Comparative Assessment of Hybrid Vehicle Power Split Transmissions

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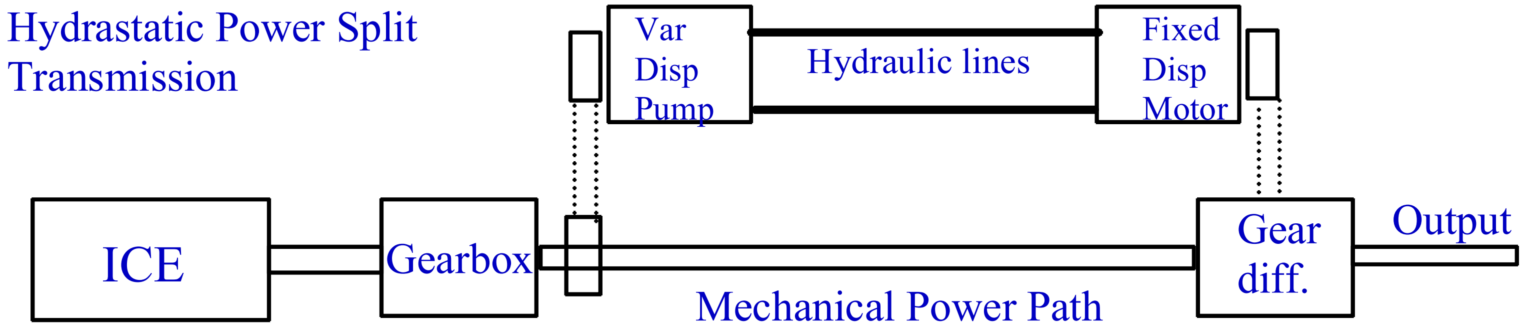
Design Services

Outline of Topics

- Presentation time: ½ day

Historical Developments: Hydrostatic

- Hydrostatic power split
  - Maintains direct mechanical power path
  - Input power splits (k/(k+1)) mechanical + (1/(k+1)) hydraulic
  - Controllable speed summer (differential) maintains desired output



Historical Developments: ElectroMechanical

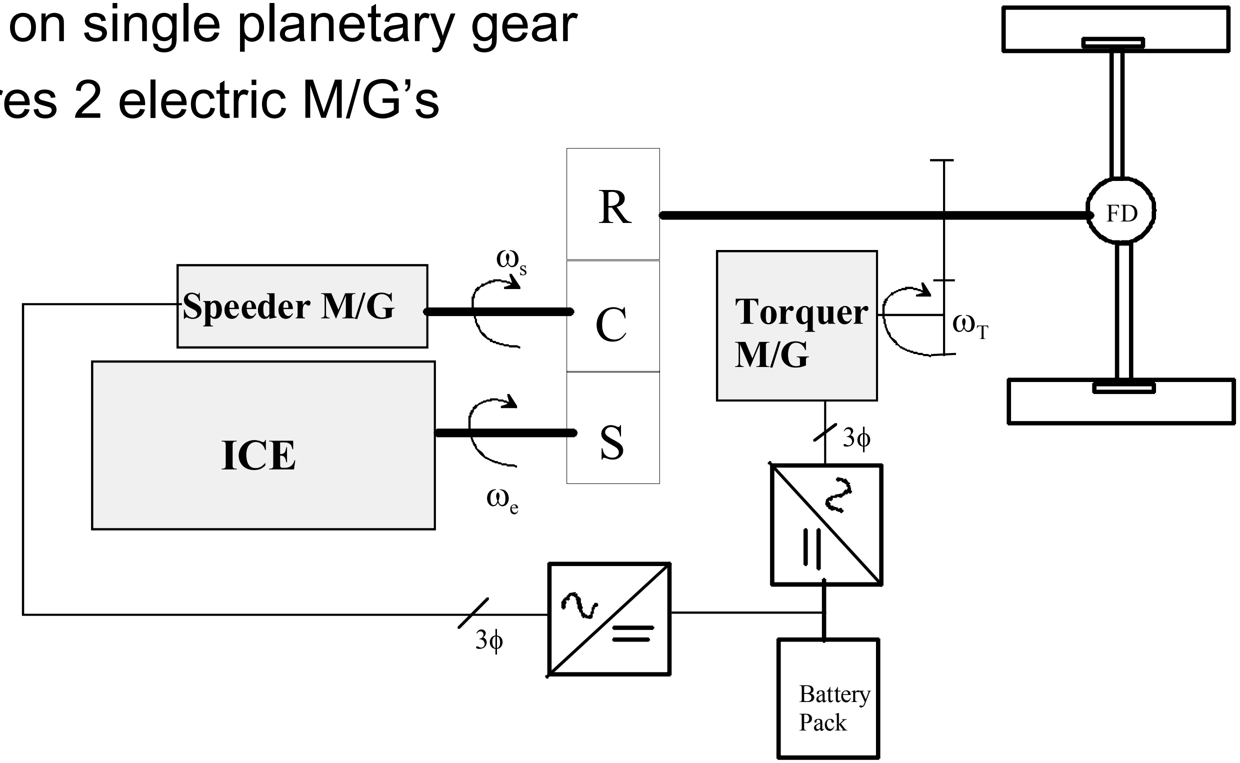
- The classic electro-mechanical power split transmission developed by TRW and published in a 1971 SAE paper is the basis of today's electric power split systems. G.H. Gelb, N. A. Richardson, T.C. Wang, B. Berman, "An Electromechanical Transmission for Hybrid Vehicle Powertrains," SAE paper no. 710235, Jan. 1971
- One electric machine provided the function of "speeder"
- A second electric machine provided the function of a "torquer"
- In the original TRW system there are no clutches and no step ratio gear shifts – the essentials of power split.

Historical Developments: ElectroMechanical

- TRW Electromechanical Transmission – EMT
  - ICE drives the planetary SUN gear
  - The “speeder” (generator) M/G connects to the carrier
  - The “torquer” (motor) M/G is connected to the ring gear via an additional gear ratio.
  - Ring gear output shaft transmits summation power to the vehicle driveline.

Historical Developments: ElectroMechanical

- Electromechanical Transmission
  - Has 5 operating modes
  - Relies on single planetary gear
  - Requires 2 electric M/G's

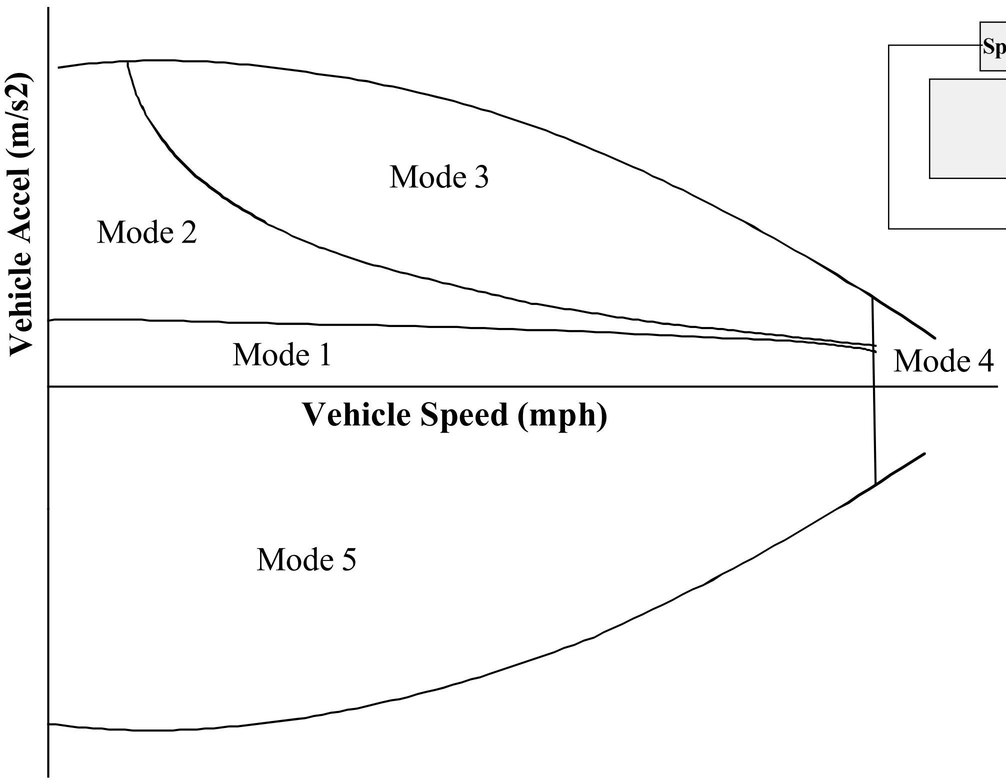


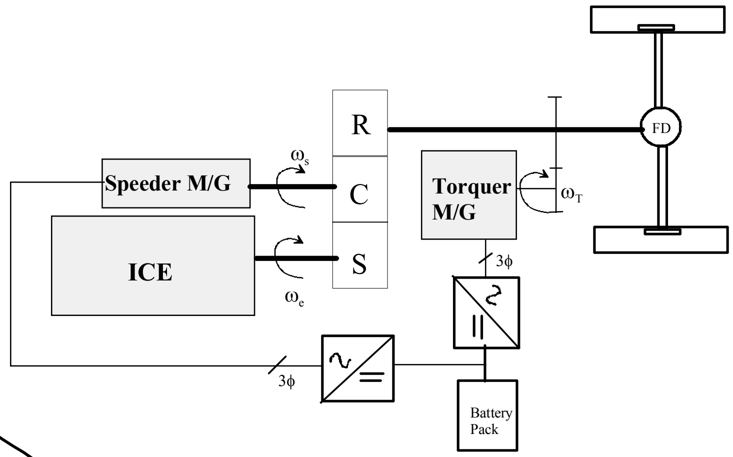
Historical Developments: ElectroMechanical

- EMT Operating Modes
- Mode 1: low acceleration events when ICE power exceeds the road load
  - Excess engine power is used to charge the battery by using M/G1 and M/G2 in their generating mode
  - When engine power matches road load but has insufficient torque, the “torquer” M/G acts as a motor to deliver additional power to the wheels by discharging the battery.
- Mode 2: low speed, launch and light cruise
  - The “speeder” M/G remains in generator mode and delivers engine power to the “torquer” via the electric path.
  - Excess electric power may be delivered to the battery

Historical Developments: ElectroMechanical

- EMT – operating regimes



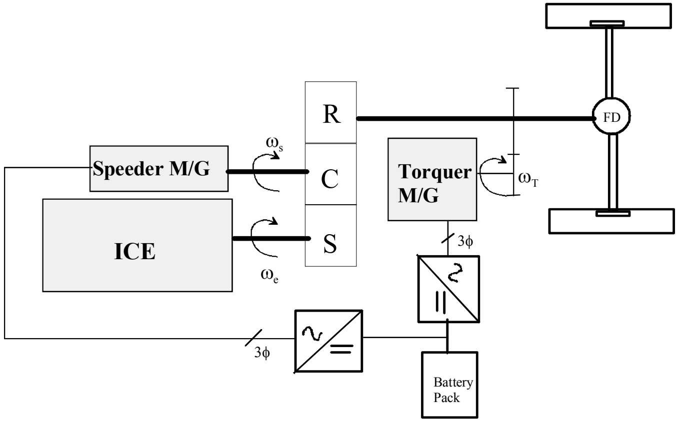


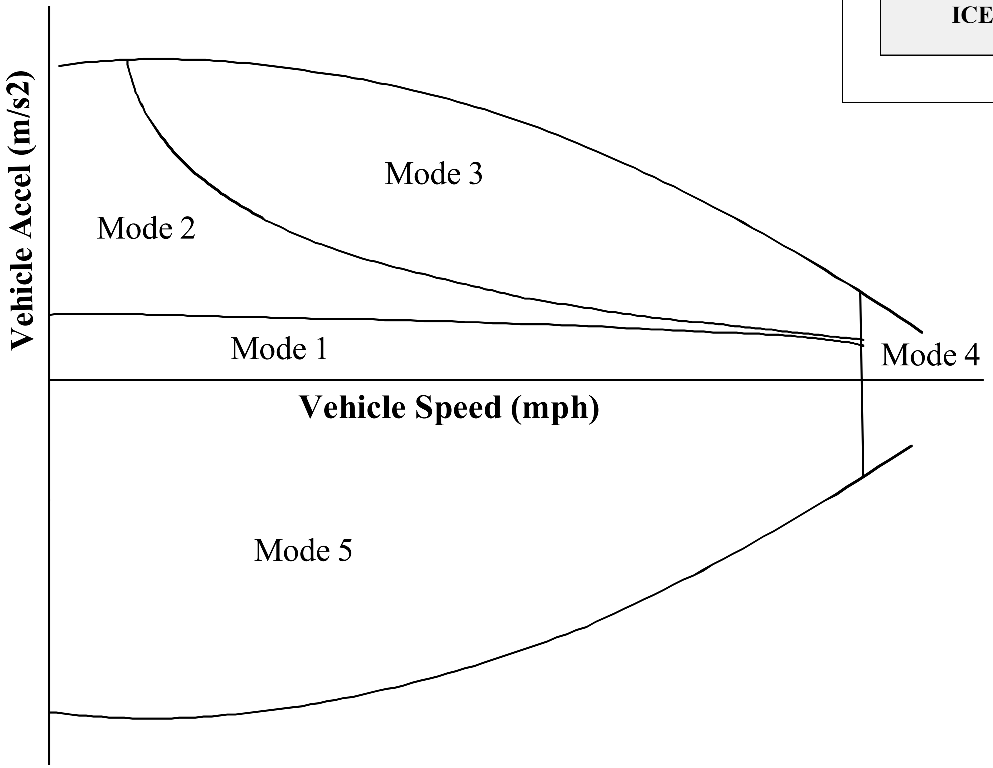
Historical Developments: ElectroMechanical

- Mode 3: High load condition
  - Road load torque and power exceed the available engine torque and power.
  - The battery (ESS) contributes additional boost power to both the motor “torquer” and generator “speeder”.
- Mode 4: High cruising speeds
  - “Speeder” is locked up and the engine is throttled up
  - “Torquer” is operated in motoring or generating mode as needed
- Mode 5: Deceleration
  - Both M/G’s operate in generating mode to recuperate vehicle kinetic energy to battery (ESS).

Historical Developments: ElectroMechanical

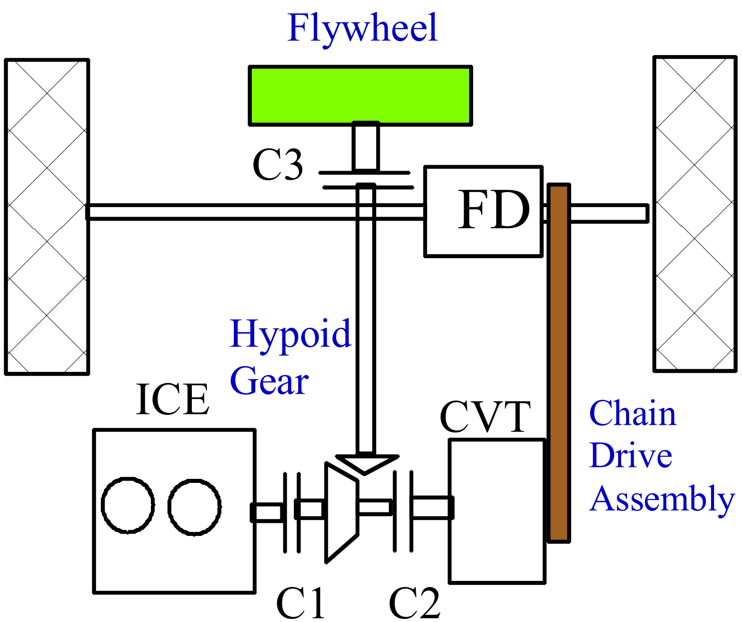
- EMT operating regimes





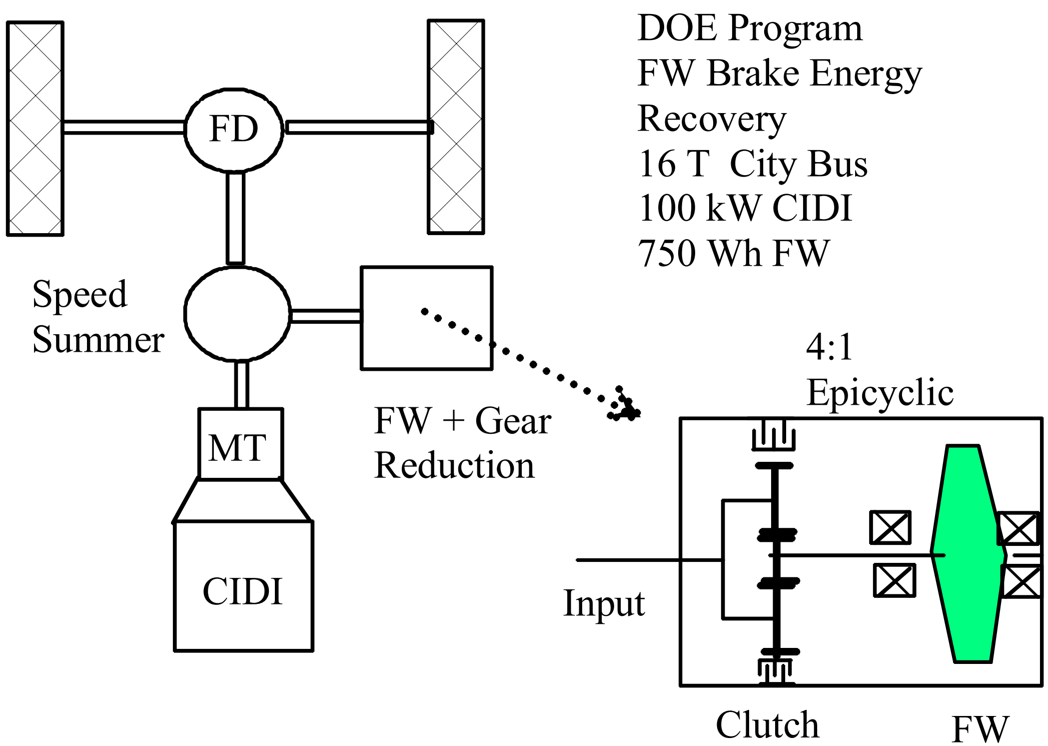
Historical Developments: Flywheel Hybrids

- During 1970's to early 1980's U.S. DOE sponsored programs investigated ICE-Flywheel hybrid concepts
  - FES is the primary energy storage system
  - Some used mechanical CVT's as matching elements



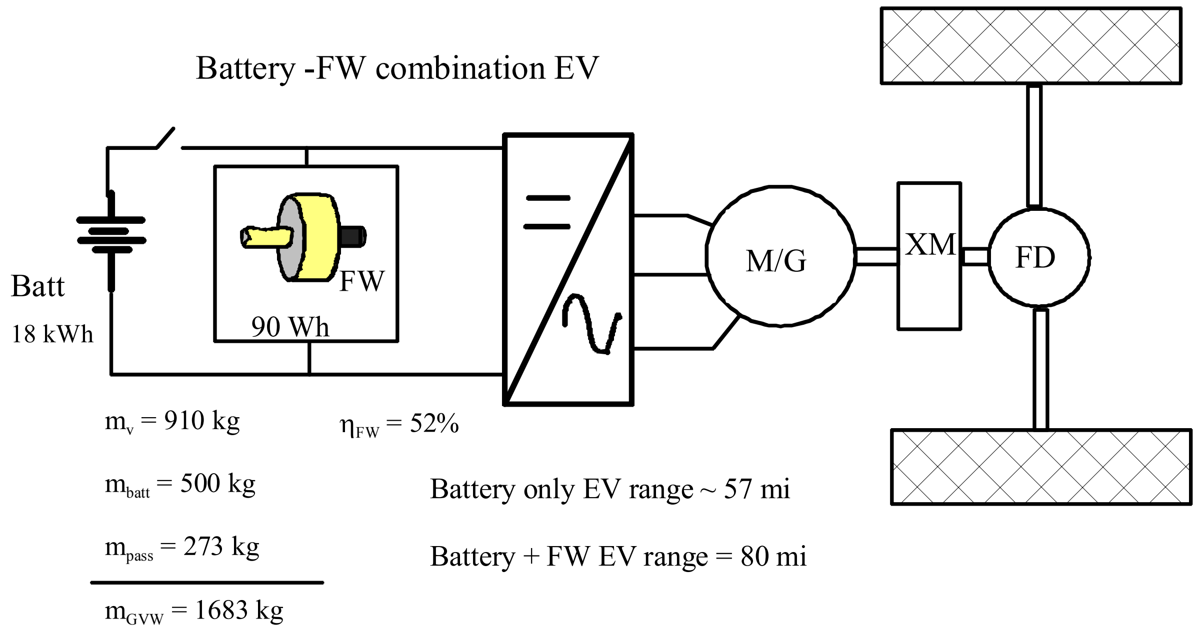
Historical Developments: Flywheel Hybrids

- Some systems used a planetary gear matching element between the driveline and the flywheel, FES
  - City bus applications were common development platforms



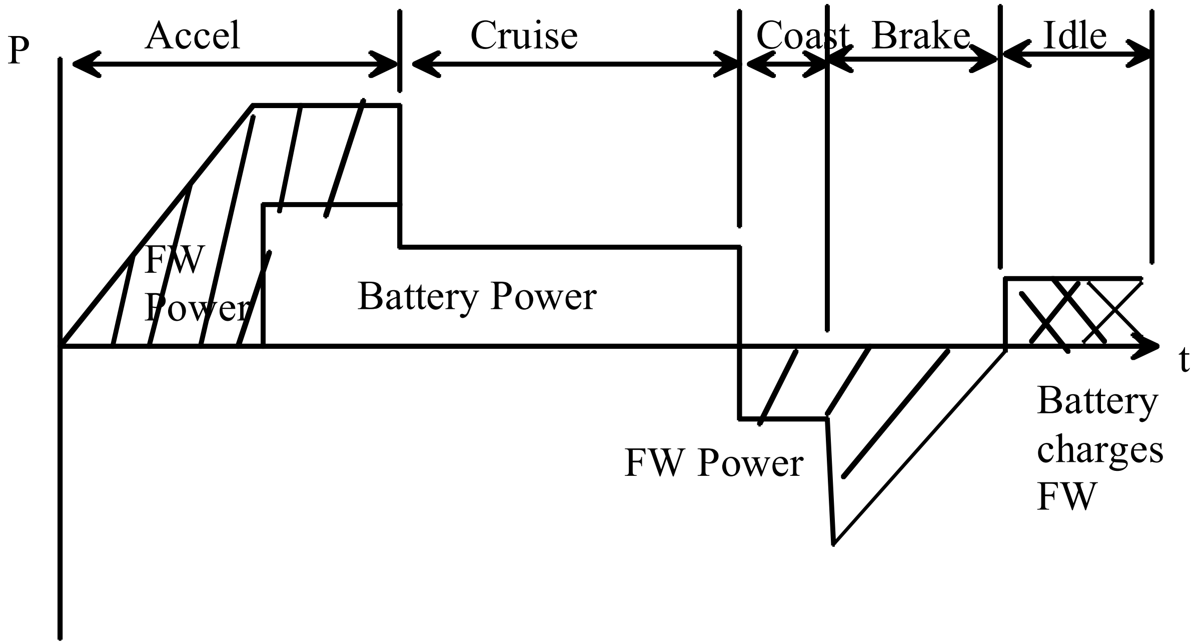
Historical Developments:Battery + Flywheel

- A novel combination relied on Lead-acid battery energy storage and a flywheel for dynamic storage
  - Battery for continuous and low dynamic events
  - FES for high dynamic events and for power boosting



Historical Developments:Battery + Flywheel

- Battery + FES system was an early attempt at combination energy storage systems for continuous and dynamic loading events
  - FES recharges during deceleration events AND
  - FES can be recharged from the battery – at slow and efficient rates



Historical Developments: Early Hybrids

- 1905 H. Piper files U.S. patent for a petrol-electric hybrid vehicle. Goal was to use the electric motor to assist the ICE so that higher speeds (25 mph) could be achieved.
  - Unfortunately, within a couple years the ICE was improved to the point that such speeds became commonplace.
- 1921 Owen Magnetic Model 60 Touring vehicle
  - Uses gasoline engine to run a generator
    That supplies electric power to motors
    Mounted in each of the rear wheels.

- 2004 Ford Hybrid Escape
  - Launches in electric mode 0→25 mph

Hybrid Functions

- Hybrid functionality improves dramatically as M/G power increases to 50% of targeted peak power – synergy with ICE

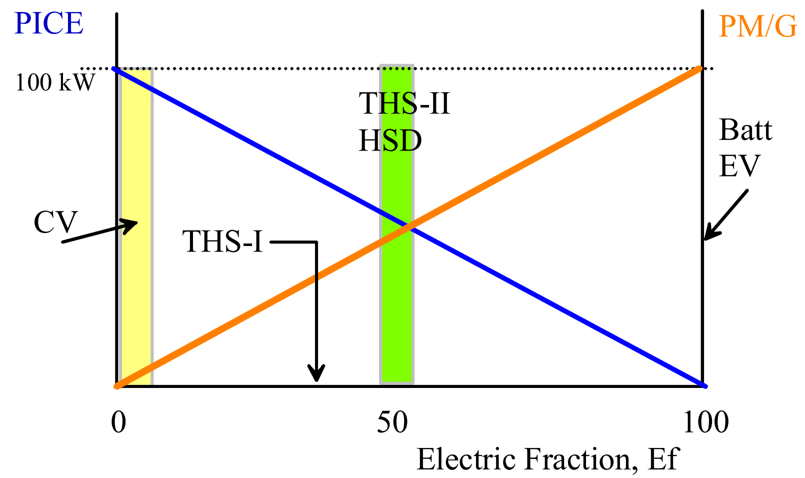
PowerTrain	Conventional	Conventional	Conventional	Downsized	Downsized	Downsized
Elect. M/G	Belt ISG 14V	Belt ISG 42V	Belt ISG 42V	Crank-ISG 42V	Crank-ISG 150V	Offset ISG >300V
Ancillaries	Conventional	Conventional	Electric	Electric	Electric	Electric
Battery	Flooded Pb-Acid, 25 kg	VRLA, 30kg	VRLA, 30kg	NiMH, 20 kg	NiMH, 40kg	NiMH, 60kg
Functions:						
Idle Stop						
Regen						
Energy Mg'mt						
Launch assist						
ZEV						
%FE Benefit	3	7	10	30	35	<40

ICE versus Electric: Achieving a balance

- What do we mean by synergy with ICE?
- Toyota: Hybrid Passenger Vehicle Industry leader
  - Prius hybrid: THS-I generation of hybrid functionality
  - New Prius hybrid: THS-II generation based on hybrid synergy drive
  - Toyota Prius-II has electric power steering, electronic controlled brakes and electric drive air conditioning.

