EV Components*

1. Introduction to EVs

1. EV issues and terminology

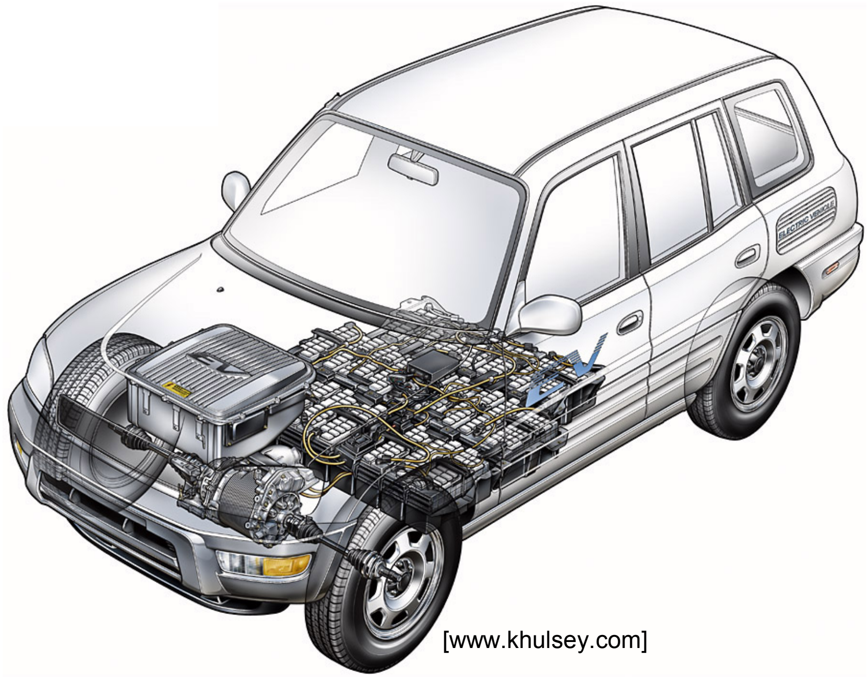
1. Batteries

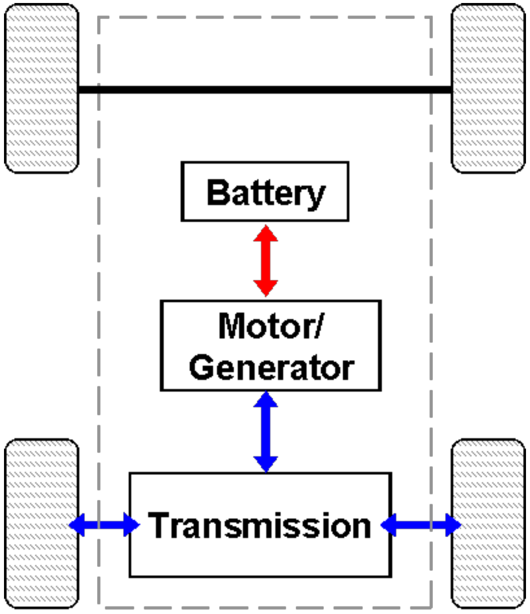
1. Motors

http://www.toonpool.com

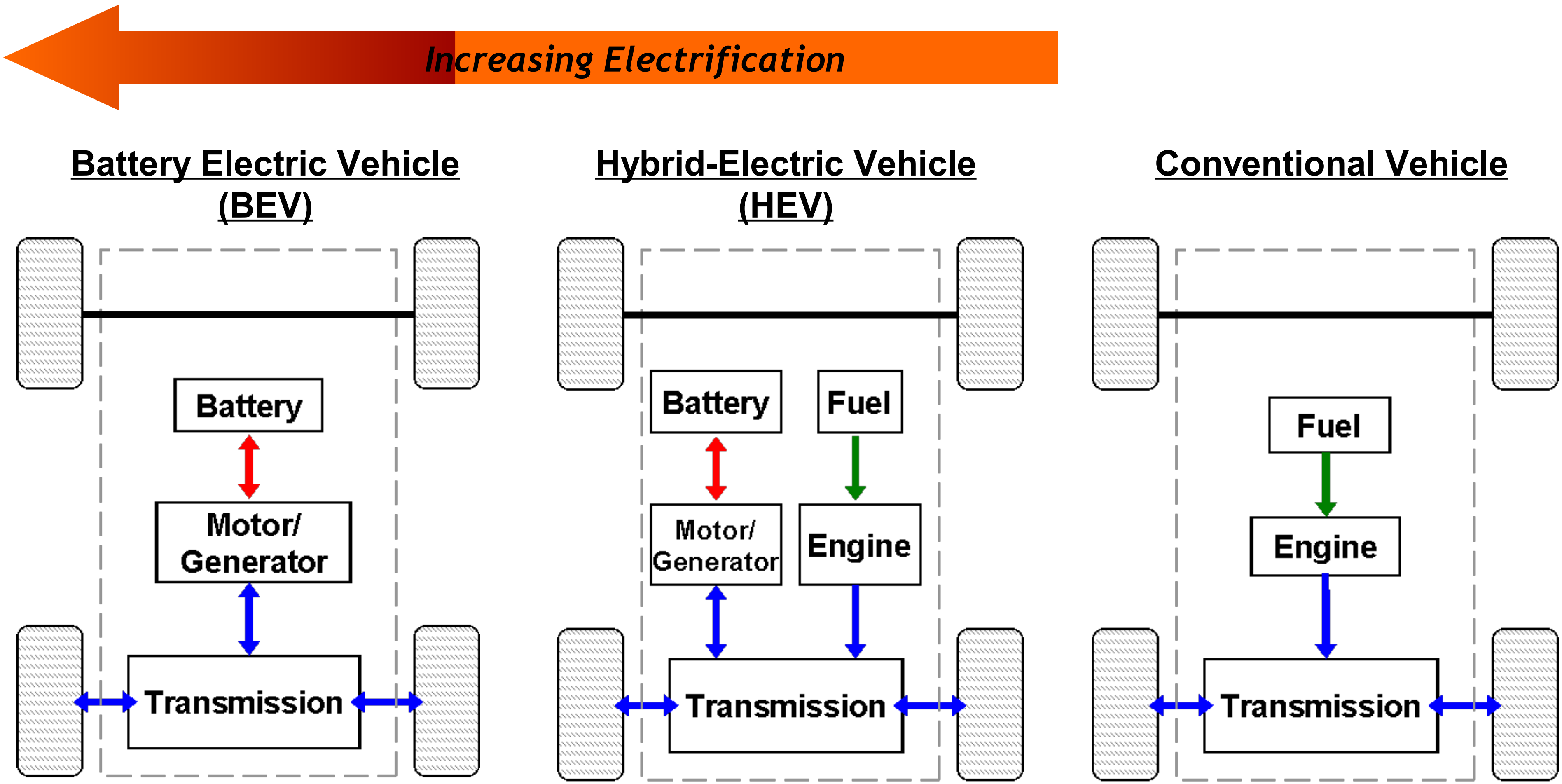
Introduction to Electric Vehicles (EVs)

A battery electric vehicle (BEV) is a vehicle that is powered by electricity stored on the vehicle in a battery through the use of one or more electric motors



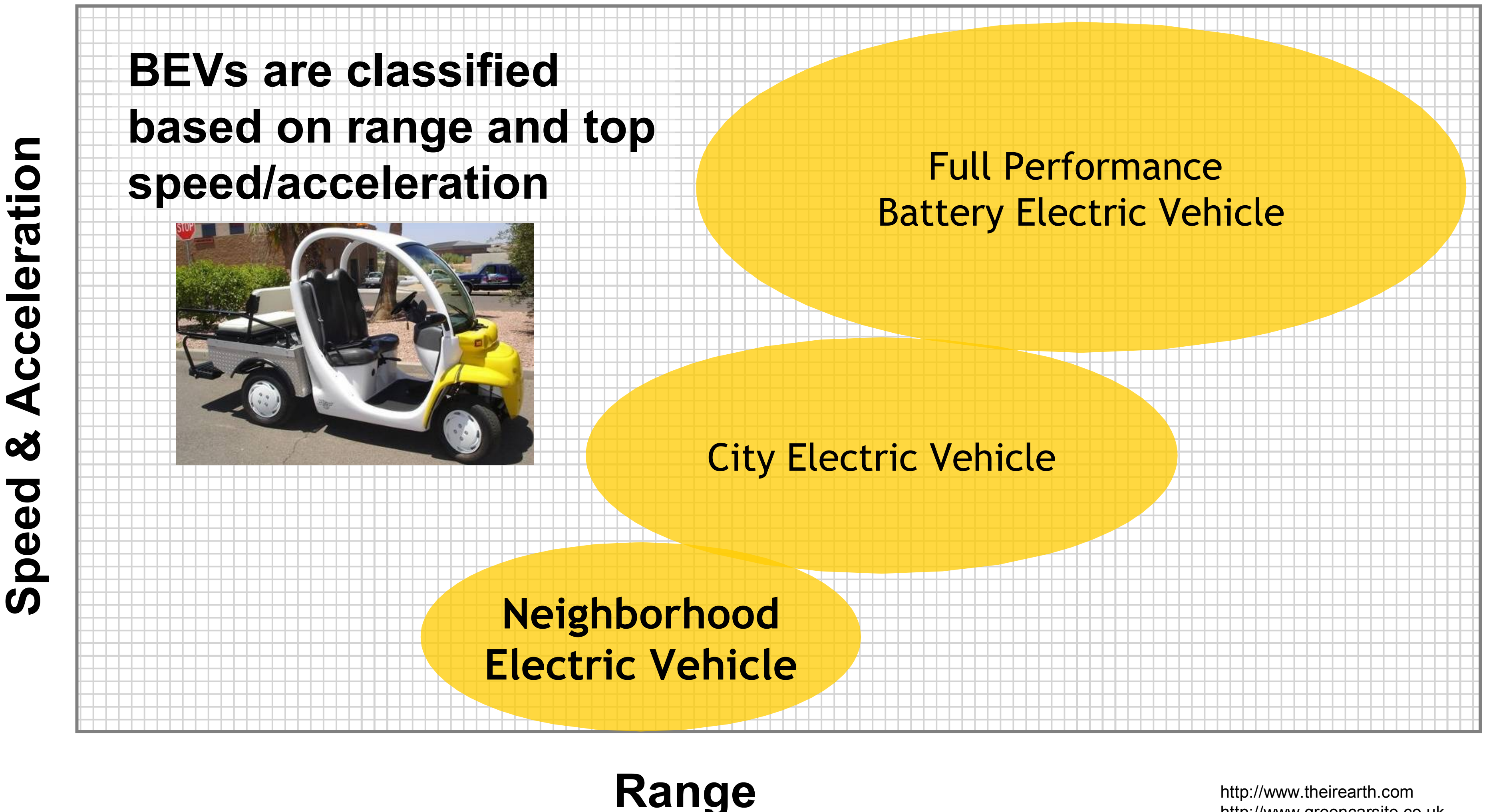


“Electric vehicles” include hybrids as well as pure battery electric vehicles



EVs also include Fuel Cell Vehicles and EVs with alternative energy storage (e.g. ultracapacitors)

There are many varieties of Battery Electric Vehicles



http://www.theirearth.com
http://www.greencarsite.co.uk
http://www.rotationalenergy.com

