2018 Fall Professional Development Course
Electric-Drive Vehicle Technology

Topic 1:
Hybrid, Electric, and Fuel-Cell Vehicle Technology

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WAYNE STATE UNIVERSITY

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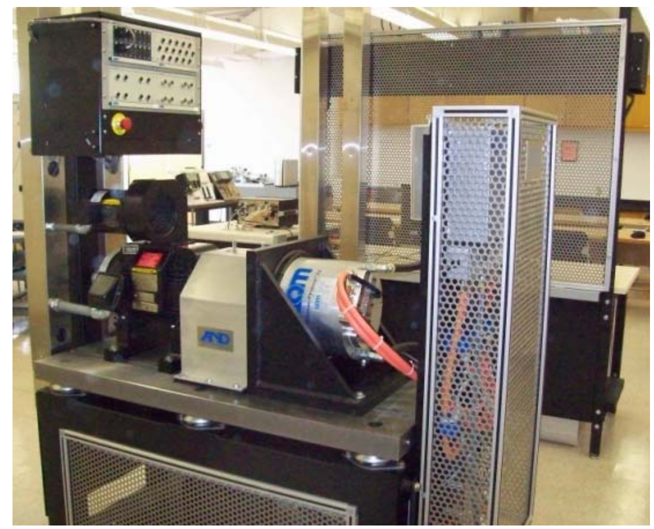
Center for Advanced Automotive Technology
C · A · A · T

Macomb Community College

Introducing the Instructors

Y. Gene Liao

- Professor and Director of Electric-drive Vehicle Engineering & Alternative Energy Technology; Engineering Technology, Wayne State University
- Doctor of Engineering, University of Michigan-Ann Arbor, 1999
- Consultant to: ASRC Primus/TARDEC, 2007-present
- University projects: NSF, DOE, DOL, DOC, 2003-present



Hybrid, Electric, and Connected Vehicle Technology

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I. **Roadmap of Vehicle Electrification**

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IV. Hybrid Powertrain Components

V. Future Directions: WTW, V2V, V2X

I. Roadmap of Vehicle Electrification

- What are Hybrid Vehicles?
- Why Hybrid Vehicles?
- Energy and Emissions
  - What is relevant for automotives?
- Motivations for Advanced Powertrains
- Types of Hybrid Vehicles
- Examples of HEV/PHEV/EVs

What are Hybrid Vehicles?

- Hybrid vehicles are powered by two or more sources of energy
- “Hybrid” can mean hybrid electric, mechanical hybrid, fuel cell hybrid, hydraulic hybrid, etc…
- Types of hybrid: hybrid electric, mechanical hybrids.
- Degree of hybridization
- Hybrid Electric Vehicle (HEV) types: series, parallel, mixed, charge-sustaining, charge-depleting

Why Hybrid Vehicles?

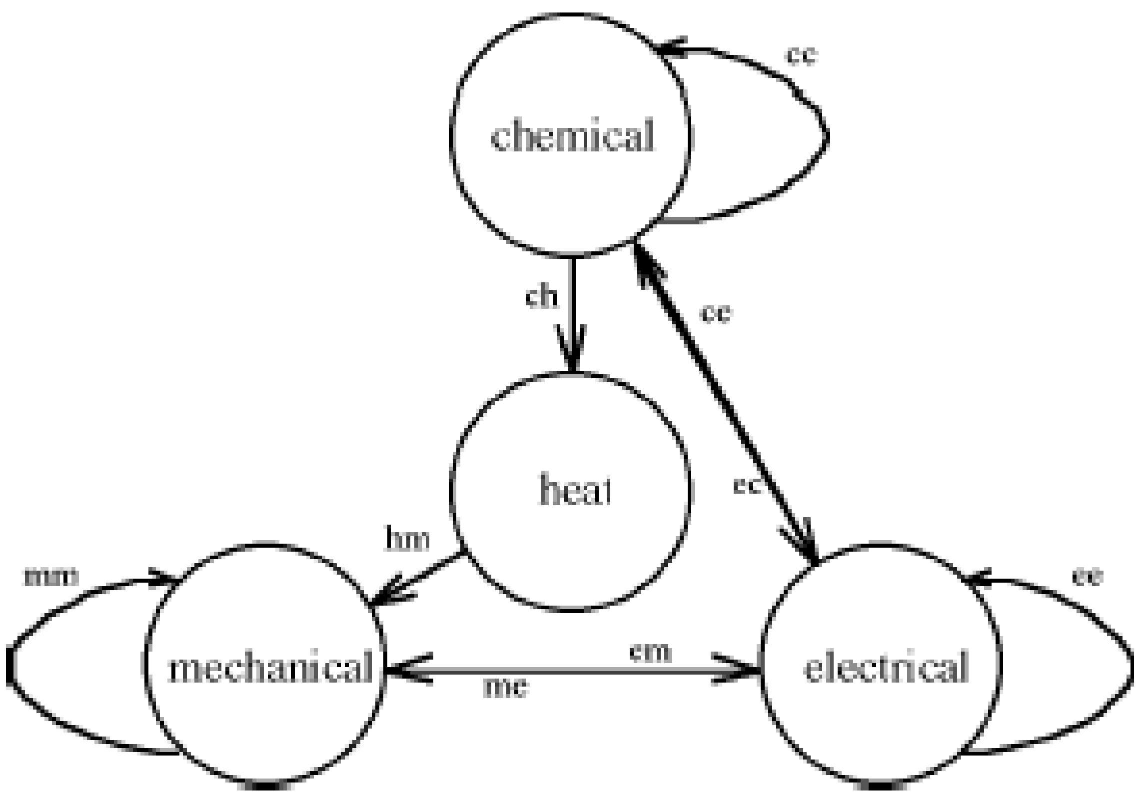
- Energy economy and emissions are and will continue to be primary concerns in the foreseeable future
- Sustainable mobility and renewable energy sources are the only long term solution
- Hybrid vehicles present medium term solution
- Economic considerations

What are Electric-Drive Vehicles?

HEV/PHEV, BEV, EV, FCEV (FCV), XEV

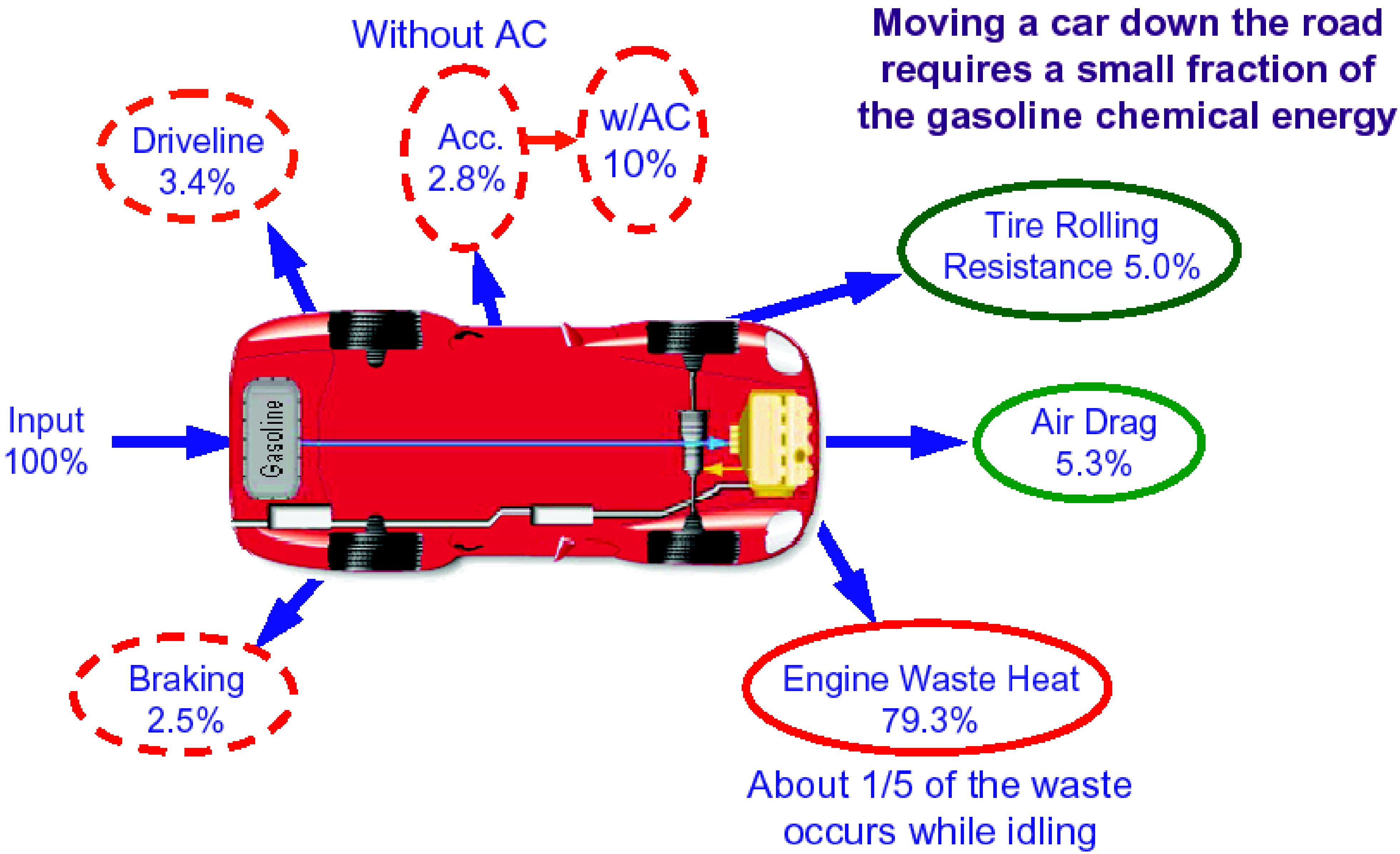
- Hybrid Vehicles are vehicles powered by two or more sources of energy
- "Hybrid" can mean hybrid electric, mechanical hybrid, hydraulic hybrid, etc…
- Degree of hybridization or electrification
- Hybrid Electric Vehicle (HEV) types: series, parallel, mixed.

Energy Flow in Vehicle



- Four energy forms are relevant in road vehicles:
  - Chemical
  - Electrical
  - Mechanical
  - Heat
- Significant energy can only be stored in chemical form

How efficient are conventional vehicles?



Motivations for Hybrid Powertrain

All these energy considerations contribute to the desirability of hybrid vehicles. Specifically, hybridization can attempt to address the following points:

- Operate the engine nearer its best efficiency.
- Downsize the engine (parallel hybrid case) and still meet the maximum power requirements.
- Use regeneration to restore some of the energy during deceleration instead of dissipating it as heat in the brakes.
- Eliminate or mitigate the idling losses by turning the engine on and off.

Why Hybrid Vehicles?

- Energy economy and emissions are and will continue to be primary concerns in the foreseeable future
- Sustainable mobility and renewable energy sources are the only long term solution
- Hybrid vehicles present medium term solution
- Economic considerations

HEV/PHEV/EV/FCV …

Energy and Emissions
– What is relevant for automotives?

- Maximize energy efficiency and emissions of vehicles, i.e., fuel utilization in the vehicle
  ⇒ hybrid electric vehicles, etc.

- Electric motors deliver maximum torque at low rpm so they are an ideal compliment to gasoline engines which generate best torque at higher rpm.

- Consider cost of energy and emissions upstream of vehicle, i.e., "well-to-wheel" (production, refining, distribution, …)

Hybrid Benefits and Features

Potential Hybrid Benefits

- Improved Fuel Economy
- Reduced Exhaust Emissions
- Improved Power Performance
- Combinations of the Above

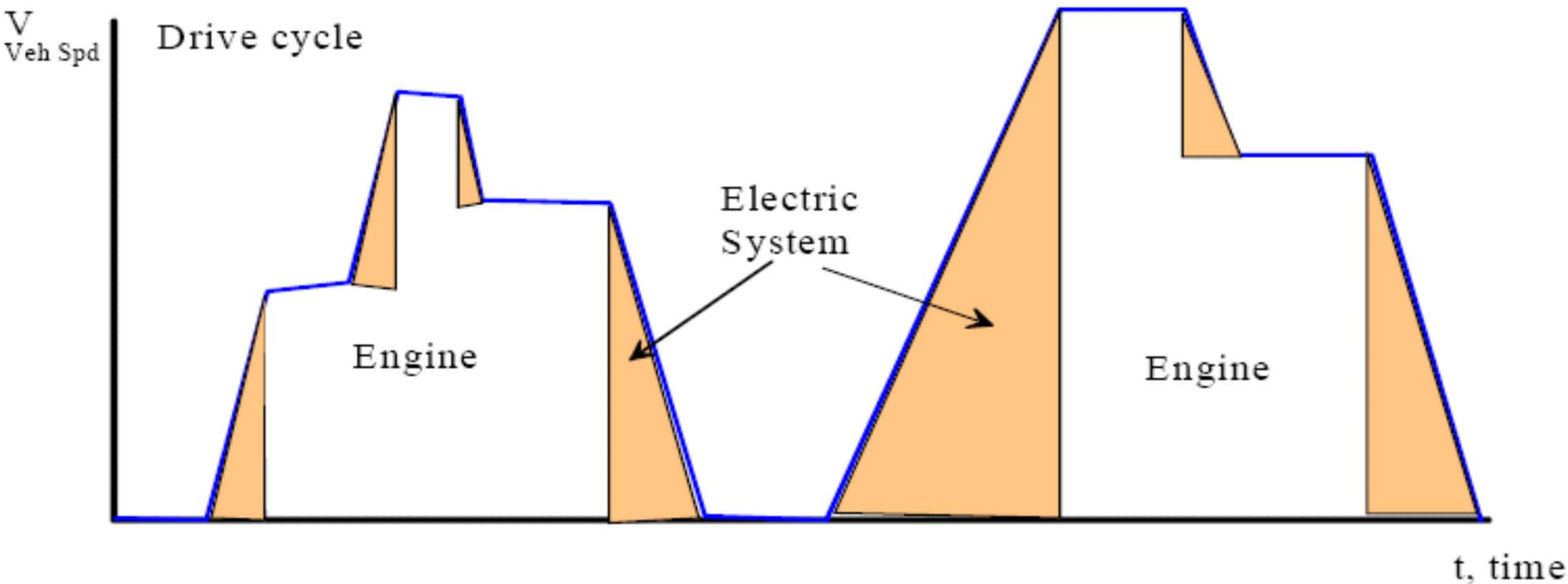
Potential Hybrid Features

- Idle Stop-Start
- Regenerative Braking
- Power Boost by Motor Assist
- Engine-off Driving: driven by electric only
- Battery Charging from the Grid

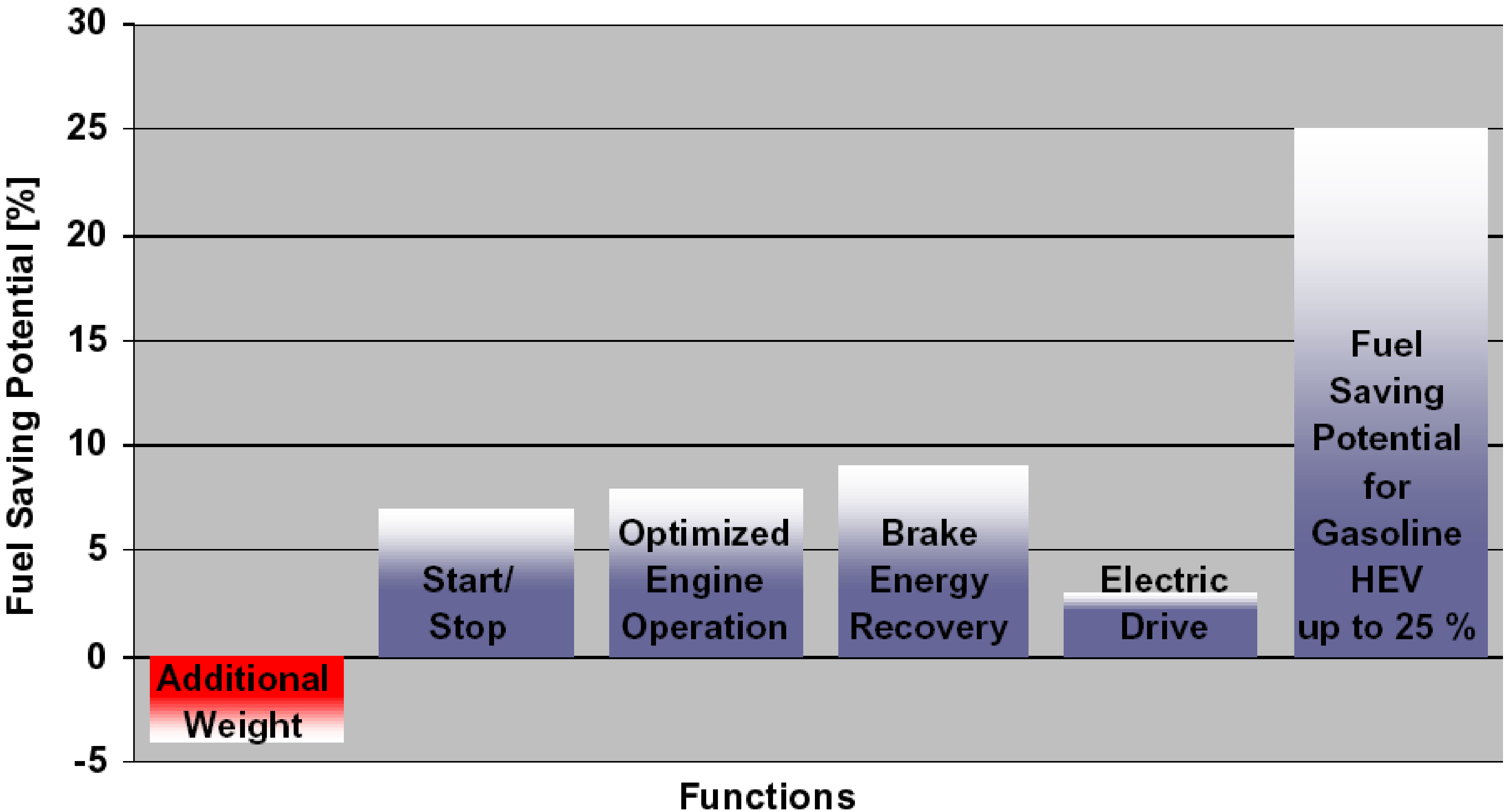
What Hybridization Does

Unloads transients from the engine

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



Fuel Saving by Hybrid Functions



Factors Affecting Vehicle Fuel Economy

Vehicle Attributes

- Weight
- Aerodynamics
  - •Drag Coeff.
  - •Frontal Area
- Parasitic Losses
  - •Accessories
  - •Driveline
  - •Brake Drag
  - •Bearings
  - •Wheels/Tires

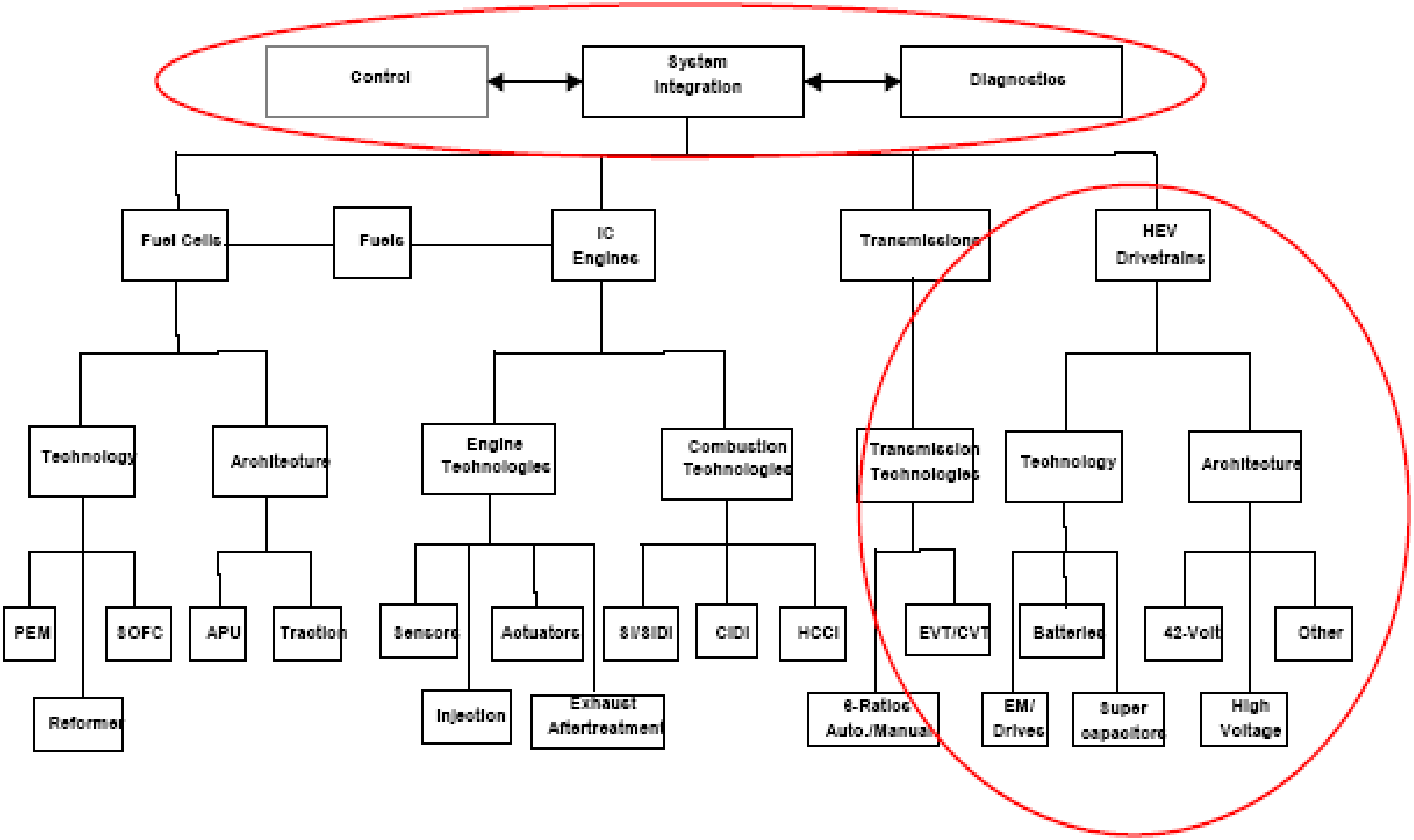
Powertrain Attributes

- Engine
  - •Parasitic Losses
  - •Thermal Eff.
  - •Dynamic Range
- Transmission
  - •Parasitic Losses
  - •Dynamic Range
- Hybridization
  - •Increase Eff.
  - •Reduce Losses

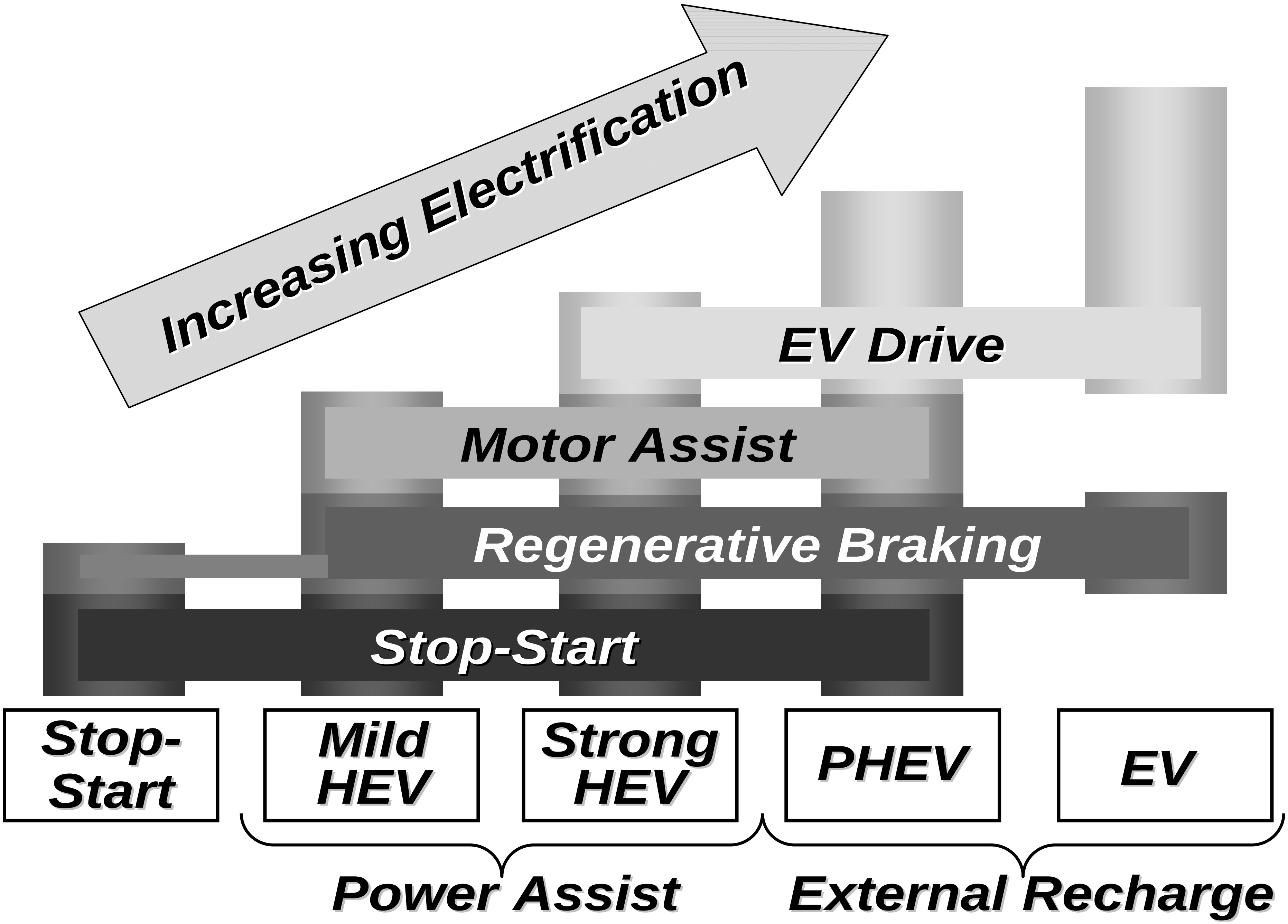
Operating Conditions

- Drive Cycle
  - •Speed
  - •Load
  - •Acceleration
- Functional Requirements
  - •Reserve Power
  - •Trailer Tow
  - •Gradeability
  - •Emissions
  - •Durability

Overview of Advanced Automotive Powertrains



Features with HEV Types (1)



II. Hybrid Powertrain Configurations

Parallel Hybrid

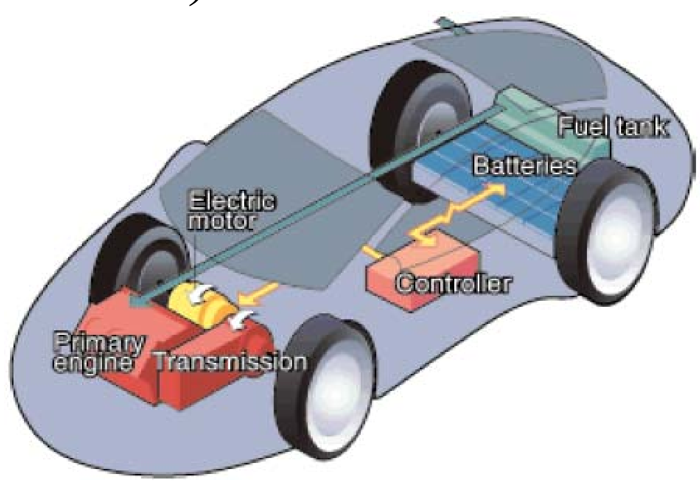
Primary energy source: fuel tank

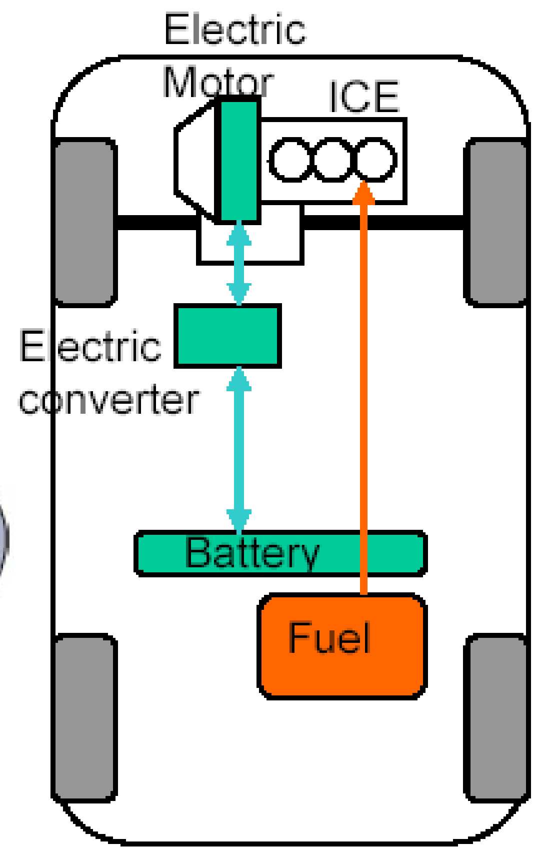
Electrical secondary energy source (batteries)

One-way energy flow from fuel tank to vehicle (mech.)

Two-way energy flow to/from secondary energy storage to/from vehicle (mech., elec.)

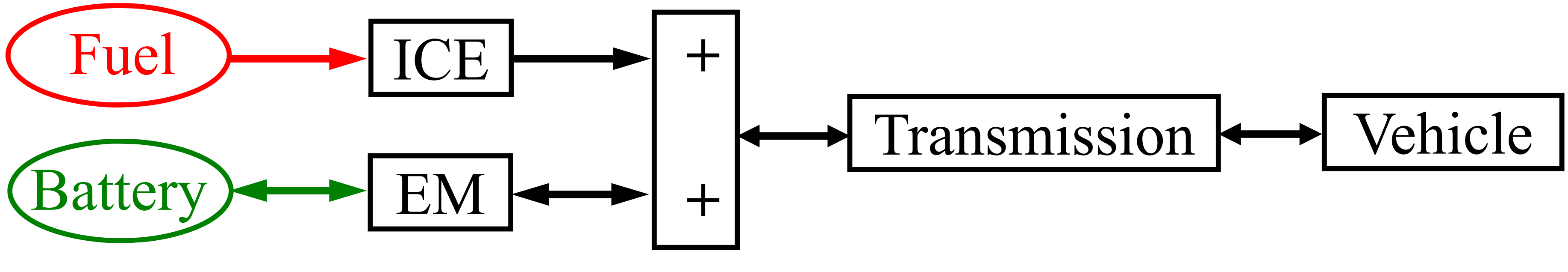
Power summation is mechanical (same shaft or parallel shafts)

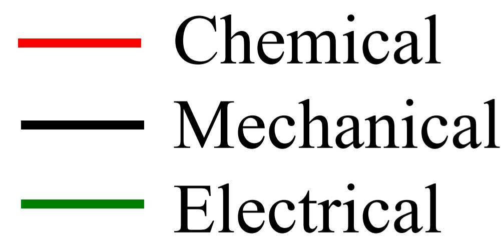




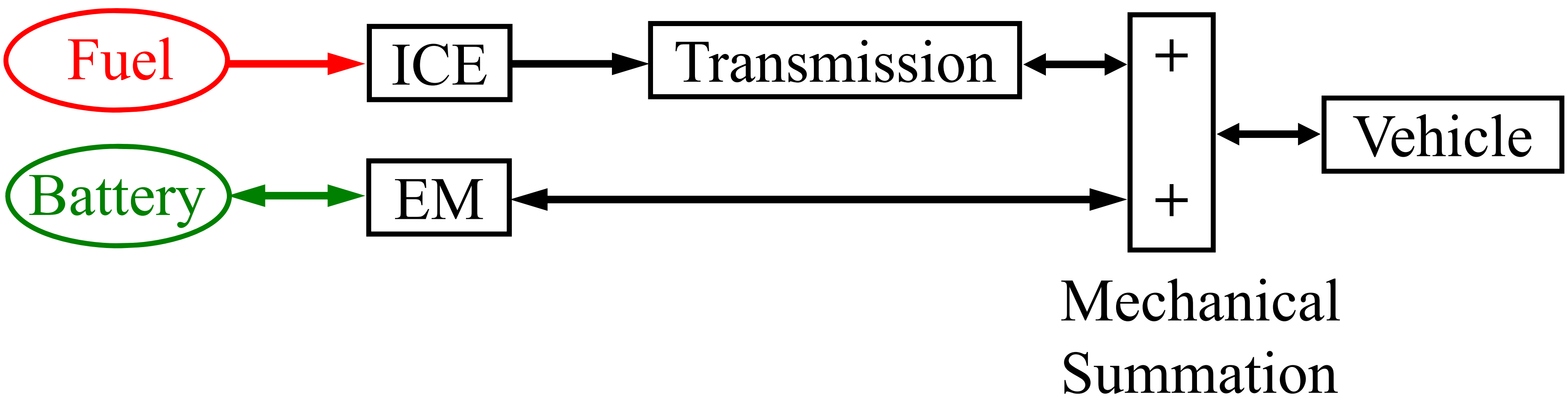
Parallel Hybrid Topologies

Mechanical coupling, Post-transmission





Mechanical coupling, Pre-transmission



Series Hybrid

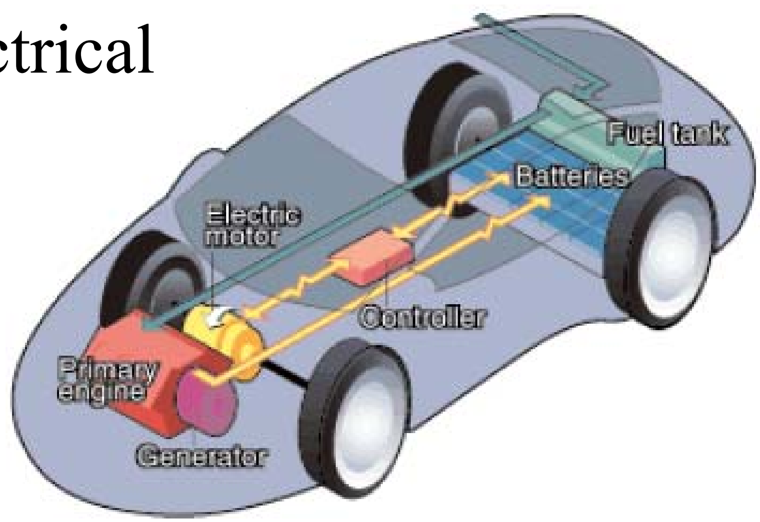
Primary energy source: fuel tank

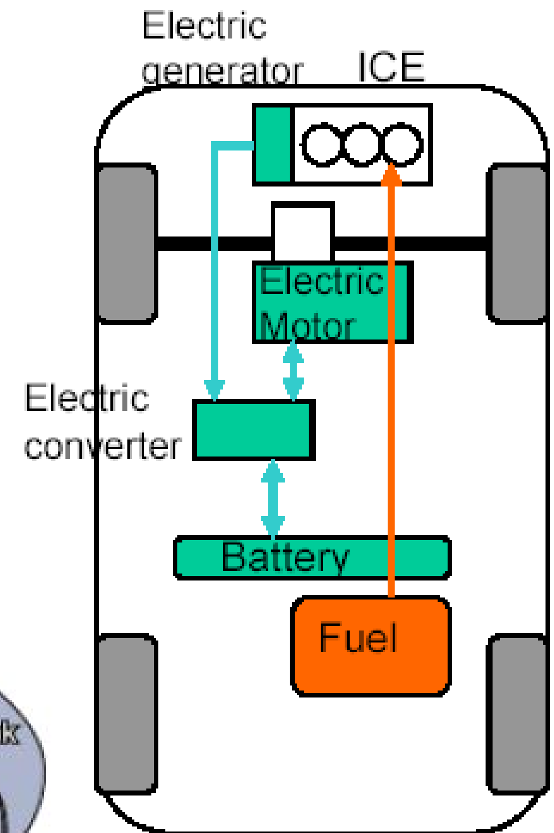
Electrical secondary energy source (batteries)

One-way energy flow from fuel tank to generator (mech.) to vehicle (elec.)