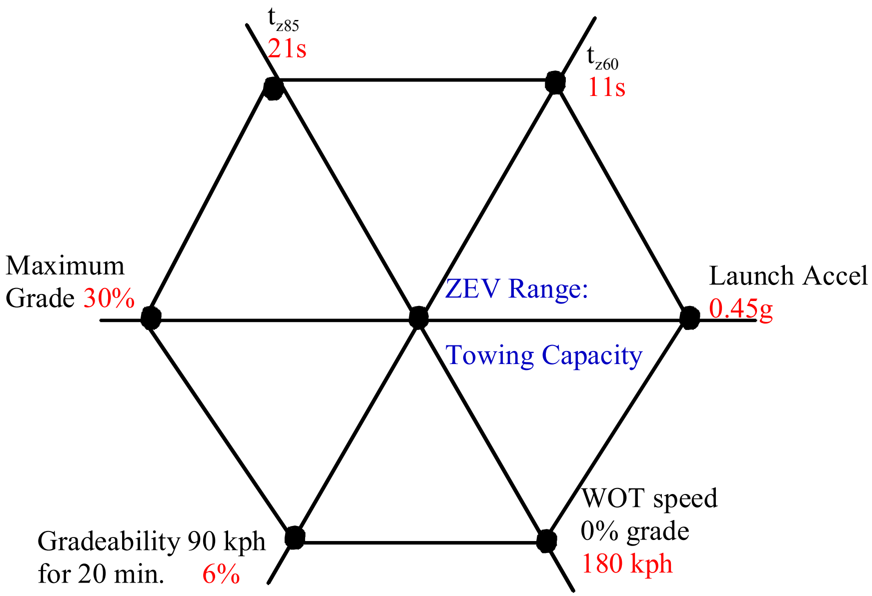
Toyota Motor Co has managed to
Raise the battery warranty from 8 years
On PRIUS-I to 150,000 miles (10 yr)
On PRIUS-II

How?
By more intelligent operation and by
Improving the battery terminations for
Lower ESR (higher efficiency)



Vehicle Performance Targets

- Hybrid vehicles today must deliver the performance customers expect. The new HSD Prius-II was released for sale October 2003 in North America. Prius-I sales for 2003 were some 38,000 in NA and customers are now lining up to purchase the new Prius-II. CY2004 sales target in N.A. is 70,000

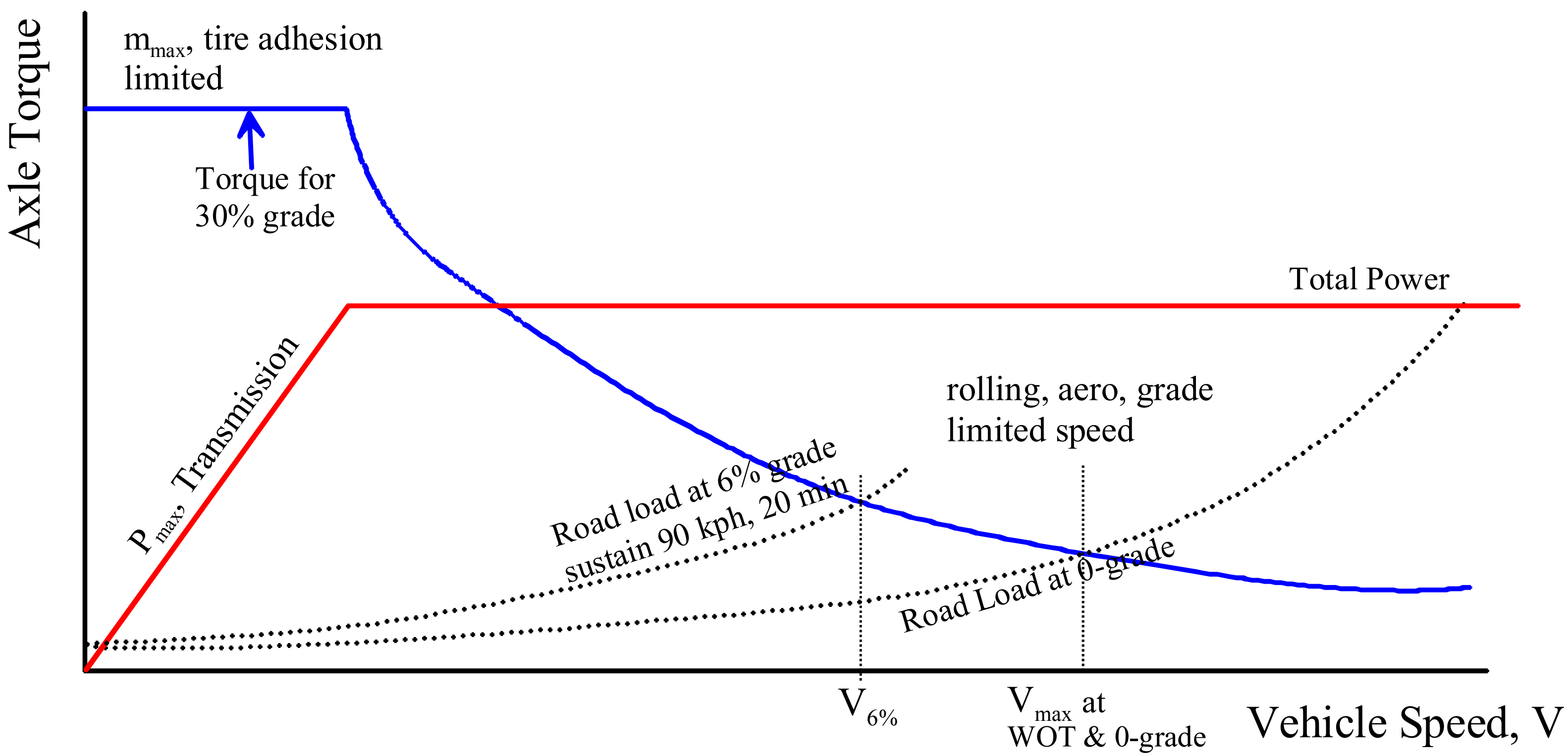


Hybrids typically do not have towing capability
– until the new Ford hybrid Escape introduced Oct. 2004 that has a tow capability of 1500# (non-hybrid Escape is rated 3500# towing). Full size pickups are rated 6500# towing.

Acceleration benchmarks:
Prius I, 0→60 mph time = 12.5s
Prius II, 0→60 mph time = 10.5s
Hybrid Escape, 0→60 mph time = 11.2s

Vehicle Performance Targets

- Applying the vehicle performance targets



Vehicle Performance Targets

- So how do recent hybrid vehicle products now offered "stack-up" in terms of performance?
  - Historically, performance targets have dictated a peak specific power (combined in case of a hybrid) of 10 kW/125 kg power plant

Vehicle	Curb mass	Engine Power	M/G Power	Electric Fraction	Peak specific power
	(kg)	(kW)	(kW)	(%)	(kW/125 kg)
Civic	1242	63	10	14	7.35
Prius	1254	53	33/10	38	8.6
Escape	2053	80	65/28	45	8.8
HSD	1295	57	50/10	47	10.3

Hybrid Synergy Drive, HSD, goal is to match V6 performance with an I4 through "electric supercharging"

Session 2

- Toyota Hybrid System:
  - THS-I and THS-II
  - Tire dynamics
  - Hybrid modes
  - Power Split operation during cruise

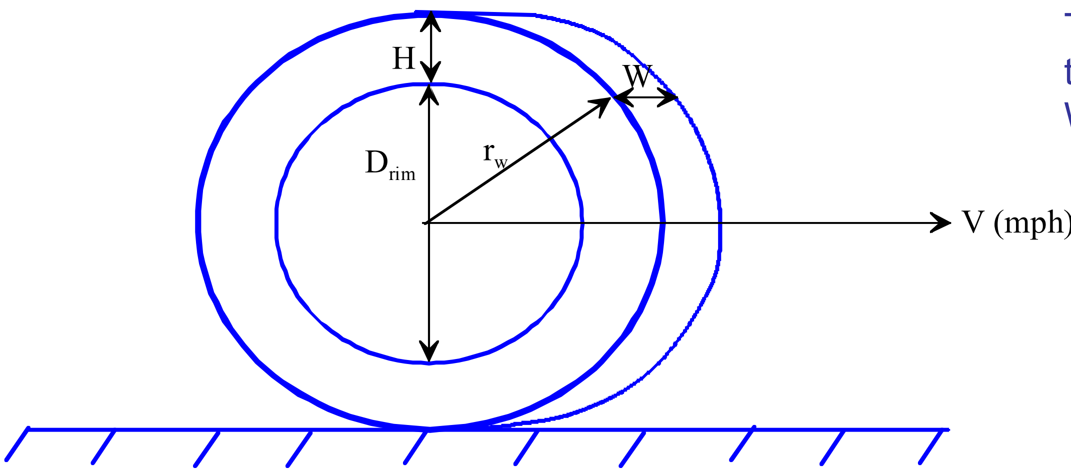
Comparison of Toyota Hybrid Technology: THS-I & THS-II Power Train & Vehicle

- Example to illustrate Prius-II vehicle specifications in comparison to Prius-I

	Prius I	Prius II
Engine displacement	1.5 liter, DOHC, I4	1.5 liter, DOHC, I4
Compression ratio	13:1 Atkinson Cycle	13:1 Atkinson Cycle
Valve system	4V/cylinder, VVT-i	4V/cylinder, VVT-i
Engine Power	52 kW at 4,500 rpm	57 kW at 5,000 rpm
Engine Torque	111 Nm at 4,200 rpm	111 Nm at 4,200 rpm
Emissions	SULEV	Advanced Tech. PZEV
Fuel Economy	52/45/48 mpg city/hwy/combined	60/51/55 mpg city/hwy/combined
Transmission	Electronic CVT	Electronic CVT
Vehicle curb weight	1257 kg	1313 kg
Drag coefficient, Cd	0.29	0.26
Frontal area *	2.23 m^2	2.29 m^2
Tires	P175/65R14	P185/65R15

Comparison of Toyota Hybrid Technology: THS-I & THS-II Power Train & Vehicle

- To understand vehicle propulsion we start at the wheels
  - Code: P175/65R14 = <veh type> <W, tread width> <H in %W> <Drim>



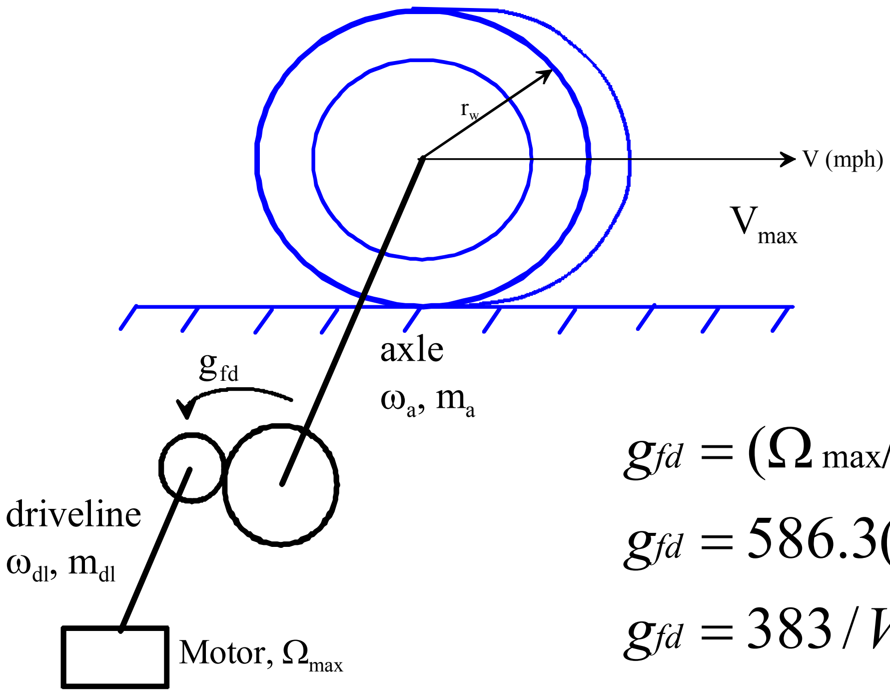
Tire code: P=passenger, 123mm tread width/sidewall height as xx% Wtread, R, rim diameter (inch)

$$r_w = 0.98 \frac{D_{rim} + 2(H\% x W_{tread})}{2}$$

= 0.292m Prius-I and 0.3045m Prius-II from which the final drive ratio comes out to Gr=3.95:1 in Prius-I and 4.0:1 in Prius-II

Comparison of Toyota Hybrid Technology: THS-I & THS-II Power Train & Vehicle

- Finding the driveline final drive ratio, g_{fd}
  - Must know V_{max} and $N_{m\text{-}max}$
  - Need tire dynamic rolling radius, r_w



$$g_{fd} = (\Omega_{max} / V_{max}) r_w$$

$$g_{fd} = 586.3(0.292)/(0.447 V_{max})$$

$$g_{fd} = 383 / V_{max} = 3.95 \,|\, v_{max} = 97 mph$$

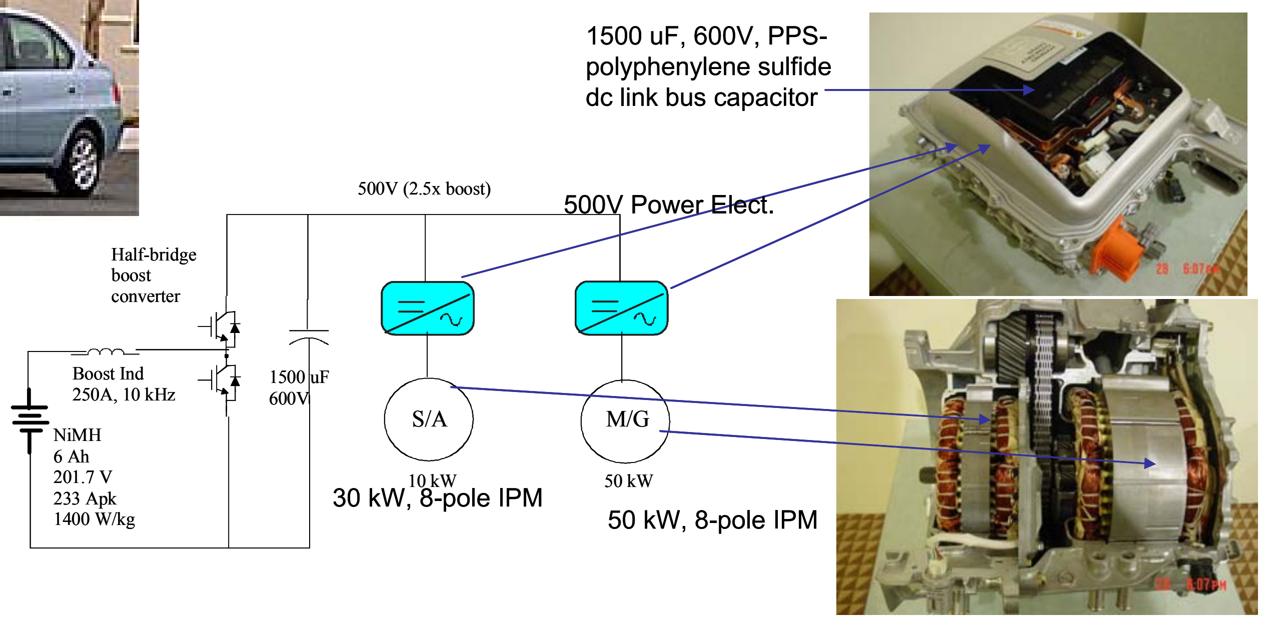
Comparison of Toyota Hybrid Technology: THS-I & THS-II Power Train & Vehicle

- Comparison of Prius-I and Prius-II continued

	Prius-I	Prius-II
Motor/Generator	Interior Permanent Magnet, IPM	Permanent Reluctance Machine, PRM
M/G Power	33 kW 1,040 to 5,600 rpm	50 kW, 1,200 to 1,540 rpm
M/G Torque	350 Nm 0 to 400 rpm	400 Nm, 0 to 1,200 rpm
System Voltage	274V	500V max
Battery type	Sealed NiMH	Sealed NiMH
Battery Power	21 kW (25 kW max)	21 kW improved internal resistance
Battery voltage	273.6V, 228 cells	201.6 V, 168 cells

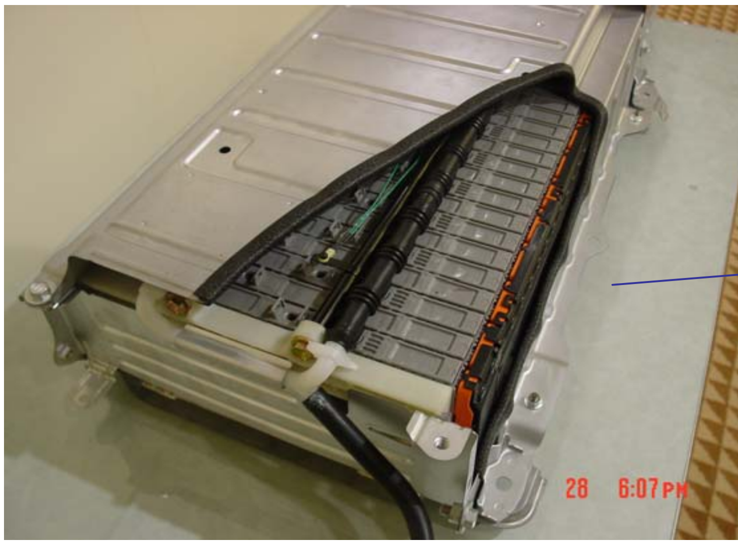
THS-II System

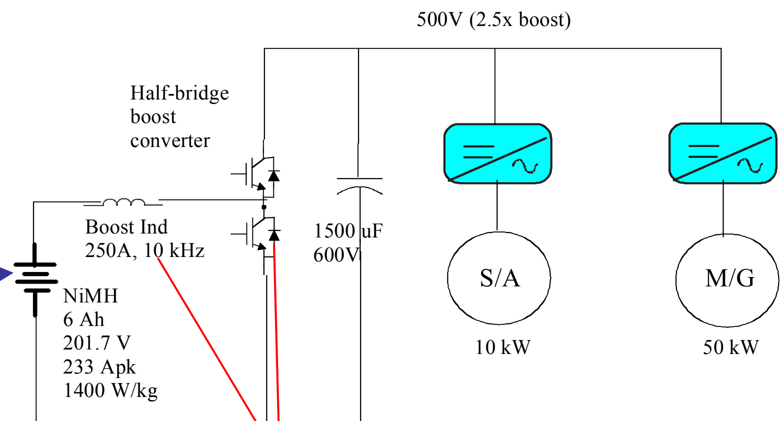
- THS-II achieves higher voltage local dc bus using a conventional half bridge converter (i.e., one additional phase leg of power electronics).
- Present cost of hybridization for THS-I and THS-II systems are $66/kW to $93/kW while cost of an SI powertrain is ~$30/kW



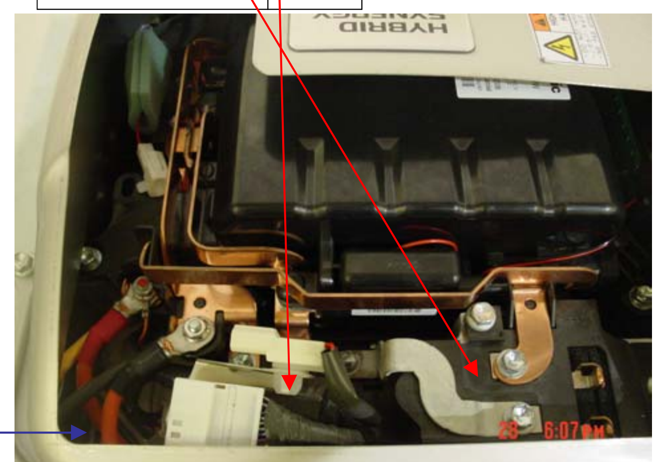
THS-II System

- NiMH battery with double welded terminations for 30% reduced ESR & more compact package.





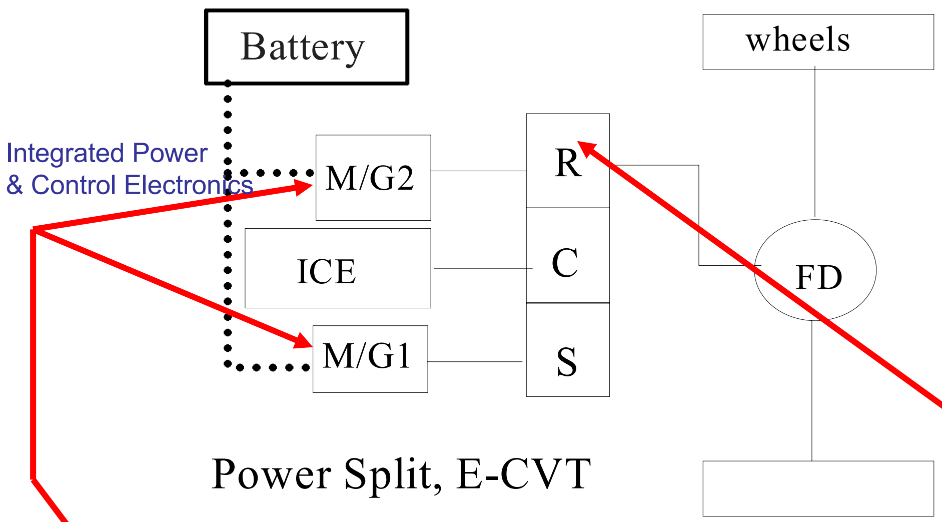
Expanded view of power electronics package. NiMH battery cable connector:

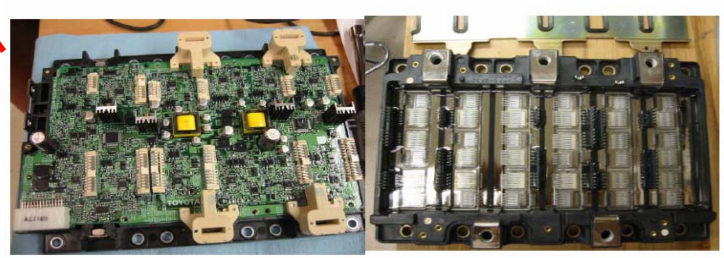


Link Ind ~100mm cube

THS-II System

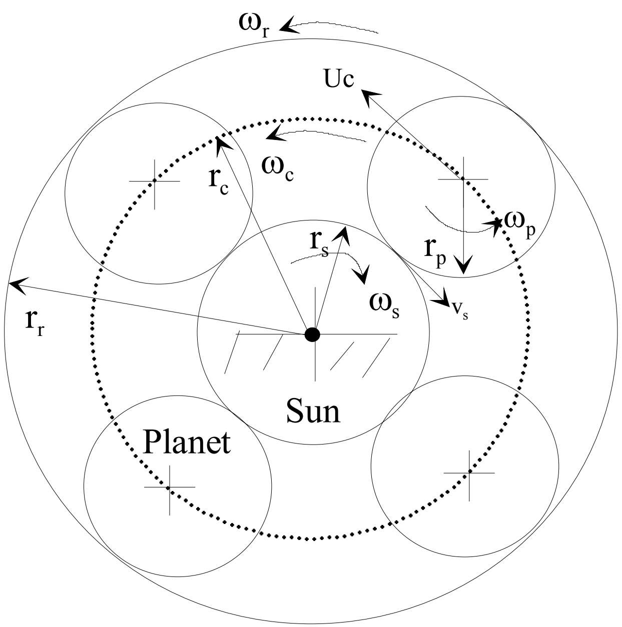
- Mechanical & Electrical Architecture
- Motor/Generators are under full electronic control





THS: Power Split Device

- Mechanical and Electrical Architecture
  - Depend fundamentally on the dynamics of a planetary gear set
  - Epicyclic gears provide speed summation
  - Torque splits according to port loading (power balance)



Ring (inside and/or outside gear)

Fundamental equation of the planetary Gear set: ratio of the difference in Angular speeds between an inner epicyclic Gear and a common gear and a second Inner gear and the common gear equals A constant – the basic ratio.

