Hybrid Propulsion Systems: The Gasoline-Electric Strong Hybrid

By

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To

NDIA Workshop
at
Hilton Resort & Spa, Traverse City, MI

Outline

- Trends in hybrid propulsion systems technology
  - Historical developments
  - Micro, mild, full hybrid systems
- What hybridization does
  - Performance targets and energy flows
- Supporting Subsystems
  - Chassis systems, Steering and Brakes
- Full Hybrid Systems Benefit from Higher Voltage
  - eCVT's are Si rich environments
- What are power split electronic CVT's?
  - Input vs. output/compound split
  - What is the power split device?
- Power flow basics in the power split configuration
  - Mechanical path and electric path power flows
- Input Split Systems: THS, FHS
- Compound Split Systems: AHS-2 (EVT), eVT, and IVT
- Summary

Terminology

- Torque and angular speed variables
  - m = torque (Nm) and ω = angular velocity (rad/s)
- Inertias, friction, efficiency variables
  - J = inertia (kg-m^2/rad), and b = coefficient of friction (Nms/rad)
  - η = efficiency (#)
- Voltage, Current, Power:
  - Voltage: U_{sys} or U_{bus}; Current: I_d or I_x; Power: P_x
- Vehicle motion:
  - Velocity: V (m/s); Tractive effort: F_t (N)

Gasoline-Electric Hybrids

- Some history of the hybrid propulsion system

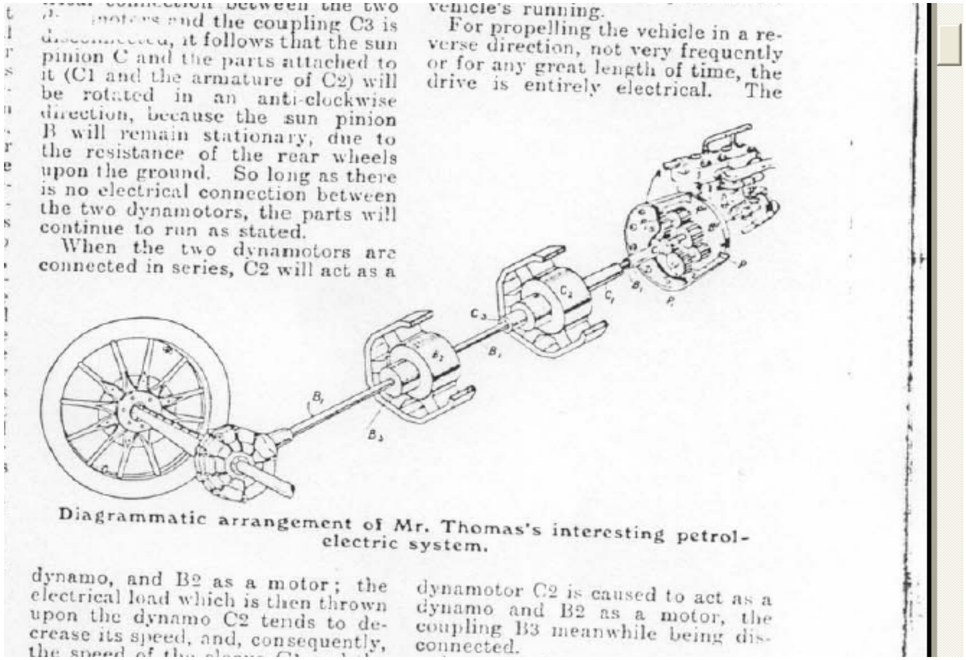
Trends in Hybrid Propulsion Systems Technology

- Hybrid vehicle technology is now a century old
  - Hybrid electric vehicles have been known, built, and driven in public since 1909
- HEV patents date to 1905 in the US and UK
- Thomas Transmission (UK – 1909)

  with two electric machines

  and a planetary gear set,

  a precursor to today's eCVT



motors and the coupling C3 is disconnected, it follows that the sun pinion C and the parts attached to it (C1 and the armature of C2) will be rotated in an anti-clockwise direction, because the sun pinion B will remain stationary, due to the resistance of the rear wheels upon the ground. So long as there is no electrical connection between the two dynamotors, the parts will continue to run as stated.

When the two dynamotors are connected in series, C2 will act as a

vehicle's running.

For propelling the vehicle in a reverse direction, not very frequently or for any great length of time, the drive is entirely electrical. The

Diagrammatic arrangement of Mr. Thomas's interesting petrol-electric system.

dynamo, and B2 as a motor; the electrical load which is then thrown upon the dynamo C2 tends to decrease its speed, and, consequently,

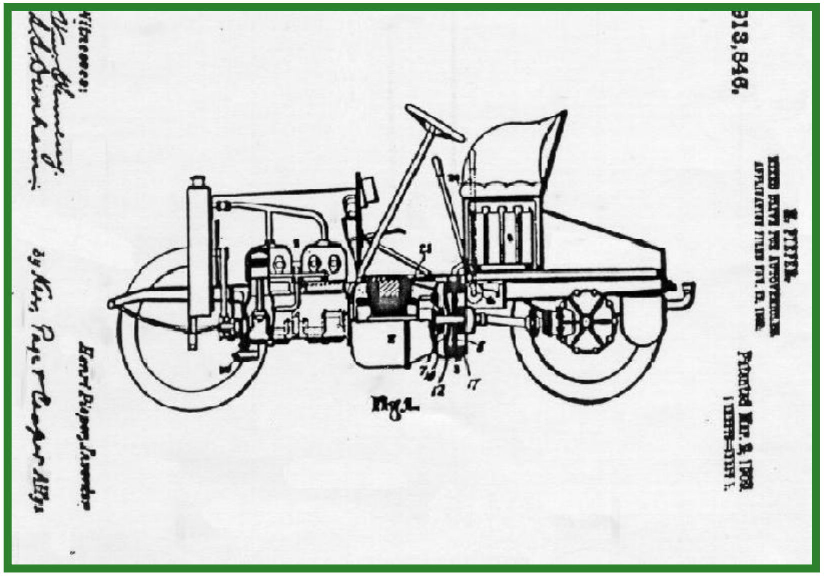
dynamotor C2 is caused to act as a dynamo and B2 as a motor, the coupling B3 meanwhile being disconnected.

Source:
Thomas Transmission System, The Commercial Motor, May 4, 1911

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.
- 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.
- Another hybrid electric, circa 1909



Source: Gerry Skellenger, GM HEV Retired, Gedask LLC

Gasoline-Electric Hybrids

- A look at current projections for HEV production

Global Automotive Serial Production

- Present status of registered automobiles:
  - 185M in N.A. alone in 2005
  - 850M globally in 2005
  - projection for 1.2B by 2020 (doubling since 1990)
- In 1990 some 2.9B Ton of CO_2 was emitted into the atmosphere by vehicles. In 2020 this will increase to 6B Ton unless measures are taken to reduce emissions.
- Honda Motor Co. projects an HEV share of 30% and a FCHV share of 10% in 2020 – this will help reduce overall CO_2 emissions.

Source: Michiyoshi Hagino, Senior Managing Director, Honda Motor Co. and President, Japan SAE. SAE Technology Theatre, 12 March, 2005

Global Automotive Production

- Automotive production is currently growing at 2.2%/year on average.

Serial Production in Millions

	2005	2009	2012	2020	HEV+FCHV in 2020
N.+S. America	18.5	20.3	20.8	22.3	8.92
EU+E.Eur+ME	21.8	23.3	23.7	25.5	10.2
Oceana	21.6	23.9	24.7	26.5	10.6
Total	61.9	67.5	69.2	74.3	29.72

  - Estimate based on 0.9%/year beyond 2012

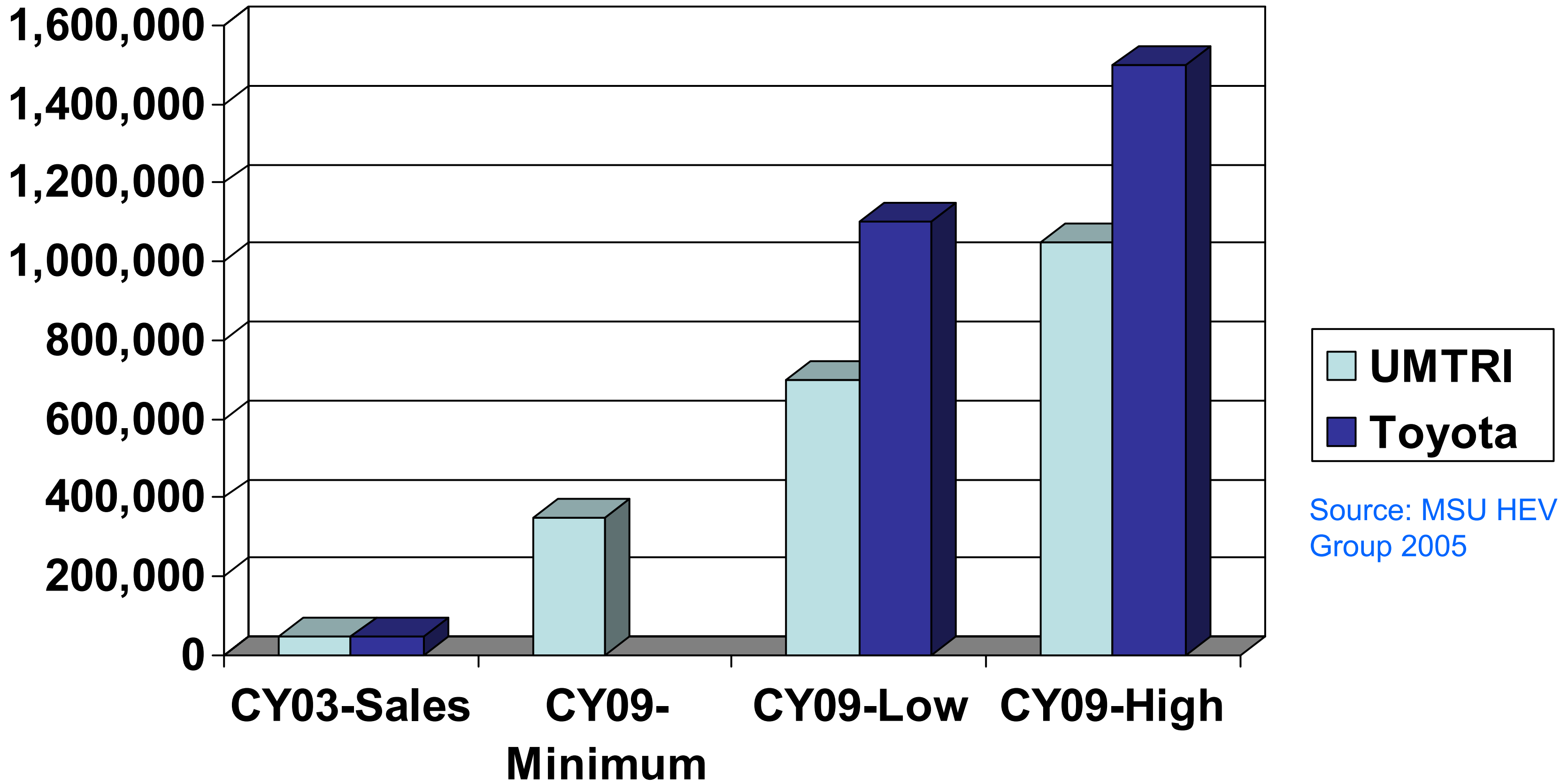
- Assuming Honda's 40% HEV+FCHV in 2020 would mean a demand for ~ 30M HEV systems/year.

Source: PriceWaterhouseCoopers, executive perspectives, 2005, Q1 data Release of global light vehicle outlook. www.autofacts.com

HEV Sales Projections: US 2003 and 2009

*based upon 15.5 million vehicles sales in 2003: 16.5 million in 2009

HEV Sales from UMTRI study & Toyota projections



Source: MSU HEV study Group 2005

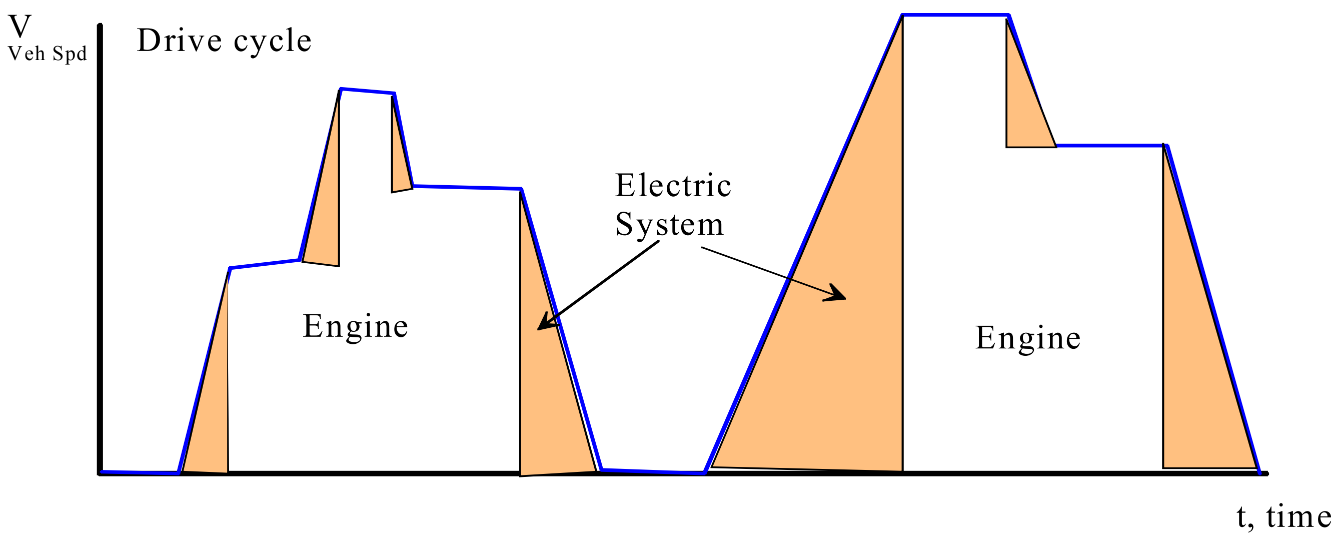
Toyota predicts production of10M HEV’s globally in 2015 (MIT-Industry Consortium meeting, Seoul, Korea, 24-25 May, 2005)

Gasoline-Electric Hybrids

- What hybridization does
- Voltage levels
- Performance

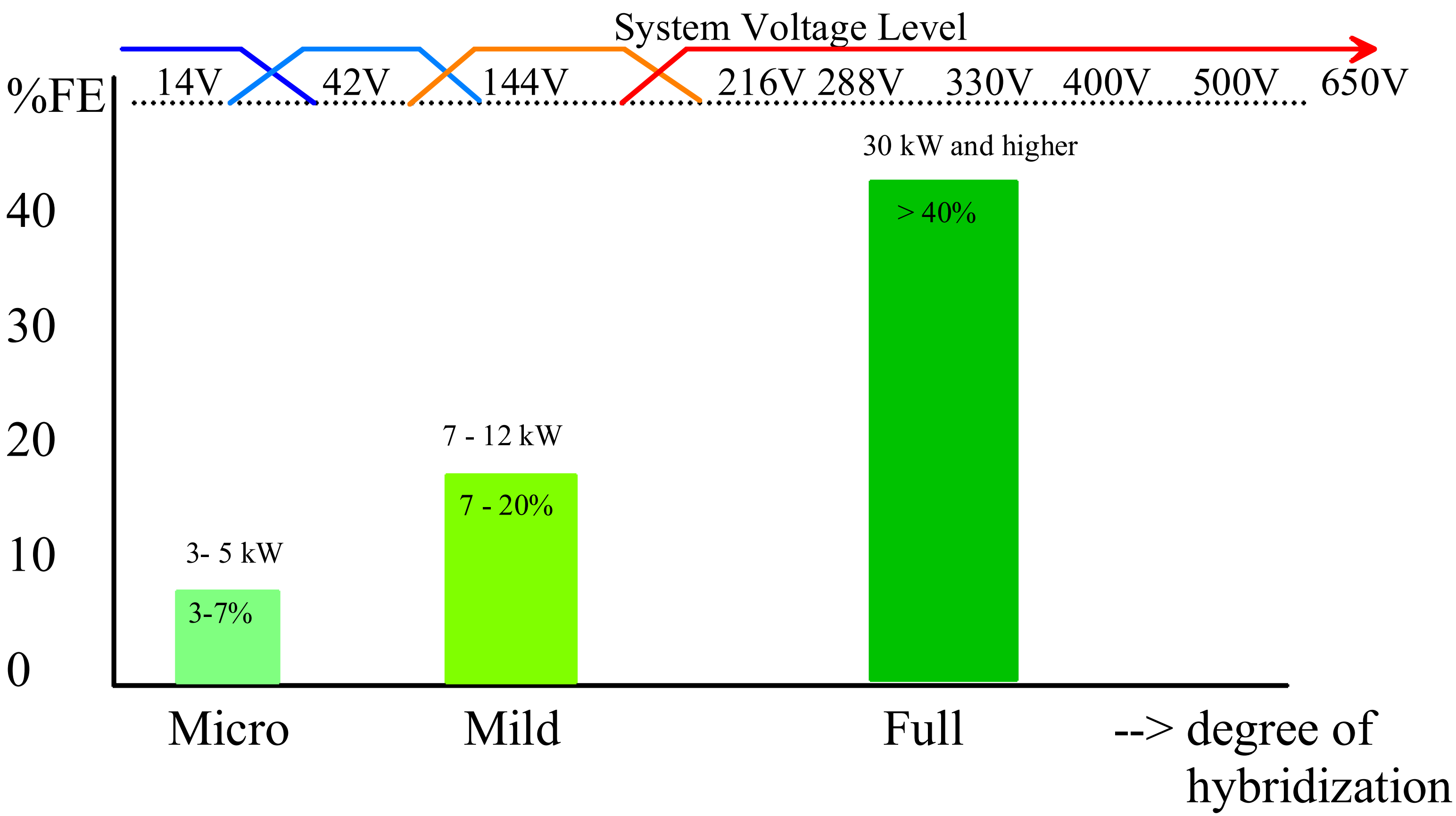
What Hybridization Does

- Unloads transients from the engine
  - Launch acceleration, passing, deceleration
  - Augments engine torque and provides boosting
  - Recuperates braking energy to replenish the energy storage system



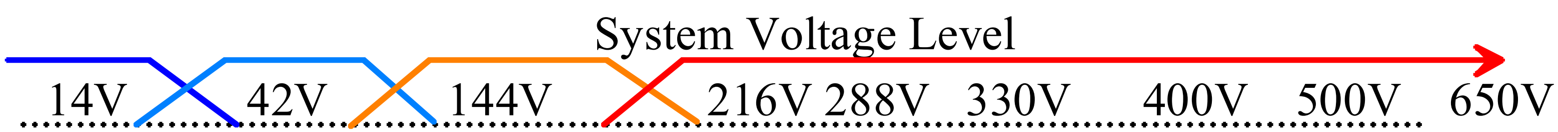
Hybrid Functions: Degree of Hybridization

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

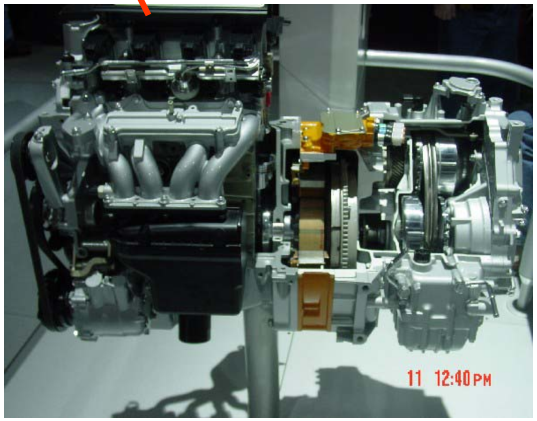


Micro, Mild, Full Hybrid Systems

- Degree of hybridization depends on electric power level which in turn dictates the system voltage



GM 42V Flywheel Alternator Starter

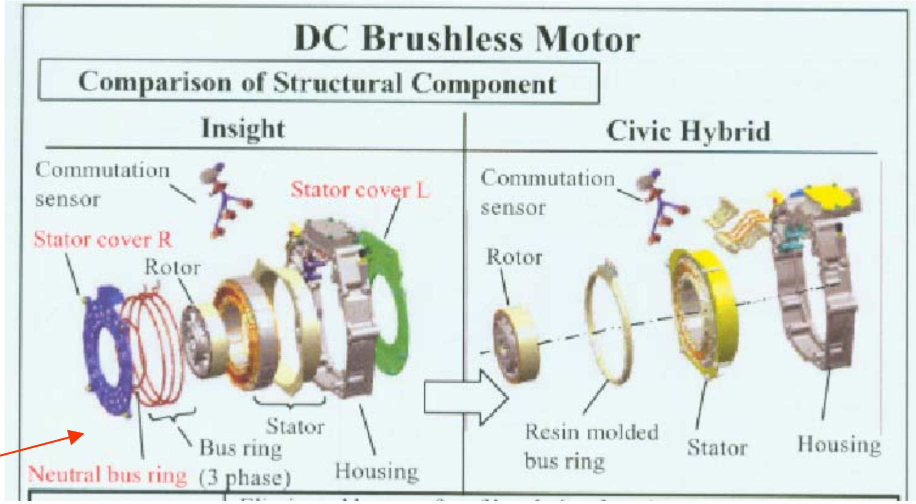


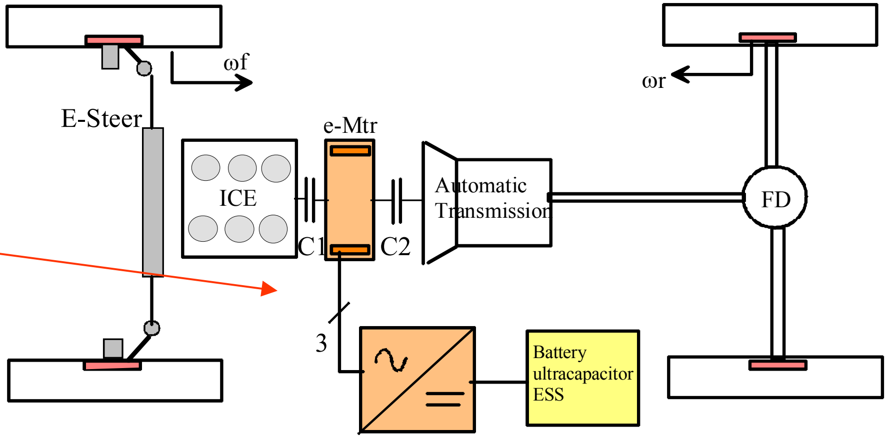
Honda Integrated Motor Assist

Toyota Hybrid System power split

Types of Hybrid Propulsion Systems of Interest

- **Micro & Mild Hybrids at power levels 3.5kW Micro and 10kW Mild**
  - Toyota Motor Co, Crown with I6 and 42V B-ISG configuration
  - GM Silverado P/U and Saturn Vue, 42V B-ISG
  - Honda Civic and Accord Hybrids with 144V IMA (a C-ISG configuration)
- **Full Hybrids at 30kW and higher power**
  - C-ISG at high power such as BMW prototype
  - Series-Parallel Switching introduced by Toyota in 2002
  - Power split architectures: Input Coupled and Compound Coupled



