Vehicle Propulsion Systems
Lecture 4
Hybrid Powertrains, Topologies and Component Modeling

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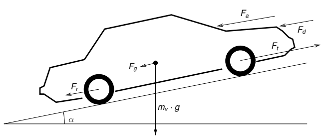
Outline

The Vehicle Motion Equation

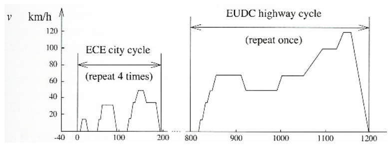
Newtons second law for a vehicle

$$m_v \frac{d}{dt} v(t) = F_t(t) - (F_a(t) + F_r(t) + F_g(t) + F_d(t))$$



- F_t – tractive force
- F_a – aerodynamic drag force
- F_r – rolling resistance force
- F_g – gravitational force
- F_d – disturbance force

Energy consumption for cycles



Numerical values for MVEG-95, ECE, EUDC

$$\text{air drag} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i^3 \, h = \{319, 82.9, 455\}$$

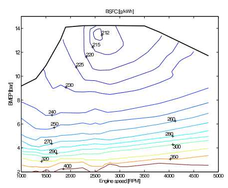
$$\text{rolling resistance} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i \, h = \{.856, 0.81, 0.88\}$$

$$\text{kinetic energy} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{a}_i \, \bar{v}_i \, h = \{0.101, 0.126, 0.086\}$$

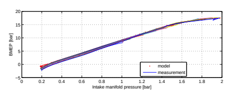
$$\bar{E}_{\text{MVEG-95}} \approx A_f \, c_d \, 1.9 \cdot 10^4 + m_v \, c_r \, 8.4 \cdot 10^2 + m_v \, 10 \quad kJ/100km$$

Engine Efficiency Maps

Measured engine efficiency map – Used very often

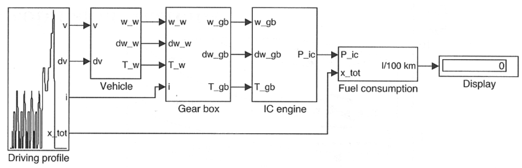


–Willans line approximation.



Model implemented in QSS

Conventional powertrain.



Efficient computations are important
–For example if we want to do optimization and sensitivity studies.

Outline

Definition

What characterizes a Hybrid-Electric Vehicle
- Energy carrier is a fossil-fuel.
- Presence of an electrochemical or electrostatic energy storage system.

Potential for Energy Savings

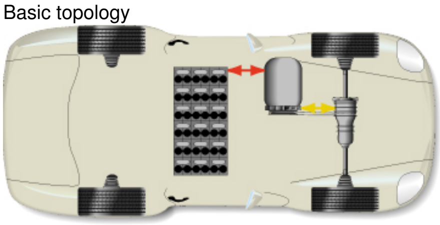
Benefits of Hybrid-Electric Vehicles

- Downsize engine while maintaining maximum power requirement
- Recover energy during deceleration (recuperation)
- Optimize energy distribution between prime movers
- Eliminate idle fuel consumption by turning off the engine (stop-and-go)
- Eliminate the clutching losses by engaging the engine only when the speeds match

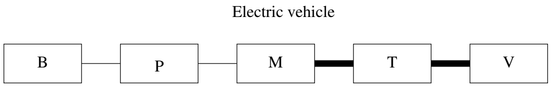
Possible improvements are counteracted by a 10-30% increase in weight.

Electric Vehicles

- Basic topology



- Sketch of the paths



Electric Vehicles

- Contain basic elements of HEV.
- Not "interesting", for optimization.
  –No in-depth coverage in the course.
- Interesting from the design point of view.
- Drawbacks compared to a conventional vehicle
  - Not autonomous
  - Refueling time
  - Low range/weight
- ⇒ Niche vehicles
- Plug-in EV:s are hot in media
- Development of plug-less vehicles
  –Inductive charging
- Range extenders (transition to series hybrid)

Electric Vehicles – From Niche to Public

- Applications requiring zero-emissions.
  - Indoor vehicles, mines ...
  - In-city distribution vehicles
  - Zero emission vehicle requirements
- Other niched vehicles