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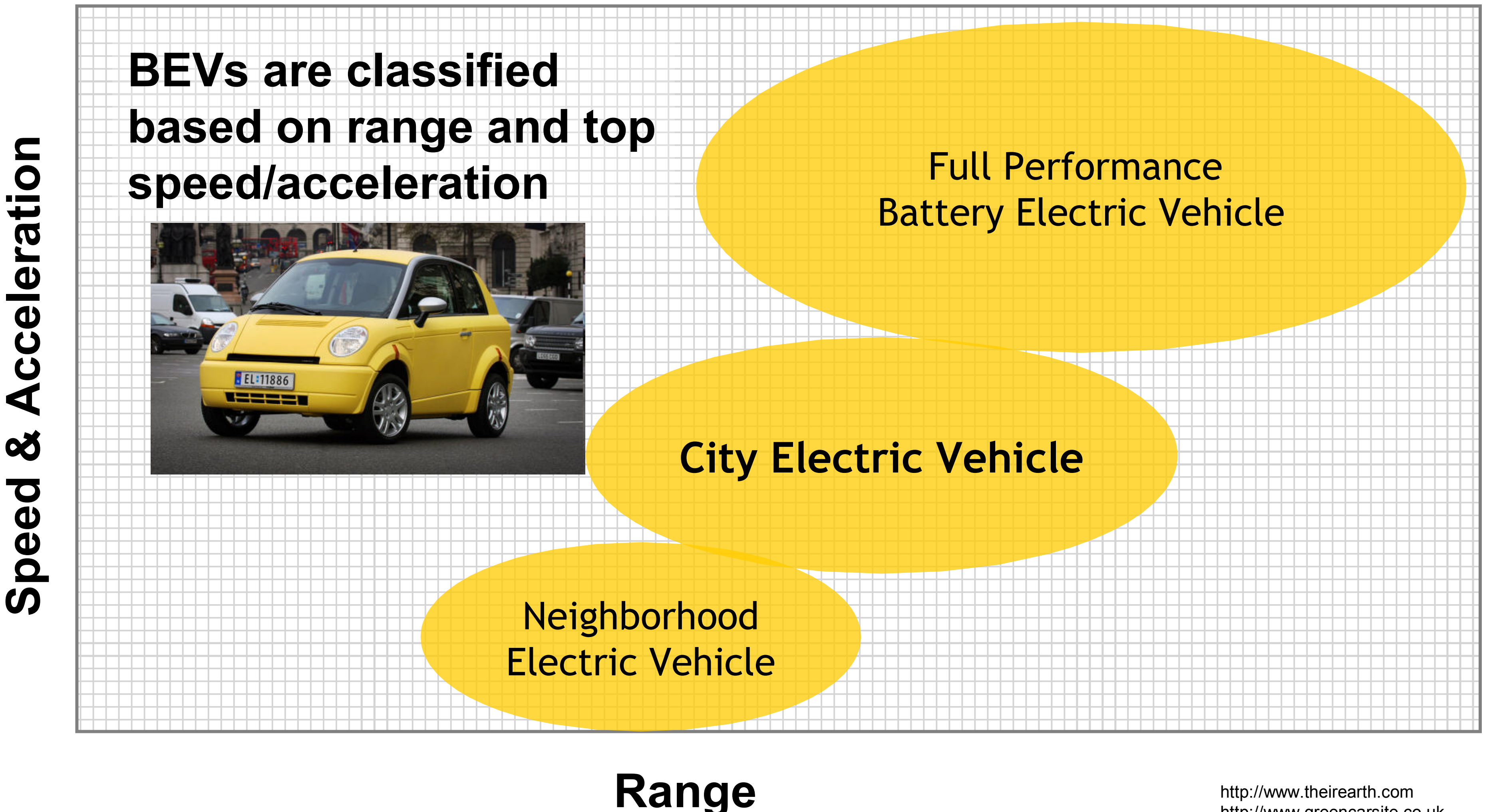

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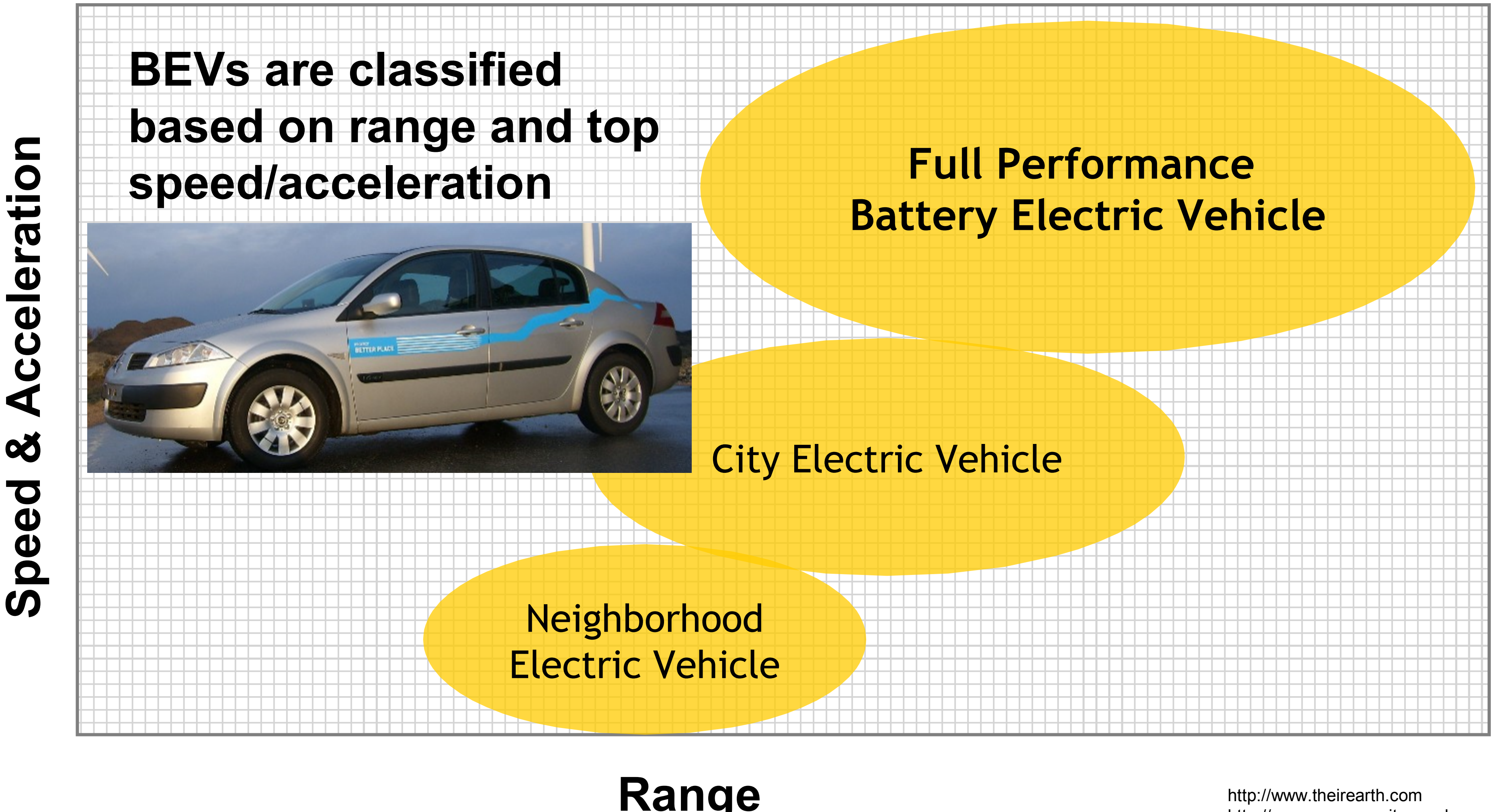
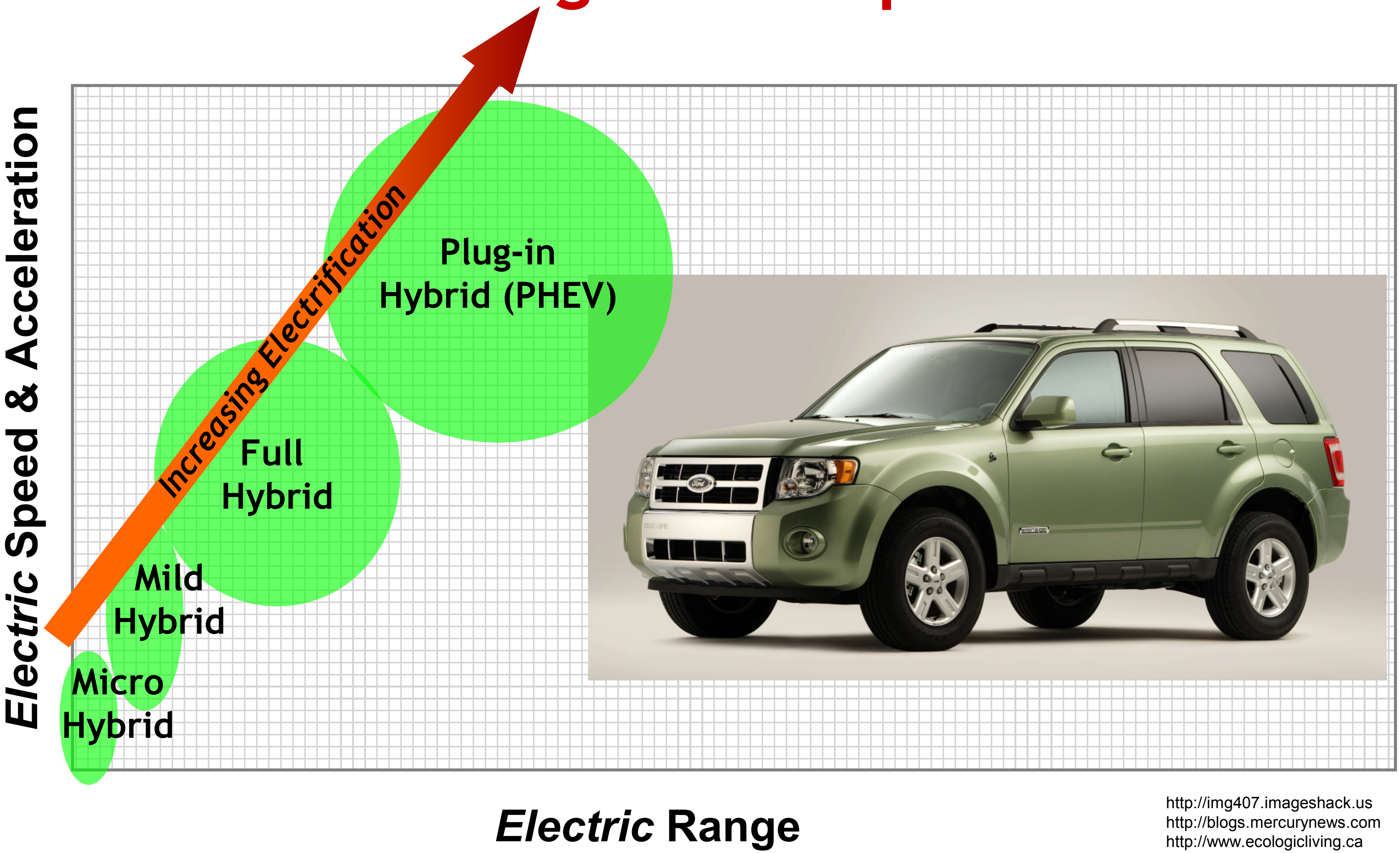