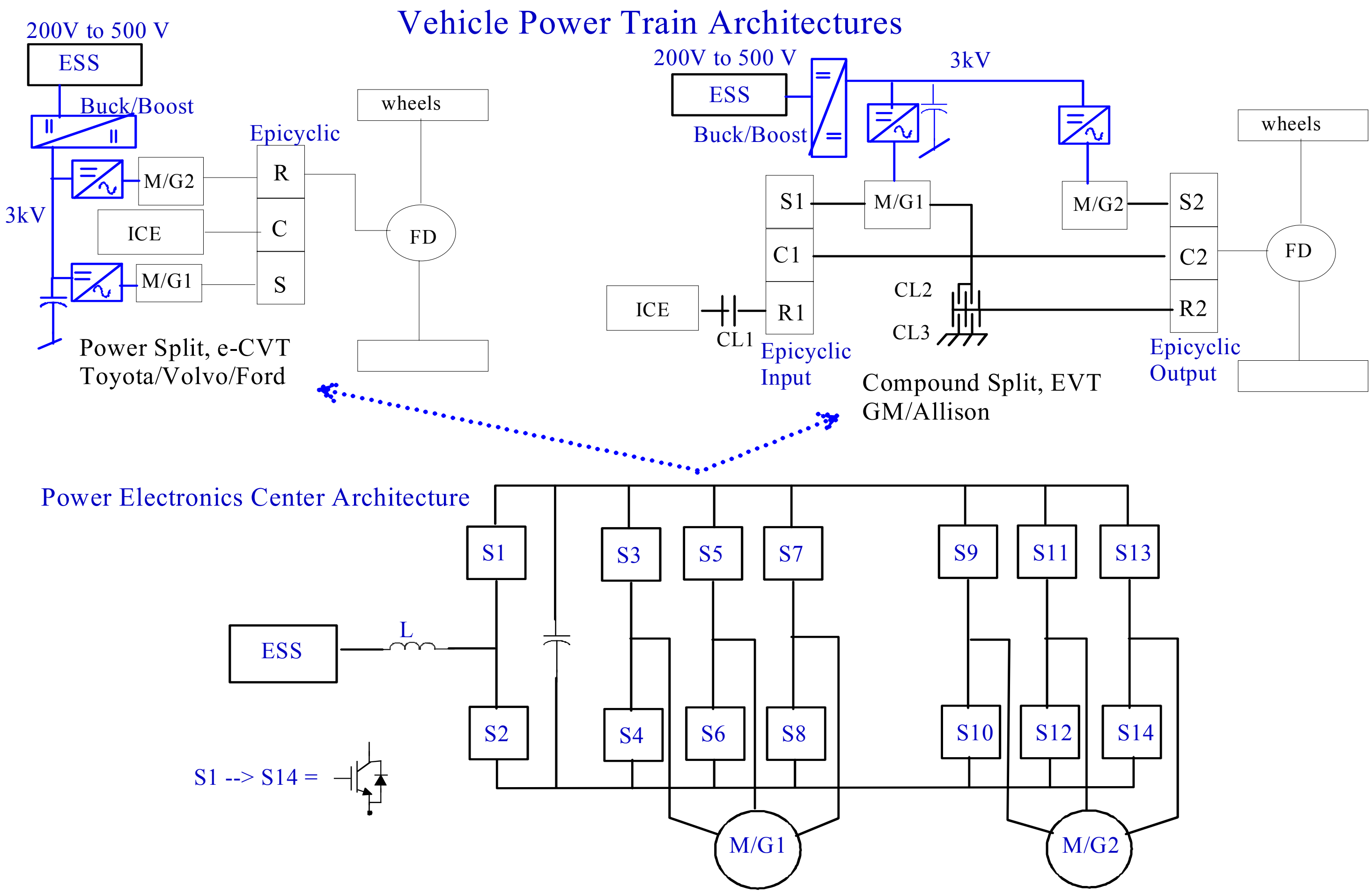


Full Hybrid Systems Benefit from Higher Voltage

- Advantages of higher voltage:
  - Toyota Motor Co has already breached this obstacle in THS-II with 201.6V NiMH battery ESS and 25 kW dc-dc converter to 500V → 550 V (Prius sport)
  - TMC Highlander SUV will use 650V floating bus architecture
  - Bus voltages of 800 V to 900 V routinely used in Batt-EV land speed record attempt vehicles.
- Benefits are
  - Reduced currents → less semiconductor content
  - Lower thermal burden
  - More compact packaging
  - Less material usage
  - Lower cost

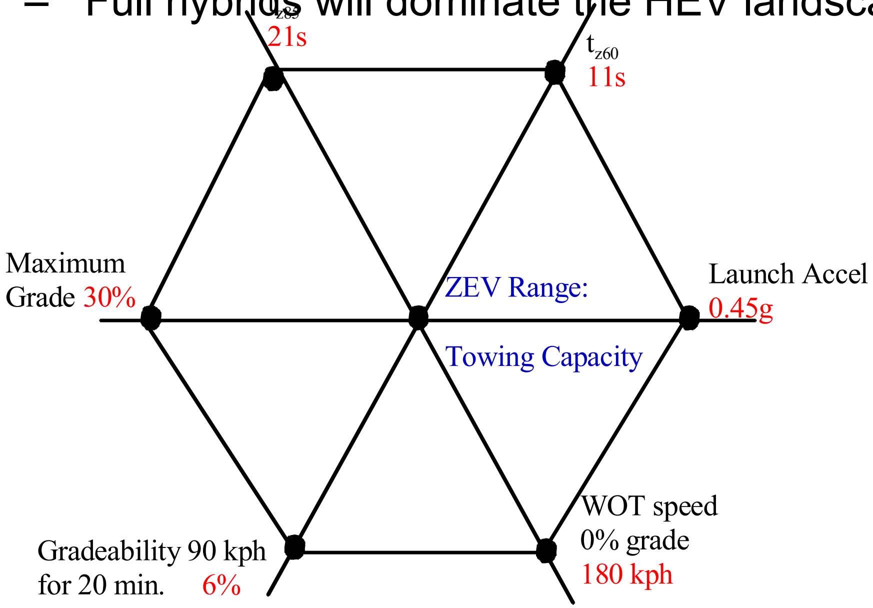
Power Split Systems Today are Silicon Rich Environments

- Dual M/G eCVT's require 2 full rated 4-quadrant ac drives



Vehicle Performance Targets

- Hybrid vehicles today must deliver the performance customers expect.
  - All OEM's are expected to offer micro-hybrids (14V & 42V)
  - Mild hybrids will retain a respectable presence (GM Silverado & Saturn Vue, Toyota Crown, Honda Civic, Accord)
  - Full hybrids will dominate the HEV landscape



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.

<u>Acceleration benchmarks:</u>

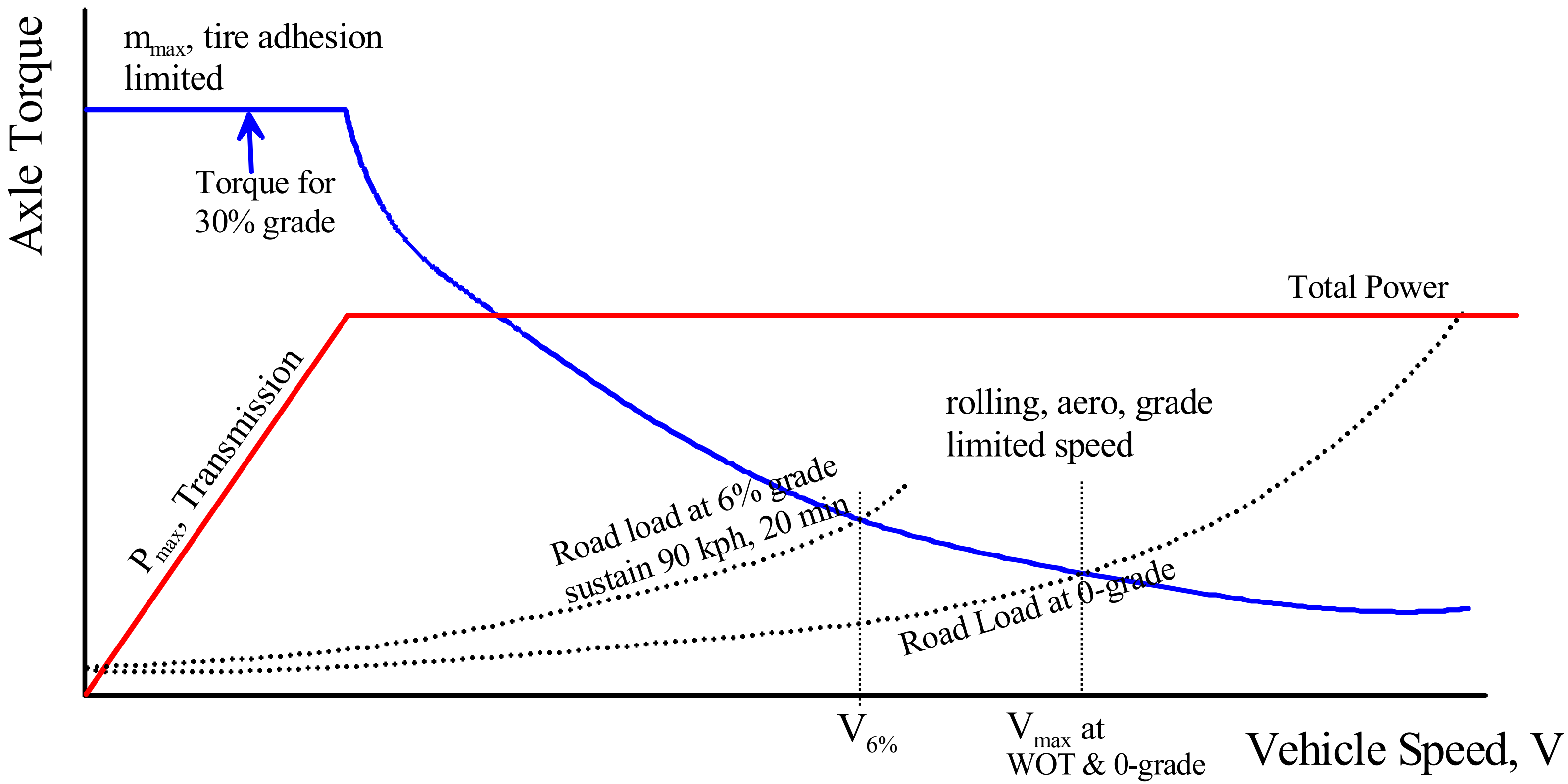
Prius I, 0→60 mph time = 12.5s

Prius II, 0→60 mph time = 10.5s

Hybrid Escape, 0→60 mph time = 11.2s

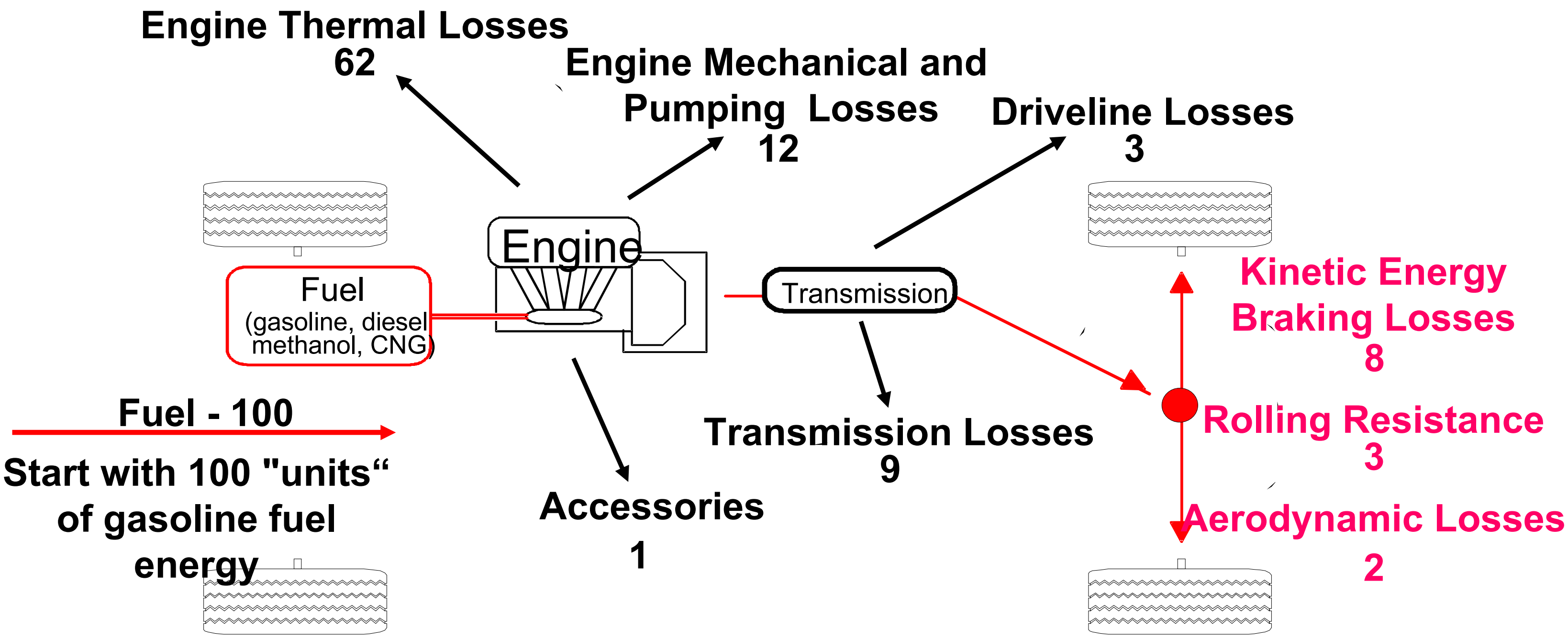
Vehicle Performance Targets

- Applying the vehicle performance targets



Energy Flows in a Passenger Vehicle

- 100 units of input energy result in only 13 units of useable propulsion energy.
  - To overcome rolling, aerodynamic drag, and acceleration/braking forces.



Source: T. Kinney, Ford Motor Company

Gasoline-Electric Hybrids

- Hybridization requires electrified ancillaries
- Electric assist power steering, EPS
- Electronically controlled brakes
- The question of 42V

Supporting Subsystems

- Chassis systems: electric assist power steering, EPS, and electronically controlled brakes, ECB, also, EHB, EMB

Power Train Systems	Chassis Systems
Belt Alternator-Starter, BAS	Electronic Stability Program, ESP
Flywheel Alternator-Starter, FAS	Electric Power Steering, EPS
Electromechanical Valve Actuator, EVA	Electrohydraulic Braking, EHB
Electric Turbo, E-Boost	Electromechanical Braking, EMB
Electric Four Wheel Drive, E4	Electric Active Suspension, EAS
In Hub Wheel Motors, etc	

- Unlikely that any OEM will opt for a high voltage EPS system. 42V auxiliary systems are already in production. GM has been the pace setter in this and Toyota introduces 42V EPS on RX & Highlander in 2005.1

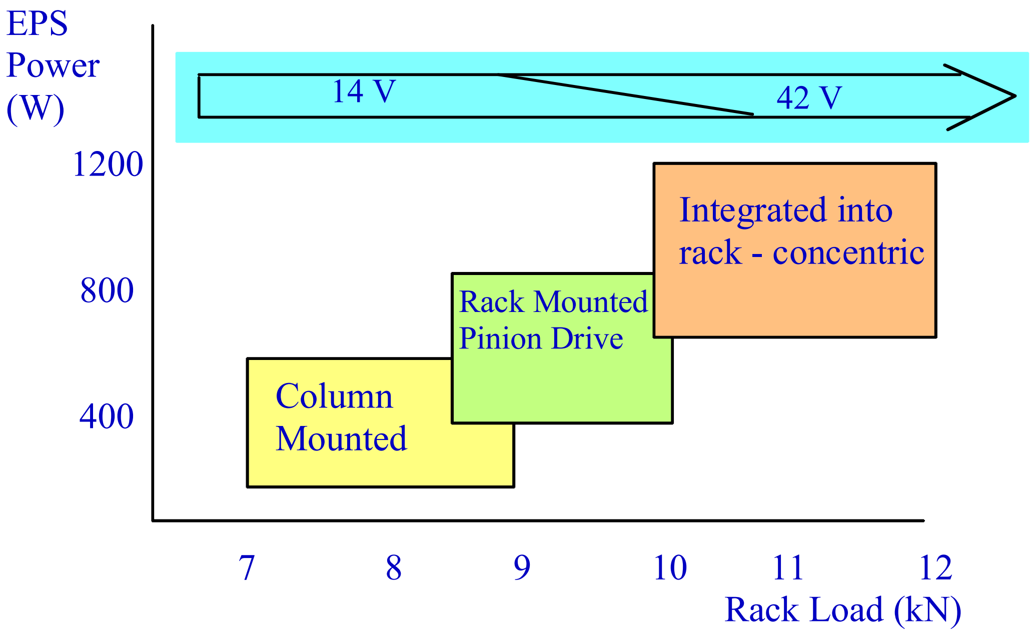
HEV Supporting Subsystems: EPS as Example

- Electric Power Steering, EPS, is a valid example of the case for a 42V auxiliary system
- Some market estimates project EPS at 20% growth for the next 3 years. This would make EPS an RPO – req'd production option, by 2010.
  - Tech. rationale: higher eff, dynamic assistance, speed sensitive steering assist, and safety
  - Business case: EPS provides ~1.5% FE at cost savings of 7 Euro/vehicle (@1.29$/Euro => $9/veh.)

Source: N. Bianchi, S. Bolognani, "Fractional-slot PM motors for electric Power steering systems," Int. J. Vehicle Autonomous Systems, Vol. 3, Nos. 3/4, 2004

HEV Supporting Subsystems: EPS as Example

- EPS production systems operate at either 14V, or from 42V when available.
  - At steering rack loads above 9kN to 11kN a higher voltage EPS is required (at 14V EPS loads trend from 85A to 130A demand)
  - It is possible to operate EPS from the Traction batt., i.e., e-A/C, but Toyota RX uses 288V to 42V converter in production SUV



HEV Supporting Subsystems: EPS as Example

- EPS systems in the marketplace today
  - GM Silverado/Sierra: 42V FAS, E/HPS at 42V
  - Toyota Crown mild hybrid: 42V B-ISG drives steering
  - Honda Civic/Accord hybrid: 144V, EPS at 12V
  - Toyota Prius-I eCVT hybrid: 288V, E/HPS at 12V
  - Toyota Prius-II eCVT hybrid: 201.6V, EPS at 12V
  - Ford Escape hybrid: 300V, EPS at 12V
  - Lexus RX400H & Highlander hybrids: 288V, EPS at 42V via HV dc-dc converter
- With the exception of Ford Escape, SUV's and P/U's use 42V EPS system

Electric Assist Steering Types

- At rack loads between 9 kN and 11 kN a transition to 42V is demanded:
  - For overall efficiency
  - For responsiveness

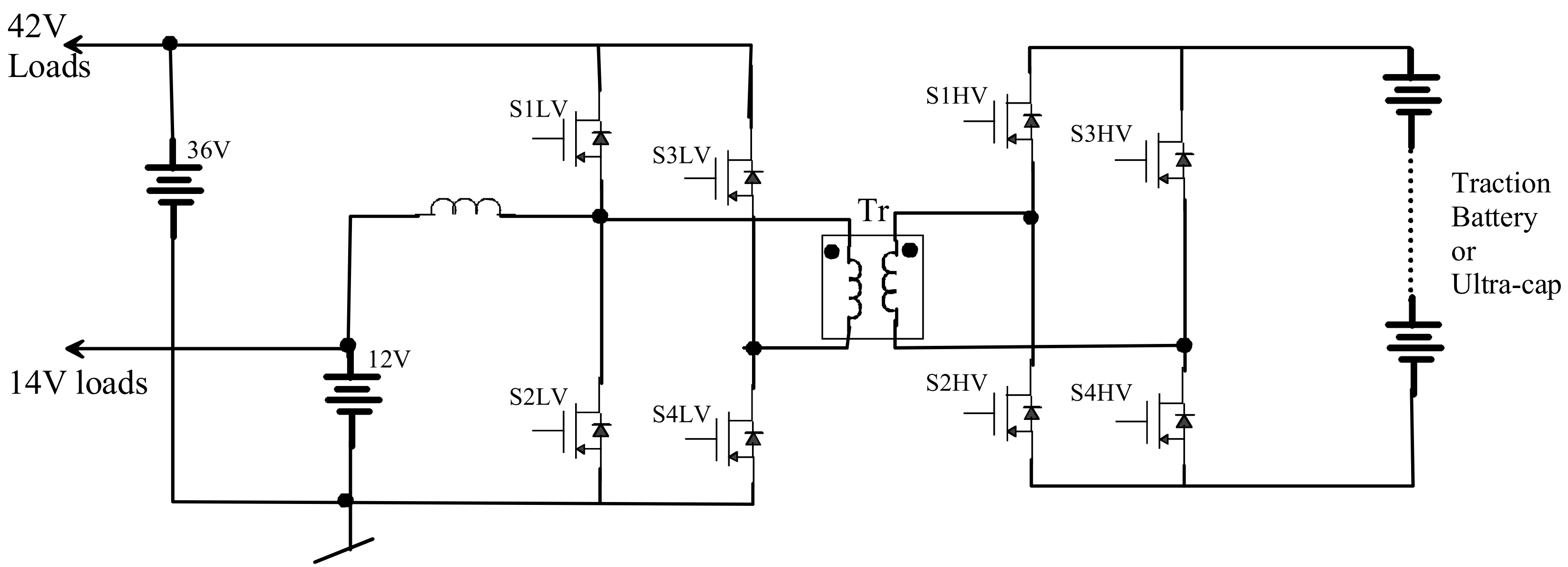
Column mounted

Rack mounted – integrated & concentric

Rack mounted - pinion

EDS Options for 42V Auxiliary Supply: dc-dc

- Dc-dc converter implementation
  - High voltage traction battery to 42V power for EPS
  - This is the Lexus SUV hybrid approach