Lightning

Tesla Roadster

- Nissan Leaf, Volvo C30 Electric

Outline

Basic configurations

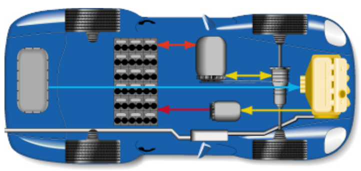
Basic classification of hybrids

- Series hybrid
- Parallel hybrid
- Series-parallel or combined hybrid

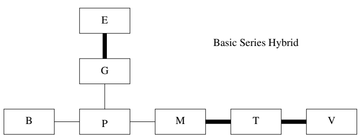
There are additional types that can not be classified into these three basic types

- Complex hybrid (sometimes)

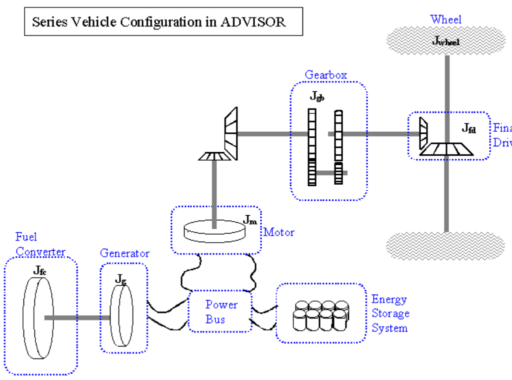
Series Hybrid – Topology



Sketch of the topology



Series Hybrid

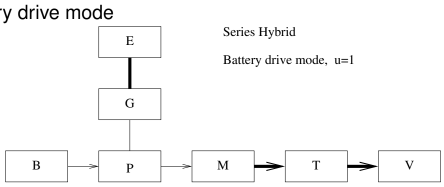


Series Hybrid – Modes and Power Flows

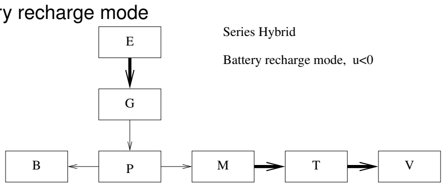
The different modes for a series hybrid

$$u \approx P_{batt}/P_{vehicle}$$

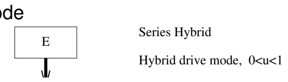
Battery drive mode



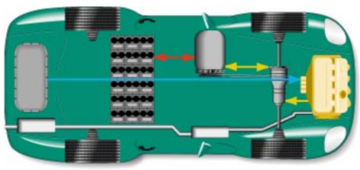
Battery recharge mode



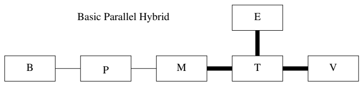
Hybrid drive mode



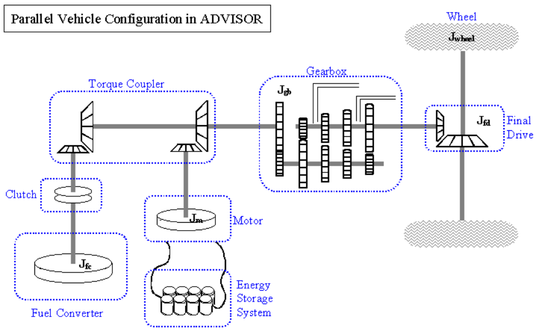
Parallel Hybrid – Topology



Sketch of the topology



Parallel Hybrid – Topology

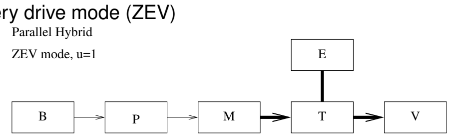


Parallel Hybrid – Modes and Power Flows

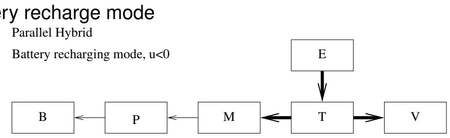
The different modes for a parallel hybrid

$$u \approx P_{batt}/P_{vehicle}$$

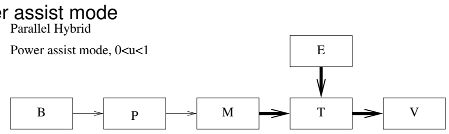
Battery drive mode (ZEV)



