UNIVERSITY OF MICHIGAN-DEARBORN

Iowa-Illinois IEEE Section
Power Engineering Chapter Meeting

Emerging Technologies of Hybrid Electric Vehicles

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Presentation Outline

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

Part I

Introduction to Hybrid Electric Vehicles

What Hybrids Are Available in 2007?

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

2006 Hybrid Sales Figure

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

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

2007 Hybrid Sales Figure (through March)

- Honda Accord: 945
- Honda Civic: 6,520
- Lexus RX400h: 3,965
- Toyota Camry: 11,277
- Toyota Highlander: 4,393
- Toyota Prius: 39,682
- Total for the vehicles above: 66,782

- 2000: 9,367
- 2001: 20,287
- 2002: 35,961
- 2003: 47,525
- 2004: 83,153
- 2005: 209,711
- 2006: 246,642

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

2007 HEV Sales (Through August)

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

What is HEV

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

Types of HEV

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

Types of HEV

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

Types of HEV

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

Why HEV ?

To Overcome the Disadvantage of Pure EV and Conventional Vehicles

Key Drawbacks of Battery EVs

- High Initial Cost
  - Many times that of conventional vehicles
- Short Driving Range
  - Less miles during each recharge
  - People need a vehicle not only for commuting (city driving), but also for pleasure (long distance highway driving)

Key Drawbacks of Battery EVs

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

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

Key Drawbacks of ICE Vehicles

- High energy consumption: resources, independent of foreign oil
- High emission, air pollution, global warming
- High maintenance cost
- Environmental hazards
- Noisy

Key Advantages of HEV’s

- Optimize the fuel economy
  - Optimize the operating point of ICE
  - Stop the ICE if not needed (ultra low speed and stops)
  - Recover the kinetic energy at braking
  - Reduce the size (hp and volume) of ICE
- Reduce emissions
  - Minimize the emissions when ICE is optimized in operation
  - Stop the ICE when it’s not needed
  - Reduced size of ICE means less emissions

Key Advantages of HEVs - continued

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

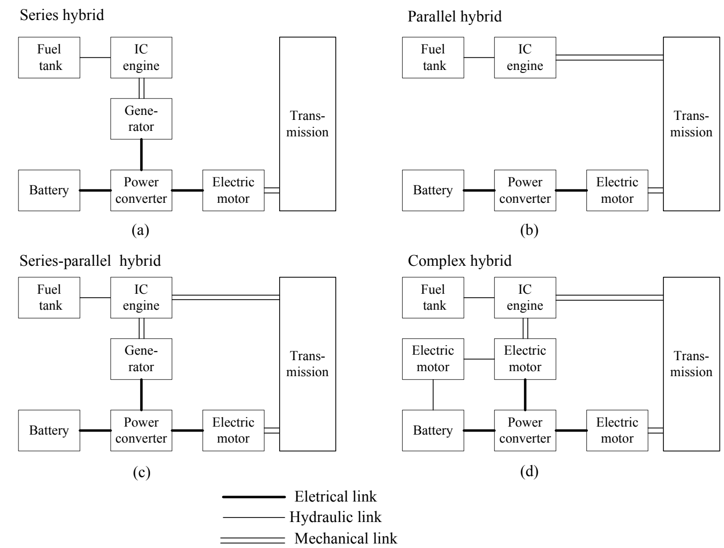
Key Advantages of HEVs - continued

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

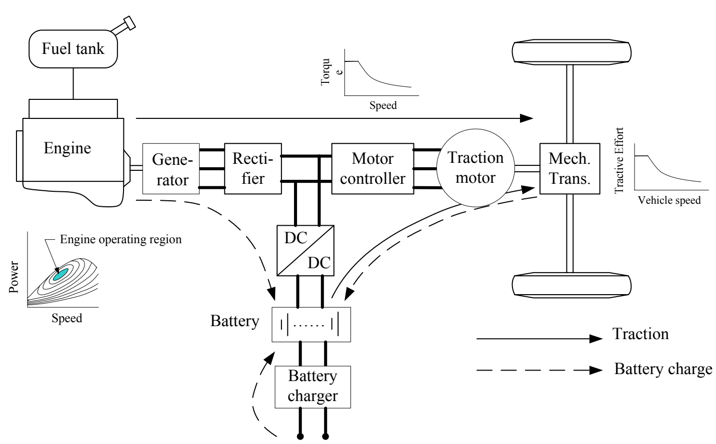
Key Concerns of HEVs

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

Architectures of HEV

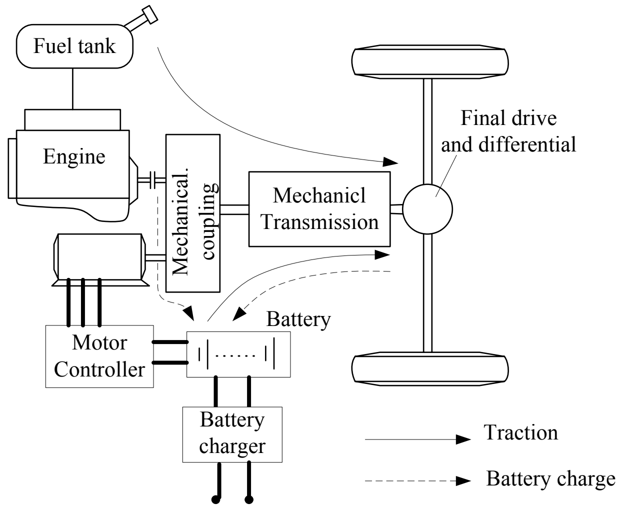


Series Architecture



Parallel Architecture

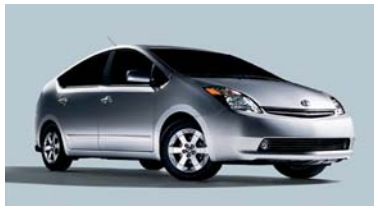
- Two energy converters
- Engine and motor mechanically coupled
- Different configurations possible



Part II

Popular HEV Designs

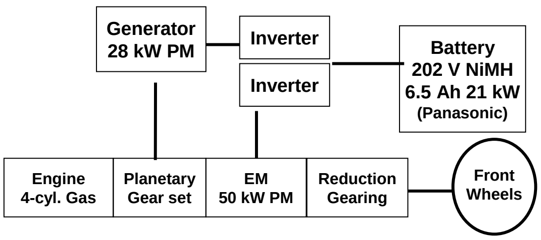
Toyota Prius (2005)



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

Motor: DC Brushless 500 V
50 kW / 400 Nm

EPA MPG	1.8L AT Corolla	HEV	Gain (%)
City	30	60	100
Highway	38	51	34



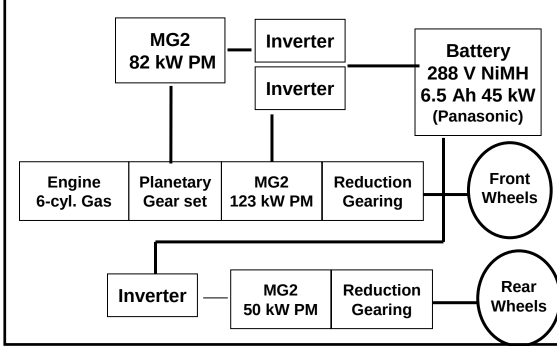
Note Corolla 1.8L 130 HP 4-speed AT
Echo 1.5L 108 HP 4-speed AT
33/39 City/Highway MPG

Toyota Highlander

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

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

EPA MPG	Conventi onal	HEV	Gain (%)
City	18	31	72%
Highway	24	27	12.5



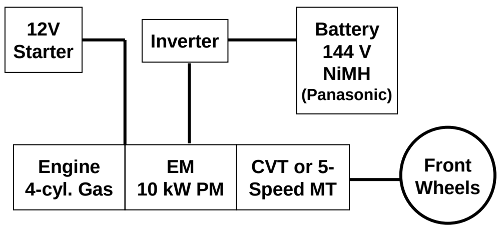
Note Conventional comparison base is, V6 and 4X4, 215hp @5600rpm, 222lb.ft @3600rpm

V4 MPG 2WD is 22/27, engine 155hp
HEV 2WD, MPG is 33/28

Honda Civic

Engine: 1.34L 85 HP (63 kW) /119 Nm

Motor: PM DC Brushless
10 kW / 62 Nm Assist
12.6 kW / 108 Nm Regen



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

Note BL Engine: 1.7L 115 HP/110lb-ft
Trans: 4-Speed AT

IMA ---- Integrated Motor Assist
Motor start/stop engine, 12V start for jump start

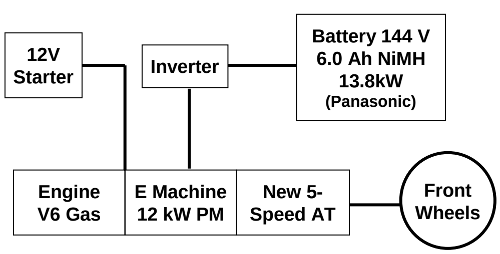
http://automobiles.honda.com/models/specifications_full_specs.asp?ModelName=Civic+Hybrid&Category=3

Honda Accord

Engine: 3.0 L VTEC V6
179kW / 290Nm
w/ Variable Cylinder Management (VCM) system

Trans: New 5_Speed AT

Motor: DC Brushless
12 kW / 74 Nm Assist
14 kW / 123 Nm Regen



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

Note BL Engine: 3.0L 240 HP/212 lb-ft
Trans: 5-speed AT

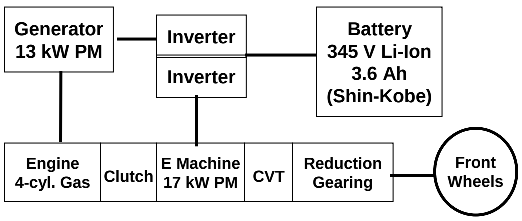
IMA ---- Integrated Motor Assist
Motor start/stop engine, 12V start for jump start

http://automobiles.honda.com/info/news/article.asp?ArticleID=2004091746959&Category=Accord+Hybrid

Nissan Tino – 2004 Production Model

Engine: 1.8 L 4-cylinders DOHC
73kW

Motor: DC Brushless 350 V
17 kW / Nm

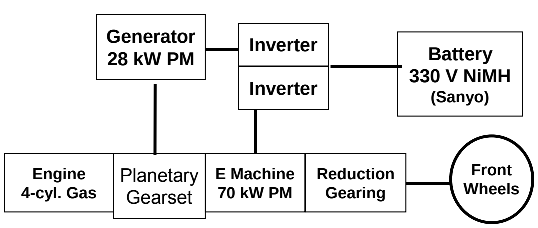


	BL	HEV	Gain
1015 MPG		23km/l	

Ford Escape

Engine: 2.3 L Inline 4-Cylinder
99kW / 172Nm

Motor: PM 330 V
70 kW



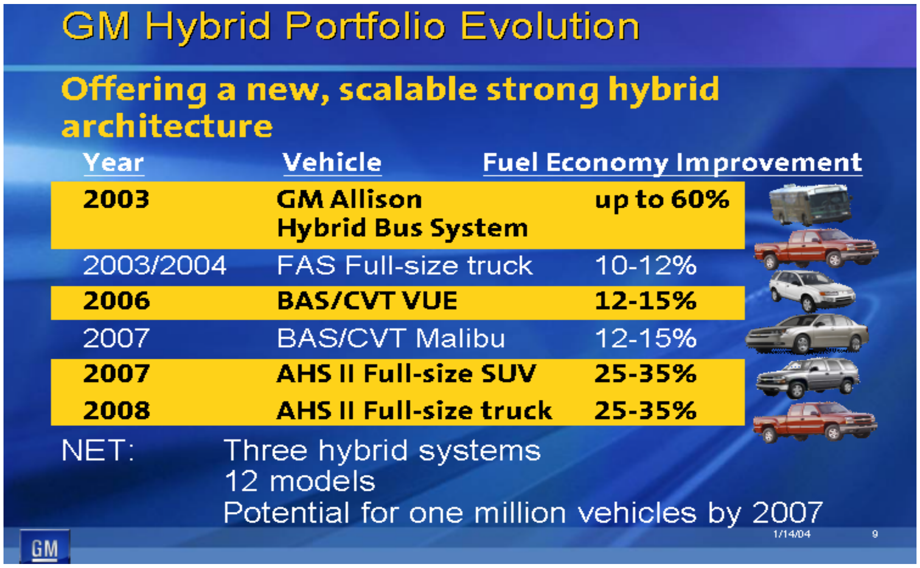
EPA MPG	3.0 L BL 1	AT HEV	Gain (%)
City	20	36	80
Highway	25	31	24