Two-way energy flow to/from secondary energy storage to/from vehicle

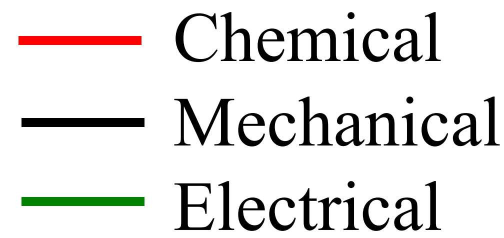
Power summation is electrical

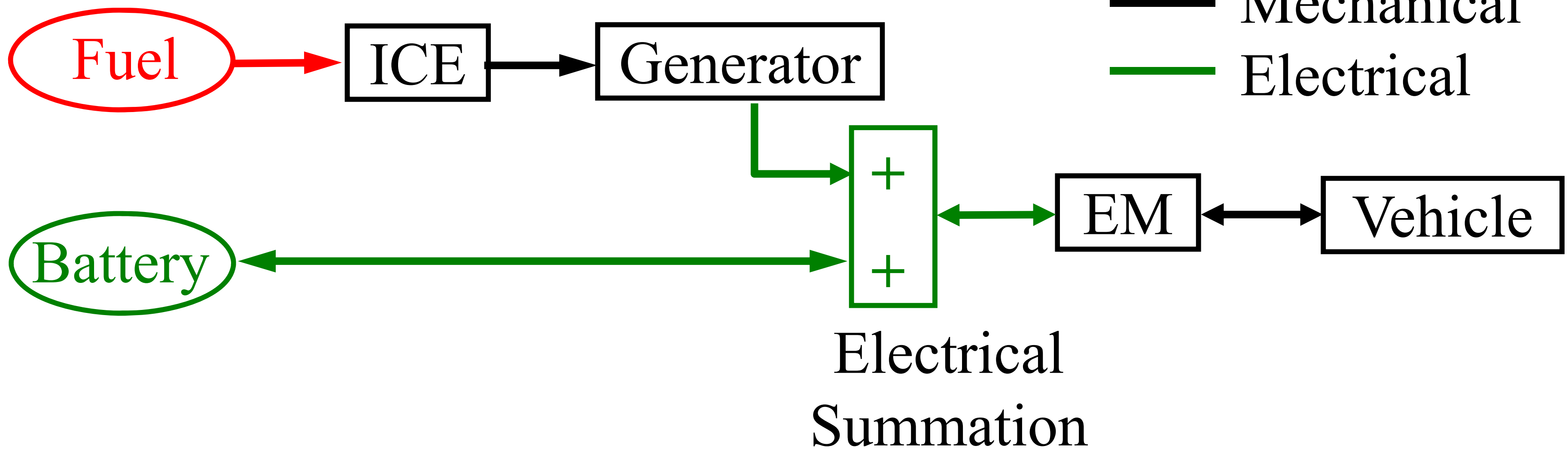




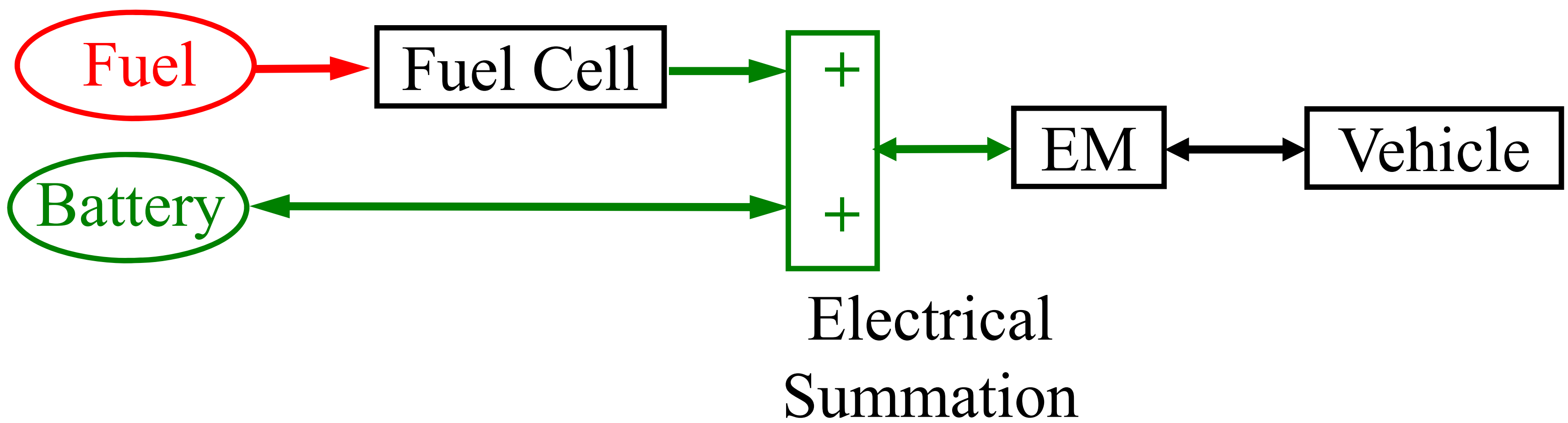
Series Hybrid Topologies

Electrical coupling



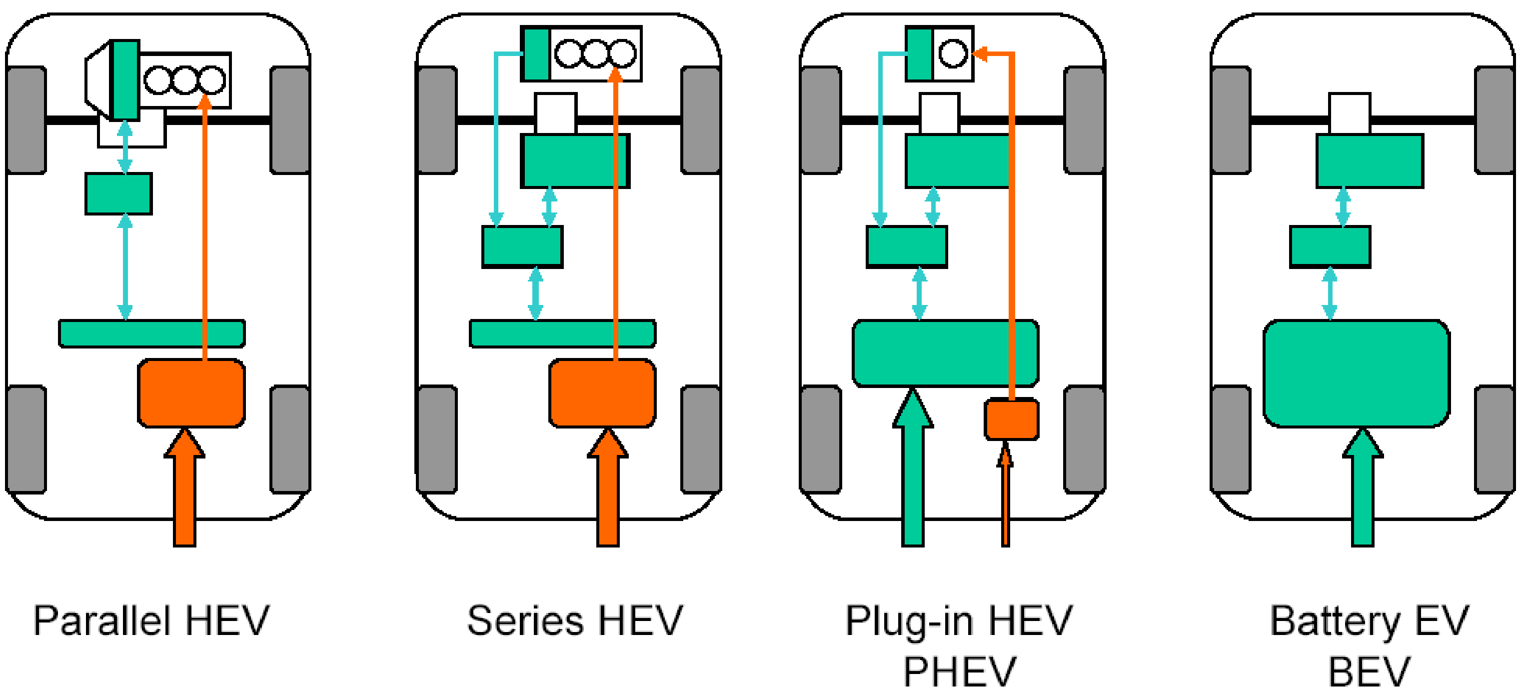


Fuel Cell Hybrid (Series Hybrid) - Electrical coupling



Plug-in Hybrid Electric Vehicle (PHEV)

- Typical vehicle usage is for urban commuting
  - 80% of trips are less than 10km and over 90% are less than 20km
- Augment the hybrid battery pack to allow electric only operation for limited range sufficient for daily commute (say 20km – PHEV20)
- Charge the battery from the electricity grid overnight
  - so this energy does not come from fuels
- Use fuels to allow longer trips



Definition of PHEV

Charge Depleting: Charge-depleting mode allows a fully charged PHEV to operate exclusively (or depending on the vehicle, almost exclusively, except during hard acceleration) on electric power alone until its battery state of charge is depleted to a predetermined level, at which time the vehicle's internal combustion engine or fuel cell will be engaged.

Charge Sustaining: Charge-sustaining mode is used by production HEV today, and combines the operation of the vehicle's two power sources in such a manner that the vehicle is operating as efficiently as possible without allowing the battery state of charge to move beyond some predetermined band.

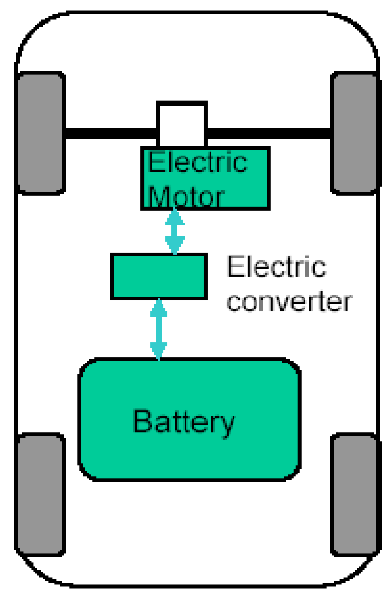
All Electric Range (AER): In a charge depleting mode, the range/period that the vehicle operates on electrical power exclusively.

PHEV20/40/60: Typically defined as a PHEV that has # of miles of AER. (i.e. PHEV20 has a 20 mile all electric range)

Electric Vehicle (EV)
Battery Electric Vehicle (BEV)

EVs have an electric only drivetrain.

- No energy conversion (e.g. ICE), rather electrical energy stored directly in battery.
- If original source of energy is converted directly to electricity, this is the most efficient W2W.
- Long range requires a large expensive battery pack
- Charge overnight from grid
  - no new fuel infrastructure required



HEVs vs. EVs

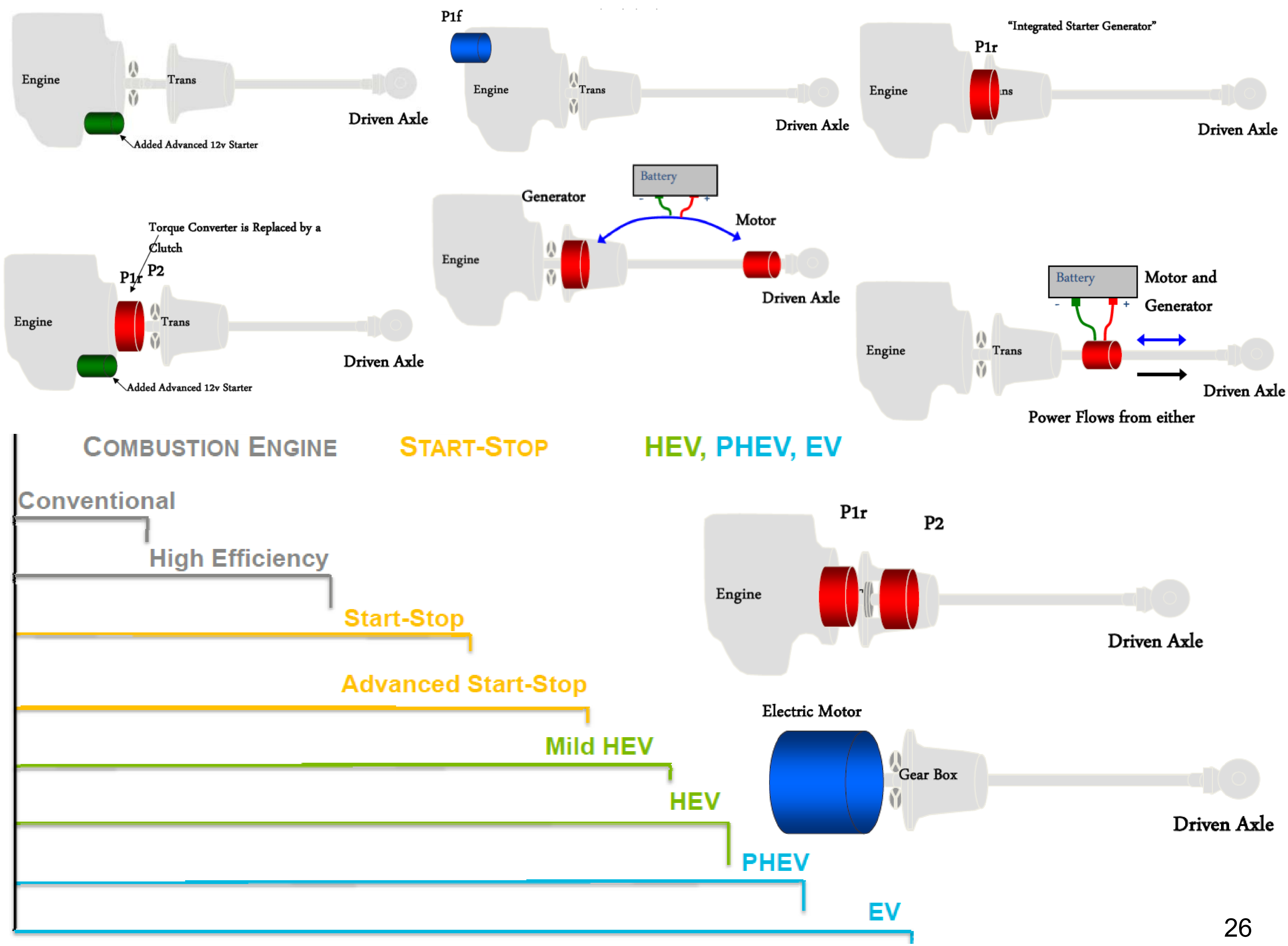
Hybrids (HEVs)

- Minimised battery pack
  - \+ Cheaper
  - \+ Long range
  - \+ Manageable lifetime
- ICE based drivetrain
  - – Incremental efficiency gain
  - – dependant on fuels

Electric Vehicles (BEVs)

- Large battery pack
  - – Expensive
  - – Limited range
  - – Uncertain life
- Pure electric drivetrain
  - \+ Excellent energy efficiency
  - \+ Independence from fuels

- Can we achieve the best of both worlds?
  - – Energy efficiency, fuel independence, and zero urban emissions by using grid electricity
  - – Long range and minimised battery requirements of a HEV


Engine
Trans
Driven Axle
Added Advanced 12v Starter
P1f
Engine
Trans
Driven Axle
"Integrated Starter Generator"
P1r
Engine
Driven Axle
Torque Converter is Replaced by a Clutch
P1r
P2
Engine
Trans
Driven Axle
Added Advanced 12v Starter
Battery
Generator
Motor
Engine
Driven Axle
Battery
Motor and Generator
Engine
Trans
Driven Axle
Power Flows from either
COMBUSTION ENGINE
START-STOP
HEV, PHEV, EV
Conventional
High Efficiency
Start-Stop
Advanced Start-Stop
Mild HEV
HEV
PHEV
EV
P1r
P2
Engine
Driven Axle
Electric Motor
Gear Box
Driven Axle

Micro Hybrid

– belt-drive starter/alternators or automated starters

– fuel saving: 3-10%, but up to 20% in heavy traffic.

– best for: urban delivery vans, Gasoline city cars.

Mild Hybrid

– small motor supplementing down-sized engine

– fuel saving:15-25% – half or more from engine downsizing

– best for: cost-effective gasoline family vehicles with mixed usage.

Full (Strong) Hybrid

– 1 or 2 electric motors of significant power.

– electric drive capability

– many different arrangements of engine & motors

– fuel saving: 30-50% – with some benefit shown at high speed cruise (transient response)

– best for: family or premium vehicles (incl SUVs) with tendency to urban use.

Micro Hybrid: Stop/Start System

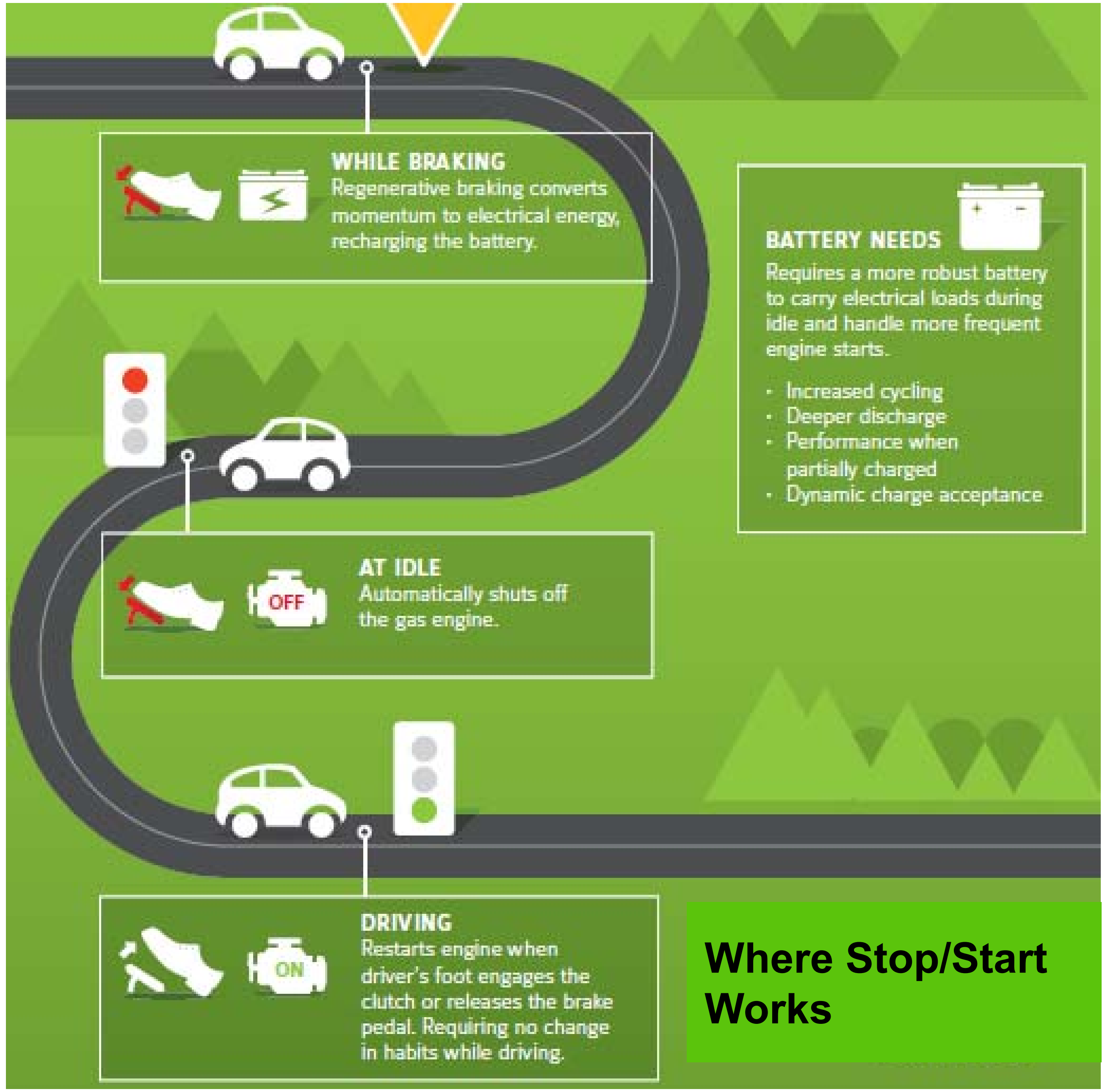
Purpose: conserves energy by automatically shut off the whenever the vehicle comes to a stop

How It Works:

- Automatically shut off the engine whenever the vehicle comes to a stop, for example at traffic lights;
- Automatically re-starting it as soon as the brake is released;
- An important energy-saving building block used in hybrid vehicles;
- Not true hybrids, but the lowest-cost hybrid alternative;
- Suitable for cold starts in diesel engines.

Vehicle parameters that influence frequency of stop/start events

- Vehicle speed
- Engine and transmission operating temperatures
- Ambient air temperature
- Shift lever position and brake pedal position
- Battery state of charge
- Climate control system setting
- Auto stop time



Micro Hybrid: Stop/Start System

(1) the starter motor with modified parts to allow re-cranking of the engine
- Bosch Smart Electronic stop-start system

(2) the generator acts as a reversible machine which starts the engine in starter mode
- Valeo StARS

Micro Hybrid: Stop/Start System

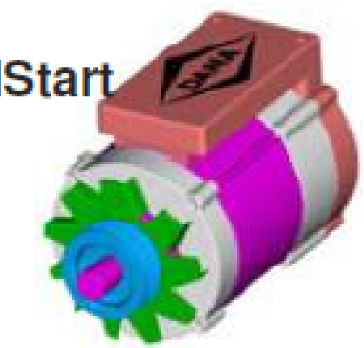
Bosch / RSG

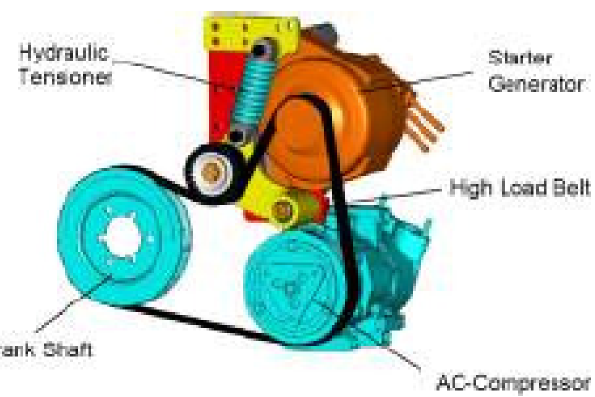
Iskra

DENSO

LuK / BAS

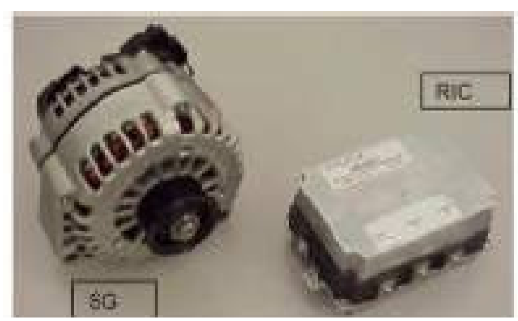
Dana / RapidStart



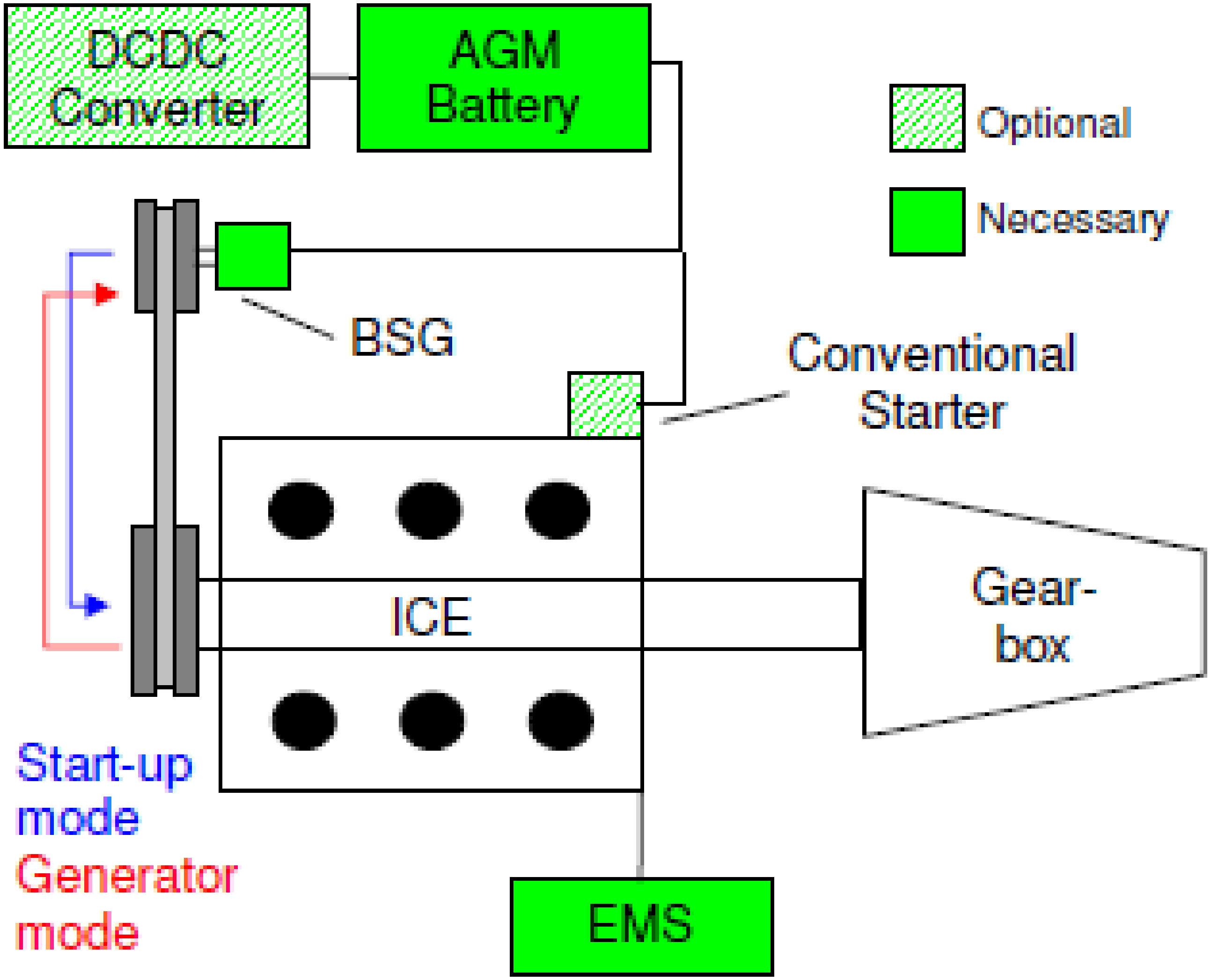


Gates

Hitachi / SG



Delphi / Energen



Mostly used Sensors

- Intelligent battery sensor
- Ambient temperature sensor
- Bonnet switch
- Clutch sensor
- Neutral gear sensor
- Driver belt sensor
- Ambient temperature sensor
- Brake pressure sensor
- Engine temperature sensor

Features

- Start-stop functionality
- Intelligent generator control
- Normal starter only necessary for bigger engines
- Optional DCDC Converter for stabilizing the 12V board net

Abbreviations

- AGM: Absorbent Glass Mat
- EMS: Engine management system
- ICE: Internal Combustion engine

Pros:

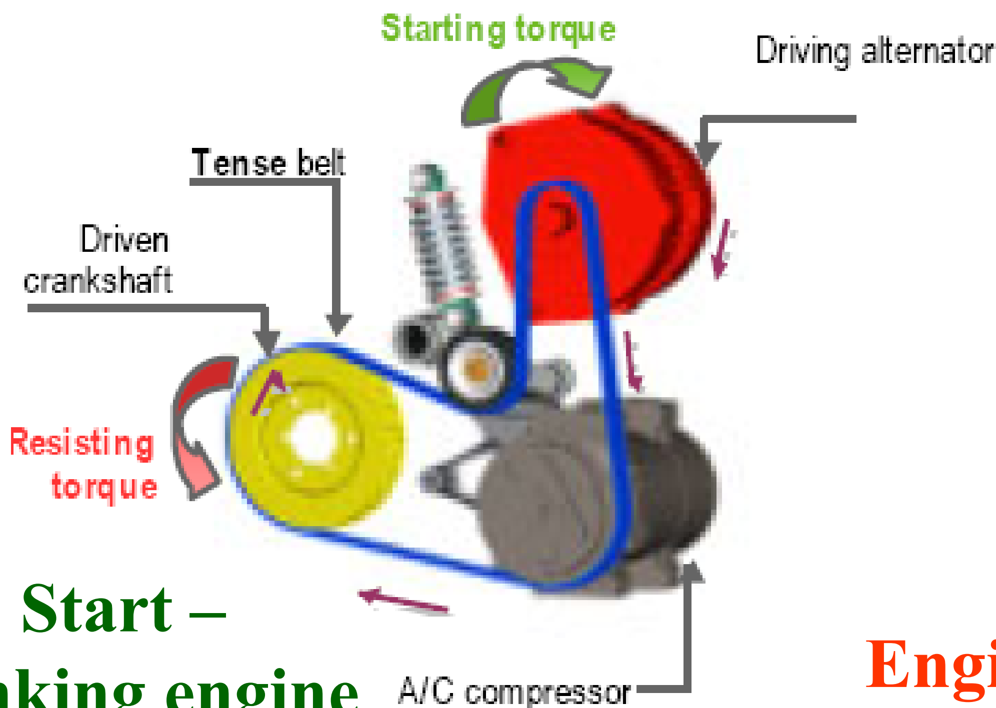
- Easy to integrate
- No additional starter necessary (in case of small engines)
- Smooth restart

Cons:

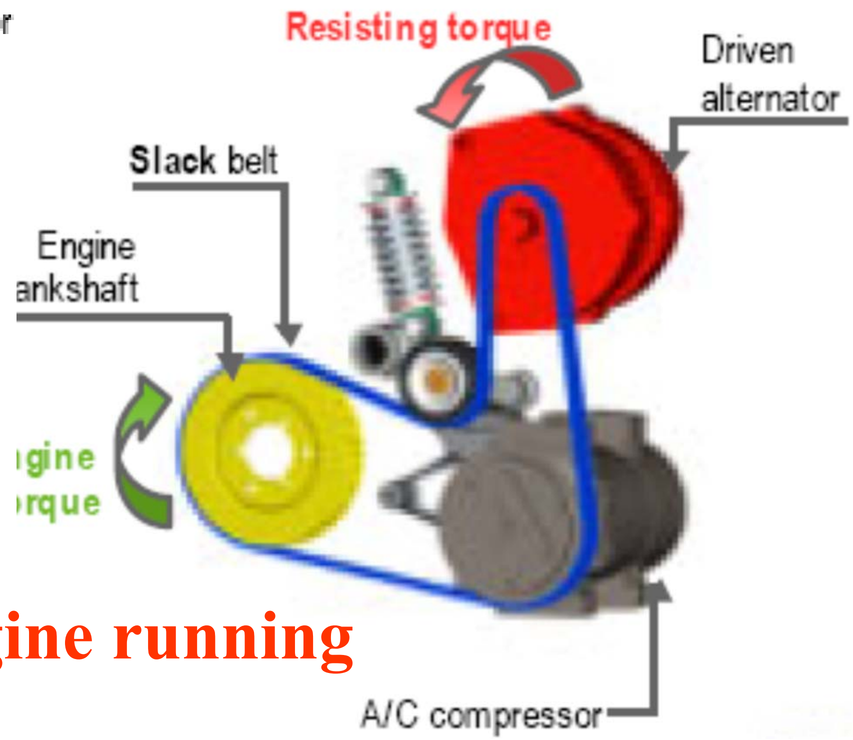
- Belt drive system has to be changed
- Cold start is difficult with bigger engines (additional conventional starter required)
- Flywheel has to be modified

Micro Hybrid: Stop/Start System - Valeo StARS

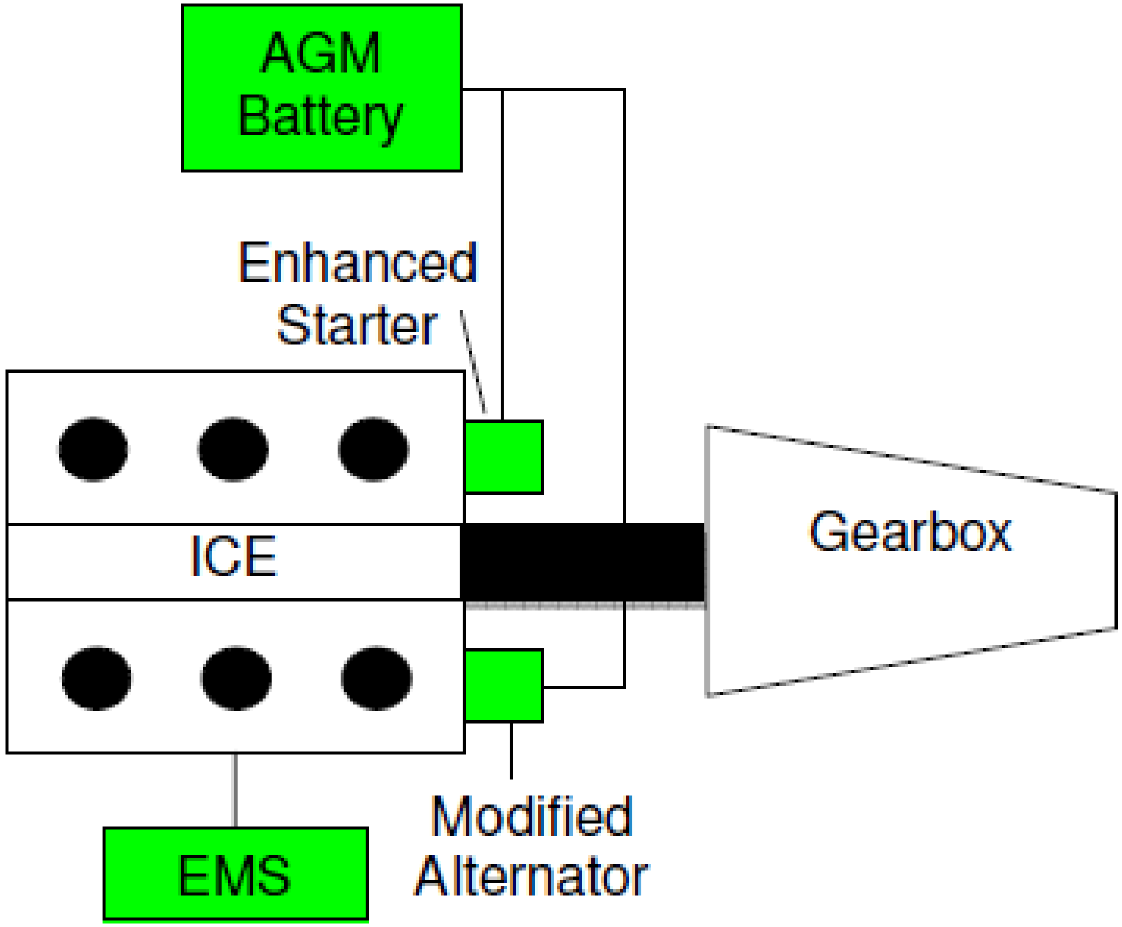
- a electrical machine with its control unit
- a bidirectional DC/DC converter
- an EDLC (Electric Double Layer Capacitor - supercapacitor)



Start – cranking engine



Engine running



Mostly used Sensors

- Intelligent Battery Sensor
- Ambient temperature sensor
- Bonnet switch
- Clutch sensor
- Neutral gear sensor
- Driver belt sensor
- Ambient temperature sensor
- Brake pressure sensor
- Engine temperature sensor

Features

- Start-stop functionality
- Intelligent generator control
- only possible with direct injection

Abbreviations

- AGM Absorbent Glass Mat
- EMS Engine management system
- ICE: Internal Combustion engine

Pros:

- Cheap solution

Cons:

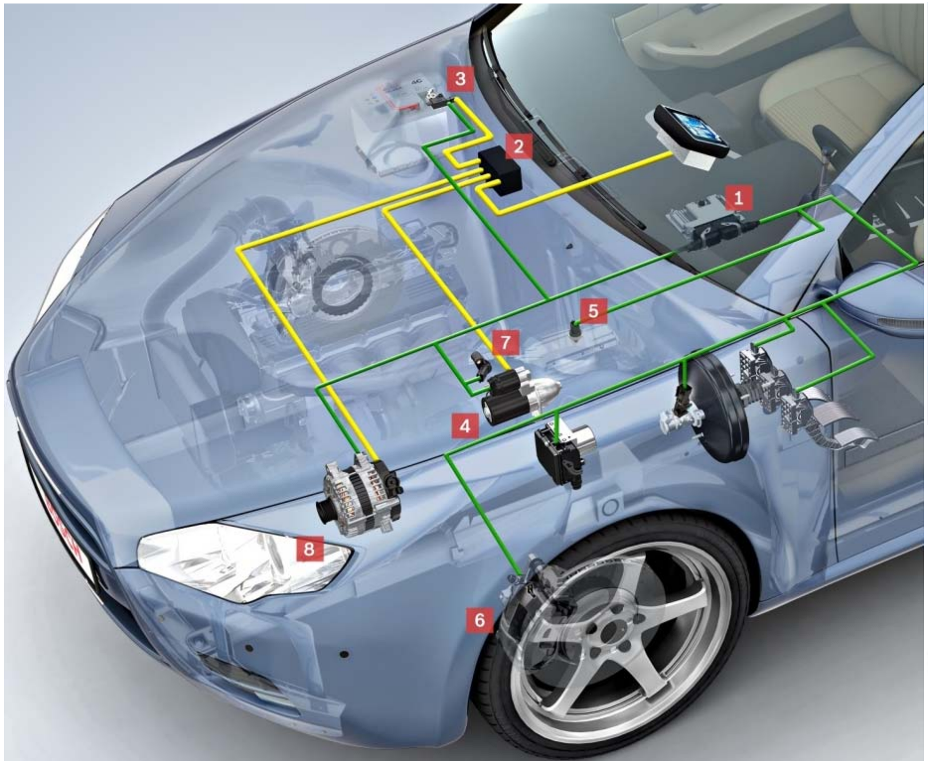
- Not very comfortable restart
- Only with the latest systems a restart from a certain speed possible

Supplier Solutions

- Bosch: Efficiency Line (EL) Products
- Denso: Enhanced Starter Products

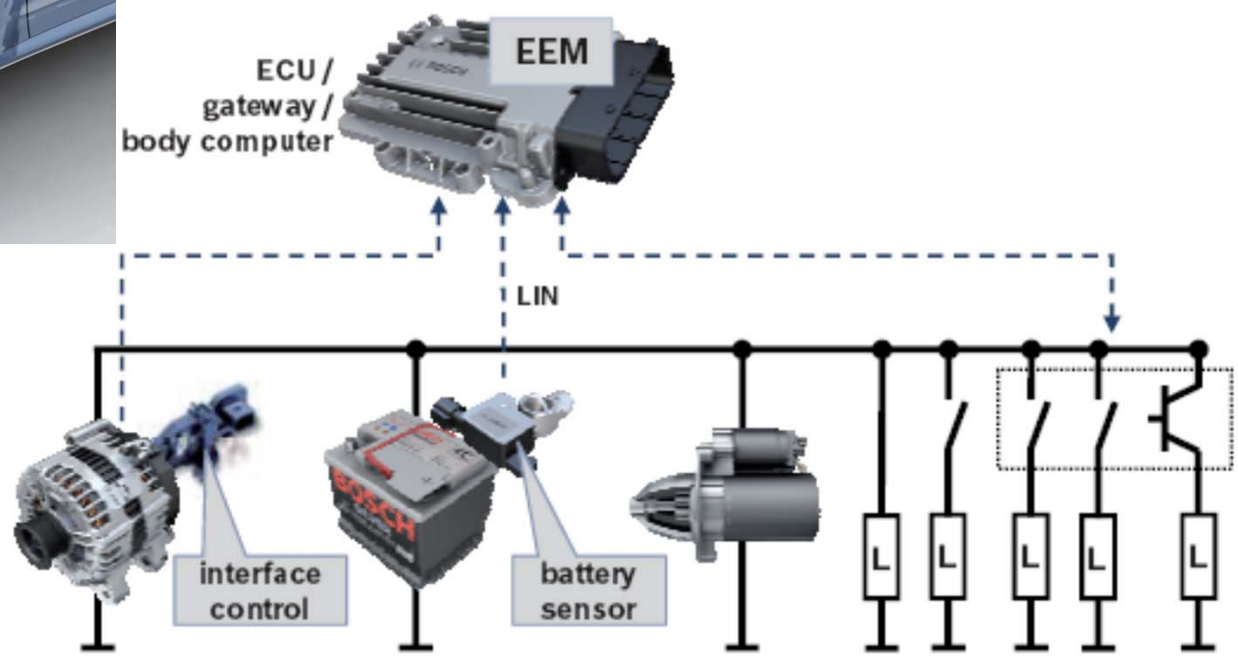
Micro Hybrid: Stop/Start System

Bosch Starter



1. engine control unit with software option start/stop
2. DC/DC converter 12-volt
3. electronic battery sensor
4. start/stop starter motor
5. neutral gear sensor
6. wheel speed sensor
7. crankshaft sensor

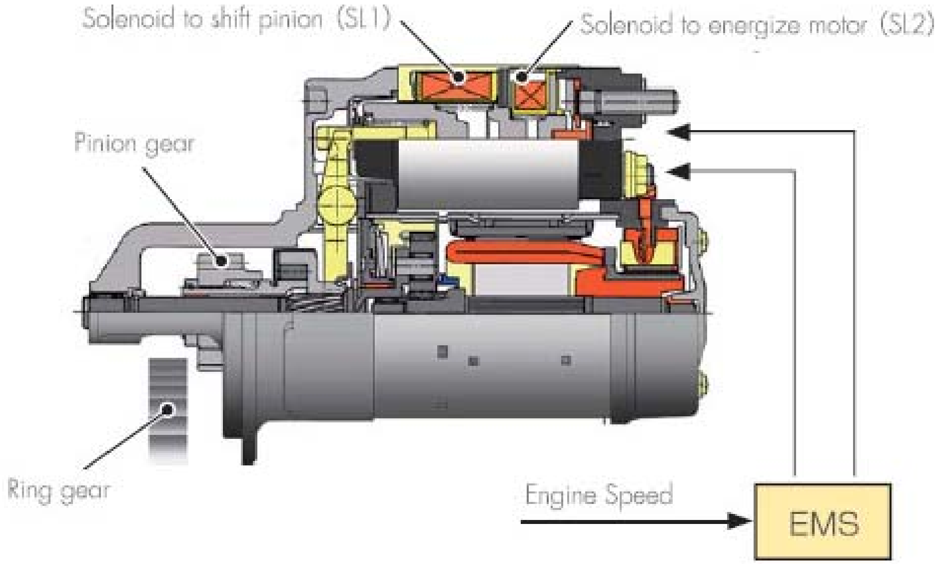
- power supply 12-volt (yellow)
- communication (green)



The number of starting operations to be performed by a starter motor in a vehicle with start-stop technology has increased considerably as compared to that of conventional vehicle.

- Bosch claims greater design strength such as strengthening of bearings subjected to heavy loading,
- improvement of planetary gear mechanism,
- strengthening of pinion-engaging mechanics,
- optimization of commutator for longer life

Denso: Tandem Solenoid (TS) Starter



Possible to engage in rotating ring gear by controlling SL1 and SL2 independently.