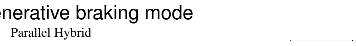
Battery recharge mode



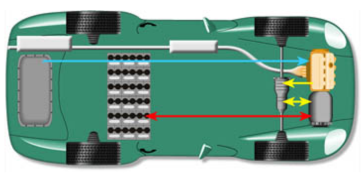
Power assist mode



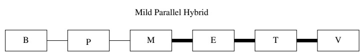
Regenerative braking mode



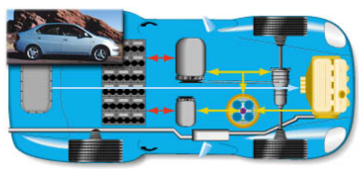
Mild Parallel Hybrid – Topology



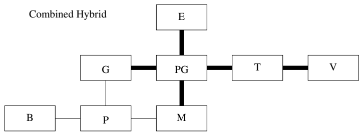
Sketch of the topology



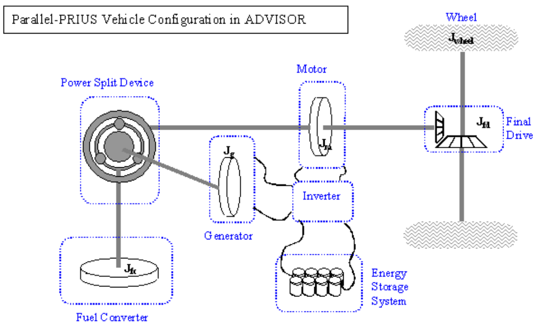
Combined Hybrid – Topology



Sketch of the topology



Combined Hybrid – Topology

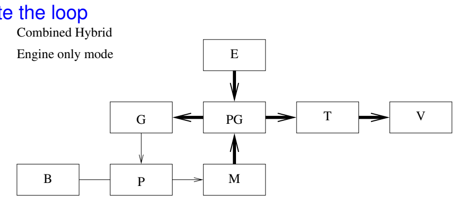


Combined Hybrid with PGS – Modes and Power Flows

The different modes for a combined hybrid

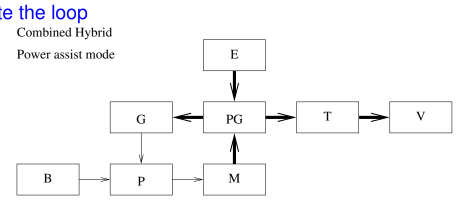
Conventional vehicle

–Note the loop

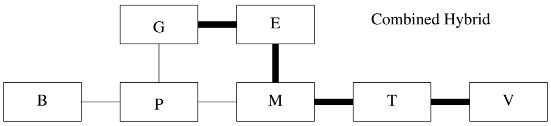


Power assist mode

–Note the loop



Combined Hybrid Without Planetary Gear



Degree of Hybridization

- Degree of hybridization
  –The ratio between electric motor power and engine power.
- Implemented hybrid concepts in cars
  Degree of hybridization varying between 15–55%
- True mild hybrid concepts
  Degree of hybridization varying 2–15%

Summary of different hybrid concepts

Feature	Conv.	Micro	Mild	Full	Plug-in
Shut of engine at stop-lights and stop-go traffic		(x)	X	X	X
Regenerative braking and operates above 42 V			X	X	X
Electric motor to assist a conventional engine			X	X	X
Can drive at times using only the electric motor				X	X
Recharges batteries using the wall plug with at least 32 km range on electricity					X

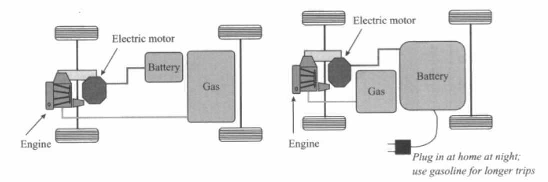
State Of Charge – SOC

- Charge condition for the battery.
- Full range SOC $\in$ 0–100%.
- Used range SOC $\in$ 50–70%.
- Generally difficult problem
  Models that include aging are not (yet) good enough.

Charge Sustaining Strategy

Charge Sustaining Strategies

- Basic control problem for a hybrid
  SOC after a driving mission is the same as it was in the beginning
  –Advisor simulation
- Plug-in hybrids
  Not charge sustaining



(a) Charge sustaining, or H0, hybrid architecture (b) Plug-in hybrid with electric range capability.

Outline

Electric Motors – Classification

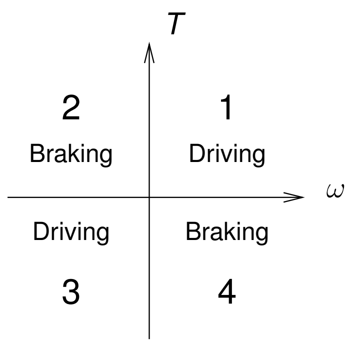
Electric motors are often classified into four groups (there are other classifications)

- DC-Machines
- Synchronous machines (sometimes including brushless DC-motor)
- Asynchronous machines
- Reluctance machines

There are also other devices:
Stepper motors (Digitally controlled Synchronous Machine), Ultrasonic motors.