Note **BL1** **3.0L 200 HP 4-speed AT**

BL 2 **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

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

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

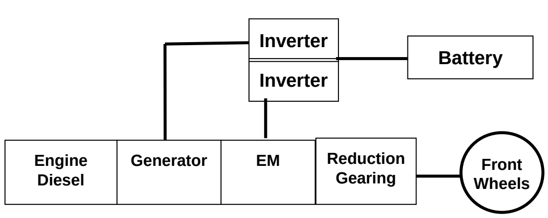
1/14/04 9

The Allison Hybrid Powertrain System

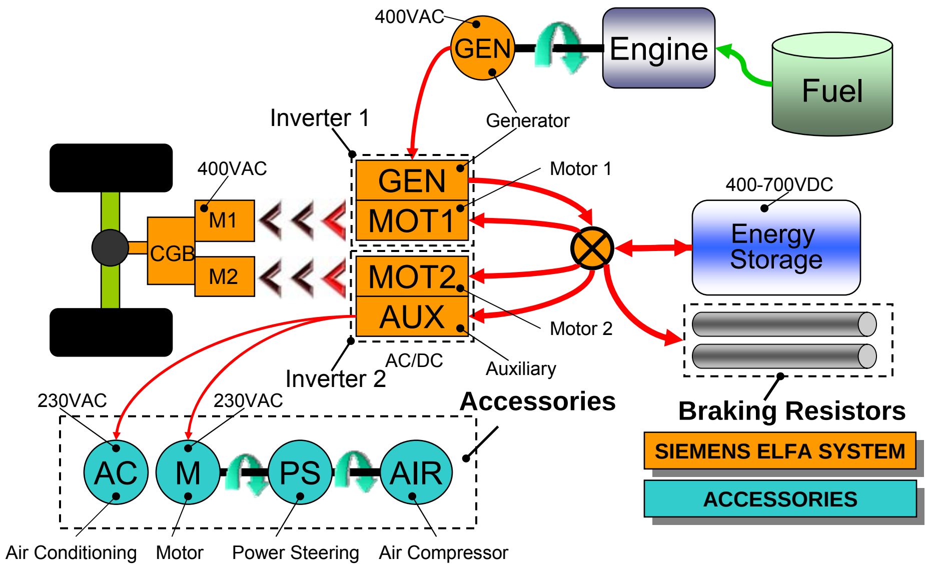
Model	E^P40	E^P 50	E^P 60
Application	Transit Bus	Sub. Coach	Articulated Bus
DPIM	430-900 VDC 160 kW 3-phase AC		
Weight	908 lbs		
Input Pwr	280 hp	330 hp	330 hp
Max In Trq	910 lb-ft	1050 lb-ft	1050 lb-ft
Rated In Spd	2300 rpm		
Accel Power	350 hp	400 hp	400 hp
Battery	NiMH 330V (Panasonic)		
Controller	Two AT1000/2000/2400 controller		

Performance	Change
MPG*	~ 60%
PM	~ 90%
NOx	~ 50%
HC	~ 90%
CO	~ 90%

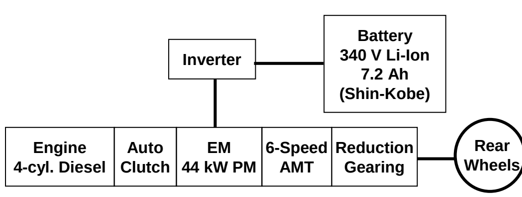
* Advertised Numbers ---- Over CBD14 Cycle



Series ISE Hybrid



Eaton Hybrid System for Commercial Trucks



Engine: 4.3 L 4-cylinders Diesel
127kW / 560Nm

Motor: PM DC 340 V
44 kW / 420 Nm

	BL	HEV	Change
MPG*	9.3	13.42	45%
PM	0.158	0.0112	93%
NOx	12.9	5.8984	54%
HC	0.02	0	100%
CO_2	1103	758	31%
CO	1.89	0.7352	60%
0~60	32.2	30	7%
Grade	4%	5.1%	28%

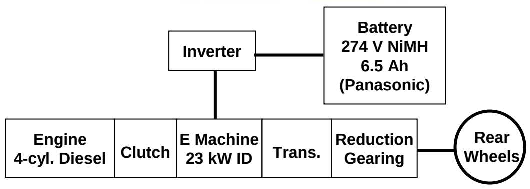
*** Over the FedEx cycle, a modified FTP cycle**

Hino 4T Ranger HEV

Engine: J05D-TI<J5-IA> 4.73 L 4-cyl. Diesel
177 HP(132 kW) / 340 lb-ft (461 Nm)

Motor: Induction AC 23 kW

Battery: 274V NiMH 6.5 Ah



	BL	HEV	Change
MPG			20%
PM			85%
NOx			50%
CO_2			17%

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.

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

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

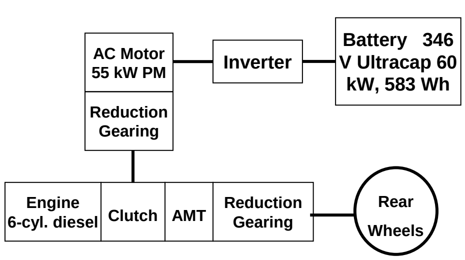
Nissan Condorr 2003 Prototype

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

Engine: 6.93 L 6-Cylinders Diesel
152kW @ 3000 / 493Nm@ 1400 rpm

Motor: PM AC
55 kW @ 4060 ~ 9000 rpm / 130 N @ 1400 rpm

Ultracap: 346 V 60kW 583 Wh 384-cell 6.3 Wh/kg
1105 x 505 x 470 mm from Okamura Laboratory

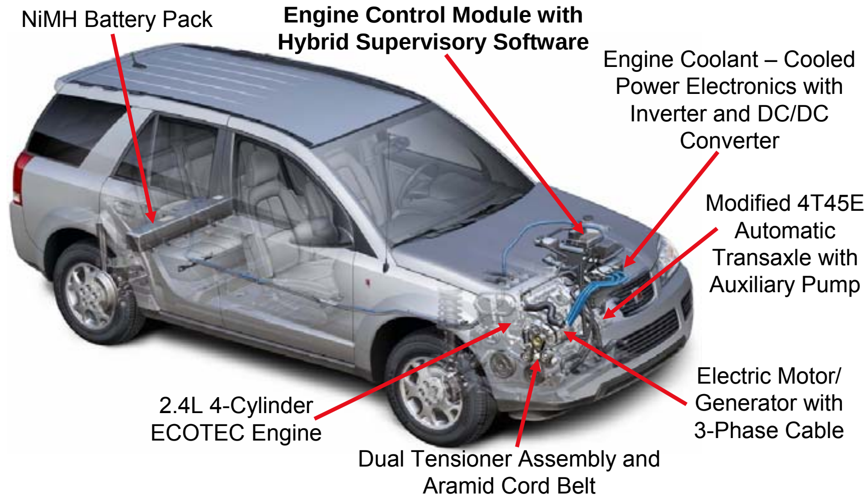


Performance	Change
MPG*	50%
CO_2	33%

*** Cycle unknown**

http://www.sae.org/automag/globalvehicles/12-2002

Saturn VUE Green Line Hybrid System

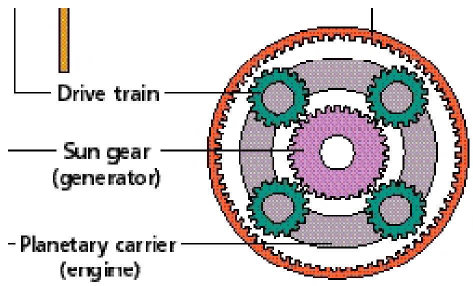


Part III

Planetary Gear and Its Power Split and
e-CVT Principle

Planetary Gear Train

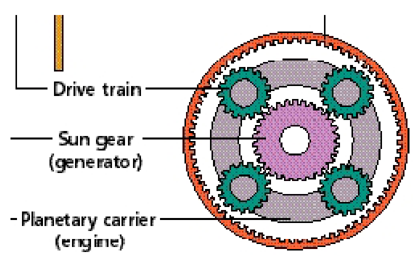
- Speed relationship
  - Number of teeth of sun gear Ns
  - Number of teeth of ring gear Nr
  - Angular speed ωs, ωr, ωc
  - (c-carrier, r-ring gear, s-sun gear)



$$\omega_c(carrier) = \frac{N_r}{N_r + N_s}\omega_r + \frac{N_s}{N_r + N_s}\omega_s$$

Planetary Gear Train

- Torque relationship
  - Neglect losses
  - P=T*ω
  - Use Tc, Tr and Ts
  - (c-carrier, r-ring gear, s-sun gear)



$$\because T_c\omega_c(carrier) = \frac{N_r}{N_r + N_s}T_c\omega_r + \frac{N_s}{N_r + N_s}T_c\omega_s$$

$$\because T_c\omega_c = T_r\omega_r + T_s\omega_s$$

$$\therefore T_r = \frac{N_r}{N_r + N_s}T_c$$

and

$$T_s = \frac{N_s}{N_r + N_s}T_c$$

- Therefore fixed torque split between sun gear and ring gear,
  - Neglect losses

Planetary Gear Train

- Tc: Carrier input torque
  - ωs can be controlled

$$\because T_c\omega_c = T_r\omega_r + T_s\omega_s$$

or

$$P_c = P_r + P_s$$

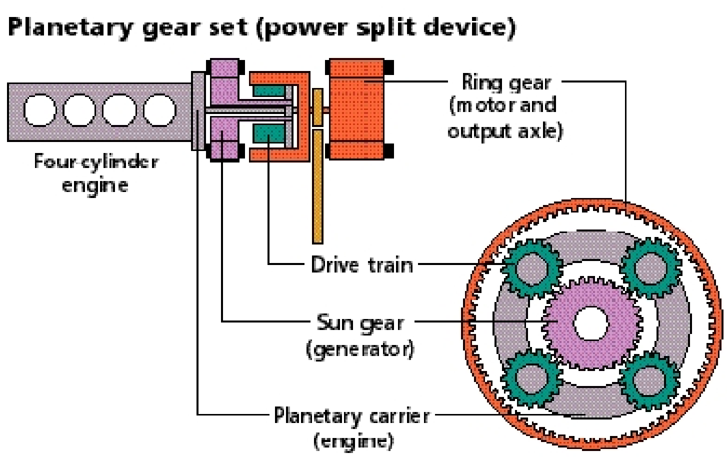
$$\therefore P_r = \frac{N_r}{N_r + N_s}\omega_r T_c$$

and

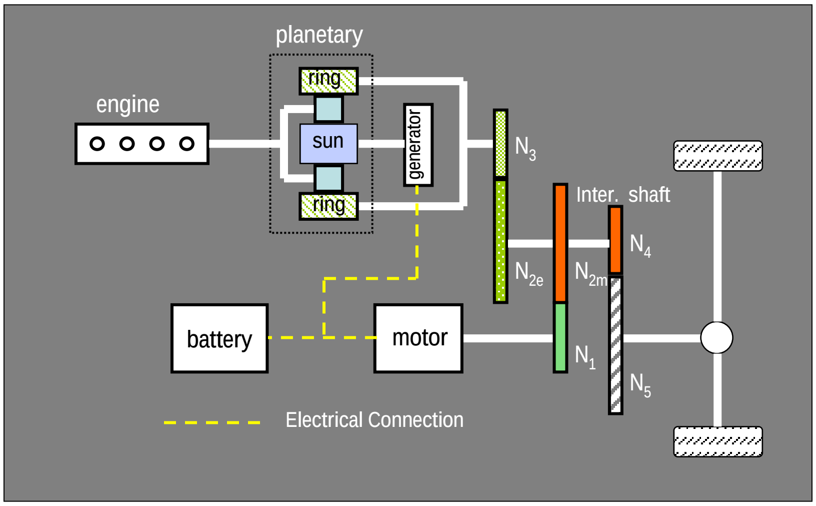
$$P_s = \frac{N_s}{N_r + N_s}\omega_s T_c$$

- Varying speed of sun gear will change the power split between the two gears
- For example,
  - if ωs=0, then Pr=Pc
  - Where ωs is controlled through other device
-

The Toyota Prius Hybrid System



Mariner HEV



Example

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

$$\omega_c(carrier) = \frac{N_r}{N_r + N_s}\omega_r + \frac{N_s}{N_r + N_s}\omega_s$$
$$= \frac{72}{72+30}\omega_r + \frac{30}{72+30}\omega_s$$
$$= 0.706\omega_r + 0.294\omega_s$$

$$\omega_s = (\omega_c - 0.706\omega_r)/0.294$$
$$= (2000 - 0.706 * 2632)/0.294$$
$$= 482rpm$$