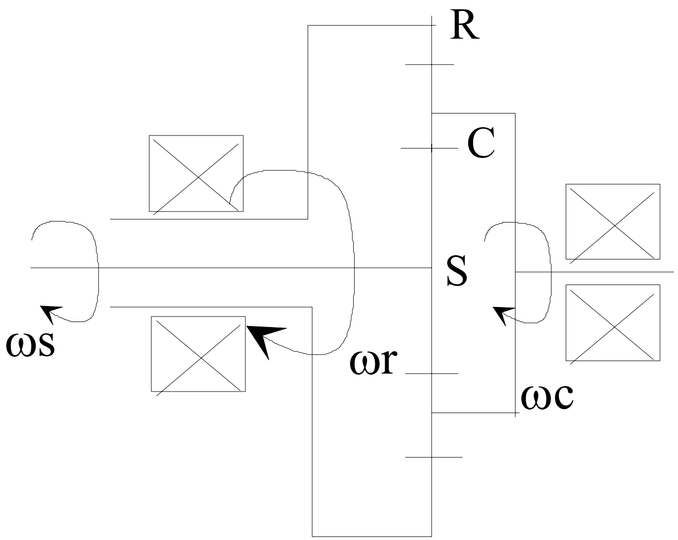
$$\frac{\omega_s - \omega_c}{\omega_r - \omega_c} = -\frac{N_r}{N_s} = -k$$

$$(\omega_s - \omega_c) = -k(\omega_r - \omega_c)$$

$$\omega_s + k\omega_r - (1+k)\omega_c = 0$$

THS: Power Split Device

- Planetery gear set
  - The basic ratio is negative for inside gears and positive for an outside epicyclic gear.
- Dynamics of the planetary gear set (ω is angular speed and m is torque, MKS units)



$$k = \frac{R_r}{R_s} = basic\_ratio$$

$$\omega_s + k\omega_r - (k+1)\omega_c = 0$$

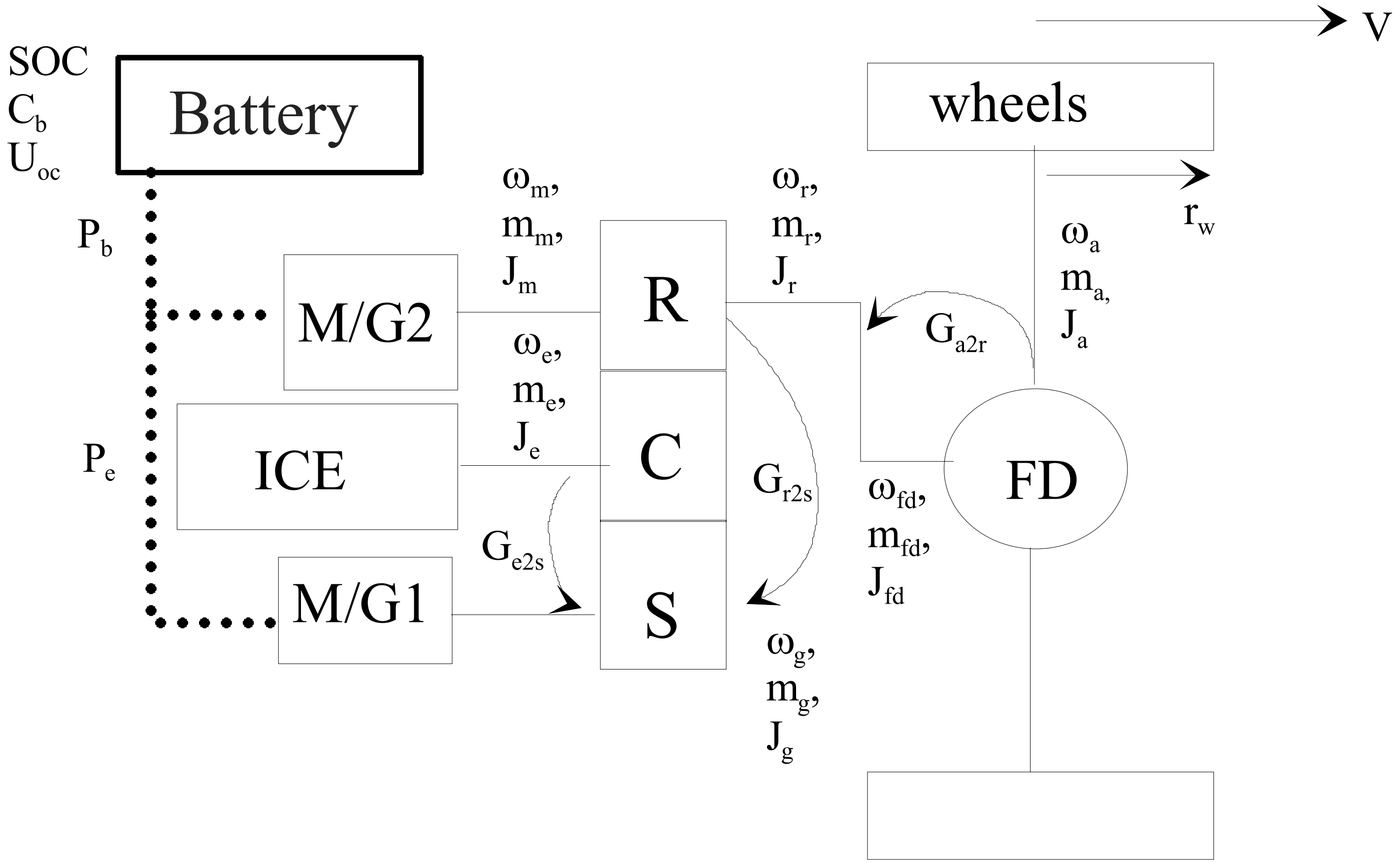
$$\eta_s M_s - \frac{1}{k}\eta_r M_r - J_s\dot{\omega}_s + \frac{1}{k}J_r\dot{\omega}_r = 0$$

$$\eta_c M_c + \frac{k+1}{k}\eta_r M_r - J_c\dot{\omega}_c - \frac{k+1}{k}J_r\dot{\omega}_r = 0$$

Prius I & II: Nr = 78, Np=24, Ns=30 from which k=78/30 = 2.6

THS: Power Split Dynamics

- THS power split dynamics



THS: Power Split Dynamics

- Expressions for M/G2 (motor) and M/G1 (gen) torque can be derived by inspection of the THS architecture
  - System inertias are lumped parameter
  - Generator effects (couple) are reflected to engine and motor ports

$$m_{dl} = m_m - \frac{g_{r2s}}{g_{e2s}} m_e + \left(\frac{g_{r2s}}{g_{e2s}} J_{eq} - J_{gc} \right) \dot{\omega}_e + \left(\frac{g_{r2s}}{g_{e2s}} J_{gc} - J_{mq} \right) \dot{\omega}_m$$

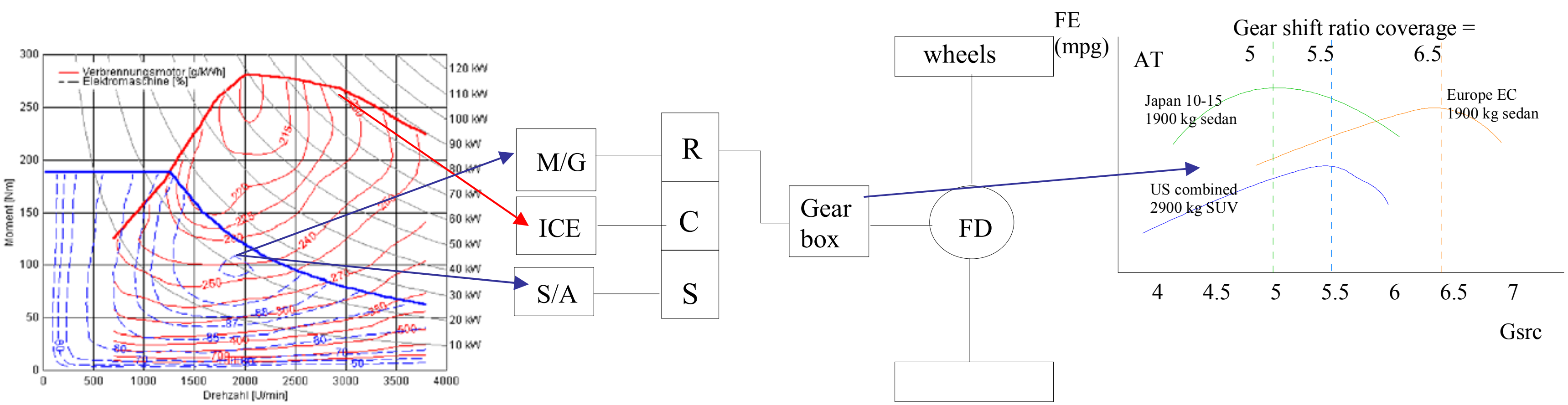
$$m_g = \frac{1}{g_{e2s}} \left(m_e - J_e \dot{\omega}_e - J_{gc} \dot{\omega}_m \right)$$

$$m_{dlss} = m_m + \frac{k}{k+1} m_e$$

Steady state driveline torque expression showing Torque contribution of motor and engine mechanical Path split

THS: Propulsion System Strategy

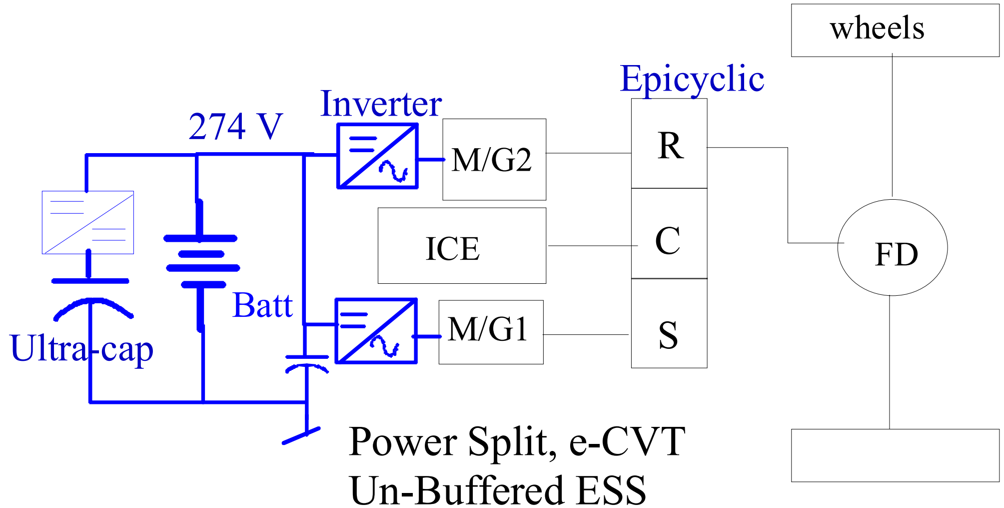
- Engine and electric system matching are essential to realize geographical preferences in the market
  - The power split device & the electric machine CPSR – constant power speed ratio are key elements in this strategy



Note: most input coupled transmissions have the ICE at the planet carrier port

THS: Propulsion System Strategy

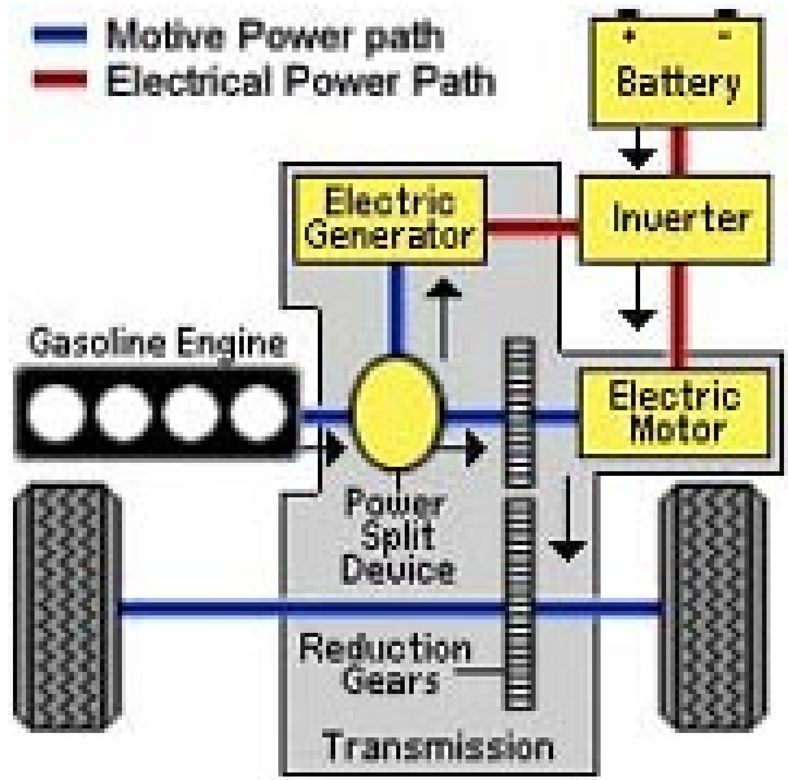
- To further develop the propulsion system strategy we first define the power split operating modes
- Then, an efficiency optimizing strategy is defined for highway cruise that aims to hold the ICE in or near the high plateau's of BSFC – brake specific fuel consumption (g/kWh)



THS: Propulsion System Strategy

- Operating modes
  - In this study five modes will be defined
- Batt-EV & Regen mode
- Normal driving mode
- Battery charge mode
- Power boost mode
- Negative split mode

- Some power split systems enter negative split as a means to further lug the engine (lower its speed at given torque)



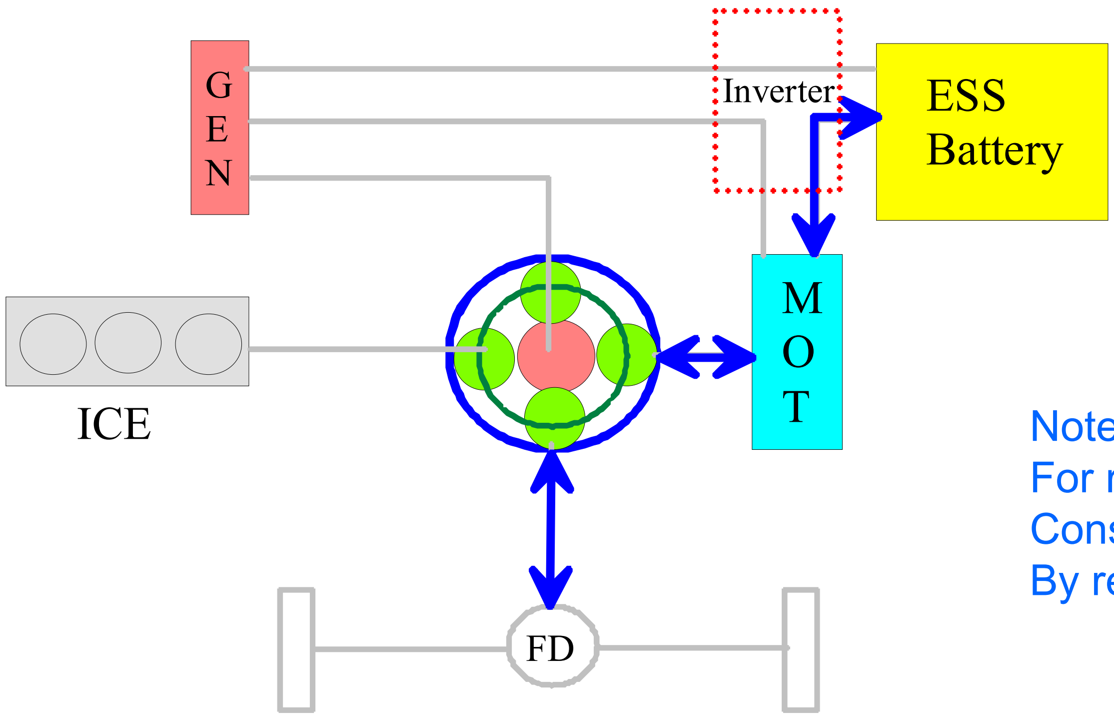
THS: Propulsion System Strategy

- Positive split is primarily used (which is most of the time) when ESS state of charge, SOC, is low, vehicle speed is relatively low and the engine delivers power to the ESS – battery.
- Negative split is used when the ESS, SOC is high, vehicle is under cruise condition with engine ON.
  - ESS discharges into generator (runs in motoring quadrant(s))
  - Generator in motoring mode drives engine speed lower to further optimize fuel efficiency
- Series mode is used when parked, during idle and for reverse (Batt-EV mode).

THS: Propulsion System Modes

- Batt-EV (electric drive and regeneration mode)
  - Engine OFF and generator not used.
  - Also called series mode

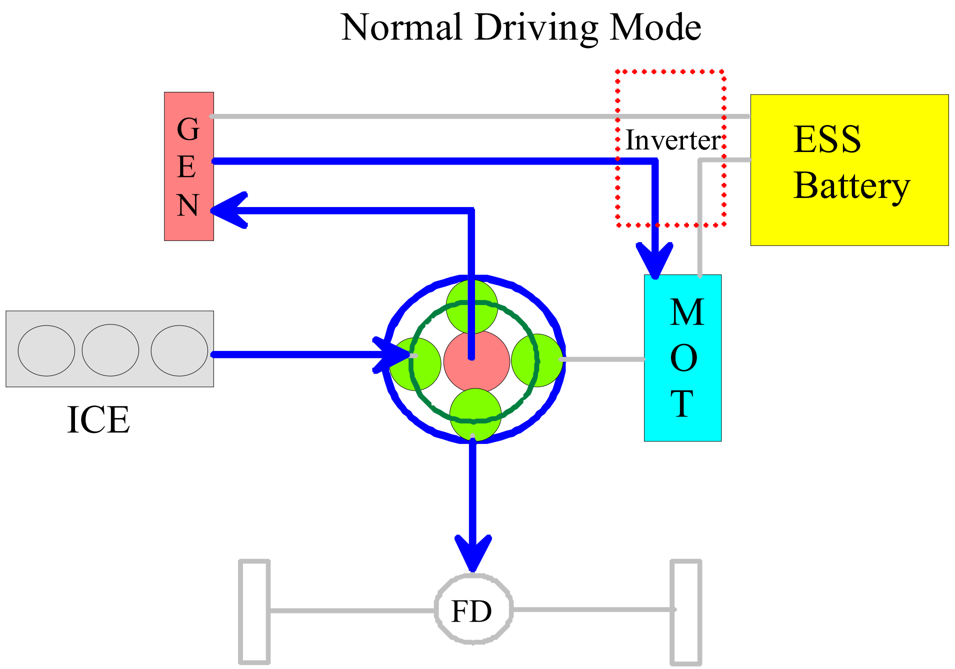
Batt-EV and Regeneration Mode



Note: series mode
For reverse – speed
Constrained in S/W
By rev limiter.

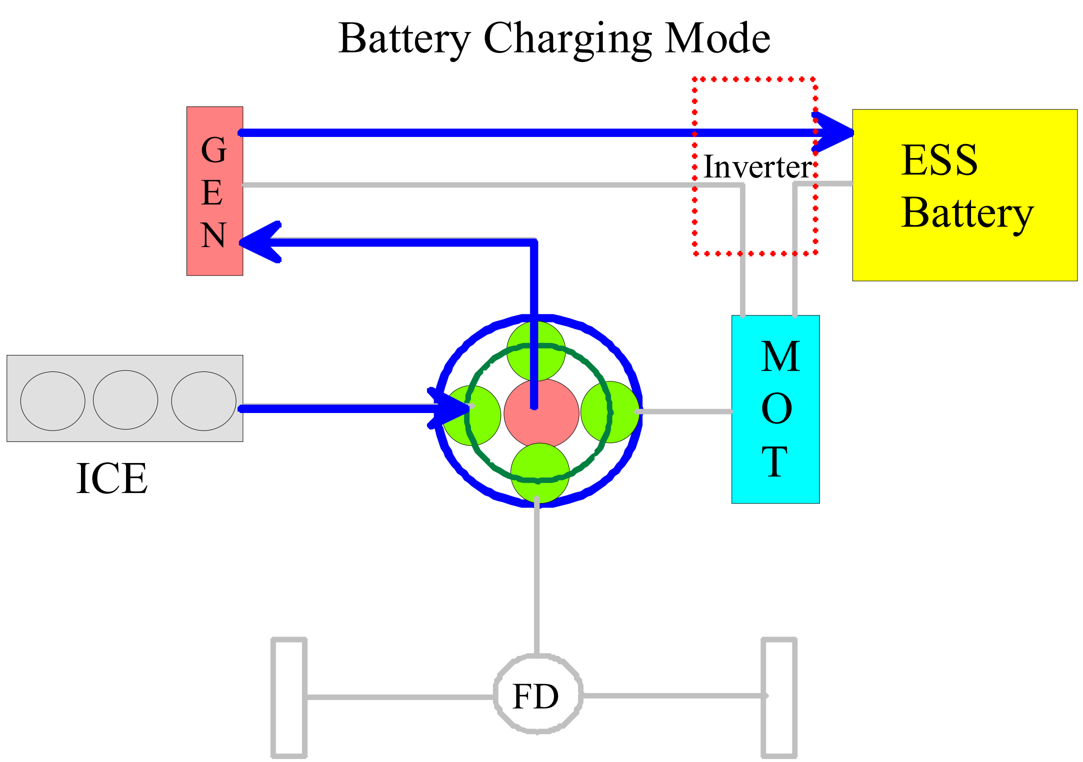
THS: Propulsion System Modes

- Normal driving, cruise mode
  - Engine ON, power splits from engine to wheels mechanically and via generator electrically.
  - ESS has nominal SOC, electrical power circulates from engine via generator to the motor where it sums mechanically with engine mechanical path power



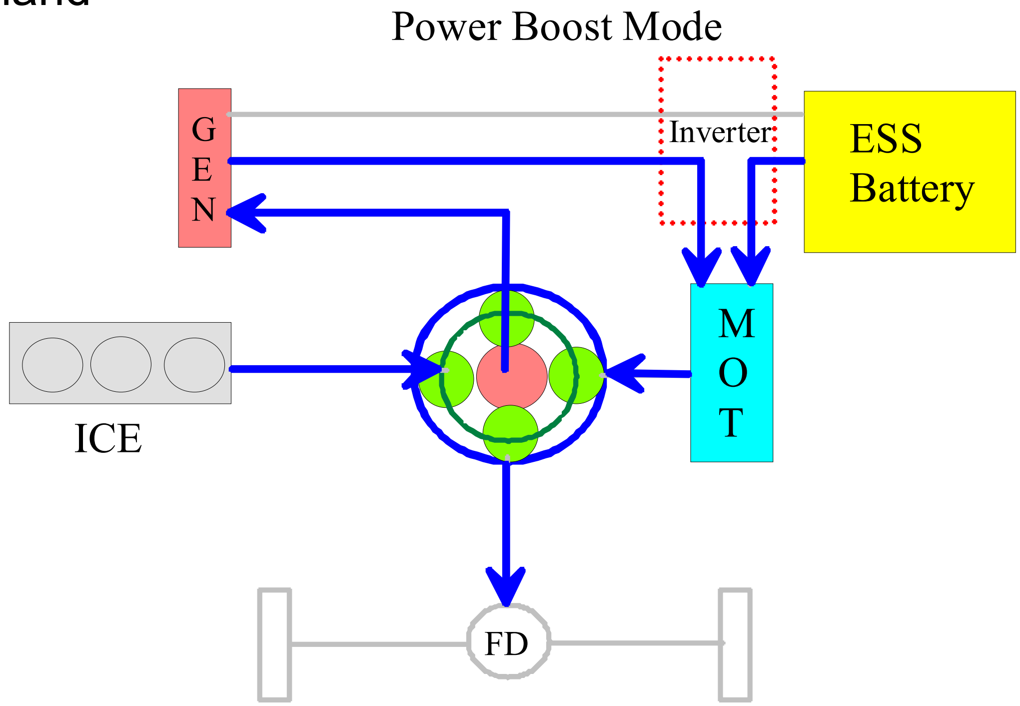
THS: Propulsion System Modes

- Battery charge mode
  - Vehicle parked or during idle



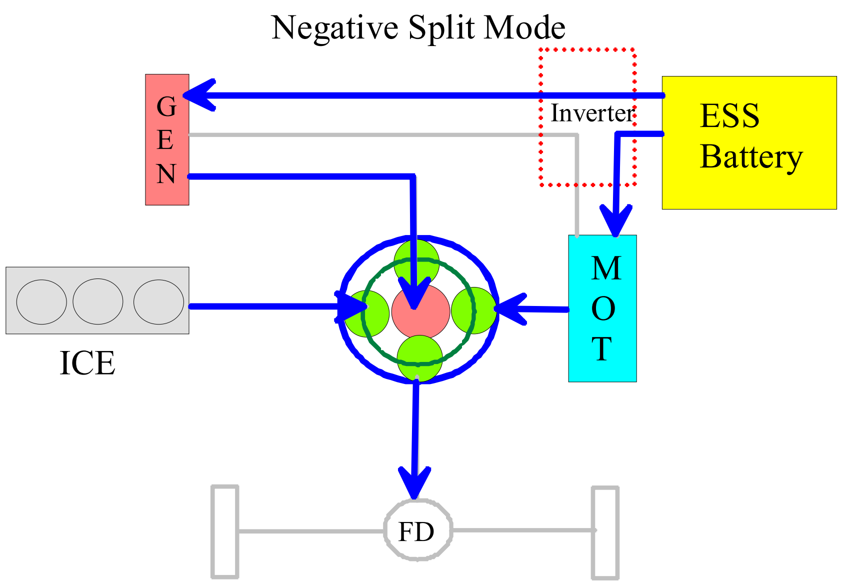
THS: Propulsion System Modes

- Power boost mode
  - Engine torque augmentation
  - Similar to EMT mode 3, engine has insufficient torque/power to meet road load demand