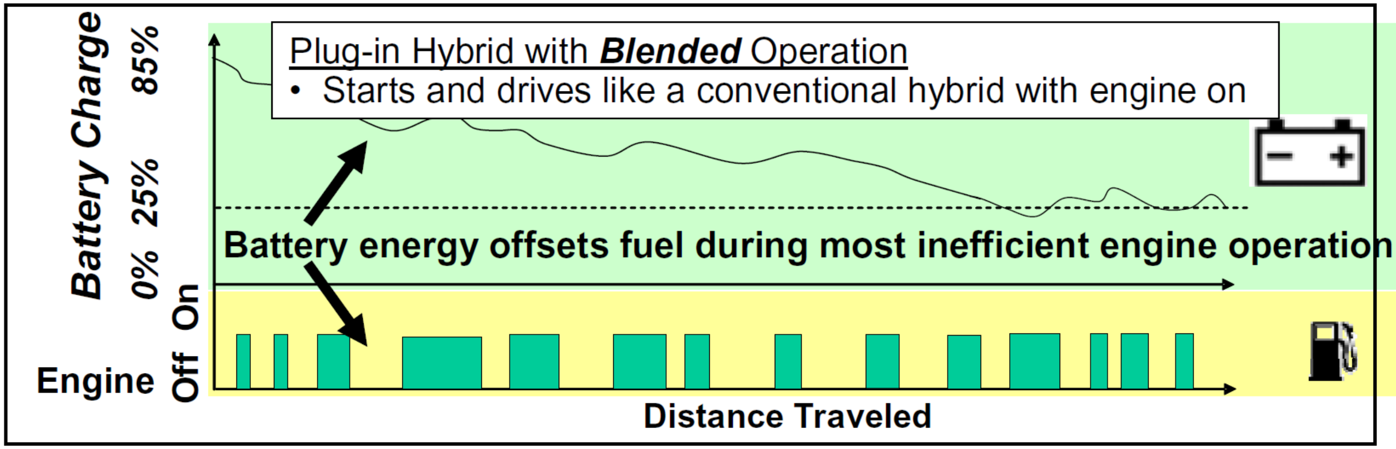
http://www.theirearth.com
http://www.greencarsite.co.uk
http://www.rotationalenergy.com

Hybrids (HEVs) vary in electrification while maintaining vehicle performance

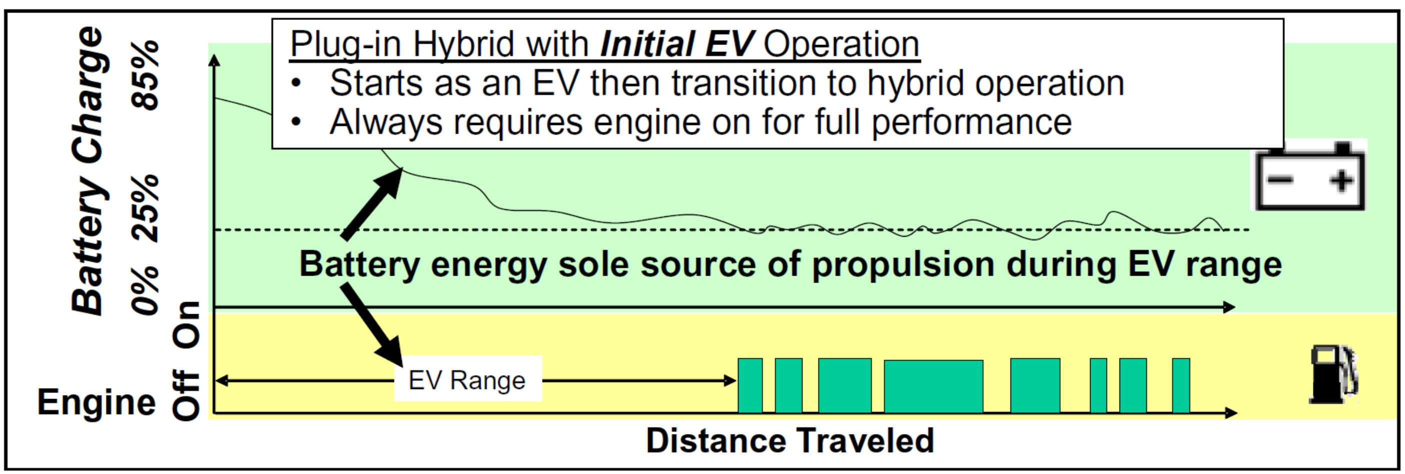


http://img407.imageshack.us
http://blogs.mercurynews.com
http://www.ecologicliving.ca
http://upload.wikimedia.org

Plug-in hybrids (PHEVs) are described by all-electric range (AER) and control



Blended operation with small AER



Charge depleting followed by charge sustaining mode: large AER

[Tate, Harpster, and Savagian 2008]

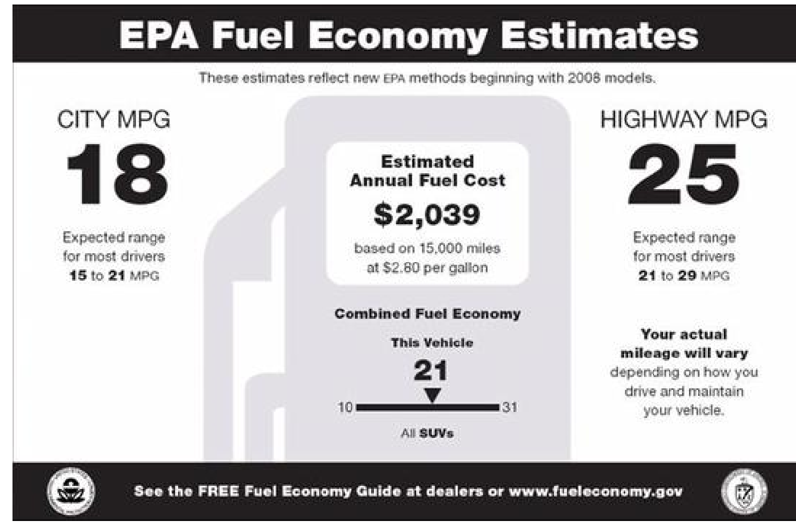
Next topic: EV Issues and Terminology

- Fuel economy
- EV, HEV, PHEV fuel economy
- Well-to-wheels (WTW) analysis
  - WTW emissions
  - WTW equivalent fuel economy

http://www.ecosherpa.com

Some notes about vehicle fuel economy

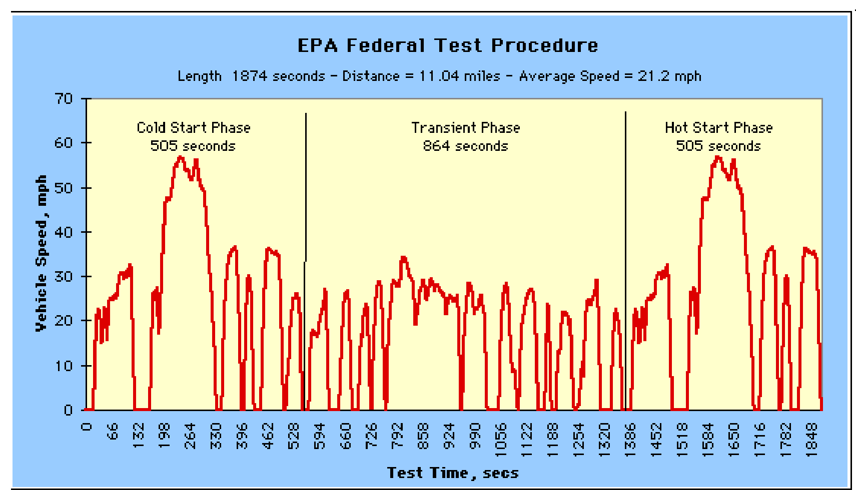
EPA fuel economy numbers, expressed in miles per gallon (MPG), are calculated from a specific combination of drive cycles, temperatures, and starts



http://static.huddler.com

<u>To understand fuel economy numbers:</u>

- **Drive cycle:** e.g. city or highway cycle, real-world, or constant speed
- **Test temperature:** air temperature
- **Start:** vehicle state (warm or cold) prior to test
- **Fuel:** convert to gasoline-equivalent
- **Test mass:** weight added (to account for passengers and cargo)



http://www.epa.gov

EV "energy economy" is reported in Wh/ mile or MPG gasoline equivalent

Vehicle	Combined City/Hwy	
	Wh/mile	**mpgge**
Nissan Altra EV (Li-ion)	310	110
Toyota RAV4 EV (NiMH)	301	113
Ford Th!nk EV (NiCd)	360	95
Ford Explorer EV (VRLA)	621	55
Ford Ranger EV (NiMH)	422	81

http://www.fueleconomy.gov

$$mpgge_{battery-to-wheel} = \frac{1}{[Wh/mi]} * (33{,}705 \text{ Wh/gal})$$

the vehicle's electrical energy consumption per mile

the energy density of gasoline by volume

Hybrid fuel economy captures both gasoline and electrical consumption

$$\frac{\text{gallons of gasoline}}{\text{miles traveled}} \neq \text{Accurate Fuel Economy}$$

http://apolloalliance.org

A more accurate measure of the energy consumption would consider the amount of energy drained (or added to) the battery

PHEV fuel economy is even more complicated

Different types of PHEVs (blended mode or charge depleting) will have very different MPGs over drive cycles of different lengths