Example

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

$$T_c(engine) = P_{engine} / \omega_{engine(carrier)} = 477Nm$$

$$T_r(Ring\_gear) = \frac{N_r}{N_r + N_s} T_c = 0.706 * 477 = 337Nm$$

$$T_s(generator) = \frac{N_s}{N_r + N_s} T_c = 0.294 * 477 = 140Nm$$

$$P_c(engine) = 100kW$$

$$P_r(\mathrm{R}ing\_gear) = T_r \omega_r = 337 * 2 * \pi * 2632 / 60 = 92.9kW$$

$$P_s(generator) = T_s \omega_s = 140 * 2 * \pi * 482 / 60 = 7.1kW$$

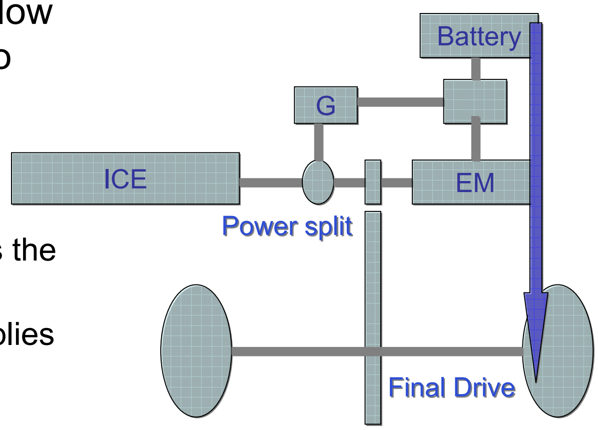
$$P_c(engine) = P_r(ring\_gear) + P_s(generator)$$

Further

- If vehicle needs 120kW of power, then motor power is Pveh – Pring = 120 – 92.9 = 27.1kW
- Pbat = P motor – Pgenerator = 27.1 – 7.1 = 20kW
- You can se here Pengine + Pbat = P vehicle