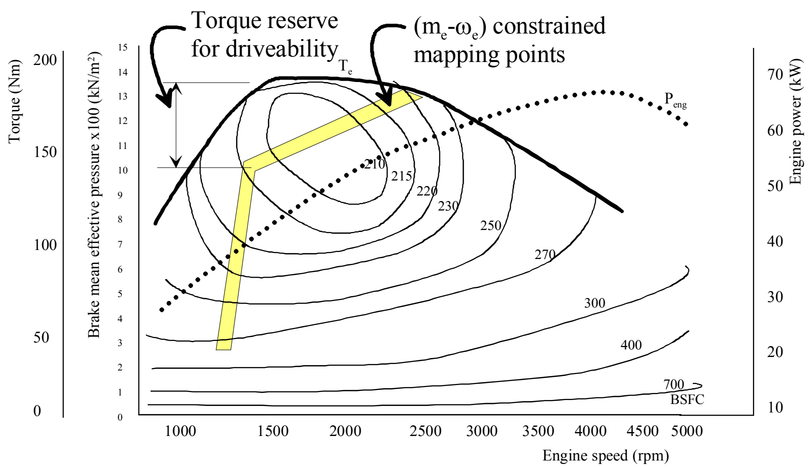
THS: Propulsion System Modes

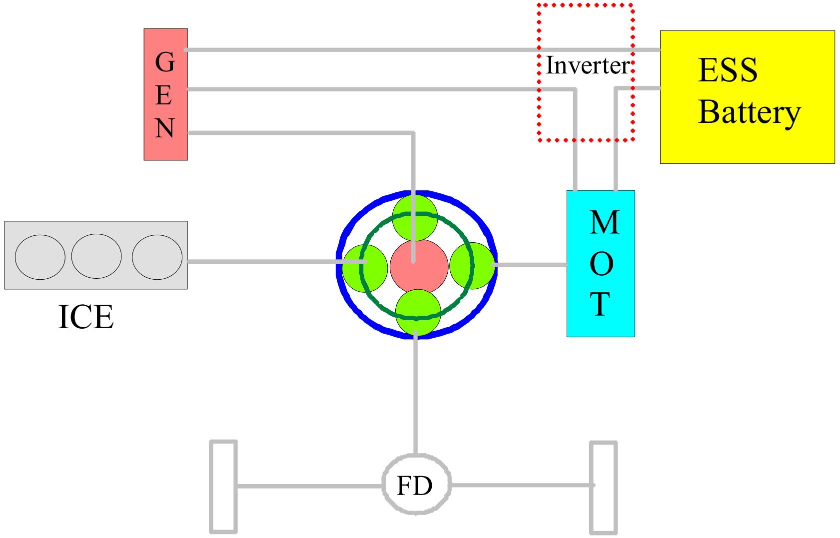
- Negative split mode
  - Forced engine lugging to optimize fuel economy
  - Engine control strategies also come into play in the form of advanced or retarded VVT when SOC is low
    - Advanced VVT lowers speed, but higher torque op point
    - Retarded VVT increases speed, lowers torque op point



THS: Propulsion System Strategy

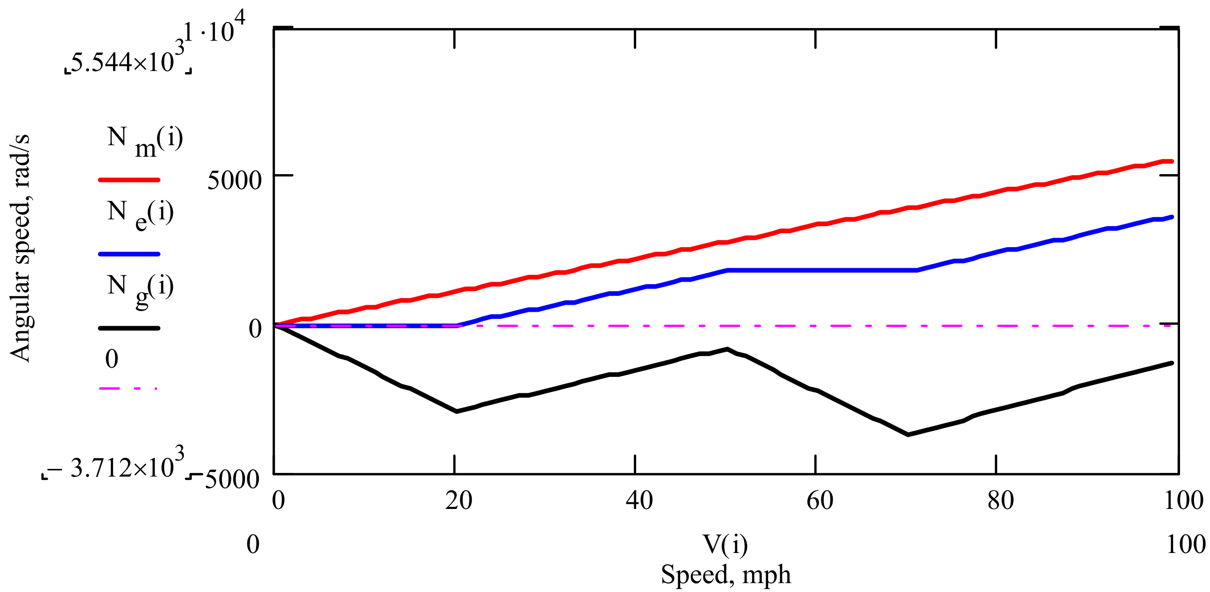
- Overall strategy is to operate the engine at high torque, low speed, most efficient operating points
  - Atkinson cycle provides inherent ~10% higher thermodynamic combustion efficiency
  - Improves highway FE





THS: Propulsion System Strategy

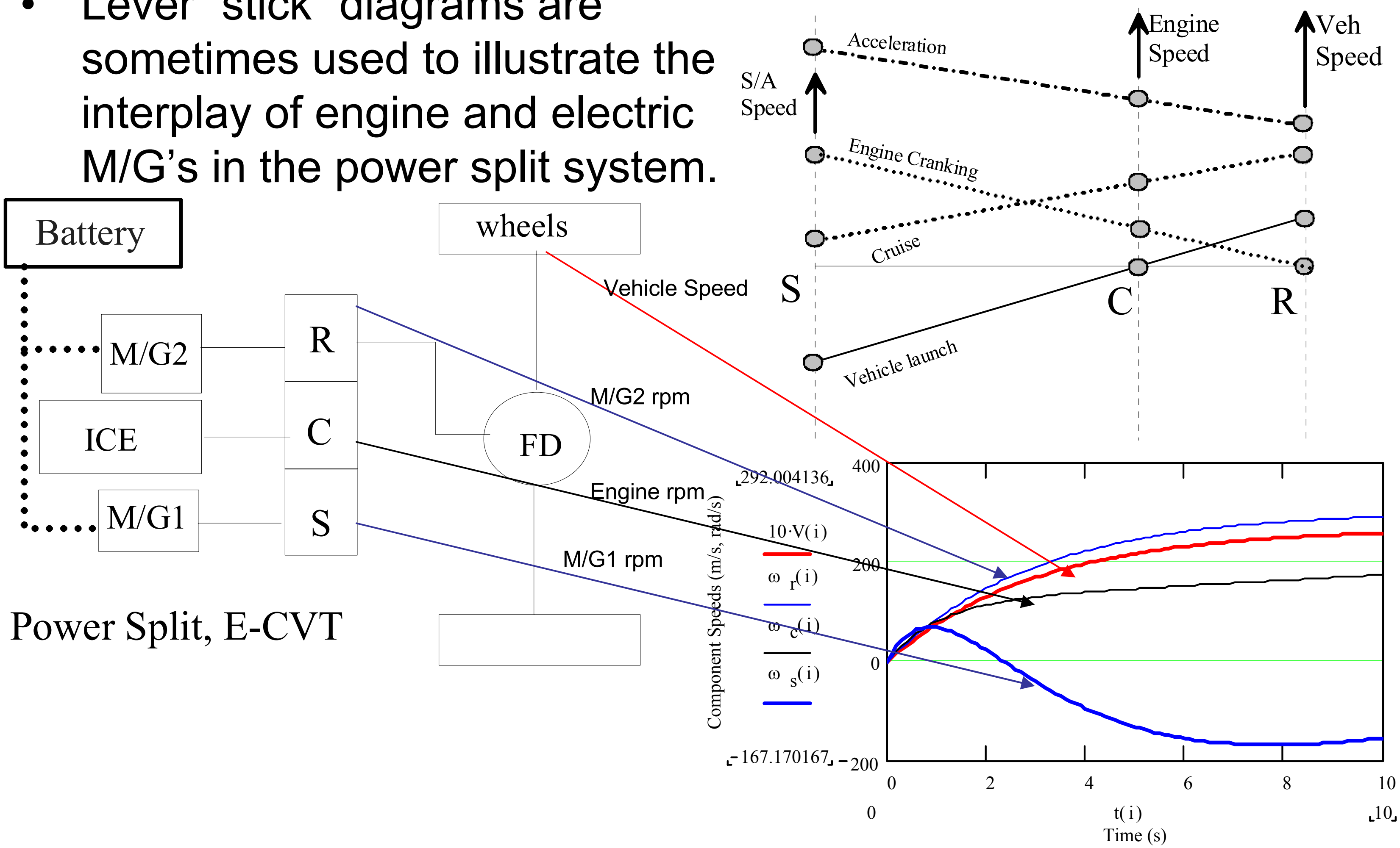
- Efficiency optimizing strategy for cruise mode
  - Define using N/V plot
  - Piecewise linear approximation of the engine control strategy
  - Generator speed responds to these discontinuties – artifact of the method



Note that the generator speed is restricted to 3rd quadrant operation. Lowering Generator speed increases engine speed and vice versa regardless of Motor speed (i.e., vehicle speed)

THS: Propulsion System Strategy

- Lever "stick" diagrams are sometimes used to illustrate the interplay of engine and electric M/G's in the power split system.



Power Split Propulsion System Strategy

- The strategy to be employed can be described in look up table format (and applied to the THS-I system)

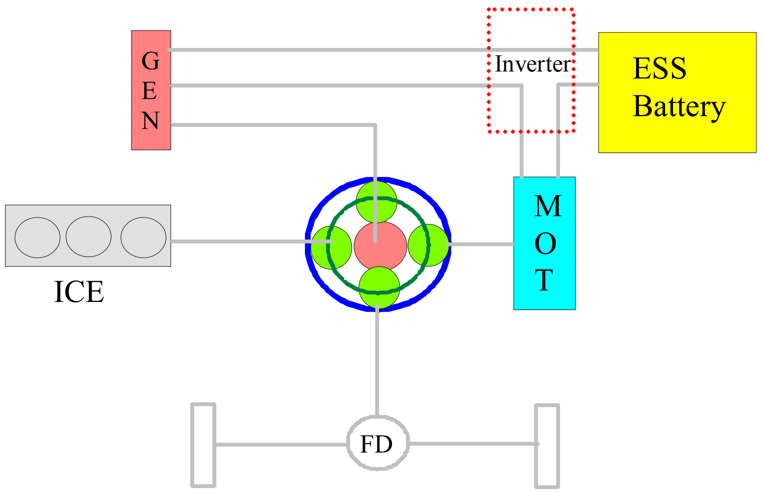
Vehicle Speed V (mph)	Engine Speed Ne (rpm)	Motor Speed Nm (rpm)	Generator Speed Ng (rpm)	Battery Power Pb (W)
0	OFF	0	0	0
30	OFF	1733	-4504	-3,290
40	1500	2310	-608	+670
50	1800	2890	-1027	+430
60	1700	3465	-2888	-860
70	2200	4043	-2604	-1110
80	2800	4620	-1937	+430

PS Propulsion System in Cruise Mode

- Observations on the selected Power Split strategy
  - Batt-EV mode 0→30mph then
  - Batt-charge mode at 40 and 50 mph
  - Power boost mode at 60 and 70 mph
  - ICE to near WOT torque at 80 mph
- At max vehicle speed the PS motor will be at max speed
  - As will the planetary gear set
- Engine operation at WOT torque (Ne~ 4000 rpm) will occur during high load conditions, grade, etc.

PS Propulsion System in Cruise Mode

- The maximum Batt-EV mode speed is limited by the generator max speed
  - Ne = 0 engine is OFF
  - Ng = 6500 rpm maximum



$$V_{ci} = \frac{\Omega_{gm} r_w}{k g_{fd}}$$

$$V_{ci} = \frac{680.6(0.292)}{2.6(3.95)} = 19.35 m/s$$

$$V_{ci} = \frac{19.35}{0.447} = 43.3 mph$$

Max engine cut-in speed can be approached
By very gradual acceleration in Batt-EV mode

PS Propulsion System in Cruise Mode

- First step is to calculate the road load during cruise

$$F_t = R_0 m_v g \cos\alpha + 0.5\rho_{air} C_d A_f V^2 + m_v g \sin\alpha$$

$$R_0 = 0.008$$

$$m_v = 1254kg$$

$$g = 9.902m/s^3$$

$$\alpha = 0 - grade$$

$$\rho_{air} = 1.225kg/m^3 @ STP$$

$$C_d = 0.29(\Pr ius)$$

$$A_f = 0.9WH = 2.31m^2$$

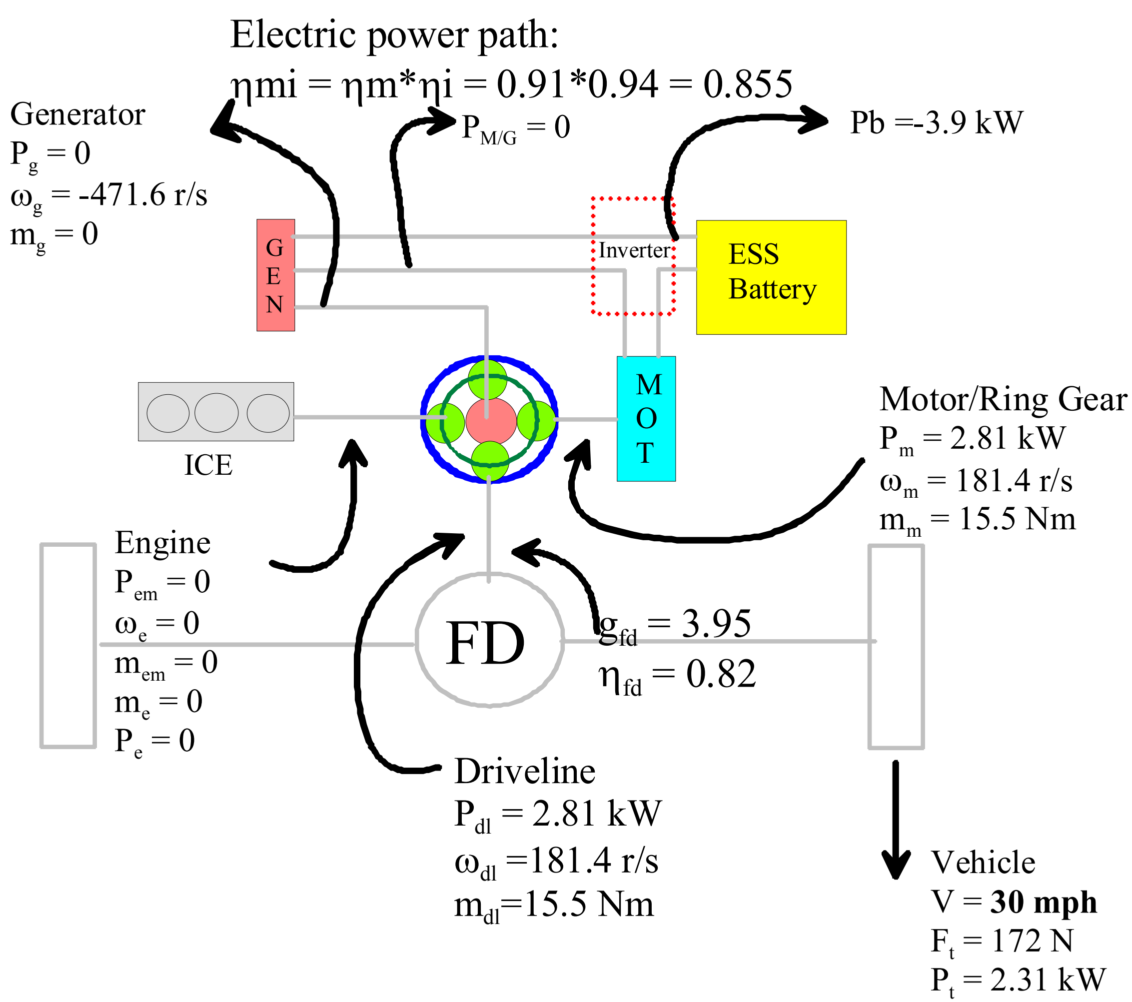
- F_{roll} = 98.33N and F_{aero} = $0.4103V^2$

PS Propulsion System in Cruise Mode

- Steps used in the evaluation of power split operation
- 1st: Calculate the road load for the stated condition
- 2nd: Reflect the road load to the driveline – speed and torque
- 3rd: Assign the engine speed per the strategy
- 4th: Use the planetary gear speed equation to determine the generator speed,
- 5th: Calculate the engine mechanical path torque per the planetary gear torque expression (see power split device slides)
- 6th: Calculate all power flows and insure balance to match the stated battery loading condition.