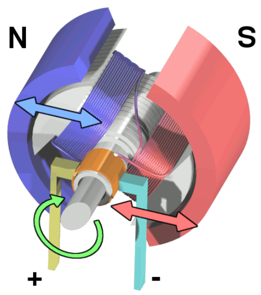
–Separate course: electrical drives.

The 4 Quadrants



1 - Motor, 4 - Generator, 2,3 - Reversing

Brushed DC-Machine



Wikipedia picture

Brush-type DC motor:

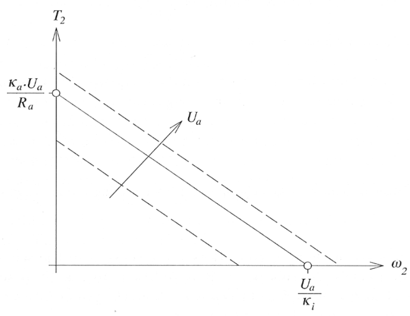
- Rotor
- Stator
- Commutator
- Two subtypes:
  –Permanent magnet
  –Separately excited

Pros and cons

+ Simple to control
– Brushes require maintenance

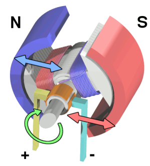
DC-motor torque characteristics

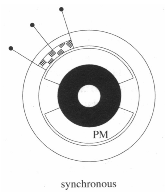
Characteristics of a separately excited DC-motor



Brushless DC-Motor

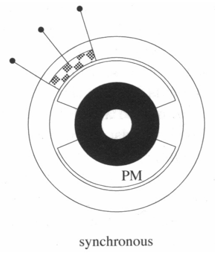
- Solves DC commutator and brushes problem
  - Replace electromagnet in rotor with permanent magnet (PM).
  - Rotate field in stator.
- DC-motor is misleading
  - DC source as input
  - Electronically controlled commutation system AC
- Linear relations between
  - current and torque
  - voltage and rpm





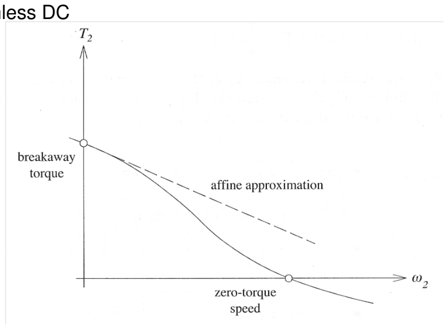
Synchronous AC machines

- AC machine
- Rotor follows the rotation of the magnetic field
- Has often *permanent magnets* in rotor
  –This is the same as the brushless DC motor.



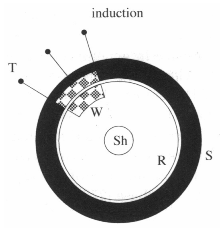
Torque Characteristics

Brushless DC



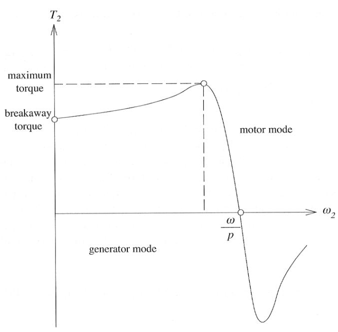
Asynchronous AC machines – Induction motors

- Stator has a rotating magnetic fiels
- Rotor has a set of windings, *squirrel cage*
  –See separate animation.
- Electric field induces a current in the windings
- Torque production depends on slip.



Torque Characteristics

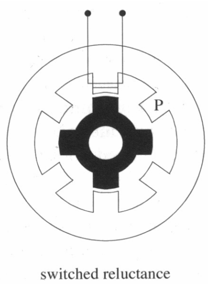
–Induction AC motor



Reluctance machines

Reluctance = Magnetic resistance.

- Synchronous machine
- Rotating field
- Magnetic material in the rotor
- Rotor tries to minimize the reluctance



Electrical Machines in Hybrids

Machines encountered

- Separately excited DC
- Permanent magnet synchronous DC
- Induction motors
- (Switched reluctance machines)
  –Considered to be interesting

AC motors (compared to DC motors)

Less expensive but more sophisticated control electronics, gives higher overall cost.
Higher power density, higher efficiency.