A co-axial dual solenoid for independent control of the starter's pinion gear shifting mechanism and motor rotation. One solenoid engages the pinion gear with flywheel ring gear and the other energizes the motor. Special software is used to control the timing and synchronization aspects for pinion gear shifting into the spinning flywheel; possibly with a crankshaft position sensor because as the flywheel is coming to a stop, its clockwise rotation may be combined with counterclockwise oscillation, increasing the complexity for engagement strategy. A sensor can identify these oscillation and precisely determine crankshaft position.

It does not needs to wait for the engine speed to reach zero speed before restarting and also as it can engage into a moving flywheel, allowing quicker restart times as compared to Advanced Engagement starter.

Examples of Micro Hybrid: Stop/Start System

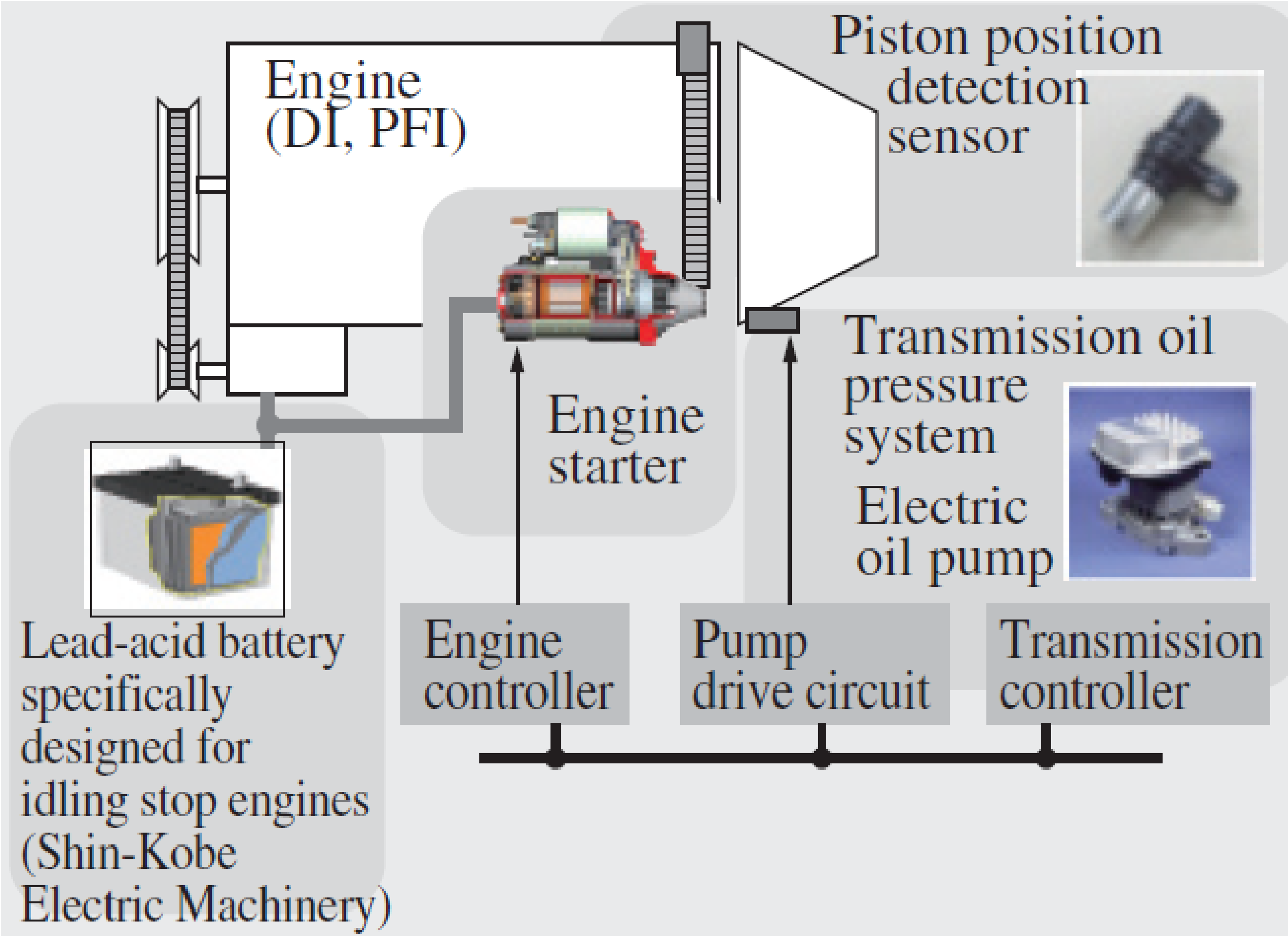
Ford Focus

Ford Transit

Fiat 500

Mercedes-Benz A-class

BMW 3-series



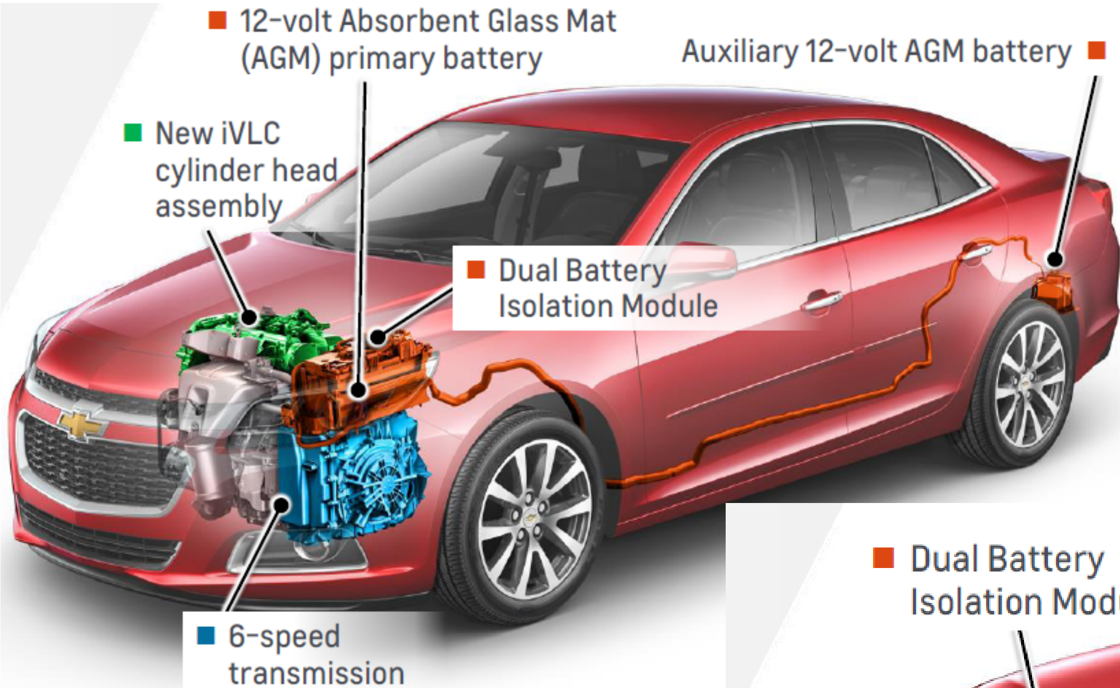
Engine (DI, PFI)
Piston position detection sensor
Engine starter
Transmission oil pressure system
Electric oil pump
Lead-acid battery specifically designed for idling stop engines (Shin-Kobe Electric Machinery)
Engine controller
Pump drive circuit
Transmission controller

Mercedes-Benz ECO Stop/Start

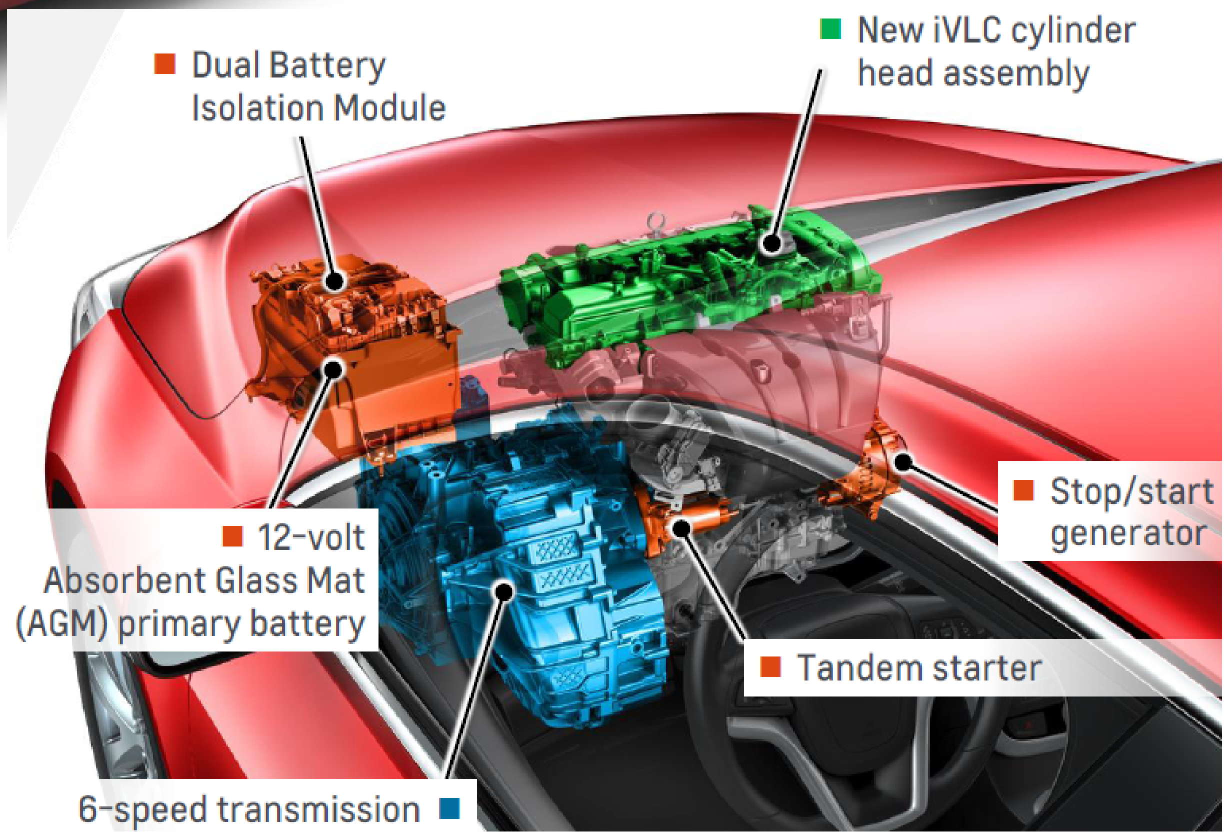
CLA class

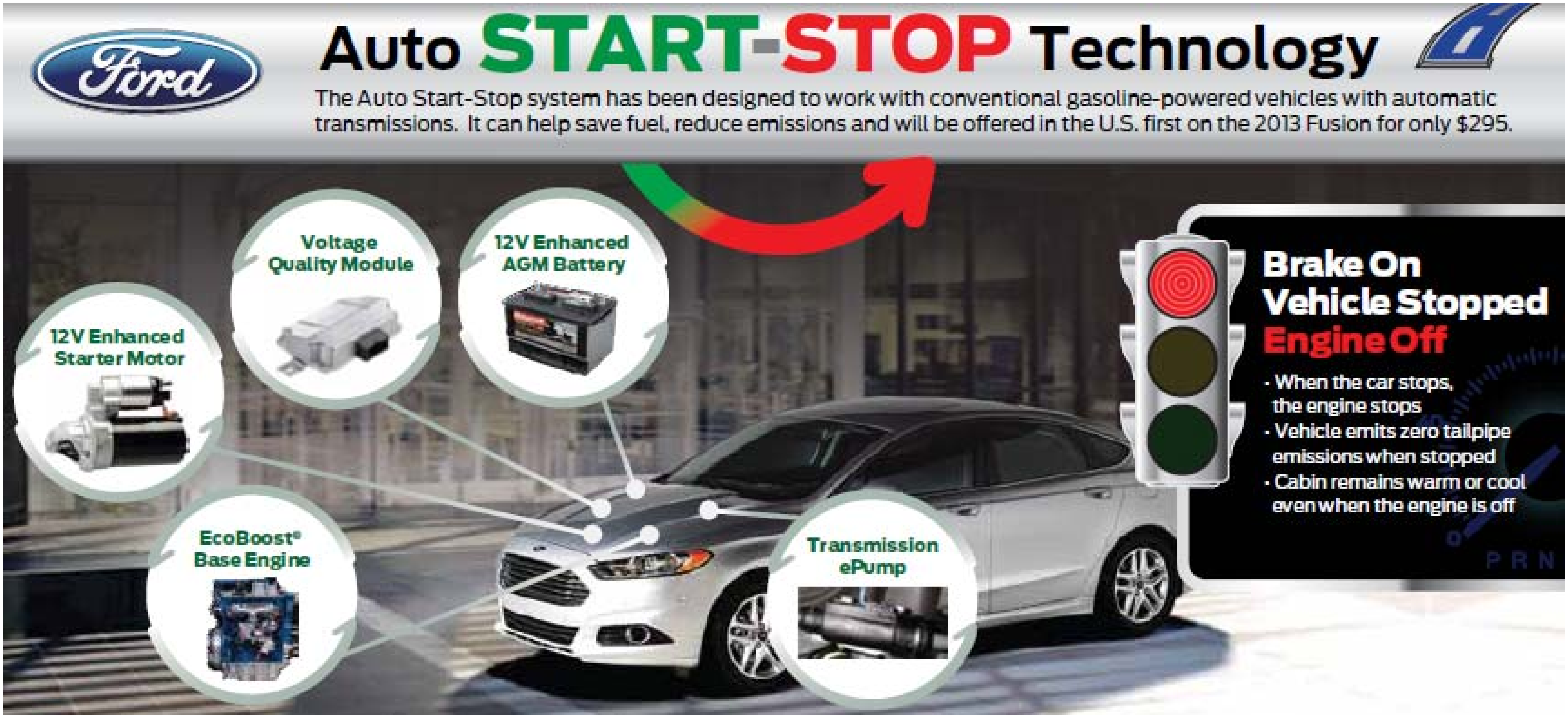
- ECO Start/Stop system automatically shuts off the engine at stoplights and other idle situations.
- As soon as the driver lifts off the brake, the engine instantly restarts, for immediate acceleration response.
- The ECO Start/Stop system can also be shut off by the driver at any time.

Chevrolet Malibu Stop/Start

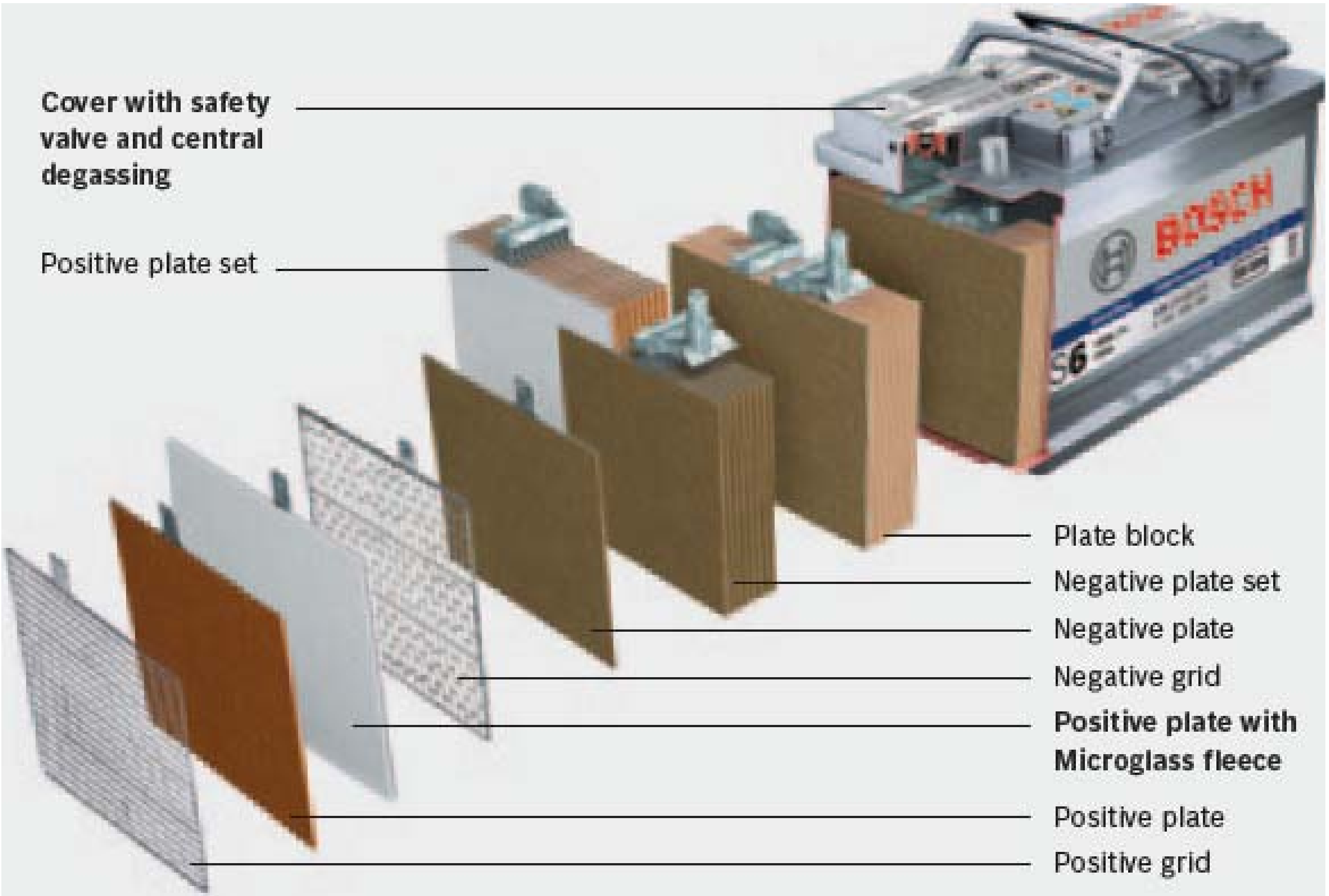


- ✓ Ecotec 2.5L with iVLC
- ✓ Enhanced 6T45 transmission
- ✓ Stop/start
- ✓ 25 MPG city/36 MPG hwy




Auto START-STOP Technology
The Auto Start-Stop system has been designed to work with conventional gasoline-powered vehicles with automatic transmissions. It can help save fuel, reduce emissions and will be offered in the U.S. first on the 2013 Fusion for only $295.
Voltage Quality Module
12V Enhanced AGM Battery
12V Enhanced Starter Motor
EcoBoost® Base Engine
Transmission ePump
Brake On
Vehicle Stopped
Engine Off
• When the car stops, the engine stops
• Vehicle emits zero tailpipe emissions when stopped
• Cabin remains warm or cool even when the engine is off

Absorbent Glass Mat (AGM) Battery

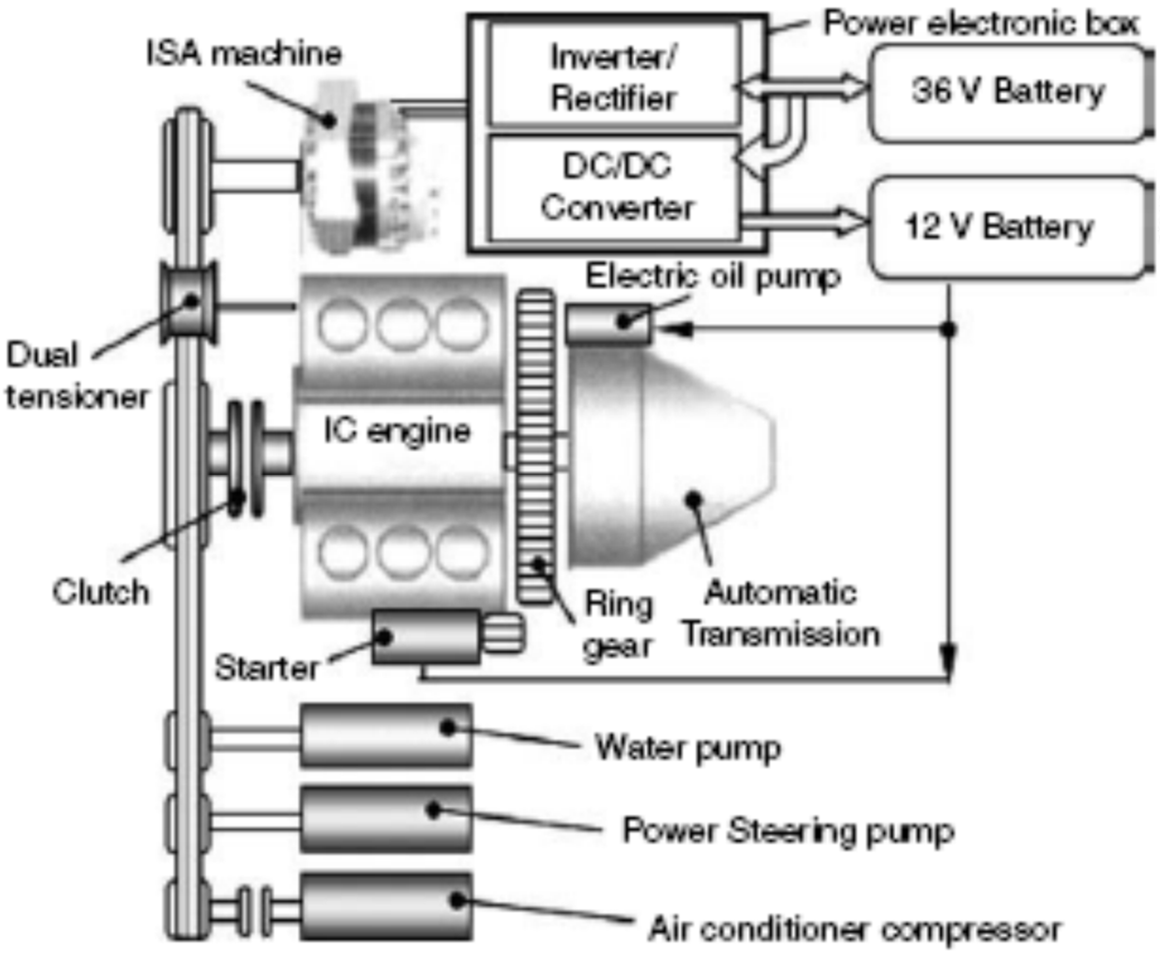


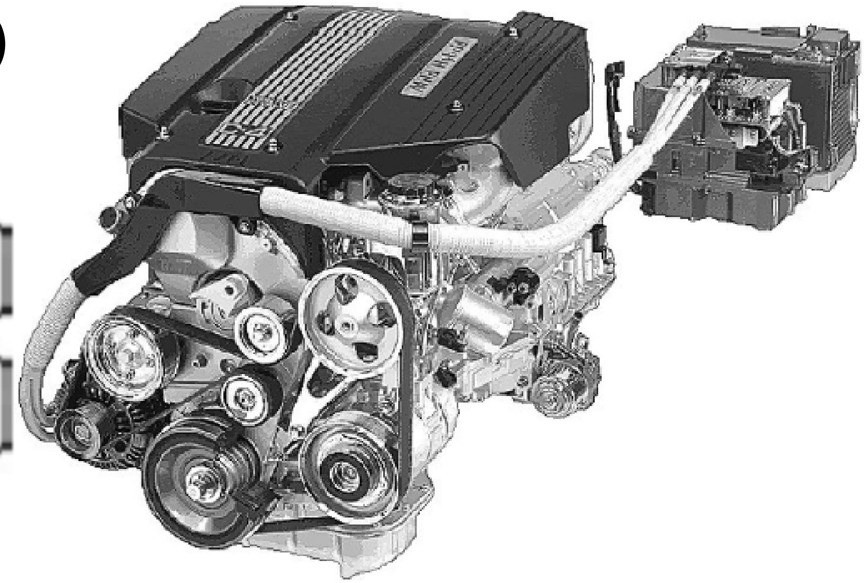
Micro-glass fiber mats are located tightly between the lead plates and bind in all of the electrolyte

- High pressure minimizes loss of the active material
- Low internal resistance
- Faster reaction between the acid and plate material
- Higher amounts of energy pass through in demanding situations

Mild Hybrid - Integrated Starter Generator (ISG)

- **B-ISG**: Belt ISG
  (or **BAS** - Belt Alternator Starter)





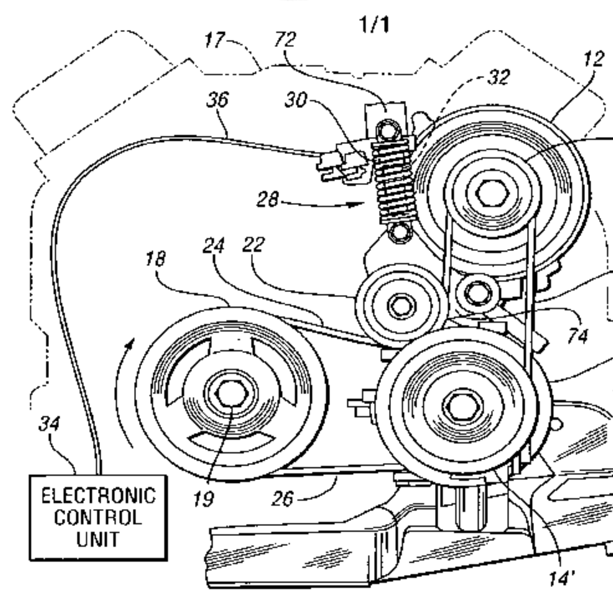
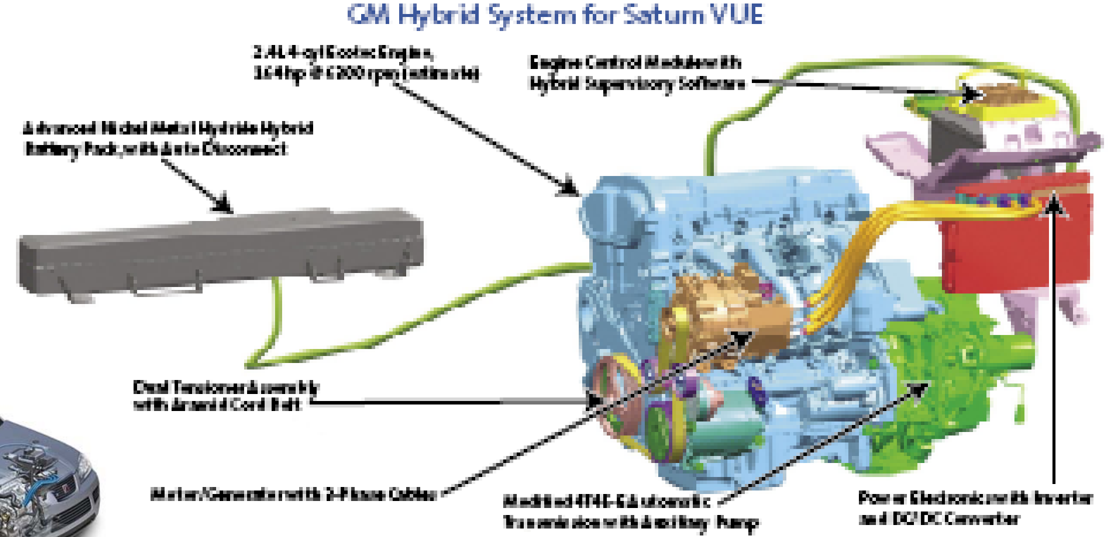
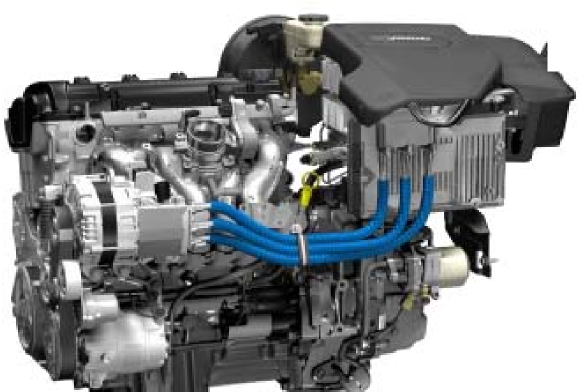


FIG. 1

Example of B-ISG Mild Hybrid

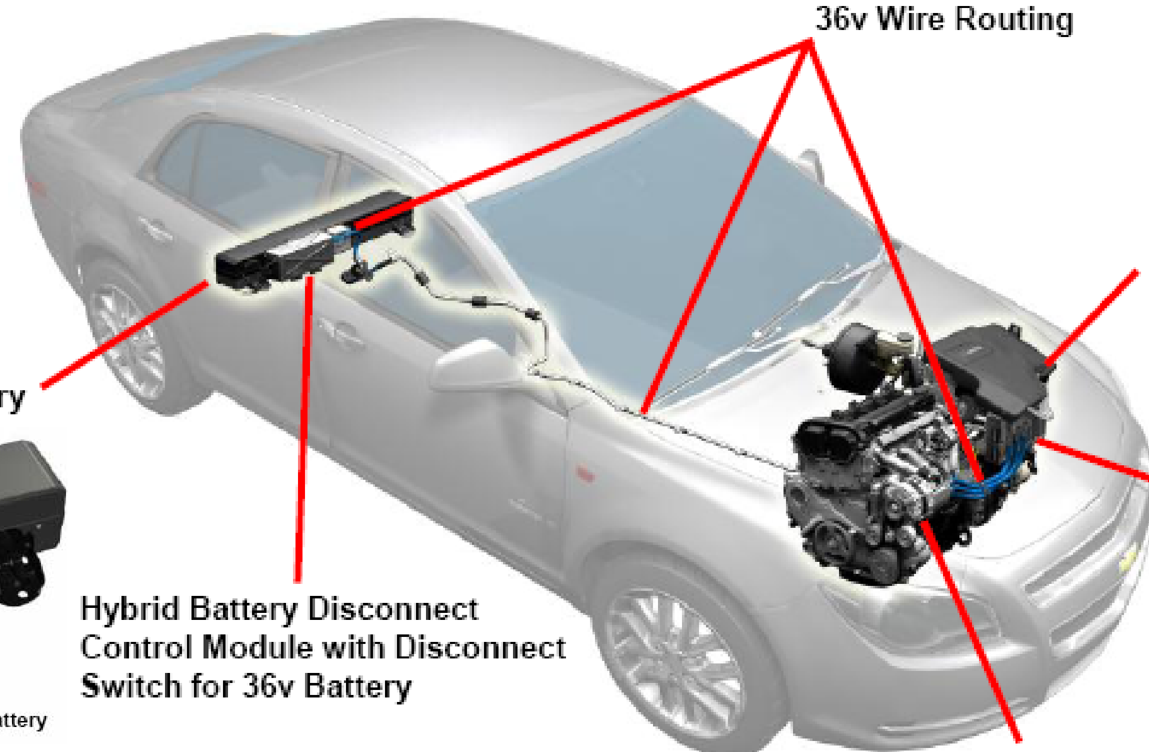
GM - Malibu, Vue
Toyota
Hyundai/Kia





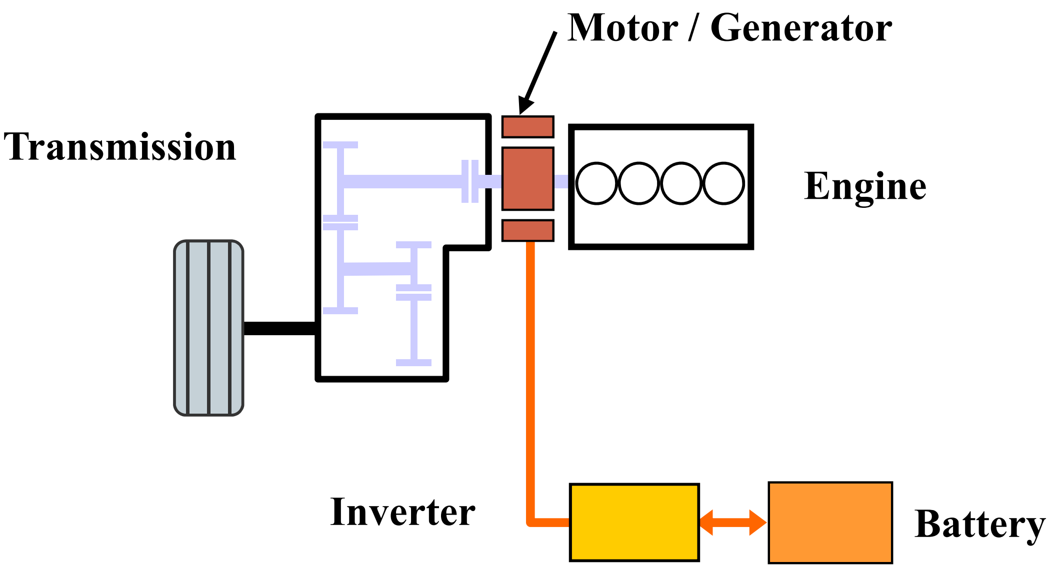
2.4 L Engine

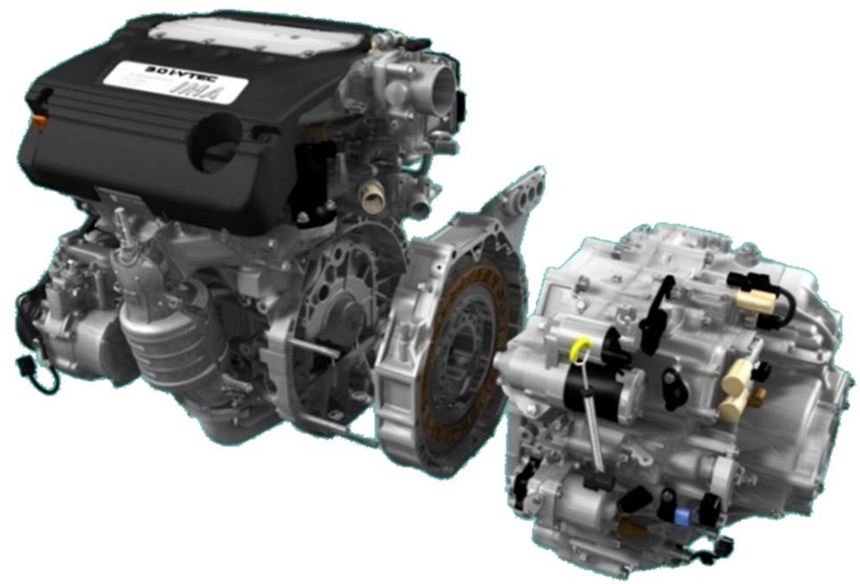
36 Volt Hybrid Battery

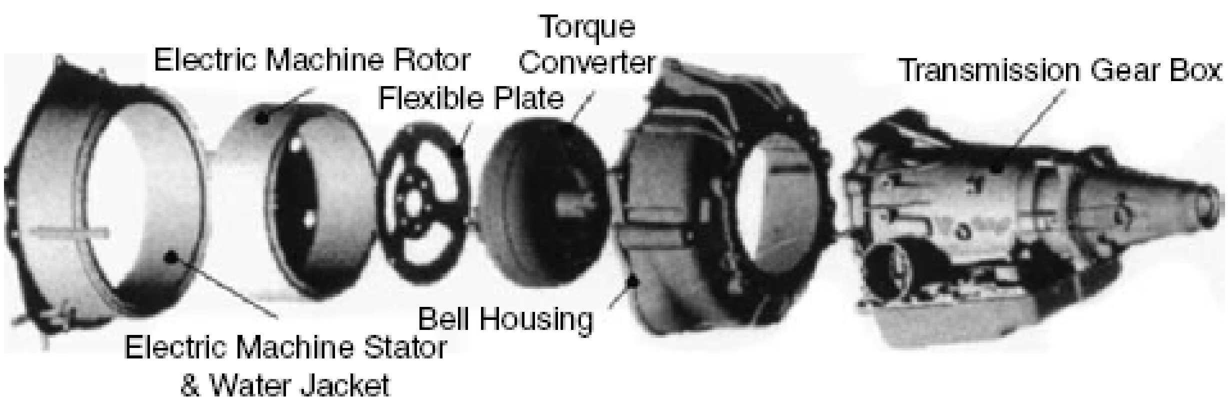


Mild Hybrid - Integrated Starter Generator (ISG)

- **C-ISG**: Crankshaft ISG
  (or **FAS** - Flywheel Alternator Starter)