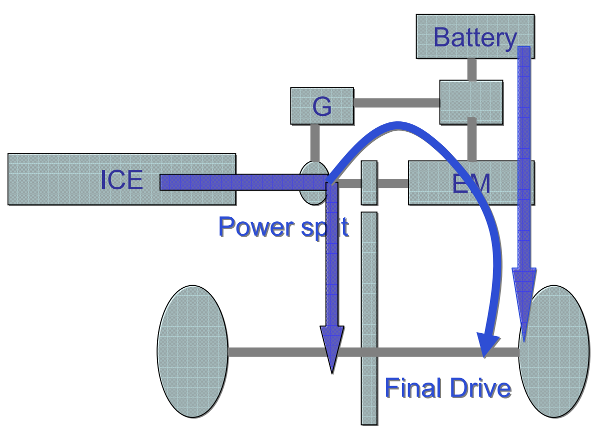
Power Flow

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



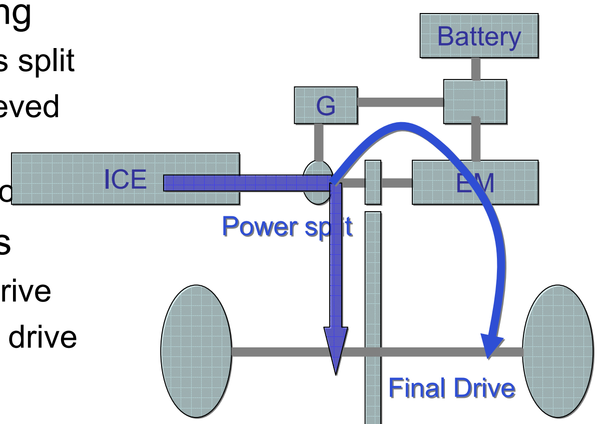
Power Flow

- Sudden Acceleration



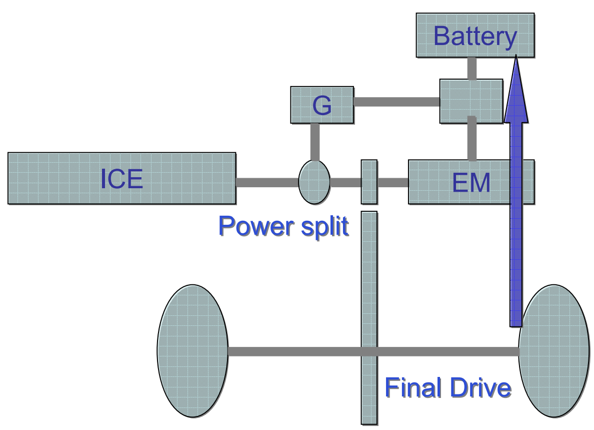
Power Flow

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



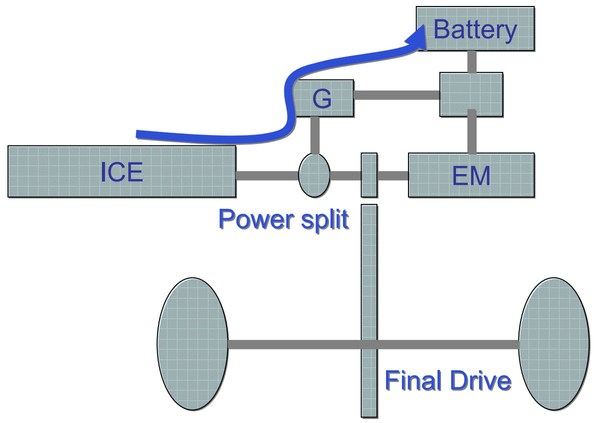
Power Flow

- Braking
  - ICE is off

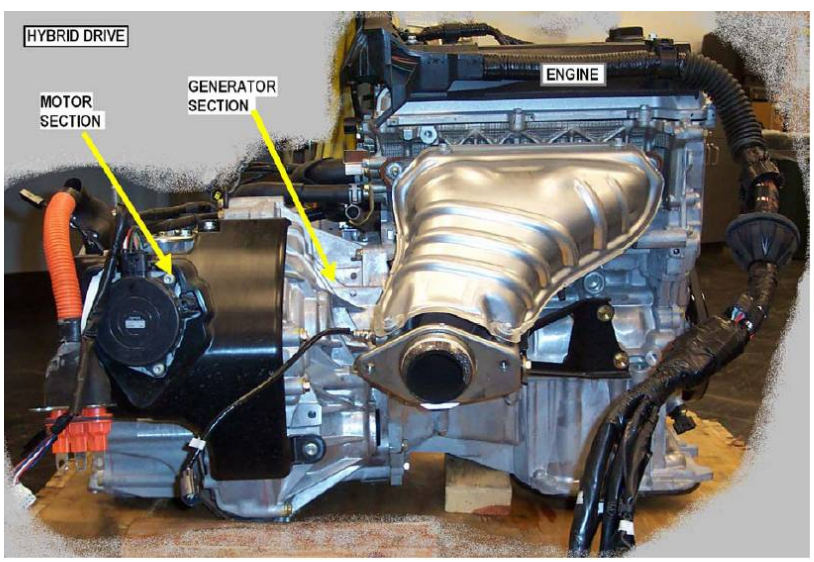


Power Flow

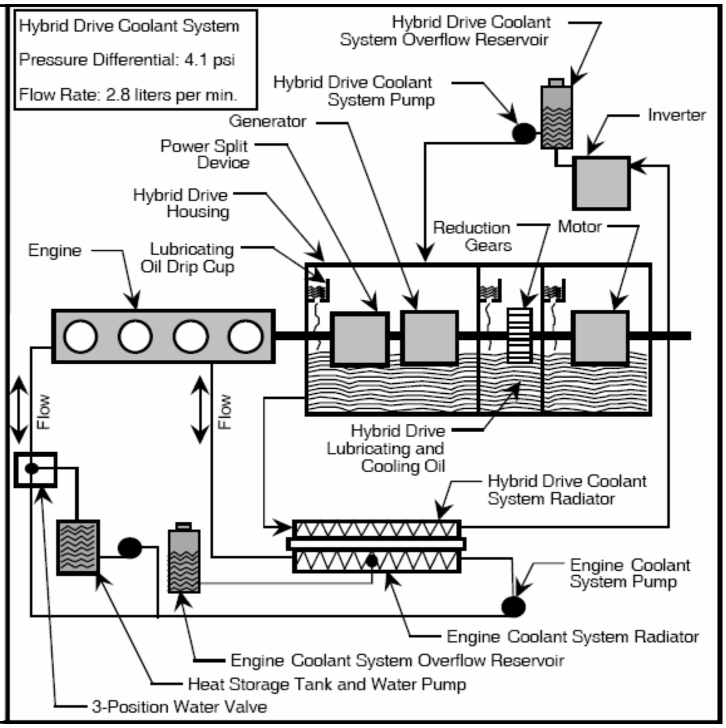
- Stationary Charging



2004 Prius Powertrain



Cooling System



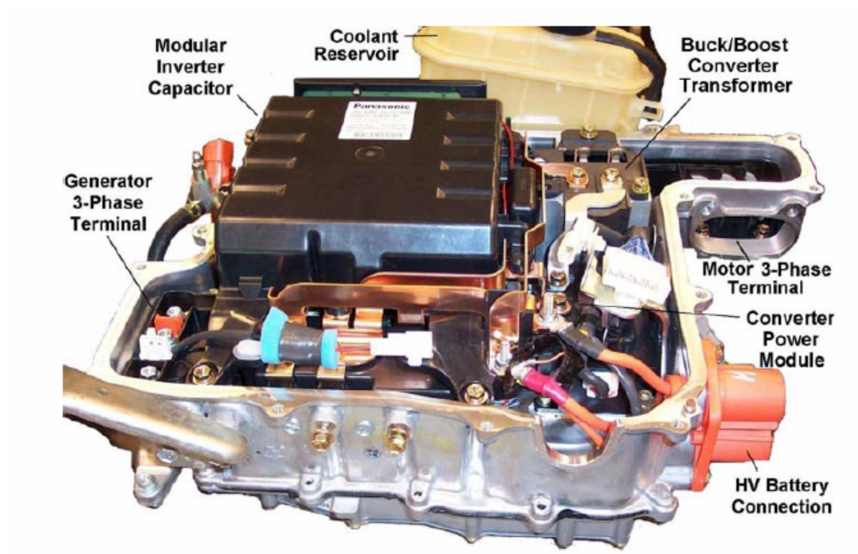
Planetary Gear

Generator Rotor

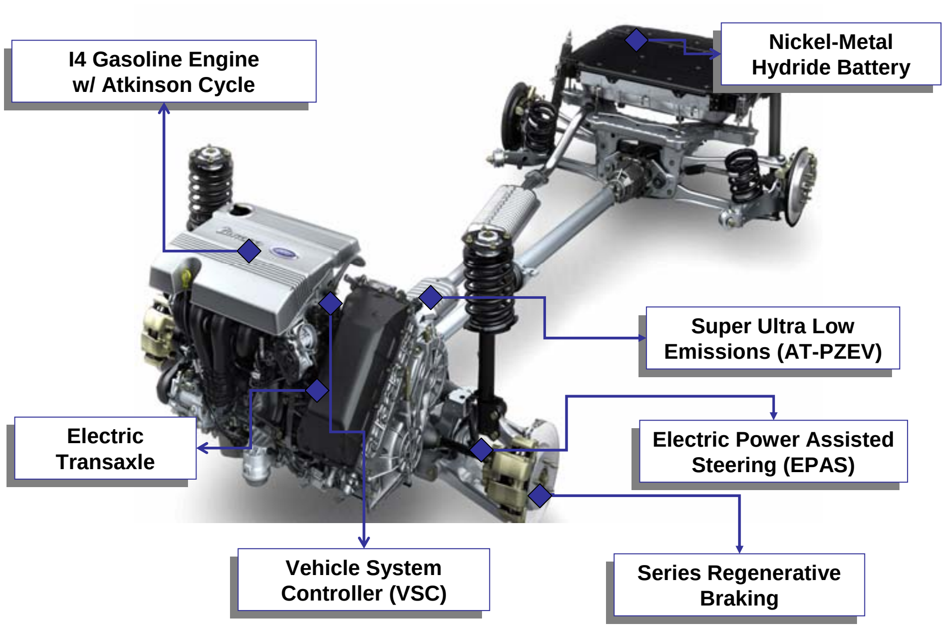
Motor Assembly

Power Converter

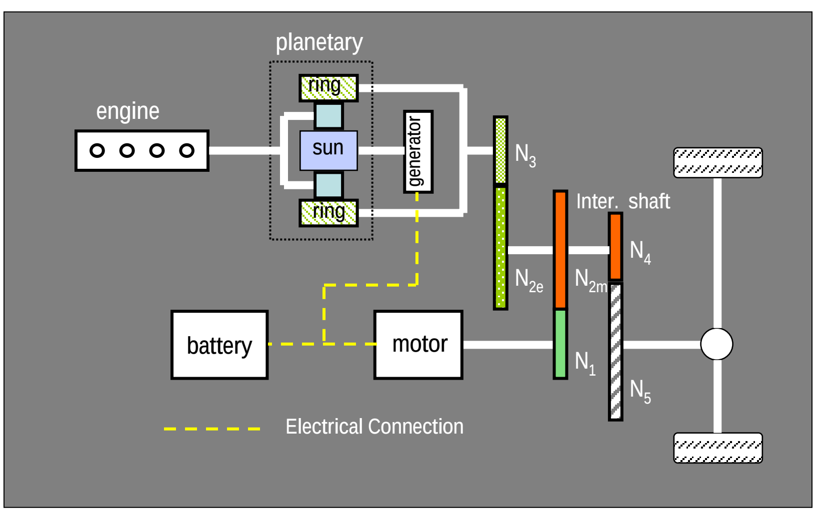
Power Converter Packaging



2006 Mercury Mariner Hybrid

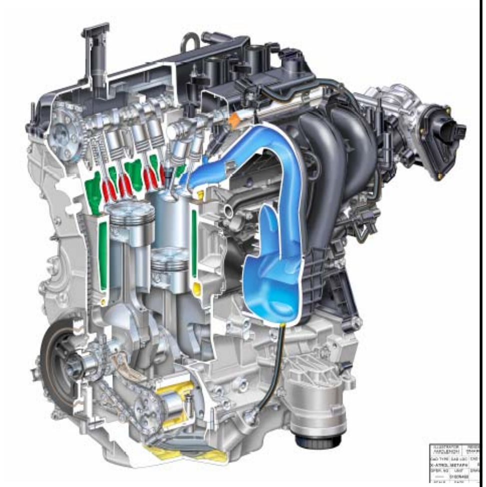


MARINER HYBRID POWER FLOW

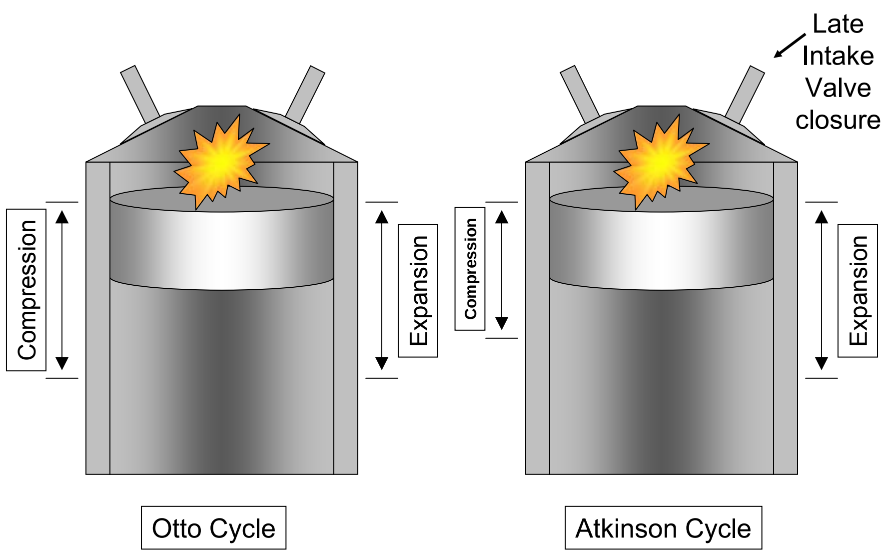


ATKINSON CYCLE ENGINE

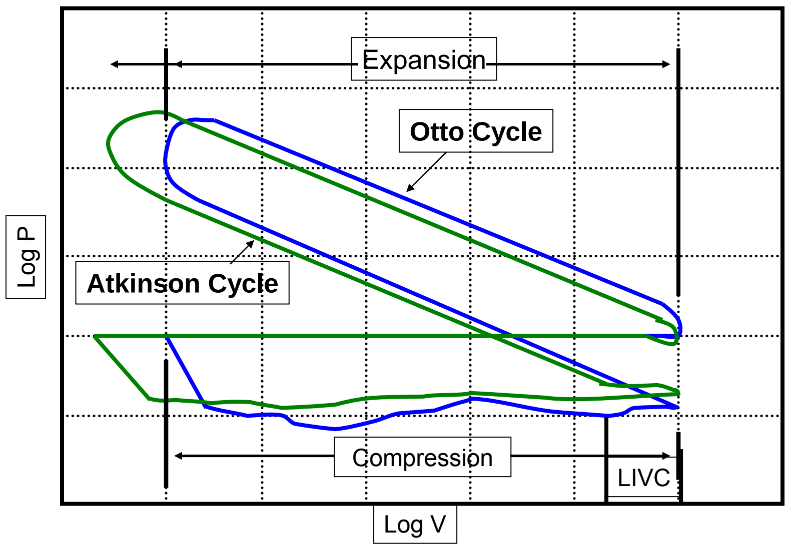
- ***2.3L I4 Gasoline Engine***
  - Atkinson Cycle to Improve Thermal Efficiency
  - 12.3 Compression Ratio
  - 99 Kw (133 HP) @ 6000 RPM
  - 168 Nm (124 ft-lb) @ 4250 RPM
- ***Electronic Throttle Control***
- ***Advance EVAP & Tailpipe Emission Control Systems***
  - Meets AT-PZEV emissions in California
  - Meets T2B3 Federally



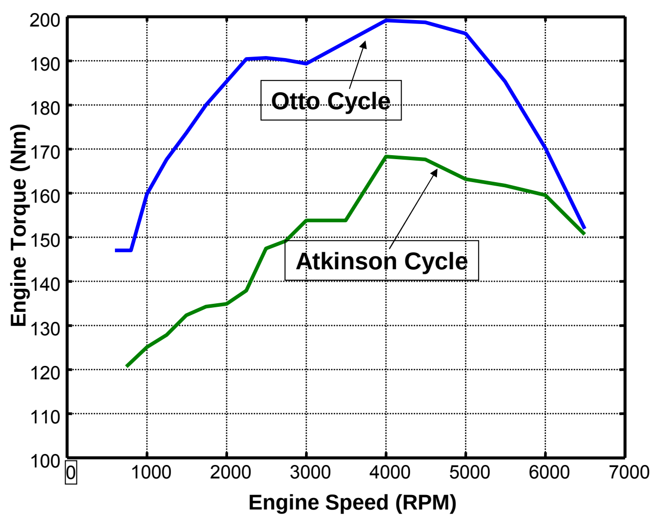
OTTO VS. ATKINSON ENGINE



PV COMPARISON

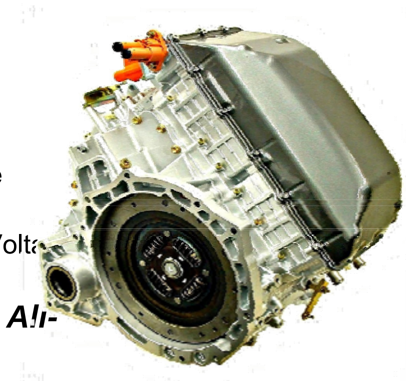


TORQUE COMPARISON

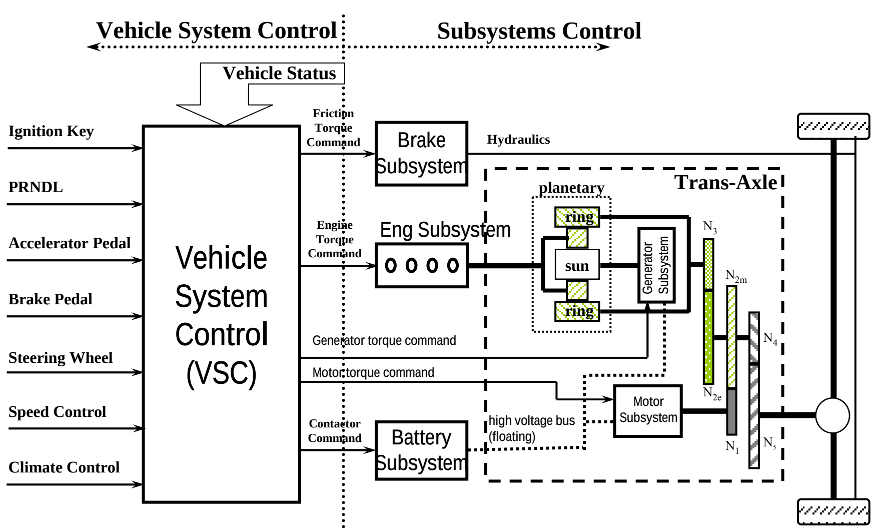


POWER SPLIT TRANSMISSION

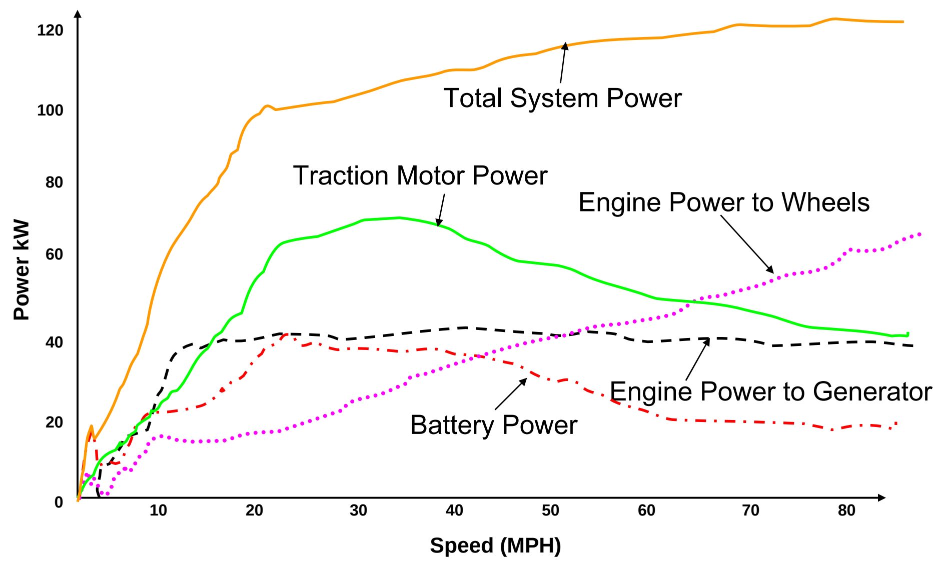
- ***Electro-Mechanical CVT with Electric Drive Capability***
  - 45 kW Permanent Magnet AC Generator/Motor
  - 70 kW Permanent Magnet AC Traction Motor
  - Planetary Gear and Final Drive Gears
  - Integrated Power Electronics/Volta Inverter
- ***Capable of Front-Wheel & All-Wheel Drive***



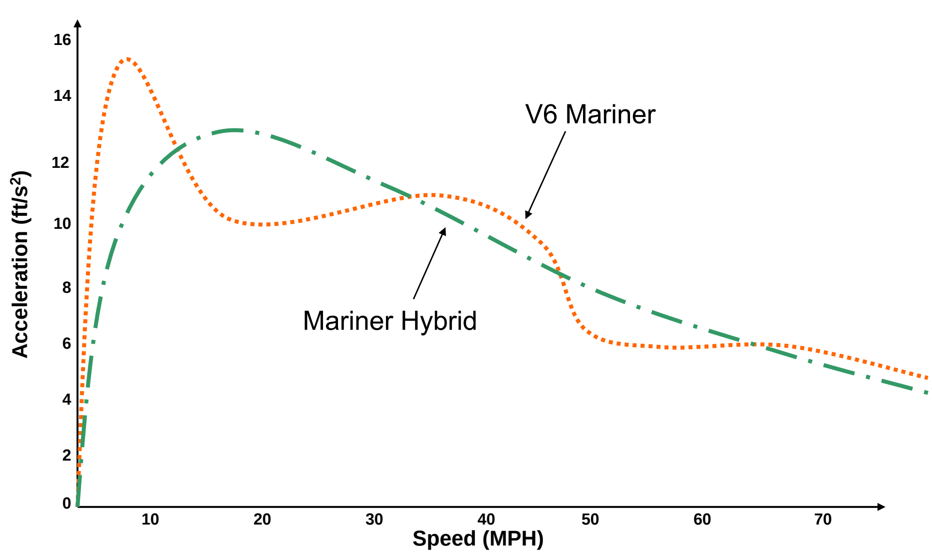
THE VSC (BRAIN) COORDINATES THE SYSTEM RESPONSE