AC motors (permanent magnet vs induction motors)

Averaged values from Advisor database.

	Efficiency	Power density
permanent magnet	92.5 %	0.66 kW/kg
induction motors	90.5 %	0.76 kW/kg

Motor – Modeling

Quasistatic (equations are general)

- Power relationships:
  –input power $P_1(t)$
  –delivered power $P_2(t) = T_2(t)\,\omega_2(t)$
- Efficiency usage

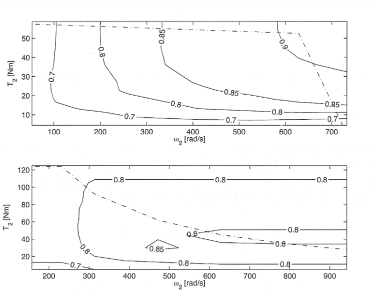
$$P_1(t) = P_2(t)/\eta_m(\omega_2(t), T_2), \qquad P_2(t) > 0$$

$$P_1(t) = P_2(t) \cdot \eta_m(\omega_2(t), -T_2), \qquad P_2(t) < 0$$

- Description of the efficiency in look-up tables
- Willans line to capture low power performance

First quadrant maps for η_m – AC machines

PM Synchronous



Induction motor, Asynchronous AC

Extending the Maps for η_m

- Traditional first quadrant drive is normally well documented
  –Supplier information for $\eta_m(\cdots)$
- Electric motor drive

$$P_2(t) = \eta_m(\omega_2(t), T_2) \cdot P_1(t), \qquad P_2(t) > 0$$

- Electric generator load

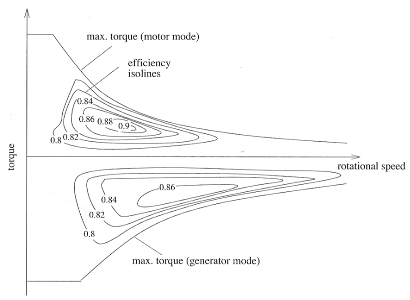
$$P_1(t) = \eta_g(\omega_2(t), T_2) \cdot P_2(t), \qquad P_2(t) < 0$$

- How to determine η_g?
- Method 1: Mirror the efficiency map

$$\eta_m(\omega_2(t), -T_2) = \eta_g(\omega_2(t), T_2)$$

- Method 2: Calculate the power losses and mirror them
- Method 3: Willans approach

Two Quadrant Maps for η_m



Mirroring efficiency is not always sufficient.

Motor – Modeling

- More advanced models
  - Use component knowledge: Inductance, resistance
  - Build physical models
- Dynamic models are developed in the book.

Outline

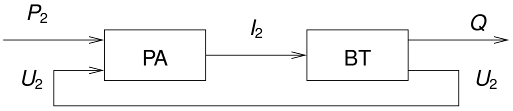
Batteries

- Energy storage devices – Energy density important
- Performance – Power density important
- Durability

Battery type	Energy Wh/kg	Power W/kg	cycles
Lead-acid	40	180	600
Nickel-cadmium	50	120	1500
Nickel-metal hydride	70	200	1000
Lithium-ion	130	430	1200

Modeling in QSS Framework

- Causality for Battery models in QSS.



- Models have two components
  - The first component is

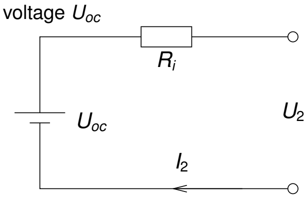
$$I_2 = \frac{P_2}{U_2}$$

  - The other, the relation between voltage and terminal current SOC

$$U_2 = f(SOC, I_2, \ldots)$$

Standard model

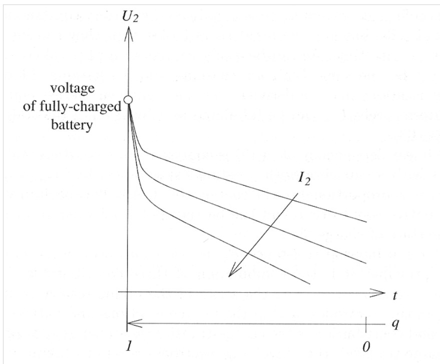
Simple model for the battery
–Open circuit voltage U_{oc}



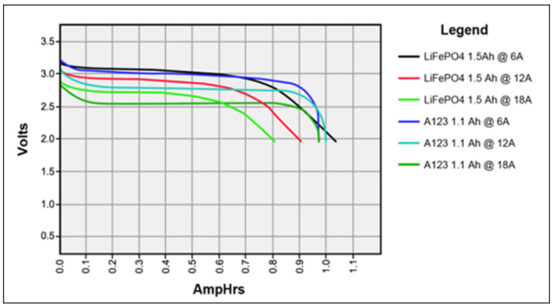
Output voltage

$$U_2 = U_{oc} - R_i\, I_2$$

Voltage and SOC



Voltage and SOC



Typical characteristics. Can extract inner resistance, and capacity.