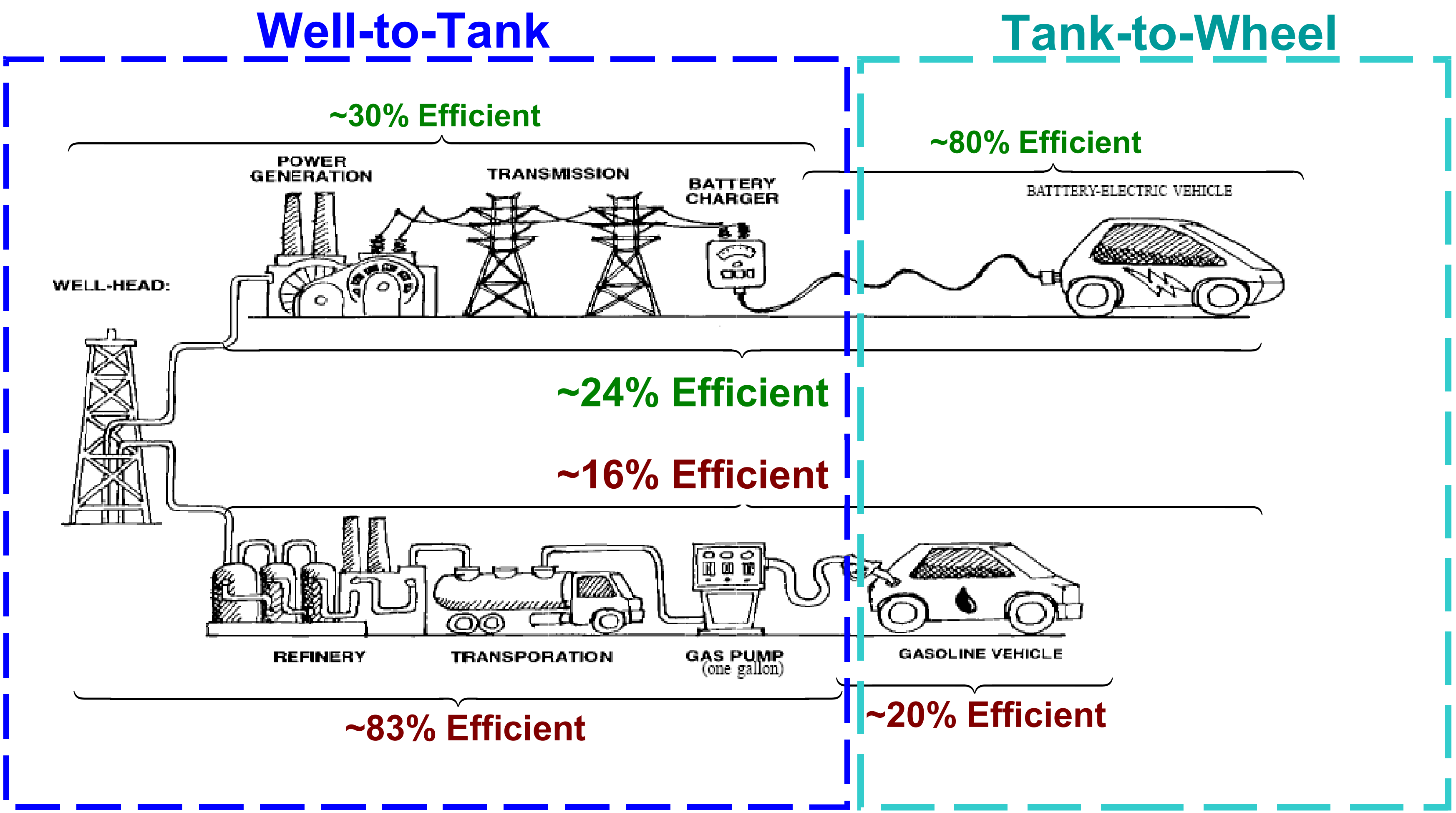
Fuel Economy (mpgge, battery-to-wheels) of different PHEV types (example only)

	Charge depleting PHEV	**Blended mode PHEV**
Initial 20-40 miles	150 (charge depleting)	100 (blended)
Remaining range	50 (charge sustaining)	80 (blended)
Total (mpgge)	? (depends on distance)	? (depends on distance)

How to compare these different vehicles?

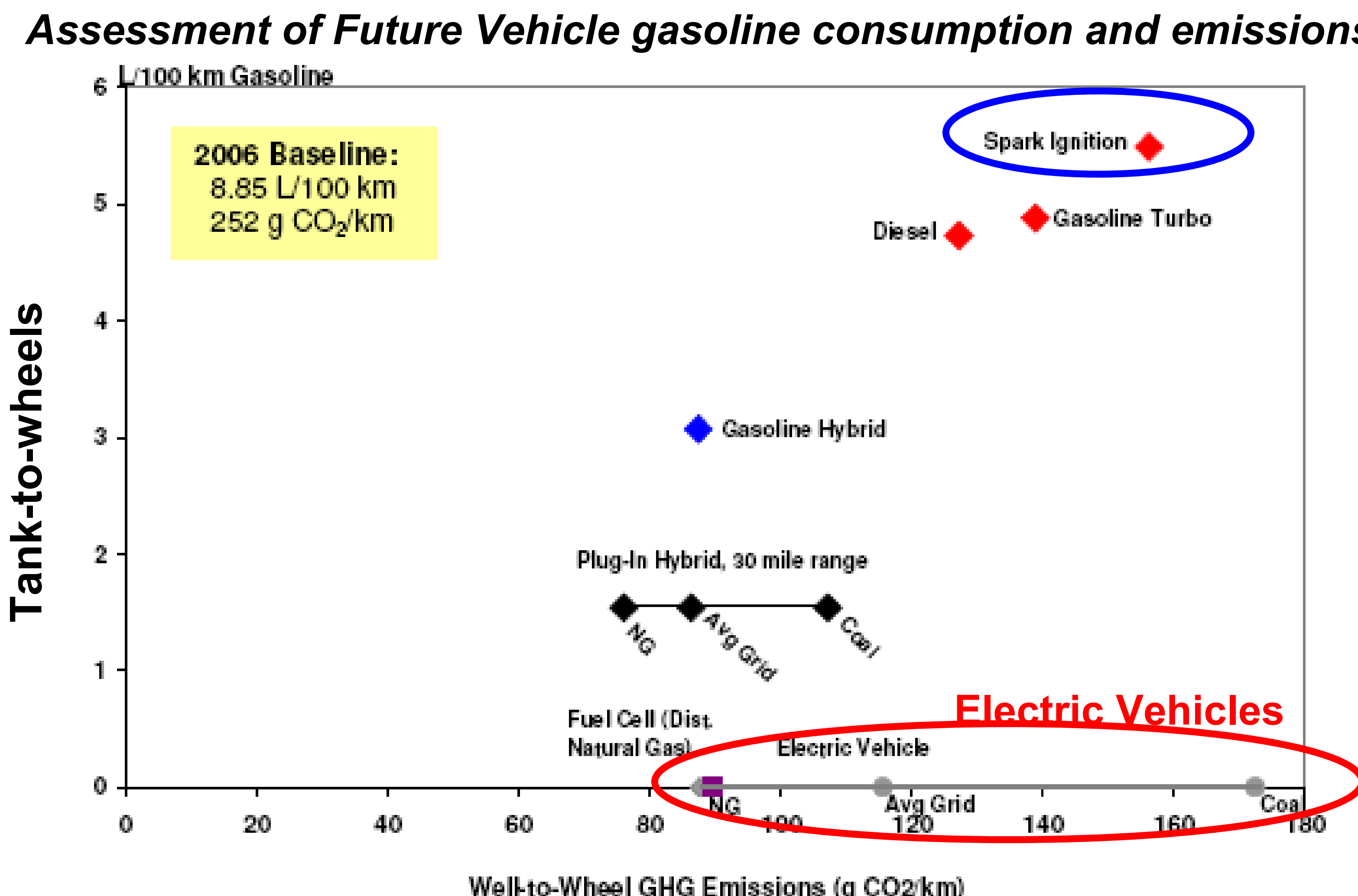
SAE J1711 prescribes that PHEV fuel economy numbers weigh charge depleting, charge sustaining, and blended modes based on average U.S. driving distances

Vehicles should be compared on a well-to-wheels basis



[http://www.nesea.org/]]

Well-to-wheels emissions for an EV depends on source of electricity



[Kromer 2007]

Well-to-wheels fuel economy reflects efficiency of entire fuel cycle

Fuel Economy (mpgge)

Vehicle	Tank-to-wheel		Well-to-wheel	
	City	Hwy	City	Hwy
Nissan Altra EV	117	130	36	39
Nissan Altima	20	27	17	22
Toyota RAV4 EV	117	91	36	28
Toyota RAV4	21	27	17	22
Ford Explorer EV	63	47	19	14
Ford Explorer	14	19	12	16
Nissan Hyper-Mini EV	120	94	36	29

$$mpgge_{well-to-wheel} = \frac{1}{[Wh/mi]} * (33{,}705 \text{ Wh/gal}) * (e)$$

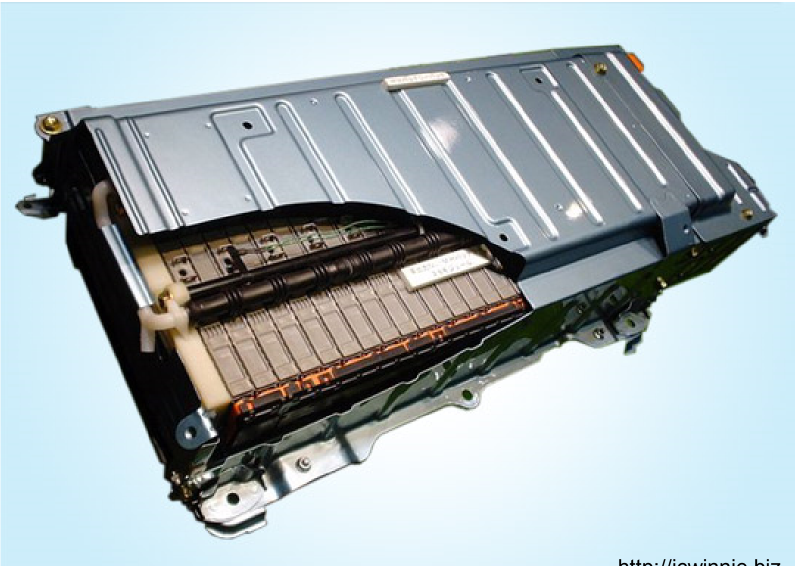
well-to-tank efficiency:
30.3% for electricity
83.0% for gasoline

Next topic: Batteries for EVs

- Key terms
- How they work
- Tradeoffs and desired characteristics
- Comparison of technologies
- Ultra-capacitors and new battery technologies