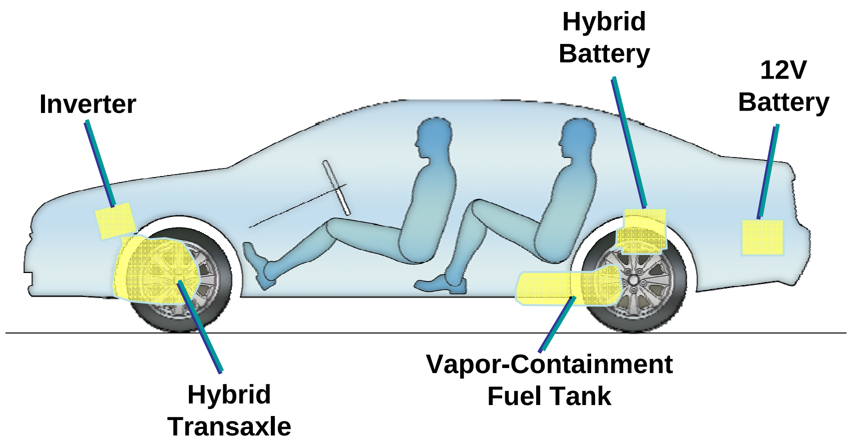
POWER SOURCES FOR ACCELERATION



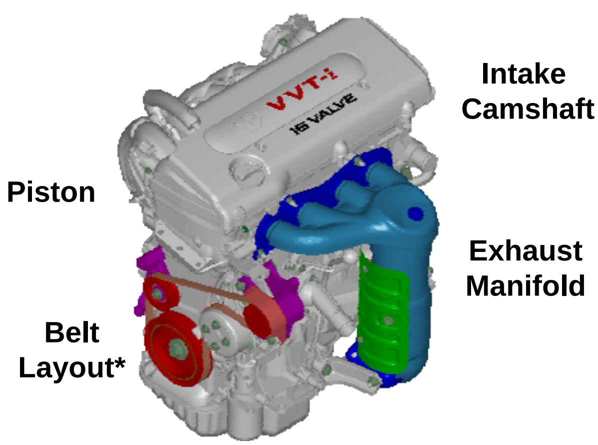
ACCELERATION CURVE COMPARISON



The 2007 Camry Hybrid



2AZ-FXE 2.4L 4-cylinder

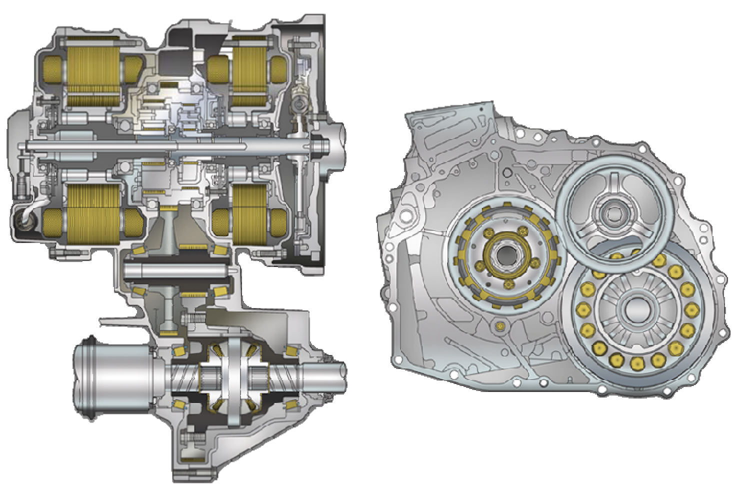


* No belt-drive for PS pump or A/C compressor

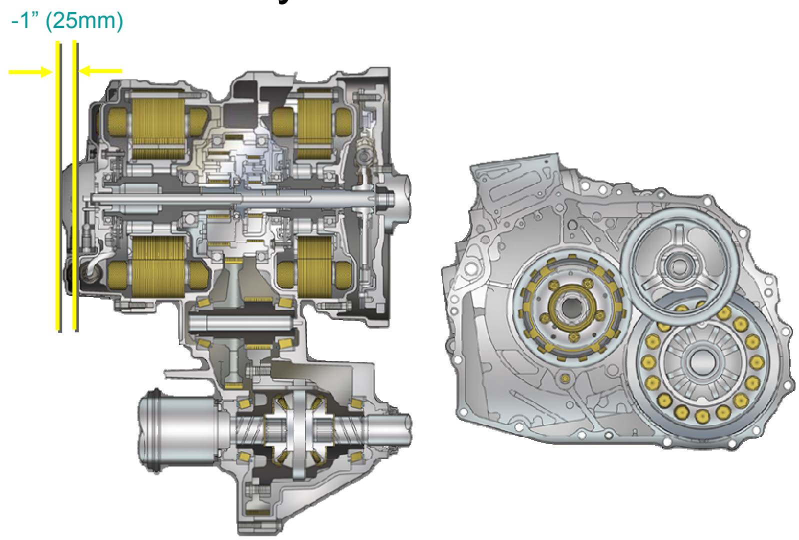
2AZ-FXE Atkinson Engine

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

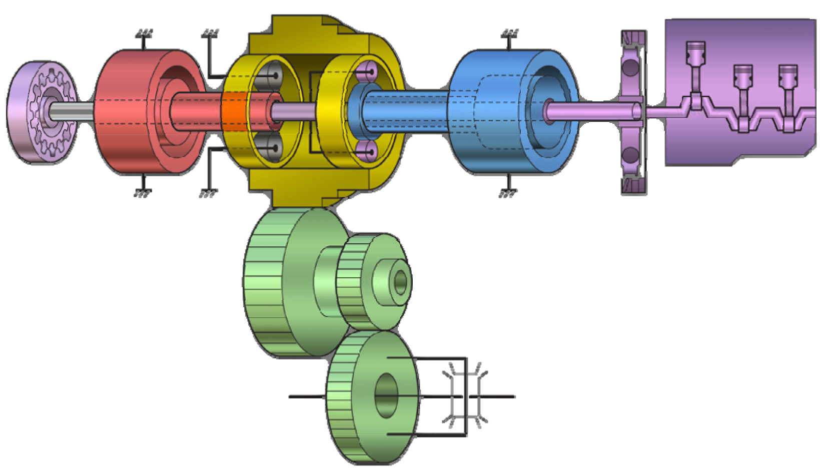
Hybrid Transaxle P311



Hybrid Transaxle



Two Planetary System



Hybrid System Components

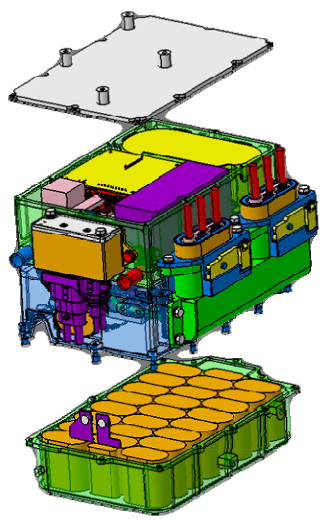
- **Two motor/generators**
  - MG1 (blue) is connected to ICE
    - acts primarily as a generator
    - also as a motor for speed control, engine starting
    - driven by 3-phase current up to 650VAC
    - speeds up to 13,000 rpm
    - water/oil-cooled permanent magnet
  - MG2 (red) connects directly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

- **Power Split Planetary Gear Set**
  - Sun gear connected to MG1 (Generator)
  - Planet carrier connected directly to engine
  - Ring gear connected to counter gear
  - 72/28% ring/sun engine torque split

- **Speed Reduction Planetary Gear Set**
  - Sun gear connected to MG2 (Motor)
  - Carrier grounded
  - Ring gear connected to counter gear
  - Speed reduction/torque increase: 2.478:1