(Source: batteryuniversity.com)

Battery – Efficiency definition

- Efficiency definition is problematic
  - Not an energy converter
  - Energy storage
  - Peukert test
    –Constant current during charge and discharge.
  - Ragone test
    –Constant power during charge and discharge.
- Efficiency will depend on the cycle.

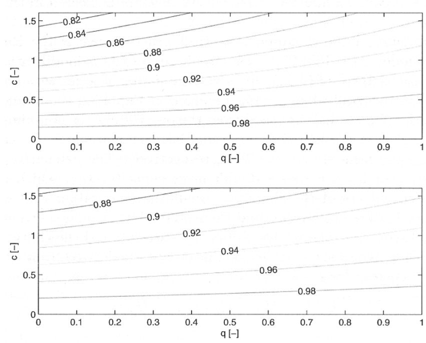
$$E_d = \int_0^{t_f} P_2(t)dt = /\text{Peukert test...}/ = t_f(U_{oc} - R_i \cdot I_2) \cdot I_2$$

$$|E_c| = \int_0^{t_f} |P_2(t)|dt = /\text{Peukert test...}/ = t_f(U_{oc} + R_i \cdot |I_2|) \cdot |I_2|$$

$$\eta_b = \frac{E_d}{E_c}$$

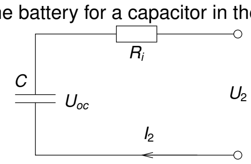
- Can also define an instantaneous efficiency.

Efficiency definition – Instantaneous



Supercapacitors

- Supercapacitors and ultracapacitors
- High power density
  –Used as short time scale energy buffer.
  –Load leveling to the battery.
- Very similar to battery in modeling
  Exchange the battery for a capacitor in the circuit below.



$$U_{oc}(t) = \frac{Q(t)}{C} = \frac{1}{C}\int I(t)dt$$

- Efficiency definitions
  Peukert and Ragone

Outline

Power Links

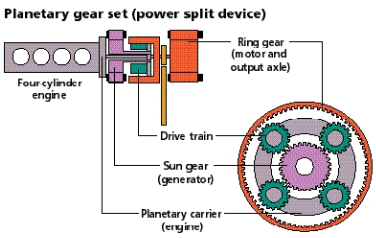
- Electrical glue components
  - DC-DC converters
  - DC-AC converter
- Account for power losses

Torque couplers

- Components that are included to:
  - Glue for mechanical systems acting on the same shaft
- Can include:
  - Gears in the coupling equation
  - Sub models for friction losses
- Basic equations
  –Angular velocities
  –Torque (from a power balance, including losses)

Power Split Devices

- Manage power splits between different components
- Important component for achieving flexibility
- Modeling approach: Speed relations with torque from power balance.



Can add more planetary gears

Outline

Implemented concepts

- Passenger cars
  - Parallel hybrids
  - Combined hybrids
  - Very few series hybrids (range extenders to EV).
- Trucks and busses
  - Series hybrids
  - Parallel hybrids
  - Combined hybrids
- Diesel trains
  – Series configuration but no storage

'08 List of Hybrid Passenger Cars (Incomplete)

- Chevrolet Silverado Hybrid Truck, Chevrolet Tahoe Hybrid
- Daihatsu Highjet
- Ford Escape, Ford Mercury Mariner Hybrid
- GMC Sierra Hybrid Truck, GMC Yukon Hybrid
- Highlander Hybrid
- Honda Accord Hybrid, Honda Civic Hybrid, Honda Insight Hybrid
- Landrover Hybrid
- Lexus GS450h, Lexus RX 400h
- Nissan Altima
- Porsche Cayenne Hybrid
- Saturn VUE Greenline Hybrid
- Suzuki Twin
- Toyota Alphard Hybrid, Toyota Camry, Toyota Estima Hybrid, Toyota Prius
- Twike