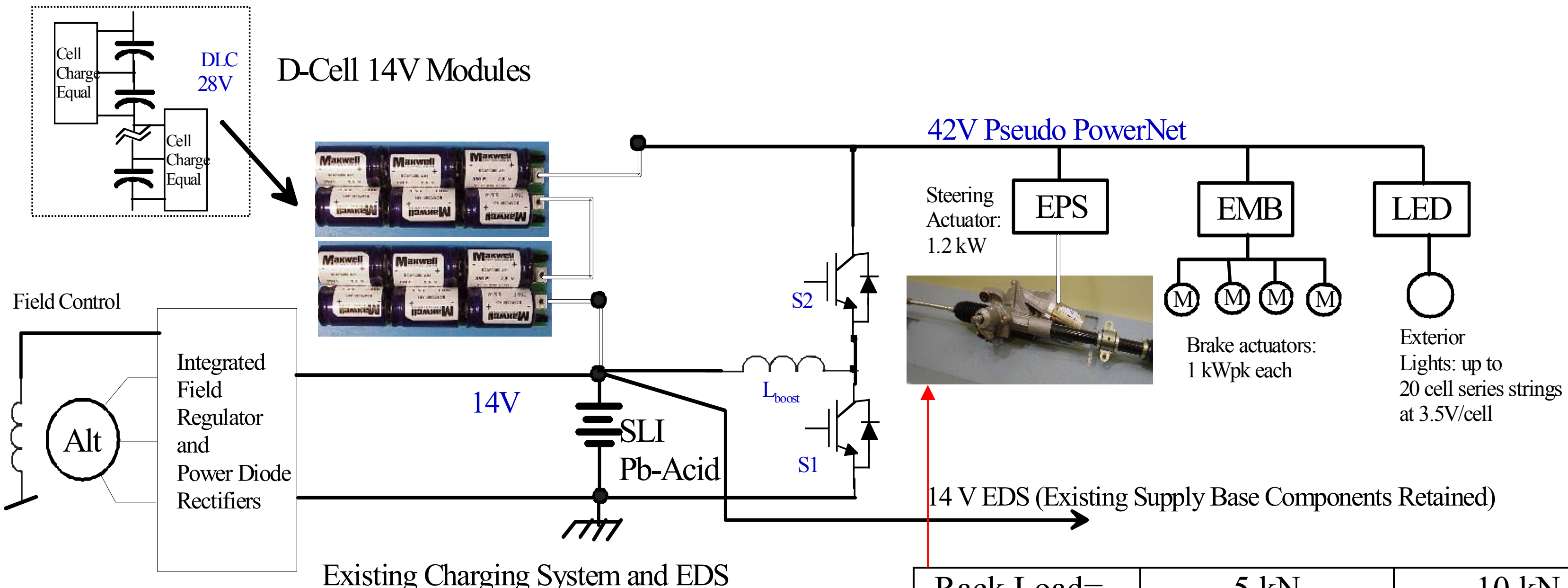


EDS Options for 42V Auxiliary Supply: dc-dc

- The bidirectional dc-dc converter for supporting an auxiliary 42V bus is very attractive:
  - No need for an additional 42V VRLA battery: cost and weight avoidance
  - Vehicle regen energy may be used to advantage in reduction of hotel loads
- Without an ultracapacitor energy storage module on the 42V auxiliary PowerNet the dc-dc converter must:
  - Deliver full EPS demand without delay
  - Have sufficient dynamic response to divert 14V system charging current to EPS on demand
  - And, insure that no voltage bounce occurs upon EPS load shedding
- With an ultracapacitor on the 42V auxiliary bus the dc-dc converter power demands are more benign.

EDS Options: 42V Pseudo-PowerNet Concept

- A 28V ultracapacitor module (pair of BMOD0350-15EA modules comprised of 6 each, D cell® units of 350F, 2.5V rating)



Rack Load=	5 kN		10 kN	
EDS Voltage	14V	42V	14V	42V
EPS Current	55A	18A	114A	25A
Harness loss	15W	1.3W	91W	7.6W
Motor Power	222W		475W	
Relative Size	1.0	0.95	3.25	2.4

Source: J.M.Miller, M. Everett, "Ultracapacitor Augmentation Of the Vehicle 14V Electrical System to Support Auxiliary 42V Subsystems," The 14th International Seminar on Double Layer Capacitors and Hybrid Energy Storage Devices, Embassy Suites Deerfield Beach Resort, Deerfield Beach, FL, Dec. 6-8, 2004

EDS Options: 42V Pseudo-PowerNet Concept

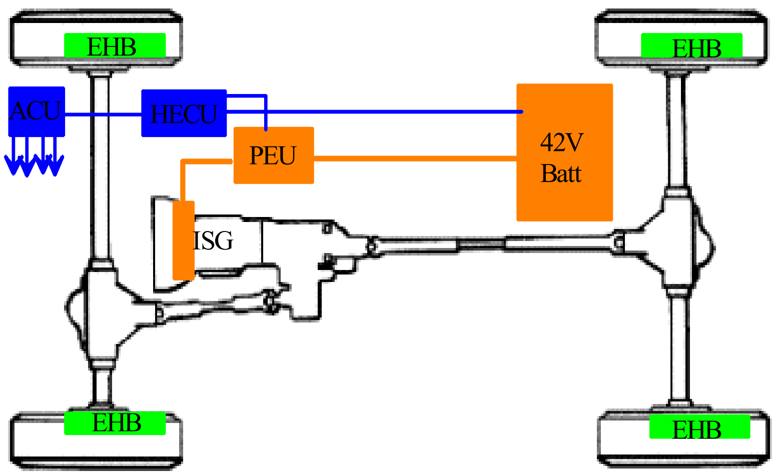
- Assume that the vehicle charging system is designed for net charge so that the energy to recharge the ultra-capacitor is derived from the alternator not from the battery. Then the relative burdens are:

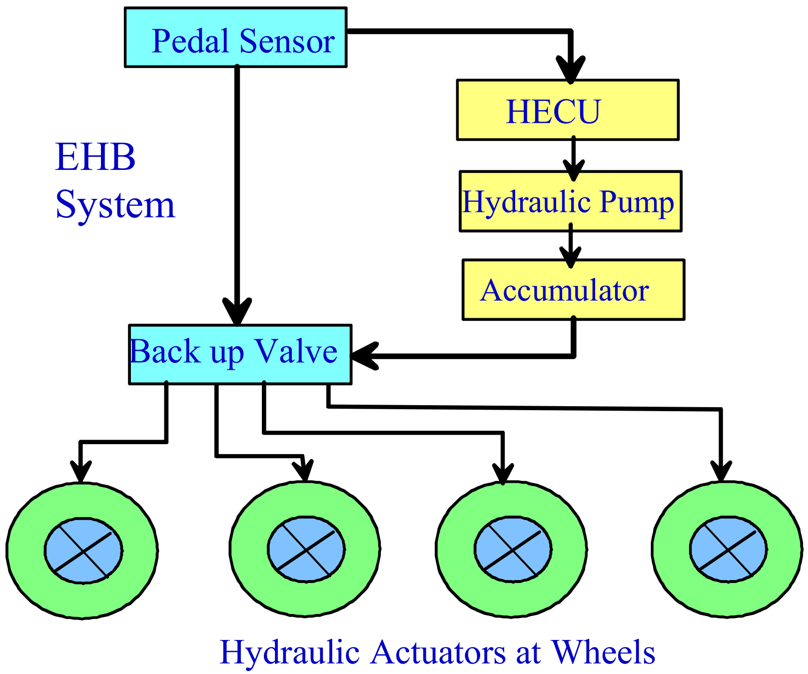
	Energy Storage System		
Energy	Units	VRLA (14V only)	VRLA+DLC(14/42V)
W_{dlc}	kJ	0	6.8
W_{bat}	kJ	11.6	4.7
W_{load}	kJ	11.6	11.6
W_{bat}/W_{load}	#	1.0	0.40

- With the Pseudo 42V PowerNet configuration the energy delivered by the VRLA battery is reduced to 40% compared to the nominal 14V case without use of a DLC.
  - Battery cycling is reduced
  - Battery warranty is improved

Chassis Systems: Electro-Hyd Braking, EHB

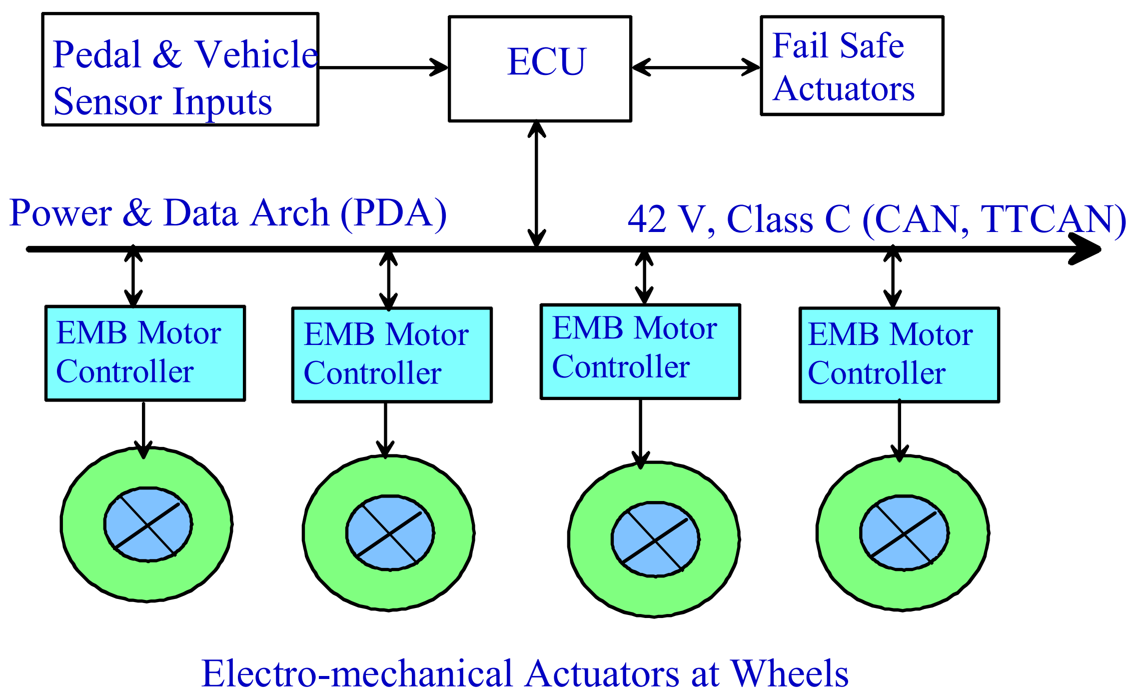
- There is no real driver for 42 V in EHB systems.
- However, in electro-mechanical brake systems, EMB, there is a need for 42 V plus back up power supply.
  - With novel electric actuator & brake caliper 12V system is possible





Future Electric Brake Systems: EMB

- Electro-mechanical brakes may have 1 kW demand per actuator (wheel). This is 40 A at 30 V on 42V PowerNet.
  - Ultra capacitor backup support may also be required (e.g., Prius-II)

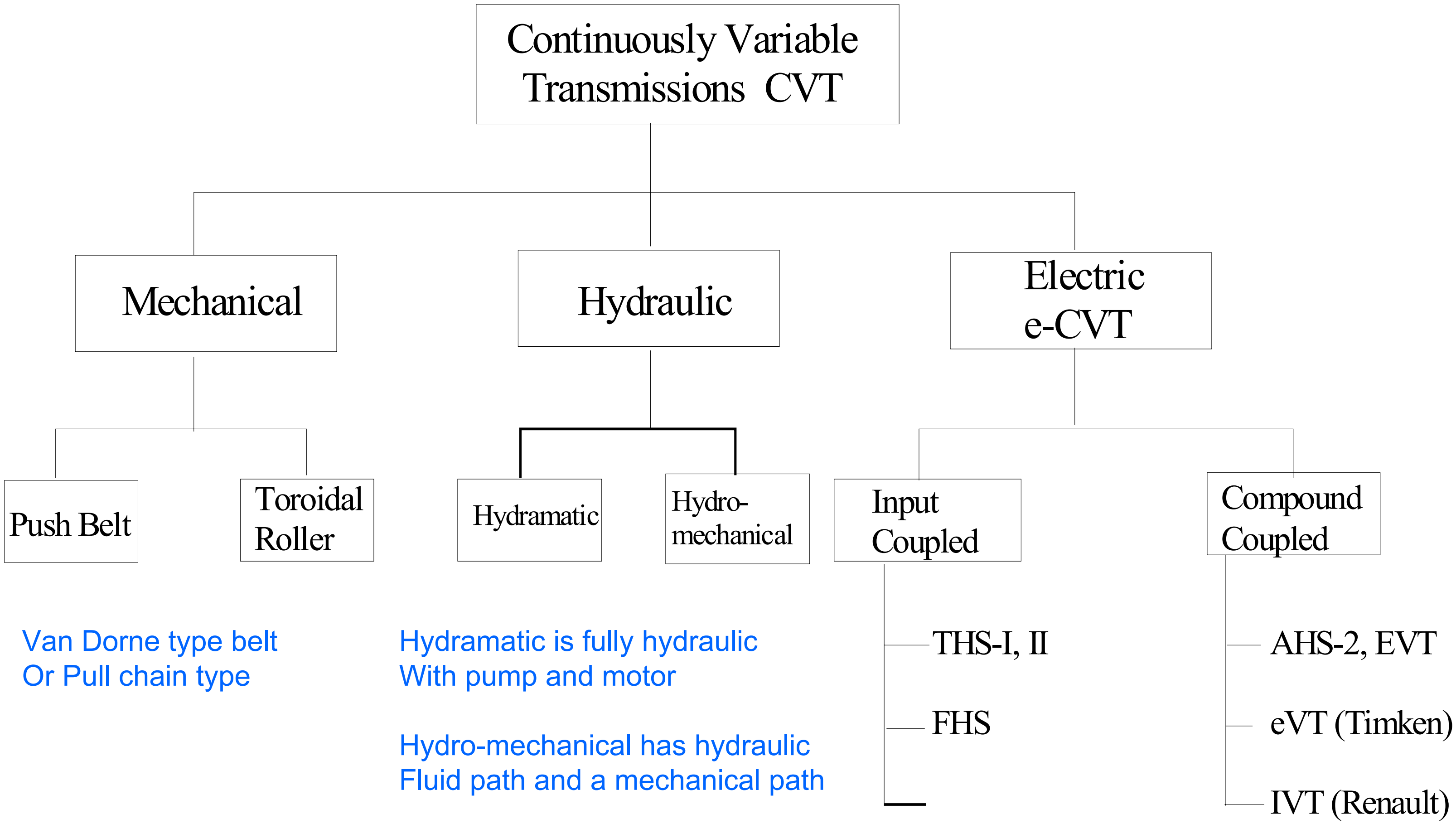


EMB will need 42V Electrical power

Gasoline-Electric Hybrids

- The electronic Continuously Variable Transmission – eCVT
- Power split device
- Introducing input and compound split eCVT's

What are Power Split e-CVT's?



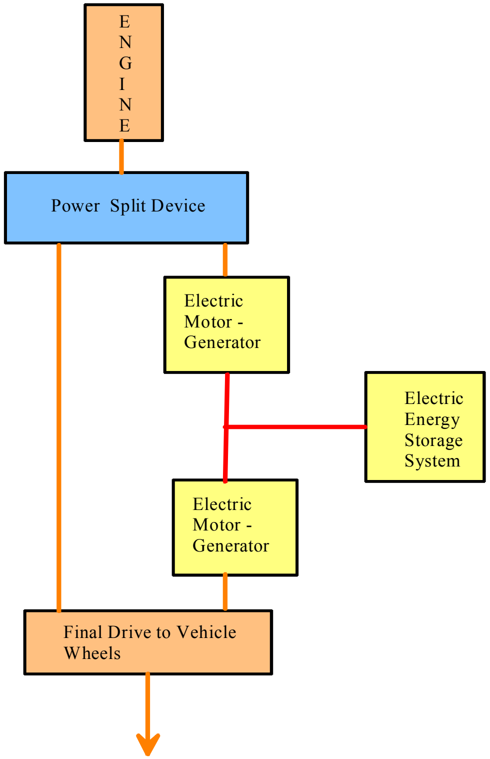
Stepless transmissions

Two Types of Power Split e-CVT's:

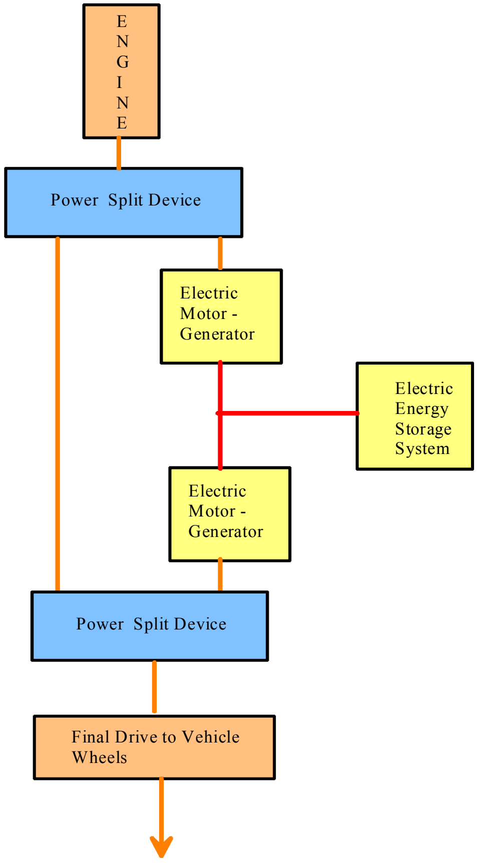
- Input coupled (split):
  - Single planetary
  - No clutches
  - Dual electric machines

- Compound coupled
  - Dual planetary
  - Two disconnect clutches
  - Dual electric machines

- Both systems have a mechanical only power path and an electric only power path



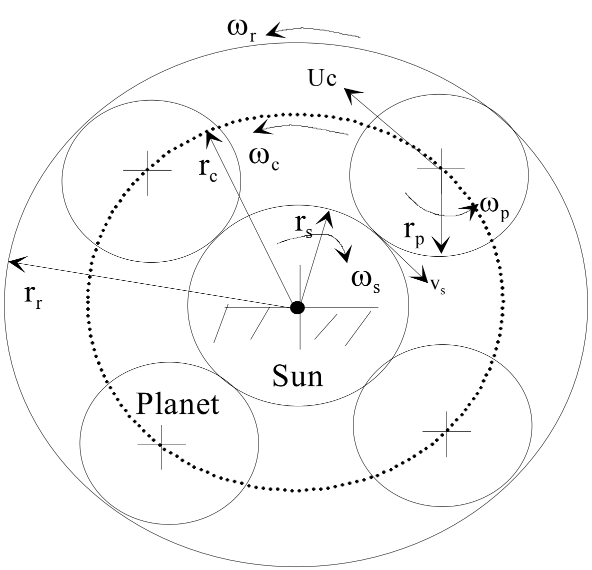
Input Split



Compound Split

What is the power split device?

- Planetary gear set:
  - Speed summation
  - Torque partition



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.

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

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

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

$$m_s - J_s\dot{\omega}_s - \frac{1}{k}(m_r - J_r\dot{\omega}_r) = 0$$

and

$$m_c - J_c\dot{\omega}_c + \frac{k+1}{k}(m_r - J_r\dot{\omega}_r) = 0$$

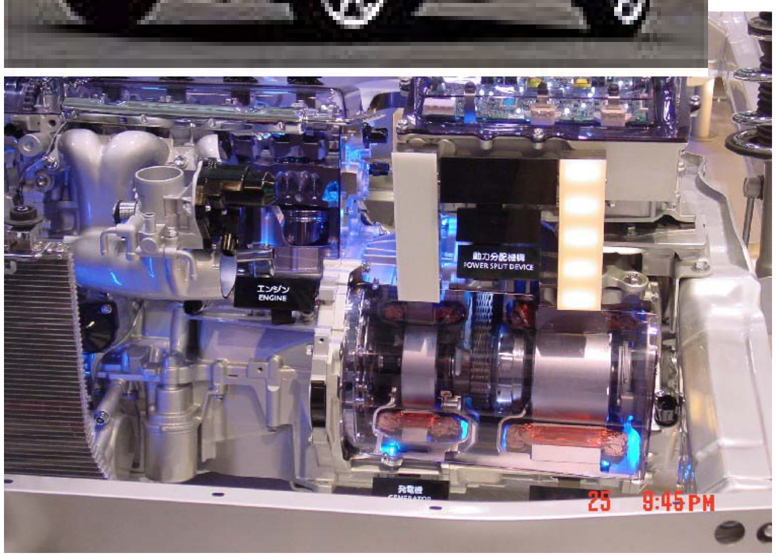
Power Split Market Introductions

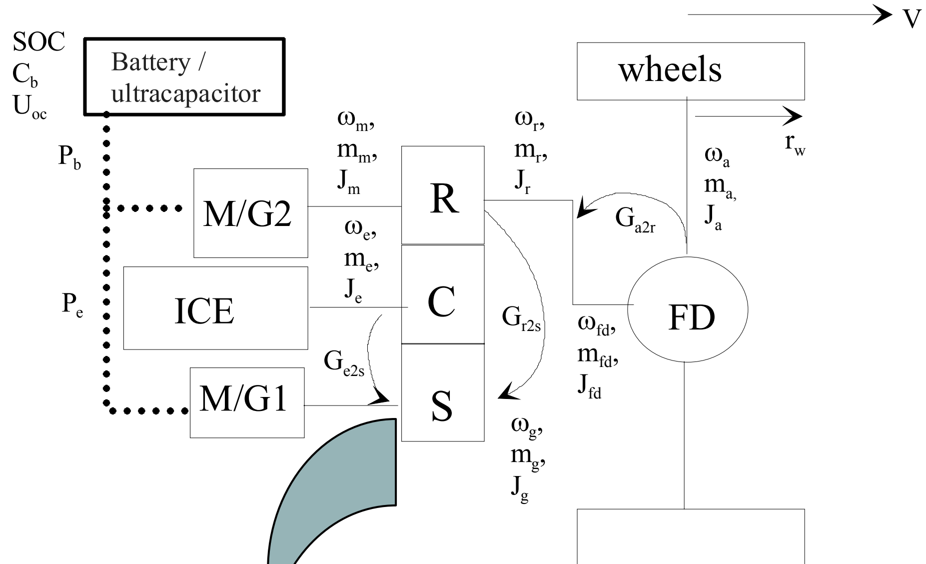
- The major automotive OEM's will introduce both input split and compound split full hybrids into the market

Introduction to N.A.