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

Inverter



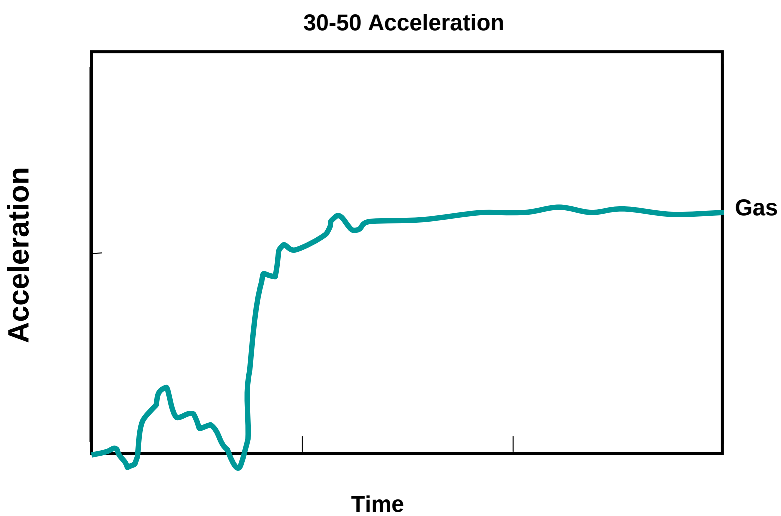
Inverter Ratings

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

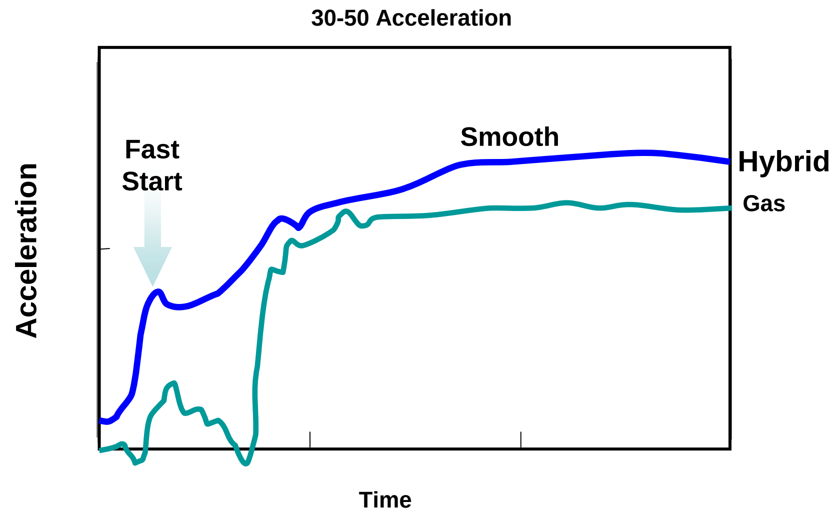
Battery Pack Assembly

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

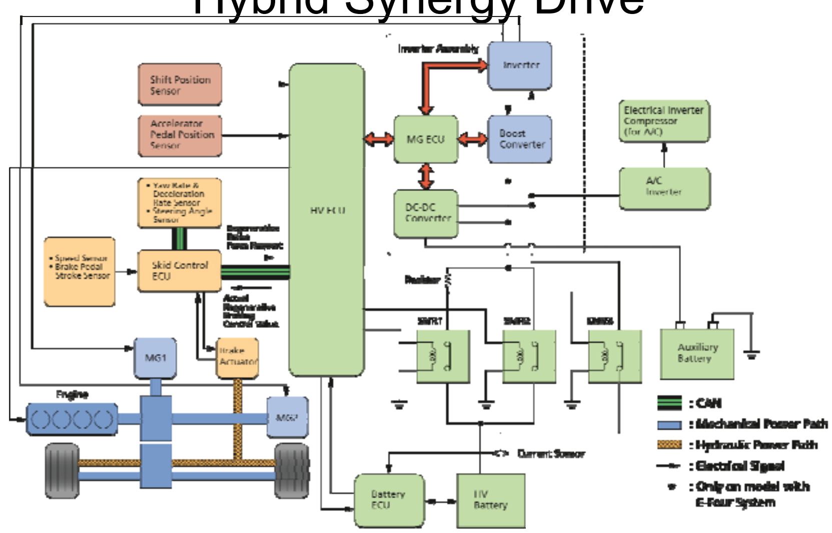
Power Delivery – Conventional



Power Delivery - Hybrid



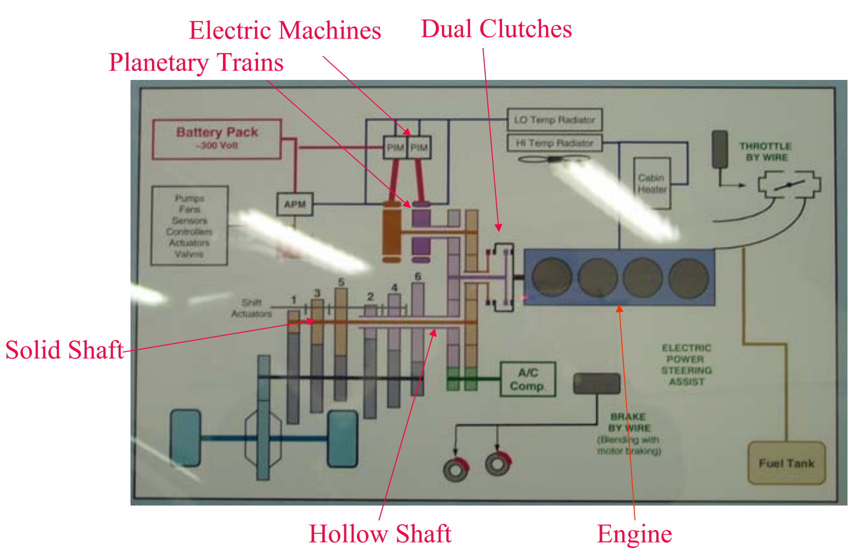
Hybrid Synergy Drive



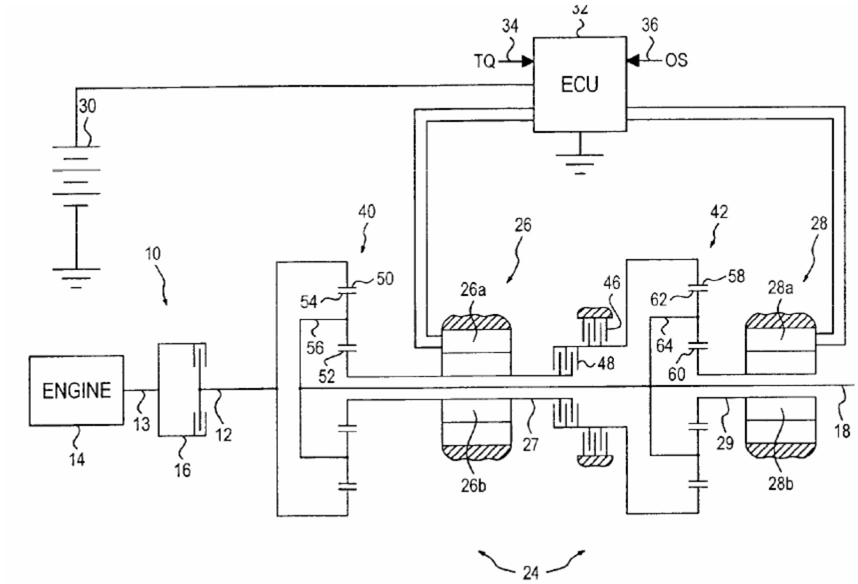
Part IV

More Complex HEV Involves Planetary Gears

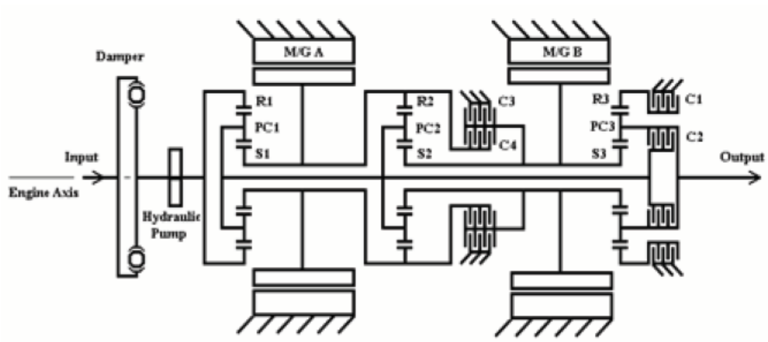
Dual Clutch AMT Based HEV Powertrain



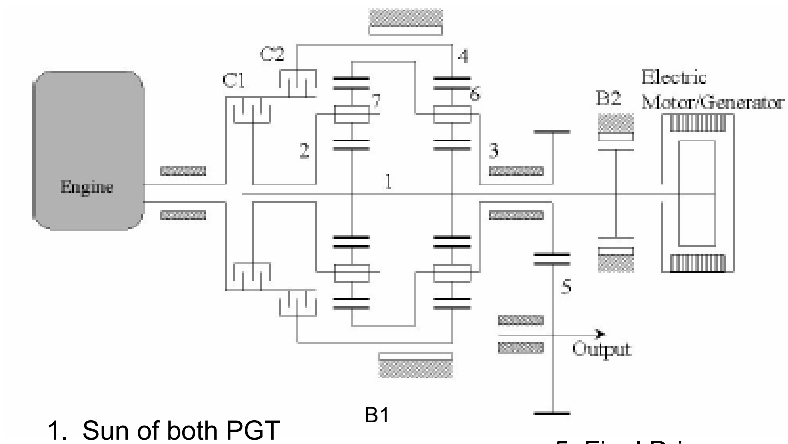
GM Two Mode Hybrid



GM Two-Mode Hybrid Variation



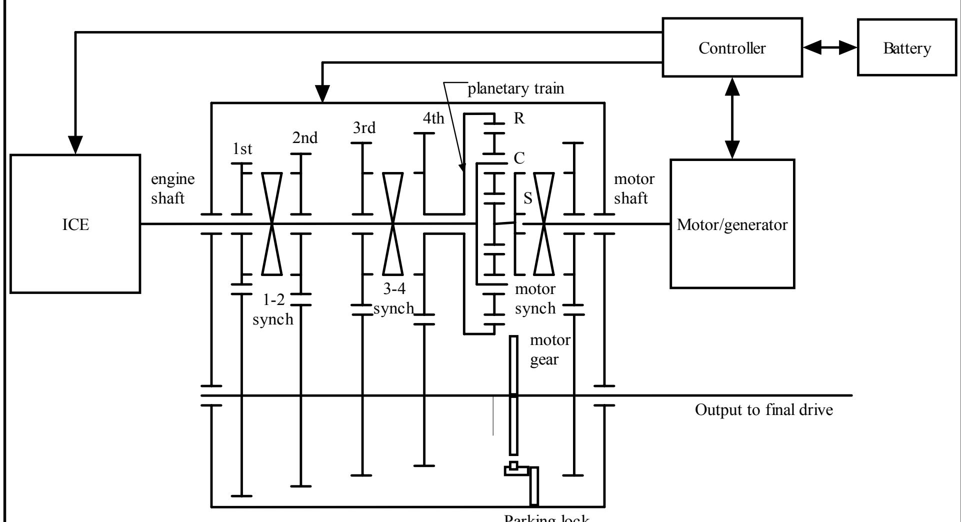
A More Complex Parallel Hybrid Drivetrain



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

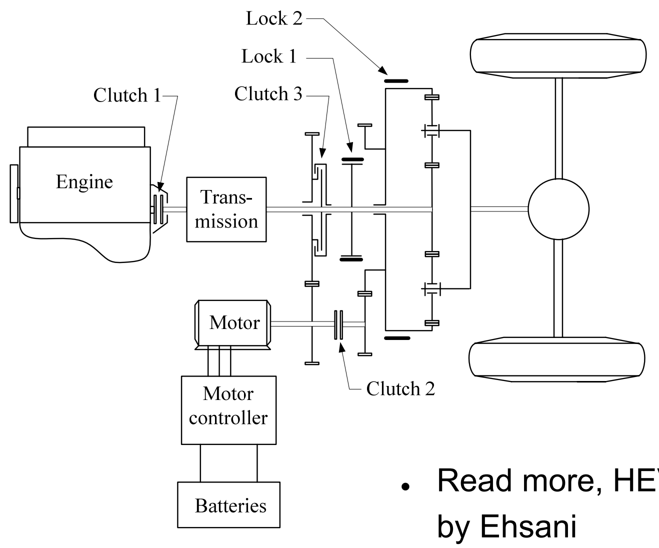
- Please read reference by Tsai

More Complex Parallel Hybrid



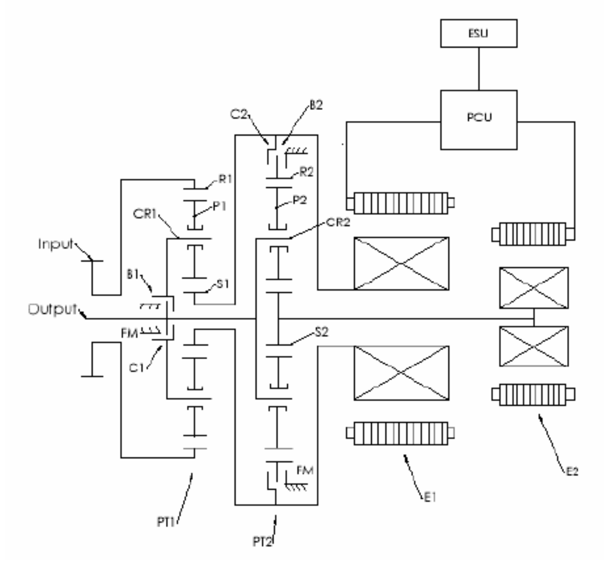
- Please read reference by Zhang, etc.

Torque and Speed Coupled Parallel Hybrid

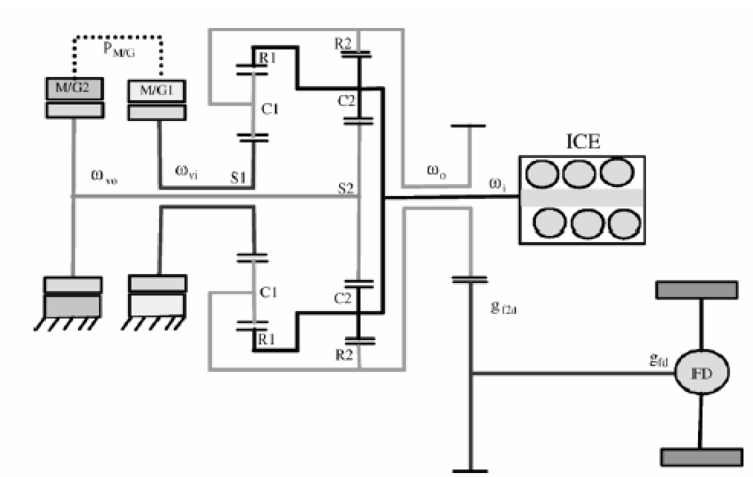


- Read more, HEV book by Ehsani

Timken Two-Mode HEV Variation



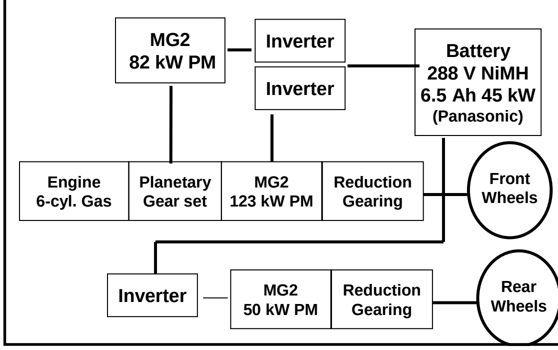
Renault HEV Powertrain



Toyota Highlander – The Toyota e-Four System

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

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



EPA MPG	Conventional	HEV	Gain (%)
City	18	31	72%
Highway	24	27	12.5

Note Conventional comparison base is, V6 and 4X4, 215hp @5600rpm, 222lb.ft @3600rpm

V4 MPG 2WD is 22/27, engine 155hp
HEV 2WD, MPG is 33/28

To Read on Complex HEV

- L. W. Tsai, G. A. Schultz, and N. Higuchi, “A Novel Parallel Hybrid Transmission,” Journal of Mechanical Design, Transactions of the ASME, Vol.123, June 2001, pp161-168.
- G. A. Schultz, L. W. Tsai, N. Higuchi, and I. C. Tong “Development of a Novel Parallel Hybrid Transmission,” SAE 2001 World Congress, Detroit, Michigan March 2001.
- Y. Zhang, H. Lin, B. Zhang, and C. Mi, “Performance modeling of a multimode parallel hybrid powertrain,” Journal of Mechanical Design, Transactions of the ASME, Vol. 128, No. 1, Jan 2006 , pp. 79-80.
- M. Ehsani, A. Emadi, Y. Gao, “Modern electric, hybrid and fuel cell vehicles,” CRC Press, 2002

References (continued)

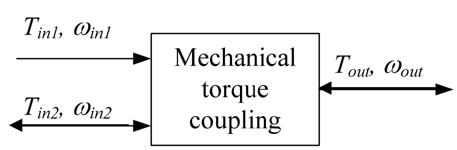
- A. G. Holmes and M. R. Schmidt, “Hybrid Electric Powertrain Including a Two-Mode Electrically Variable Transmission,” U.S. Patent 6 478 705 B1, Nov. 12, 2002.
- X. Ai, T. Mohr, and S. Anderson, “An electro-mechanical infinitely variable speed transmission,” presented at the Proc. SAE Congress Expo, 2004.
- A. Villeneuve, “Dual mode electric infinitely variable transmission,” in *Proc. SAE TOPTECH Meeting Continuously Variable Transmission.*, 2004, pp. 1–11.
- Sungtae Cho, Kukhyun Ahn*, and Jang Moo Lee, “Efficiency of the planetary gear hybrid powertrain,” Proc. IMechE Vol. 220 Part D: J. Automobile Engineering, vol. 220, 2006, pp.1445-1544.