http://www.hybridcars.com

EV battery packs are assembled from connected battery cells and modules



http://jcwinnie.biz

http://blogs.edmunds.com

http://jcwinnie.biz/

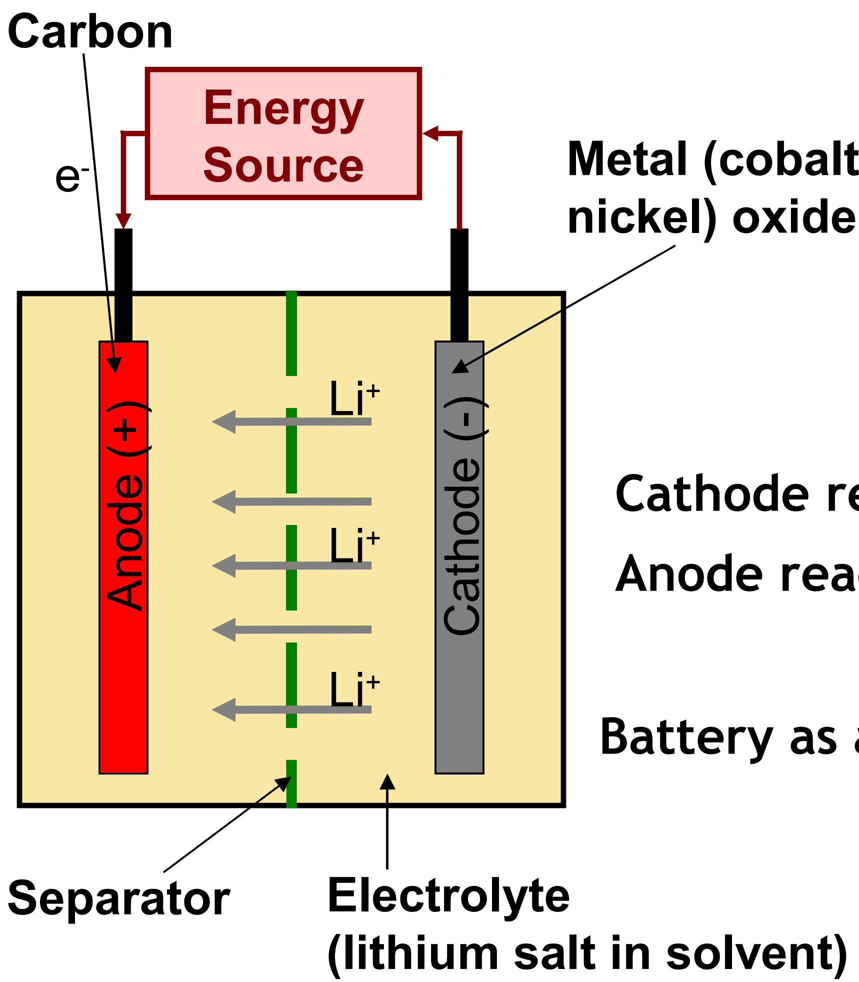
http://www.gadgets-reviews.com

Some Important Battery Terms

- **State of charge (SOC)**
  - Battery capacity, expressed as a percentage of maximum capacity
- **Depth of Discharge (DOD)**
  - The percentage of battery capacity that has been discharged
- **Capacity**
  - The total ***Amp-hours (Amp-hr)*** available when the battery is discharged at a specific current (specified as a C-rate) from 100% SOC
- **Energy**
  - The total ***Watt-hours (Wh)*** available when the battery is discharged at a specific current (specified as a C-rate) from 100% SOC
- **Specific Energy (Wh/kg)**
  - The total Watt-hours (Wh) per unit mass
- **Specific Power (W/kg)**
  - Maximum power (*Watts)* that the battery can provide per unit mass, function of internal resistance of battery

A battery stores electricity through reversible chemical reactions

Typical Lithium-ion cell



CHARGE REACTIONS

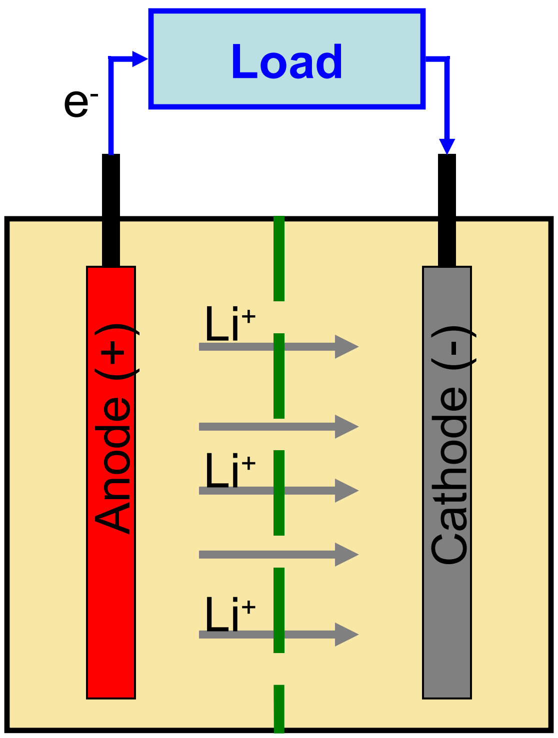
Cathode reaction: $LiCoO_2 \rightarrow Li_{1-x}CoO_2 + xLi^+ + xe^-$

Anode reaction: $C + xLi^+ + xe^- \rightarrow CLi_x$

Battery as a whole: $LiCoO_2 + C \rightarrow Li_{1-x}CoO_2 + CLi_x$

A battery provides electricity through reversible chemical reactions

Typical Lithium-ion cell



DISCHARGE REACTIONS

Cathode reaction: $LiCoO_2 \leftarrow Li_{1-x}CoO_2 + xLi^+ + xe^-$

Anode reaction: $C + xLi^+ + xe^- \leftarrow CLi_x$

Battery as a whole: $LiCoO_2 + C \leftarrow Li_{1-x}CoO_2 + CLi_x$

Number of electrons generated determines the current provided by a given size battery

Battery voltage is determined by the energy of the reactions

Cathode (Reduction) Half-Reaction	Standard Potential E ° (volts)
$Li^+(aq) + e^- \rightarrow Li(s)$	-3.04
$K^+(aq) + e^- \rightarrow K(s)$	-2.92
$Ca^{2+}(aq) + 2e^- \rightarrow Ca(s)$	-2.76
$Na^+(aq) + e^- \rightarrow Na(s)$	-2.71
$Zn^{2+}(aq) + 2e^- \rightarrow Zn(s)$	-0.76
$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$	0.34
$O_3(g) + 2H^+(aq) + 2e^- \rightarrow O_2(g) + H_2O(l)$	2.07
$F_2(g) + 2e^- \rightarrow 2F^-(aq)$	2.87

Best Anode

Best Cathode

http://www.mpoweruk.com/chemistries.htm

Higher voltage → higher power and efficiency at lower pack cost and weight, more stable voltage profile

Trade-offs in Battery Design

Power & Energy

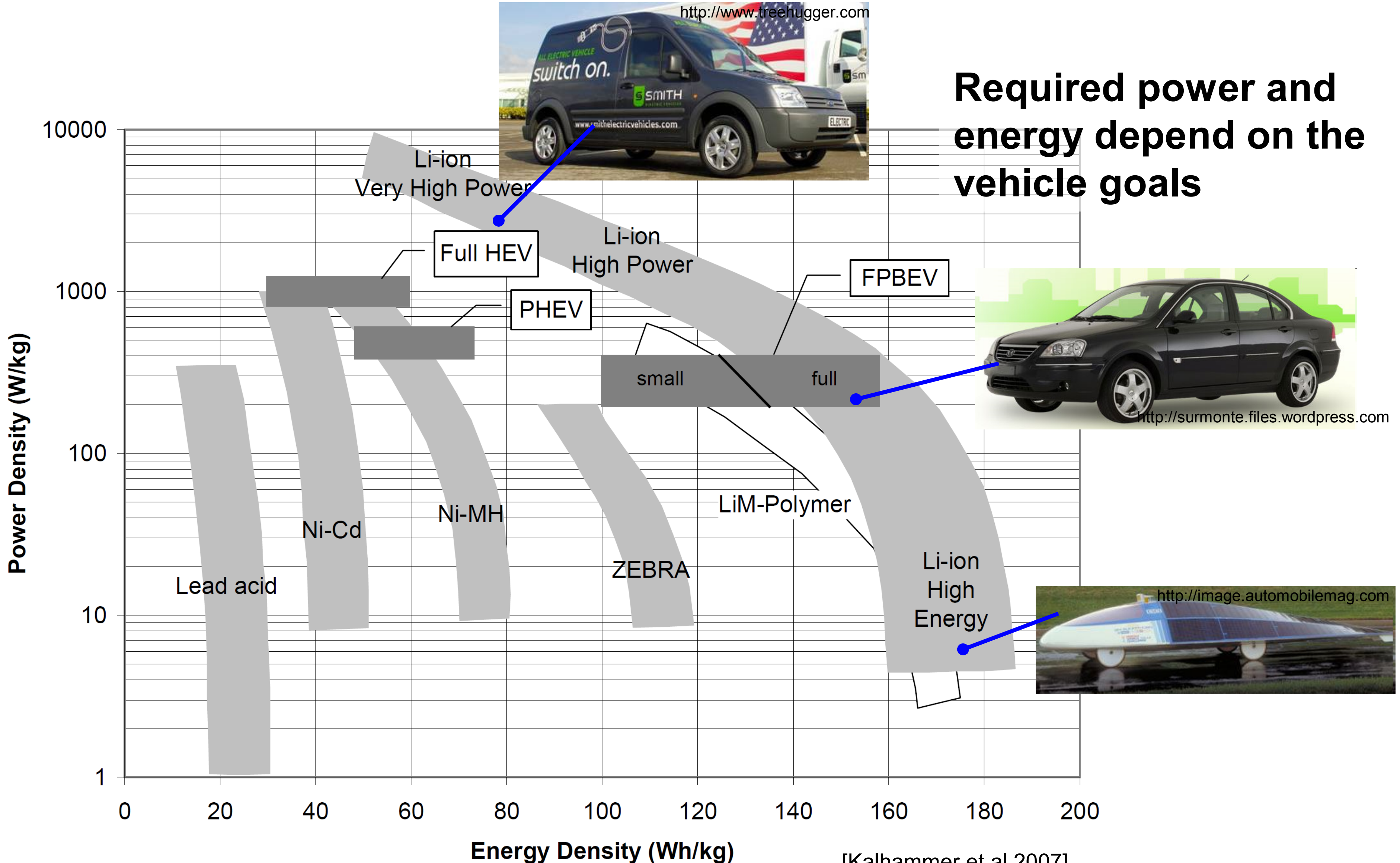
Lifetime, safety, & cost

Power

Energy

The power-energy tradeoff affects vehicle performance and range

Required power and energy depend on the vehicle goals



[Kalhammer et al 2007]

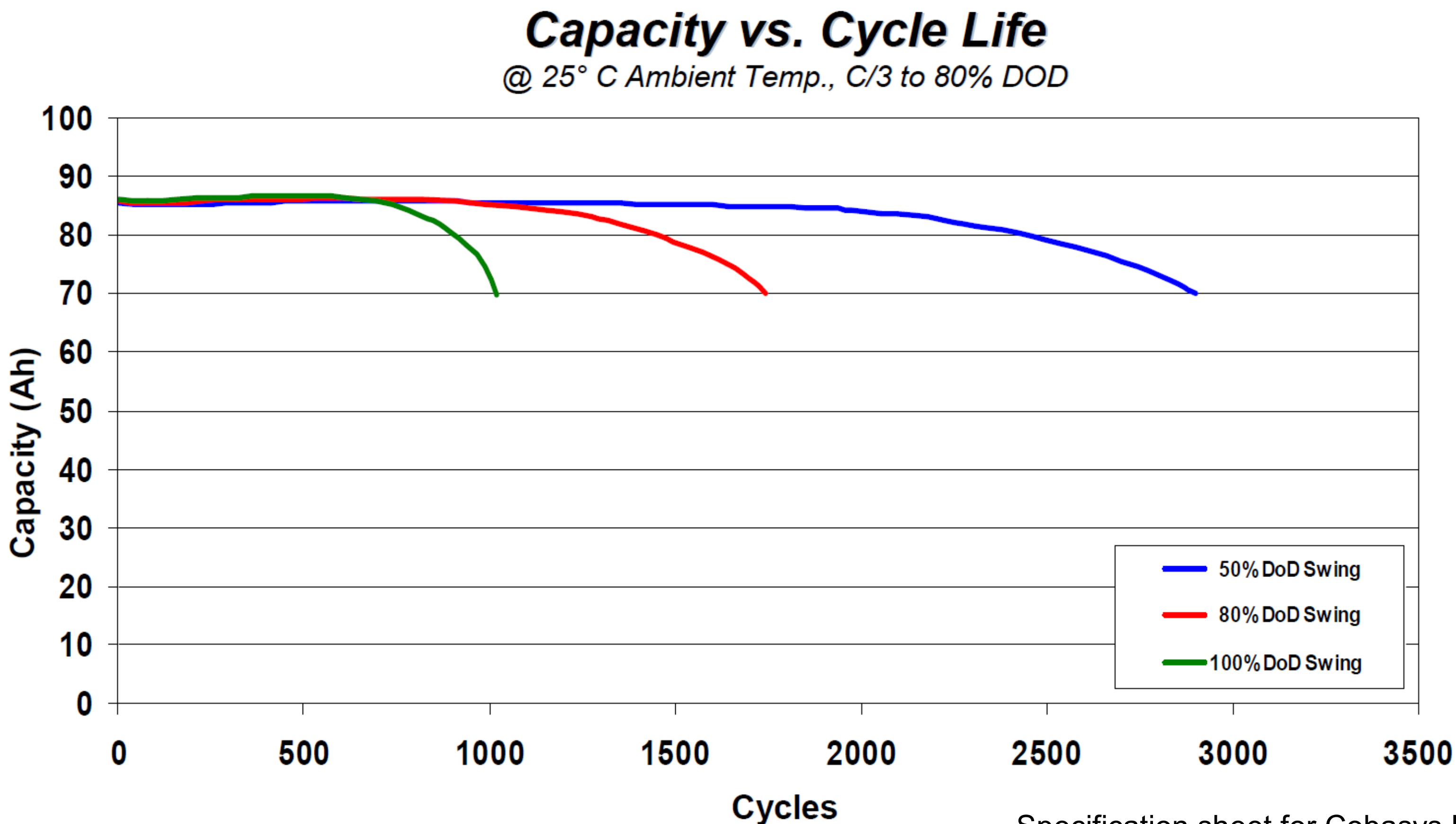
Battery goals come from assumptions about vehicle characteristics and use