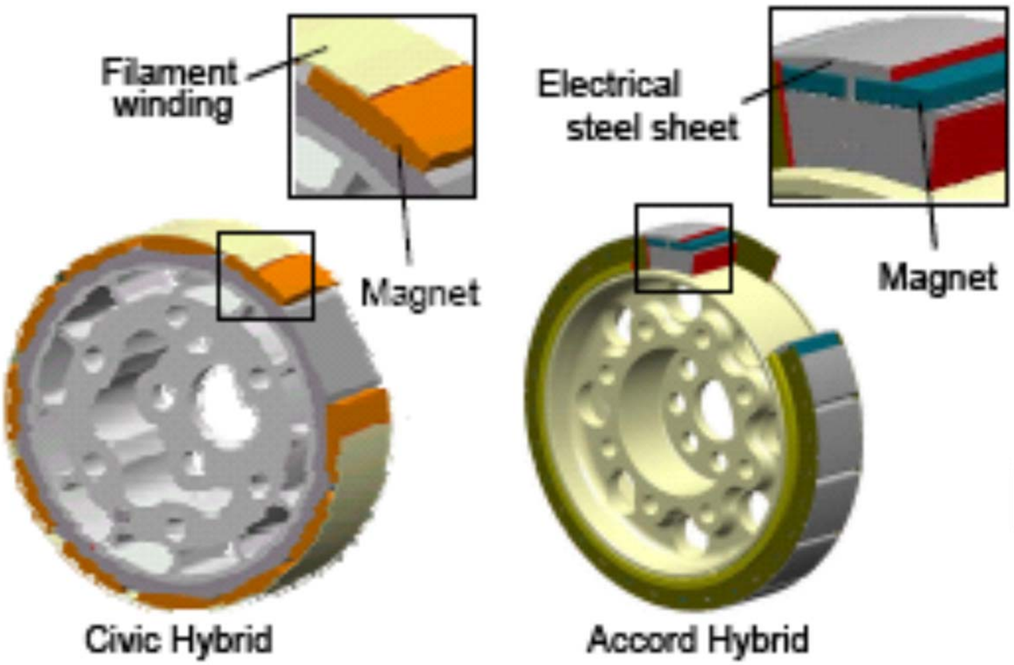


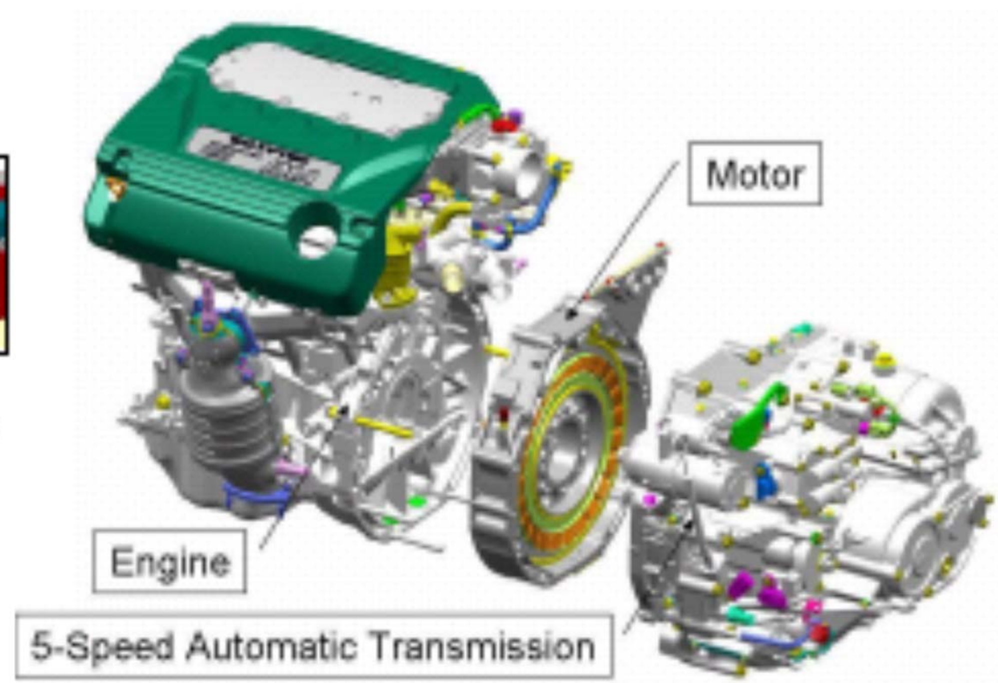




Example of C-ISG Mild Hybrid

Honda Civic Hybrid, Insight





C-ISG vs. B-ISG

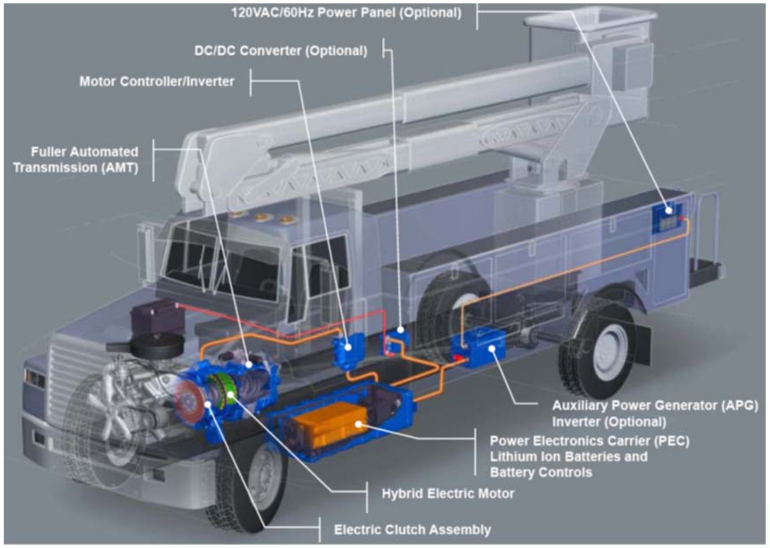
C-ISG

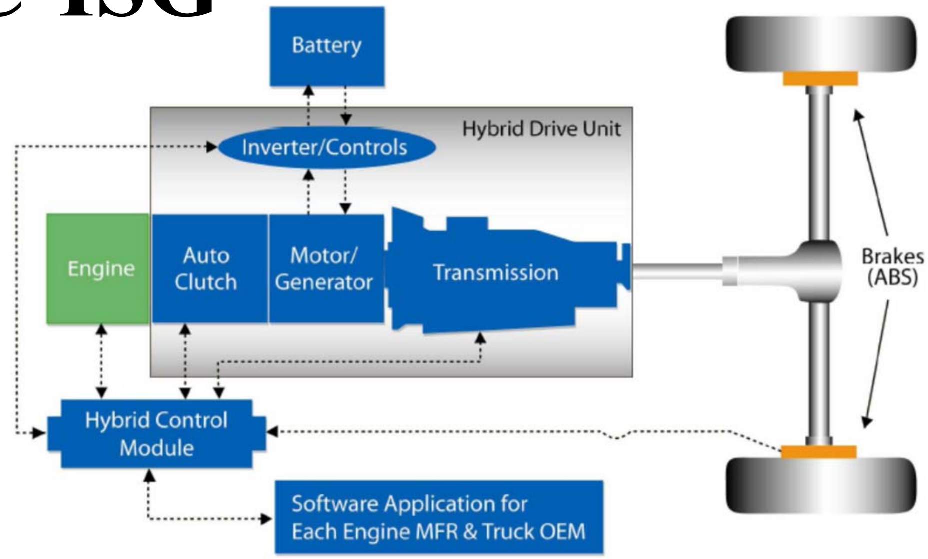
- **C-ISG can be Strong Hybrid**
- Crank mounted
- Transfer torque directly to shaft
- Requires major modifications powertrain
- Extremely difficult not to increase powertrain length
- Can reach high power level (42V limited to 10kW but high voltage can reach 30+ kW)
- Allows power assist (performance impact)
- More visible to costumer (bragging rights)

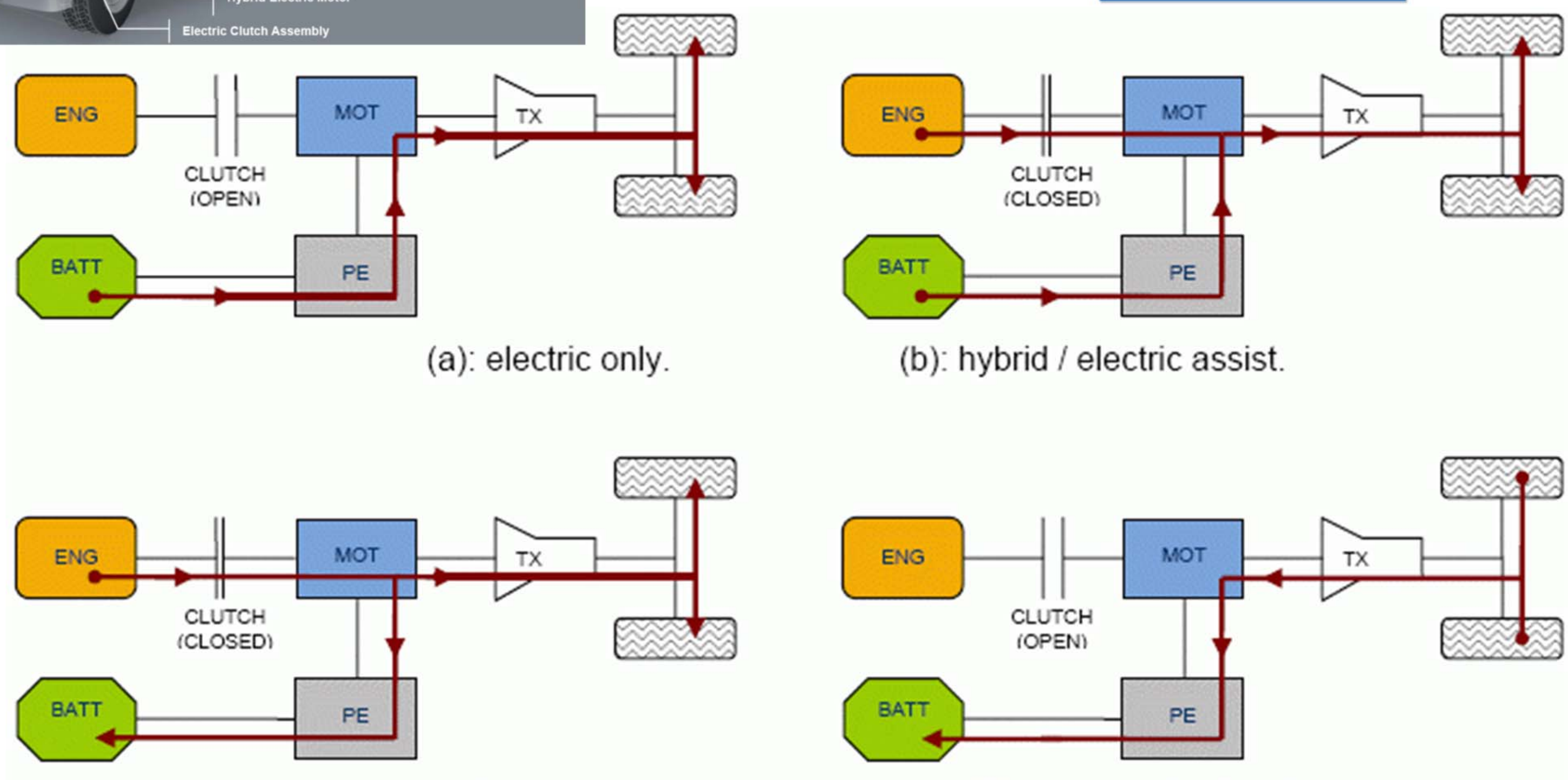
B-ISG

- FEAD mounted
- Directly replaced alternator
- Requires minor modifications to belt and tensioner
- Minimize modification to powertrain
- Torque limited by belt
- $1.5 < \text{Power} < 5\text{kW}$
- Limited functionality
- Limited FE benefits (useful for CAFÉmore than customer)

Full Hybrid: C-ISG





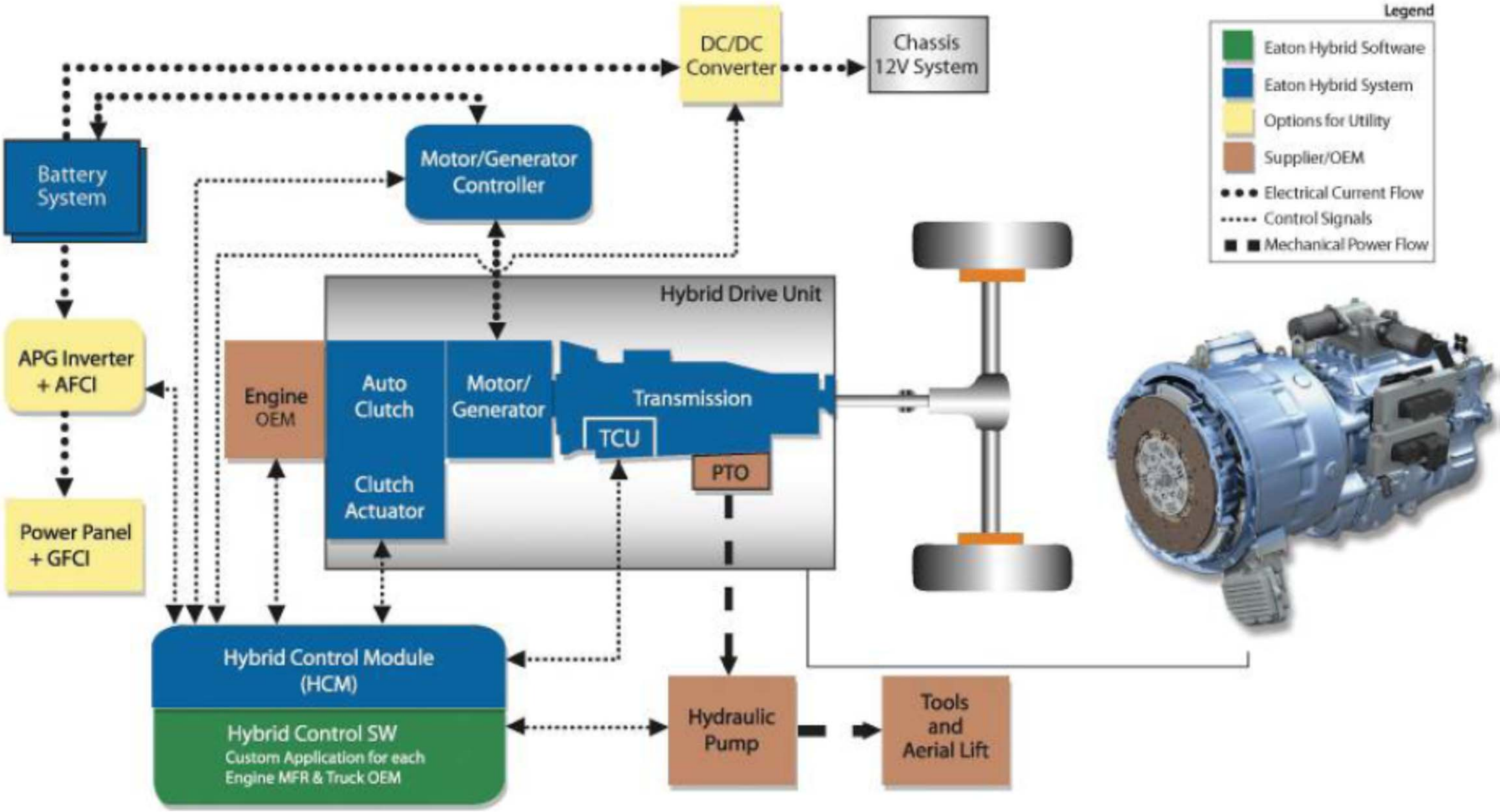


(a): electric only.

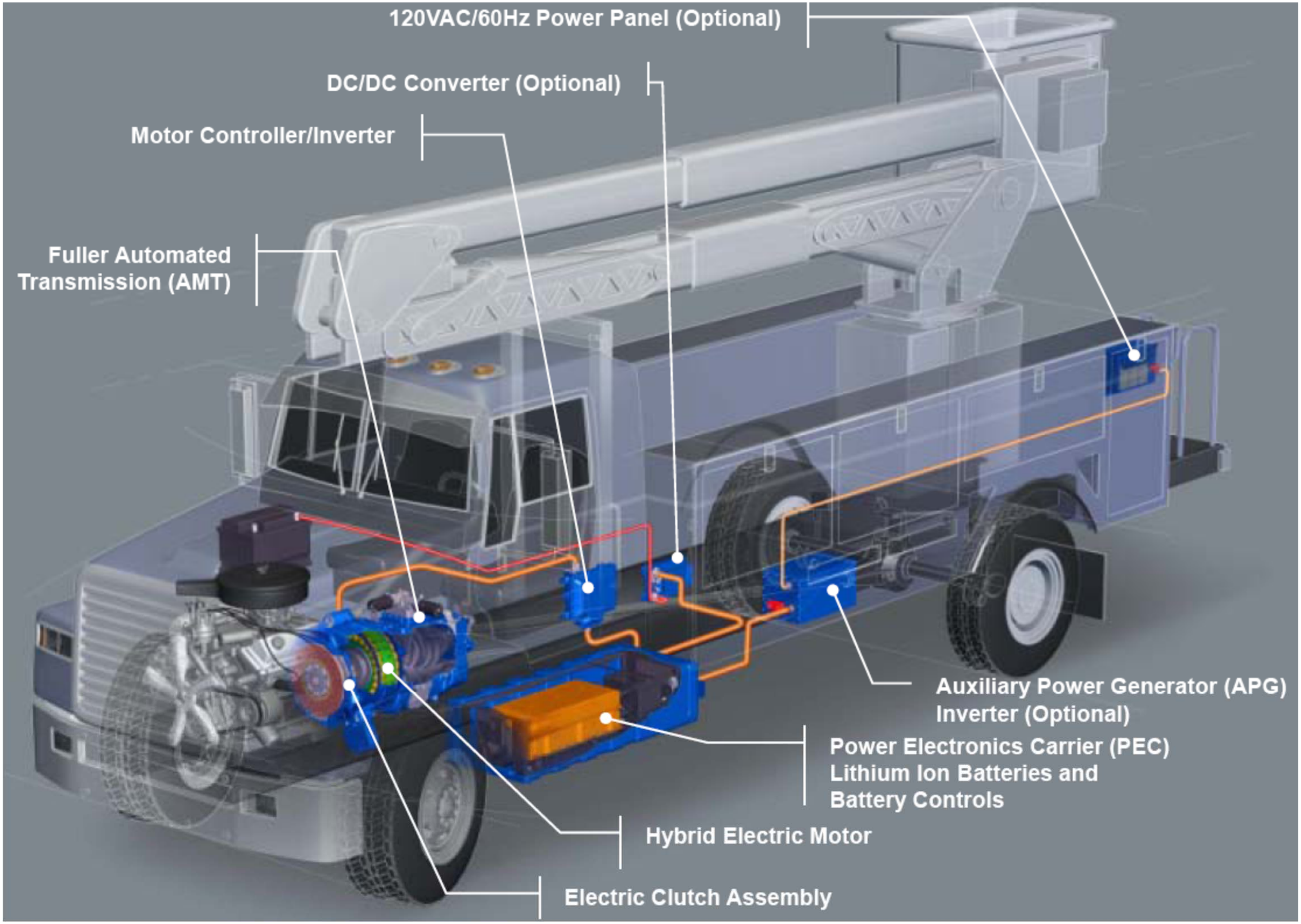
(b): hybrid / electric assist.

(c): battery charging.

(d): regenerative braking.



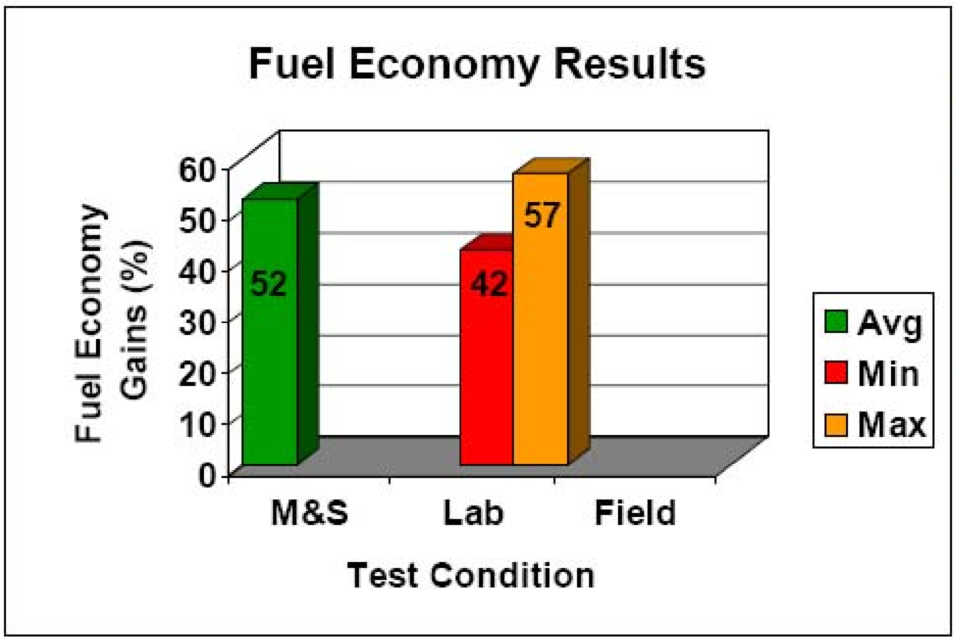
DC/DC Converter
Chassis 12V System
Legend
Eaton Hybrid Software
Eaton Hybrid System
Options for Utility
Supplier/OEM
Electrical Current Flow
Control Signals
Mechanical Power Flow
Battery System
Motor/Generator Controller
APG Inverter + AFCI
Power Panel + GFCI
Hybrid Drive Unit
Engine OEM
Auto Clutch
Clutch Actuator
Motor/ Generator
Transmission
TCU
PTO
Hybrid Control Module (HCM)
Hybrid Control SW
Custom Application for each Engine MFR & Truck OEM
Hydraulic Pump
Tools and Aerial Lift



120VAC/60Hz Power Panel (Optional)
DC/DC Converter (Optional)
Motor Controller/Inverter
Fuller Automated Transmission (AMT)
Auxiliary Power Generator (APG) Inverter (Optional)
Power Electronics Carrier (PEC) Lithium Ion Batteries and Battery Controls
Hybrid Electric Motor
Electric Clutch Assembly

Eaton Hybrid Electric FedEx Program Status

- 93 trucks at 20 stations (US & Canada)
- 45 production trucks delivered in May 2008
- In-Service Date:
  - FedEx 18 – February 2004 (initial units)
  - FedEx 75 – October 2006
- Mileage & Availability:
  - FedEx 18: 760K miles @ Cum 98% (100% in January 2008)
  - FedEx 75: 1.2M miles @ Cum 95% (96% in January 2008)



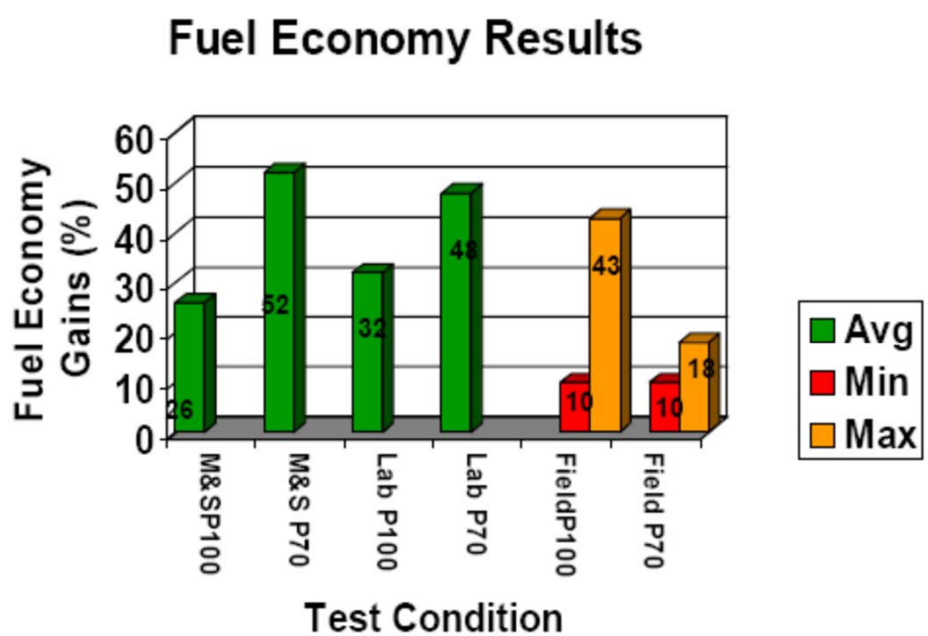
- Typical Driving Cycle - City Delivery
- Baseline Engine: Cummins ISB, 6 cyl, 5.9L 175 HP (AT)
- Hybrid Engine: MBE-904, 4 cyl, 4.3L, 170 HP (AMT)

IRS Tax Credit APPROVED

Lab Test: Southwest Research Institute; SwRI

Eaton Hybrid Electric UPS Program Status

- 50 trucks at 4 stations in US
  - In-Service Date: April 2007
  - 501k miles @ 96% availability
- 200 trucks ordered in June 2008



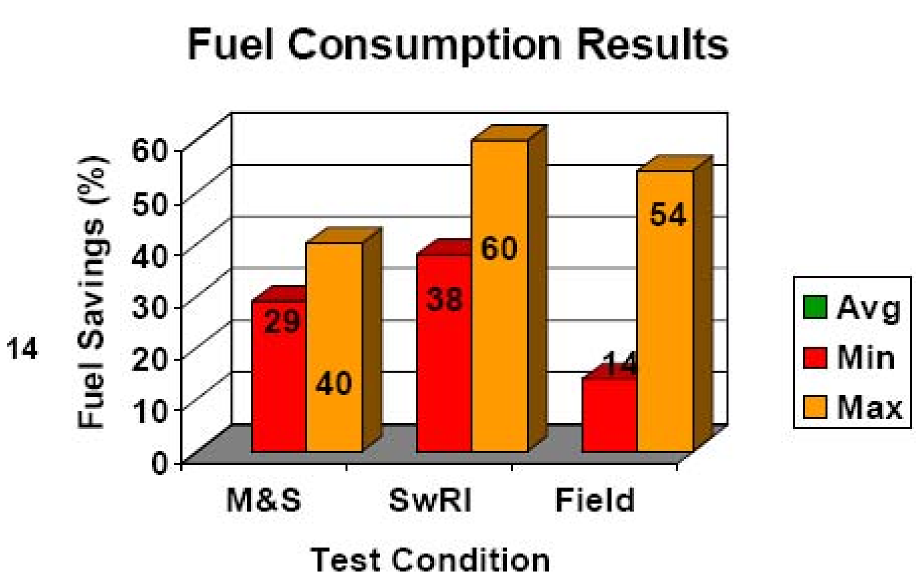
- Typical Driving Cycle - City Delivery
- Baseline Engines:
  - P100: ITEC VT365 V8 200 HP (AT/MT)
  - P70: Cummins ISB I6 185 HP (AT/MT)
- Hybrid Engine:
  - P100: ITEC VT275 V6 180HP (AMT)
  - P70: MB904 I4 170HP (AMT)

IRS Tax Credit APPROVED

Lab Test: Independent Research Facility – NREL
Field Test: UPS - NREL Controlled Tests Planned

Eaton Hybrid Electric HTUF Program Status

- 24 Vehicles, 14 Fleets (US and Canada)
- In Service Date:
  - May 2006, 18 Month Field Trial
- Mileage & Availability
  - 480k miles @ 99%



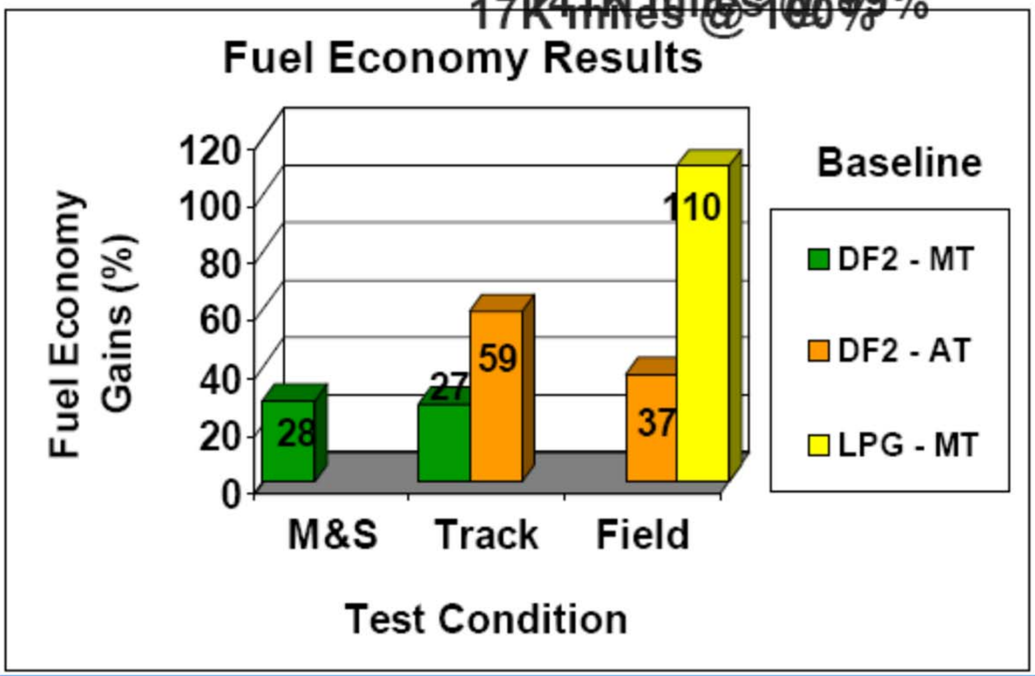
- Typical Driving Cycle: CILCC Job Site: Varied Hydraulic Duty Cycle (**3-6** Hrs. M&S and Lab; **0-3** Hrs. Field Test)
- Field Test/Lab/M&S Baseline and Hybrid Engine: DT466, 6 cylinder, 7.6L, 225 HP

IRS Tax Credit APPROVED

Lab Test: Southwest Research Institute

Eaton Hybrid Electric
Foton Bus Program Status

- **31 buses in Guangzhou, China**
- **In-Service Date:**
  - **Prototype 1:** April 2007
  - **Production 6:** January 11, 2008
- **Mileage & Availability:**
  - **Prototype 1:** 17K miles @ 100%
  - **Production 30:** 141K miles @ 99%



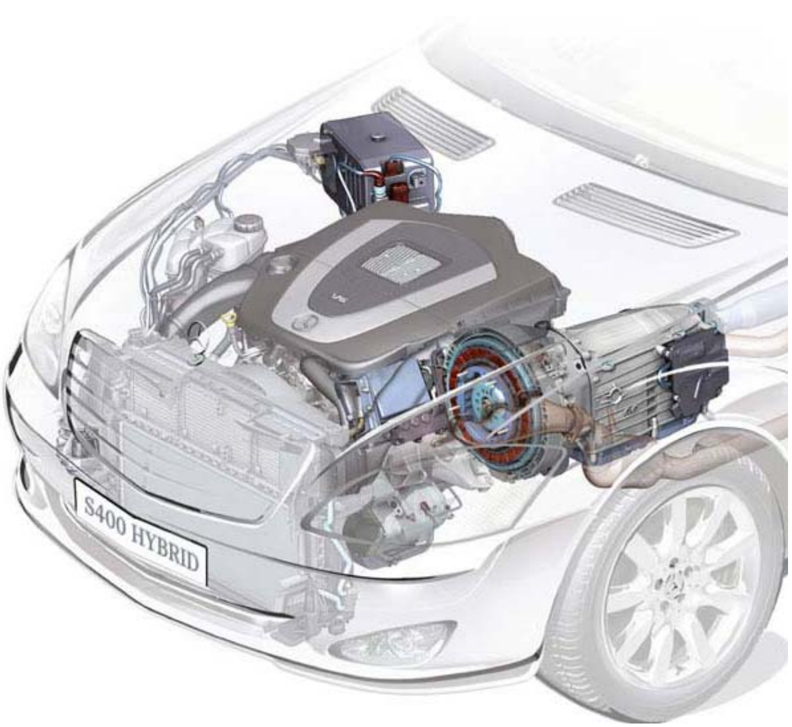
- **Typical Driving Cycle:**
  New Chinese Bus Cycle
- **Baseline Engine:**
  Various makers, typically 6-Cyl, 220 – 260 HP, Euro 2-3
- **Hybrid Engine:**
  ISBe 6-Cyl, 185 – 220 HP, Euro 3

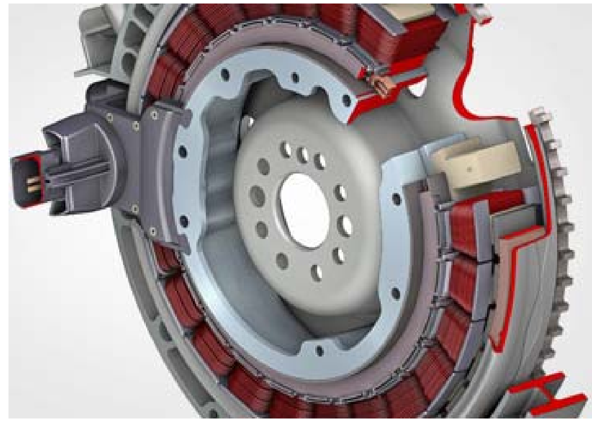
Track Test: China Chongqing Bus Test Center
Field Test: Guangzhou Yiqi Bus Company

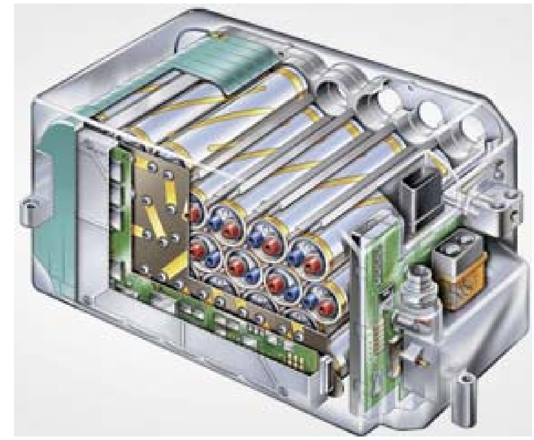
MT–Manual Trans; AT–Automatic Trans

Example of C-ISG
Full (or Strong) Hybrid

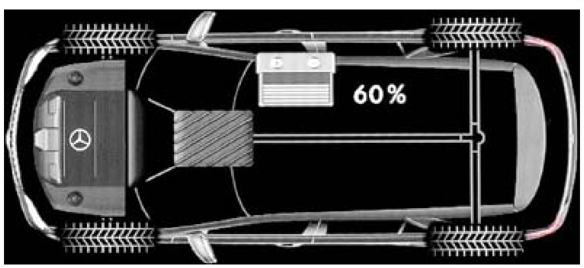
Mercedes-Benz



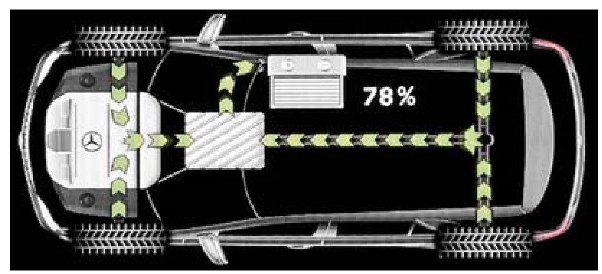




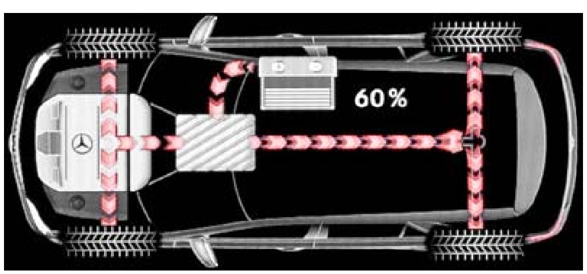
S400 Hybrid
E400 Hybrid can even travel short distances on electricity along



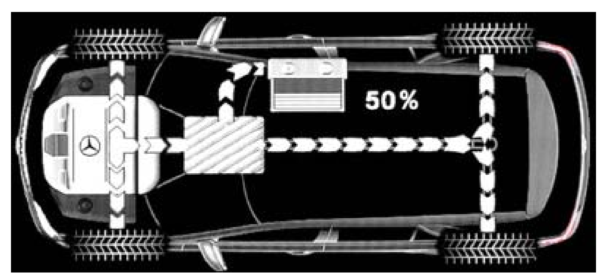
Stop/start



Regenerative braking

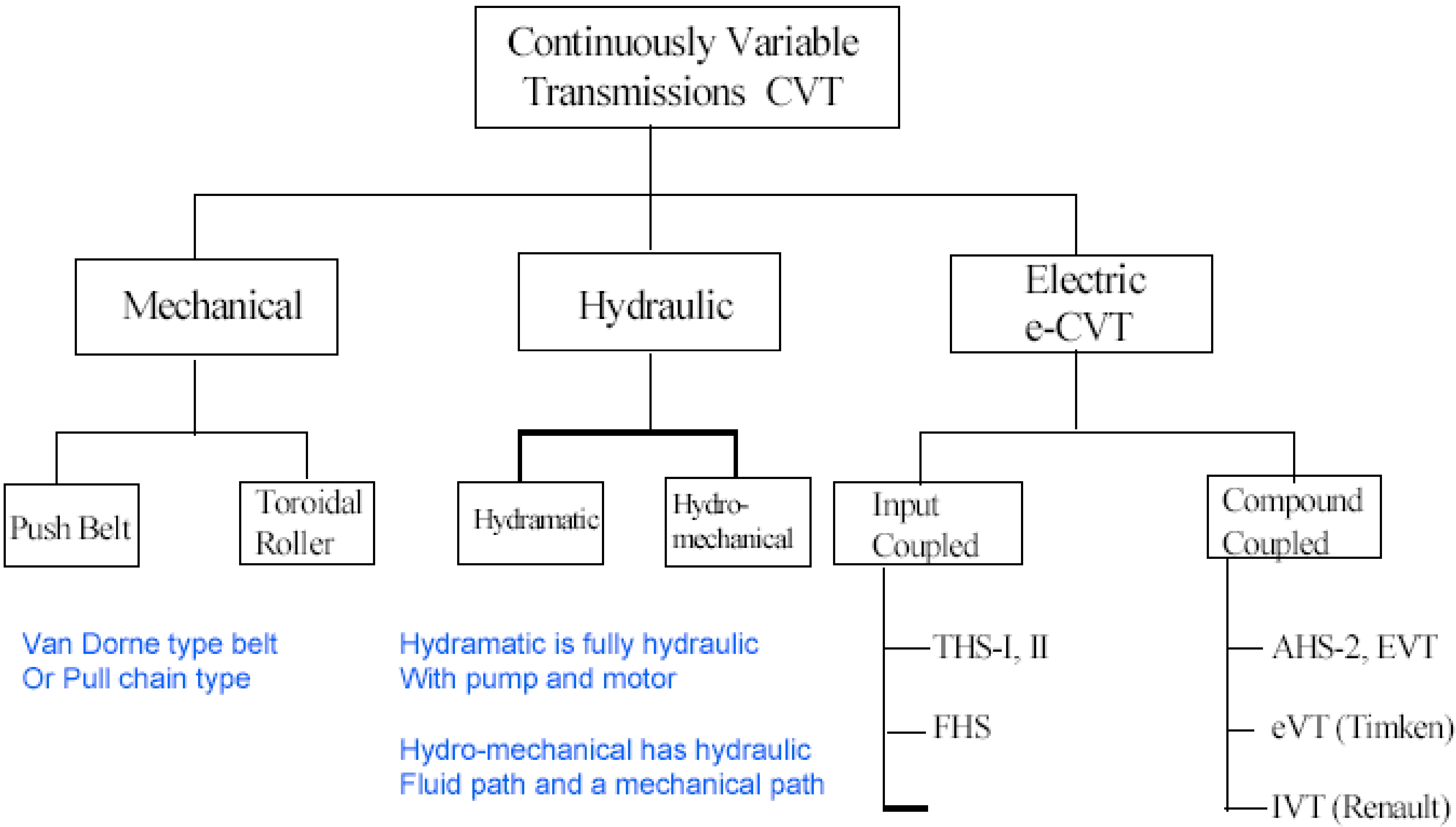


Boost acceleration



Highway driving

Power Split e-CVT



Stepless transmissions

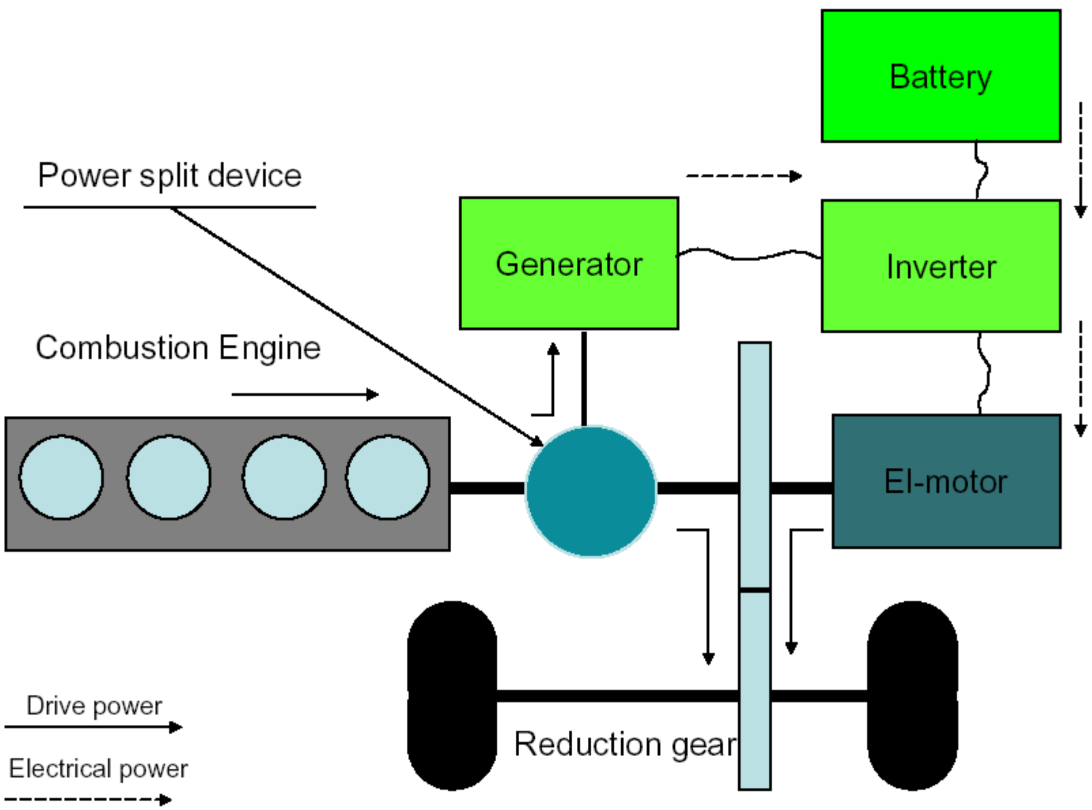
Electrically Variable Transmissions (EVT)

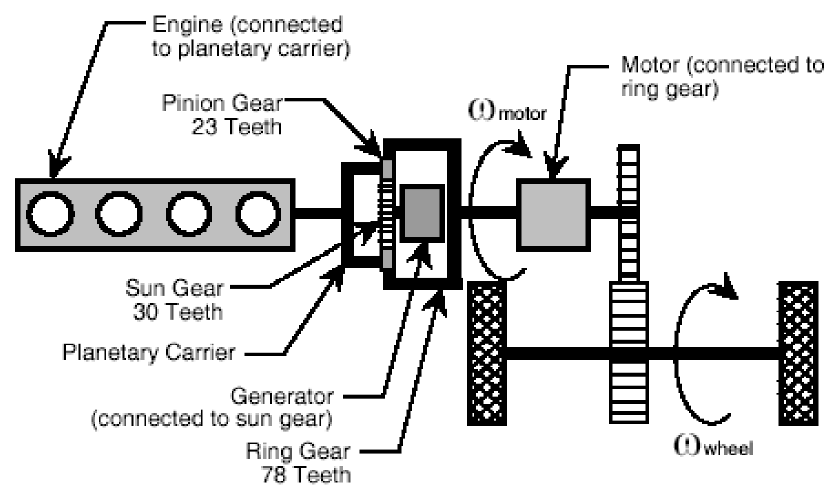
- Electronic Variable Transmissions (EVT) are not new in their principle. They exploit the kinematic relationships afforded by planetary gear sets.
- The torque and speed inputs can be applied to sun, ring and carrier shafts in any combination.
- This multiple input / multiple output system provides a large number of combinations by appropriately driving one of the shafts with the IC engine, and another by an electric motor.
- Owing to the existence of (at least) one electric motor as part of the drivetrain in a hybrid electric vehicles, these EVT configurations are quite attractive.