Part V

Speed and Torque Coupling Principle

Torque Coupling

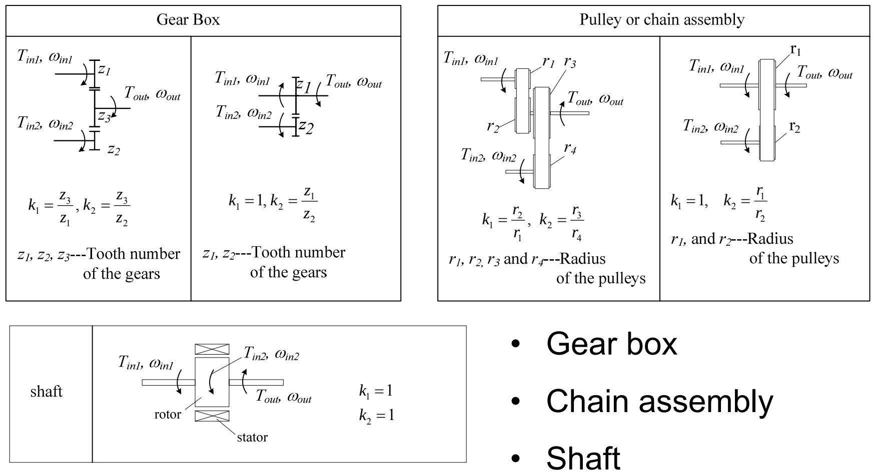
- Splits engine torque
- Or combine engine torque and motor torque
- Regenerative braking



$$T_{out} = k_1 T_1 + k_2 T_2$$

$$\omega_{out} = \frac{\omega_1}{k_1} = \frac{\omega_2}{k_2}$$

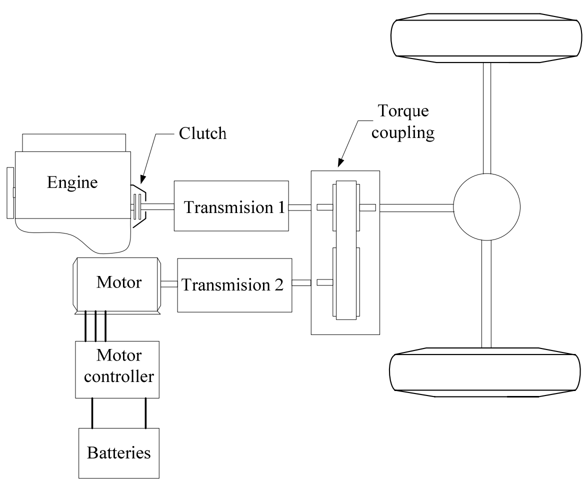
Commonly Used Torque Coupling



- Gear box
- Chain assembly
- Shaft

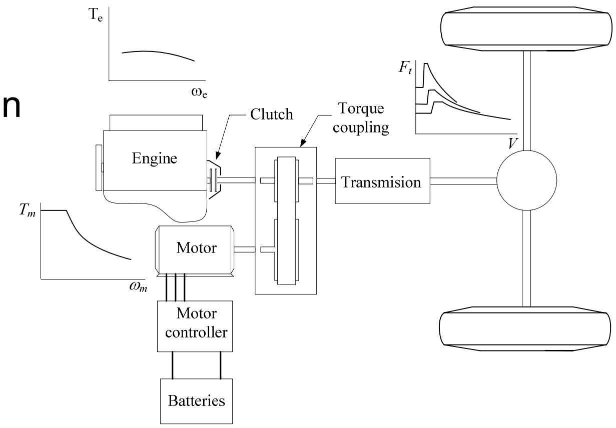
Two Transmission Design

- Flexibility in design
- Complex two transmissions

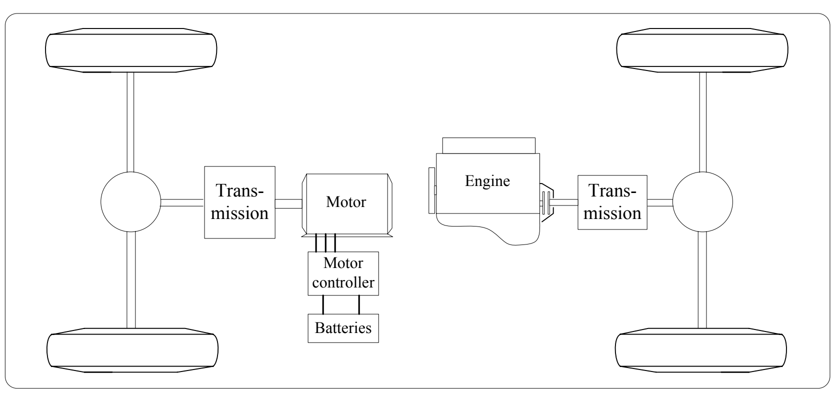


Two Shaft Design – torque before transmission

- One transmission design

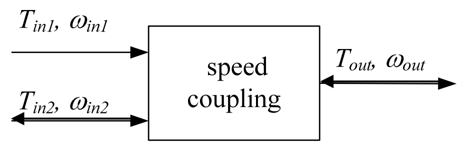


Separated Axle Configuration



Speed Coupling

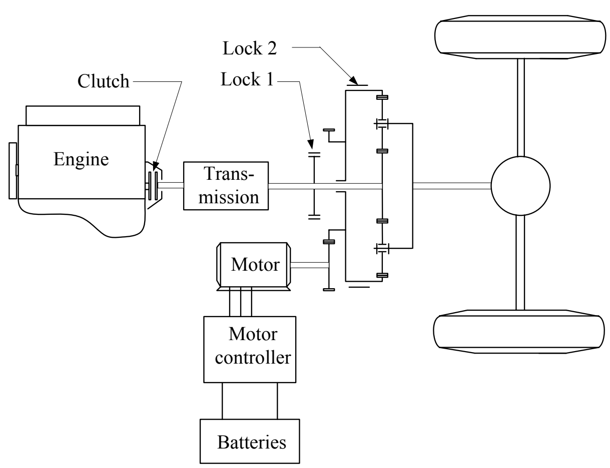
- Splits engine torque
- Combines engine speed and motor speed
- Regenerative braking



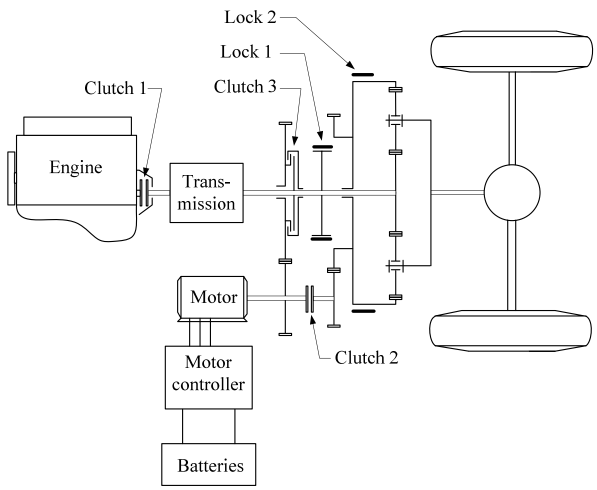
$$\omega_{out} = k_1\omega_1 + k_2\omega_2$$

$$T_{out} = \frac{T_1}{k_1} = \frac{T_2}{k_2}$$

Speed Coupled HEV



Torque and Speed Coupling



Reference

- M. Ehsani, A. Emadi, Y. Gao, "Modern electric, hybrid and fuel cell vehicles," CRC Press, 2002
- Chan, Chau, "Modern Electric and Hybrid Vehicle Technology," Oxford, 2001

Part VI

Energy Storage Challenges

Energy Source, Energy Converter, and Energy Storage

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

Comparison of Energy Sources/storage

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

Battery Types

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

Secondary batteries are primary topic for HEV/EV's

A Comparison of Batteries

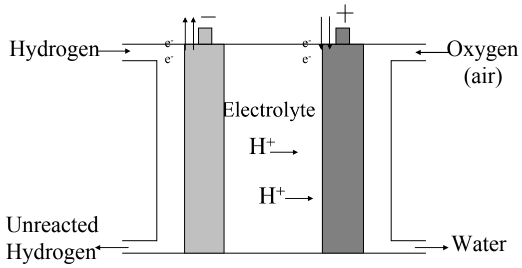
System	Specific energy (Wh/kg)	Peak power (W/kg)	Energy efficiency (%)	Cycle life	Self-discharge (% per 48h)	Cost (US$/kWh)
Acidic aqueous solution						
Lead/acid	35-50	150-400	>80	500-1000	0.6	120-150
Alkaline aqueous solution						
Nickel/cadmium	50-60	80-150	75	800	1	250-350
Nickel/iron	50-60	80-150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

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

Fuel Cells

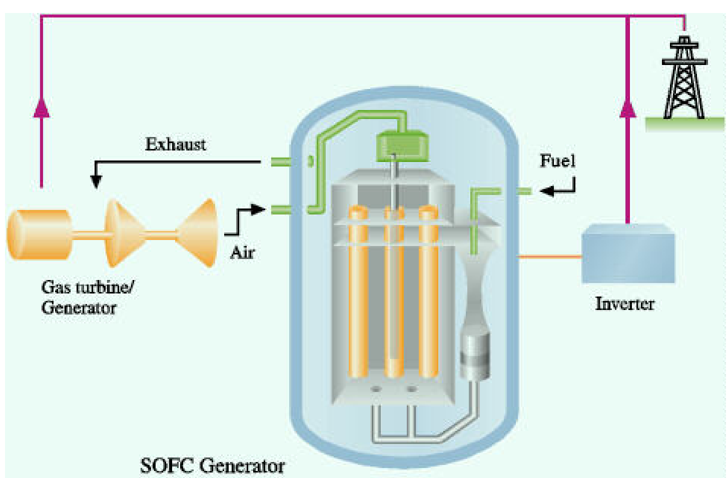
- Fuel: hydrogen and oxygen
- Concept: Opposite of electrolysis
- A catalyst speeds the reactions
- An electrolyte allows the hydrogen to move to cathode
- Flow of electrons from anode to cathode in the external circuit produces electricity
- Oxygen or air is passed over cathode

Fuel Cell Reaction



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

A fuel cell



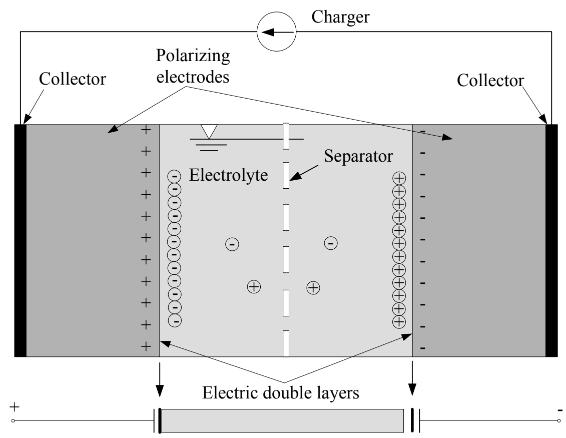
Fuel Cell Comparison

Fuel Cell Variety	Fuel	Electrolyte	Operating Temperature	Efficiency	Applications
Phosphoric Acid	H_2, reformate (LNG, methanol)	Phosporic acid	~200^{0}C	40-50%	Stationary (>250kW)
Alkaline	H_2	Potassium hydroxide solution	~80^{0}C	40-50%	Mobile
Proton Exchange Membrane	H_2, reformate (LNG, methanol)	Polymer ion exchange film	~80^{0}C	40-50%	EV/HEV, Industrial up to ~80kW
Direct Methanol	Methanol, ethanol	Solid polymer	90-100^{0}C	~30%	EV/HEVs, small portable devices (1W-70kW)
Molten Carbonate	H_2, CO (coal gas, LNG, methanol)	Carbonate	600-700^{0}C	50-60%	Stationary (>250kW)
Solid Oxide	H_2, CO (coal gas, LNG, methanol)	Yttria-stabilized zirconia	~1000^{0}C	50-65%	Stationary