Date	Company	Hybrid Brand	Vehicle Segment	Engine Power, kWpk	Power Split Type	M/G1 rating, kWpk	M/G2 rating, kWpk	System voltage, V	Electric Fraction, Ef
2000	Toyota	Prius-I	car	53	I	10	30	288	0.36
2004	Toyota	Prius-II	car	57	I	30	50	500	0.47
2005	Toyota	RX400H	Lt-SUV	100	I	35	60	500	0.38
2005	Toyota	Highlander	F-SUV	100	I	35	60	650	0.38
2004	Ford	Escape	Lt-SUV	98	I	45	70	300	0.42
2006	Mercury	Mariner	Lt-SUV	98	I	45	70	300	0.42
2007	Mazda	Tribute	Lt-SUV	98	I	45	70	300	0.42
2008	Ford	Fusion	Lt-SUV	98	I	45	70	300	0.42
2007	GM-DCX	Tahoe	F-SUV	164	C	60	60	300	0.27
2007	GM-DCX	Yukon	F-SUV	164	C	60	60	300	0.27
2008	GM-DCX	Durango	F-SUV	164	C	60	60	300	0.27
2008	GM-DCX	Mercedes	F-SUV	164	C	60	60	300	0.27
2006	Nissan	Altima	Car	57	I	30	50	500	0.47
?	FAW	THS-II	car	57	I	30	50	500	0.47
2007	Porsche	Cayenne	Lt-SUV						

Toyota's THS-II Input Split System

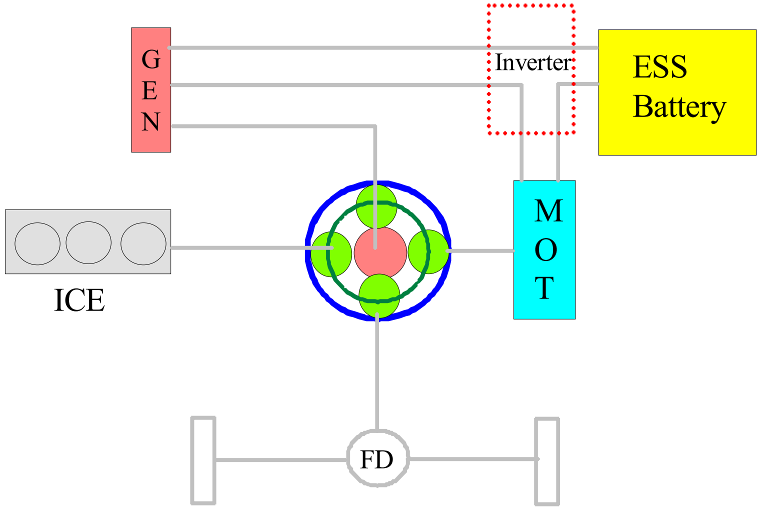




The Power Split Device

THS Propulsion System in Batt-EV Mode

- The maximum Batt-EV mode speed is limited by the max speed of M/G2 – the traction motor (6500 rpm in THS-II)
  - Ne = 0 engine is OFF
  - Ng = 6500 rpm maximum



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

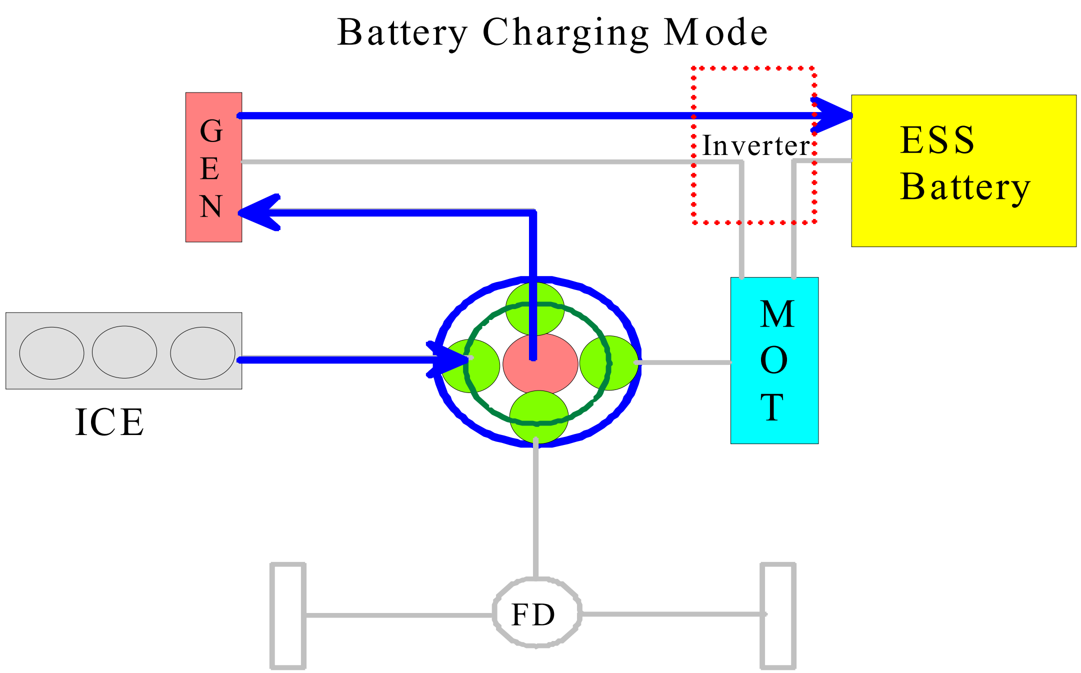
$$V_{ci} = \frac{680.6(0.292)}{2.6(3.95)} = 19.35 m/s$$

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

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

THS Propulsion System in Batt-Charge Mode

- Battery charge mode
  - Vehicle parked or during idle → M/G2 speed =0 so the maximum torque of the generator, M/G1, reaction is limited by engine torque.



$$m_g = \frac{1}{k+1} m_e$$

$$m_g = \frac{1}{3.6}(110) = 30Nm$$

$$\omega_{g\_maz} = 1047 r/s$$

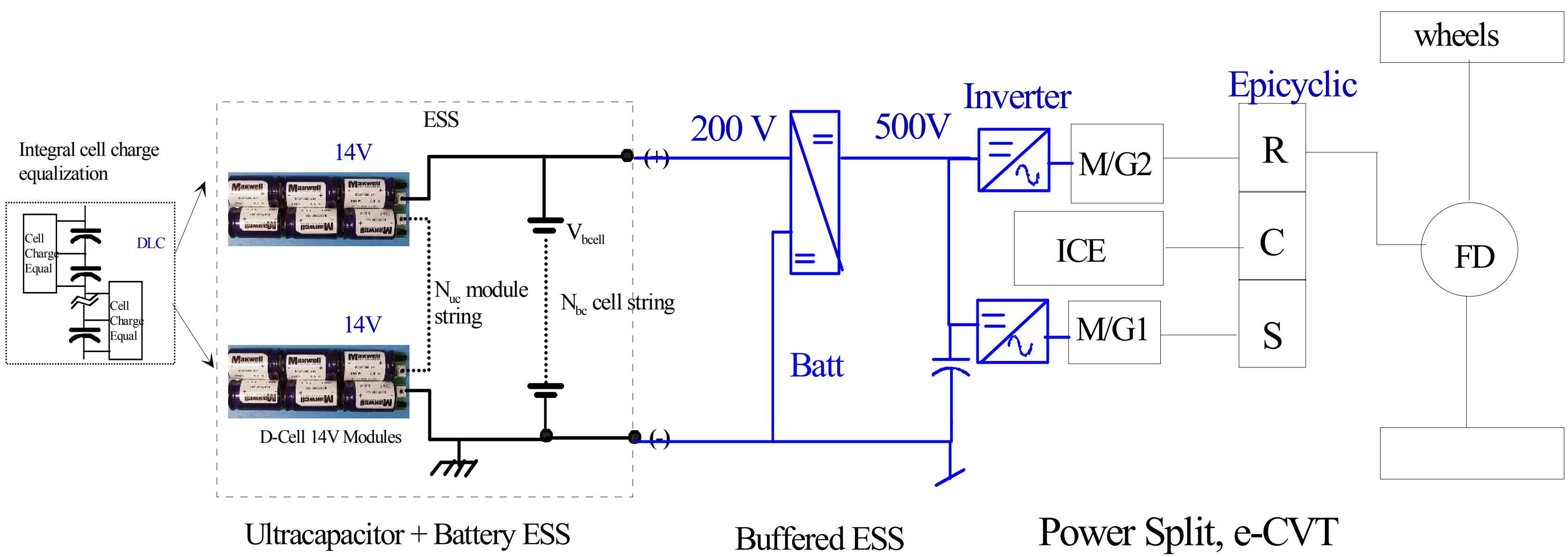
$$P_g = m_g \omega_g = 30kW$$

$$\omega_e = \frac{1}{k+1}\omega_g = \frac{1047}{3.6} = 290.8 r/s$$

$$n_e = 2{,}777 rpm$$

Input Split System with Ultra-capacitor Power Cache

- The ultracapacitor provides high pulse power during power split transient events
  - Reduces battery cycling
  - Reduces battery high C-rate events



Gasoline-Electric Hybrids

- Energy storage systems: a critical technology in HEV propulsion
- Is the ultra capacitor a viable ESS component for serial production HEV's
- Sizing the ESS

Why Ultra-capacitors in Hybrid Powertrains?

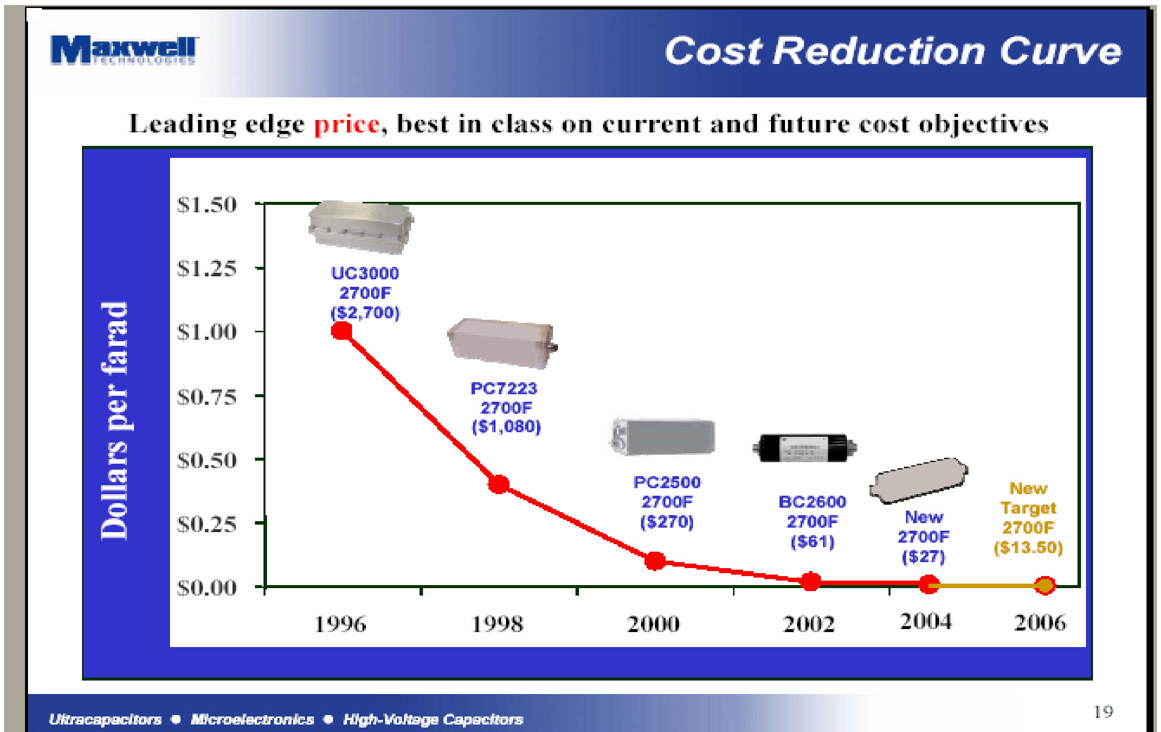
- Hybrid propulsion systems can be broadly classified as power assist or dual mode:

Power Assist	Dual Mode
Low storage capacity	High storage capacity (energy)
High transient power	Moderate transient power
No electric only range	Electric only range is capacity dependent

- Ultra-capacitors can be the only energy storage component in a power assist hybrid.
- Or, used in combination with a storage battery in a dual mode hybrid

ESS Technologies: Ultracapacitors

- Ultracapacitors are becoming a viable ESS technology
- Maxwell and NessCap are among leaders in DLC's

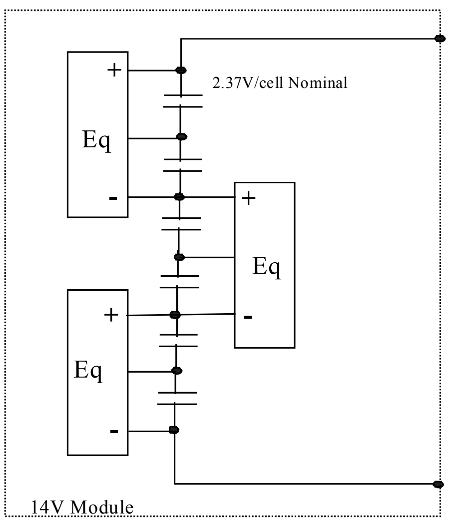


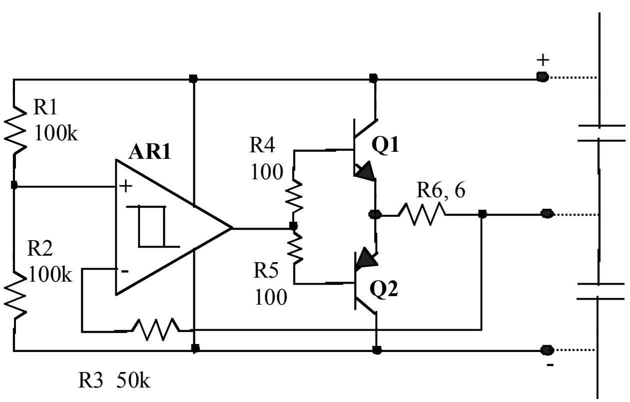
Above, 2700F BoostCAP & New D-Cell BoostCAP.
Below, D-Cell 15V 58 F module

BMOD0350-15EA

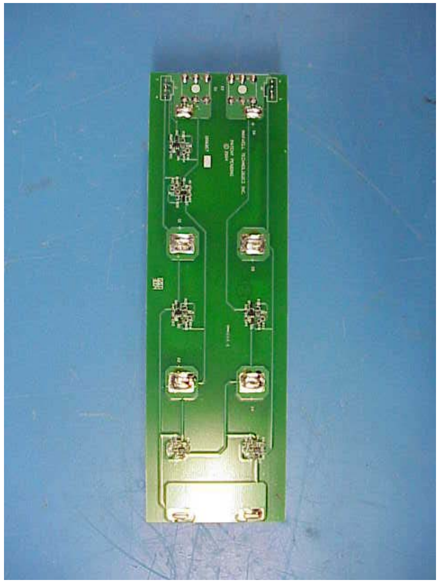
ESS Technologies: Ultracapacitors

- For long term durability (quality and reliability) the distributed module must charge equalize its constituent cells:
  - to prevent voltage overstress of any single cell and
  - to provide a margin in the event of network overvoltage
- The D-Cell 14V Module is equipped with such charge equalization on the PWB (patent pending).





Non Dissipative Cell Equalizer



ESS Technologies: Ultracapacitors

Comments on efficiency

Matched load efficiency: RL = ESR

$$P_{ML} = \frac{V_{c0}^2}{4ESR_{ac}}$$

D-Cell Module rating

Nc = 6 cells in series:

ESRmod = NcESRcell, Cmod = Ccell/Nc

–

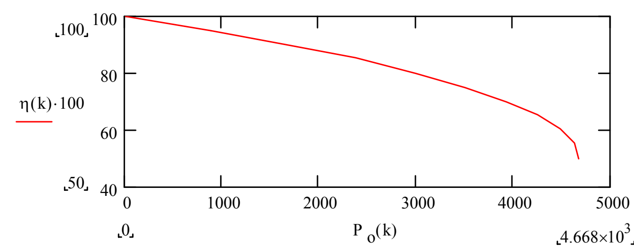
Attribute	Value	Units	Comments
Capacity	350	F	Nameplate +30/-10%
Mass	54	g	Including case
Volume	51	cc	Including case
Rated Voltage	2.5	V	Nominal
Cell ESR	3.2	mΩ	For energy cell
Specific pulse power	9.0	kW/kg	At matched load
Specific energy	5.66	Wh/kg	Nameplate rating

Module power, P_o, as a function of efficiency

$$P_0 = \frac{\eta(1-\eta)V_{c0}^2}{ESR_{ac}}$$

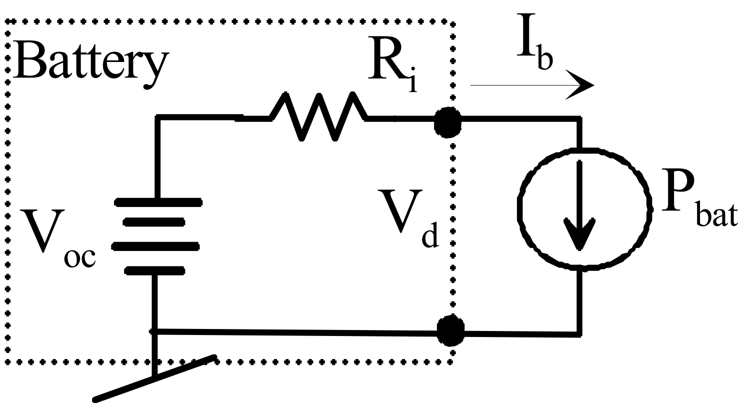
Efficiency given operating Power, P_o, and P_{ML}

$$\eta = \frac{1}{2} + \frac{1}{2}\sqrt{1 - \frac{P_o}{P_{ML}}}$$



Energy Storage System Sizing

- Model must account for ESS SOC variation



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

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

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

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

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

$$Find\_that:$$

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

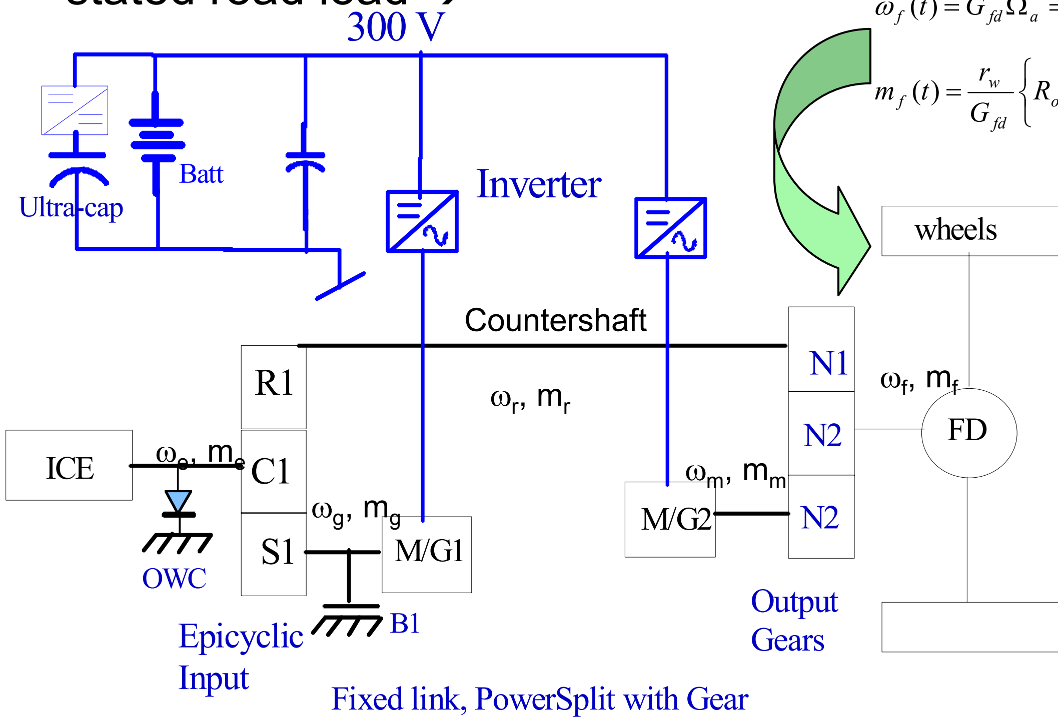
Define C_{br} = battery rated capacity, Ah
Noting that: $R_i C_{br} = \tau_{bat}$

Energy Storage System Sizing

- Mechanical System Modeling
- Size ESS Energy for range under stated road load →

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

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



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

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

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

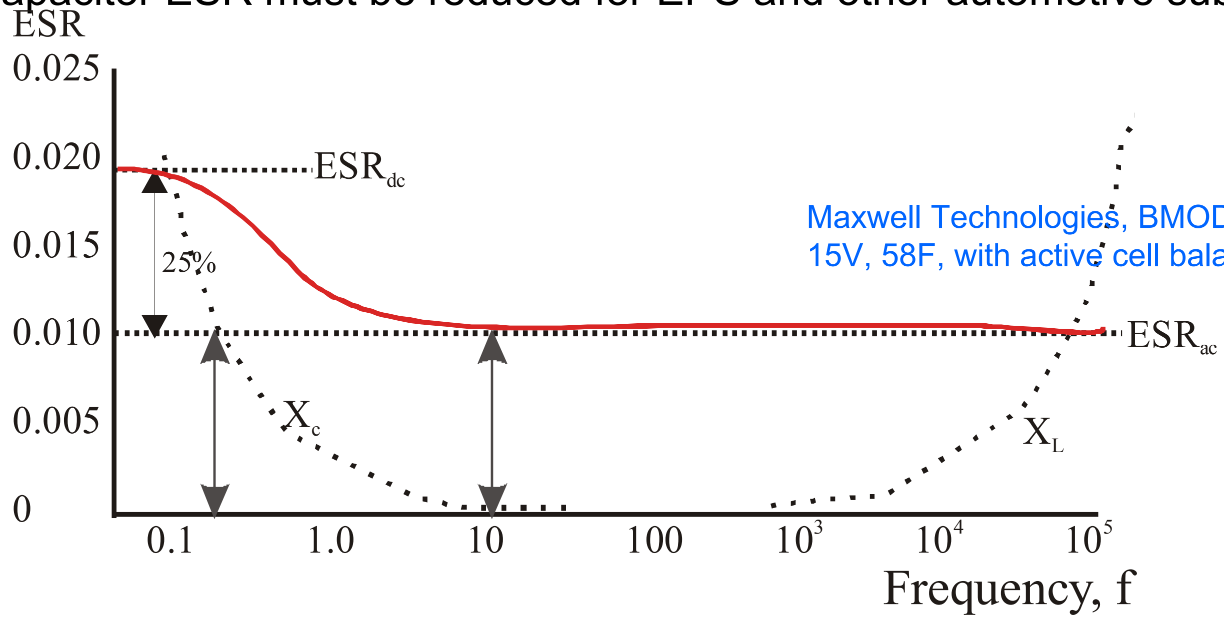
$$\frac{k+1}{k^2}J_r\dot{\omega}_g + \left(J_e - \left(\frac{k+1}{k}\right)^2 J_r\right)\dot{\omega}_e = m_e + \frac{k+1}{k}m_r$$

$$noting\_that:$$

$$m_r = m_m = m_f$$

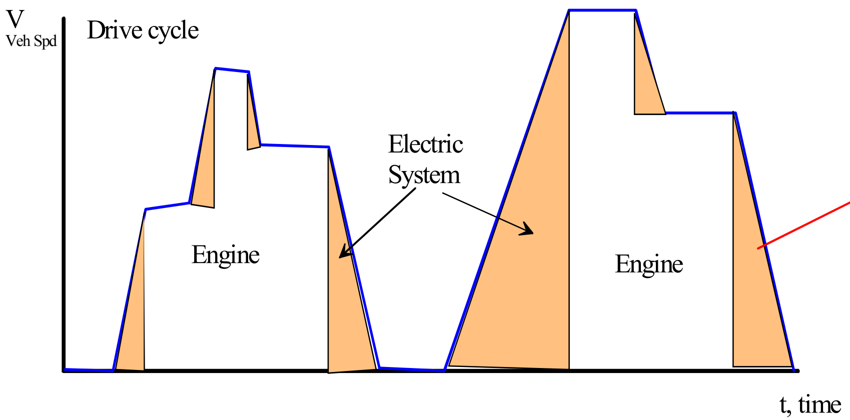
The Challenge of Applying Ultracapacitors

- Automotive chassis and power train systems are very cost sensitive. Today, EPS is the most viable chassis system that requires 42V power.
- OEM's are unlikely to introduce additional VRLA packs to support an auxiliary 42V bus. Converters, YES.
- Ultracapacitor modules such as Maxwell BMOD0350-15EA with internal active balancing are amenable to 28V and higher strings. As costs reduce to 1/2 cent/F and lower the DLC will meet automotive targets provided its main parameters maintain uniform tolerance. Toyota is using DLC's in ECB at cost of 2 cent/F.
- Ultracapacitor ESR must be reduced for EPS and other automotive subsystems.