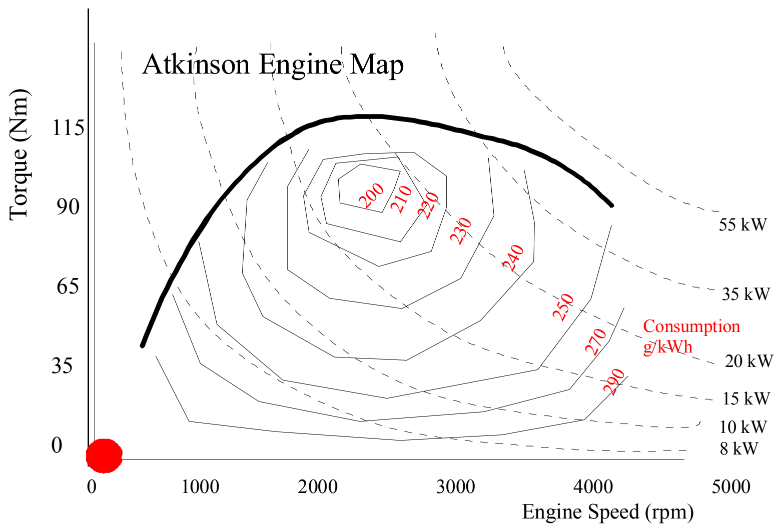
PS Propulsion System in Cruise Mode

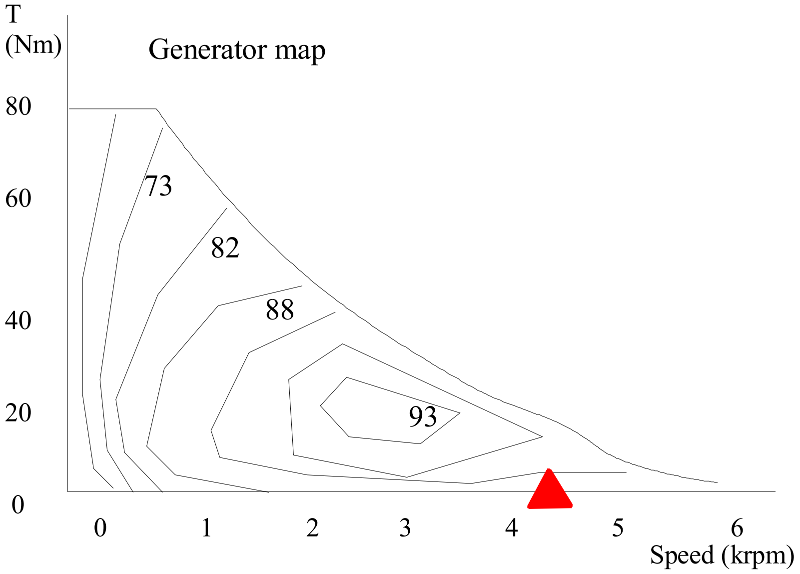
- V=30 mph



PS Propulsion System in Cruise Mode

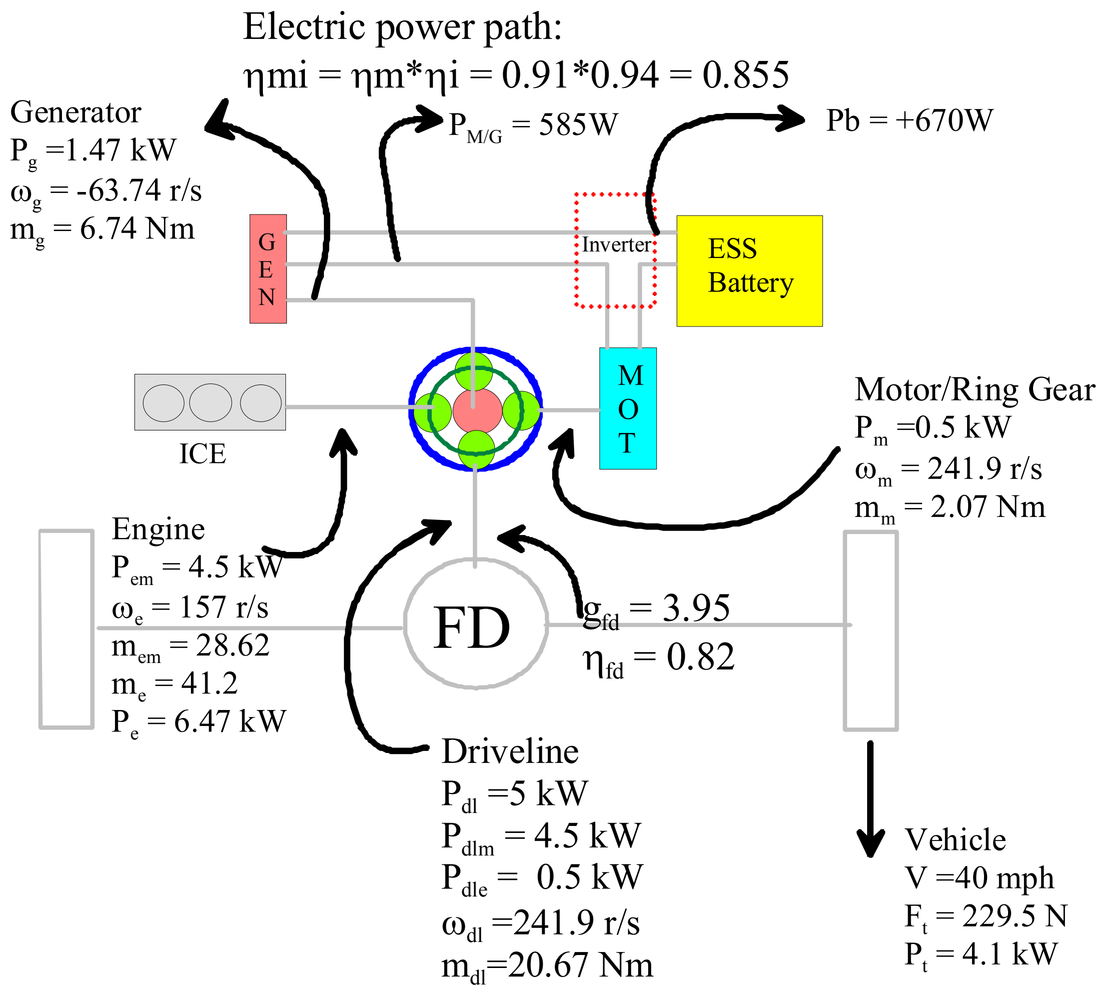
- Engine and M/G maps for 30 mph





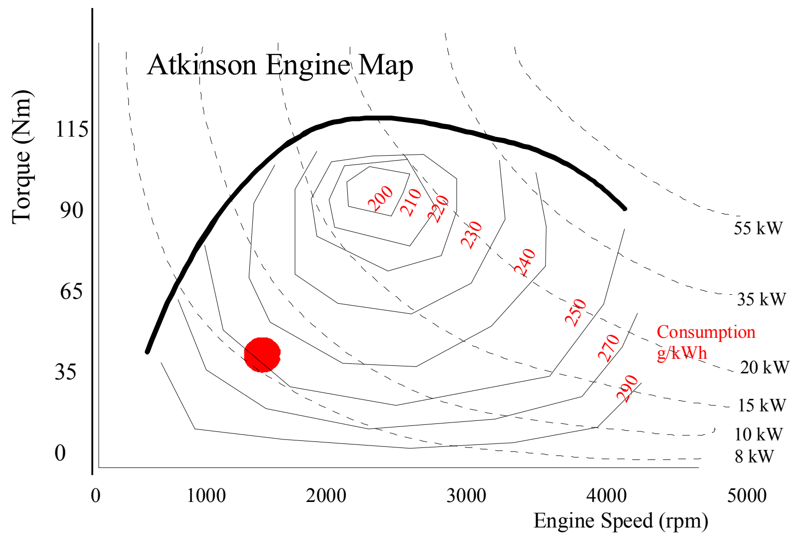
PS Propulsion System in Cruise Mode

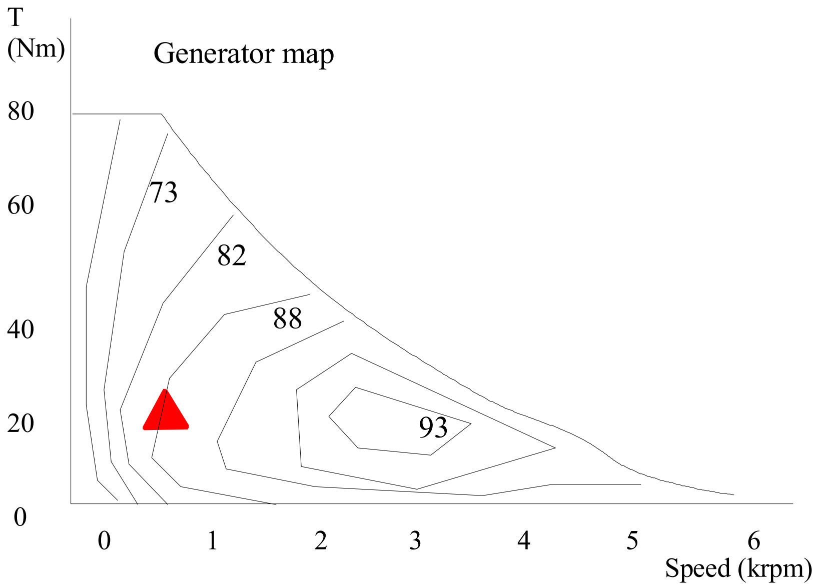
- V=40 mph



PS Propulsion System in Cruise Mode

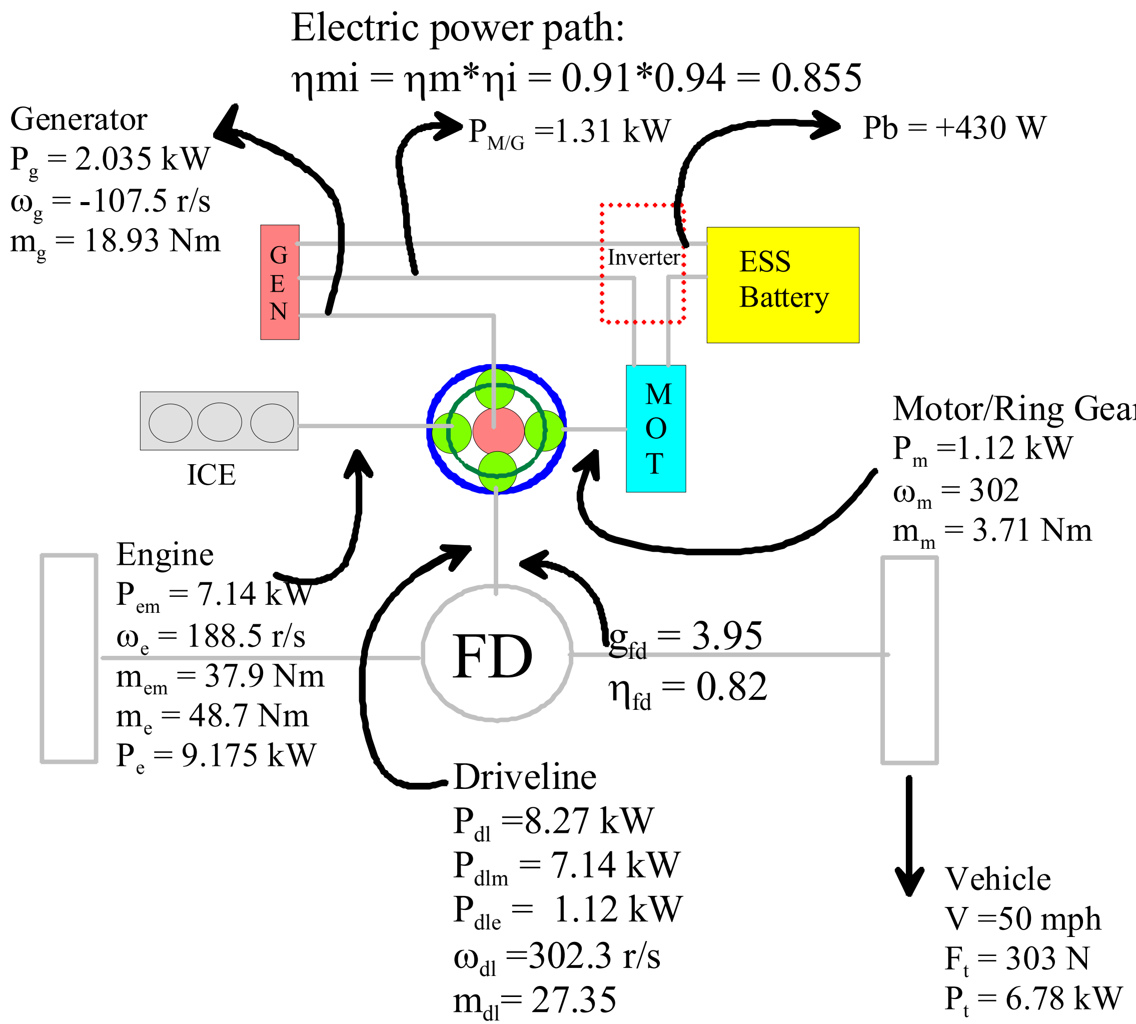
- Engine and M/G maps for 40 mph





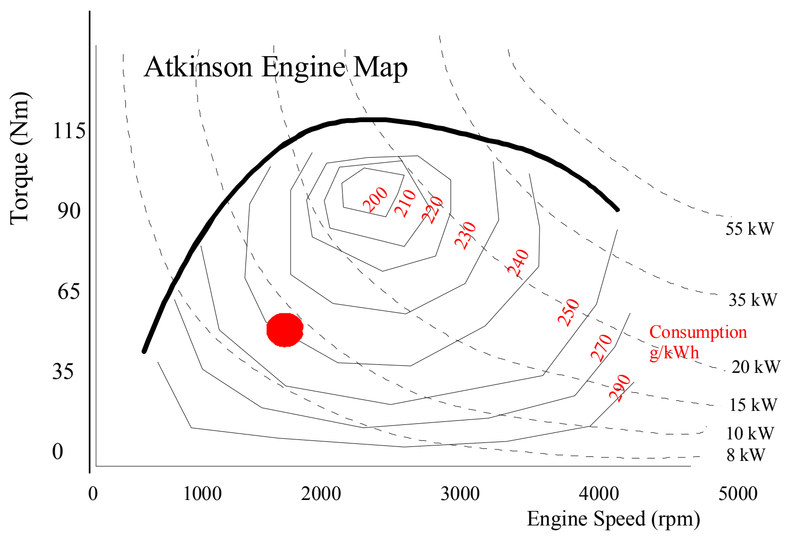
PS Propulsion System in Cruise Mode

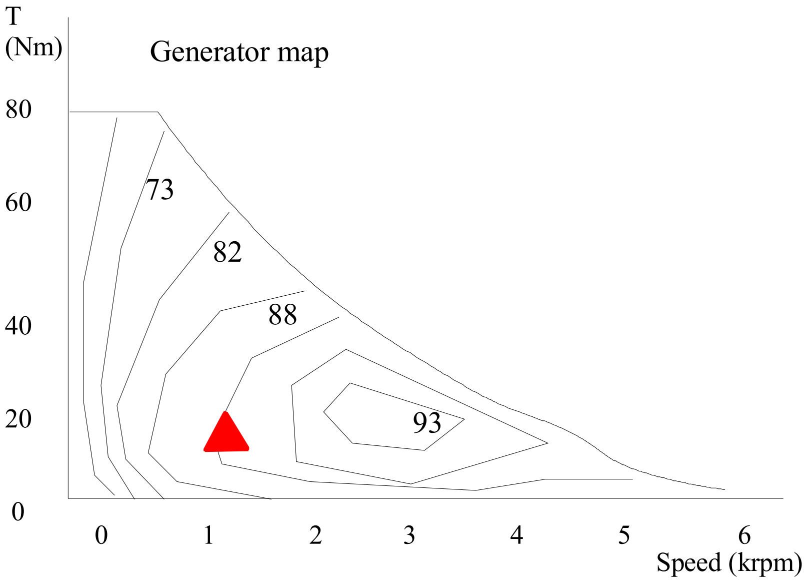
- V=50 mph



PS Propulsion System in Cruise Mode

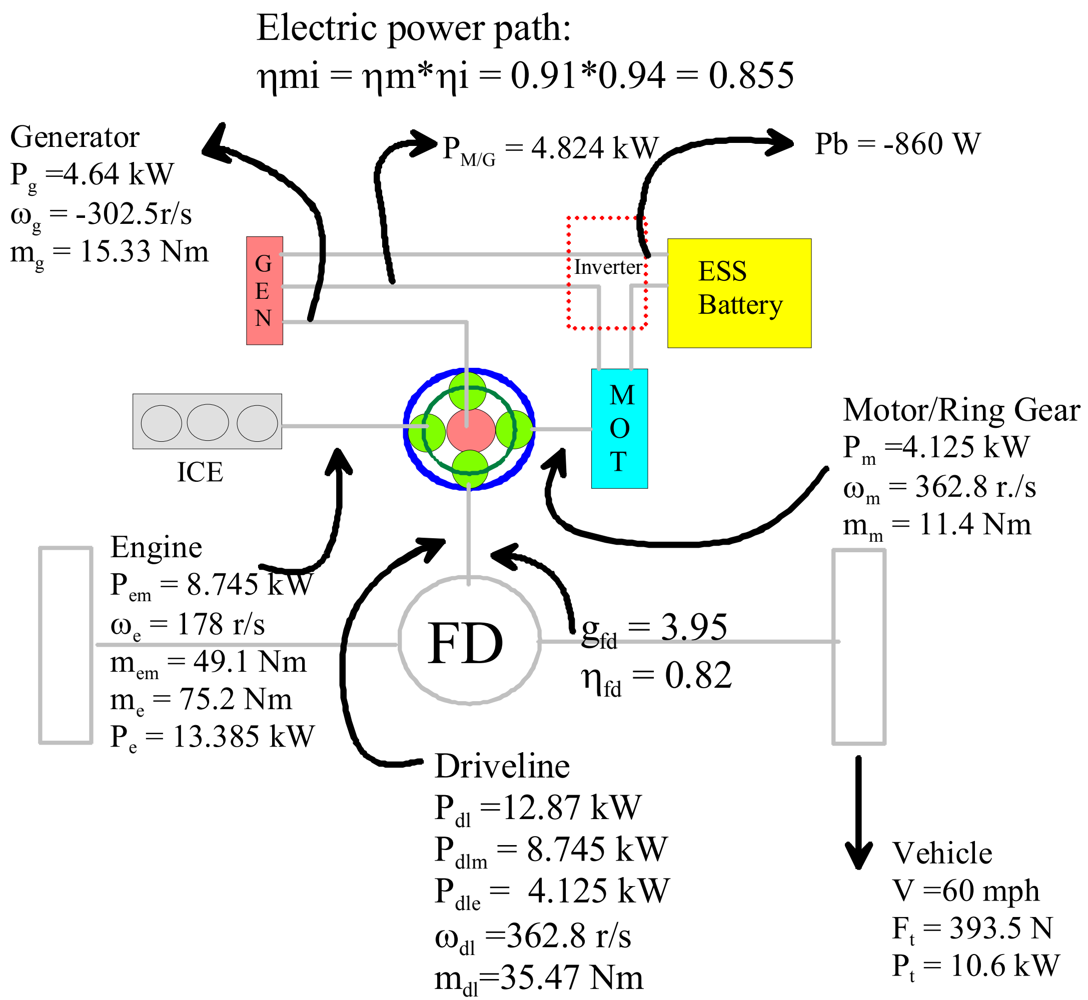
- Engine and M/G maps for 50 mph





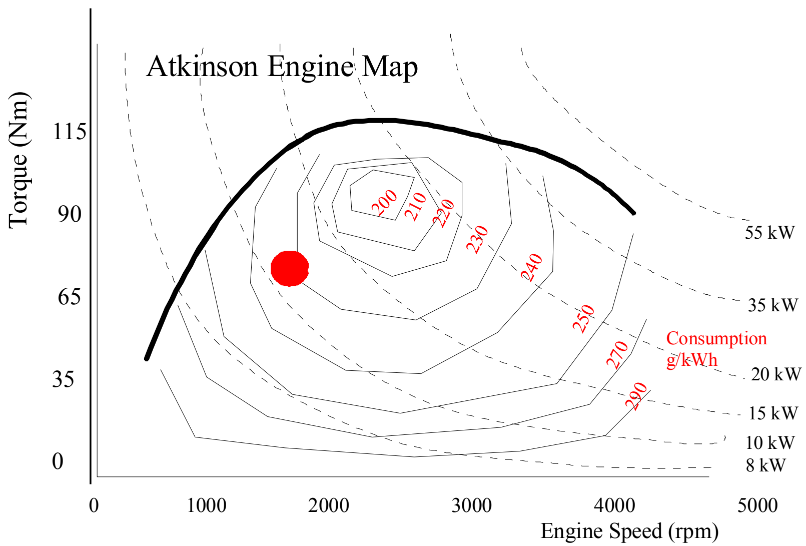
PS Propulsion System in Cruise Mode

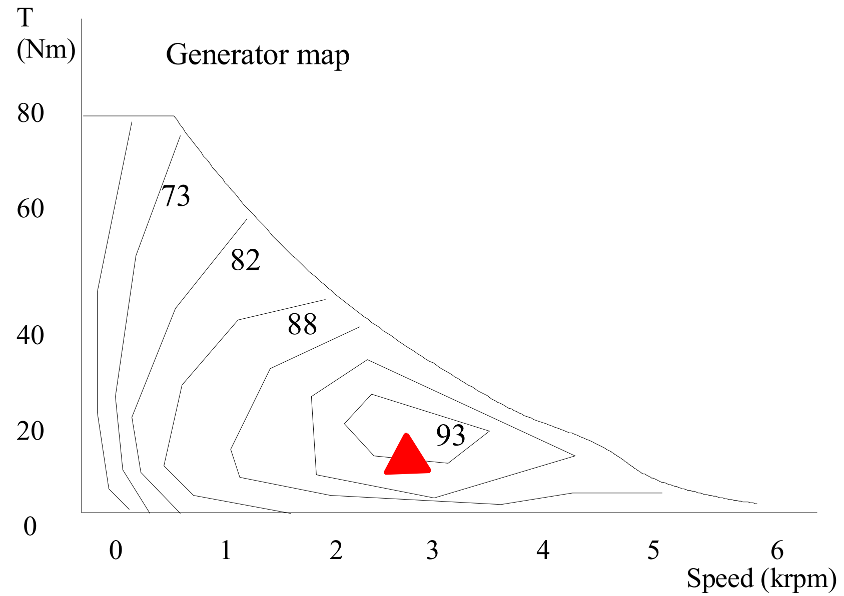
- V=60 mph



PS Propulsion System in Cruise Mode

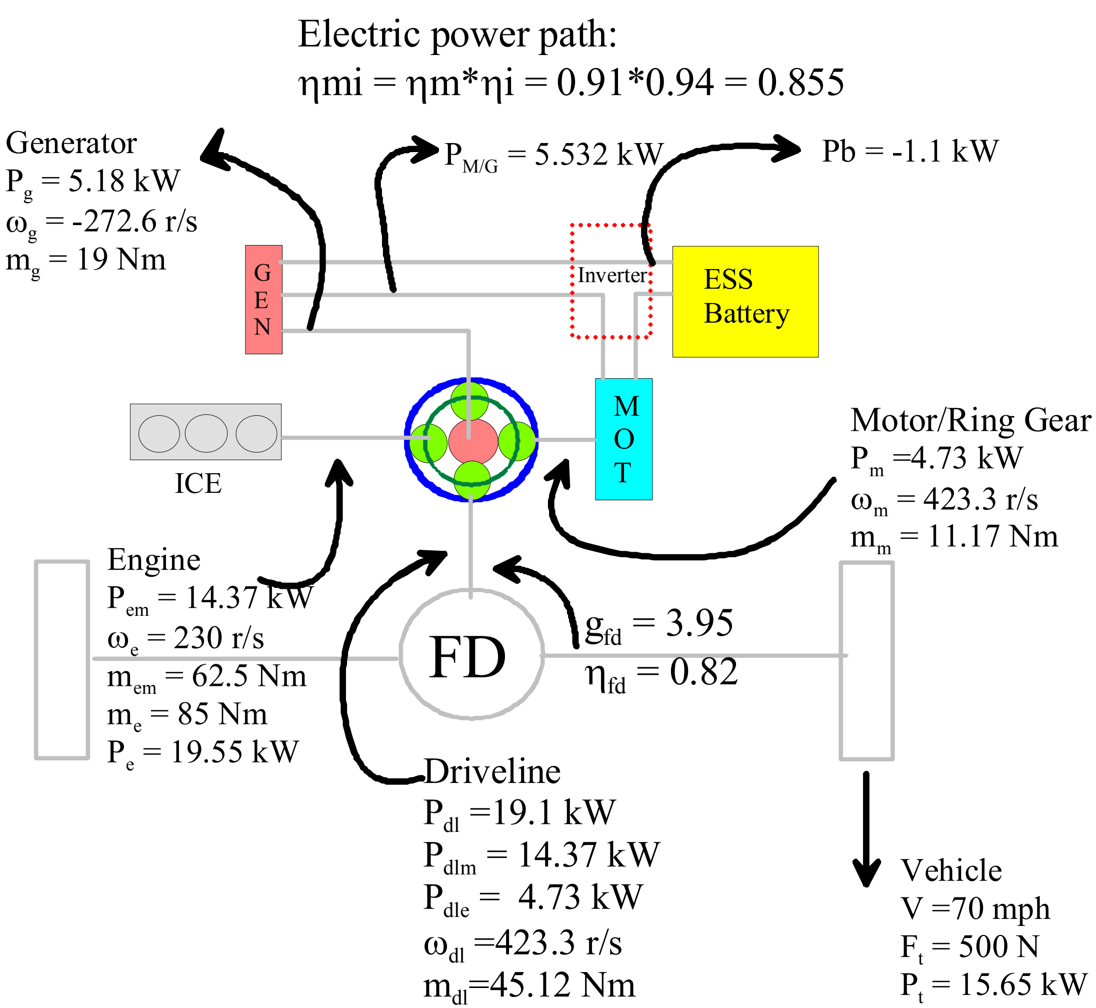
- Engine and M/G maps for 60 mph





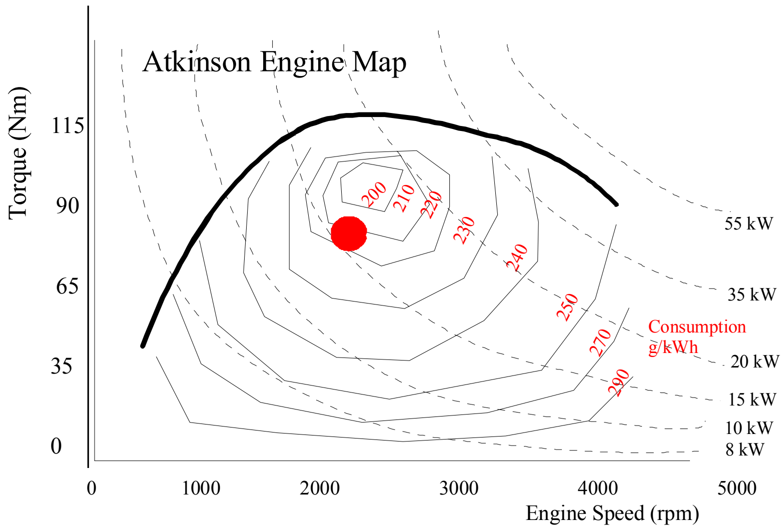
PS Propulsion System in Cruise Mode

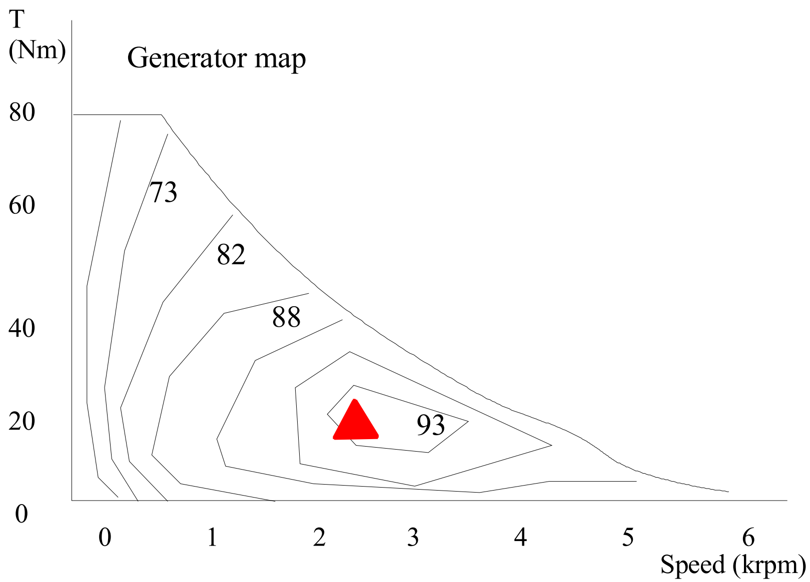
- V= 70 mph



PS Propulsion System in Cruise Mode

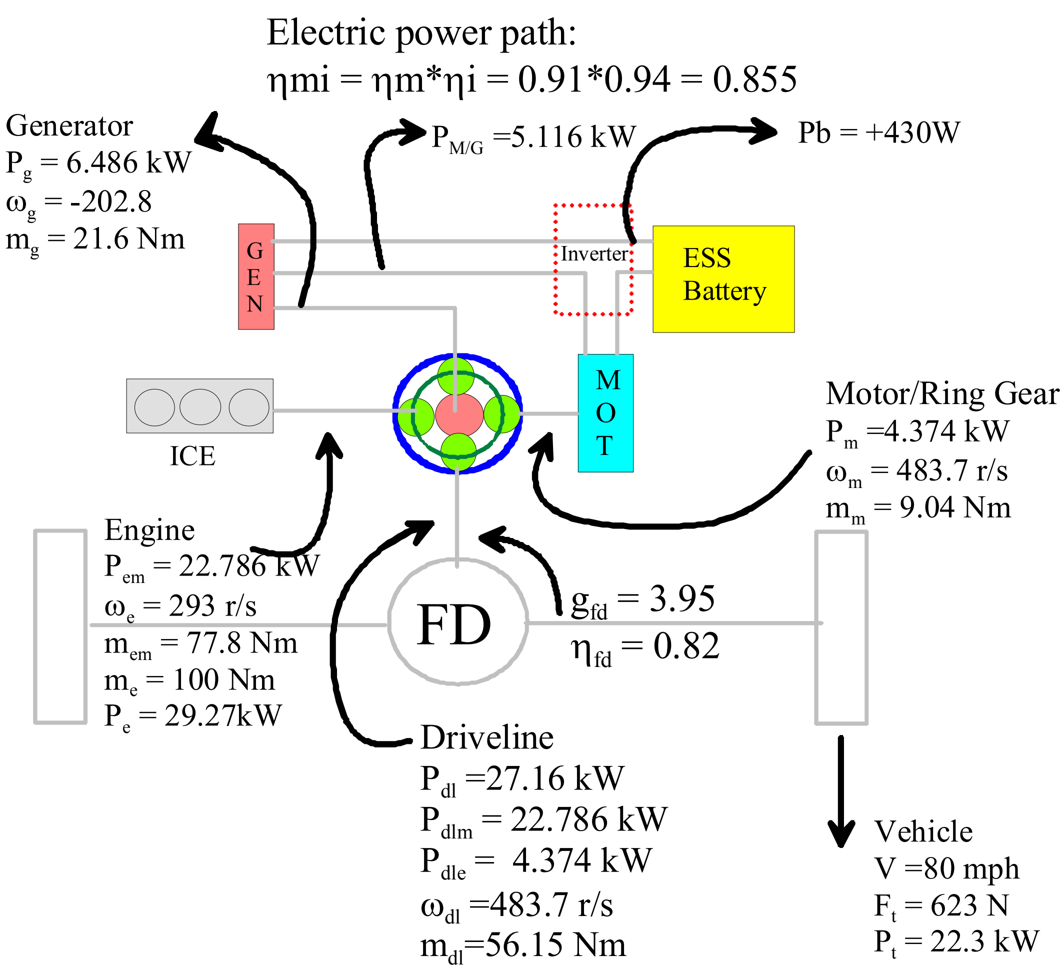
- Engine and M/G maps for 70 mph





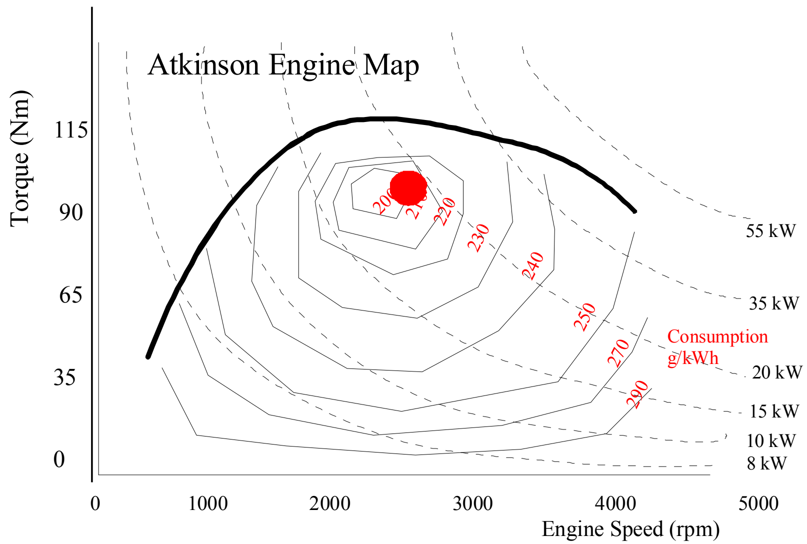
PS Propulsion System in Cruise Mode

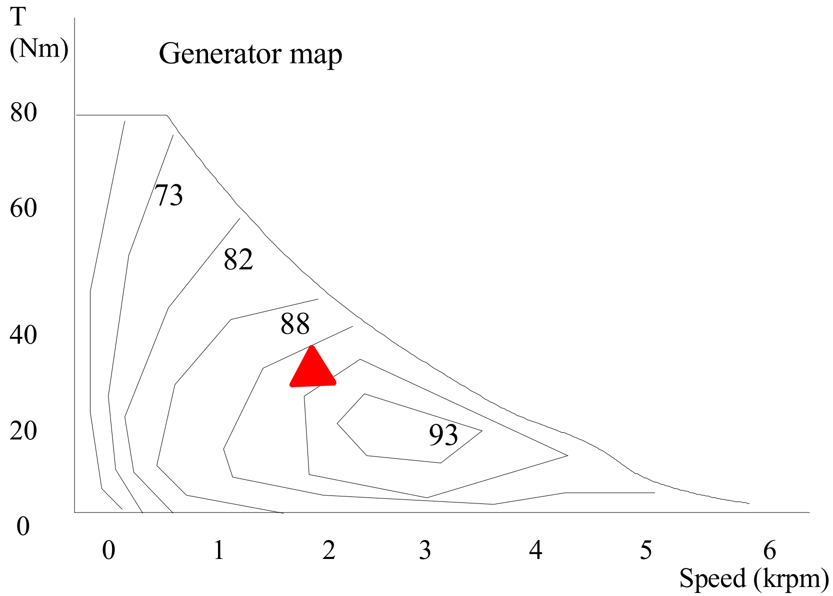
- V=80 mph



PS Propulsion System in Cruise Mode

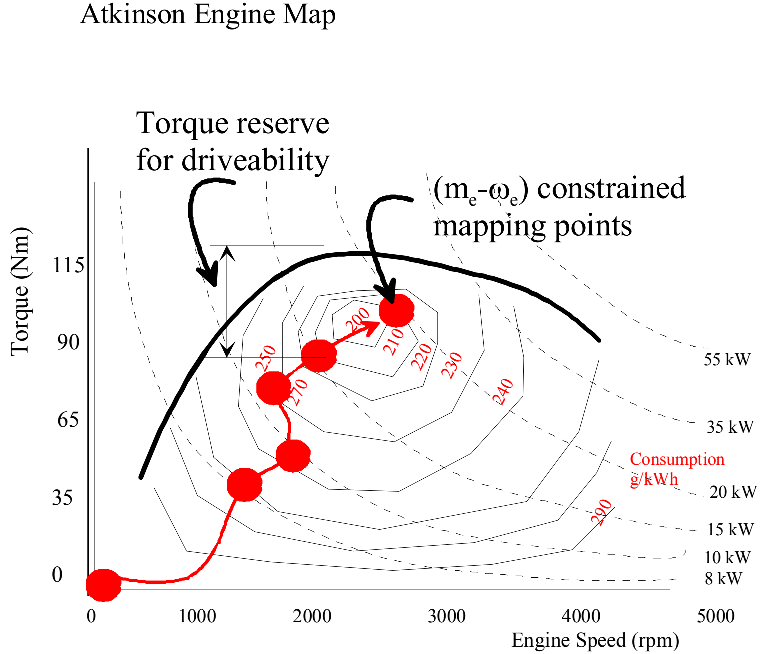
- Engine and M/G maps for 80 mph

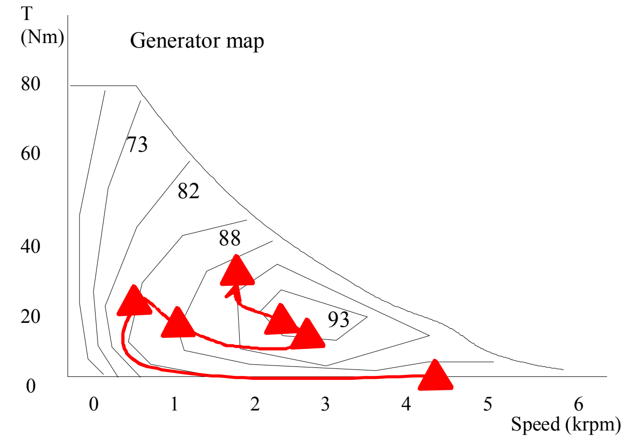


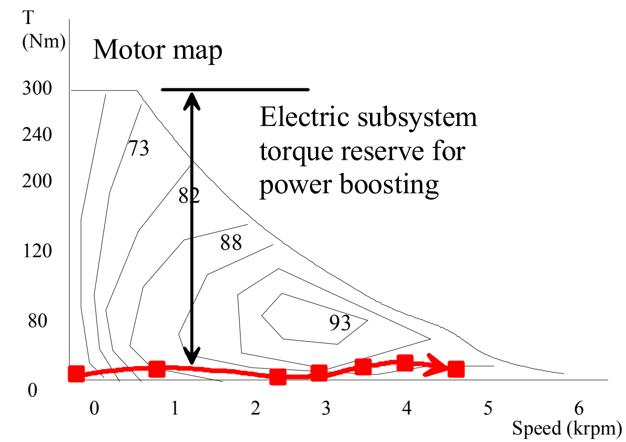


PS Propulsion System in Cruise Mode

- Composite engine and M/G maps







PS System Summary

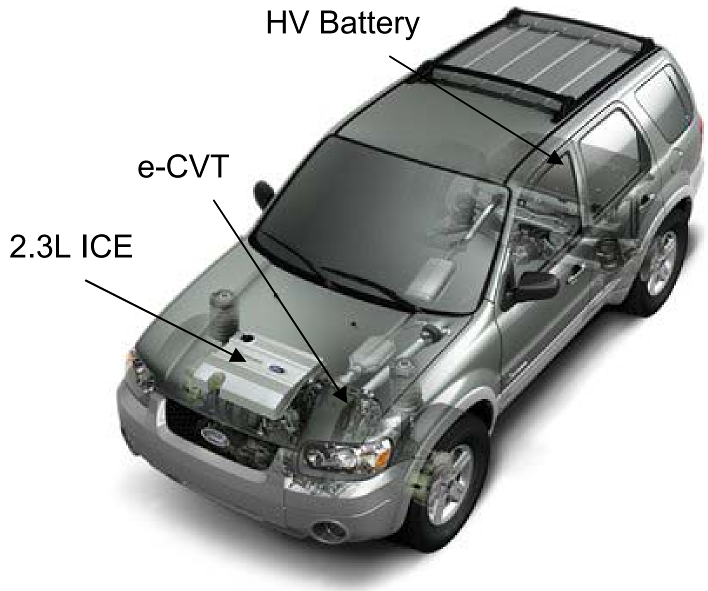
- Conclusions
  - Cruise mode control strategy must optimize both engine and generator efficiency
  - Hybrid strategy pushes engine operation high on T-N map resulting in reduced engine torque for transients
  - Motor operates at relatively low power levels during cruise
  - But, the motor maintains sufficient reserve to augment the engine torque during transient maneuvers, passing, negotiating grades, braking, etc
  - Battery SOC is maintained via the generator by additional loading on the engine
  - During boosting the battery augments generator power

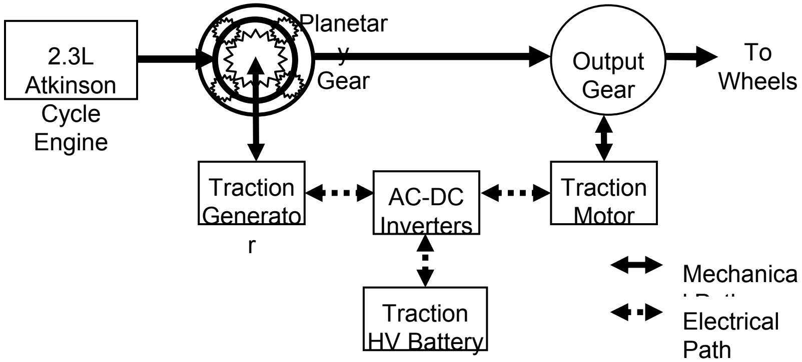
Session 3

- Ford-Volvo-Aisin, FHS System
  - Very similar to the THS system, with the addition of output gearing
  - Still an input coupled power split
  - Motor is now offset geared from planetary ring gear
  - Power and control electronics are now integral to the e-CVT transmission.
- Hybrid Escape introduced in Oct. 2004 as MY2005 hyb SUV

Hybrid Escape e-CVT

- Ford Hybrid System

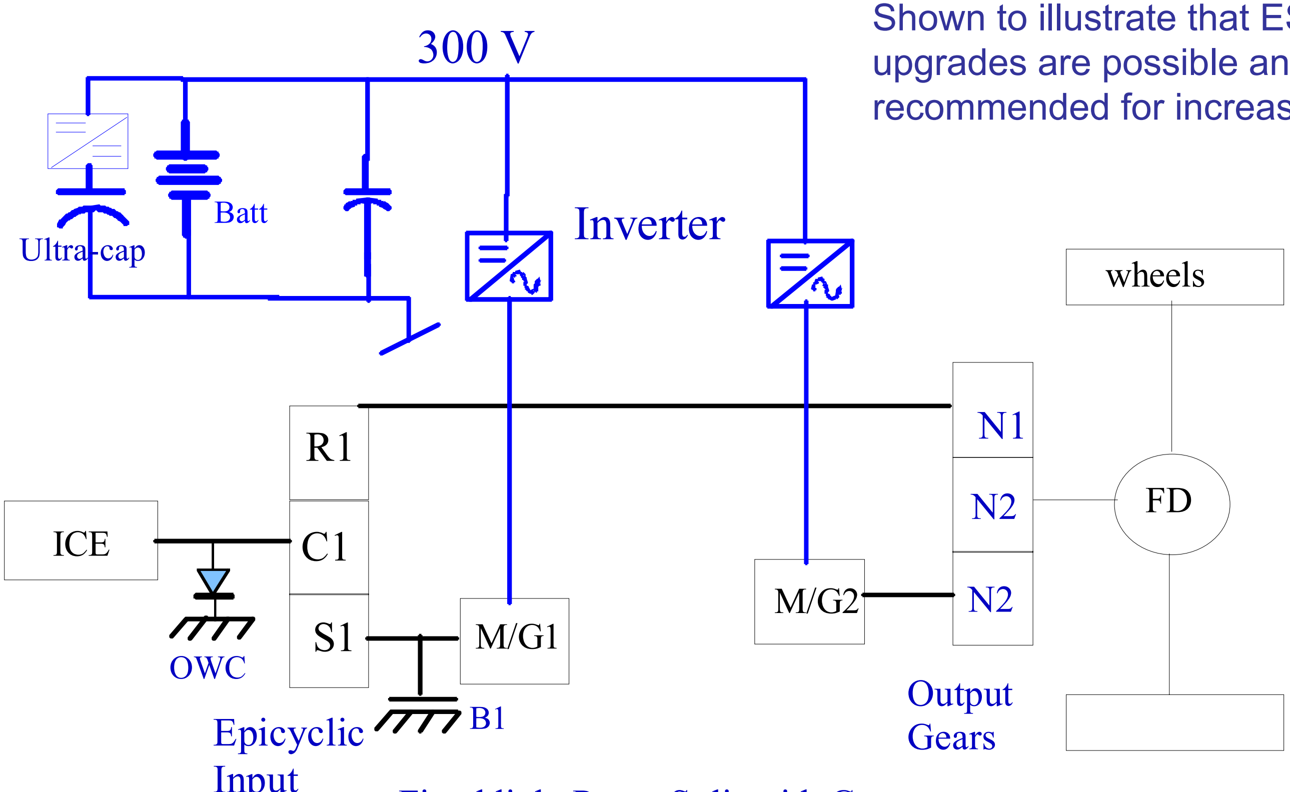




Hybrid Escape e-CVT

- Model development

An ultracapacitor and battery combination is Shown to illustrate that ESS system upgrades are possible and also recommended for increased ESS longevity



Fixed link, PowerSplit with Gear

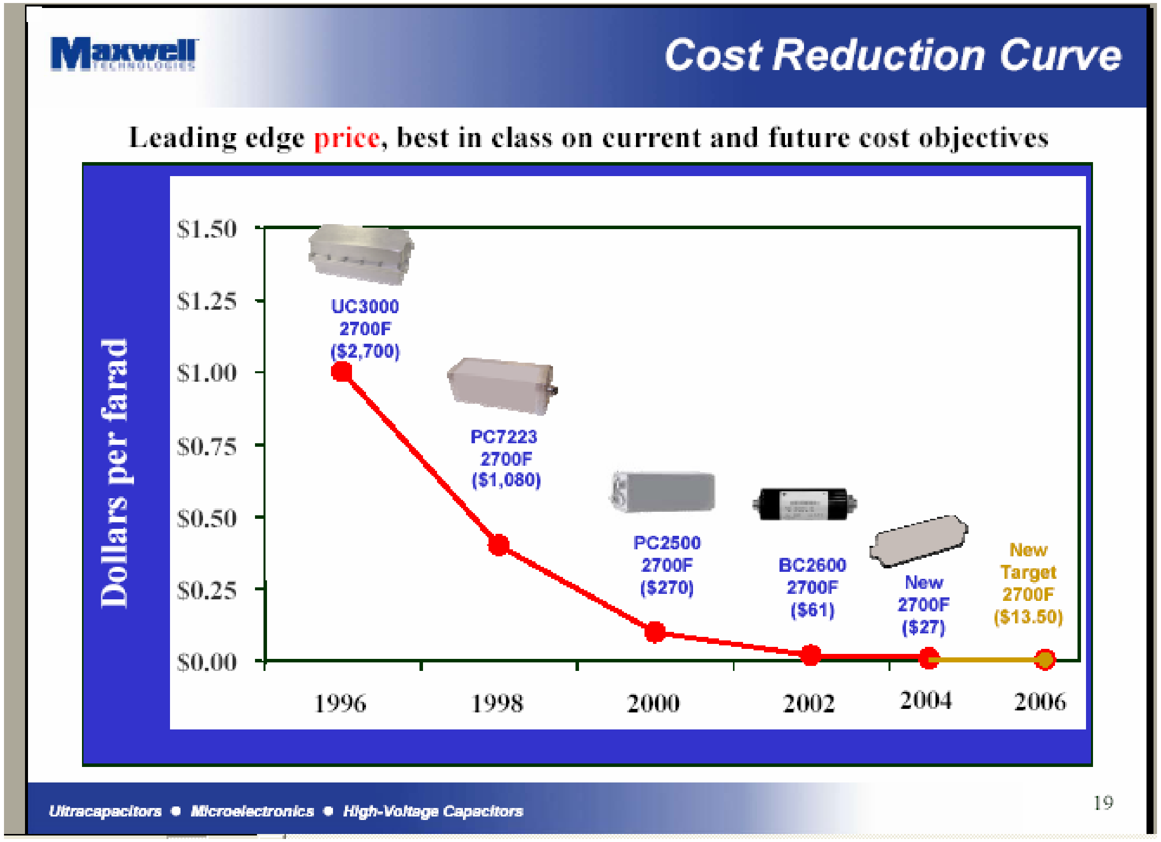
Hybrid e-CVT: Sidebar on ESS

- It is small wonder then, with this discussion of hybrid vehicles and energy storage systems that energy storage may indeed represent a >$10B market by 2010.

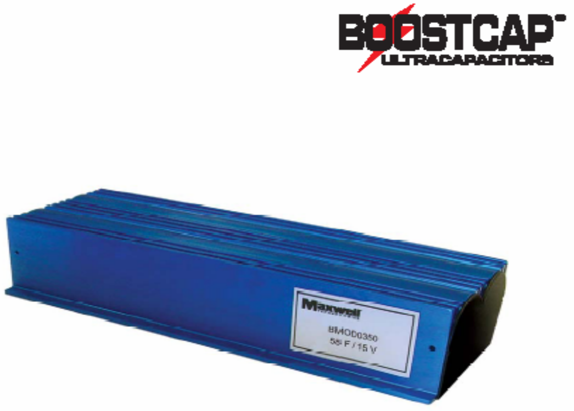