Possible to build BEV with lead-acid batteries, but range and storage space will be limited

http://www.elektroauto.ba

Long-range BEVs using high-power batteries require a large battery pack and provide more power than the motor can use

Battery capacity and power are degraded by full use of the battery capacity



Specification sheet for Cobasys Ni-MH battery

PHEVs and BEVs experience more deep discharges, decreasing usable battery life and increasing cycle life requirements

Lead-Acid and Nickel-Cadmium Batteries are not good for EVs

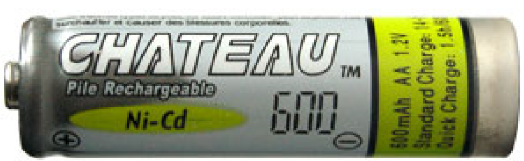
Lead-acid

+ moderate specific power (kW/kg)
+ long cycle life
+ low cost
+ mature technology
- very low specific energy (Wh/kg)
- Used for regular car batteries

www.germes-online.com

Nickel-Cadmium (Ni-Cd)

+ high specific power (kW/kg)
+ long cycle life
+ low cost
+ mature technology
- low specific energy (Wh/kg)
- toxic chemicals
- memory effect
- Used for medial devices



http://www.onlybatteries.com

Neither lead-acid or Ni-Cd meet the energy needs of EVs

Nickel-Metal Hydride and Lithium-ion Batteries are the best for EVs today

Nickel-Metal Hydride (Ni-MH)

+ high specific power (kW/kg)
+ long cycle life
+ good safety and stability
~ moderate specific energy
- high initial cost

Lithium-ion (Li-ion)

+ higher cell voltage
+ higher specific power (kW/kg)
+ higher specific energy (Wh/kg)
+ low self-discharge
- higher initial cost
- lower cycle life
- need for control and protection

Ni-MH provides needed power and energy for HEVs, but does not meet the higher energy needs of PHEVs and BEVs
→ Emphasis on Li-ion research to meet future needs

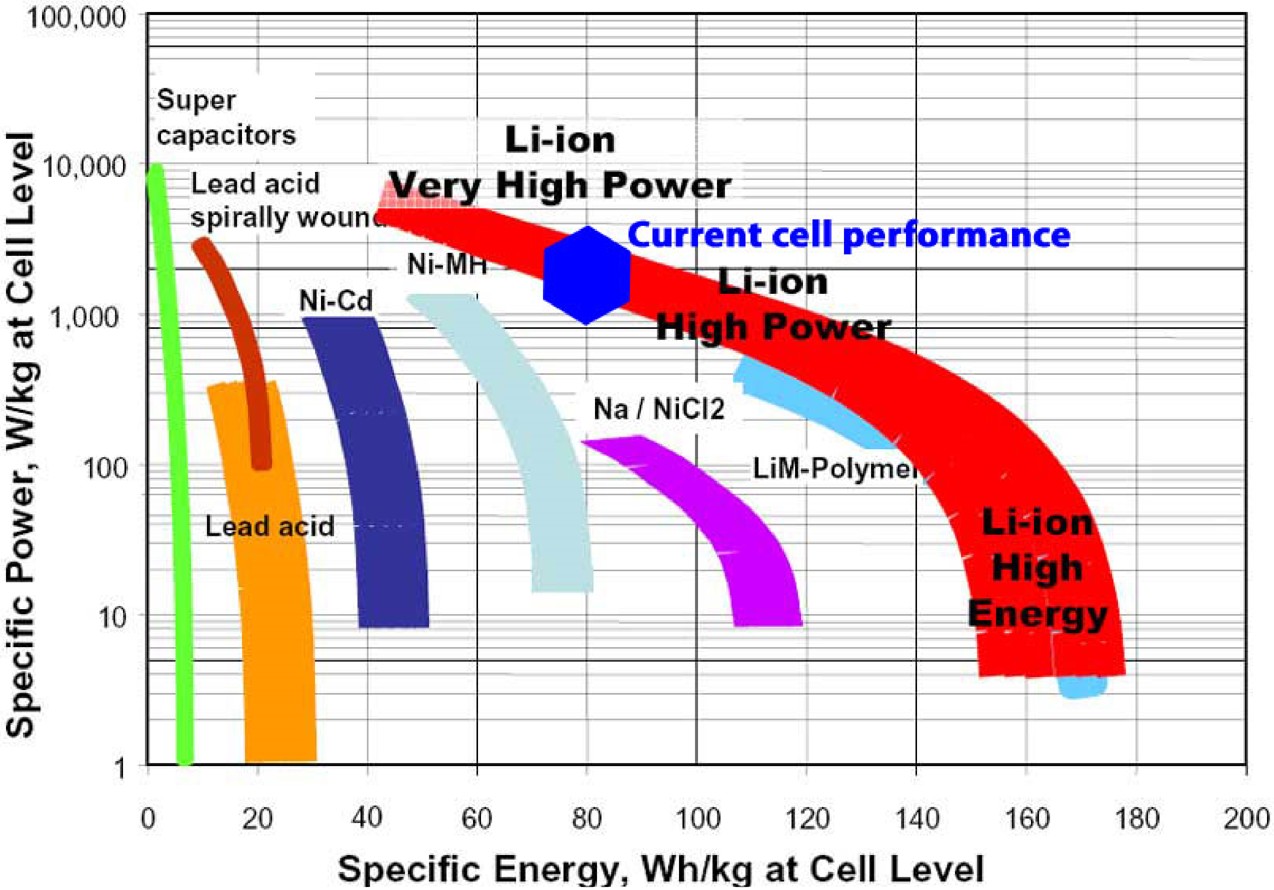
Not all Lithium-ion batteries are equal

	Name	Description	Automotive Status	Power	Energy	Safety	Life	Cost
Unsafe for EVs	LCO	Lithium cobalt oxide	Limited auto applications (due to safety)	Good[4]	Good[4]	Low[2,4], Mod.[3]	Low[2,4]	Poor[2,3]
In prototype EVs, reaching production	NCA	Lithium nickel, cobalt and aluminum	Pilot[1]	Good[1,3]	Good[1,3]	Mod.[1]	Good[1]	Mod.[1,3]
	LFP	Lithium iron phosphate	Pilot[1]	Good[1]	Mod.[2,6]	Mod.[1,2,4]	Good[1,4]	Mod.[1], Good[2,3]
	NCM	Lithium nickel, cobalt and manganese	Pilot[3]	Mod.[3]	Mod.[3], Good[7]	Mod.[3]	Poor[3]	Mod.[3]
In R&D stages	LMS	Lithium manganese spinel	Devel.[1]	Mod.[2]	Poor[1,2,3]	Excel.[1], Good[2]	Excel.[1] Mod.[6]	Mod.[2]
	LTO	Lithium titanium	Devel.[3]	Poor[3], Mod.[7]	Poor[3]	Good[3]	Good[3]	Poor[3]
	MNS	Manganese titanium	Research[1]	Good[1]	Mod.[1]	Excel.[1]	Unkwn.	Mod.[1]
	MN	Manganese titanium	Research[1]	Excel.[1]	Excel.[1]	Excel.[1]	Unkwn.	Mod.[1]

[Axsen, Burke, and Kurani 2008]

Ultra-capacitors are very high power, but very low energy

Some research into coupling high-power ultra-capacitors and high-energy Li-ion for an optimal, hybrid energy storage device



http://www.whnet.com

Where is battery technology heading?

- **Nano-technology offer potential to:**
  - increase energy storage and carrying capacity of Li-ion electrodes
  - decrease charge times without degrading battery life

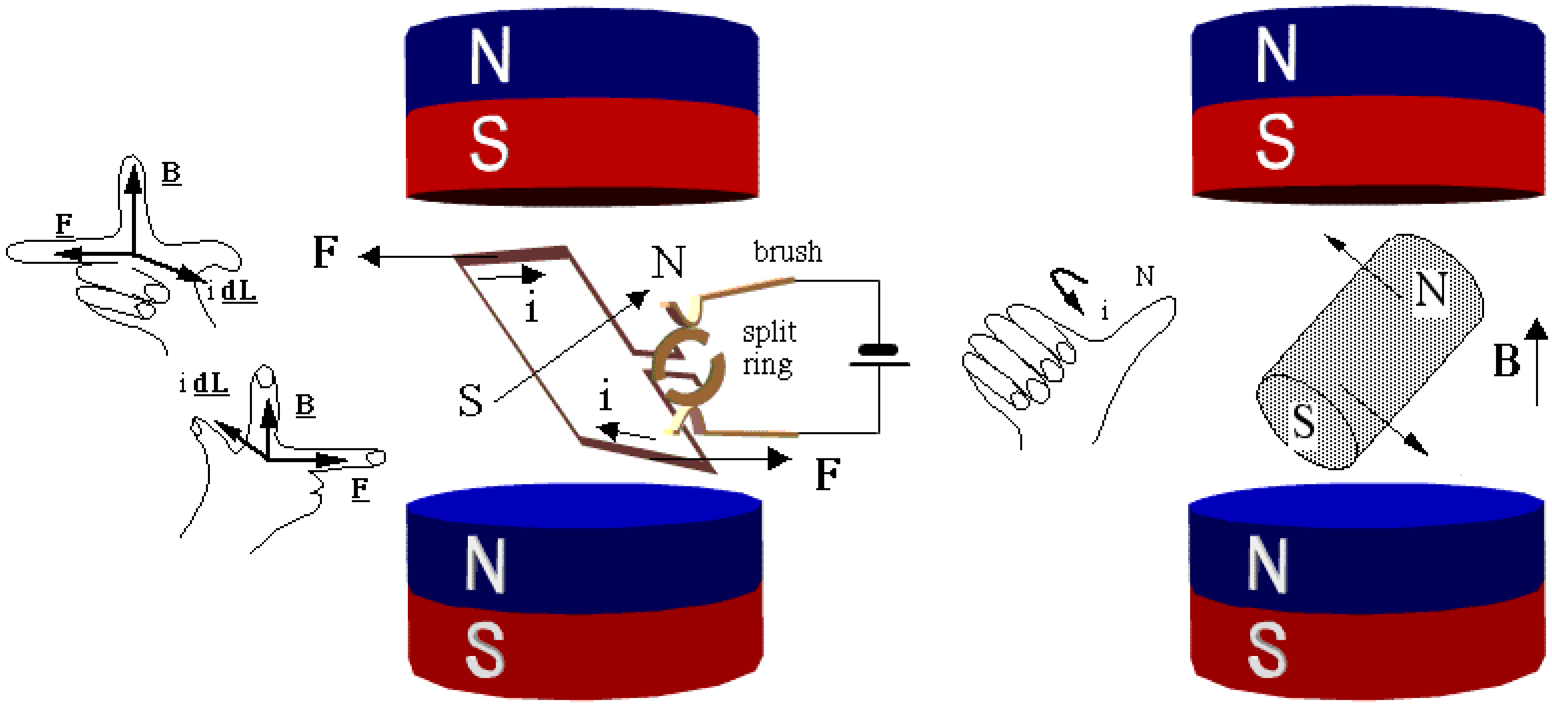
- **Manganese/titanium Li-ion cells:**
  - demonstrated exceptional power, energy, and safety in the lab
  - potential for faster charge times than tradition Li-ion