ESS Sizing and Pulse Power Requirement

- Power split transmissions have low (or minimal) compliance in their drivelines
  - Road shock events are therefore transmitted directly to the inertial elements of the powertrain



$$a = \frac{r_w}{g_{a2r}} \dot{\omega}_m$$

$$\dot{\omega}_m = \frac{m_{mo} + m_{eA} - \dfrac{r_w g M_{vP} R_o}{g_{a2r}}}{k^2 (J_g + J_s) - \dfrac{k}{k+1}\left\{J_{mot} + J_r + J_{fd} + 2g_{r2s}^2 J_g^{'}\right\} + \dfrac{r_w^2 M_{vp}}{g_{a2r}}}$$

  - High ESS pulse power is therefore demanded for high m/J

$$C_p = \frac{P_b}{0.69 V_{boc} C_b}$$

ESS Technologies: Advanced Batteries

- Energy storage systems are optimized for energy or power.

	Battery-EV					Hybrid Vehicle					Temp
	Energy	Power	Cycles	P/E	Energy-life	Energy	Power	Cycles	P/E	Energy-Life	Range
Type	Wh/kg	W/kg	# @80% DOD	#	#Wh/kg	Wh/kg	W/kg	# @80% DOD	#	#Wh/kg	^{o}C
VRLA	35	250	400	7	11,200	25	80	300	3.2	6,000	-30, +70
TMF						30	800	?	27	?	0, +60
NiMH	70	180	1200	2.6	67,200	40	1000	5500	25	176,000	0, +40
Li-Ion	90	220	600	2.4	43,200	65	1500	2500	23	130,000	0,+35
Li-Pol	140	300	800	2.1	89,600						0,+40
EDLC						4	9000	500k	2250	1,600,000	-35, +65

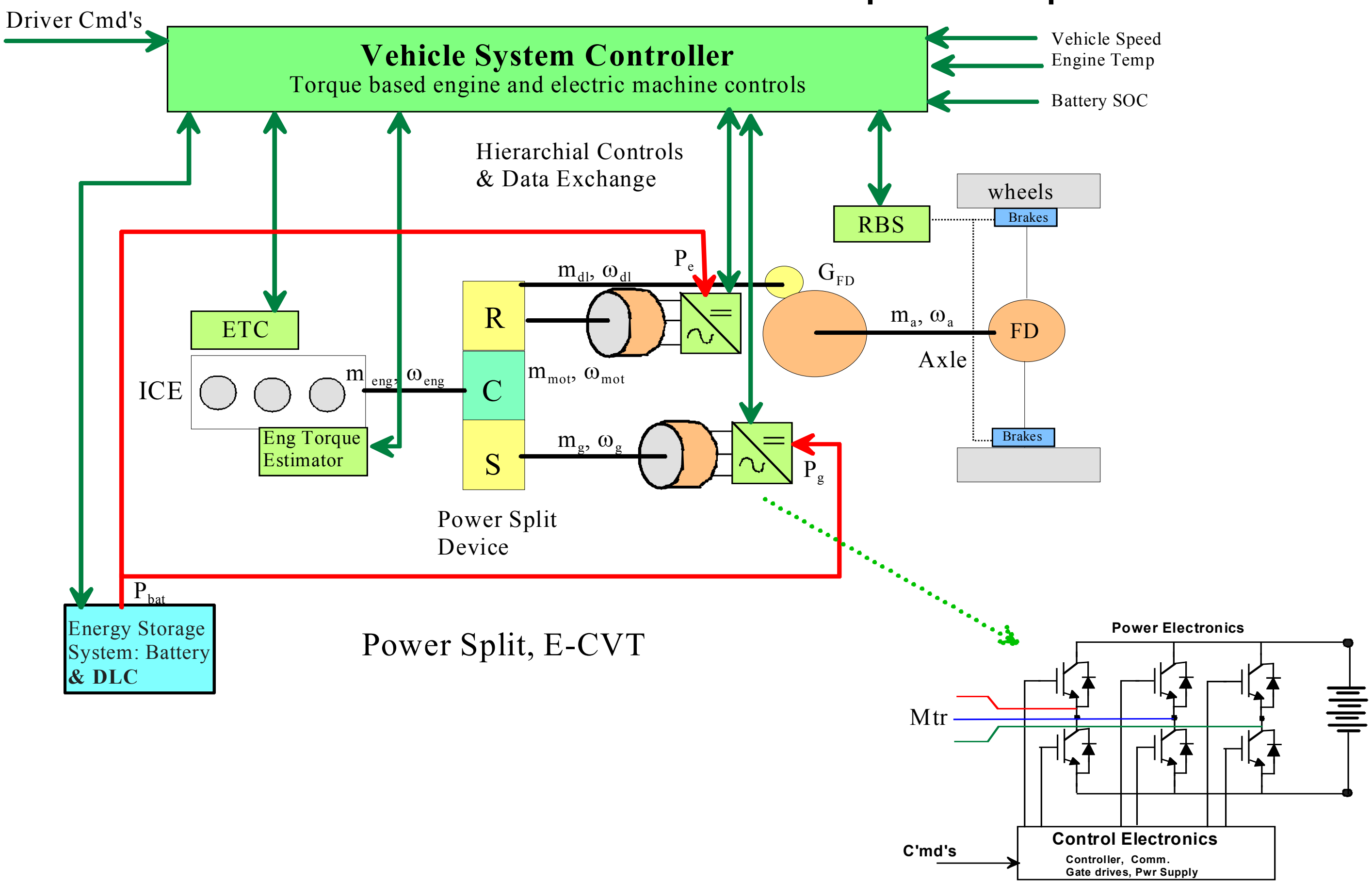
- Energy batteries are designed for deep discharge. Power batteries for shallow discharge of <4% (HV cycle data is taken from log-log plot)

Gasoline-Electric Hybrids

- Input split eCVT power flow basics
- Discussion of input split dynamics

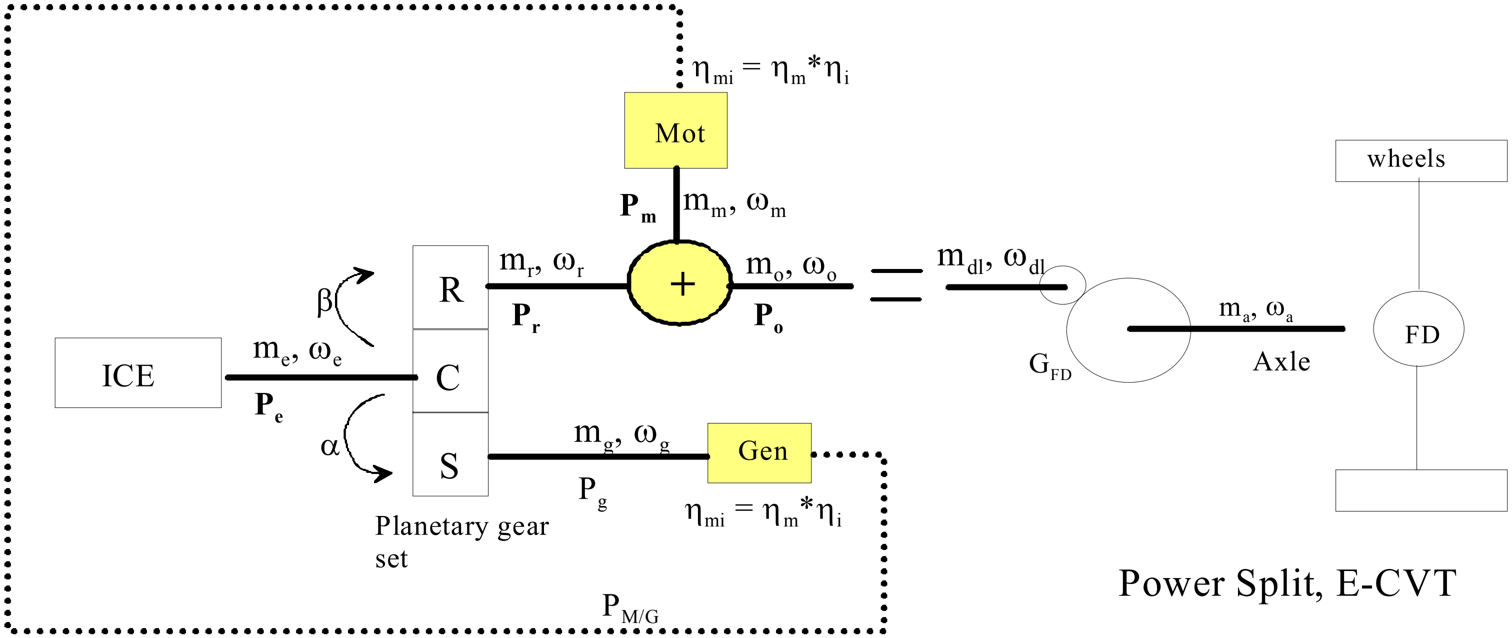
Power Flow Basics

- The vehicle system controller manages the torque arbitration between the ICE and the dual ac drives of power split



Input Split: Power Flow Basics

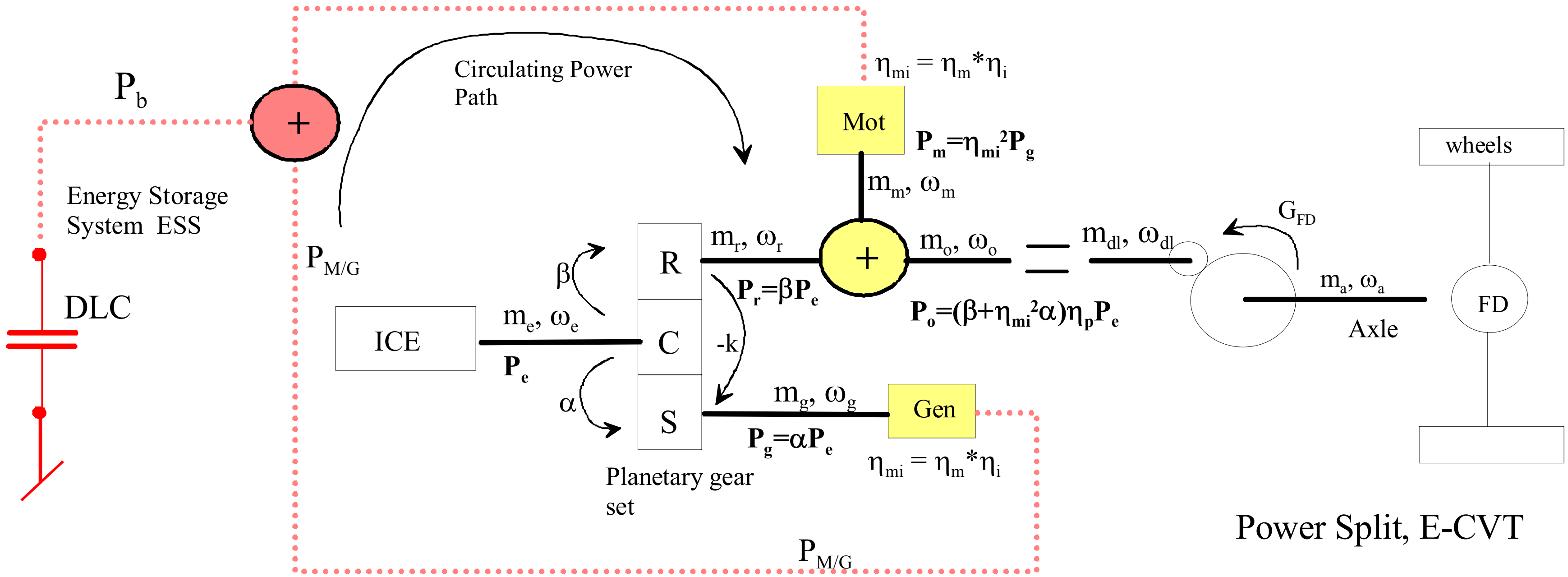
- Power split with floating bus is a near ideal application for ultracapacitor energy storage components
- Input split systems deliver mechanical power flow to the output only if the electric “variator” path circulates a fraction of the power



Power Split, E-CVT

Input Split: Power Flow Basics

- Electric power flow of fraction α enable the flow of a mechanical fraction, β between the engine and wheels of the input split trans.



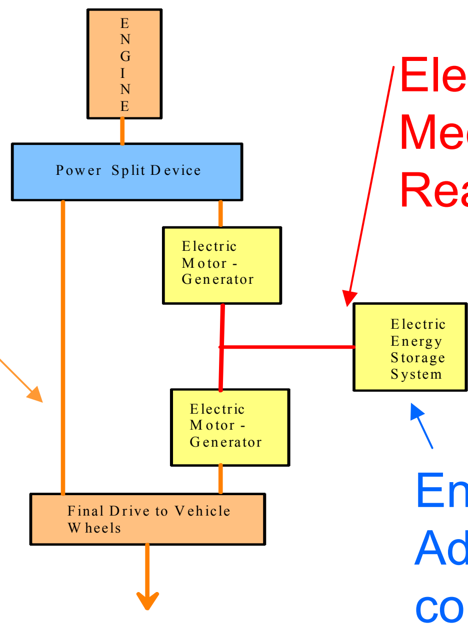
Power Split, E-CVT

Input Coupled Power Split Systems

- Electric variator power flow essential to transmit power via most efficient mechanical path.
- Input coupled eCVT's are characterized by a single planetary gear at the transmission input shaft.

Electric path enables transmission of Mechanical path power by providing Reaction torque at the engine

Mechanical Path is most efficient



Input Split

Energy storage system, ESS, can be Adv. Battery or Ultra-capacitor, or some combination.

Input Coupled Power Split Systems

- Analysis procedure for eCVT transmissions is the following:
  - From architecture write the planetary speed relationship
  - Define the torque expression at each source point
  - Reflect the generator torque to both ICE and to traction motor shafts to eliminate redundancy as eCVT's are still dual torque source systems.
- Reflect the road load to the eCVT driveline
- The eCVT output power must match reflected road load

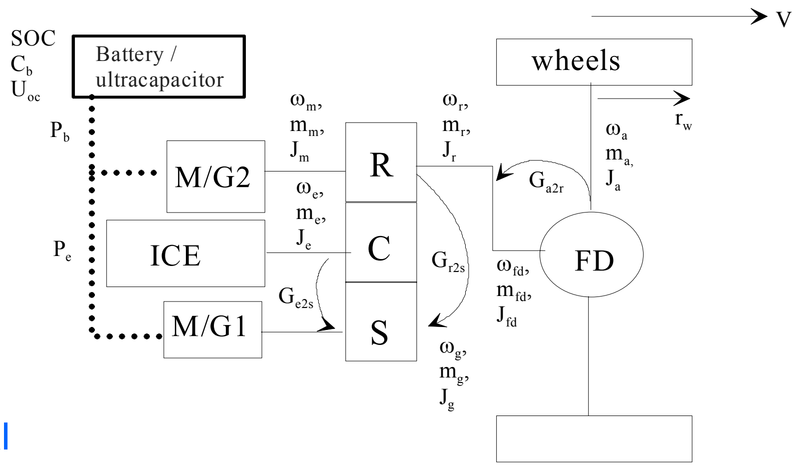
THS: Power Split Dynamics

- 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: Power Flow

- In actuality, one must follow the power flows in a power split rather than torque partitions.
  - Torque partition at the engine port establishes the fraction of power that follows the mechanical path and what fraction will take the electric path.

$$P_i = P_e = m_e \omega_e$$

$$\omega_i = \omega_e = \alpha \omega_g + \beta \omega_r$$

$$\alpha = \frac{1}{k+1}$$

$$\beta = \frac{k}{k+1}$$

$$m_r = \beta \eta_p m_e$$

$$P_r = \beta \eta_p m_e \omega_e = \beta \eta_p P_e$$

$$\eta_p = 0.98$$

$$m_g = \alpha \eta_p m_e$$

$$P_g = \alpha \eta_p m_e \omega_e = \alpha \eta_p P_e$$

- α and β determine the power split fraction, so choice of “k” is critical.
  - Toyota Prius I and Prius II, k=2.6

$$\eta_{mi} = \eta_m \eta_i$$

$$\eta_m = 0.93(motor)$$

$$\eta_i = 0.97(inverter)$$

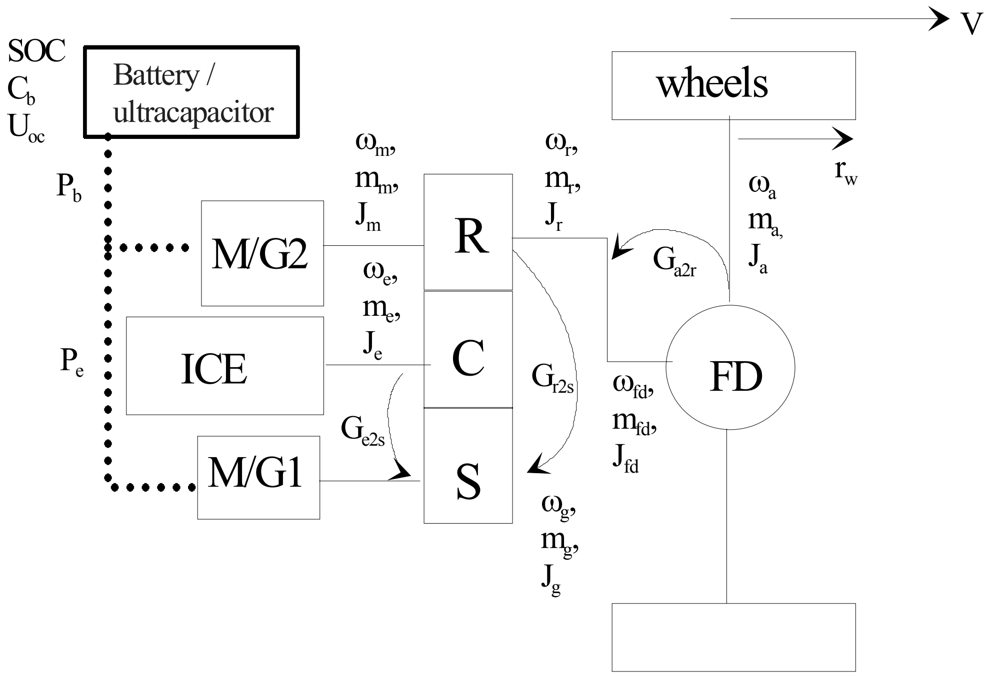
$$P_{M/G} = \eta_{mi} P_g$$

$$P_m = \eta_{mi} P_{M/G} = \eta_{mi}^2 P_g$$

$$P_m = \eta_{mi}^2 \eta_p \alpha P_e$$

Input Split: THS System Dynamics

- The dynamic model consists of an expression for engine torque and an expression for traction motor torque.
- Generator torque (and speed) is dependent on road load input once an engine strategy is selected.