Full Hybrid: EVT

Power Split e-CVT, or
Electric Variable Transmission (EVT)

- Most common in production HEVs
- Continuously variable transmission



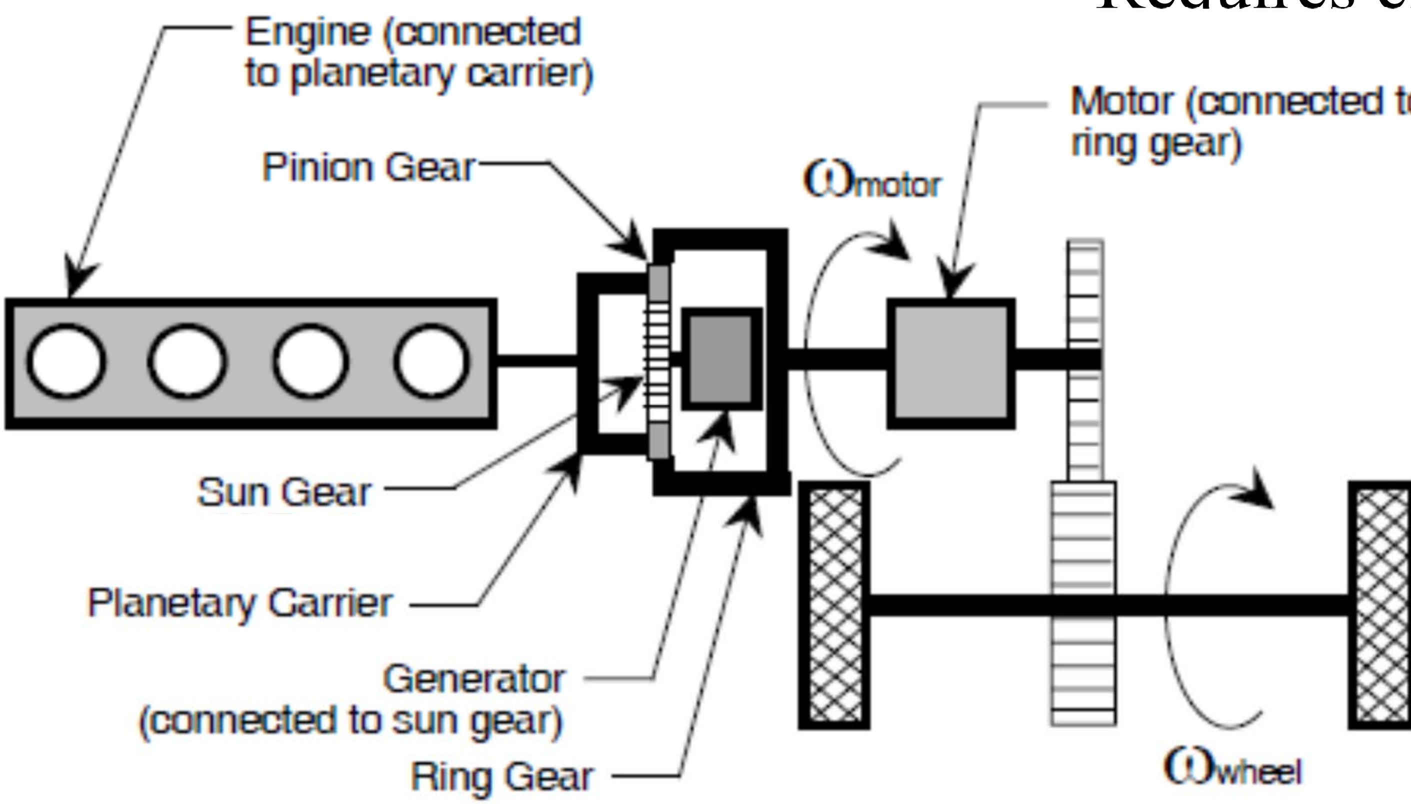


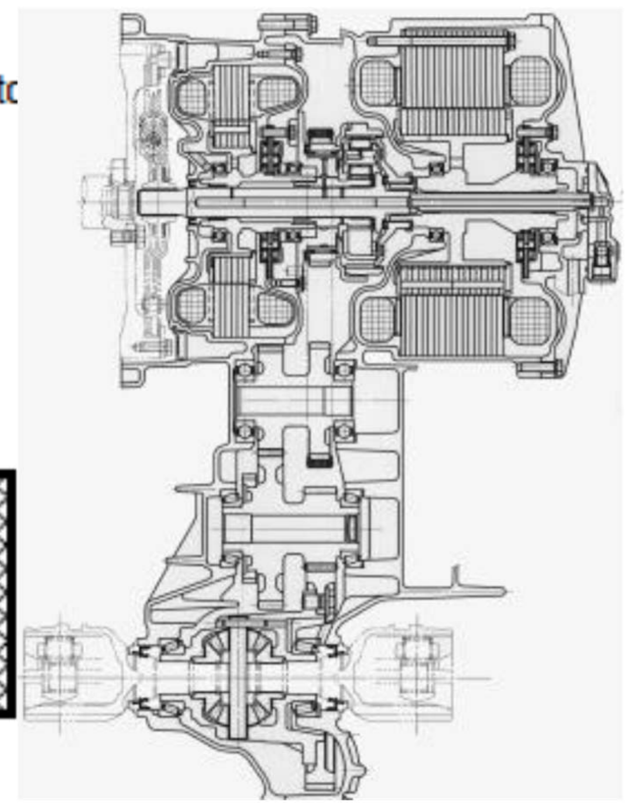
One-Mode EVT

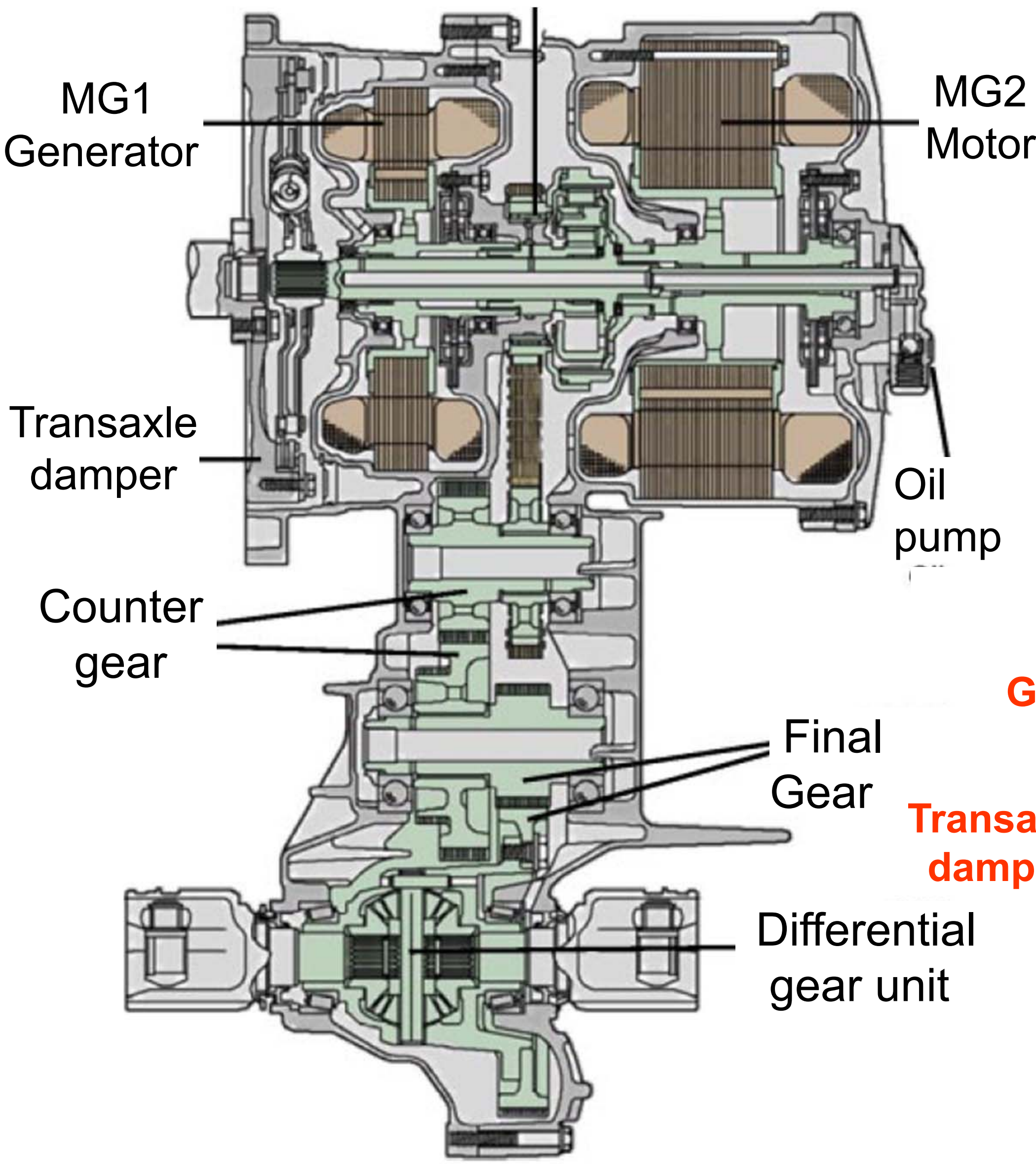
- ICE input to carrier
- Motor and final drive output on ring
- Generator on sun

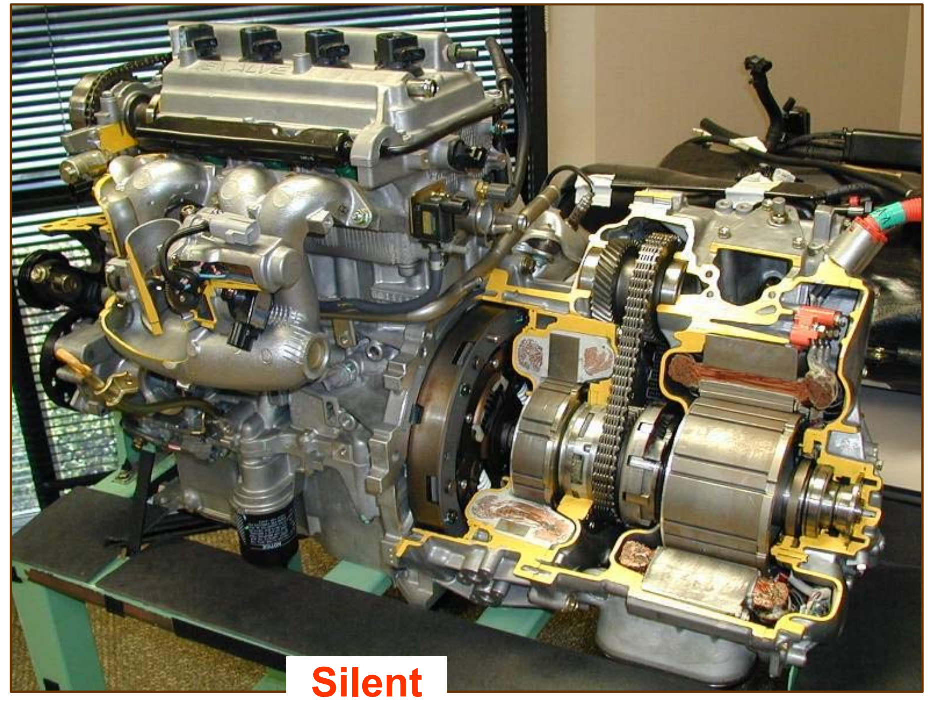
Configuration Shifting

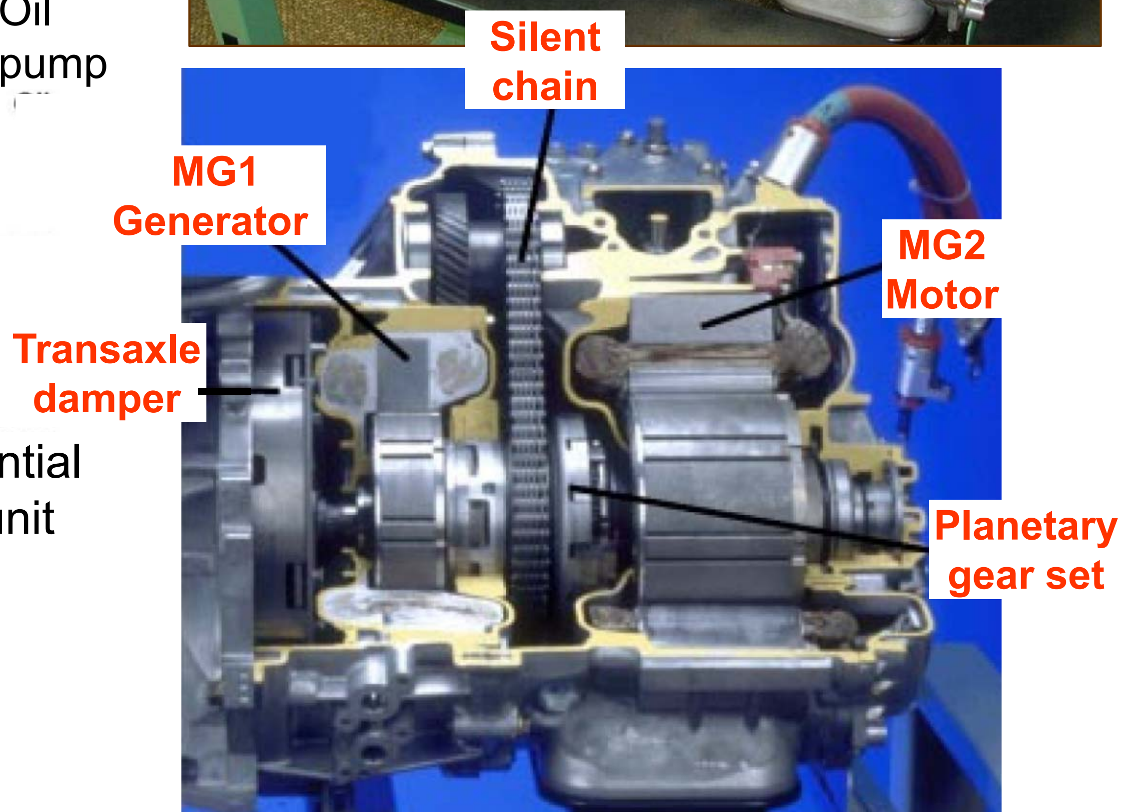
- Two or more configurations
- Two or more efficiency peaks
- Synchronous shifting Immediately and smooth
- Requires clutches





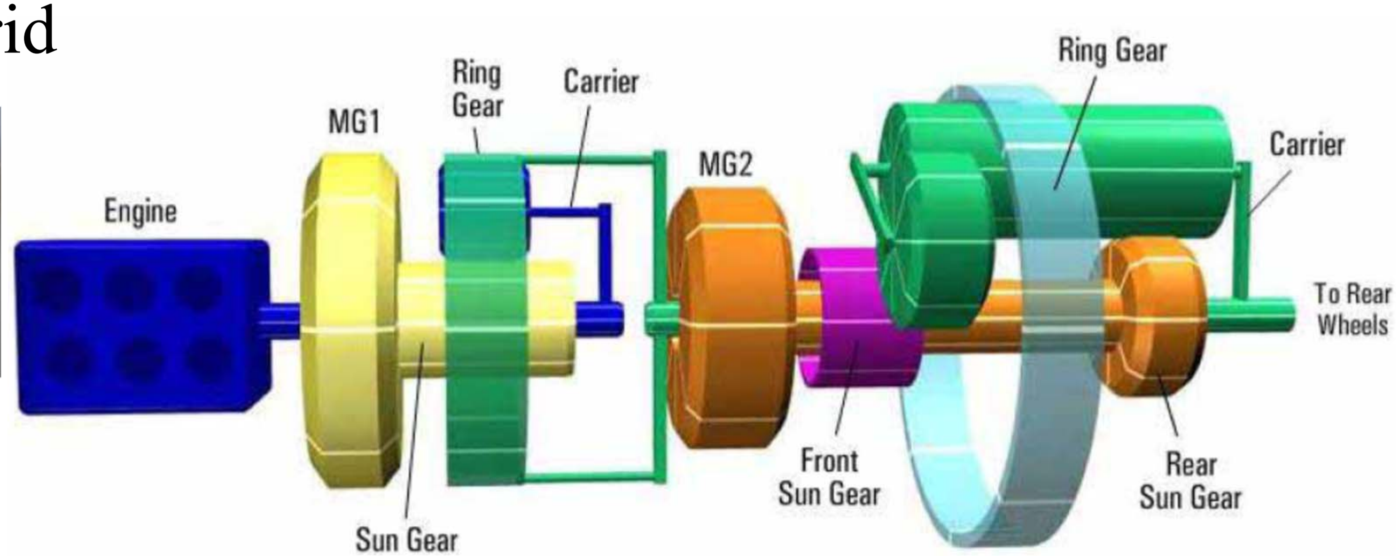

MG1
Generator
MG2
Motor
Transaxle
damper
Oil
pump
Counter
gear
Final
Gear
Differential
gear unit

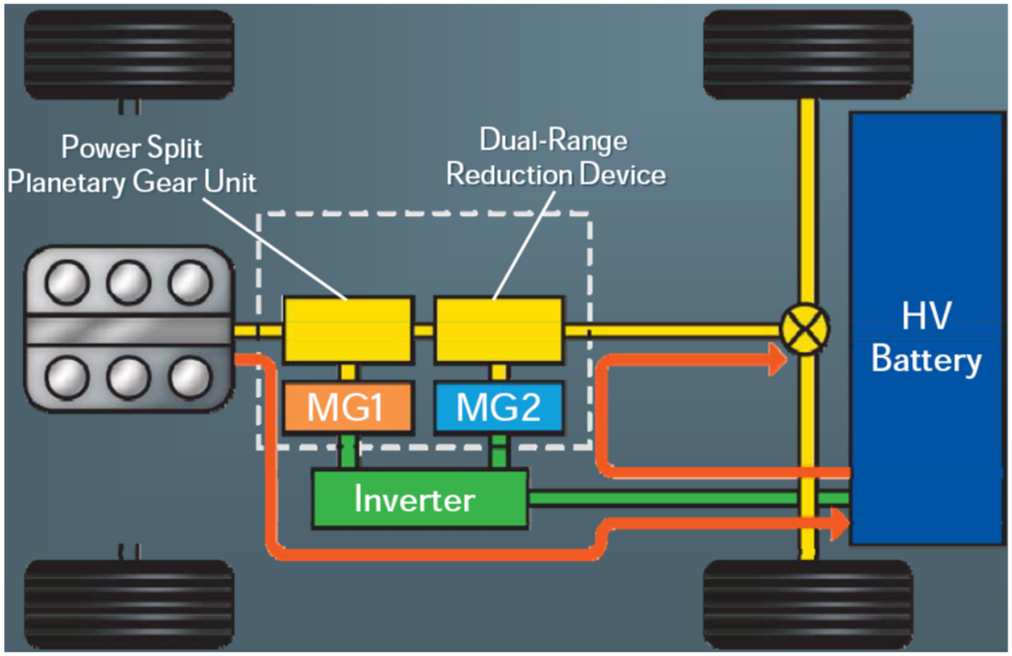


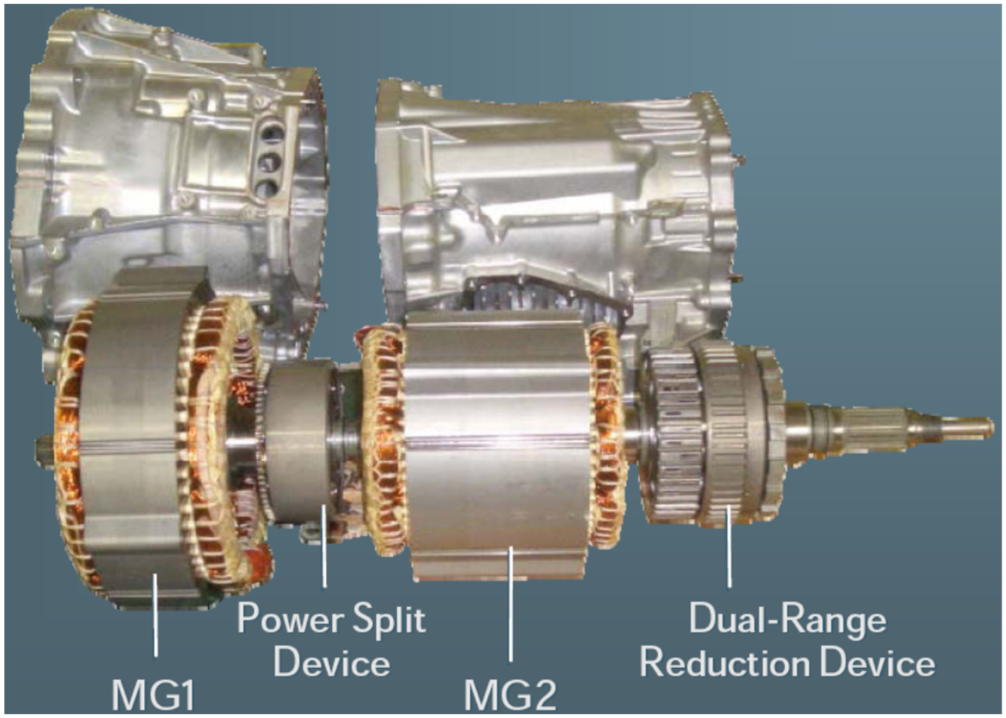

Silent
chain
MG1
Generator
MG2
Motor
Transaxle
damper
Planetary
gear set

One-Mode EVT for Rear-Wheel Drive HEV

Lexus GS 450h Hybrid

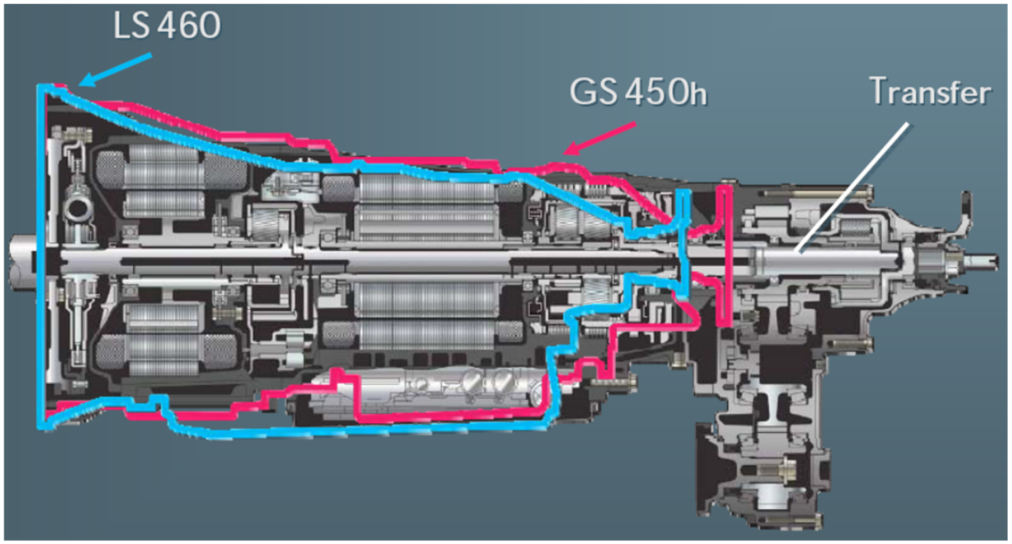




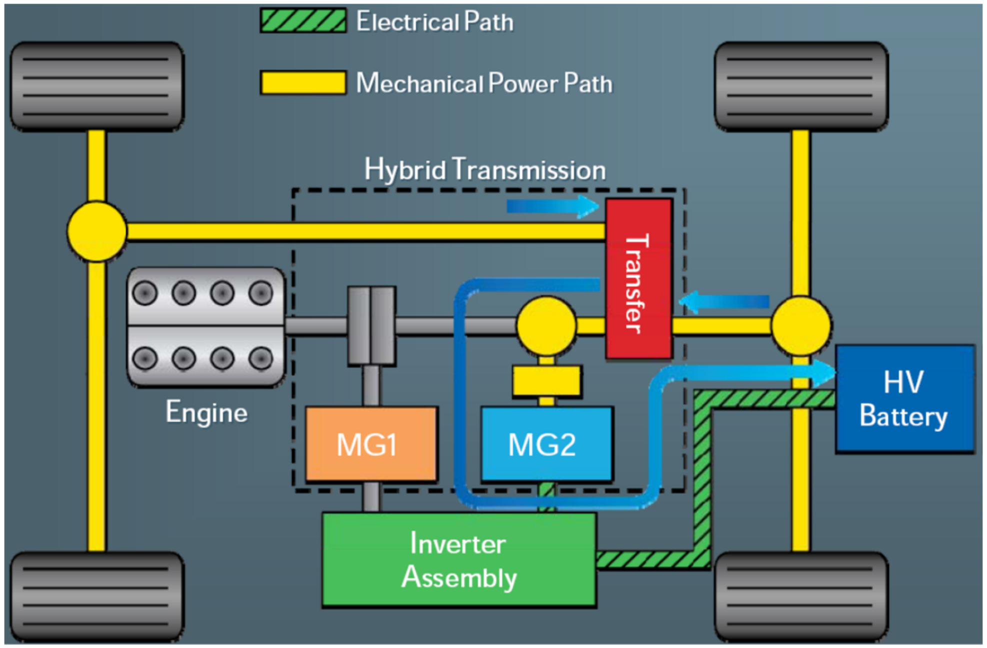


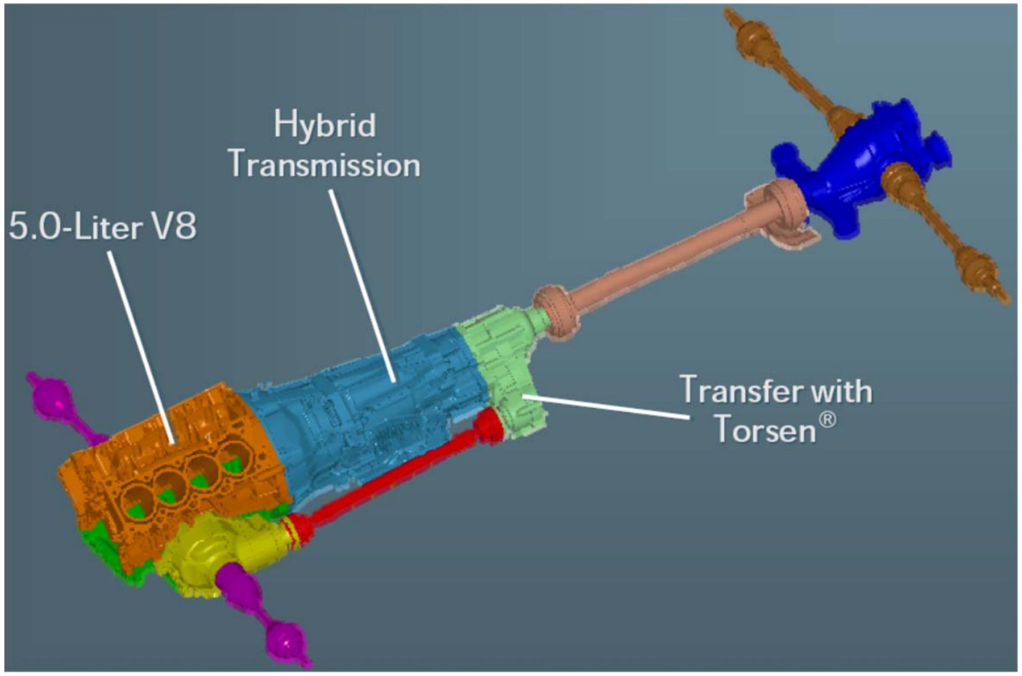
One-Mode EVT for All-Wheel Drive HEV

Lexus 600h L Hybrid



Regenerative Braking





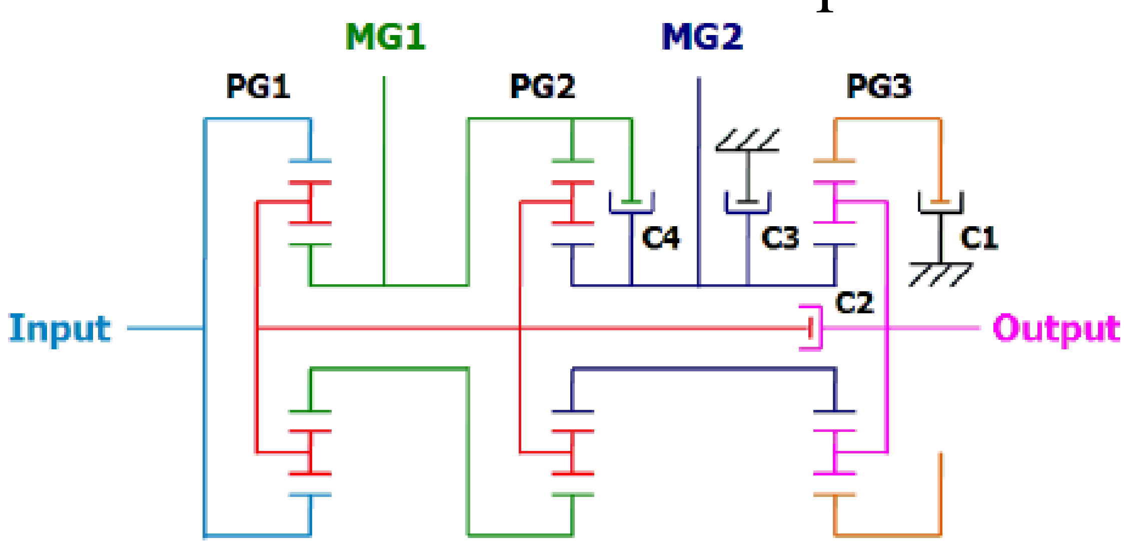
Toyota Hybrid System **THS/Hybrid Synergy Drive**

- One-mode single power-split device (incorporated as a single 3 shaft planetary gearset)
- Simple in mechanical terms
- Drawbacks: the maximum speed is mainly limited by the speed of the smaller electric motor (usually functioning as a generator)
- The efficiency of the transmission is heavily dependent on the amount of power being transmitted over the electrical path
- Low efficiency of electric path (~0.7) compared with the purely mechanical path (~0.98)
- Especially in higher speed regimes (>120 km/h or 70 mph), the efficiency (of the transmission alone) therefore drops below that of a generic automatic transmission.

GM Two-mode, Input and Compound Split EVT

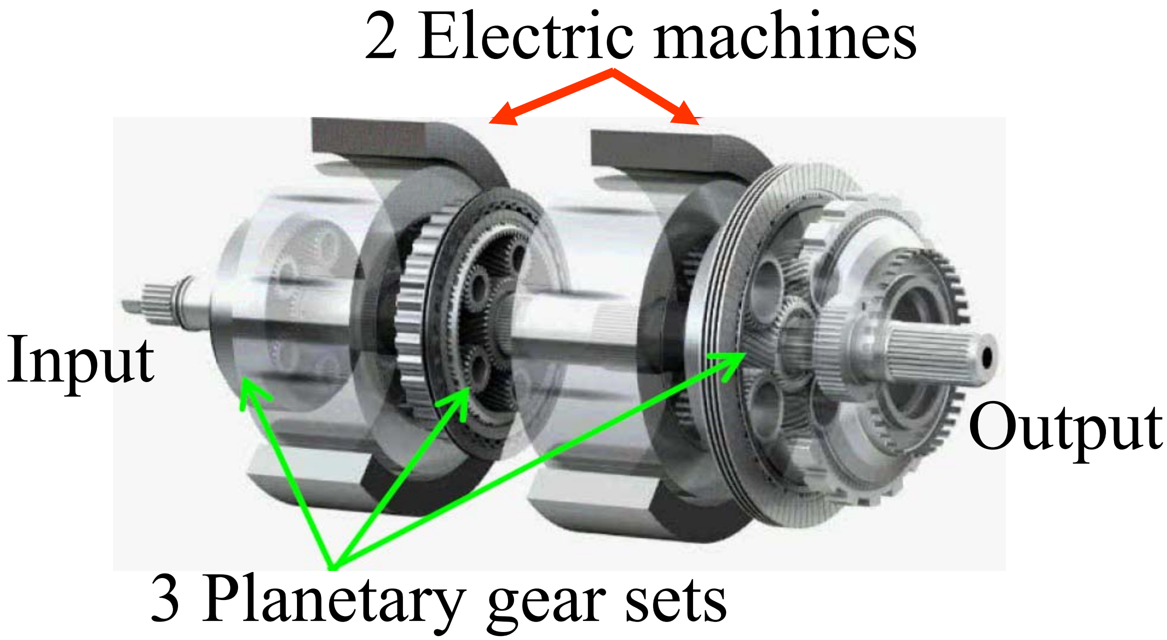
- Differential gearing splits power into parallel paths: mechanical and electrical
- Three planetary gear sets
- Two electric machines
- Two modes means two ranges of infinitely variable gear ratios

- The input split mode is used for launching the vehicle from a stop, driving at low speeds, or providing moderate load trailer towing.
- The compound split mode is used primarily when the vehicle is at higher speeds to provide efficient cruising

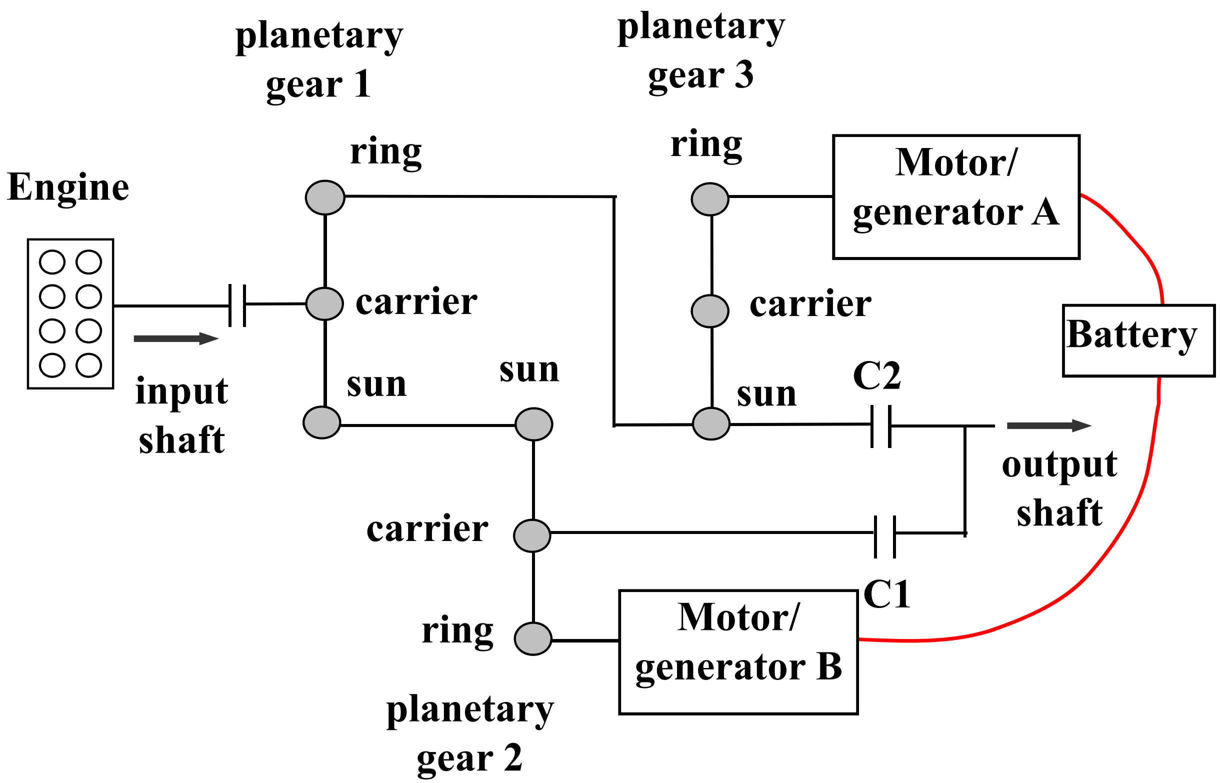


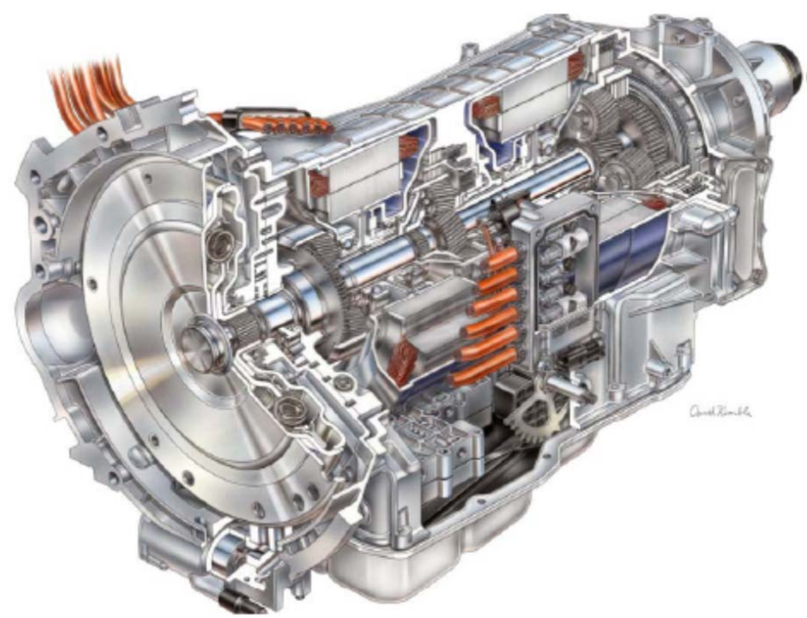
The **Two-Mode EVT** name is intended to emphasize the drivetrain's ability to operate in **all-electric (Mode 1)** as well as **hybrid (Mode 2)** modes. The design, however, allows for operation in more than two modes; two power-split modes are available along with several fixed gear (essentially parallel hybrid) regimes. For this reason, the design can be referred to as a multi-regime design. The Two-Mode Hybrid powertrain design can be classified as:

- A compound-split design, since the addition of four clutches within the transmission allows for multiple configurations of engine power-splitting.
- In addition to the clutches, this transmission also has a second planetary gearset. The objective of the design is to vary the percentage of mechanically vs. electrically transmitted power to cope both with low-speed and high-speed operating conditions.
- This enables smaller motors to do the job of larger motors when compared to single-mode systems.
- The four fixed gears enable the Two-Mode Hybrid to function like a conventional parallel hybrid under high continuous power regions such as sustained high speed cruising or trailer towing.
- Full electric boost is available in fixed gear modes.