Battery Type	Energy Density [Wh/kg]	Power Density [W/kg]	Cycle Life	Operating Temp. [C]	Storage Temp. [C]	Self Discharge Rate [% per month]	Maturity	Current Cost [$/kWh]	Future Cost {$/kWh]	Principal Manuf.	Vehicles Used_In	Other Notes
Lead-Acid	25 to 35	75 to 130	200 to 400	-18 to +70	ambient	2 to 3	production	100 to 125	75	Trojan, Hawker, Exide, Interstate	CARTA bus, Solectria E10 (sealed)	
Advanced Lead Acid	35 to 42	240 to 412	500 to 800				production			Delphi, Horizon, Electrosource	Audi Duo, GM EV1 (VLRA), Solectria Force	Potential: 55 Wh/kg, 450 W/kg, and 2000 cycle life
Nickel-Metal Hydride	50 to 80	150 to 250	600 to 1500				prototype	525 to 540	115 to 300	Panasonic, Ovonic, SAFT	Toyota RAV4-EV, Toyota Prius, Chrysler Epic minivan, Honda EV, Chevy S-10	Potential: 120 Wh/kg, and 2200 cycle life
Nickel-Cadmium	35 to 57	50 to 200	1000 to 2000	-40 to +60	-60 to +60	10 to 20	mature	300 to 600	110	SAFT	WWU Viking 23	Potential: 2200 cycle life
Lithium-Ion	100 to 150	300	400 to 1200				laboratory			SONY, SAFT	Nissan Altra EV	Potential: 1000 Wh/kg

Hybrid e-CVT: Sidebar on ESS

- Ultracapacitors are becoming a viable ESS technology



Above, 2700F BoostCAP & New D-Cell BoostCAP.
Below, D-Cell 15V 58 F module



Power Split: Electrical System Modeling

- Motor-generator and power electronics are modeled conventionally:
  - M/G as torque source or sink dependent on angular speed with load dependent loss
  - Inverter as switching elements with load dependent losses
- Control strategy is modeled as state transition map based on hybrid dynamical systems theory
  - Each operating mode must be modeled:
  - (1) standstill, (2) Creep, (3) Power split, (4) Parallel, (5) Regen brake
- Electrical Energy Storage System model for state-of-charge variation with load demand

Power Split: Electrical System Modeling

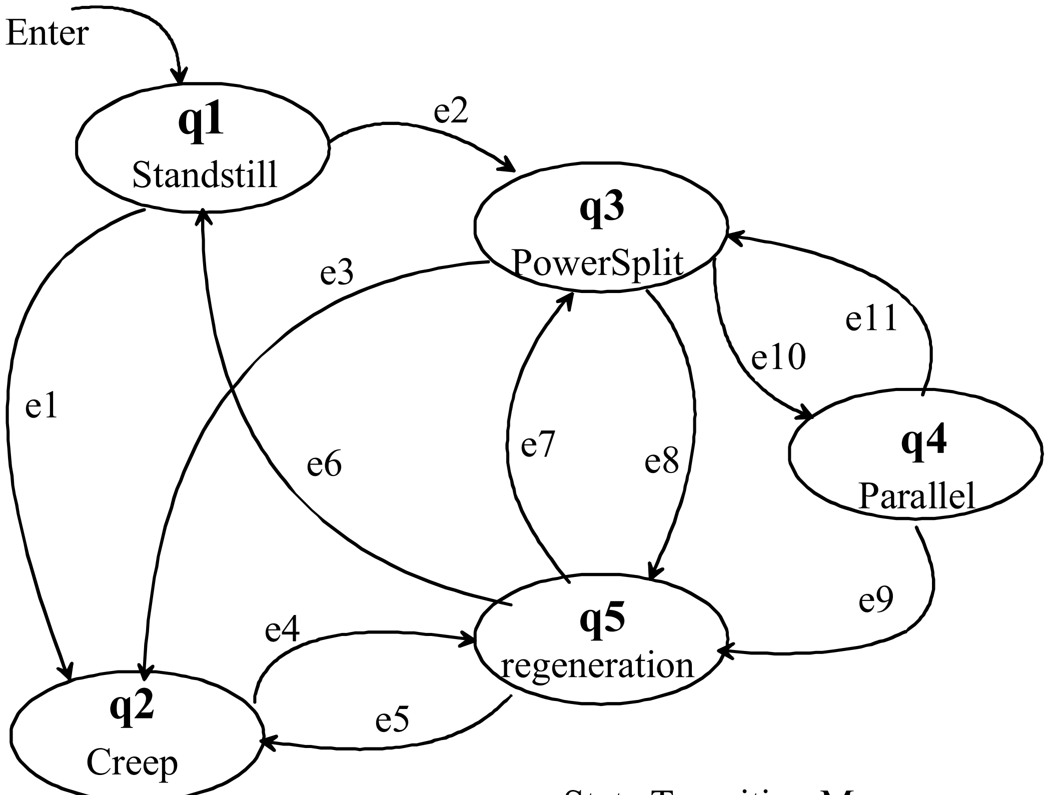
- State transition map

In state q4 we have that (ρ=1/k):

$$\omega_e = \frac{1}{1+\rho}\omega_r$$

$$\omega_g = 0 \longrightarrow \text{Brake B1=ON}$$

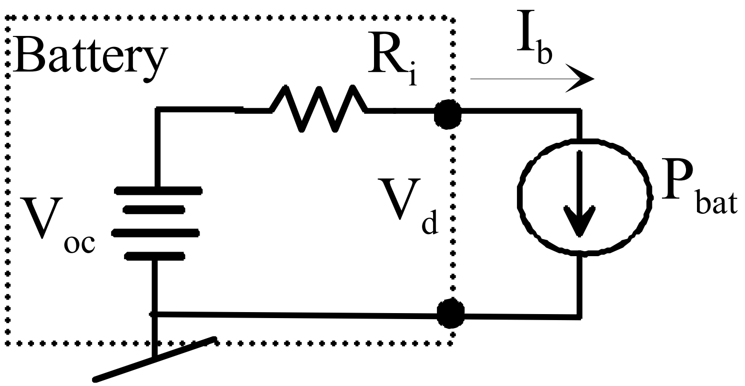
$$J_r + \frac{J_e}{(1+\rho)^2}\dot{\omega}_e = \frac{m_e}{1+\rho} + m_m - m_f$$



State Transition Map, e_x

Power Split: Electrical System Modeling

- Model must account for ESS SOC variation



Define C_{br} = battery rated capacity, Ah
Noting that: $R_i C_{br} = \tau_{bat}$

$$P_{bat} = V_d I_b = I_b (V_{oc} - I_b R_i) = P_{avail}$$

$$\frac{dW_c}{dt} = V_{oc} C_{br} \frac{d(SOC)}{dt} = P_{stored} = V_{oc} I_b$$

$$\therefore I_b = C_{br} \frac{d(S0C)}{dt}$$

Substitute for I_b in equation for P_{bat}
Then solve the resulting quadratic to obtain:

$$P_{bat} = C_{br} \frac{d(SOC)}{dt} \left\{ V_{oc} - R_i C_{br} \frac{d(SOC)}{dt} \right\}$$

$$Find\_that:$$

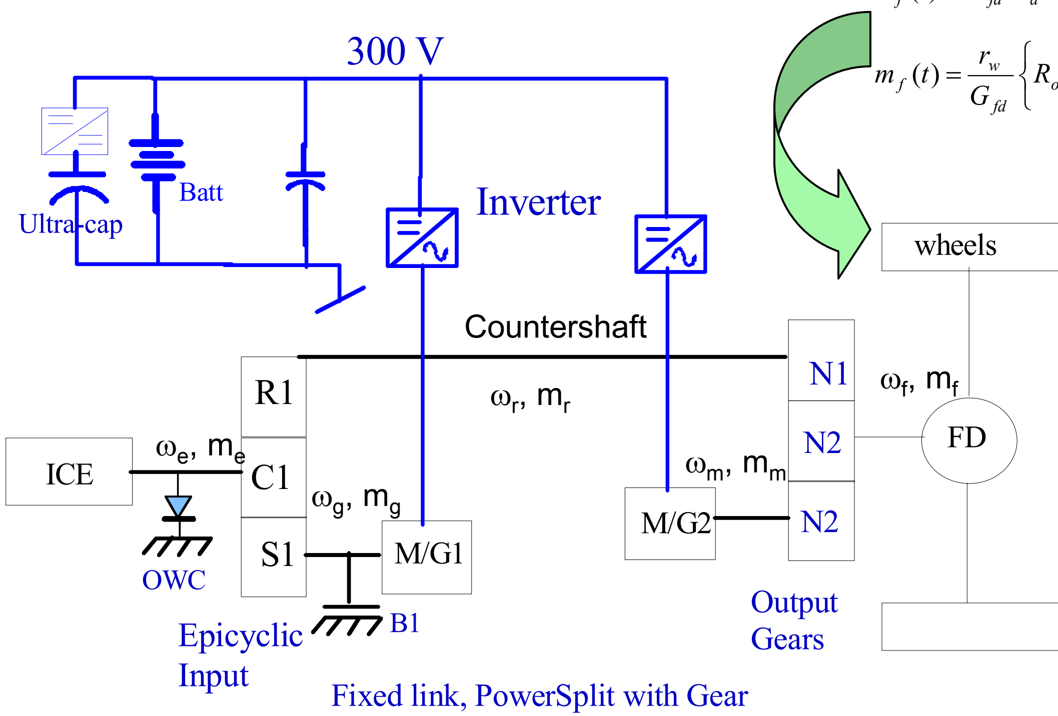
$$\frac{d(SOC)}{dt} = {}^{-}\!/_{+} \frac{\sqrt{\left(V_{oc}^2 - 4P_{bat}R_i\right)} - V_{oc}}{2R_i C_{br}}$$

Power Split: Electrical System Modeling

- Mechanical System Modeling

$$\omega_f(t) = G_{fd}\Omega_a = \frac{G_{fd}U(t)}{r_w}$$

$$m_f(t) = \frac{r_w}{G_{fd}}\left\{R_o M_v g + \frac{1}{2}\rho C_d A_f (U(t)+U_o)^2 + M_v g \sin(\alpha) + M_v \frac{dU(t)}{dt}\right\}$$



Fixed link, PowerSplit with Gear

For each operating state reflect Road load conditions to power split M/G's and engine

$$Define: k = \frac{1}{\rho}$$

$$\left(J_g + \frac{1}{k^2}J_r\right)\dot{\omega}_g - (k+1)J_r\dot{\omega}_e = m_g - \frac{1}{k}m_r$$