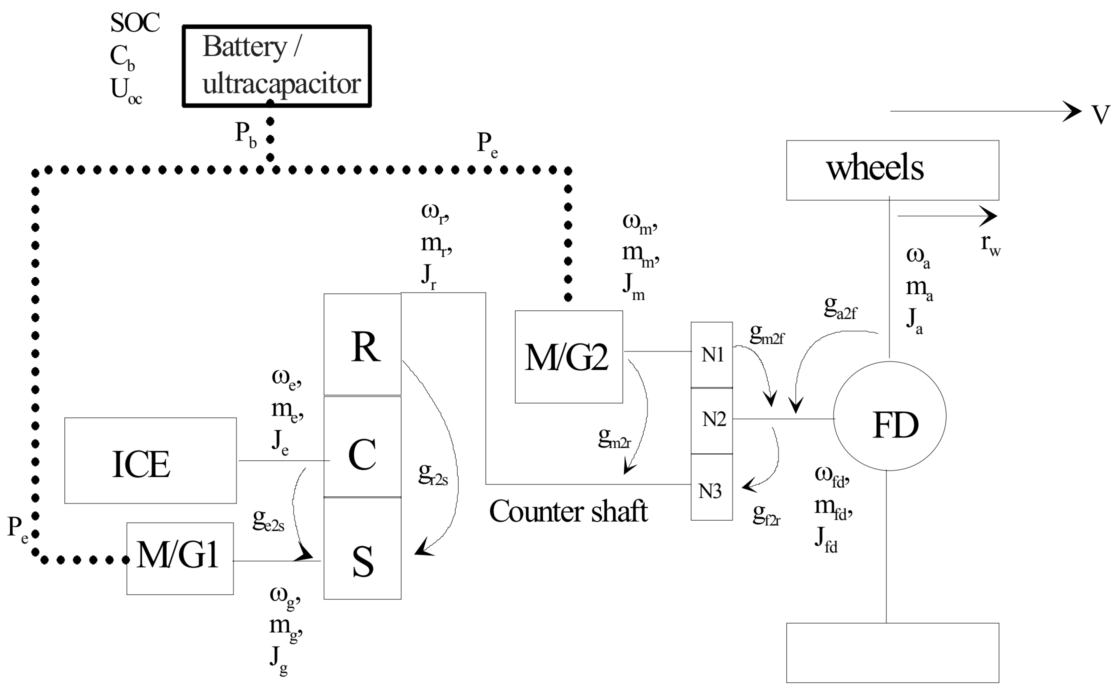
$$m_{gss} = \frac{1}{k+1} m_e$$

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

In the input split system NET DRIVELINE POWER is the sum of engine power AND energy storage system power, i.e., in the THS-II 57kW + 25 kW = 82 kW

Input Split System Dynamics: FHS

- An input coupled power split may also have output stage gearing
  - But only a single planetary gear set (speed summer) at the engine port.



Input split with fixed output gearing

Generator torque in the FHS
Is the same as in THS.

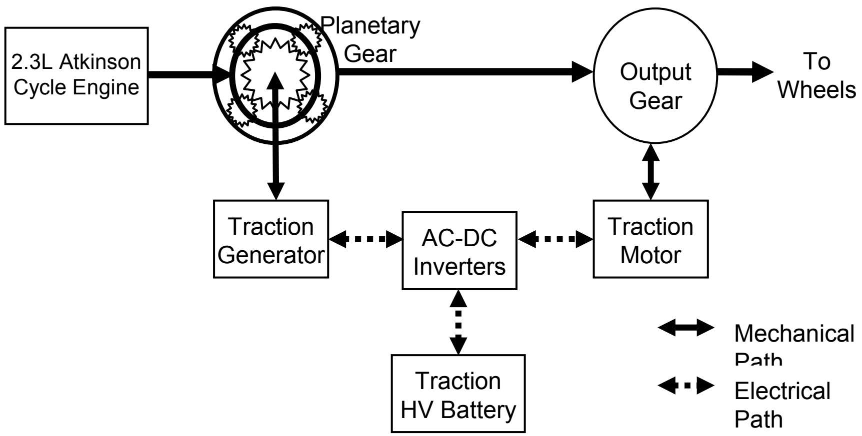
Final drive torque is modified by
The output stage gearing

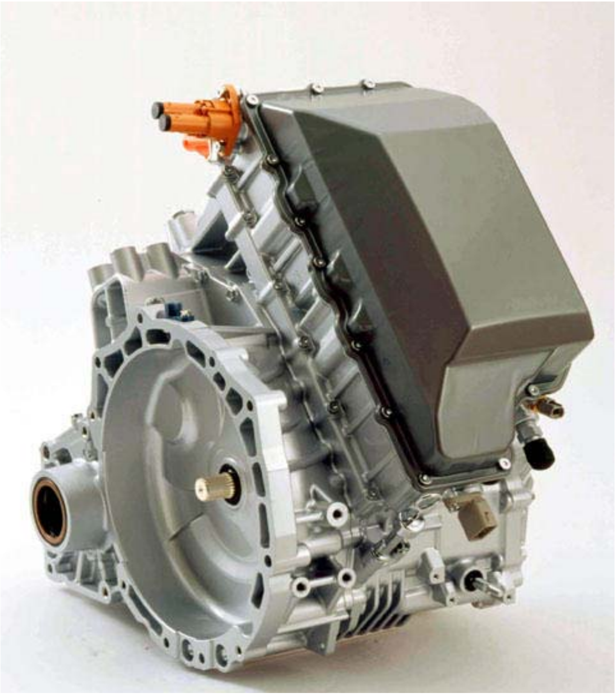
$$m_{fd} = \left(\frac{N_2}{N_1}\right) m_m + \left(\frac{k}{k+1}\right)\left(\frac{N_2}{N_3}\right) m_e$$

Which is very similar to the
THS steady state net
driveline torque, but with
added mechanical advantage

Input Coupled eCVT with Output Gearing

- Output gearing for enhanced traction motor performance





Recent generation of eCVT are highly Integrated with power electronics Mounted to the Transmission Case.

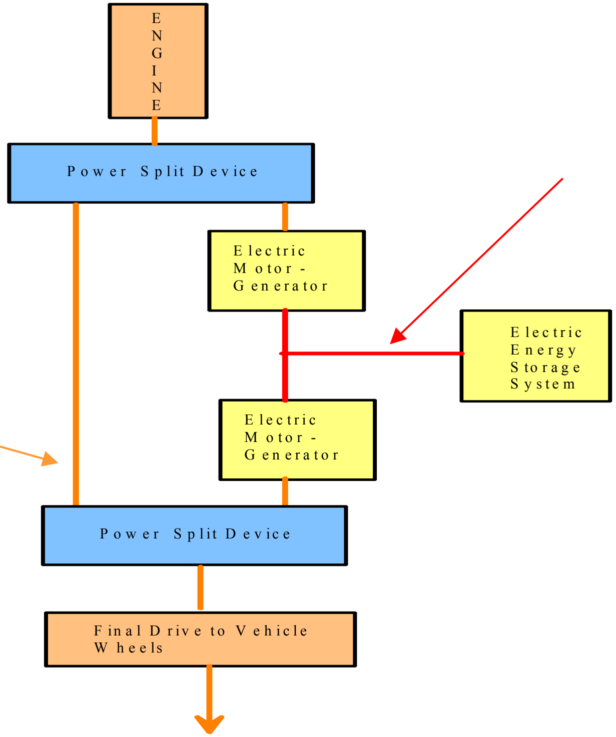
Gasoline-Electric Hybrids

- Compound split eCVT power flow basics
- Dynamics of the compound split eCVT
- Types of 2-mode systems

Compound Coupled Power Split Systems

- Compound split, or 2-mode, are full 4-port eCVT transmissions having at least 2 mechanical nodes.
- 2-mode eCVT's are characterized by input & output planetary gears

Mechanical path is most efficient power transmission link from engine to wheels.



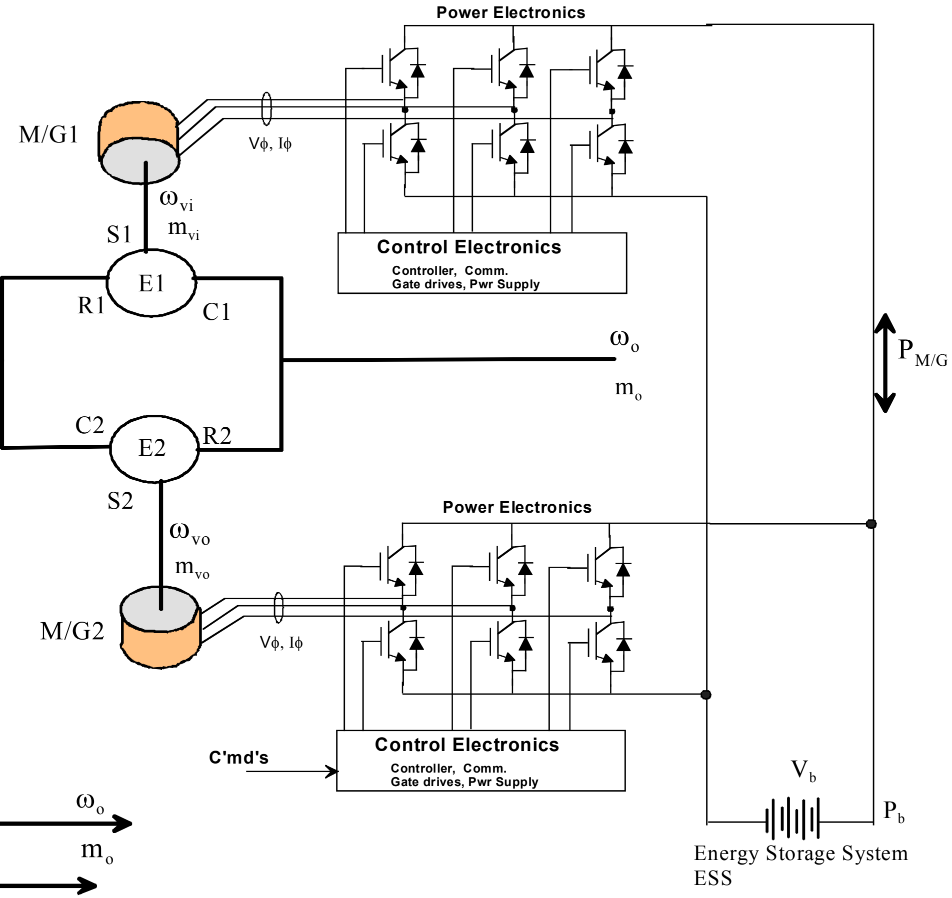
Compound Split

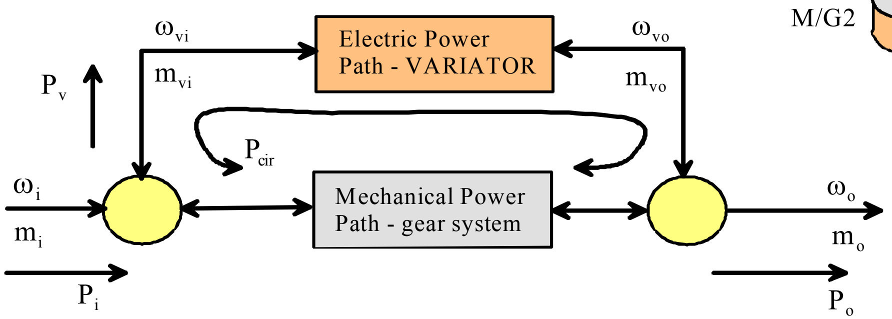
Electric variator path provides eCVT action and may operate w/o need of ESS to be present.

At mechanical nodes one or the Other of the M/G's will encounter Zero speed and direction reversal

Compound Split: Power Flow Basics

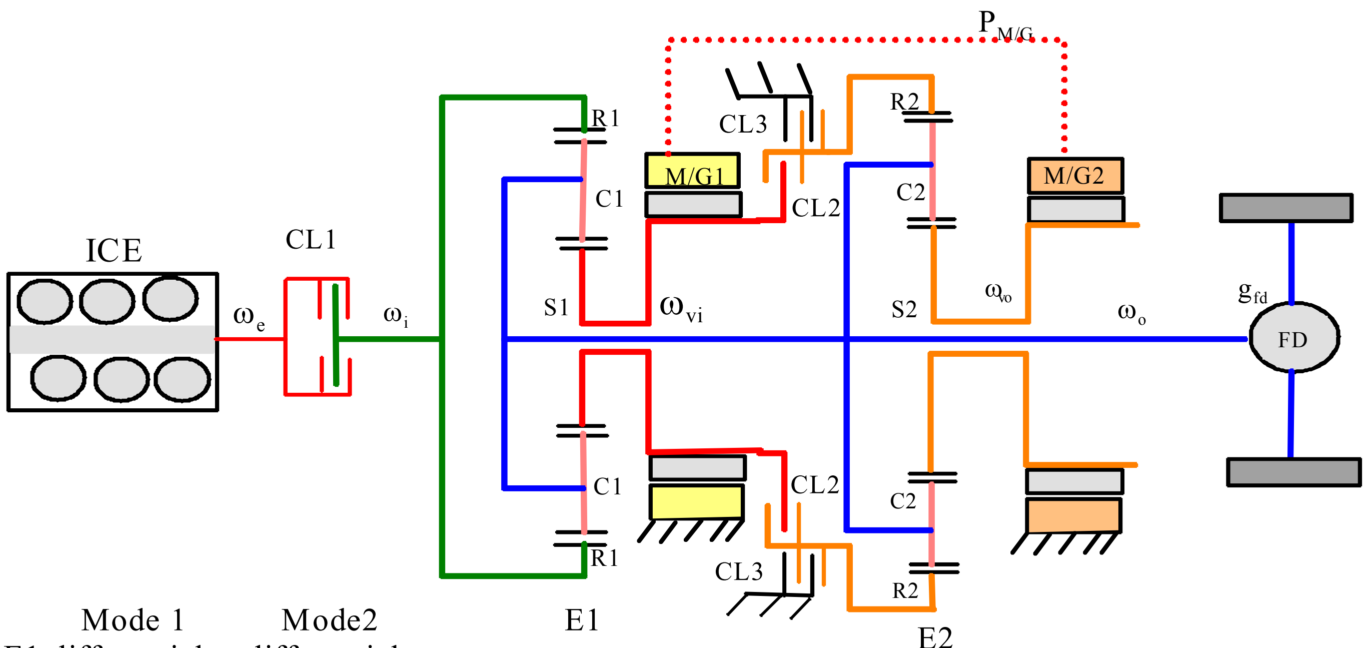
- Compound split systems are full 4-port converters
  - Use variator system theory for full understanding





Compound Split: GM-Allison AHS-2 (aka, EVT)

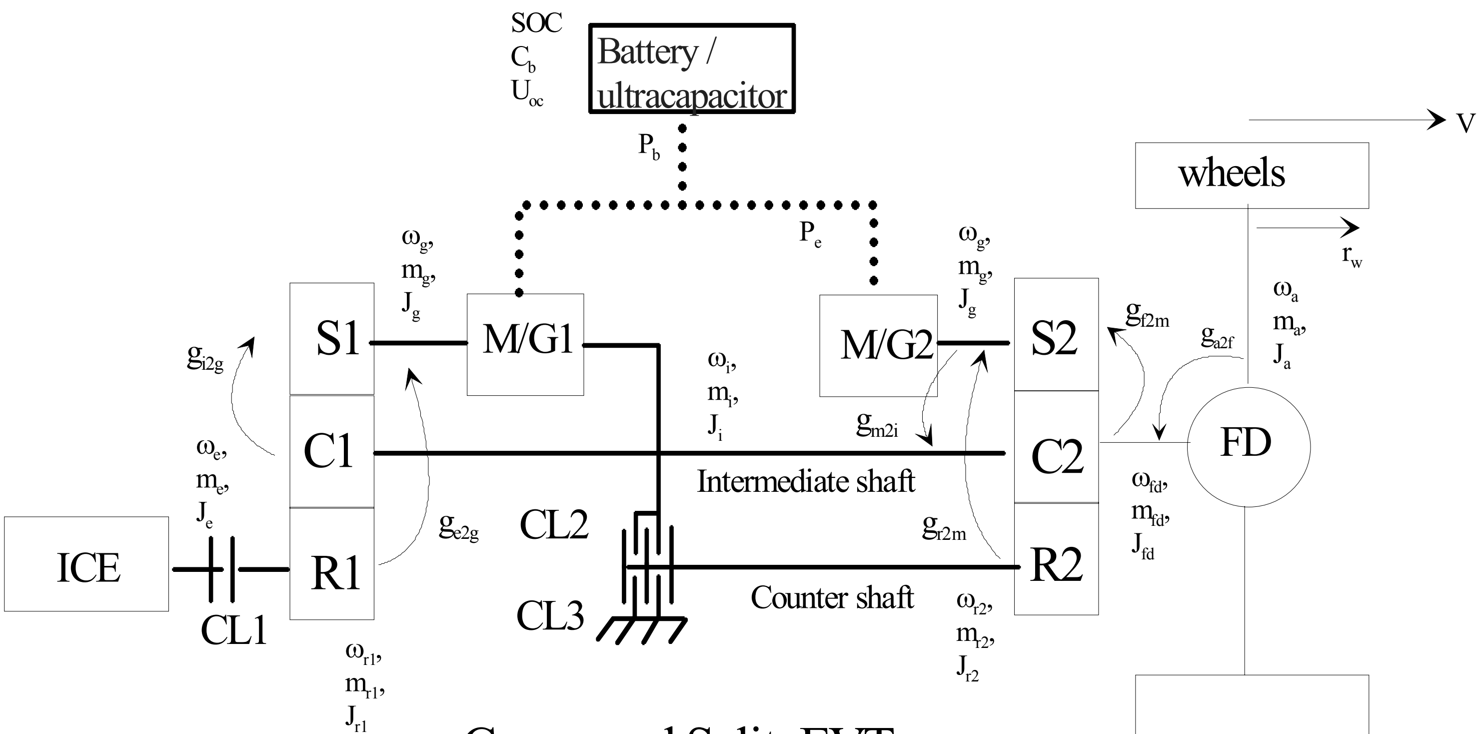
- The Advanced Hybrid System, AHS-2, or 2-mode eCVT is the first of the compound split systems developed.



	Mode 1	Mode2	
E1	differential	differential	
E2	Torque mult	differential	Neutral
CL1	1	1	
CL2	0	1	0
CL3	1	0	0

Compound Split: GM-Allison AHS-2

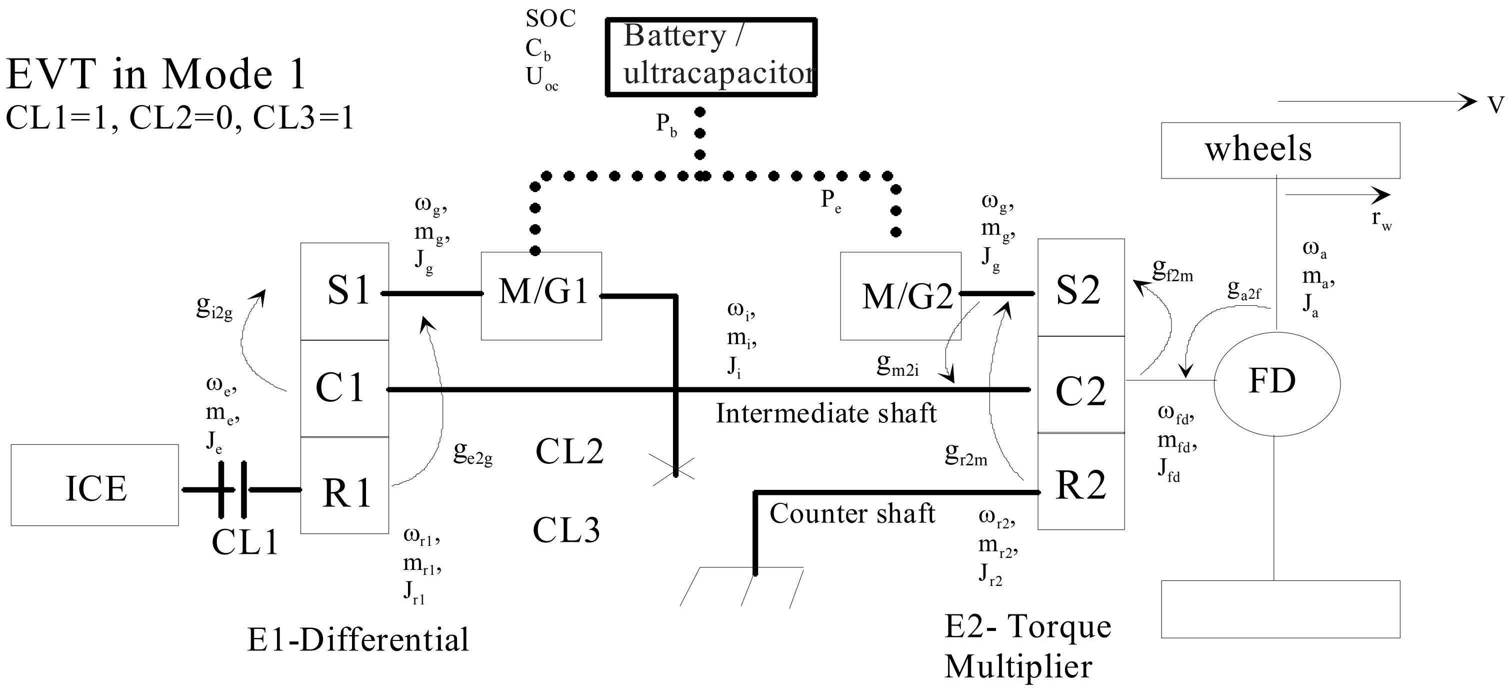
- The Advanced Hybrid System – 2 Mode replaces the output port gearing of the FHS with a 2nd planetary gear stage