2 Electric machines
Input
Output
3 Planetary gear sets

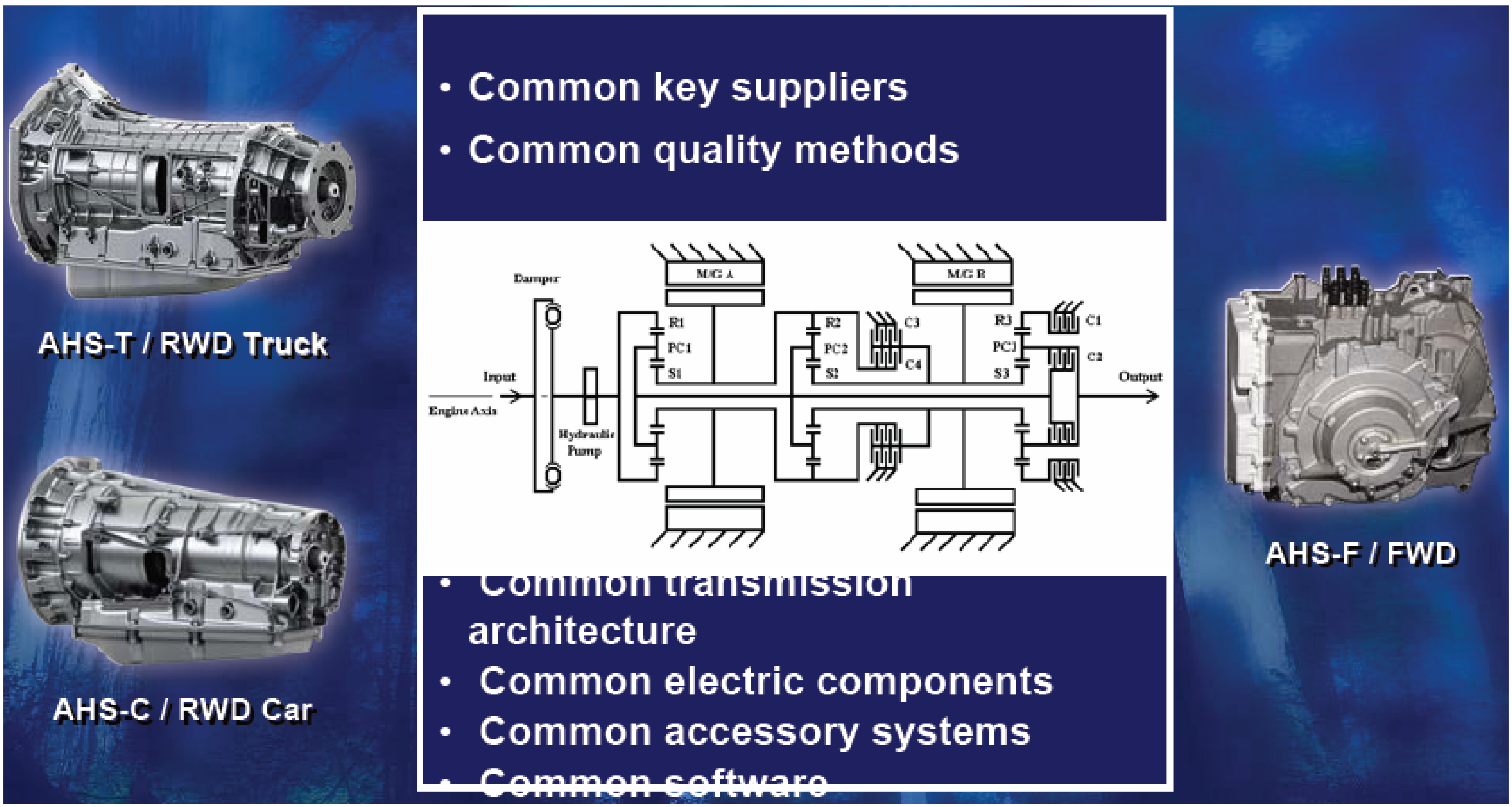

he battery)

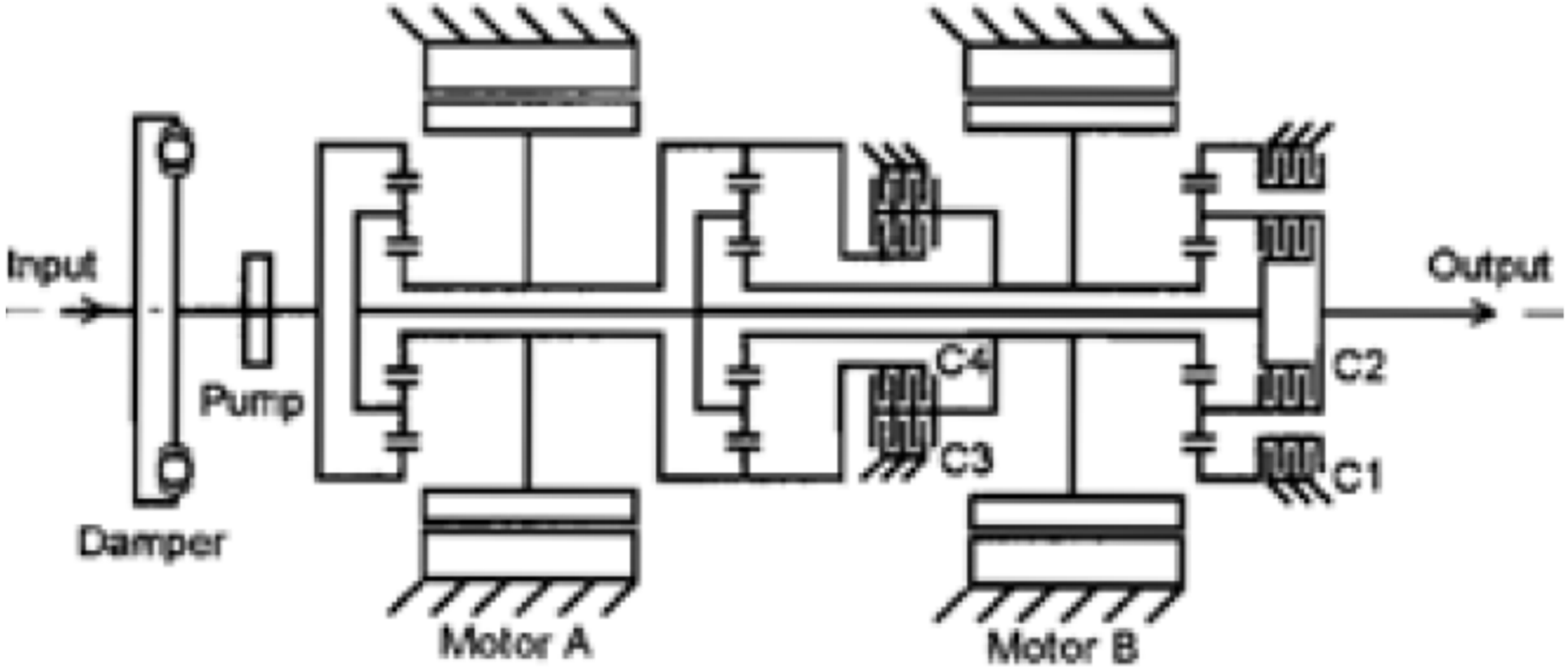

Engine
input
shaft
planetary
gear 1
ring
carrier
sun
sun
carrier
ring
planetary
gear 2
planetary
gear 3
ring
carrier
sun
C2
C1
Motor/
generator A
Motor/
generator B
Battery
output
shaft



Two-Mode Hybrid	 Chevrolet Tahoe Hybrid  GMC Yukon Hybrid

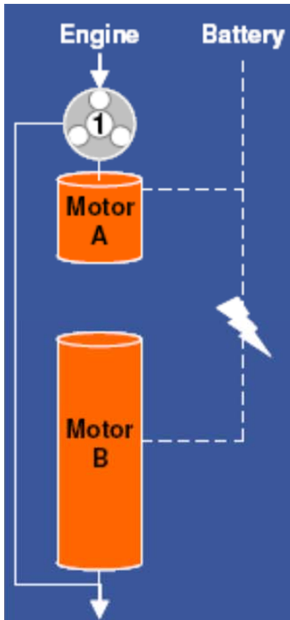
Technology	Found in:
Two-Mode Hybrid	 GM Hybrid Bus



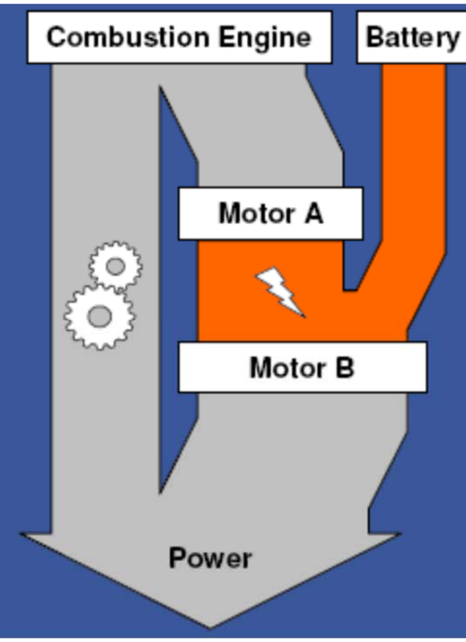


2-Mode Hybrid Operation		C1	C2	C3	C4
Electric Launch	EVT 1	On			
Engine Starting	EVT 1	On			
EVT Mode / Range 1	EVT 1	On			
1st Fixed Gear Ratio	FG 1	On			On
EVT Mode / Range 1	EVT 1	On			
2nd Fixed Gear Ratio	FG 2	On	On		
EVT Mode / Range 2	EVT 2		On		
3rd Fixed Gear Ratio	FG 3		On		On
EVT Mode / Range 2	EVT 2		On		
4th Fixed Gear Ratio	FG 4		On	On	

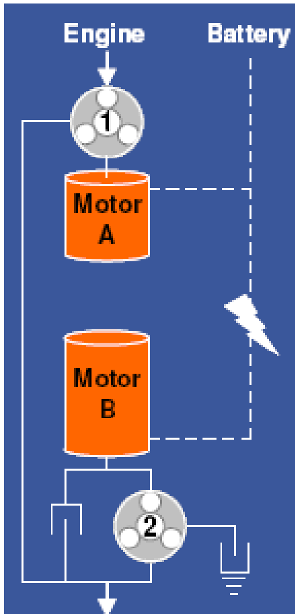
One-Mode



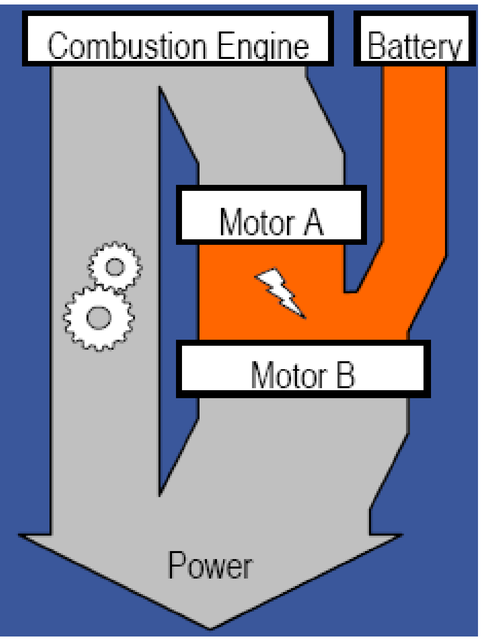
- Planetary gears split engine power
- One unchanging mechanical arrangement
- Combined motor power requirement typically exceeds engine power



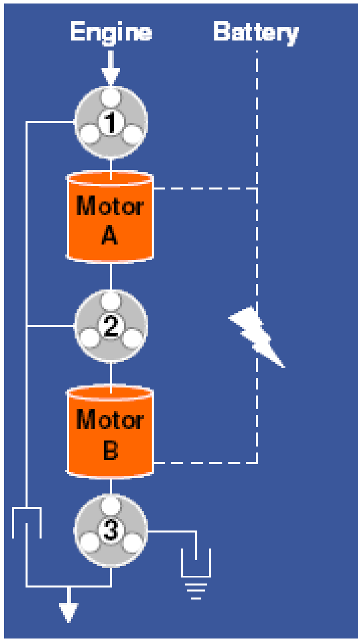
One-Mode + Two-Speed Motor Gearing



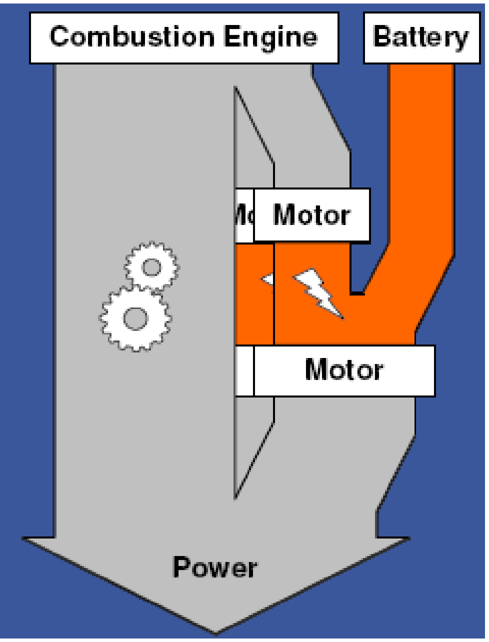
- Planetary gears split engine power and can multiply motor torque
- Clutches change motor ratio only
- Combined motor power requirement is not changed by shifting motor ratio



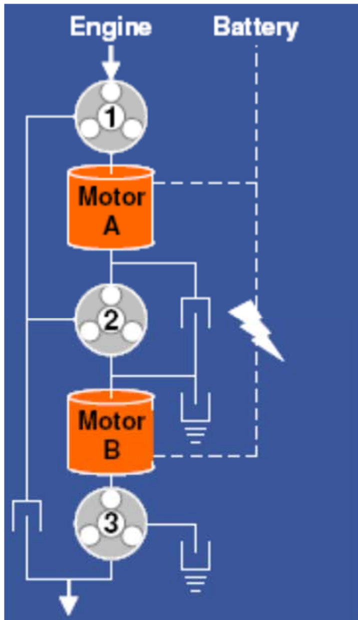
Two-Mode



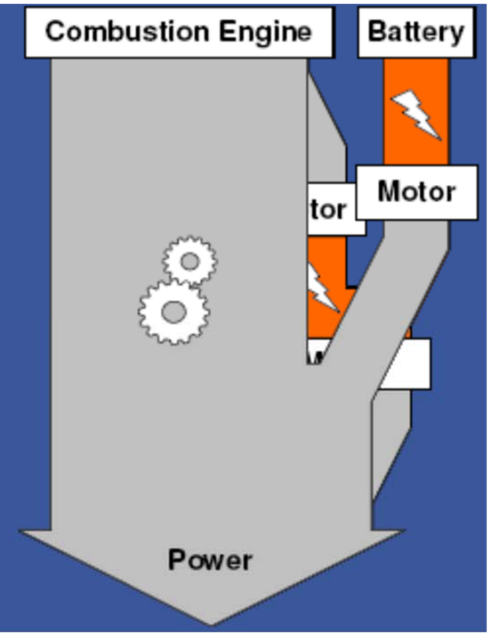
- Planetary gears split engine power and can multiply all torque
- Clutches change EVT modes smoothly
- Combined motor power requirement is much improved with two modes



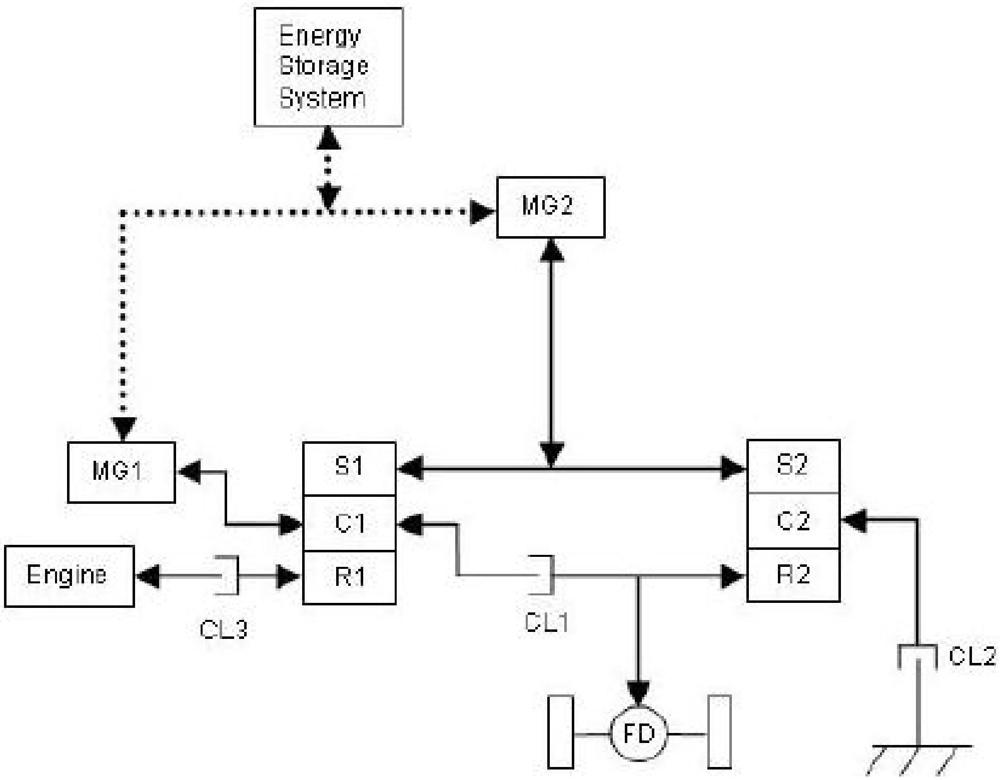
Two-Mode + Four Fixed Mechanical Gears



- Planetary gears split engine power and can multiply all torque
- Clutches activate EVT modes and fixed gear ratios
- Motors are not required to carry engine power when using fixed gear ratios

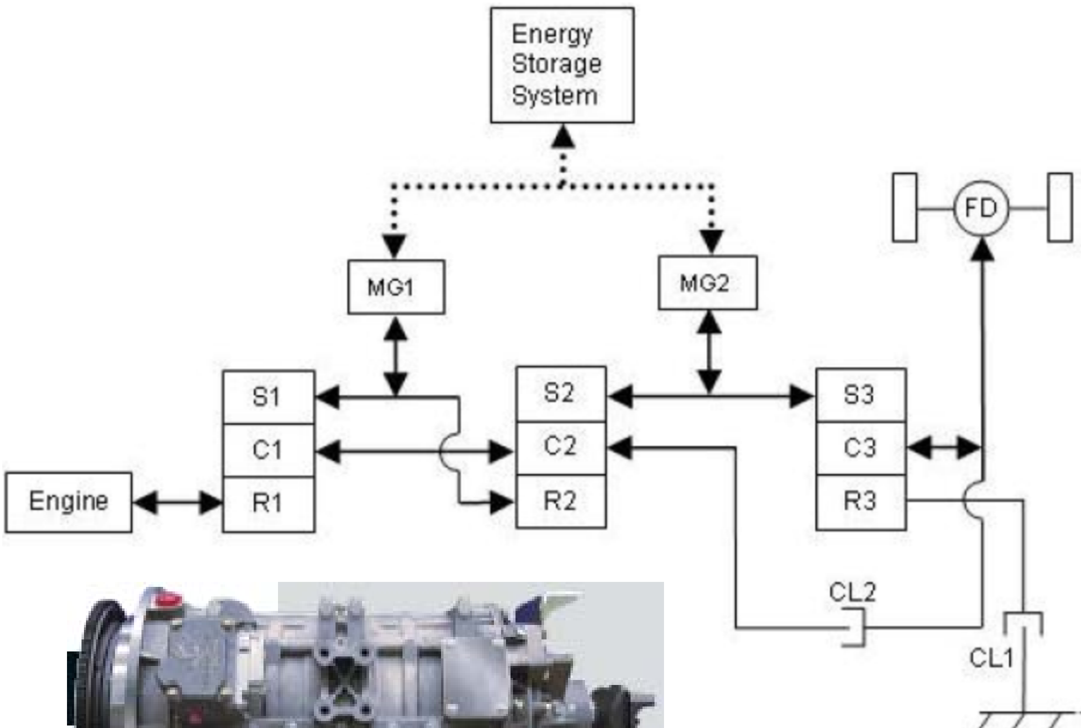


Original Two-Mode U.S. patent number 5,558,588 (1996)

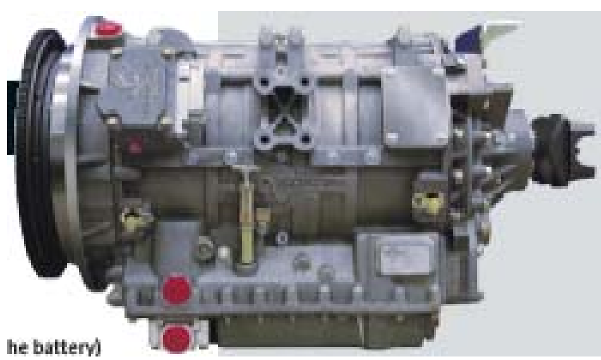


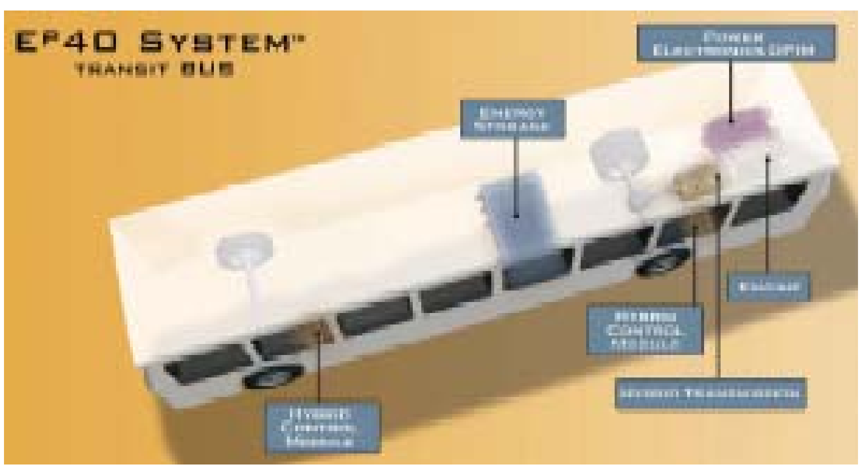
Regime	Electric Machines	CL1	CL2	CL3
Forward:				
AER (slow)	MG1: off; MG2: motor	On	On	Off
AER (fast)	MG1, MG2: motor	On	Off	Off
eCVT (slow)	MG1: generator; MG2: motor	Off	On	On
eCVT (medium)	MG1: motor; MG2: generator	On	Off	On
eCVT (fast)	MG1: generator; MG2: motor	On	Off	On
Hybrid (very slow)	MG1: generator; MG2: motor	Off	On	On
Hybrid (slow)	MG1: motor; MG2: generator	On	Off	On
Hybrid (medium)	MG1, MG2: motor	On	Off	On
Hybrid (fast)	MG1: generator; MG2: motor	On	Off	On
ESS Charge (slow, Mode 1)	MG1: generator; MG2: motor	Off	On	On
ESS Charge (medium, Mode 1)	MG1, MG2: generator	Off	On	On
ESS Charge (slow, Mode 2)	MG1: motor; MG2: generator	On	Off	On
ESS Charge (medium, Mode 2)	MG1, MG2: generator	On	Off	On
ESS Charge (fast, Mode 2)	MG1: generator; MG2: motor	On	Off	On
Braking:				
Regen (slow)	MG1, MG2: generator	On	On	Off
Regen (fast)	MG1: generator; MG2: off	On	Off	Off
Engine lagging (slow)	MG1: motor; MG2: generator	Off	On	On
Engine lagging (medium)	MG1: generator; MG2: off	On	Off	On
Engine lagging (fast)	MG1: motor; MG2: generator	On	Off	On
Regen+Engine lagging (very slow)	MG1: motor; MG2: generator	Off	On	On
Regen+Engine lagging (slow)	MG1: generator; MG2: off	On	Off	On
Regen+Engine lagging (medium)	MG1, MG2: generator	On	Off	On
Regen+Engine lagging (fast)	MG1: motor; MG2: generator	On	Off	On

Two-Mode U.S. patent number 5,931,757 (1999)



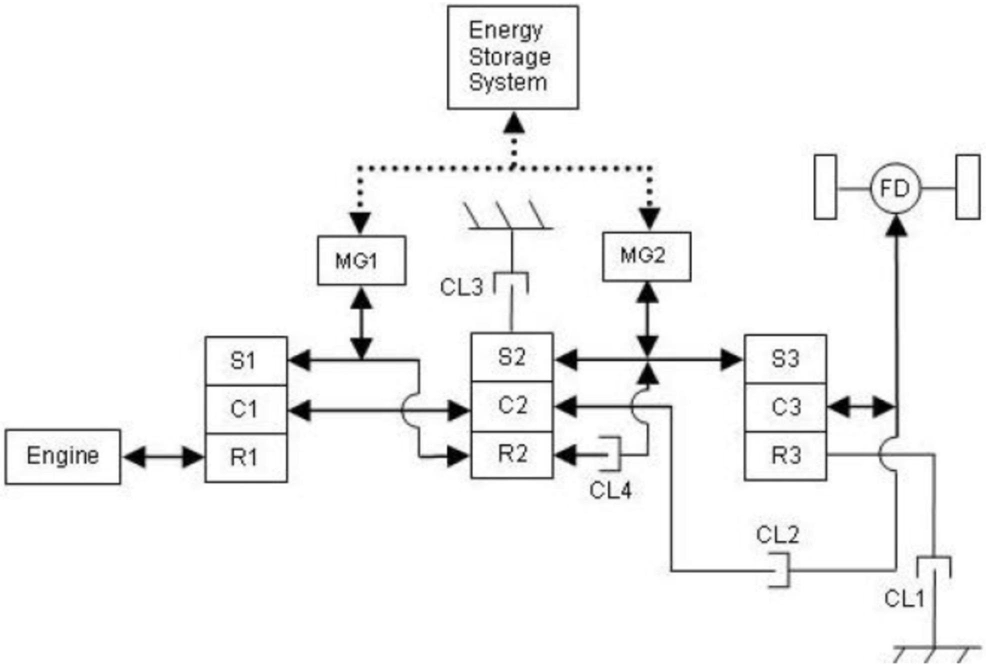
The design is also known as the EP40/50 and Installed in transit buses

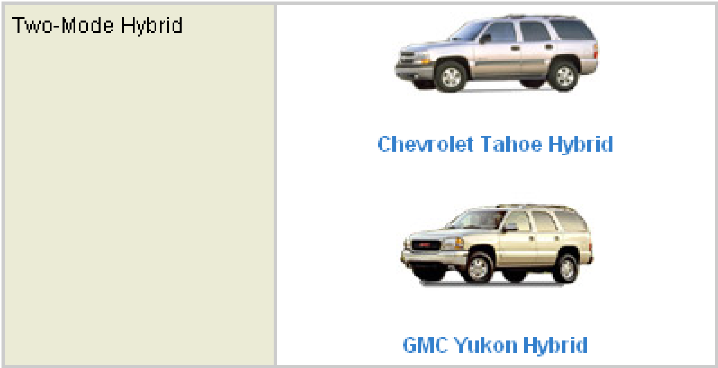


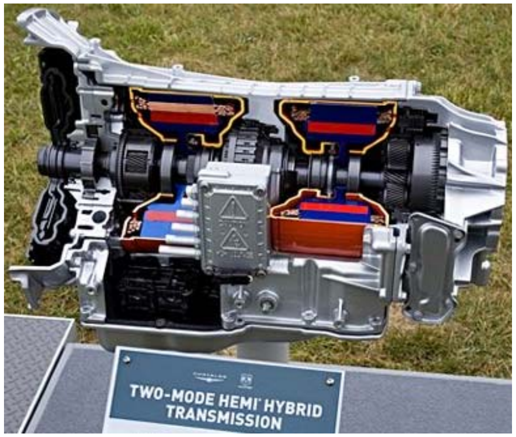


Regime	Electric Machines	CL1	CL2
Forward:			
AER†	MG1: off/motor MG2: motor	On	Off
Mode 1, slow	MG1: generator MG2: motor	On	Off
Mode 1, fast	MG1, MG2: motors	On	Off
Mode 2, slow	MG1: generator MG2: motor	Off	On
Mode 2, medium	MG1, MG2: motors	Off	On
Mode 2, fast	MG1: motor MG2: generator	Off	On

Two-Mode + Four Fixed Mechanical Gears
U.S. patent number 6,953,409 B2 (2005)

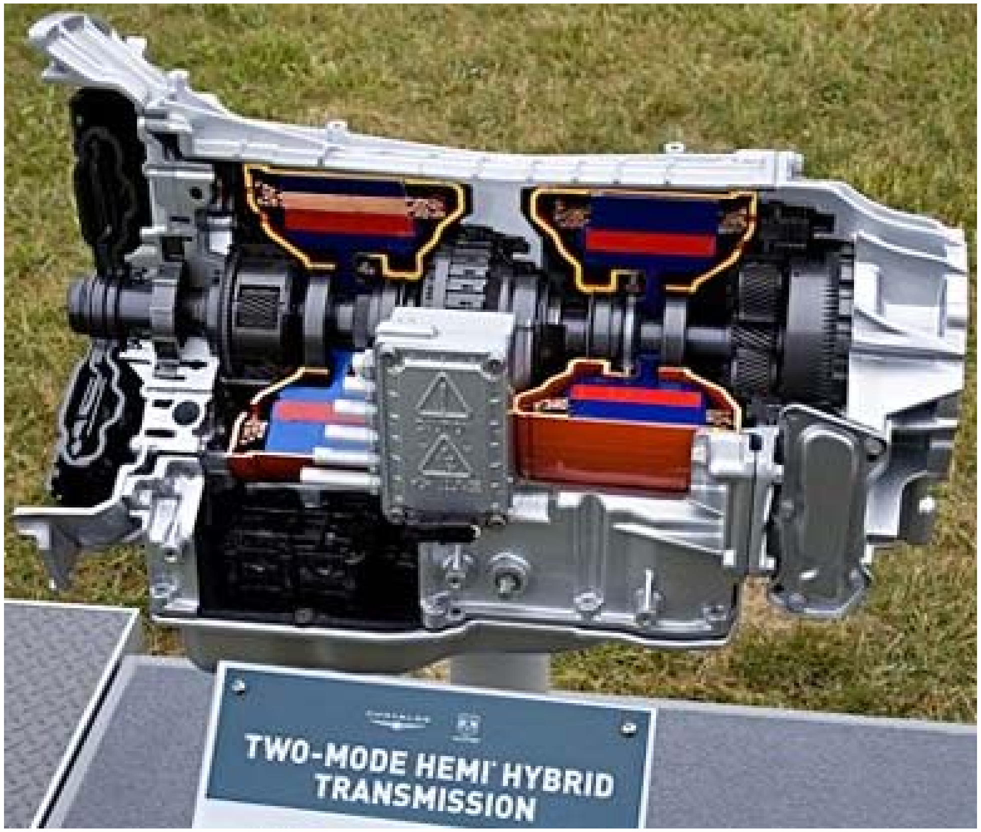






Regime	Electric Machines	CL1	CL2	CL3	CL4
Forward:					
AER†	MG1: off; MG2: motor	On	Off	Off	Off
Power-split 1, slow	MG1: generator; MG2: motor	On	Off	Off	Off
Fixed 1	MG1, MG2: off/motors	On	Off	Off	On
Power-split 1, medium	MG1, MG2: motors	On	Off	Off	Off
Fixed 2	MG1, MG2: off/motors	On	On	Off	Off
Power-split 2, slow	MG1, MG2: motors	Off	On	Off	Off
Fixed 3	MG1, MG2: off/motors	Off	On	Off	On
Power-split 2, medium	MG1: generator; MG2: motor	Off	On	Off	Off
Fixed 4	MG1, MG2: off/motors	Off	On	On	Off

2009 Dodge Durango Hybrid and Chrysler Aspen Hybrid



	2009 Chrysler Aspen Hybrid/Dodge Durango Hybrid
Base Price	$45,340 (Dodge); $45,570 (Chrysler)
Vehicle layout	Front engine, AWD, 8-pass, 4-door SUV
Engine	5.7L/345-hp/380 lb-ft OHV 16-valve V-8 plus 87-hp/235 lb-ft. electric motor
Transmission	Hybrid-electric with two variable modes, four fixed gears
Curb weight (dist f/r)	5550 lbs
Wheelbase	119.2 in
Length x width x height	202.1 x 76.0 x 73.6 in
0-60 mph	7.5 sec (MT est)
EPA city/hwy fuel econ	19/20 mpg (EPA)
CO2 emissions	1.00 lb/mile

Mercedes-Benz ML 450 Hybrid

Combustion engine	
Type	Atkinson-style petrol engine
Number of cylinders/arrangement	V6
Displacement cc	3498
Valves per cylinder / valve control system	4 / continuously variable
Rated output kW	205
Rpm	6000
Max. torque Nm	350
RPM	3000 - 5500
Electric motors	
Rated output, electric motor 1 kW	62
Rated output, electric motor 2 kW	60
Max. torque, electric motor 1 Nm	235
Max. torque, electric motor 2 Nm	260
Combined system output	
Rated output kW	250
Max. torque Nm	517
Fuel consumption FE Label mpg	
City	21
Highway	24
Combined	22
Tank capacity l (gal)	90 (23.8)
Theor. range km (mls)	840 (520)
Emissions standard	SULEV
Performance	
0-60 mph sec	7.8
¼ mile	15.8
Top speed mph	131

The two-mode hybrid technology in the ML 450 HYBRID, whose drive architecture supports purely electric operation and purely combustion engine operation or any combination of the two, takes its lead from the fundamental work undertaken by the "Global Hybrid Cooperation". This group brought together research and development work undertaken by the companies Daimler AG, BMW Group, General Motors and Chrysler.

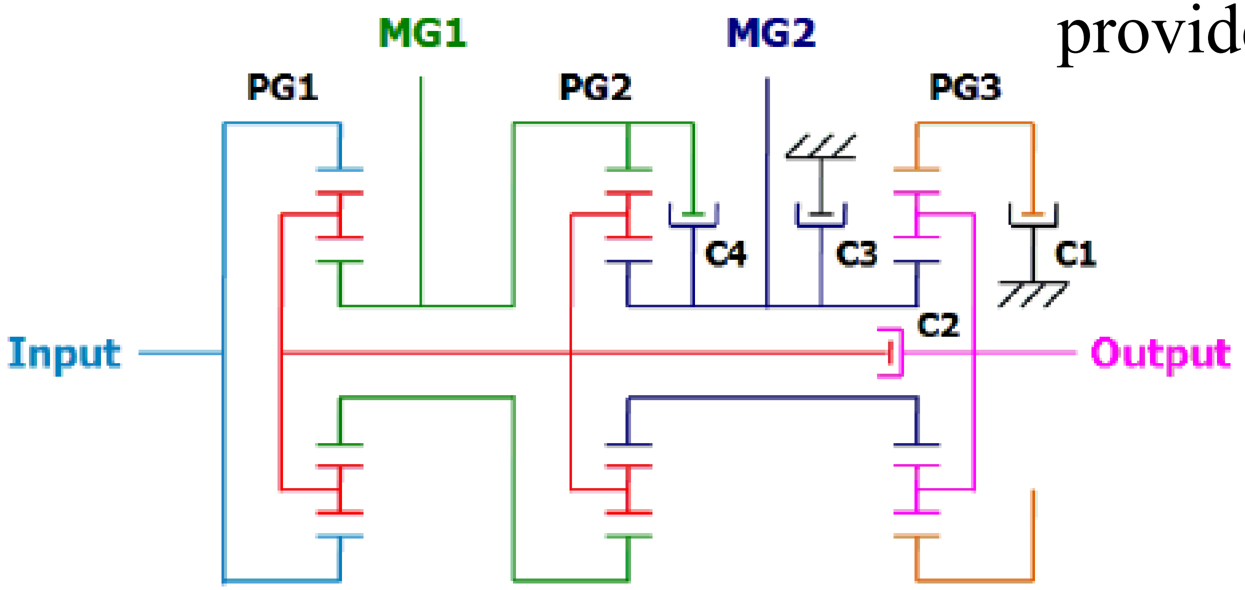
Toyota Hybrid System **THS/Hybrid Synergy Drive**

- One-mode single power-split device (incorporated as a single 3 shaft planetary gearset)
- Simple in mechanical terms
- Drawbacks: the maximum speed is mainly limited by the speed of the smaller electric motor (usually functioning as a generator)
- The efficiency of the transmission is heavily dependent on the amount of power being transmitted over the electrical path
- Low efficiency of electric path (~0.7) compared with the purely mechanical path (~0.98)
- Especially in higher speed regimes (>120 km/h or 70 mph), the efficiency (of the transmission alone) therefore drops below that of a generic automatic transmission.