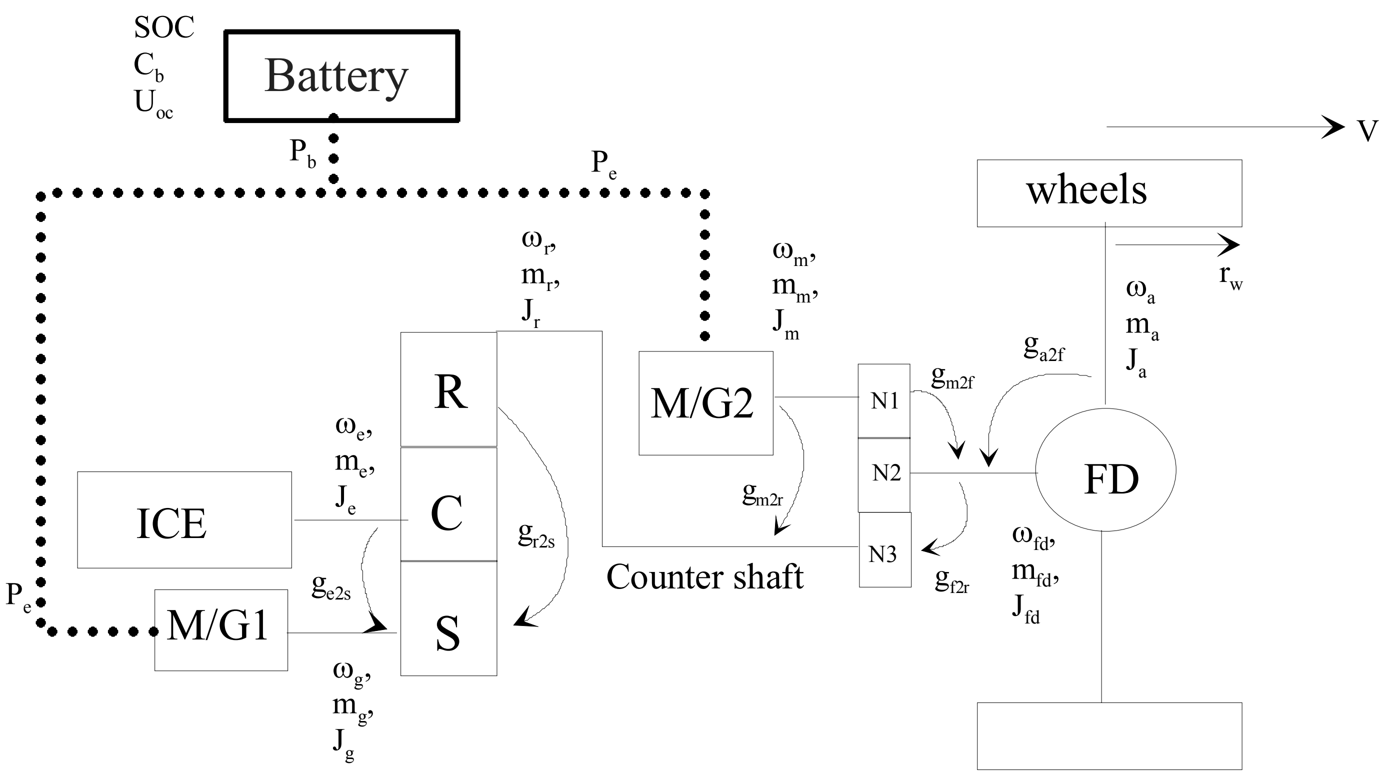
$$\frac{k+1}{k^2}J_r\dot{\omega}_g + \left(J_e - \left(\frac{k+1}{k}\right)^2 J_r\right)\dot{\omega}_e = m_e + \frac{k+1}{k}m_r$$

$noting\_that:$

$$m_r = m_m = m_f$$

Power Split: e-CVT Dynamics

- FHS system dynamics



Input split with fixed output gearing

FHS: e-CVT Power Split Dynamics

- Expressions for M/G2 (motor) and M/G1 (gen) torque can be derived by inspection of the THS architecture
  - System inertias are lumped parameter
  - Generator effects (couple) are reflected to engine and motor ports

$$m_{fd} = \frac{1}{g_{m2f}} m_m - g_{cs} m_e + \left(g_{cs} J_{eq} - \frac{1}{g_{a2f}} J_{gc} \right) \dot{\omega}_e + \left(g_{cs} J_{gc} - \frac{1}{g_{a2f}} J_{mq} \right) \dot{\omega}_m$$

$$m_g = \frac{1}{g_{e2s}} \left(m_e - J_{eq} \dot{\omega}_e - J_{gc} \dot{\omega}_m \right)$$

$$g_{cs} = \frac{g_{m2r} g_{r2s}}{g_{m2f} g_{e2s}}$$

$$m_{fdss} = \left(\frac{N_2}{N_1} \right) m_m + \left(\frac{k}{k+1} \right) \left(\frac{N_2}{N_3} \right) m_e$$

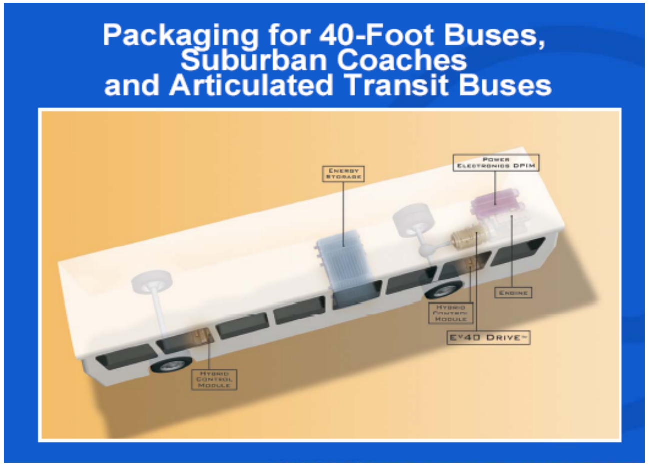
Steady state driveline torque expression showing Torque contribution of motor and engine mechanical Path split

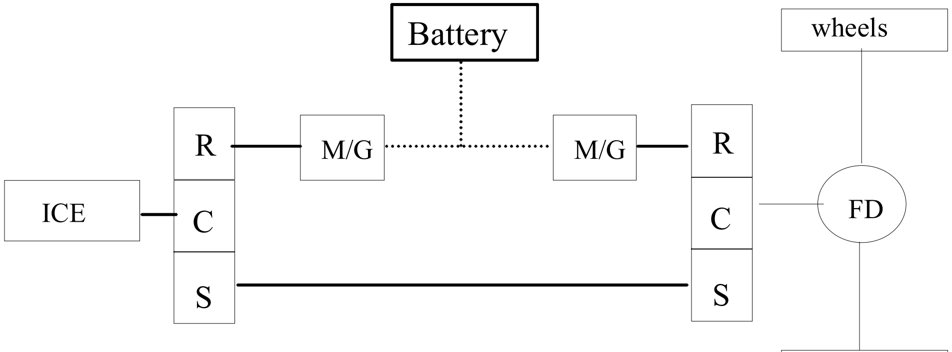
Session 4

- GM-Allision Advanced Hybrid System, 2-mode
  - Introduces clutches into basic power split
  - Dual planetary e-CVT with both input and output coupling
  - Input split and compound split performance
  - Synchronous shift from low range to high range
- Compound split promotes induction machine use

GM-Allision Advanced Hybrid System, 2-mode

- AHS-2 system
  - Mechanical and electrical architecture



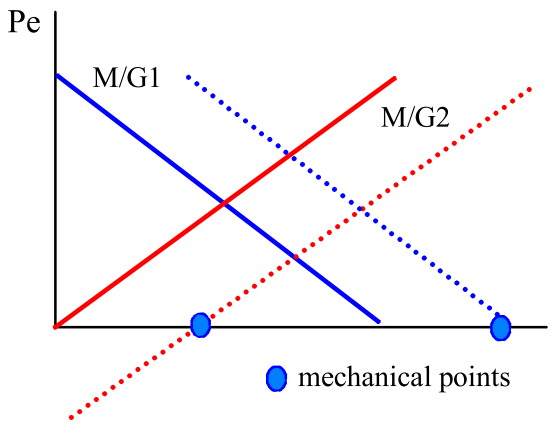


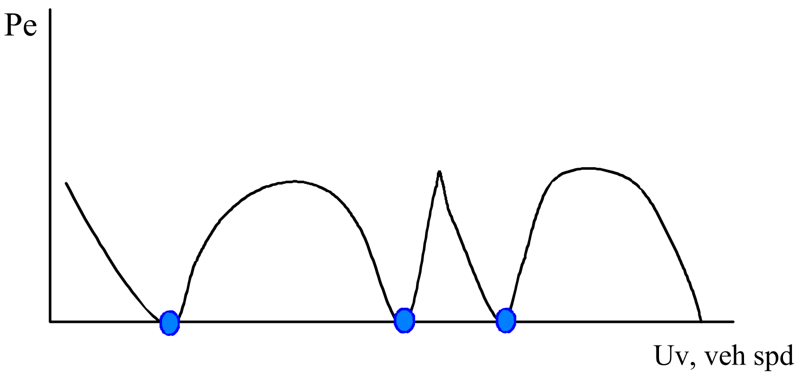
Compound Split, e-CVT

The AHS-2 system appears suited to heavy Vehicles such as city buses, trucks and full Size SUV's.

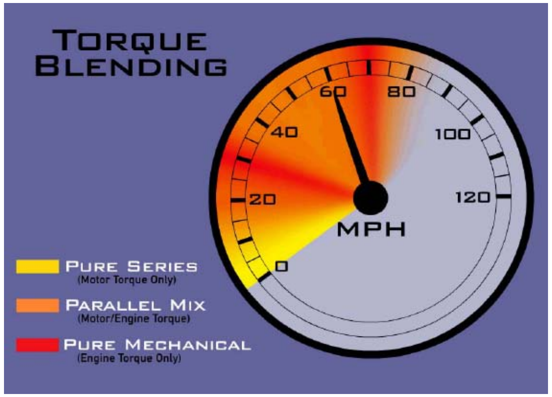
GM-Allison, AHS-2

- Compound split E-VT exhibits 2-modes: high and low range without need for gear shifts.
  - Two "mechanical" points of power split at input plus two "mechanical" points of output split.
  - M/G electrical power versus vehicle speed exhibits the mechanical points:



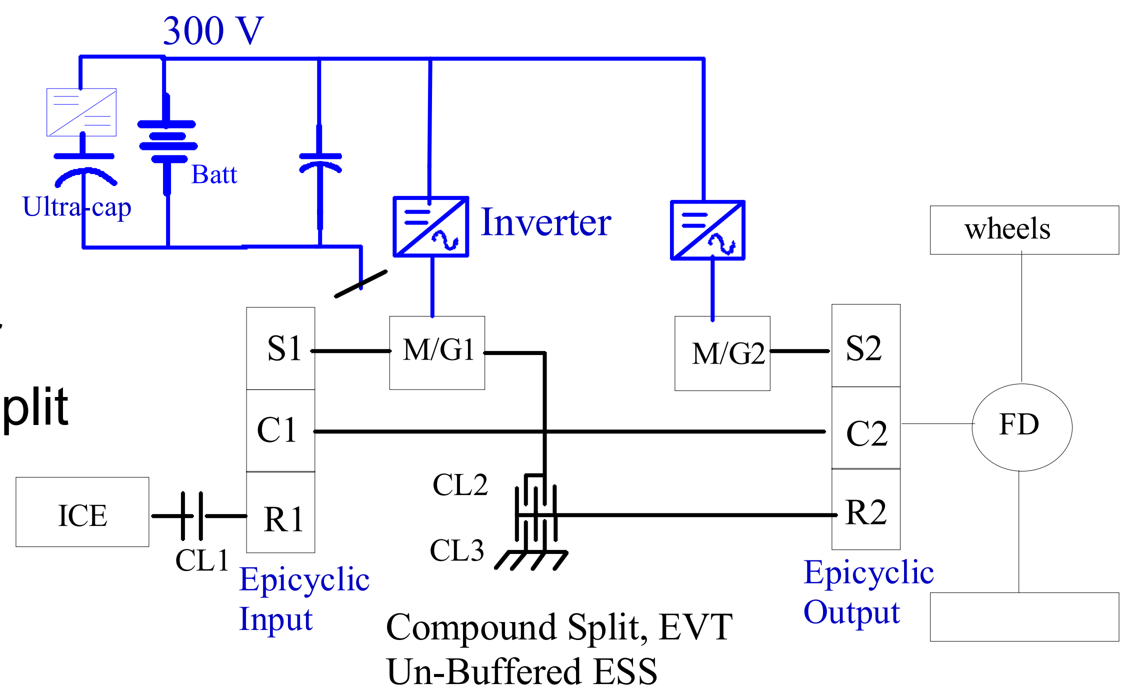


Mode switching requires clutch activations synchronously with M/G speed = zero points



AHS-2 System

- AHS-2 model development
- Mode 1 = Input Split
  - Low range & reverse
  - E1 = differential
  - E2 = torque mult
  - C1=1, C2=0, C3=1
  - M/G1=gen, M/G2=mtr
- Mode 2 = Compound Split
  - High range, highway
  - Towing, grades
  - E1=E2=differential
  - C1=1, C2=1, C3=0
- Neutral mode: C2=C3=0

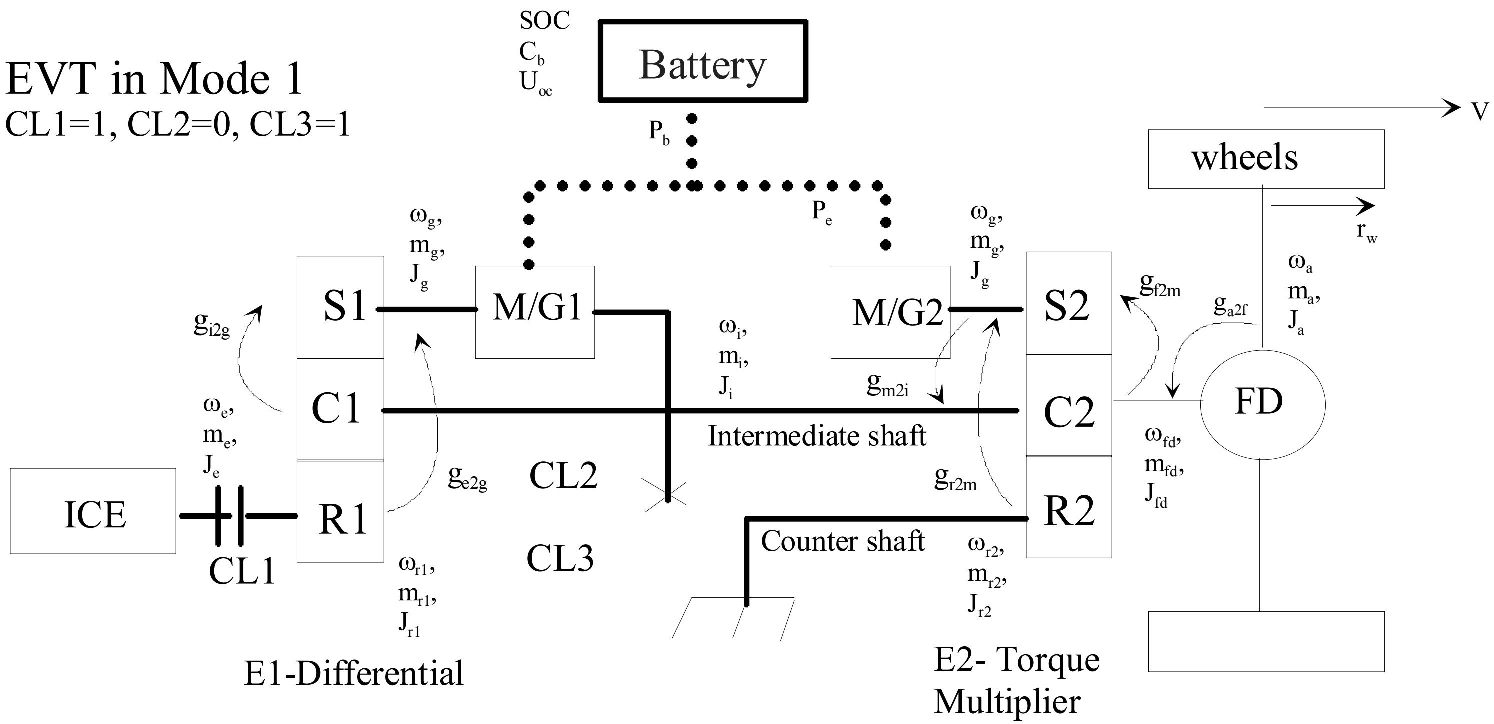


AHS-2 System

- AH2 model development
  - Compound split mode: input power splits into 2 paths which recombine at the output differential, E2
  - Benefit of compound split is reduced M/G speed range made possible by introduction of clutches and synch shift
  - M/G1 and M/G2 can be induction machines
- M/G operating modes versus vehicle speed
  - V<0 reverse, engine at idle, M/G2 = motoring in (-) dir and M/G1 spins faster in (-) direction
  - V>0 forward, engine speed ramps up, M/G2=motoring in (+) dir and M/G1 spins in (-) direction but slowing down.
  - At a particular vehicle speed, Vshift, M/G1 speed =0

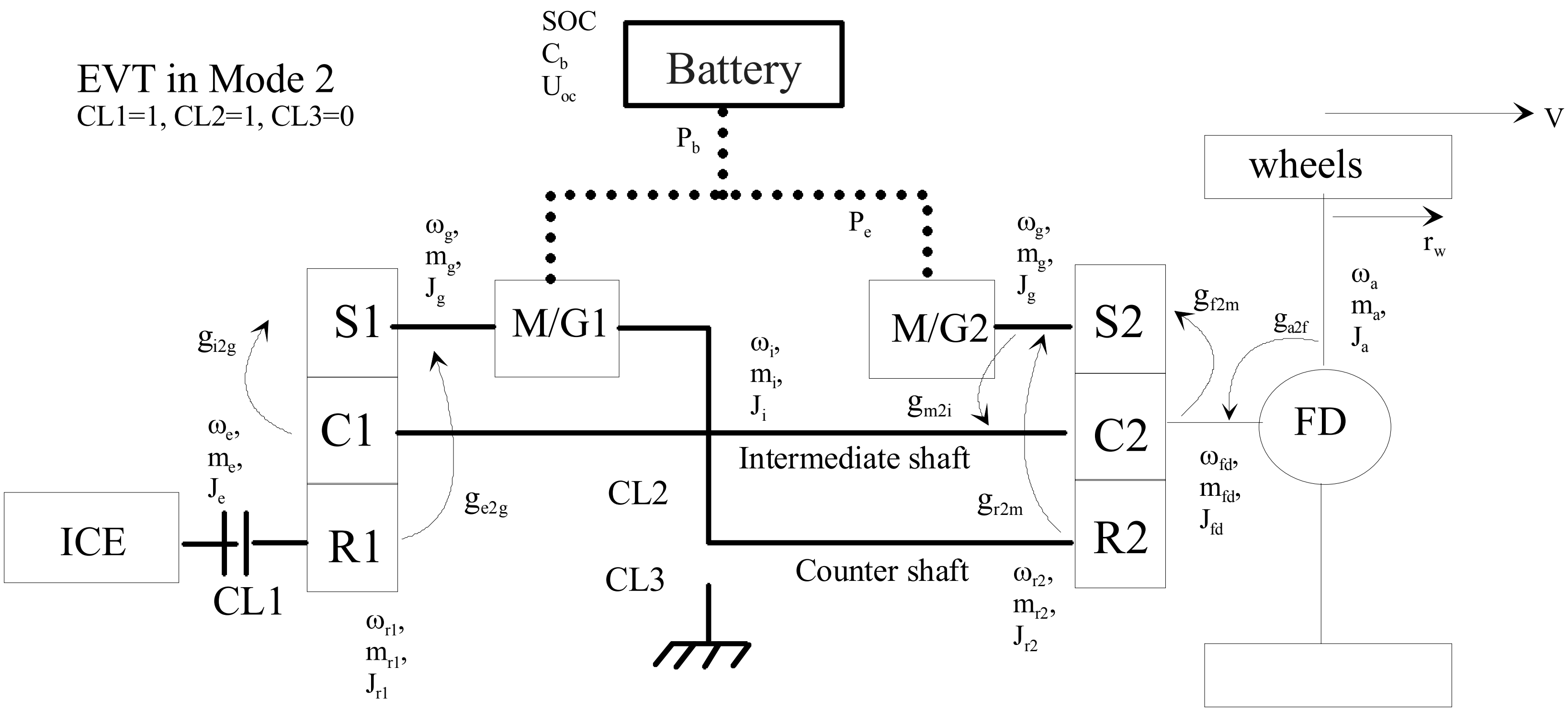
AHS-2 System Modes & Dynamics

- Input split (mode 1)



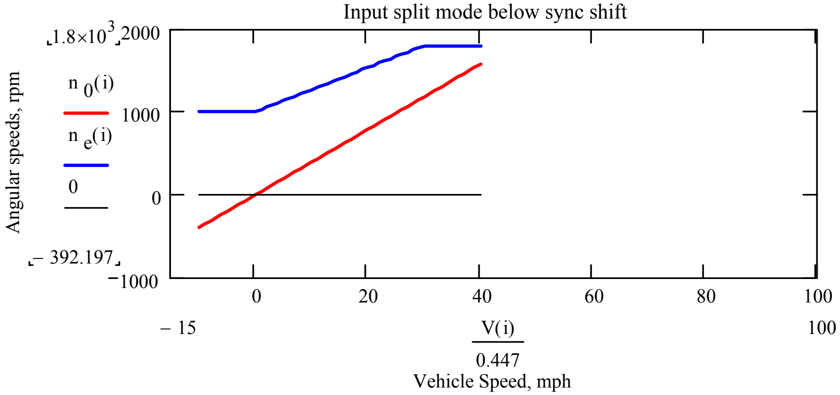
AHS-2 System Modes & Dynamics

- Compound split (mode 2)

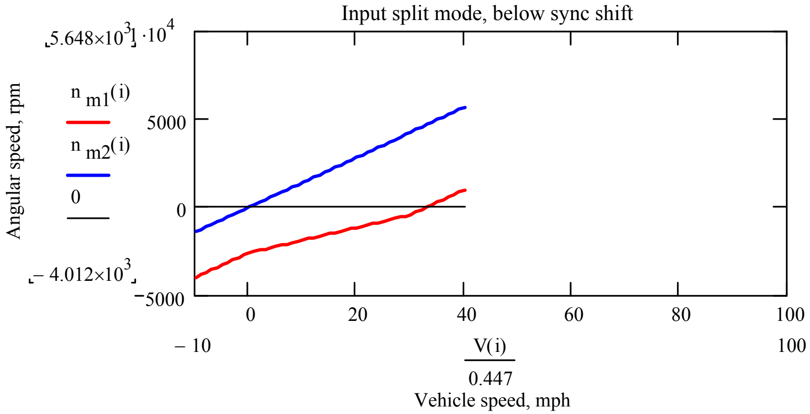


AHS-2 System

- M/G operating modes versus vehicle speed
  - Synchronous shift when V=Vshift, M/G1 speed = 0 (1st mech pt)
  - Vshift<V< Vs3, both M/G1 and M/G2 motoring in (+) dir
  - At Vs3, M/G2 speed =0 (2nd mechanical point)
  - Vs3<V<Vs4 have M/G2 motoring in (-) dir to add torque to M/G1 and to the engine
  - V>Vs4 have M/G1 = gen.



Engine ramps to steady state, Nss, at V=30 mph



At synchronous shift point, Vshift = 33 mph, the Output shaft speed, No=1294 rpm and Nm1=4659 rpm

AHS-2 System

- M/G operating points versus vehicle speed
- Input split mode:

$$n_0 = \frac{g_{fd}}{0.1047}\frac{V}{r_w}$$

$$n_{m1} = (k+1)n_0 - kn_e$$

$$n_{m2} = (k+1)n_0$$

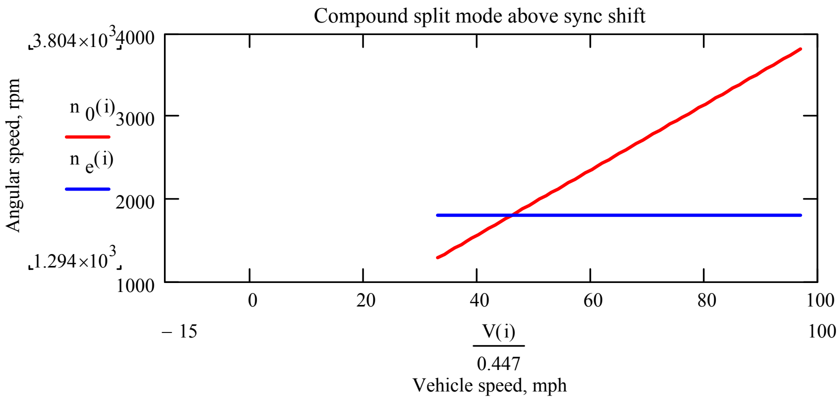
- Compound split mode

$$n_e = N_{ss} = 1800$$

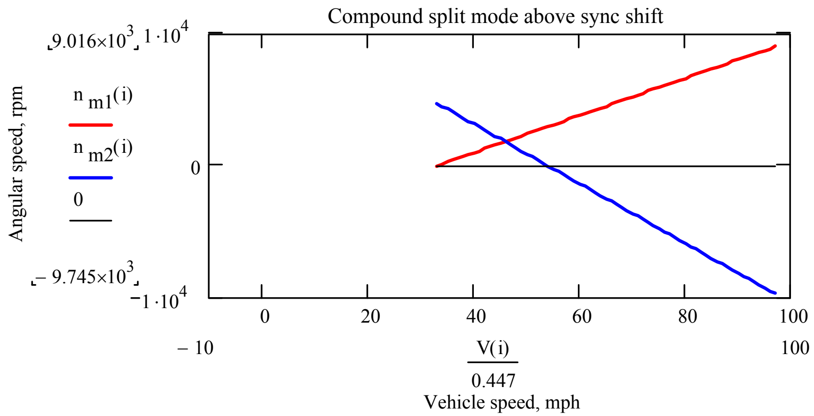
$$n_{m1} = (k+1)n_0 - kn_e$$

$$n_{m2} = k^2 n_e - (k-1)(k+1)n_0$$

$$k^{E1} = k^{E2} = k$$



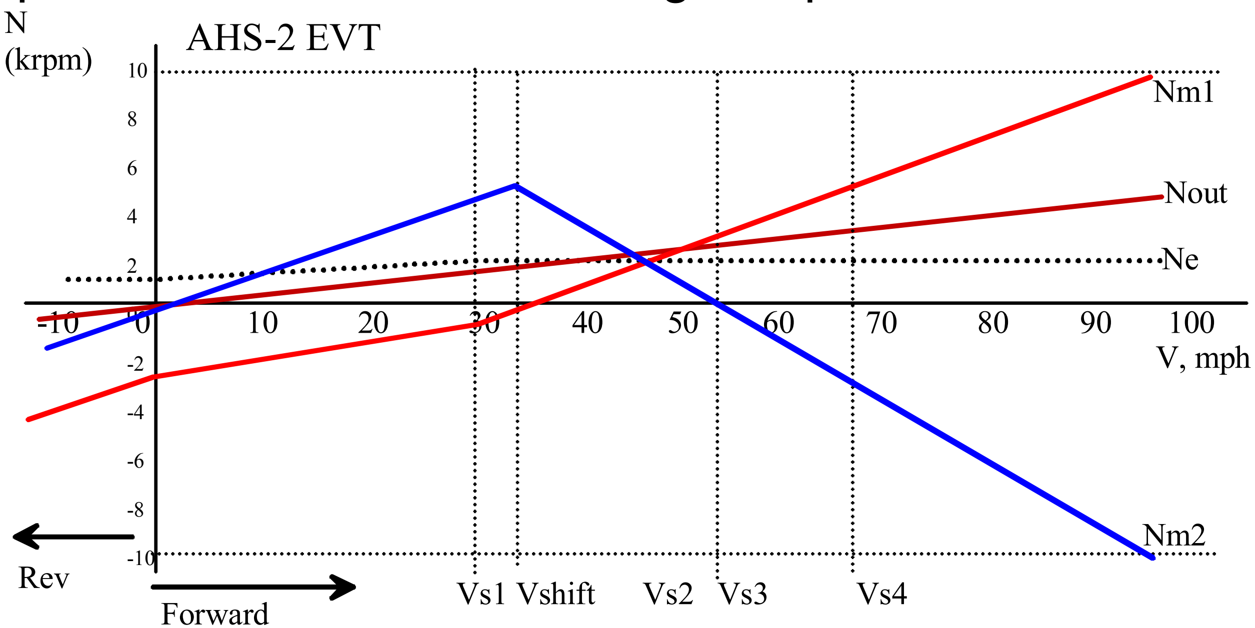
Engine remains at Nss, No continues to climb in Direct relation to vehicle speed, V