- **Hybrid energy storage with ultra-capacitors??**
  - Provide high power of ultra-capacitor and high energy of Li-ion

Next Topic: Electric Motors and Generators

- Fundamentals of Electric Motors and Generators
- Various types of motors
  - Motor characterization + Commutator motors
  - Commutatorless motors
    - DC Motor Drives
    - Induction Motor Drives
    - Permanent Magnetic Brushless Motor Drives
    - Switched Reluctance Motor Drives
- Performance Curve of Electric Motors vs. Engine
- Regenerative Braking (1 slide)
- In-Wheel Motor Technology (2 slides of pure animation)
- Summary: Comparison different motor types (DC Brushless vs. inductance)

Quick Intro to Electric Motor



The force F on a wire of length L carrying a current i in a magnetic field B:

F = BIL cos α

Quick Into to Electric Motor

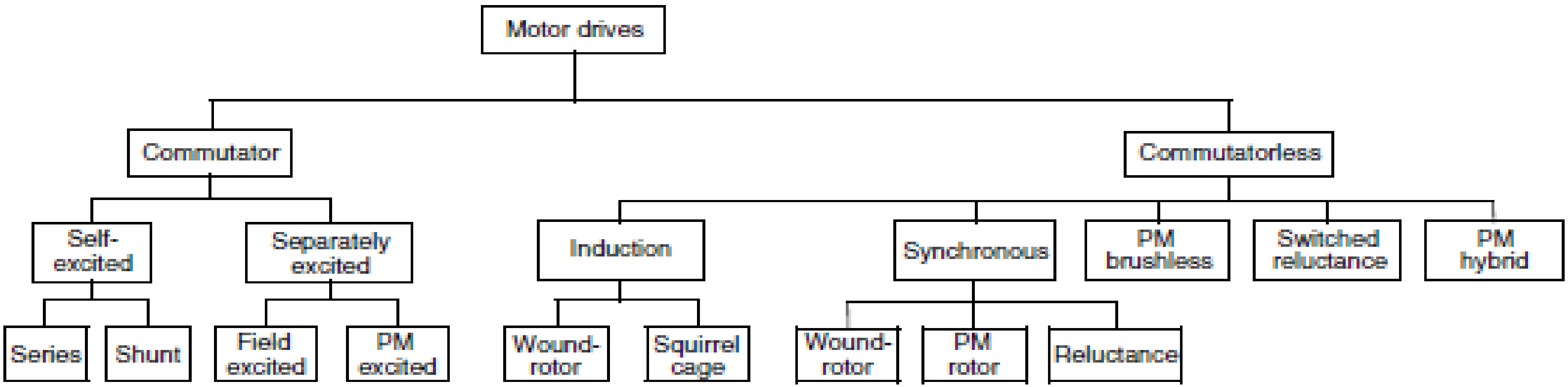
- Motor Case
  - DC Motor Circuit split_ring1.swf
  - AC Motor Circuit alternator1.swf

- Specific Attention of EVs Motors Compared to Ordinary Industrial Application Motors
  - Requires high rate starts and stops
  - High rate of acceleration / deceleration
  - High torque low speed hill climbing
  - Low torque high speed cruising
  - Wide speed range of operation

Motor as Generator

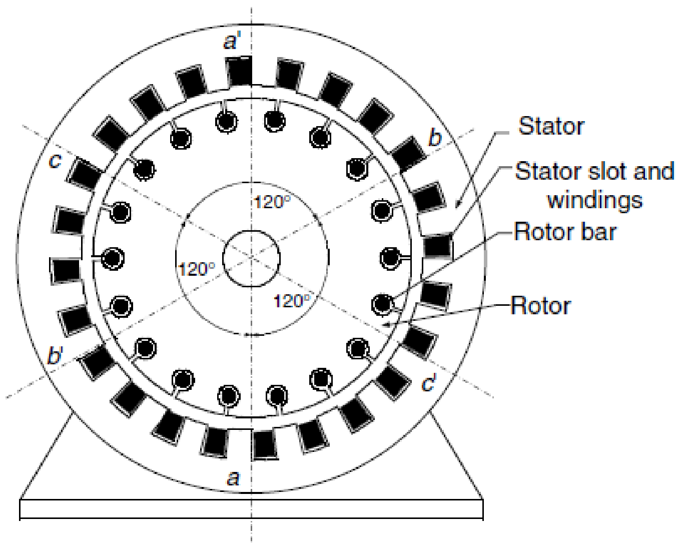
- Applying mechanical force to rotor causes electric current
- Conceptually same efficiency as motor and as generator
- Modern power electronics controls the mode of operation

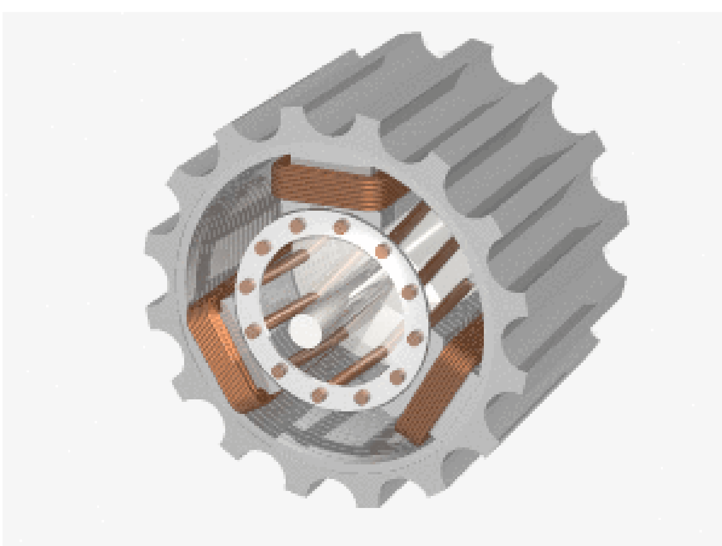
Electric Motor Characterization



- Commutator vs. Commutatorless
- Commutatorless
  - Induction motor drives (AC)
  - Synchronous motor (AC)
    - Switch reluctance motor drives (AC)
    - Permanent magnet brushless DC motor drives (AC)

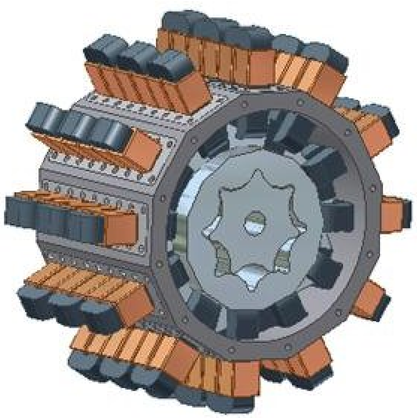
Induction Motor

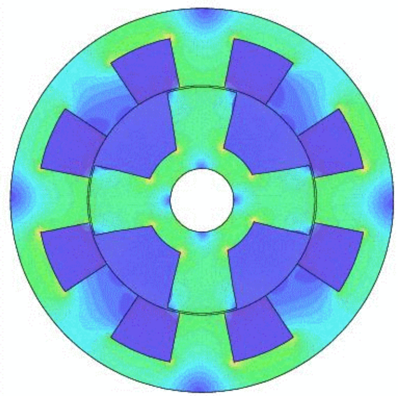


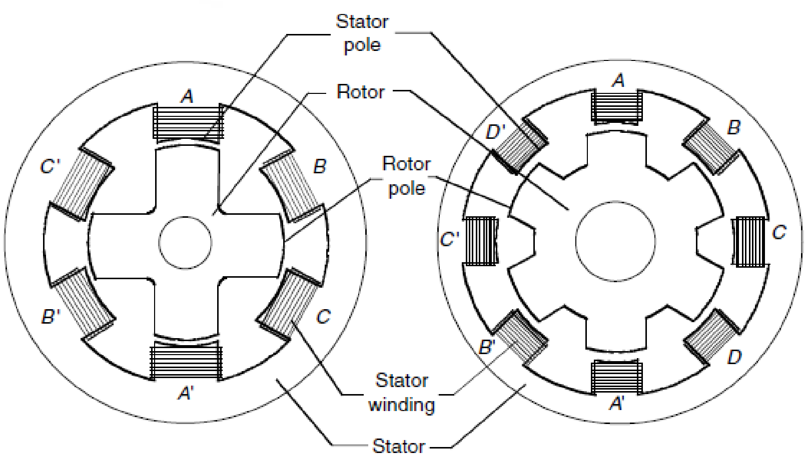


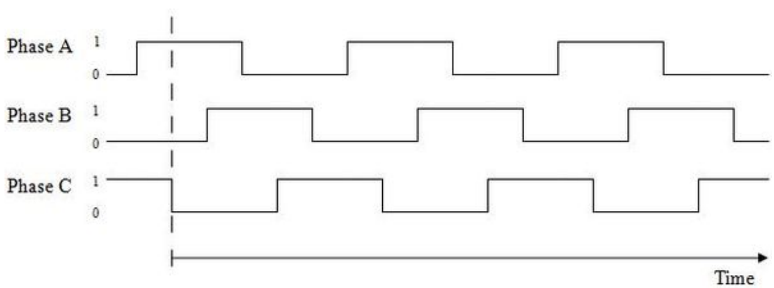
- Asynchronous AC motor
- No permanent magnets
- Current induced in rotor
- Mature technology among commuatorless motors
- Light weight, small volume, low cost, high efficiency
- Heat accumulation at rotor

Switched Reluctance Motor Drive









- Synchronous AC motor
- No permanent magnet or coil at rotor
- Concentrated winding on stator, allowing reduced cost and high speed operation capability
- Reliable inverter topology
- Failure of one leg phase does not interfere operation of remaining leg phases
- Salient structure causes high acoustic noise
- Large filter capacitor required due to torque ripple