GM Two-mode, Input and Compound Split EVT

- Differential gearing splits power into parallel paths: mechanical and electrical
- Three planetary gear sets
- Two electric machines in series
- Two modes means two ranges of infinitely variable gear ratios

- The input split mode is used for launching the vehicle from a stop, driving at low speeds, or providing moderate load trailer towing.
- The compound split mode is used primarily when the vehicle is at higher speeds to provide efficient cruising

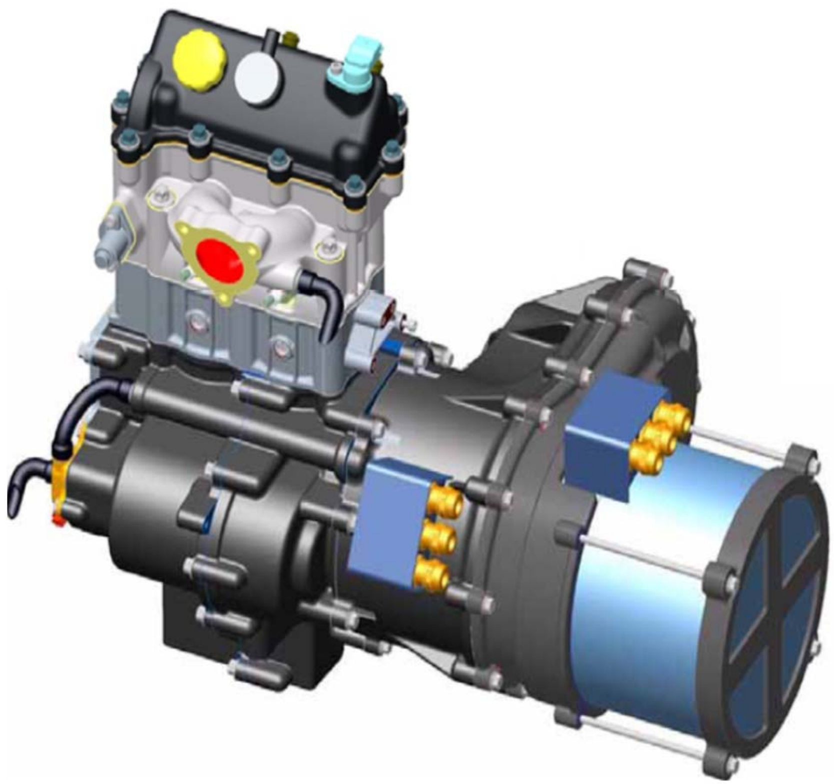


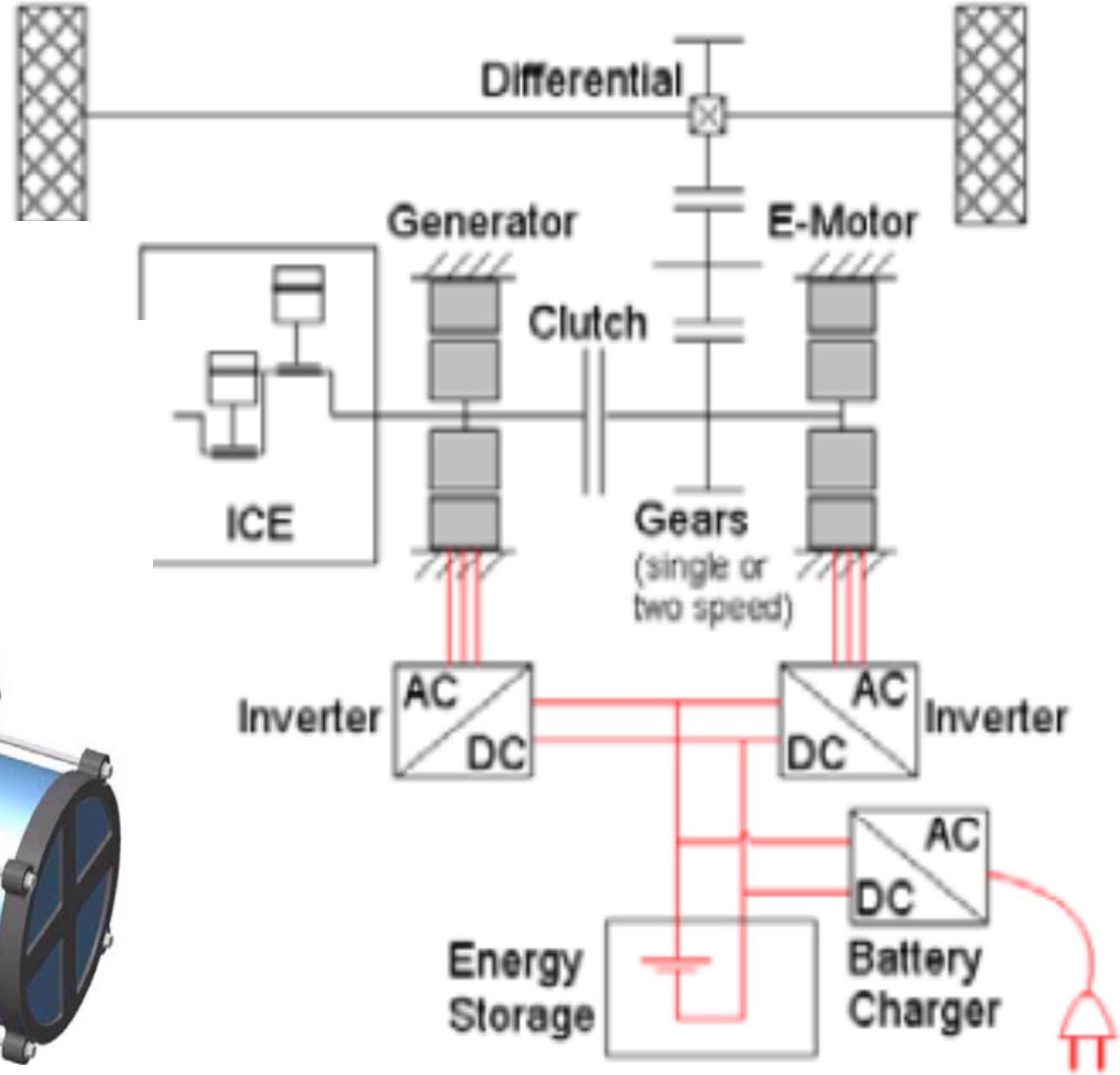
The **Two-Mode Hybrid** name is intended to emphasize the drivetrain's ability to operate in **all-electric (Mode 1)** as well as **hybrid (Mode 2)** modes. The design, however, allows for operation in more than two modes; two power-split modes are available along with several fixed gear (essentially parallel hybrid) regimes. For this reason, the design can be referred to as a multi-regime design. The Two-Mode Hybrid powertrain design can be classified as:

- A compound-split design, since the addition of four clutches within the transmission allows for multiple configurations of engine power-splitting.
- In addition to the clutches, this transmission also has a second planetary gearset. The objective of the design is to vary the percentage of mechanically vs. electrically transmitted power to cope both with low-speed and high-speed operating conditions.
- This enables smaller motors to do the job of larger motors when compared to single-mode systems.
- The four fixed gears enable the Two-Mode Hybrid to function like a conventional parallel hybrid under high continuous power regions such as sustained high speed cruising or trailer towing.
- Full electric boost is available in fixed gear modes.

So, what is this hybrid powertrain system?

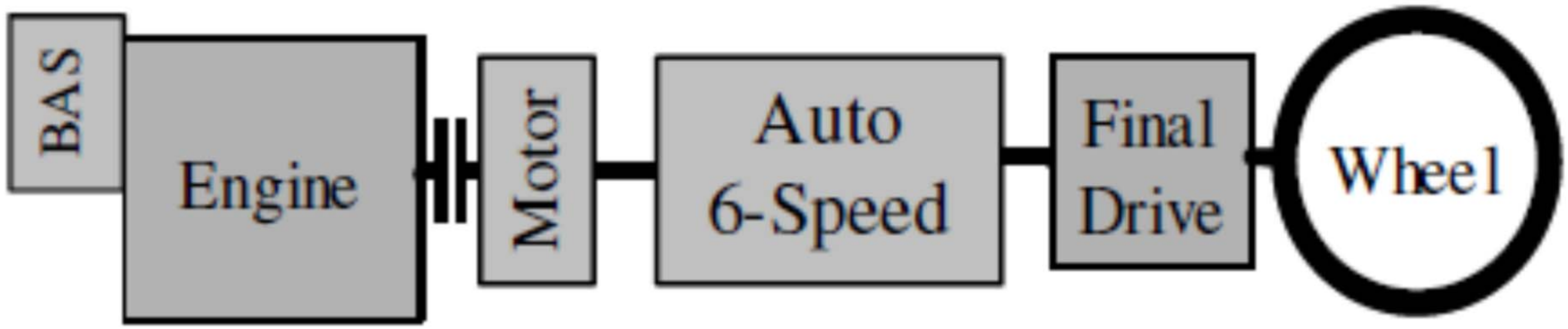
(a)



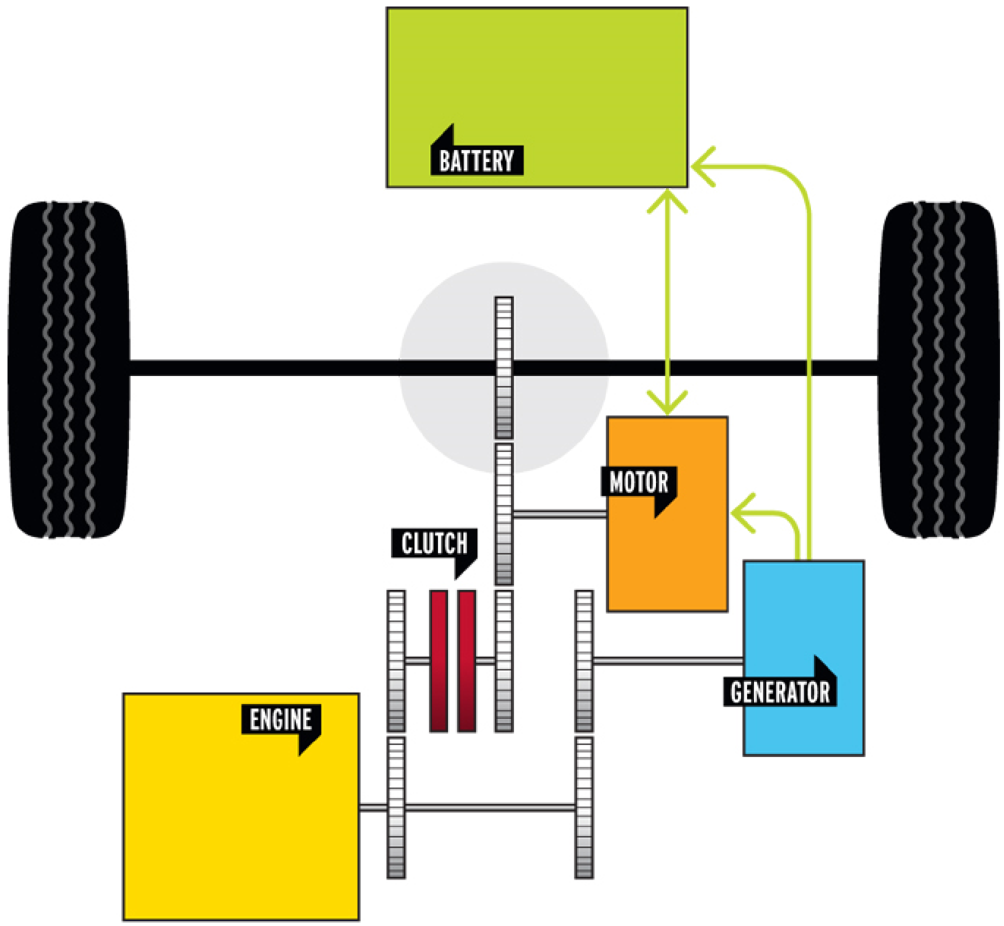


So, what is this hybrid powertrain system?

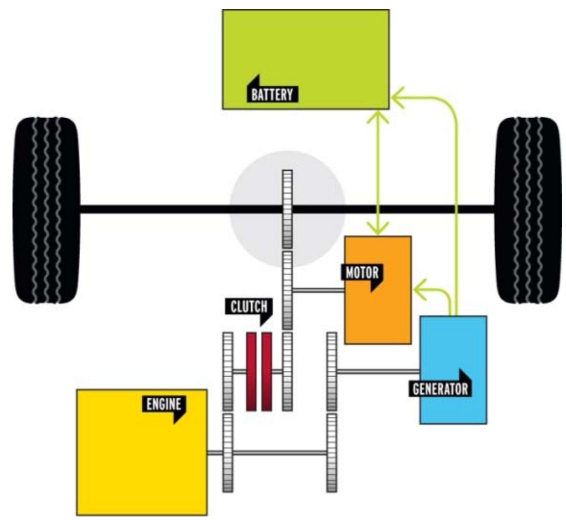
(b)



(c)

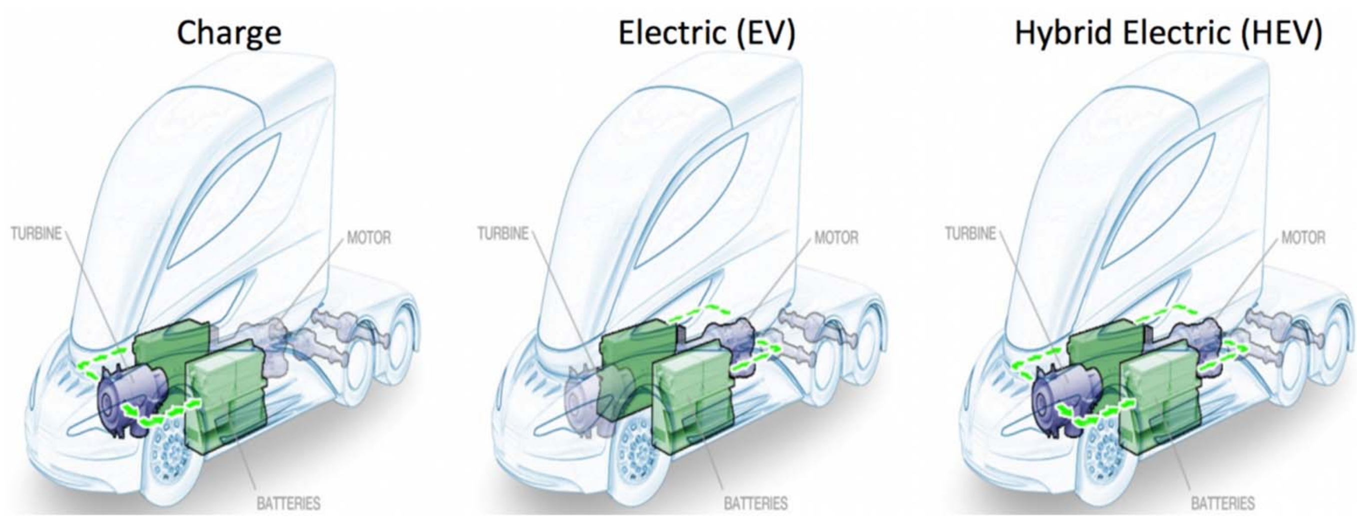


Full Hybrid 2014 Honda Accord Hybrid, Accord Plug-in

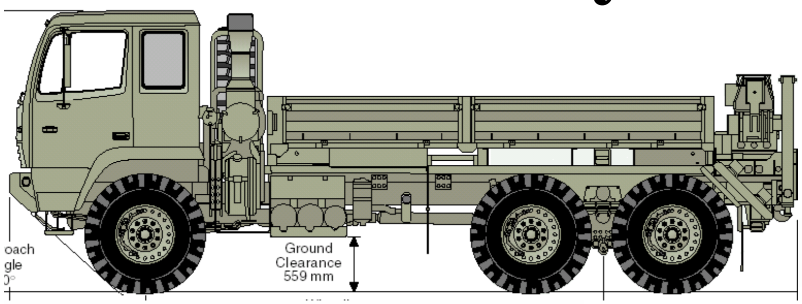


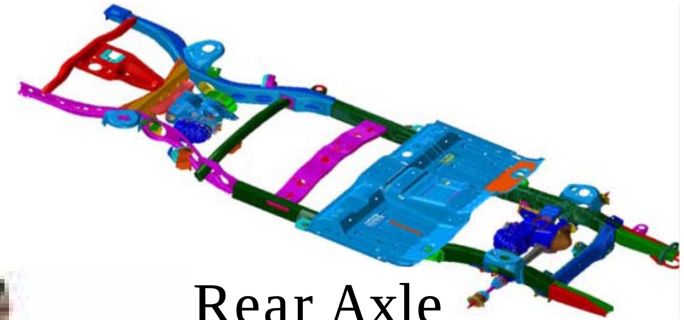
WAVE (Walmart Advanced Vehicle Experience)

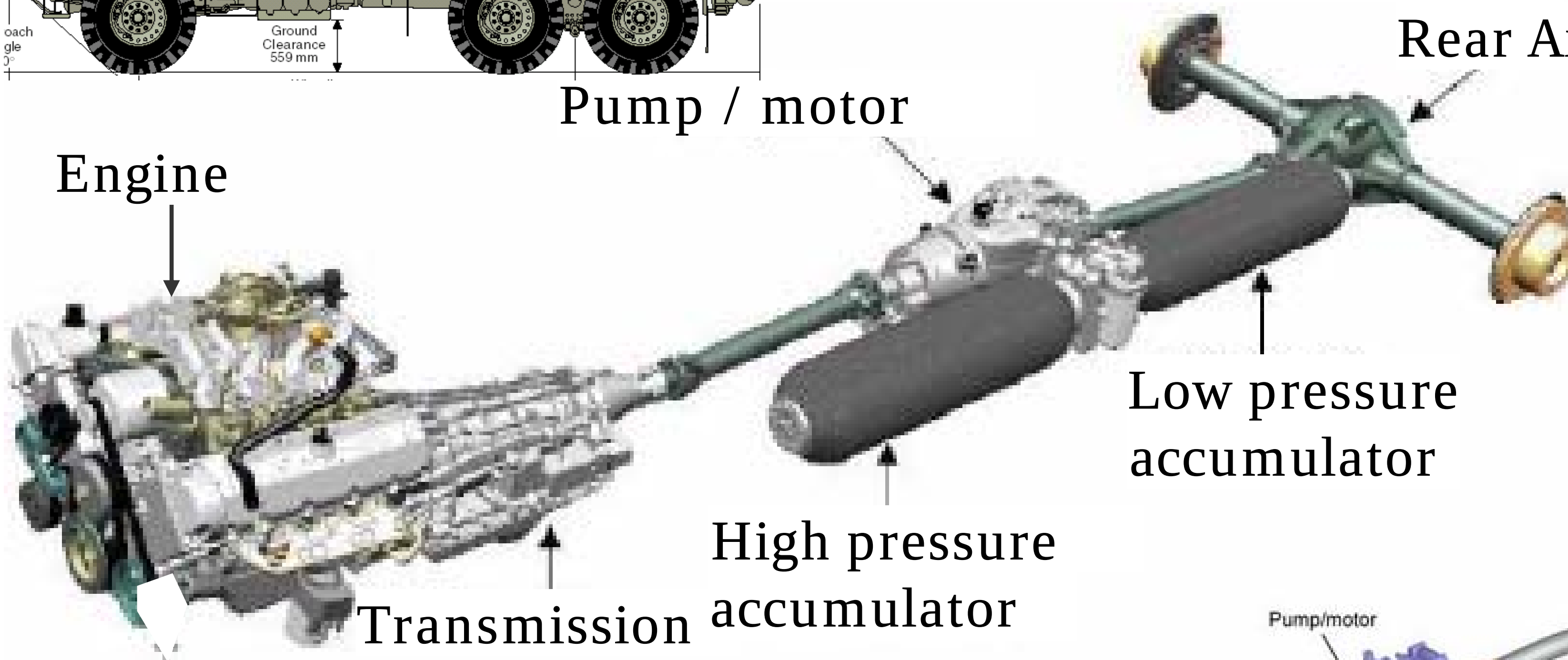
- Average semi-truck: 5.5 ~ 6.5 MPG
- Goal: over 10 MPG
- Cost saving: $25,000 per truck per 120,000 miles

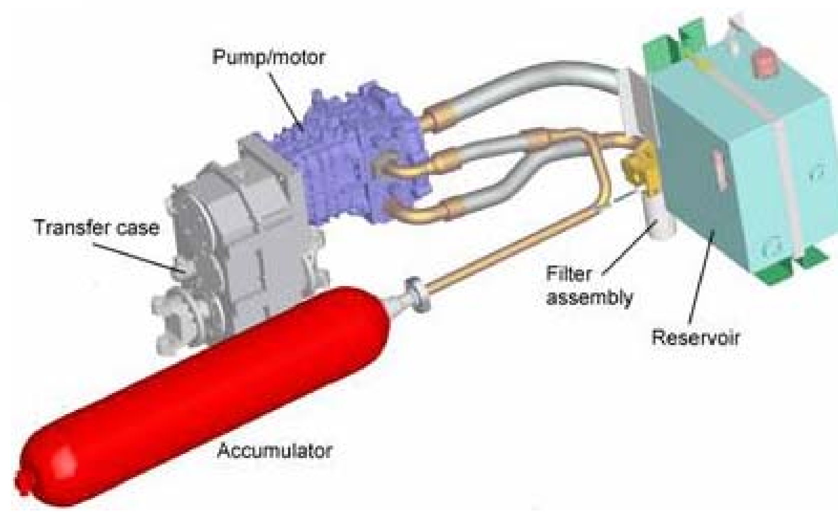


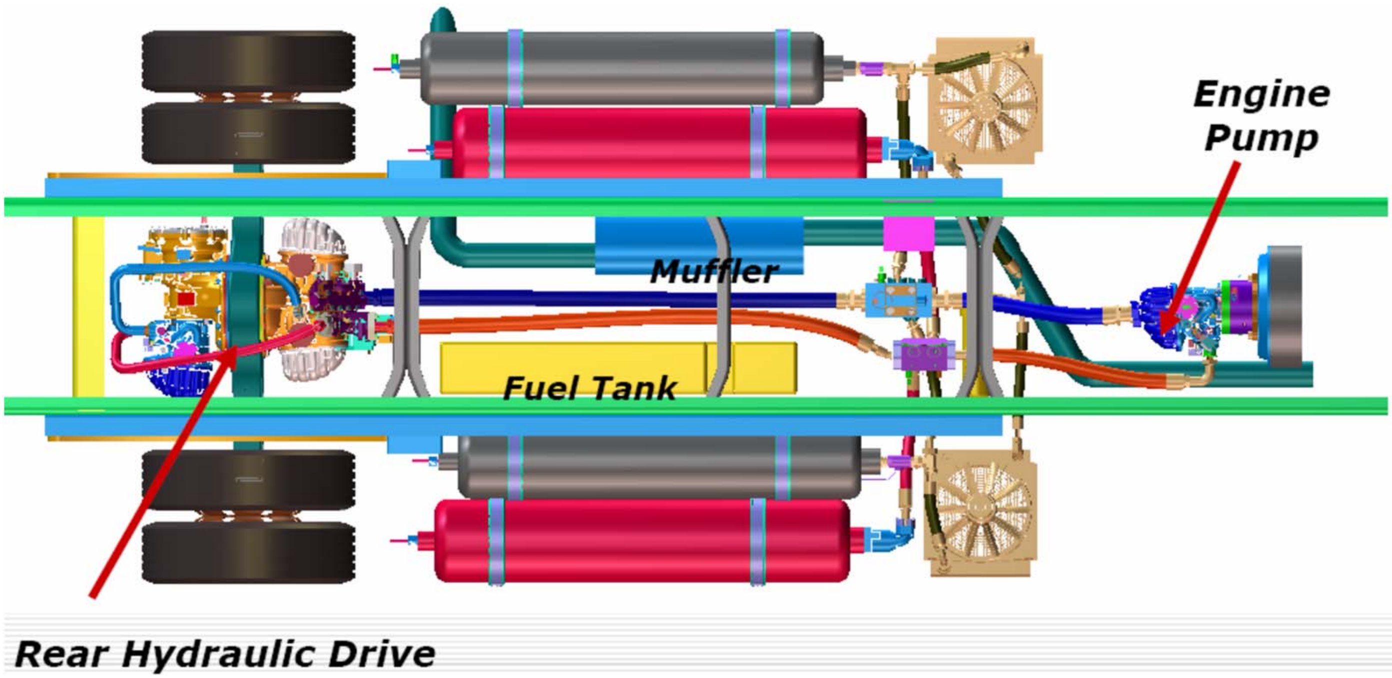
Hydraulic Hybrid

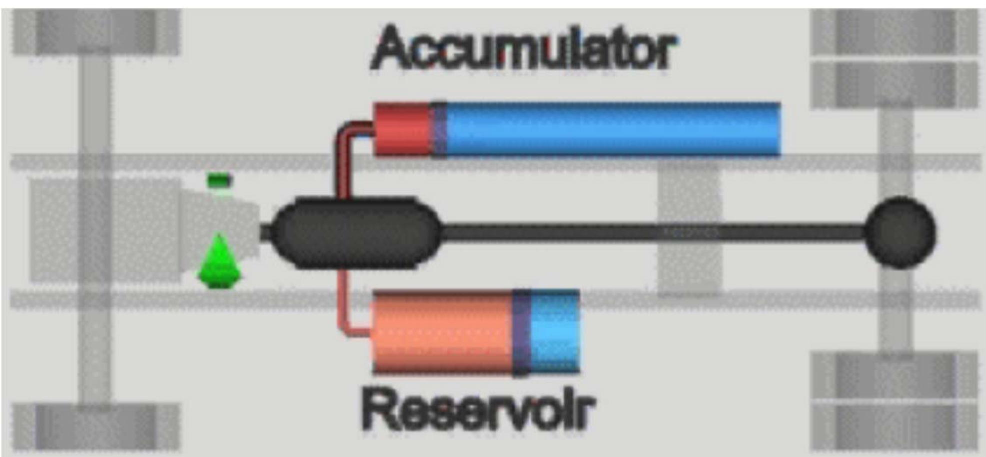




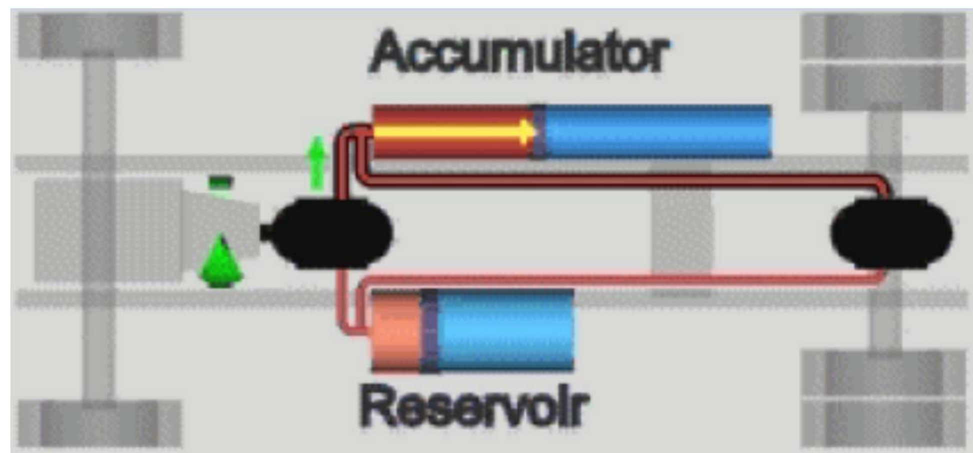








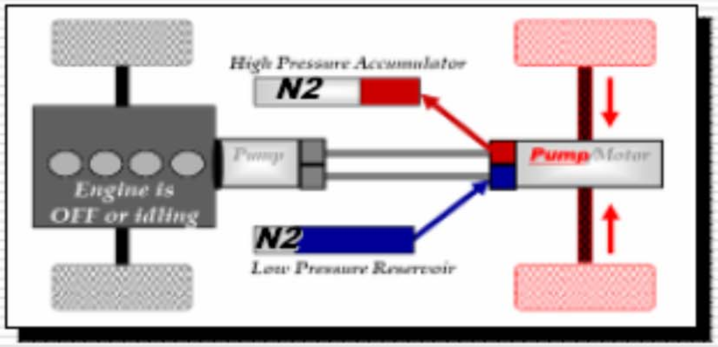
Parallel HHV



Series HHV

How HHVs Work

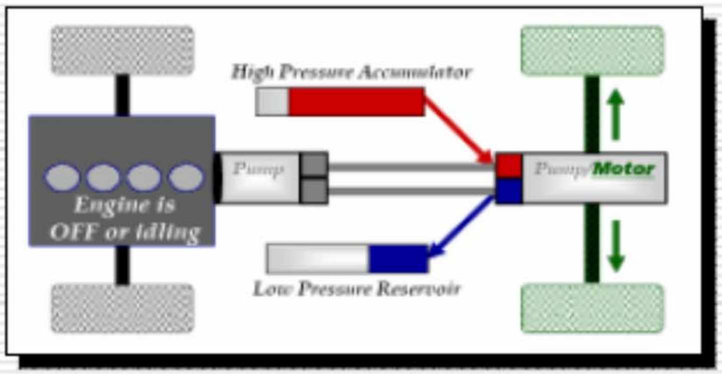
Mode 1 – Braking
Saving Energy Normally Wasted While Braking



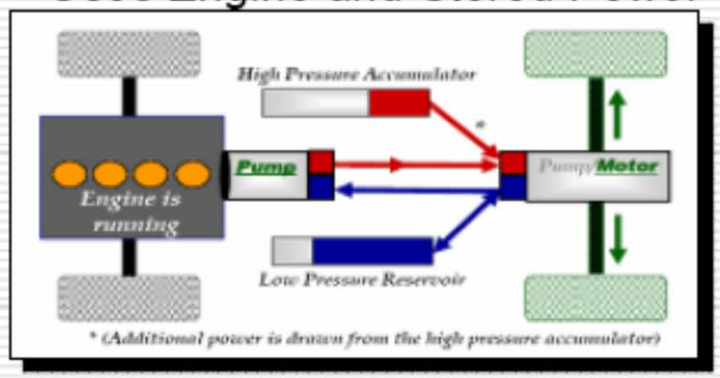
High Pressure Hydraulic Fluid (oil)

Low Pressure Hydraulic Fluid (oil)

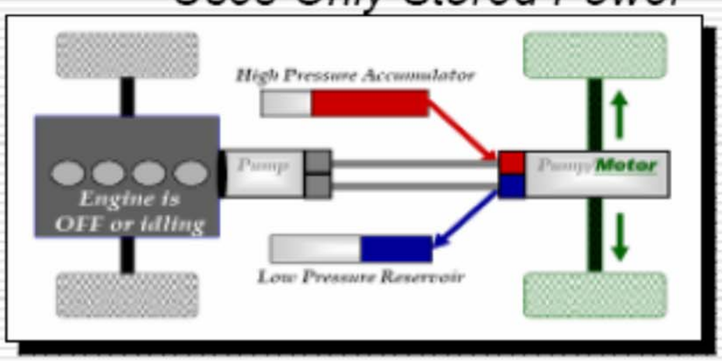
Mode 2 – Initial Acceleration
Uses Only Stored Power



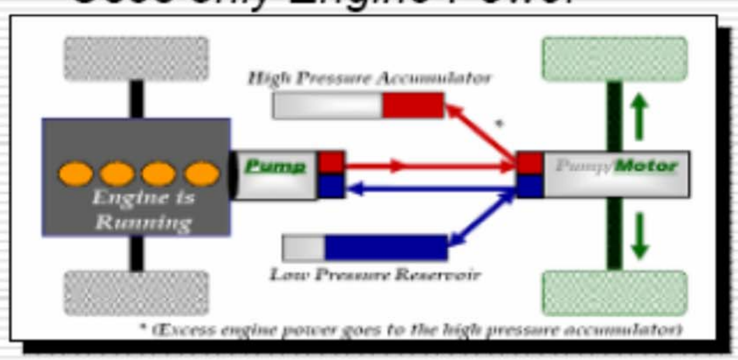
Mode 3 – Sustained Acceleration
Uses Engine and Stored Power



Mode 4 – Cruising
Uses Only Stored Power



Mode 5 – Extended Cruising
*Uses only Engine Power**



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Home » Media » What's New » New Refuse Trucks Help Detroit Save Money and Operate More Efficiently

New Refuse Trucks Help Detroit Save Money and Operate More Efficiently

February 4, 2013

The City of Detroit recently purchased 8 new hybrid refuse trucks, thanks in part to funding from Clean Energy Coalition's Michigan Green Fleets program.

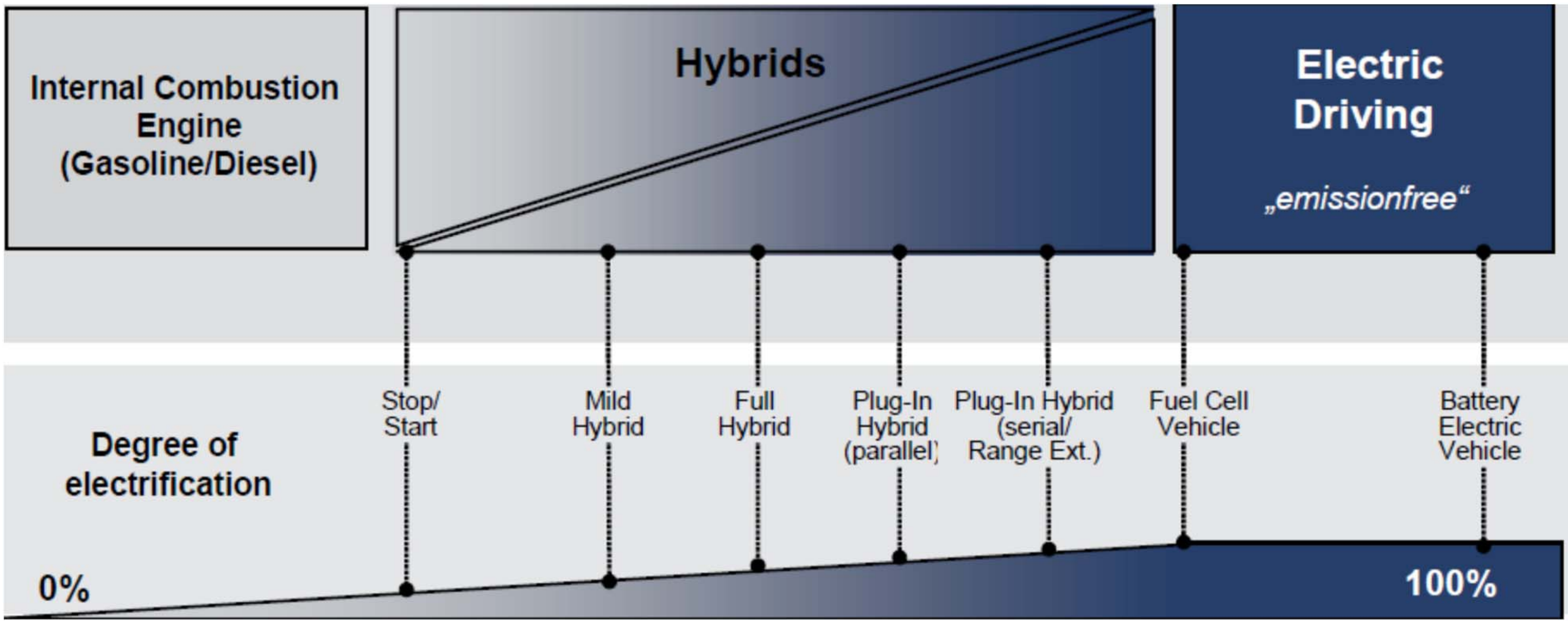
The trucks, Mack LEU chassis with Bosch Rexroth hybrid technology, each cost $180,000. Clean Energy Coalition provided the City of Detroit with grant funding totaling $40,000 per truck, which offset the additional cost of the hybrid system.

Innovative Technology from Bosch Rexroth

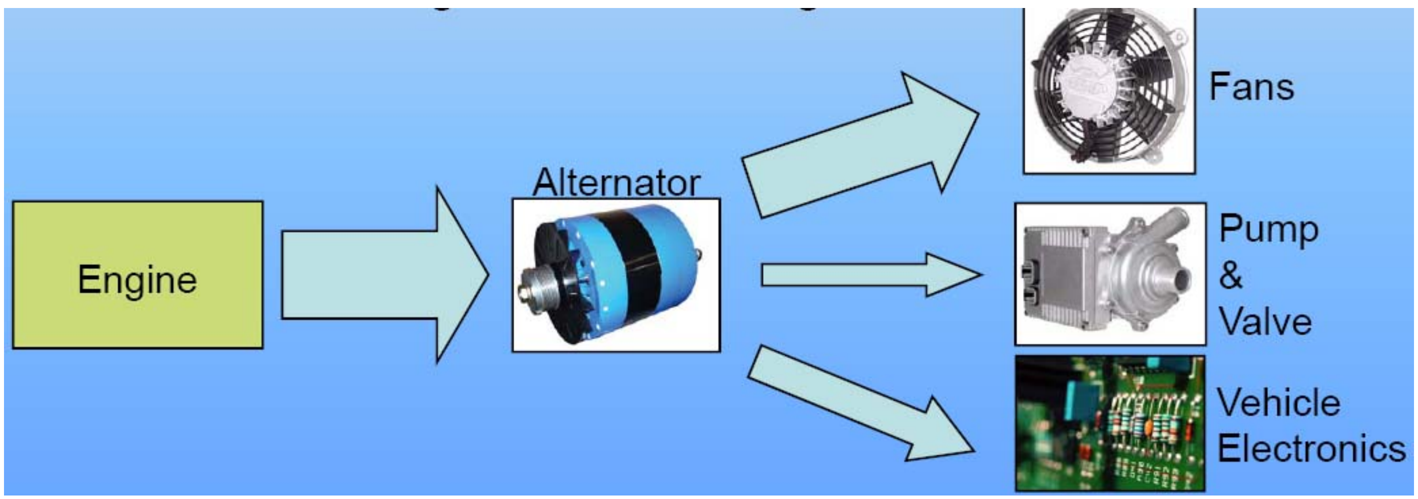
The Bosch Rexroth hydrostatic regenerative braking (HRB) system installed in each truck operates in parallel with the vehicle's engine. According to Dave Brosky, sales product manager at Bosch Rexroth, "This means that if there were a problem with the hydraulic system, the truck could still operate. This is important for work vehicles."

Vehicle Electrification Needs On-Board Electric Energy Storage

Vehicle Drivetrain Electrification



Vehicle Auxiliary Functions (Accessories) Electrification



Advantages of Auxiliaries Electrification

There are several advantages of Auxiliaries Electrification:

1. The load can be more freely placed within the vehicle since they do not have to be connected to the belt in the front of the ICE. This give both a weight and volume benefit.

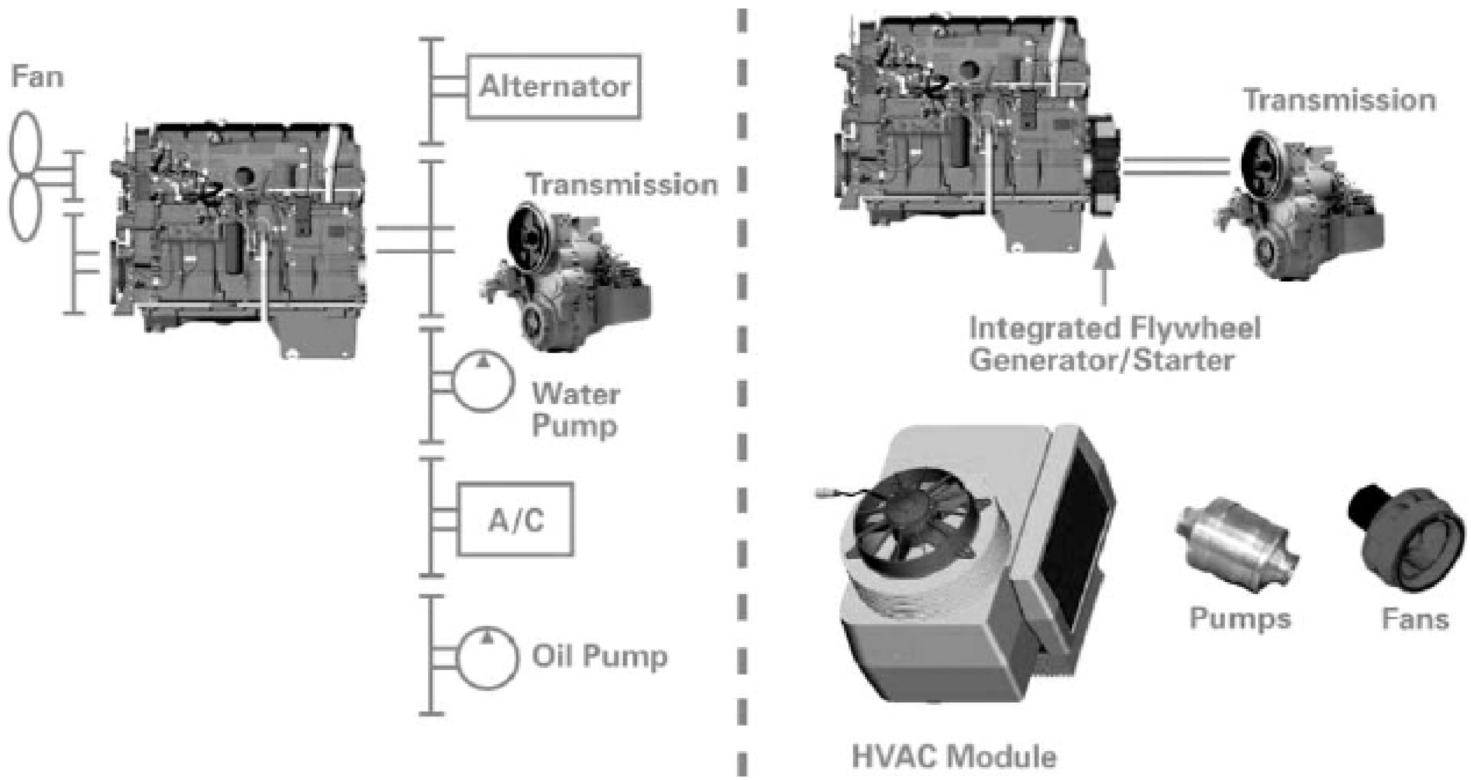
2. The efficiency can be significantly increased, since the possibilities to control the power consumption is bigger when an electric machine is driving the load.
   The AC compressor, as an example, can be driven at the optimal speed all the time. In a conventional vehicle the AC compressor is tied hard to the ICE speed which is related to the vehicle speed, not to what is best for the AC compressor.