At 1st mech point, Vs1 Nm2=0 while V=53.3 mph Nm1=2940 rpm. At 97 mph, Nm1=9 krpm, Nm2=-9750

AHS-2 System

- AHS-2 summary
  - For modest values of the epicyclic basic ratio the M/G speed regimes are indeed reasonable.
  - For k>3 the speeds tend to become excessive
  - K=2.6 was assumed here
- Composite M/G, Vehicle and Engine speeds



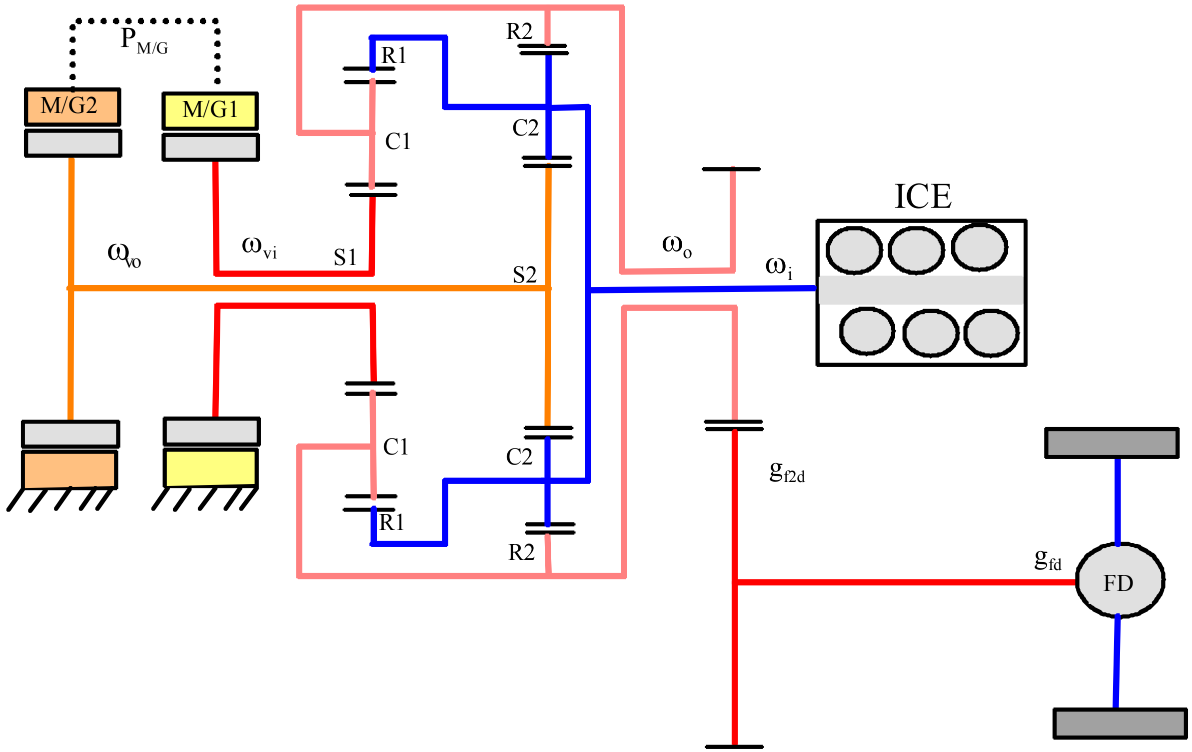
Session 5

- Renault Infinitely Variable Transmission, IVT
  - Appears derived from GM-Allision AHS-2 concept
  - Emphasis on bulk of power transmission via mechanical path
  - Variator path is electrical
  - Variator controls the overall transmission ratio

- Compound split (electric variator) promotes induction machine use

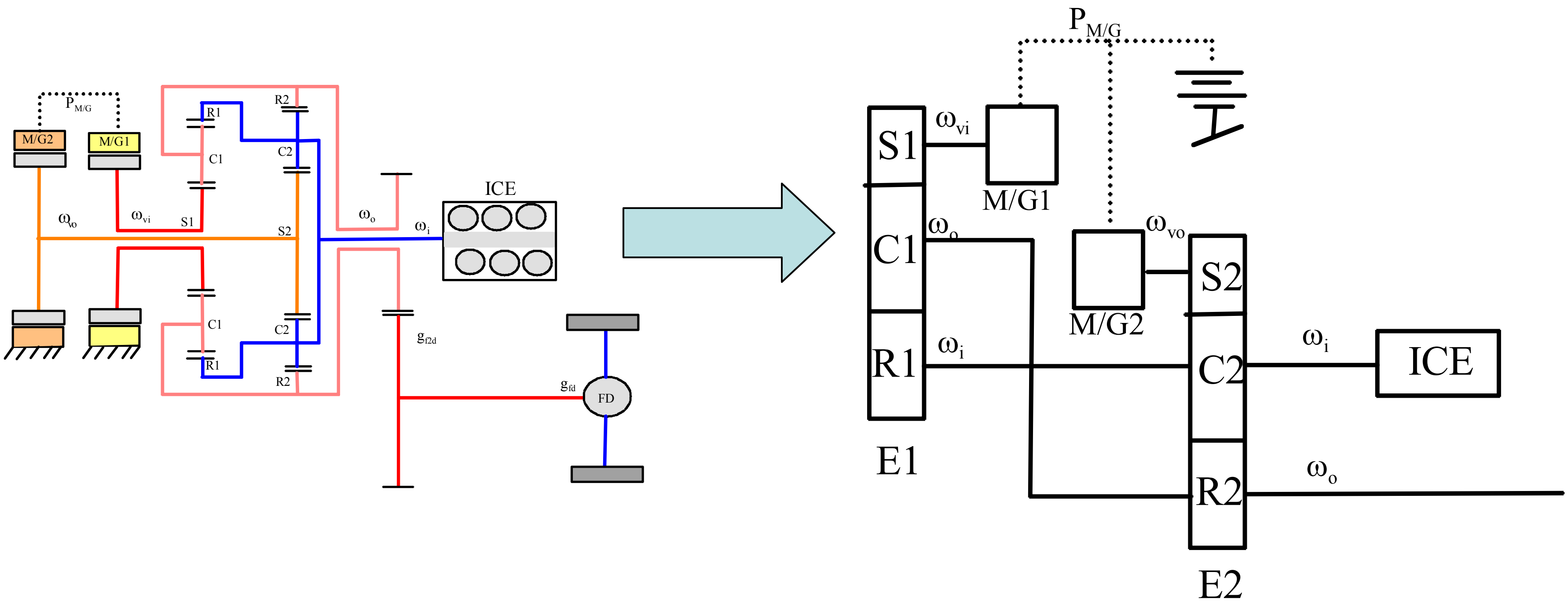
Renault IVT System

- Compound split without synchronous shift
  - Renault sought out the most flexible and most efficient variator topology
  - An electric variator was selected
- The IVT transmission concept



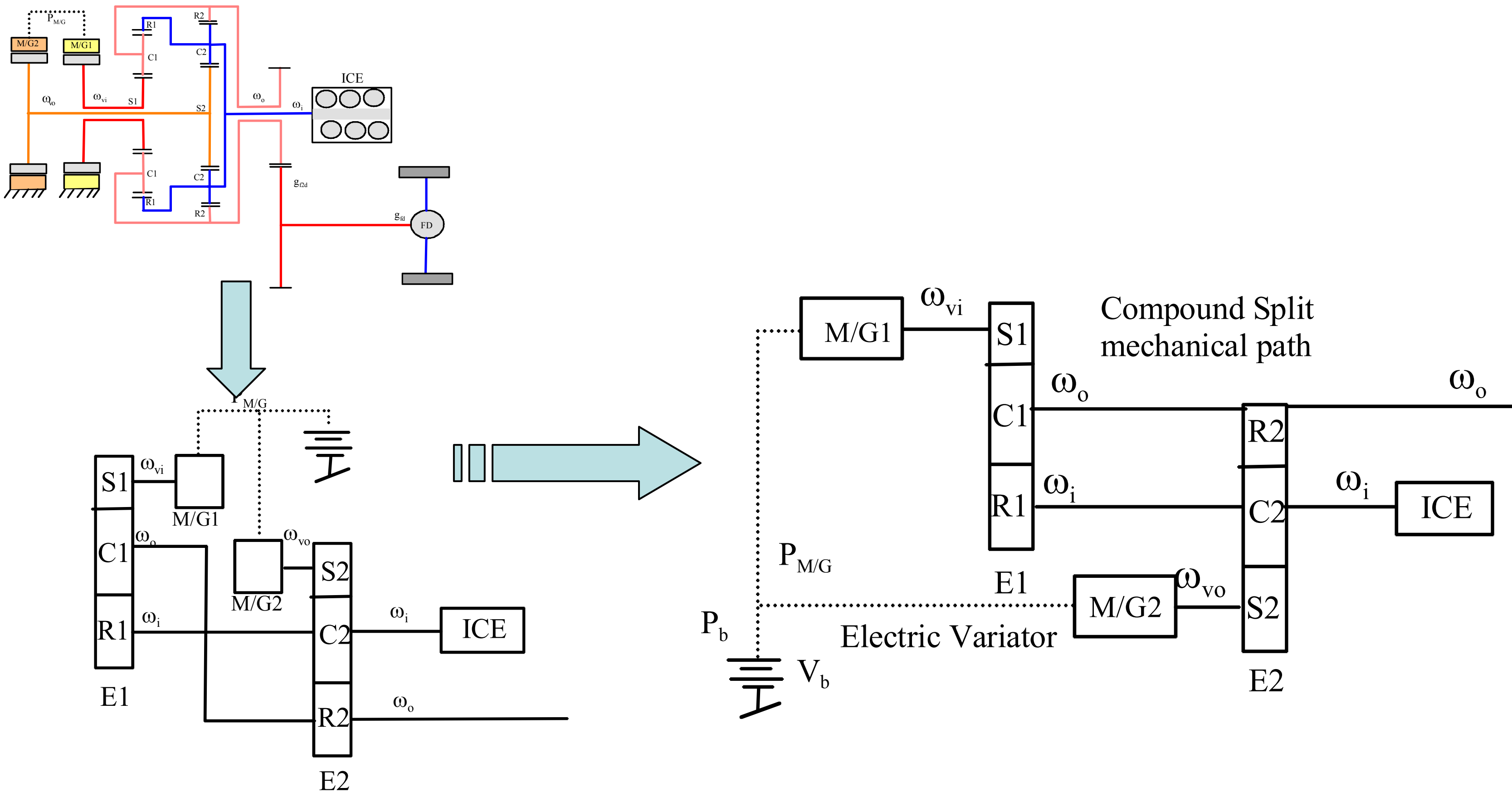
Renault IVT System

- IVT model development



Renault IVT System

- IVT model development

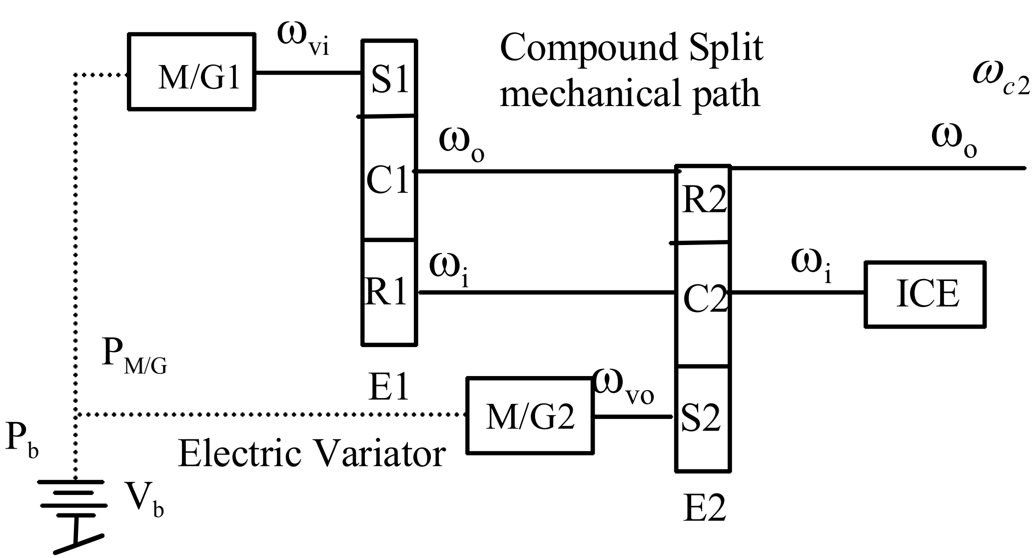


Renault IVT System

- IVT model development
  - Planetary gear sets E1 & E2 may have different basic ratios
  - Define the planetary gear element speeds at each carrier
  - This will result in expressions for ω_i and ω_o.

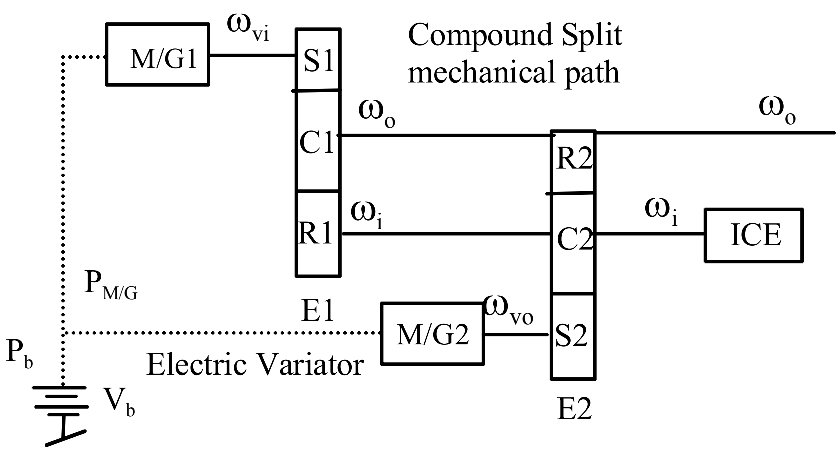
$$\omega_{c1} = \left(\frac{1}{1+k^{E1}}\right)\omega_{s1} + \left(\frac{k^{E1}}{1+k^{E1}}\right)\omega_{r1}$$

$$\omega_{c2} = \left(\frac{1}{1+k^{E2}}\right)\omega_{s2} + \left(\frac{k^{E2}}{1+k^{E2}}\right)\omega_{r2}$$



Renault IVT System

- IVT model development



$$\omega_{c1} = \left(\frac{1}{1+k^{E1}}\right)\omega_{s1} + \left(\frac{k^{E1}}{1+k^{E1}}\right)\omega_{r1}$$

$$\omega_{c2} = \left(\frac{1}{1+k^{E2}}\right)\omega_{s2} + \left(\frac{k^{E2}}{1+k^{E2}}\right)\omega_{r2}$$

$$\omega_{o} = \left(\frac{1}{1+k^{E1}}\right)\omega_{vi} + \left(\frac{k^{E1}}{1+k^{E1}}\right)\omega_{i}$$

$$\omega_{i} = \left(\frac{1}{1+k^{E2}}\right)\omega_{vo} + \left(\frac{k^{E2}}{1+k^{E2}}\right)\omega_{o}$$

Renault IVT System

- IVT model development
  - Some definitions, then solve the preceding sets of equations for E1 and E2 speeds as:

$$\alpha_1 = \frac{1}{1+k^{E1}}$$

$$\beta_1 = \frac{k^{E1}}{1+k^{E1}}$$

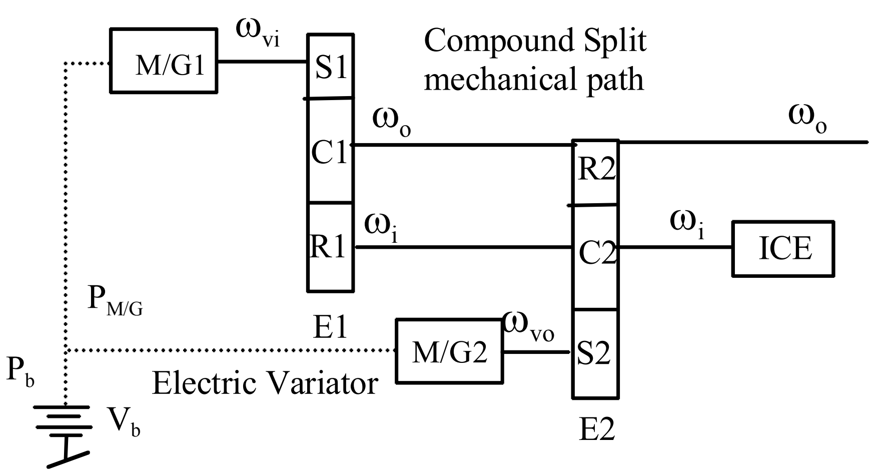
$$\alpha_2 = \frac{1}{1+k^{E2}}$$

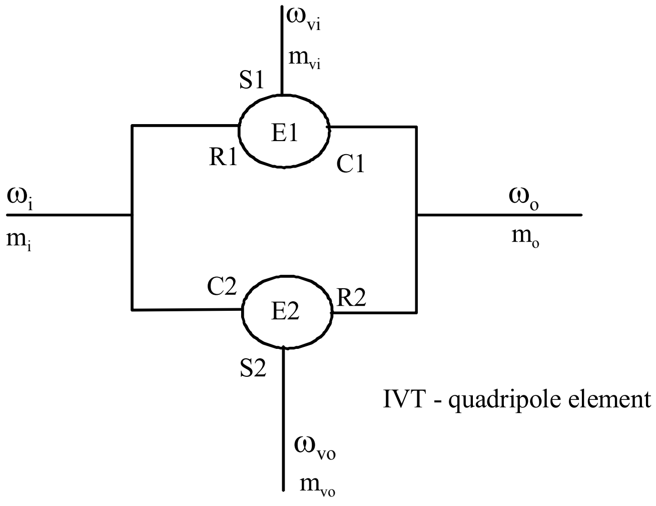
$$\beta_2 = \frac{k^{E2}}{1+k^{E2}}$$

$$\begin{bmatrix} \omega_i \\ \omega_o \end{bmatrix} = \begin{bmatrix} \frac{\alpha_1 \beta_2}{1-\beta_1\beta_2} & \frac{\alpha_2}{1-\beta_1\beta_2} \\ \frac{\alpha_1}{1-\beta_1\beta_2} & \frac{\beta_1 \alpha_2}{1-\beta_1\beta_2} \end{bmatrix} \begin{bmatrix} \omega_{vi} \\ \omega_{vo} \end{bmatrix}$$

Renault IVT System

- IVT model development
  - Electric variator system
  - ESS capacity = 0 system is "AT-like"
  - ESS capacity = low, system is "mild" hybrid w/ stop/start, regen, boost
  - ESS capacity = high, system is "full" hybrid w/ "mild" + ZEV range





Conclusions and Wrap-up

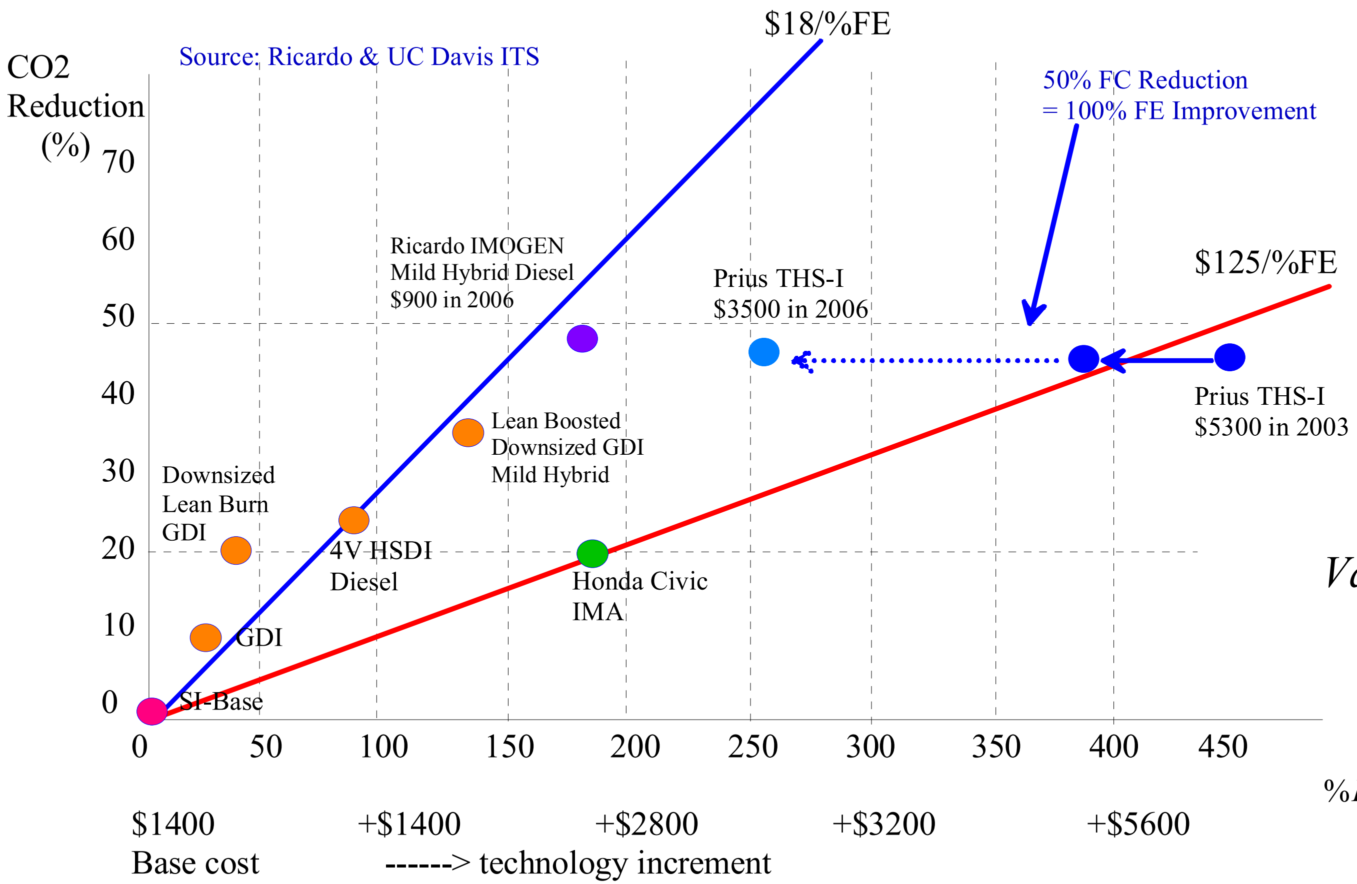
- Historical developments during the early 20th century explored combining ICE’s with electric machines – hybrid
- Globally, automotive OEM’s have converged to the power split hybrid transmission
  - Decouples engine from wheels so long as output power is met
  - Provides all hybrid transmission features plus emissions reduction
  - Transmits bulk of engine power mechanically to wheels whereas variator – electric path, determines its overall ratio
- Power split transmissions rely on 2 electric machines

Conclusions and Wrap-up

- Power split transmissions, or, electronic CVT's, have emerged along two distinct development paths
  - Single planetary gear, input coupled, power split preferred by Toyota and Ford
  - Dual planetary gear, input/compound split, preferred by GM and Renault (and others)
- Efficiency of the variator, as in mechanical CVT's, remains the main development area:
  - Need for high power density & efficient electric machines
  - Need for compact and highly efficient power electronics
  - Need for high energy throughput electric energy storage system

Conclusions and Wrap-up

- Economics of hybrids:
- CO_2 reduction = Fuel consumption reduction = Fuel economy benefit



$$Value_{metric} = \frac{\$_{incremental}}{\%FE_{benefit}}$$

$$\%FE_{benefit} = 100\left(\frac{\%FC_{benefit}}{100 - \%FC_{benefit}}\right)$$

Conclusions and Wrap-up

- Current market prices for hybrid electric cars
  - Hybrid vehicle market expected to reach 4.5 M units/yr (6%) in 2013
  - Drivers: higher energy costs and more stringent emissions regulations

Ford Escape Hybrid

MSRP Range: $26,780 - $28,405
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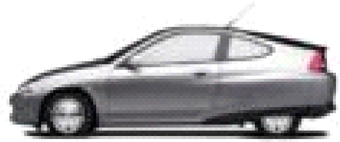
Honda Insight



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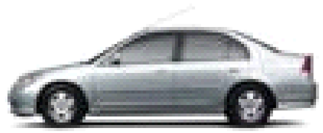

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Toyota Prius

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