Permanent Magnetic Brush-Less DC Motor

- Synchronous DC motor
- Rotating permanent magnets
- High efficiency, reliability, life duration
- Lower noise and EMI
- Highest efficiency at lower-load conditions
- High Cost from rare-earth magnets, complex electronic speed control and less developed supply chain
- Safety issues with permanent magnet and inverter

Applications:

•Consumer electronics: Hard Drives, CD/DVD players, PC Fans

•Automotive industry

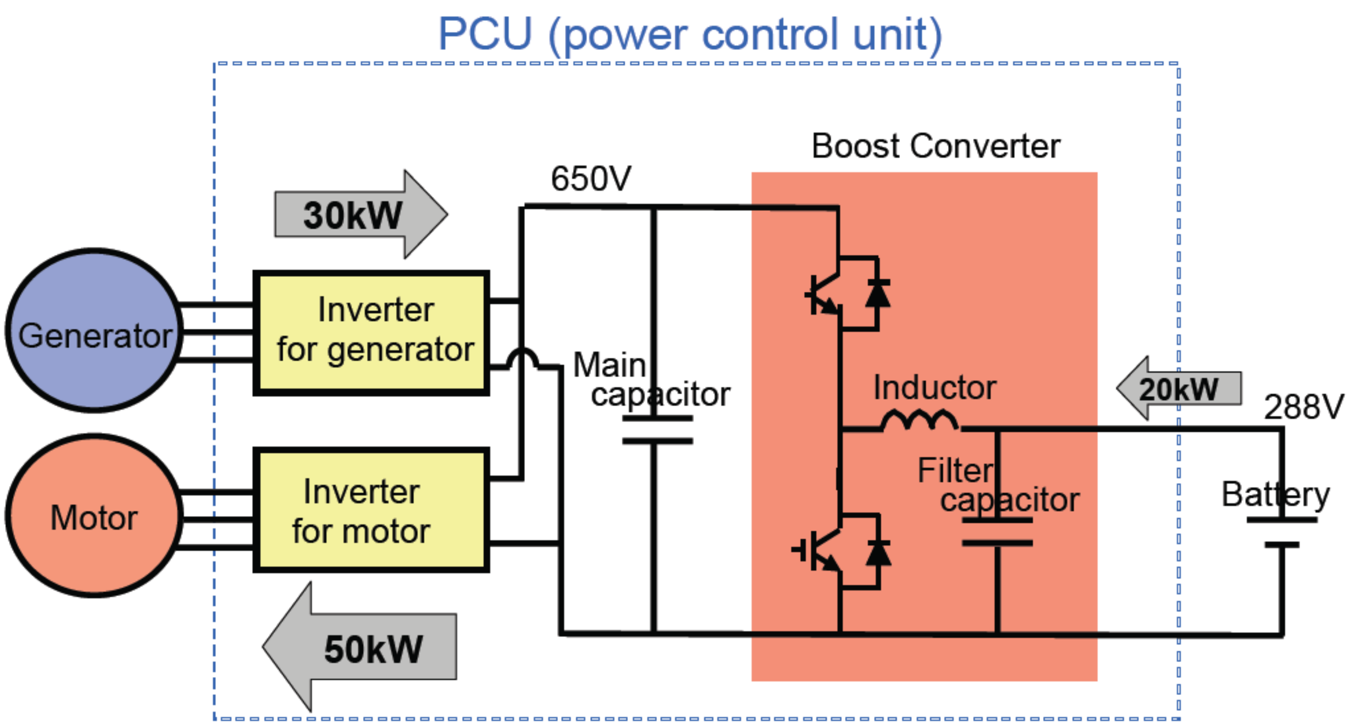
Electric Motor Comparisons

Motor Type	Advantages	Disadvantages
Induction Motor	Low initial cost High power High average efficiency Light weight	Rotation slips from frequency Accumulation of rotor heat
Switched Reluctance Motor	Low initial cost High average efficiency Highly reliable and robust Very simple control	High acoustic noise Require large filter capacitor
PM Brushless DC Motor	Long lifespan Least rotor heat generated Low maintenance High peak efficiency	High initial cost Requires a controller Poor high speed capability Unadjustable magnetic field
Brushed DC Motor	Low initial cost Simple speed control	High maintenance (brushes) Low lifespan High heat

Motor and Generator controls

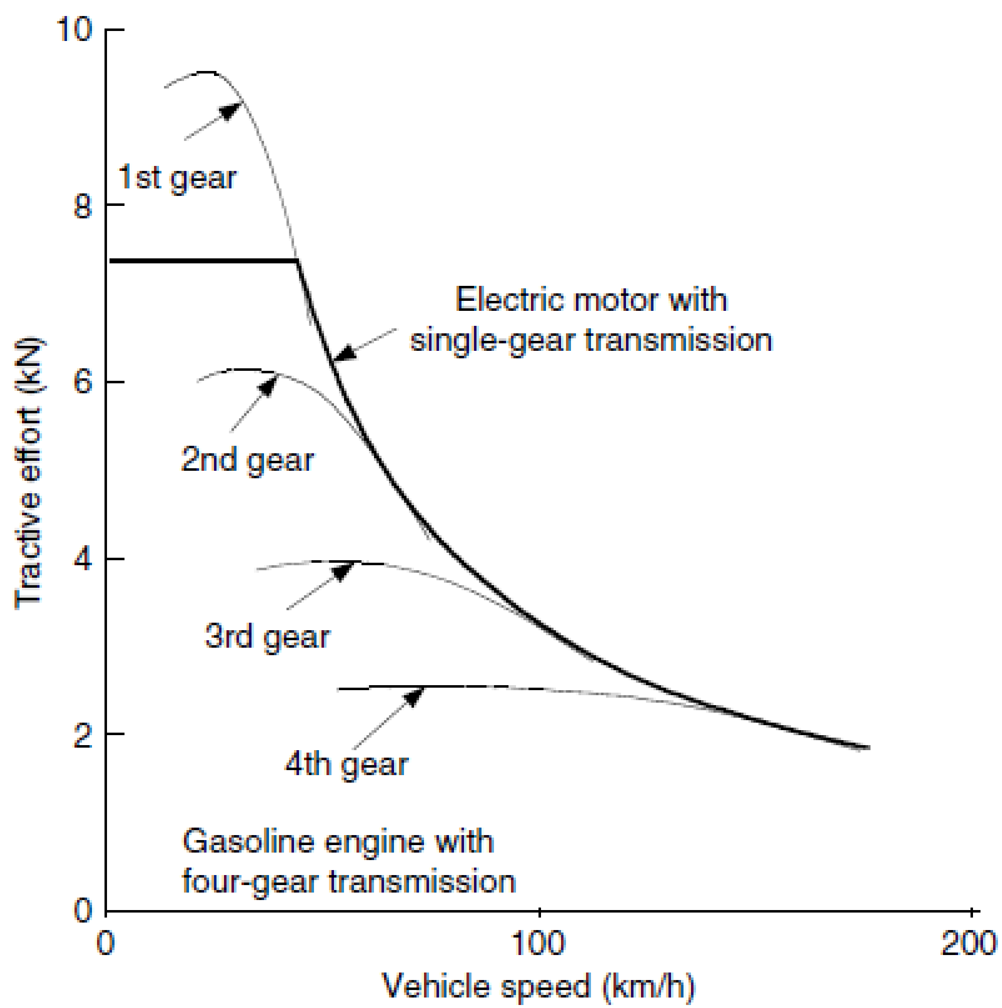
Key enabling technology:

- IGBT high power transistors



Source: Toyota Hybrid Synergy Drive II

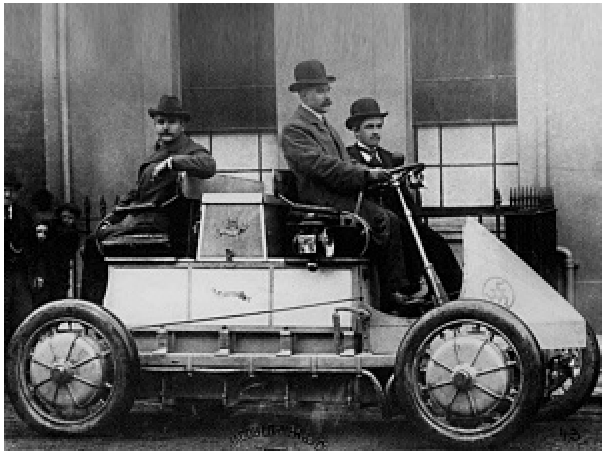
Transmission Characteristics



In-Wheel Motor

- Only one gasoline engine per vehicle
- How many electric motors?

Lohner-Porsche Mixte
Hybrid, 1902



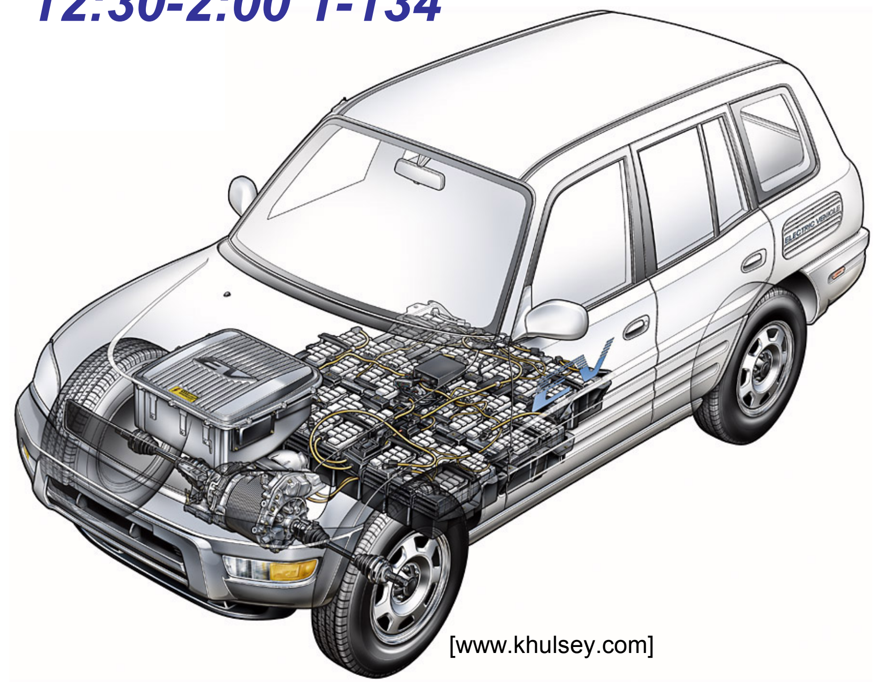
Mitsubishi MiEV Sport, 2007

In conclusion; today we introduced EVs, batteries, and electric motors

Outline for Thursday:

1. EV Powertrains
   - Micro and Mild Hybrids
   - Full Hybrids
   - PHEVs and BEVs
2. EV and PHEV Conversions
3. EV Initiatives

Thursday, Jan 22
12:30-2:00 1-134



[www.khulsey.com]

For more information:
web.mit.edu/evt/iap2009

Contact:
iberry@mit.edu
mkhusid@mit.edu

Questions?