Compound Split, EVT

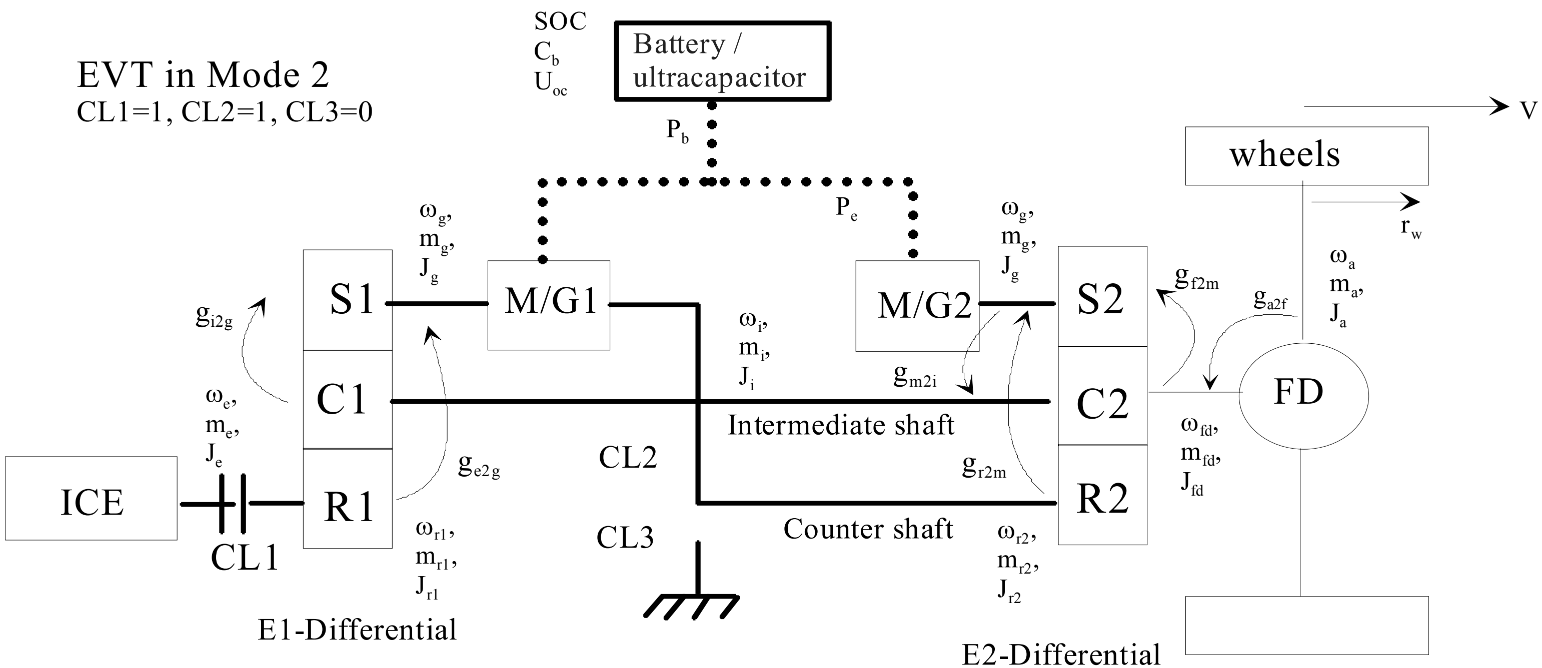
Modeling the Hybrid System Dynamics: AHS-2

- AHS-2 in Low Range mode
  - Used for light loads, in city driving, relatively low speed regimes



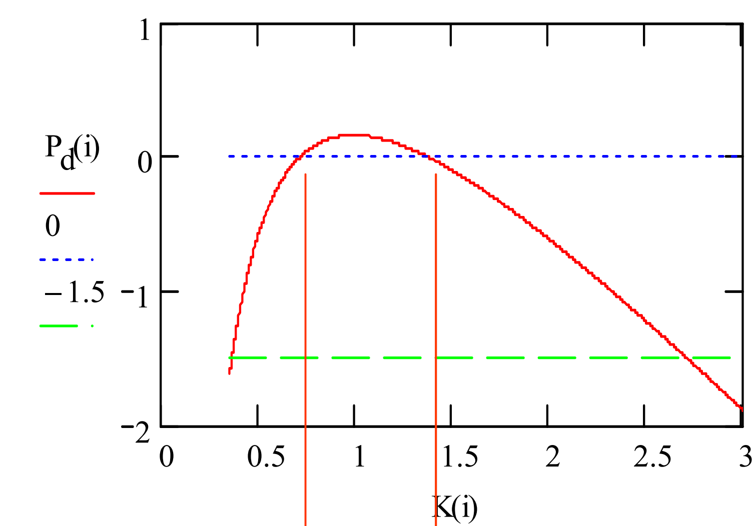
Modeling the Hybrid System Dynamics: AHS-2

- AHS-2 in High Range mode
  - Used for heavy loads, towing, pulling grades, highway driving, high speed regimes



Modeling the Hybrid System Dynamics: AHS-2

- Illustration of compound split transmission ratio and corresponding variator ratio requirements



Variator roots

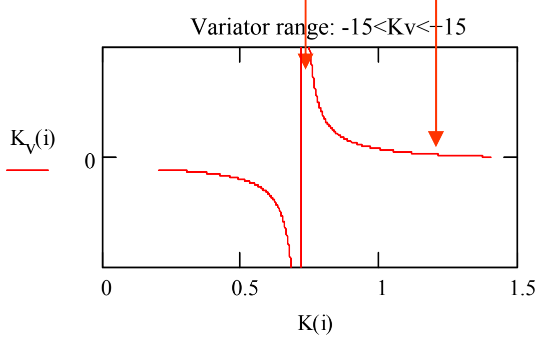
$K_{v1} = 0.714$

$K_{v2} = 1.37$

Case of: k1=:
and k2 = 2.7

Klow = 0.365

Khigh = 2.68



Has roots at:

$K_{v1} := \frac{D}{B}$ $\quad K_{v1} = 0.714$

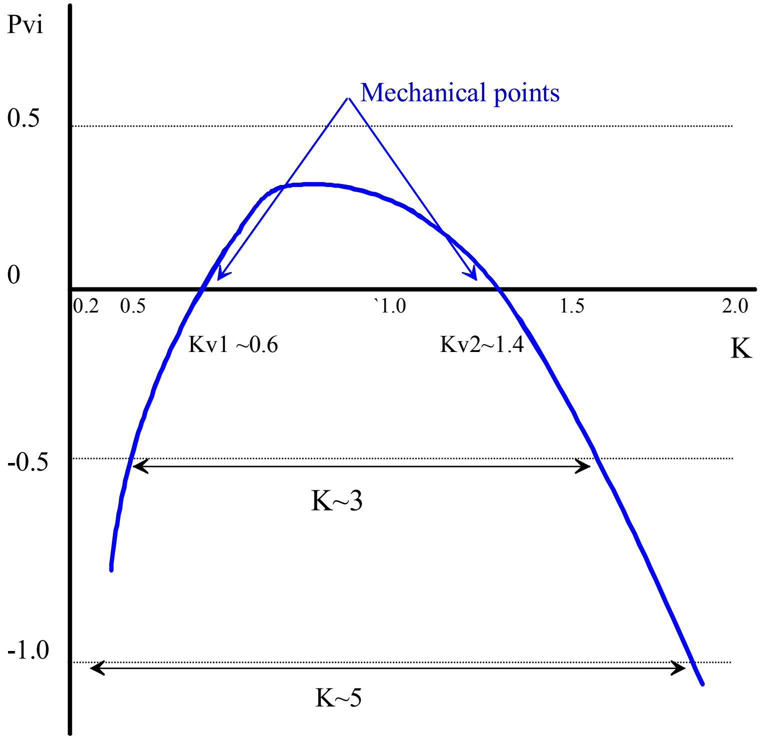
$K_{v2} := \frac{C}{A}$ $\quad K_{v2} = 1.37$

Case where k1= 2.5 and k2=
spread about k=2.6 nominal

K=Khigh/Klow
K=7.3, But
Pelec = 1.5pu

Modeling the Hybrid System Dynamics: 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:



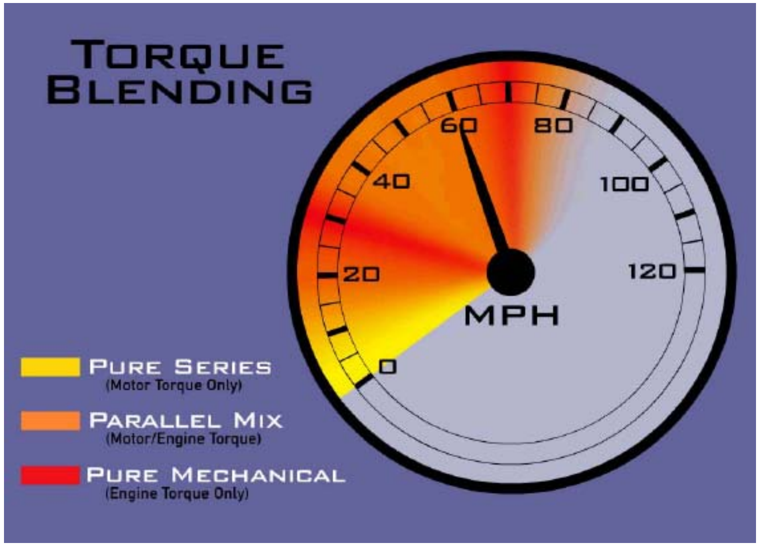
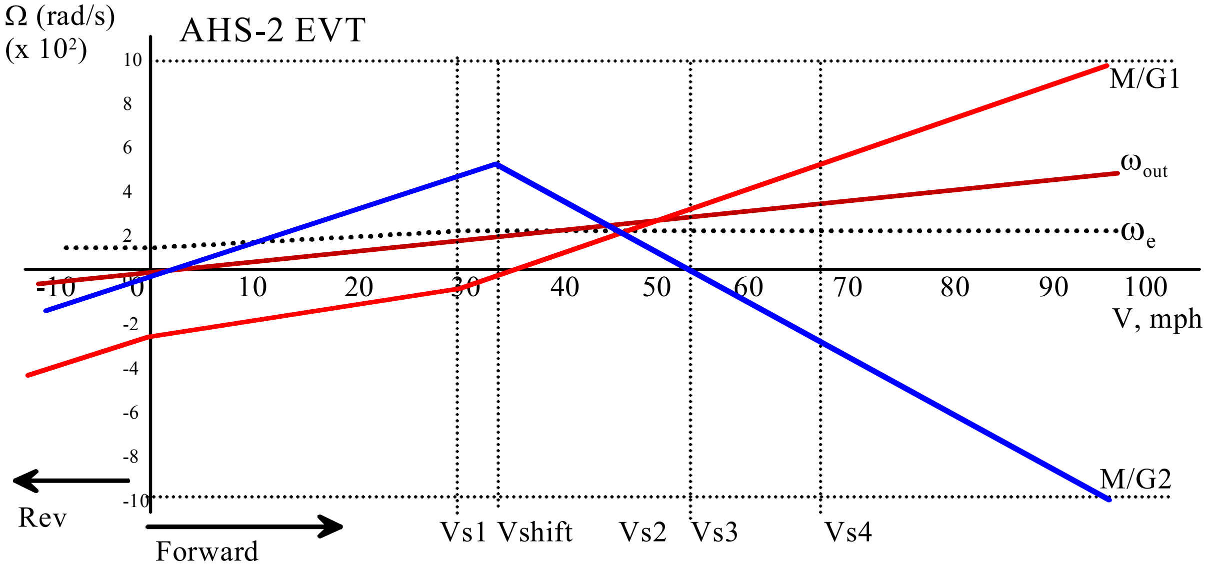


Illustration courtesy of GM/Allison

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

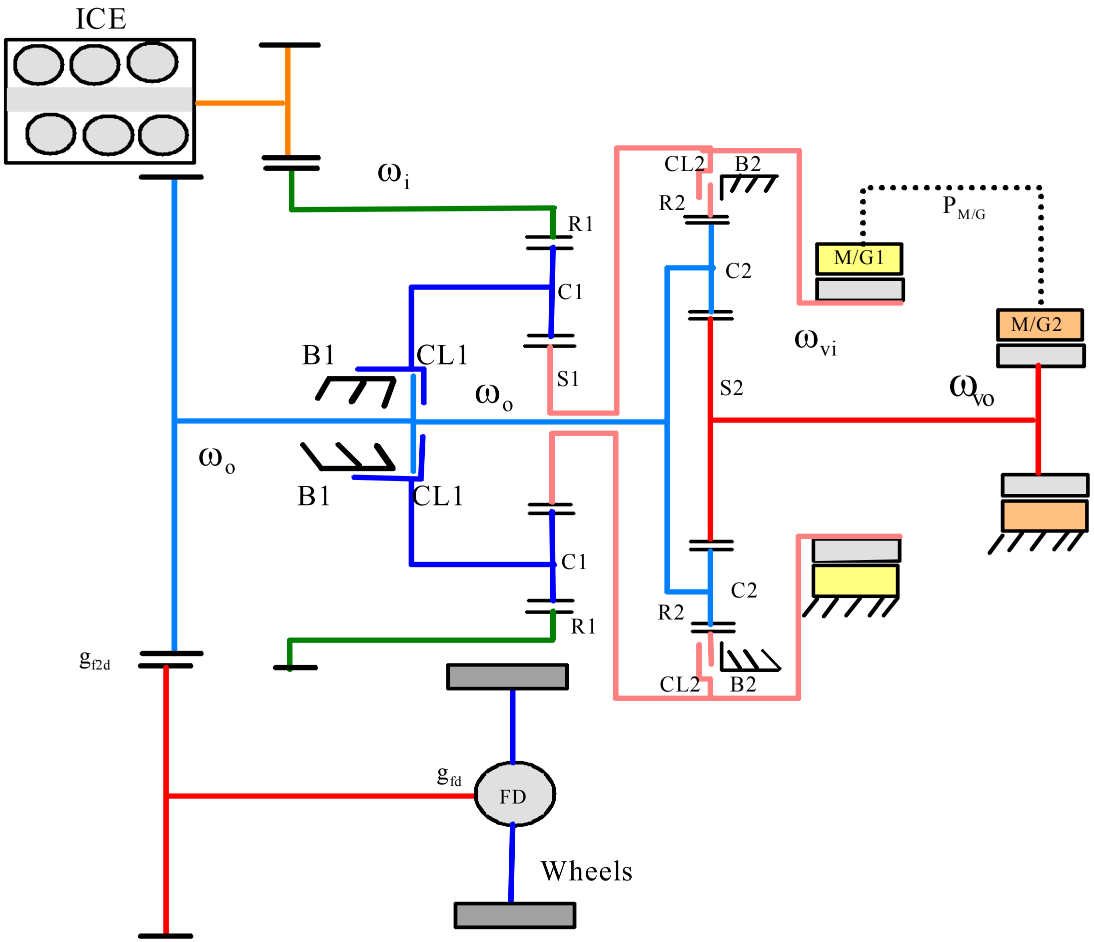
Modeling the Hybrid System Dynamics: AHS-2

- In the 2-mode, or compound split, transmission the 1st node occurs when M/G1 (or M/G2) speed equals zero.
  - At nodal points a synchronous "shift" (clutch toggle) is performed since no clutch slipping is involved
- A 2nd node occurs when M/G2 (or M/G1) speed equals zero.
- The "spread" between 1st and 2nd nodal points is a measure of the effective ratio range of the transmission when its electric path power is relatively low or zero



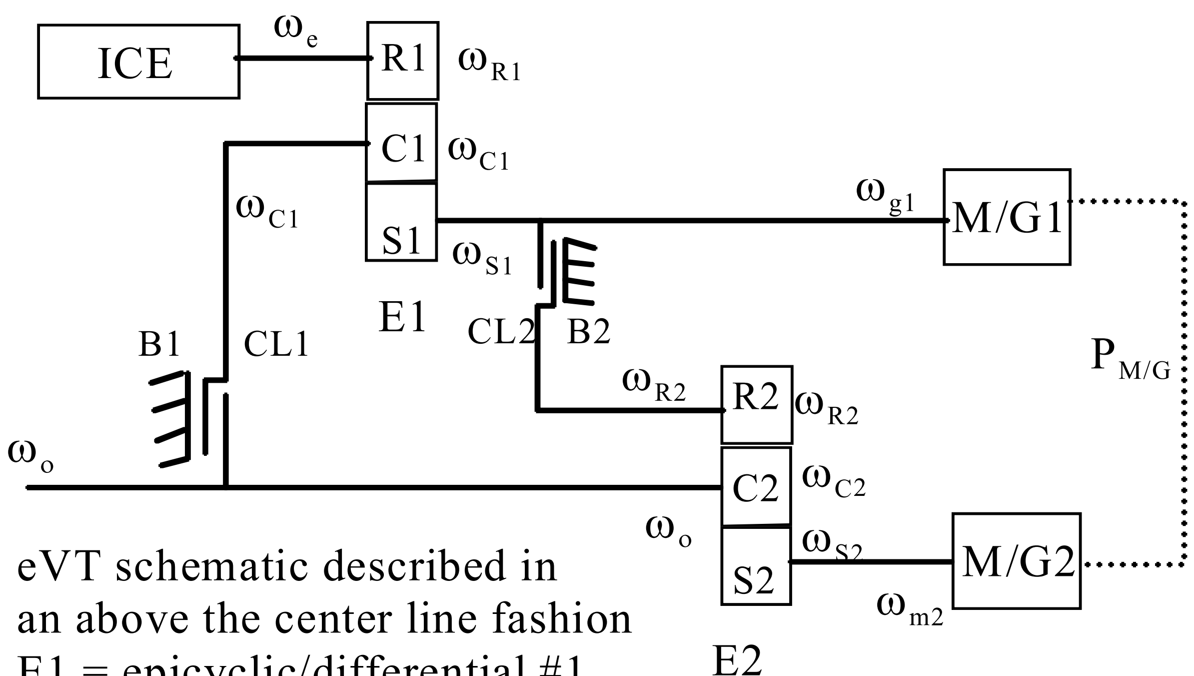
Compound Split System: Timken eVT

- The electro-mechanical variable transmission, eVT, system with ICE and final drive shown
- eVT has 2 mechanical nodes
- Clutches and brakes are activated at the nodal points



eVT Compound Split System

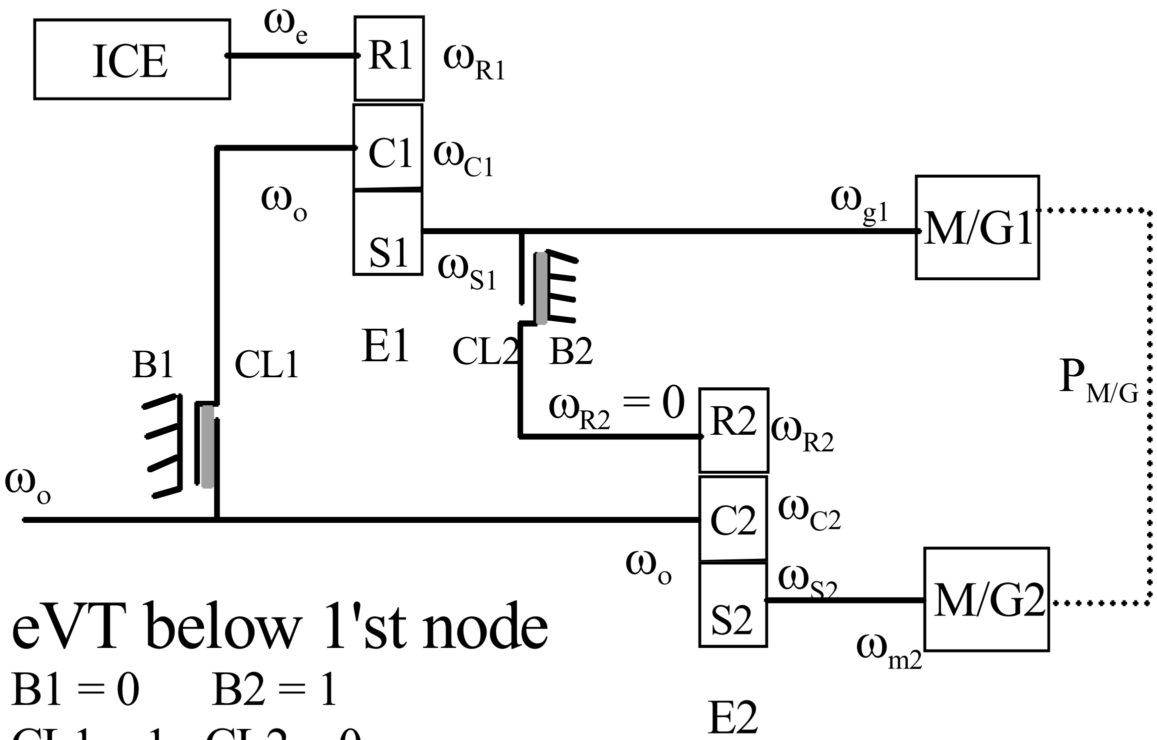
- Schematic of the eVT
  - Definition of all angular speed variables in the system.