Ultra-Capacitors

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

How an Ultra-Capacitor Works



$$Energy = \frac{1}{2} C V^2$$

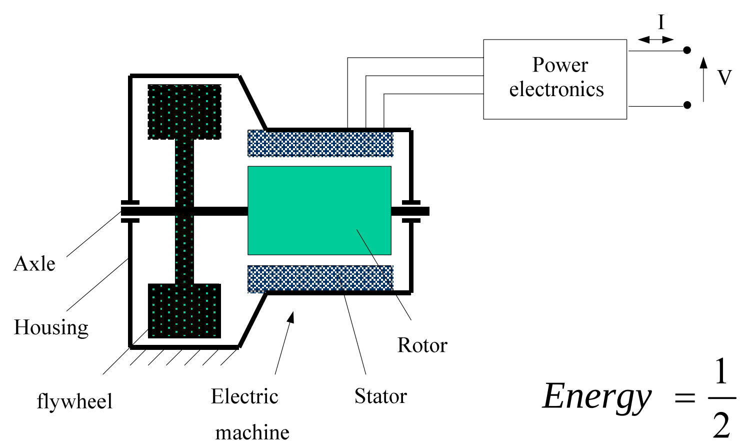
Flywheels

- 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

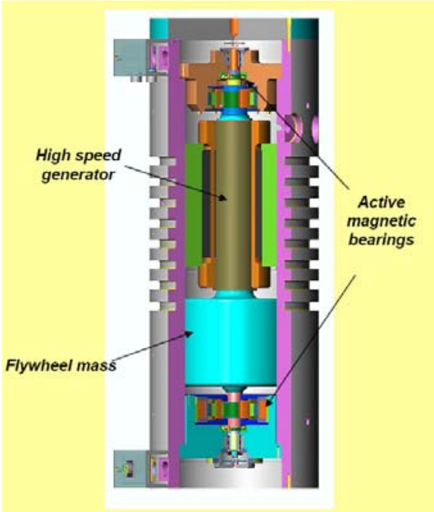
Basic Structure



$$Energy = \frac{1}{2} J\omega^2$$

High Speed Flywheel Example

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



Hybridization of Energy Storage

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

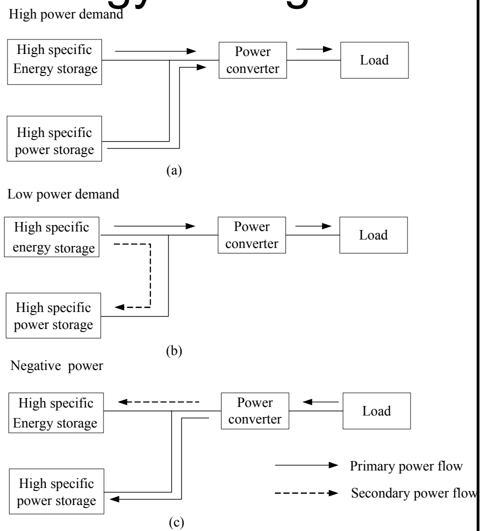
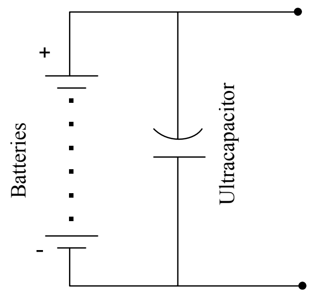
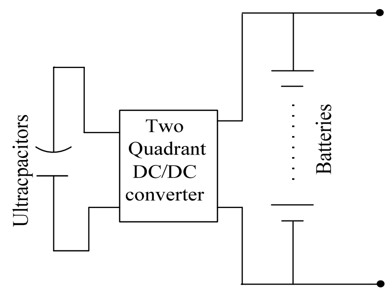


Fig. 10.18

Two Topologies of Hybridization

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





Current Issues with NMH Batteries

- Efficiency
- Self Discharge

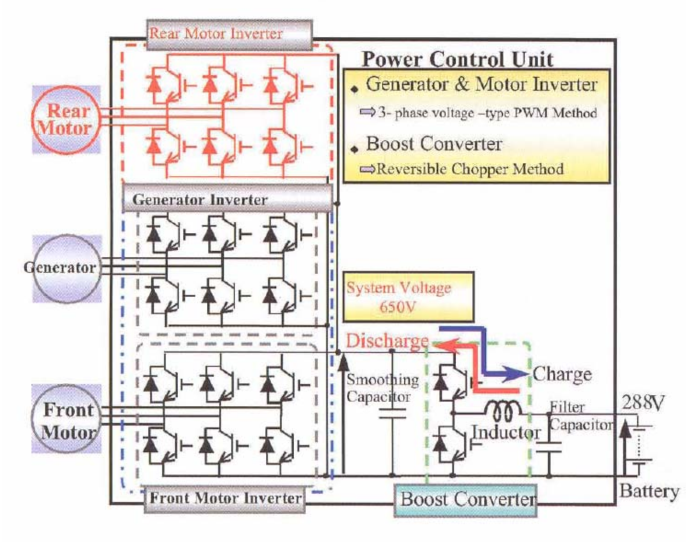
Current Issues with Lithium Battery

- **Cost**
  - Cost is above FreedomCAR targets
  - Raw materials & materials processing
  - Cell and module packaging
  - Electrical and mechanical safety devices
- **Abuse tolerance**
  - Overcharge
  - Crush
  - Short circuits
- **Life**
  - Calendar life

Part VII

Power Electronics Challenges

RX400 Hybrid Power Electronic Unit



Emerging Issues

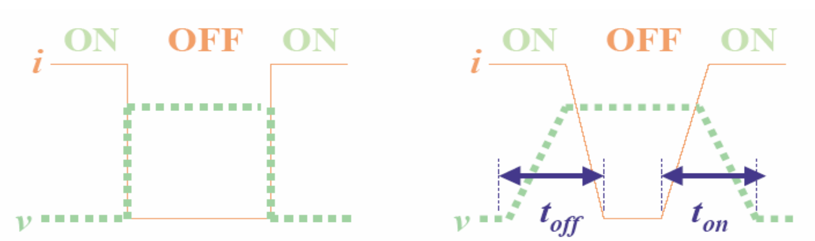
- Power losses and efficiency
- Reliability
- Novel thermal management technology
- Cost reduction with better power bus regulation
- EMC concerns
- Emerging and new semiconductor devices
- EMC due to power electronics switching and transmission
- Increased use of microcontrollers
- Increased of sensors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

Power loss and conversion efficiency

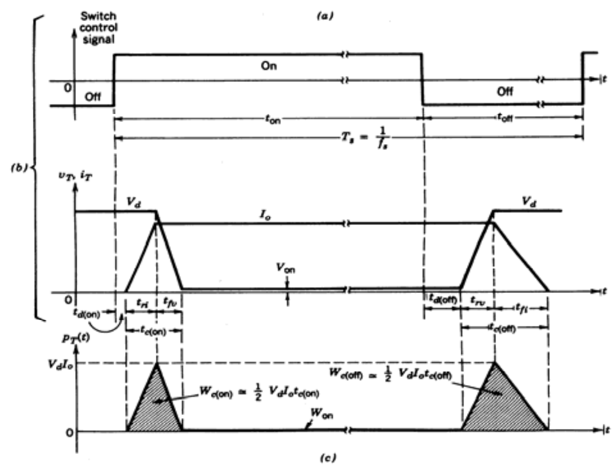
- Power loss of semiconductor devices, especially switching power circuits, is a serious issue in the conversion efficiency, and thermal management is key design issue for many automotive electronics applications
- New circuit topologies, such as cascade circuits, multilevel converters, soft switching,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

Non-ideal switching

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



Losses – ideal case



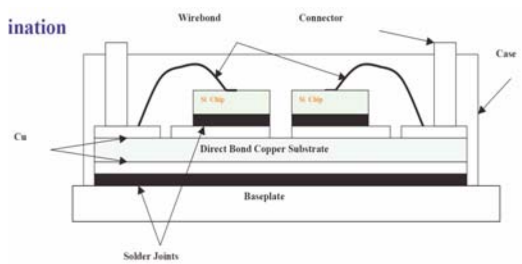
Switching and conduction loss

Reliability

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

Failure Mechanism

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

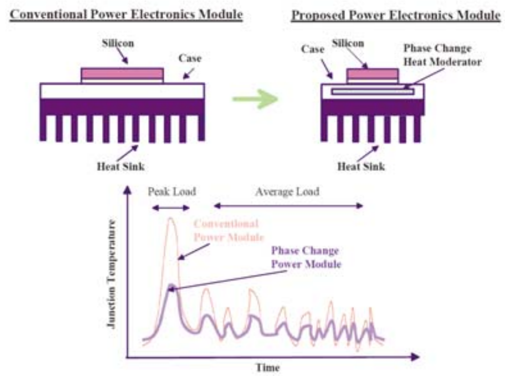


Novel thermal management

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

Phase changing material

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



EMC Concerns

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

Emerging Devices

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

Silicon Carbide (SiC)

- **Silicon carbide** (SiC) is a ceramic compound of silicon and carbon.
- Wide band semiconductors material (SiC 3-3.3eV vs 1.12 eV Si)
- High electric Breakdown field (SiC 1.5-4e6V/cm vs Si 2-8e5 V/cm)

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

One electronvolt is a very small amount of energy:

> 1 eV = 1.602 176 53 (14)×10−19 J. (Source: CODATA 2002 recommended values)

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

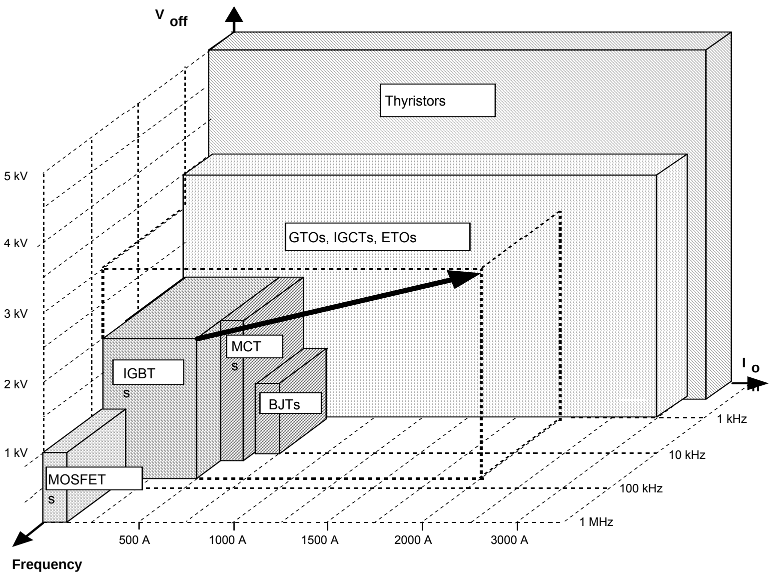
Property of SiC

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

Challenges of SiC

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

Summary of Silicon Power Device Capabilities



New Semiconductor Materials for Power Devices

- Silicon not optimum material for power devices

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

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

- Diamond potentially the best materials for power devices
  - Largest bandgap
  - Largest breakdown field strength
  - Largest thermal conductivity
  - Larger mobilities than silicon but less than GaAs

On-State Resistance Comparison with Different Materials

- Specific drift region resistance of majority carrier device
  - $R_{on} \bullet A - \frac{4\,q\,(BV_{BD})^2}{e\,m_n\,(E_{BD})^3}$
  - Normalize to silicon - assume identical areas and breakdown voltages

$$\frac{R_{on}(x)\,A}{R_{on}(Si)\,A} = \text{resistance ratio} = \frac{e_{Si}\,m_{Si}}{e_x\,m_x}\left[\frac{E_{BD,Si}}{E_{BD,x}}\right]^3$$

  - Numerical comparison

Material	**Resistance Ratio**
Si	1
GaAs	$6.4\text{x}10^{-2}$
SiC	$9.6\text{x}10^{-3}$
Diamond	$3.7\text{x}10^{-5}$

Part VIII

Other Challenges and Opportunities

Plug-in HEV

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

Diesel HEV

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

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

Emerging Issues

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

Opportunities

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

Thank You!

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