eVT schematic described in
an above the center line fashion
E1 = epicyclic/differential #1
E2 = epicyclic/differential #2

eVT Compound Split System

- eVT operation below the 1st node (low speed range)
  - And some definitions of Transmission ratio, K, and variator ratio, Kv:



eVT below 1'st node

B1 = 0   B2 = 1

CL1 = 1   CL2 = 0

$$K = \frac{\omega_0}{\omega_e}$$

$$K_v = \frac{\omega_{vo}}{\omega_{vi}} = \frac{\omega_{m2}}{\omega_{g1}}$$

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

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

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

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

eVT Compound Split System

- eVT operation below the 1st node (low speed range)
  - Get the variator response of:

$$\omega_e = \alpha_1 \omega_{g1} + \beta_1 \omega_0$$

$$\omega_0 = \alpha_2 \omega_{m2}$$

$$Let:$$

$$K_{-1}(K_v) = \frac{\omega_0}{\omega_e}\Big|_{K_v}$$

$$K_{-1}(K_v) = \frac{\alpha_2 \omega_{m2}}{\alpha_1 \omega_{g1} + \beta_1 \alpha_2 \omega_{m2}}$$

$$K_{-1}(K_v) = \frac{\alpha_2 K_v}{\alpha_1 + \beta_1 \alpha_2 K_v}$$

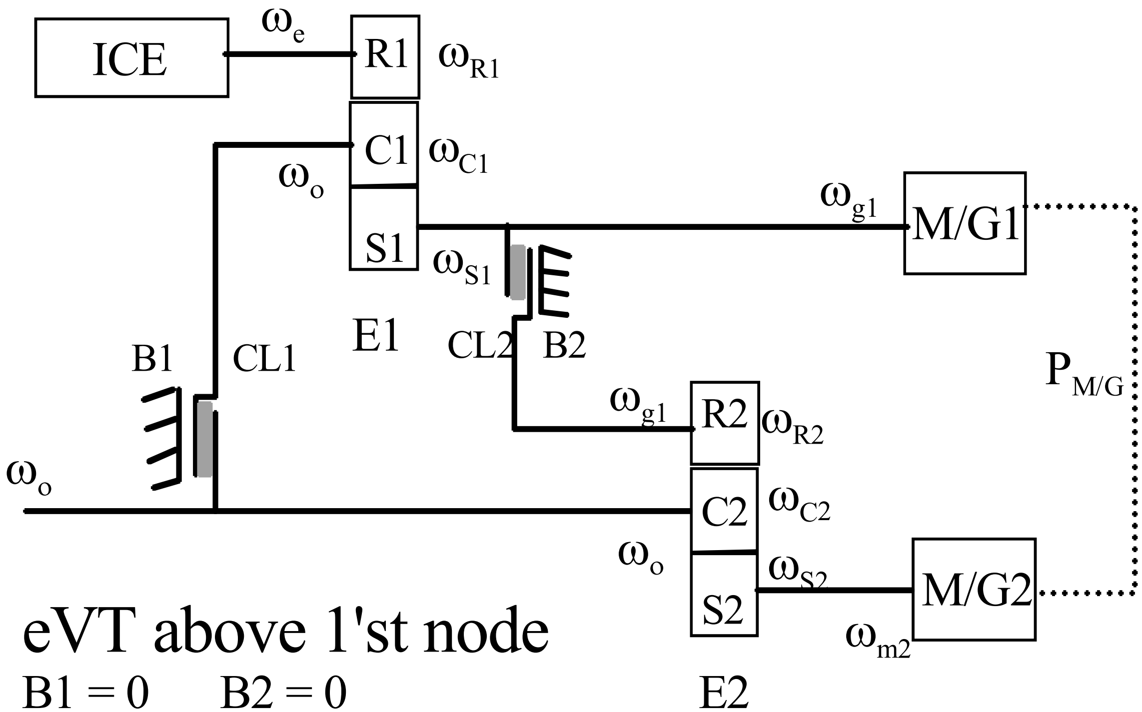
$$K_v = \frac{\alpha_1 K_{-1}}{\alpha_2 - \beta_1 \alpha_2 K_{-1}}$$

$$where,$$

$$0.15 < K_{-1} < 0.8$$

eVT Compound Split System

- eVT operation above the 1st node (high speed range)
  - At the epicyclic gear sets, E1 and E2 the following apply:



eVT above 1'st node

$B1 = 0 \quad B2 = 0$

$CL1 = 1 \quad CL2 = 1$

At E1:

$$\omega_{g1} + k^{E1}\omega_e = (k^{E1} + 1)\omega_0$$

At E2:

$$\omega_{m2} + k^{E2}\omega_{g1} = (k^{E2} + 1)\omega_0$$

eVT Compound Split System

- eVT operation above the 1st node (high speed range)
  - And solving the expressions at E1 and E2:

$$\omega_e = \frac{-1}{k^{E1}}\omega_{g1} + \frac{1}{\beta_1}\omega_0$$

$$\omega_0 = \beta_2\omega_{g1} + \alpha_2\omega_{m2}$$

$$noting\_that:$$

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

$$Get\_that:$$

$$\omega_e = \left[\frac{\alpha_1}{\alpha_1 - 1)} + \frac{\beta_2}{\beta_1}\right]\omega_{g1} + \frac{\alpha_2}{\beta_1}\omega_{m2}$$

$$\omega_0 = \beta_2\omega_{g1} + \alpha_2\omega_{m2}$$

Solving for the transmission ratio, K
Above the 1st node results in:

$$K_{+1}(K_v) = \frac{\beta_2 + \alpha_2 K_v}{\left[\frac{\alpha_1}{\alpha_1 - 1} + \frac{\beta_2}{\beta_1}\right] + \frac{\alpha_2}{\beta_1}K_v}$$

$$Solve\_for\_K_v:$$

$$K_v = \frac{\left[\frac{\alpha_1\beta_1}{\alpha_1 - 1} + \beta_2\right]K_{+1} - \beta_1\beta_2}{(\alpha_2\beta_1 - \alpha_2 K_{+1}}$$

eVT Compound Split System

- Defining the mechanical nodes of the eVT
  - Below the 1st node set $K_v(K_{-1})$ =0 & $1/K_v$ =0

$$K_v = \frac{\alpha_1 K_{-1}}{\alpha_2 - \beta_1 \alpha_2 K_{-1}} = 0$$

$$\therefore K_{-1} = 0 ....Vehicle.stopped$$

$$\frac{1}{K_v} = 0$$

$$\therefore K_{-1} = \frac{\alpha_2}{\beta_1 \alpha_2} = \frac{k^{E1} + 1}{k^{E1}}$$

  - Above the 1st node set $K_v(K_{+1})$ =0 & $1/K_v$ =0

$$K_{+1}(K_v) = \frac{\beta_2 + \alpha_2 K_v}{\left[\frac{\alpha_1}{\alpha_1 - 1} + \frac{\beta_2}{\beta_1}\right] + \frac{\alpha_2}{\beta_1} K_v}$$

$$K_v = 0..so,$$

$$K_{+1} = \frac{\beta_1 \beta_2}{\left(\frac{\alpha_1 \beta_1}{\alpha_1 - 1} + \beta_2\right)} = \frac{k^{E1} k^{E2}}{k^{E1} k^{E2} - 1}$$

eVT Compound Split System

- The nodes of the eVT are therefore at the following E1 and E2 ratio points:

$$K_{-1} = 0 \ldots\ldots\ldots\ldots\ldots K_{-1} = \frac{k^{E1}}{k^{E1}+1}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots K_{+1} = \frac{k^{E1}}{k^{E1}+1} \ldots\ldots\ldots\ldots\ldots K_{+1} = \frac{k^{E1}k^{E2}}{k^{E1}k^{E2}-1}$$

  - The transmission ratio spread is therefore:

$$K_{+1} - K_{-1} = \frac{k(k+1)}{(k^2-1)(k+1)} = \frac{k}{(k^2-1)}$$

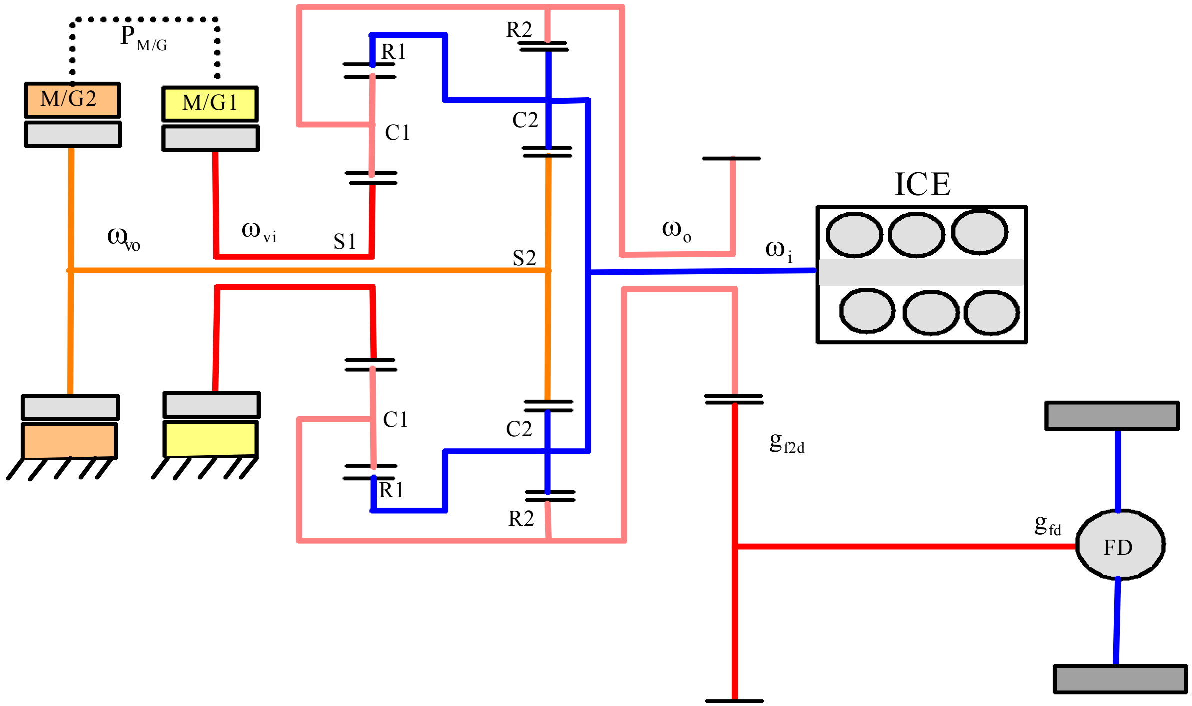
  - For which the best overall ratio is achieved when $k=k_{lowest}$
  - k~1.6 in the eVT

eVT Compound Split System

- The eVT must, as should all eCVT's, deliver conventional automatic transmission performance:
  - Braking and Parked
    - CL1 = 1 and B1 = 1
    - CL2 = 0 and B2 = 0
  - Reverse
    - CL1 = 0 and CL2 = 0
    - B1 = 1 and B2 = 1
  - Geared Neutral
    - M/G1 freewheels
    - M/G2 is locked
- Recall, there is no PRNDL (Park, Reverse, Neutral, Drive, Low gear) in an eCVT
  - The PRNDL functions are digital commands to the eCVT.

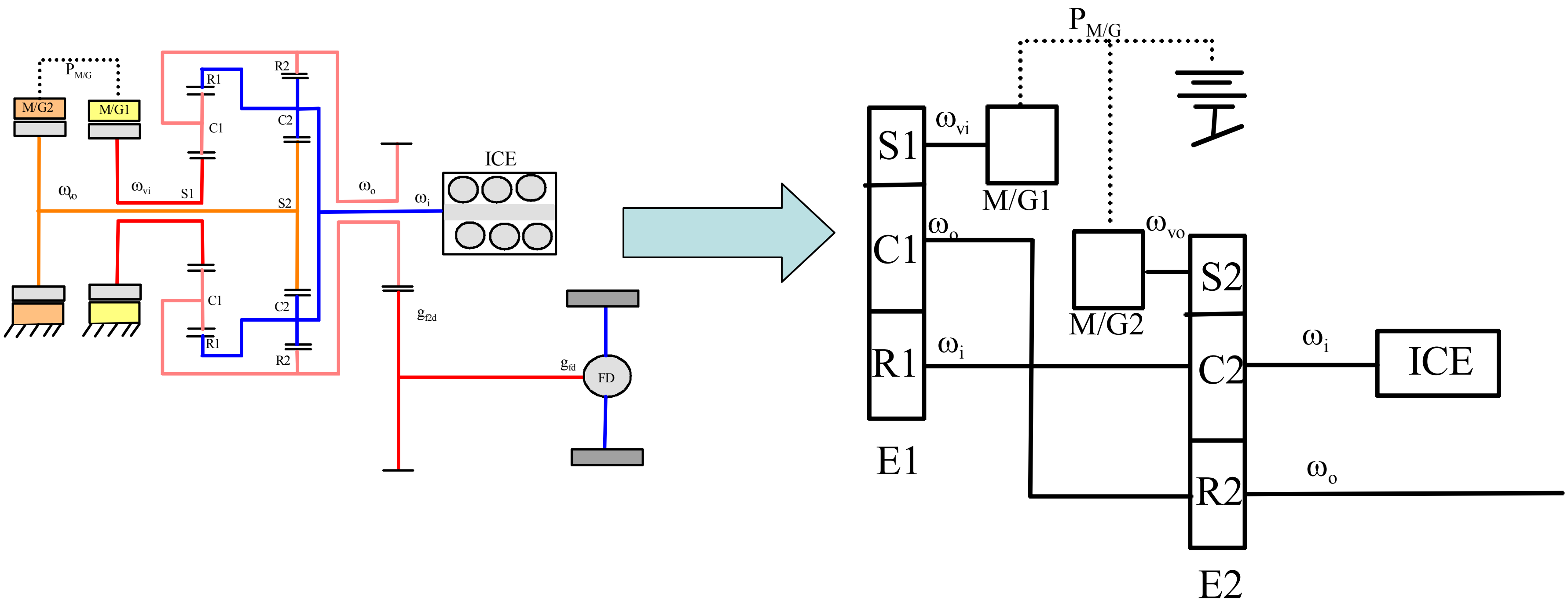
Renault IVT System

- 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



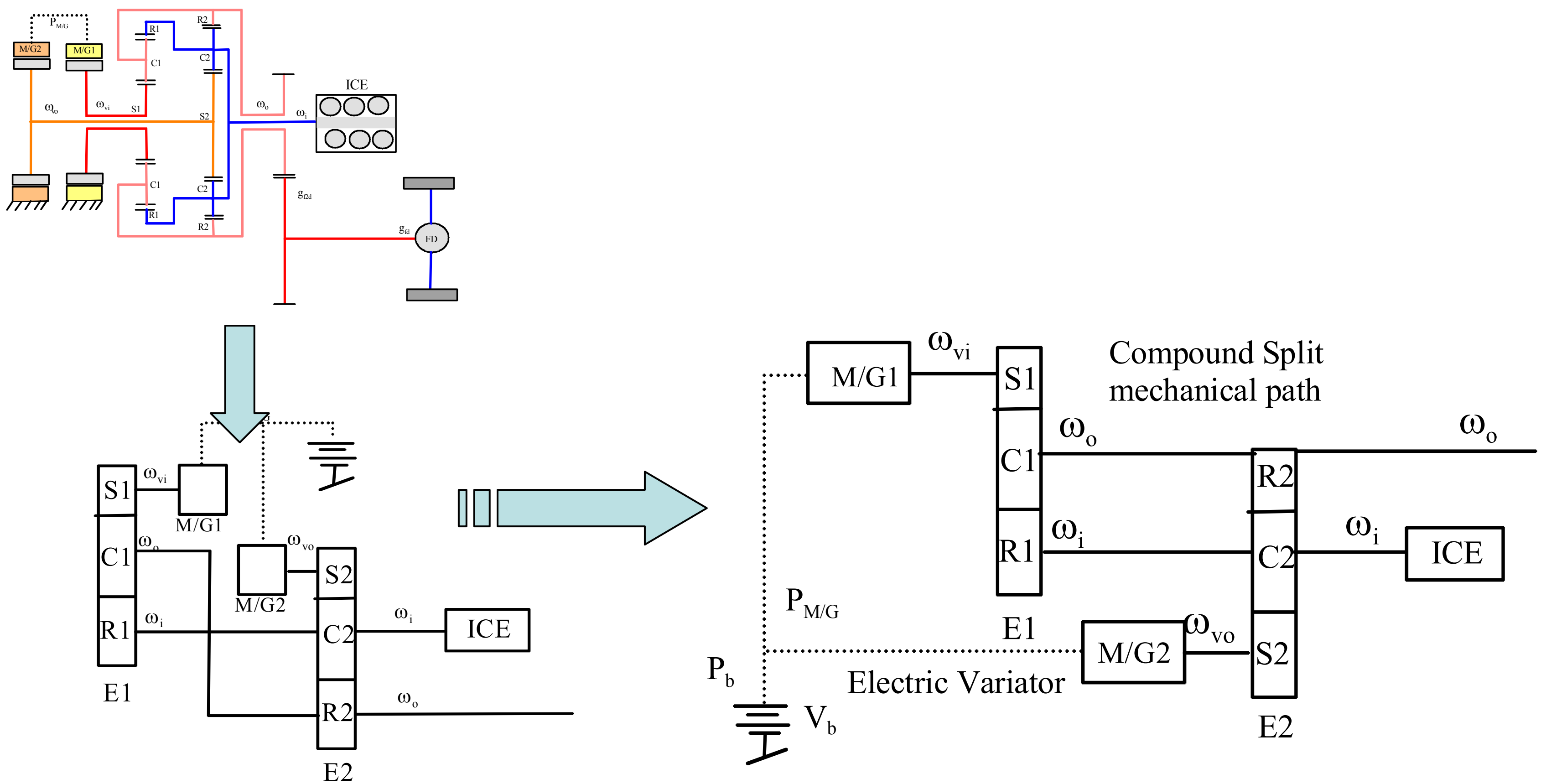
Renault IVT System

- IVT model development



Renault IVT System

- IVT model development

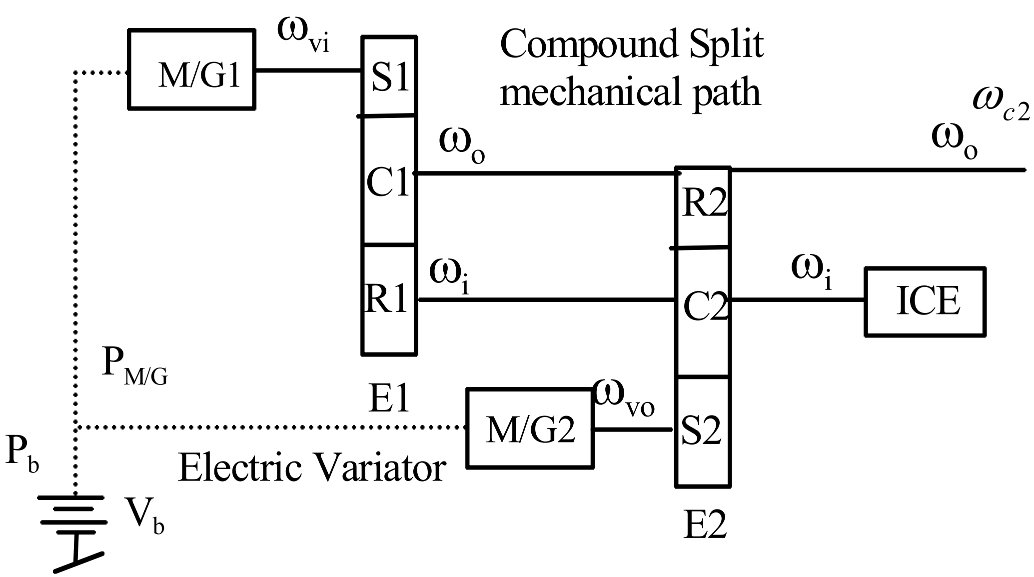


Renault IVT System

- 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.

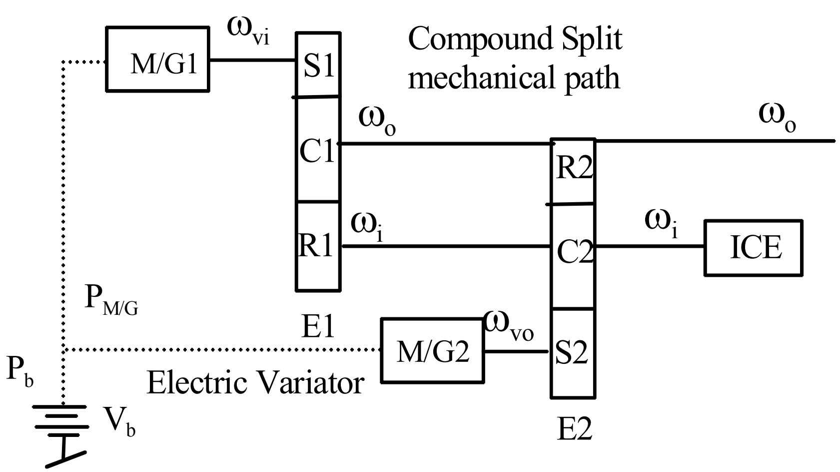
$$\omega_{c1} = \left(\frac{1}{1+k^{E1}}\right)\omega_{s1} + \left(\frac{k^{E1}}{1+k^{E1}}\right)\omega_{r1}$$

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



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:

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

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

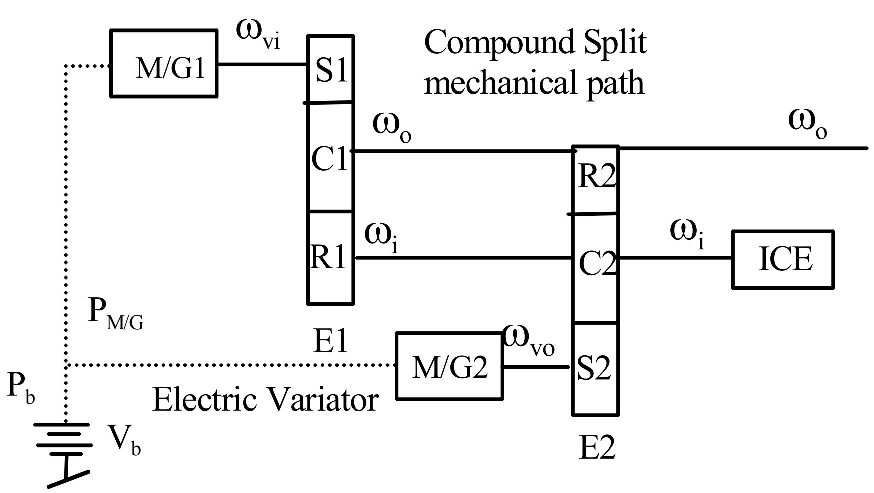
$$\alpha_2 = \frac{1}{1+k^{E2}}$$

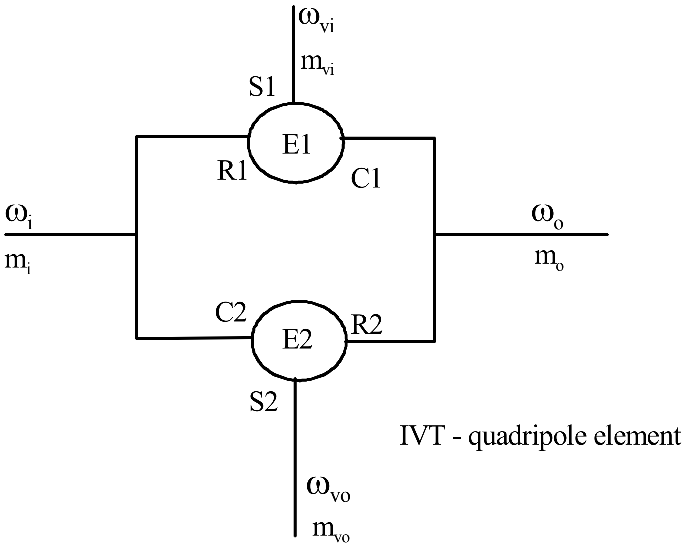
$$\beta_2 = \frac{k^{E2}}{1+k^{E2}}$$

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

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
- Power split transmissions rely on 2 electric machines – hence 2 full 4-quadrant ac drives.
- 2-mode systems have a significant advantage over single mode systems:
  - The M/G's are reduced power
  - Compound split scales better to SUV and P/U's than input split

Summary

- Power split transmissions, in general, do not rely on mechanical compliances to provide driveline “windup” in the event of sharp longitudinal acceleration events
- 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 while the variator – or electric path, determines its overall ratio
- The ESS must deliver very high C-rate discharges (charges) so that the traction motor (M/G2 in P/S) is capable of very high m/J rates
- The ultracapacitor has inherently high P/E making it an ideal electric path component

Appendix

- 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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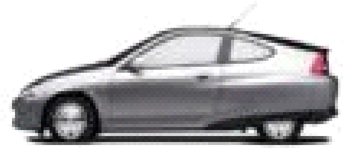
Honda Insight



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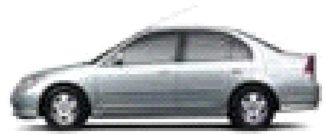
Honda Civic



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Toyota Prius

MSRP: $20,295
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