Auxiliary Functions (Accessories):

Cooling Fan
Air Condition (AC)
Air Compressor
Water Pump
Steering System

- The power of the auxiliary function loads will only be less than 10% of the driving power when accelerating. Nevertheless most auxiliary sub systems loads the propulsion system under all driving conditions, leading to a relatively high energy consumption.
- In urban duty cycles, low maximum speed and many stop-and-go situations, the energy consumption of the auxiliary sub systems will be high compared to the energy consumption of the driveline. In a hybrid electric urban bus equipped with AC the auxiliary sub systems might well consume as much energy as the driveline.

- It is not only the traction system on board a vehicle that consumes power. The number of, and diversity of, loads that are used either to just facilitate the operation of the vehicle, or to increase the comfort and usability of the vehicle is steadily increasing.
- Some of these loads are mechanically driven via a belt from the crankshaft of the ICE, and yet some are electrically driven. In HEVs, and especially those without an ICE like the BEVs and FCEVs, it is necessary to drive the auxiliary loads with electric power.



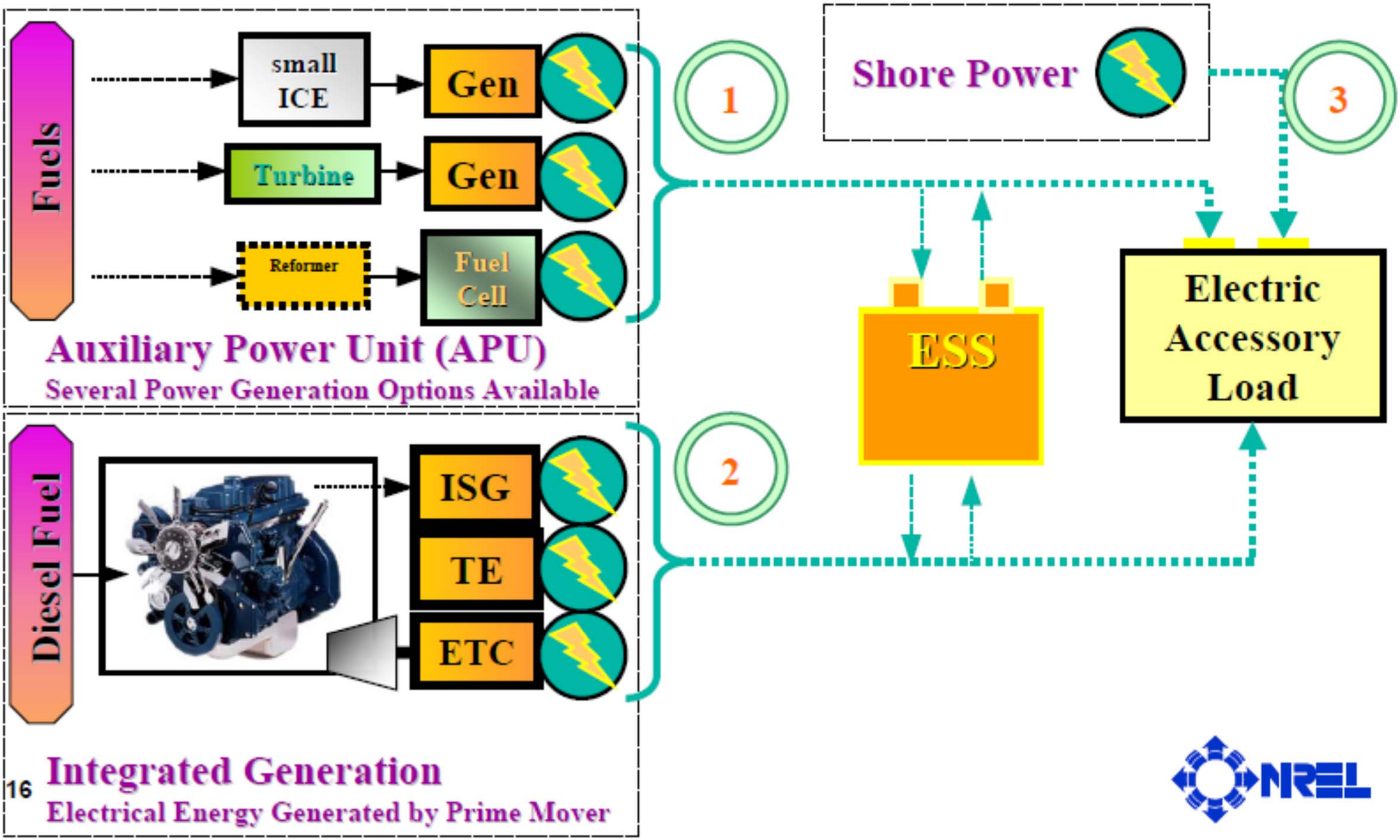
Heavy-Duty Vehicle Auxiliary Power Requirement

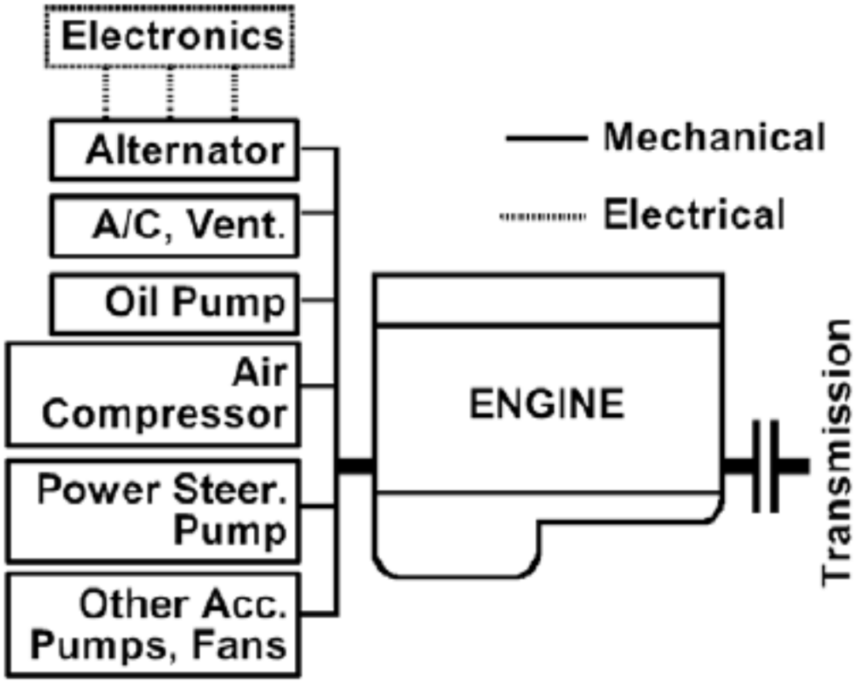
Accessory Type	Average Load (kW)	Max. Load (kW)
Electrical Accessories	0.7	1.0
Air Compressor	2.3	6.0
AC Compressor	2.2	4.5
Engine Cooling Fan	1.1	22.0
Power Steering	0.8	7.5
TOTAL	7.1	41.0

The 21st Century Truck Partnership

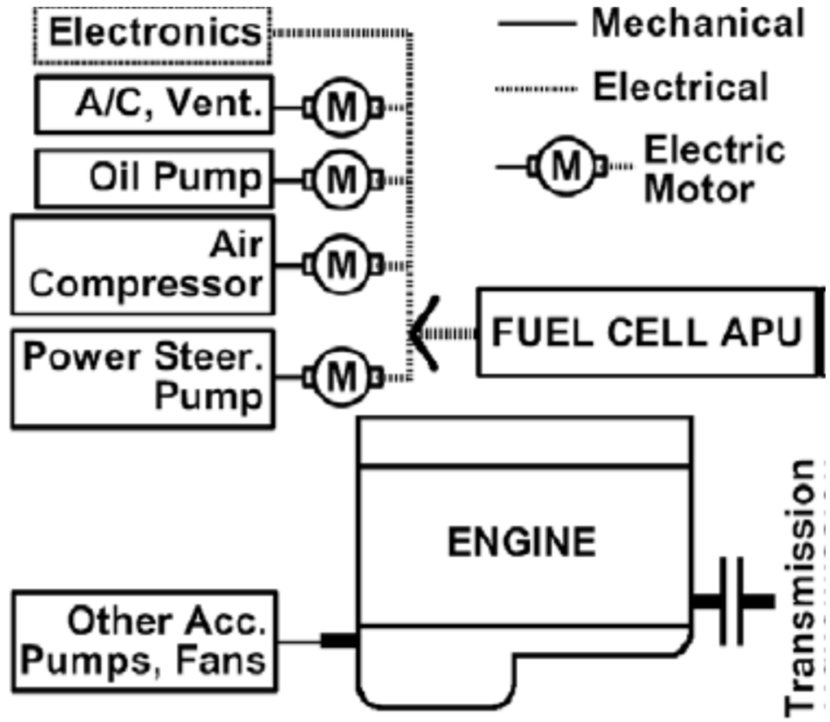
Fuel Cell Technologies for Auxiliary Power

APU Electrification for Heavy-Duty Vehicle

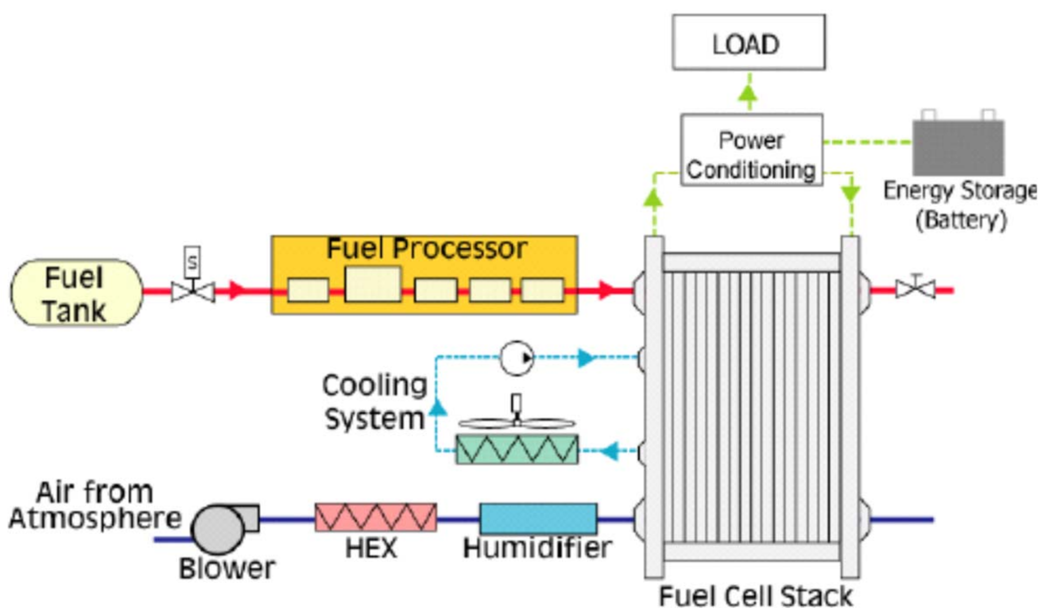




Schematic of the engine with accessories - original configuration

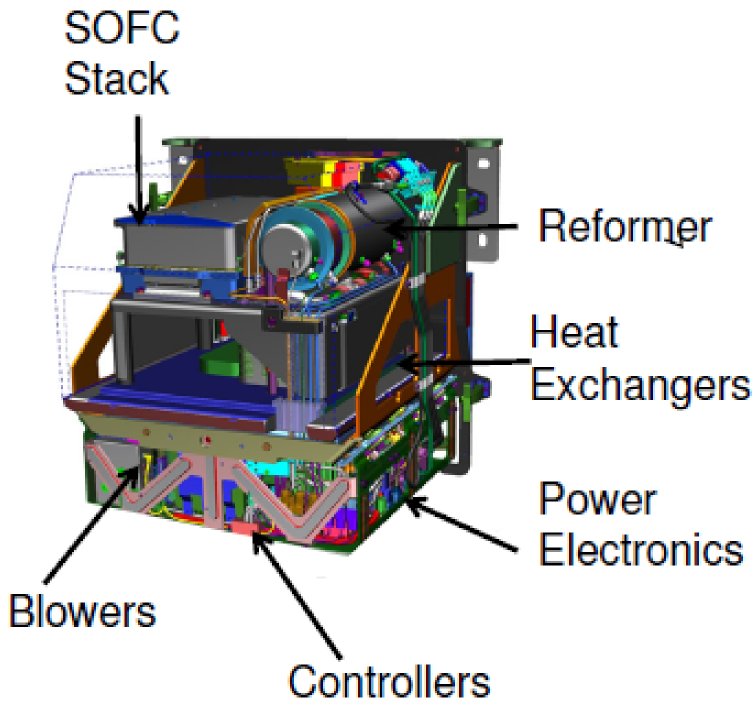


Accessory electrification - use of FC APU

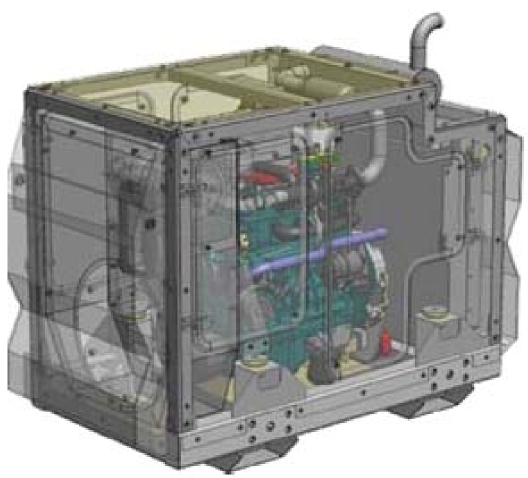


APU Options

Fuel Cell



Small Engine-Generator Set

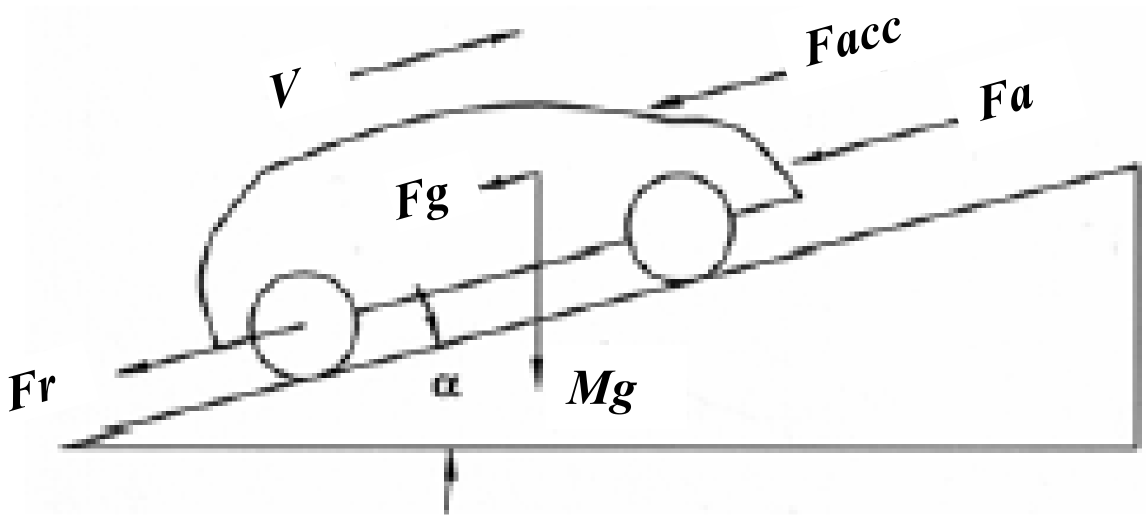


III. Overview of Vehicle Road Load

- Road Load: The Power Consumption Side of Vehicle
- Kinetic Energy Stored in Vehicle Motion
- Powertrain Sizing Based on Road Load
- Driving Cycles: Definition
- Impacts of Driving Cycles
- Types of Driving Cycles

Power Consumption Side of Vehicle: Road Load

Consider a vehicle of mass M, moving at a speed V on a grade of angle α. The frontal area of the vehicle is A_f.



$\boldsymbol{F_a}$: Aerodynamic resistance force $\boldsymbol{F_r}$: Rolling resistance force

$\boldsymbol{F_g}$: Grade resistance force (+ or -)

$\boldsymbol{F_{acc}}$: Accessories and other sources forces

Power Consumption Side of Vehicle: Road Load

Under typical driving conditions, all these forces are functions of time, *t,* due to varying vehicle speed and road/environmental conditions. Hence, the total load (force) on the vehicle is:

$$F_{total}(t) = F_a(t) + F_g(t) + F_r(t) + F_{acc}(t)$$

Similarly, the total power associated with this load is:

$$P_{total}(t) = F_{total}(t) \cdot V(t)$$

where *V(t)* is the instantaneous vehicle speed

To overcome this road load $F_{total}(t)$, the powertrain (conventional or hybrid) is supplying a motive force at the wheel, $F_M(t)$. The balance of these 2 forces determines the net acceleration/deceleration of the vehicle according to Newton's law of motion (in the direction of motion of the vehicle):

$$Ma = M\frac{dV}{dt} = F_M(t) - F_{total}(t)$$

where a represents the (longitudinal) acceleration of the vehicle.

Aerodynamic Resistance Force (1)

$$F_a = F_a(V) = \frac{1}{2}\rho_a A_f C_d V_{eff}^{\ 2}$$

where:

C_d : Aerodynamic drag coefficient (constant or weak function of V)

A_f : Vehicle frontal area

ρ_a : Air density

V_{eff} : Effective air/vehicle relative velocity

$V_{eff} = V + V_{wind}$

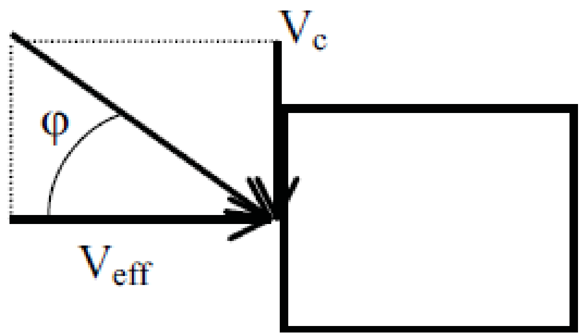
where V: Vehicle speed and V_{wind} : Head wind (against car motion)

For a typical passenger car, A_f : 1.5 – 2 m^2 ,
C_d : 0.35 – 0.45 (possibly 0.45 or 0.6 for utility vehicles, 0.7 - 1.2 for trucks, more with trailer, 0.15 - 0.20 lowest practically achievable).

Typical breakdown of C_d for passenger car	
	~ 65% from basic body shape
	~ 20% from tires and wheels
	~ 10% from mirrors, window frames, antennas, etc.
	~ 5% from motor cooling/radiator

Aerodynamic Resistance Force (2)

In case of a cross-wind, the aerodynamic drag goes up:



$$F_{ac} = \frac{1}{2}\rho_a C_{dc}(\varphi) A_c \left(V_{eff}^{\;2} + V_c^{\;2}\right) \qquad \varphi = \tan^{-1}\left(\frac{V_c}{V_{eff}}\right)$$

where:

$V_{eff} = V + V_{wind}$

V_{eff} Effective head wind

V_{wind} Head wind

V_c Cross wind

F_{ac} Aerodynamic additional force due to cross wind

A_c Cross wind area

$C_{dc}(\varphi) \approx 0.5\,\varphi$ (φ in radians) (can be as little as 0.15 φ on some cars, specifically strong on semi-trailers)

Rolling Resistance Force

The rolling resistance force can be modeled as:

$$F_r(V,\alpha) = Mg\cos\alpha \; C_r(V)$$

- C_r typically $\approx 0.013 - 0.02$ (smooth pavement)
- Lower limit with light vehicle and special low resistance tires: $C_r \approx 0.008$
- C_r depends on tire inflation pressure: $\left(C_r \propto \frac{1}{\sqrt{p}}\right)$
- C_r depends strongly on rolling surface quality (geometrical and environmental)

  $C_r \approx 0.015$ concrete, asphalt (normal road)

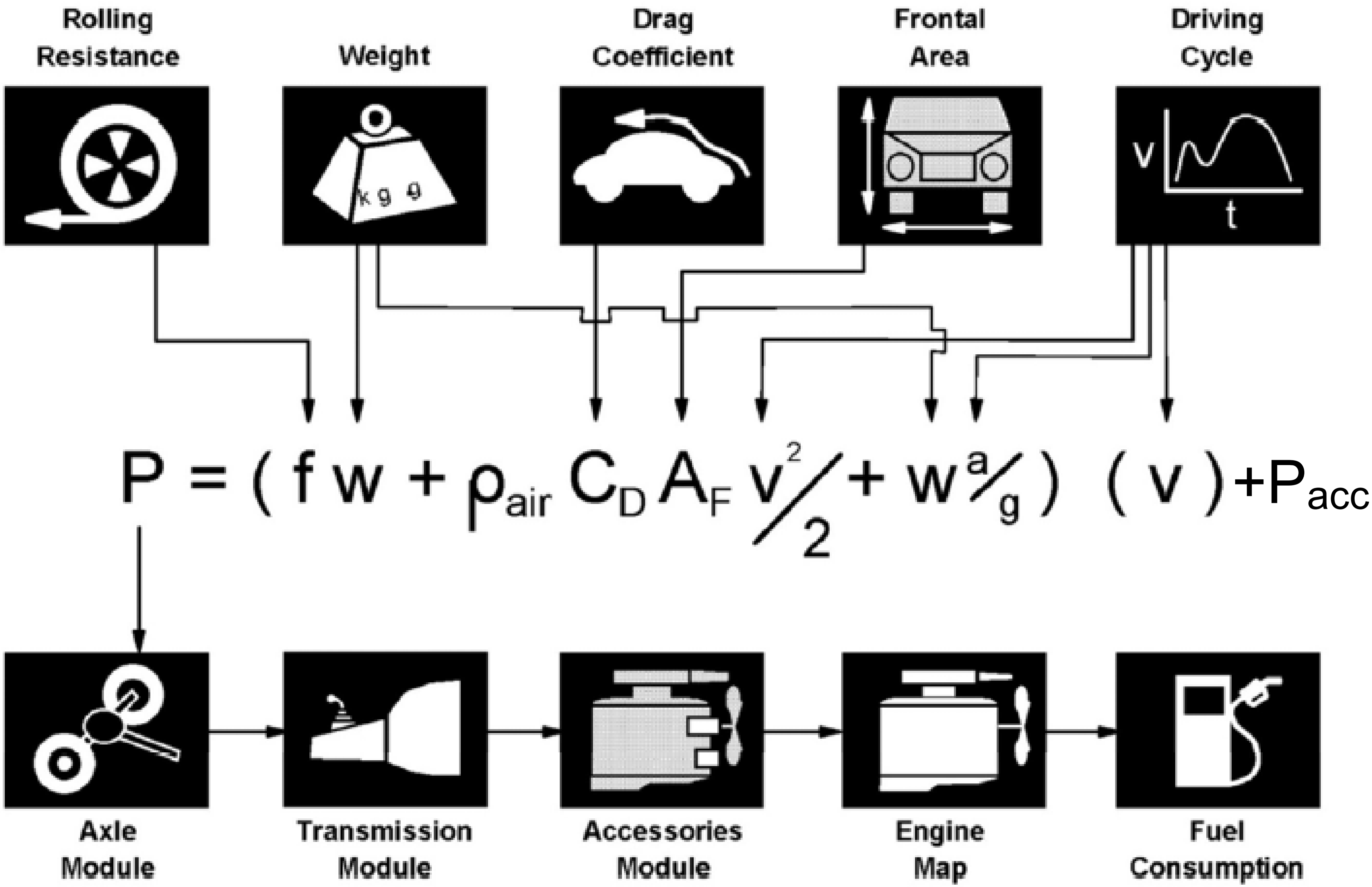
  $C_r \approx 0.25 - 0.5$ for sand, loose gravel, etc.

Grade Force

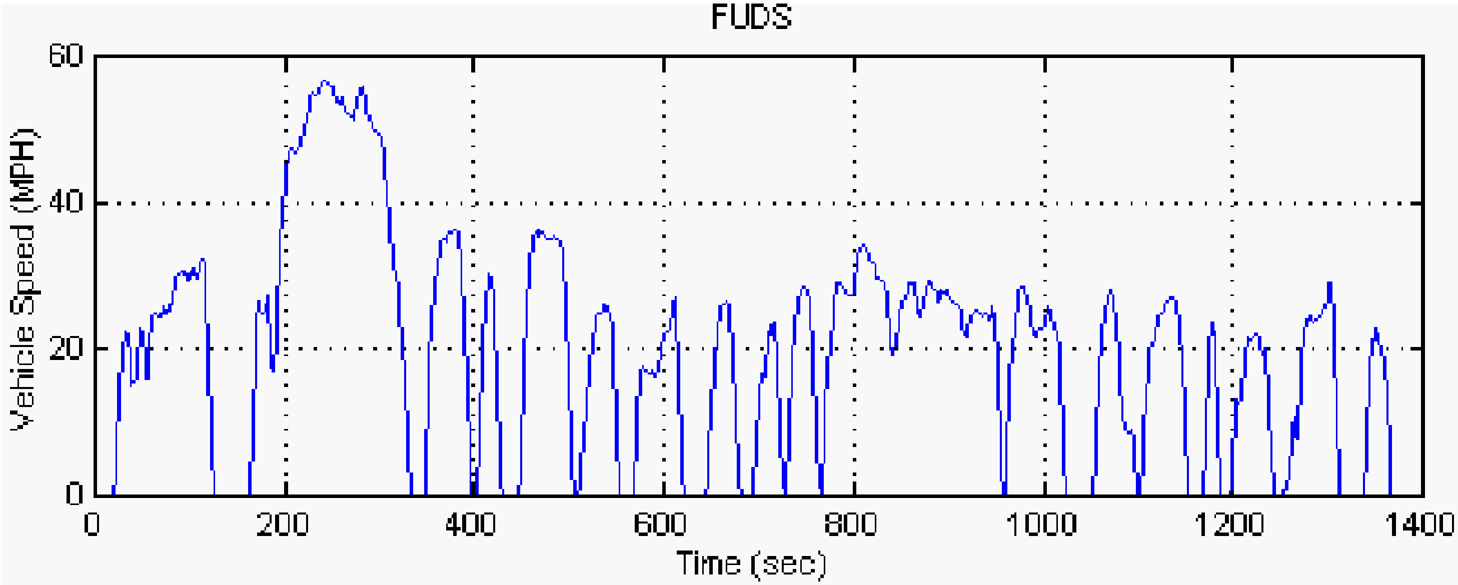
The grade force can be modeled as:

$$F_g = Mg\sin\alpha$$

Where α is the angle of the road with the horizontal

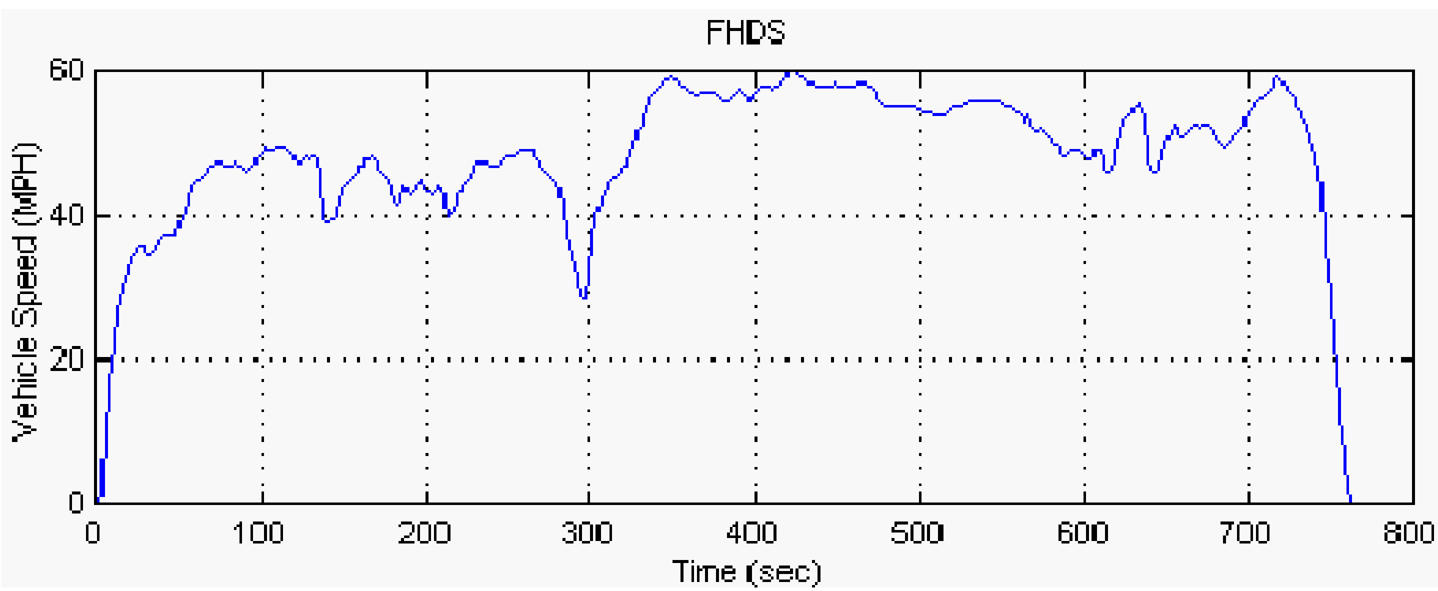

Rolling Resistance
Weight
Drag Coefficient
Frontal Area
Driving Cycle
kg
v
t
P = (f w + ρair CD AF v²/2 + w a/g) (v) +Pacc
Axle Module
Transmission Module
Accessories Module
Engine Map
Fuel Consumption

Driving Cycle: US FUDS and FHDS



FUDS

Federal Urban Driving Cycle



FHDS

Federal Highway Driving Cycle

US EPA Driving Cycle

- The fuel economy prediction is based on the U.S. Environmental Protection Agency (EPA) driving cycle.
- The EPA driving cycle is divided into two main portions: urban and highway drive cycles.
- The urban cycle contains lower vehicle speeds and more stop and go (or accelerating, decelerating, and idle). Cold start fuel penalty also applies to reward urban cycle.
- The highway cycle represents freeway conditions and contains higher vehicle speeds and more steady state cruise regions.

- These two cycles are combined into a formula to obtain the metro-highway fuel economy value that appears on the window sticker on vehicles. The combined fuel economy is computed as:

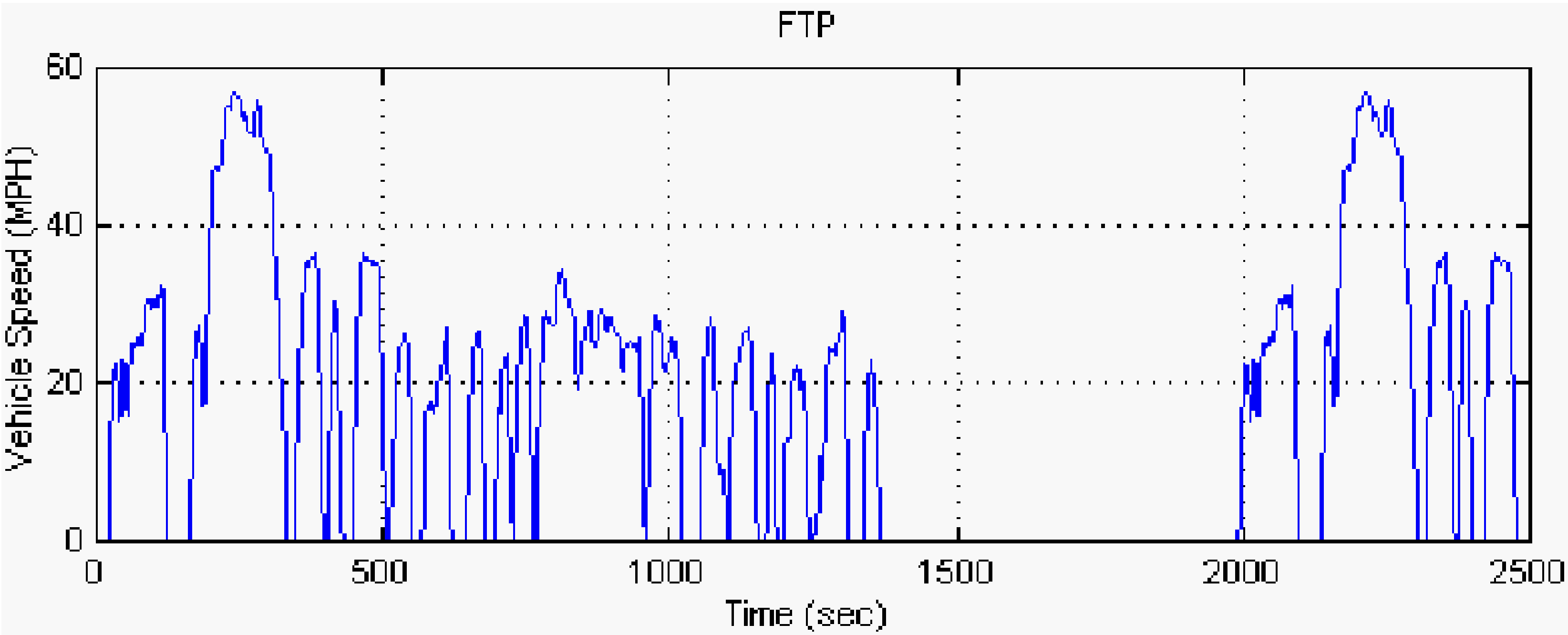
$$\frac{1}{\left(\frac{0.55}{urban \quad fuel \quad economy} + \frac{0.45}{highway \quad fuel \quad economy}\right)}$$

- The label numbers that appear on the vehicle sticker are adjusted by the EPA to represent fuel economy closer to the real world driving conditions.

- Adjusted or label urban fuel economy
  = Simulated or test of urban fuel economy * 0.9

- Adjusted or label highway fuel economy
  = Simulated or test of highway fuel economy * 0.78

Driving Cycle: US FTP



FTP

Federal Test Procedure

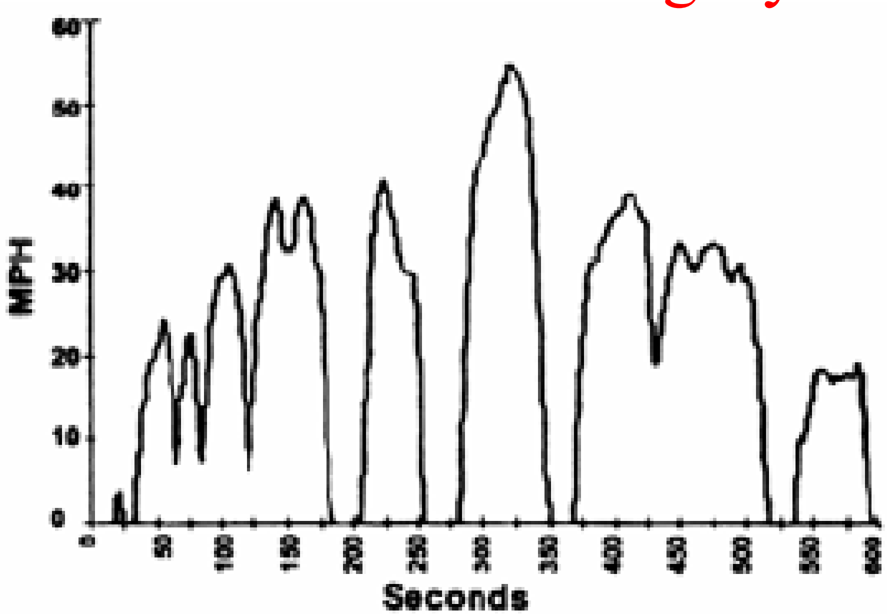
- The FTP cycle represents approximately one and a half FUDS cycle. However, it is performed according to a specific thermal schedule.
- This overall procedure is designed to provide a representative sample of vehicle during their warm-up phase and operating at nominal operating temperatures.

Driving Cycle: US SC-03 and US-06

Additional cycles are also defined and used to assess specific aspects of vehicles. Examples of an air conditioning cycle (SC-03) and high speed/high load cycle (US-06).

Supplement Federal Test Procedure

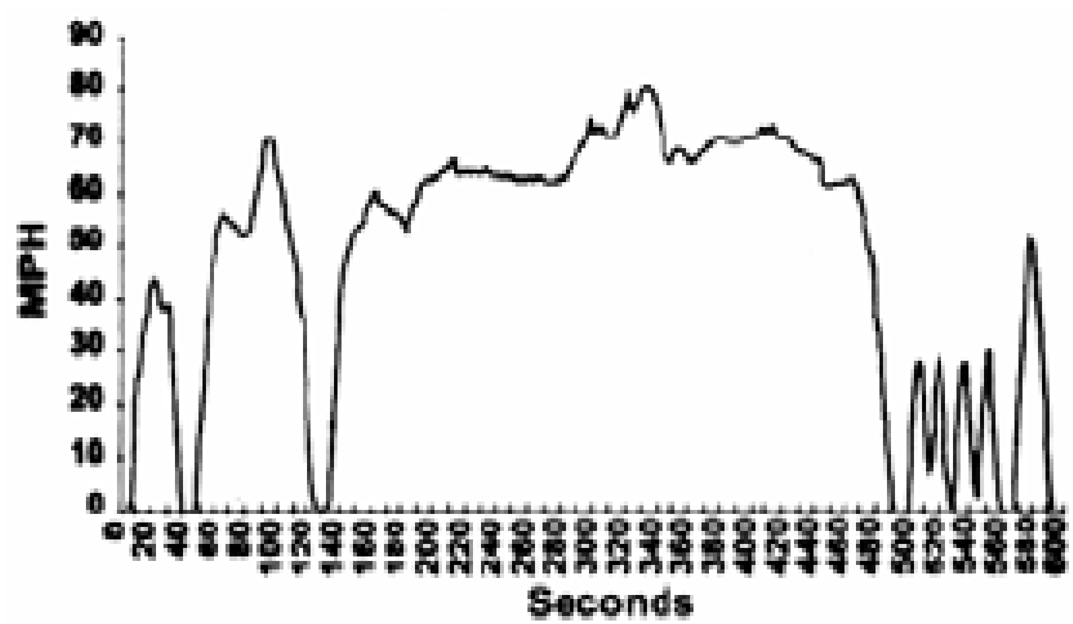
SC03 Air Conditioning Cycle



Total duration: 594 s

Max speed: 54.8 mph

US06 High speed/high load Cycle

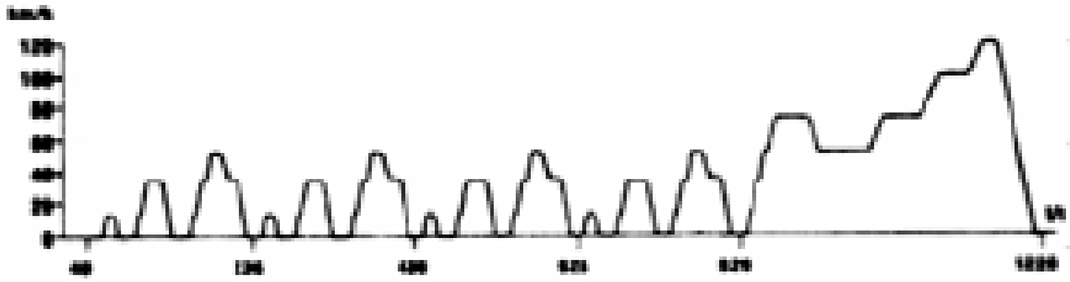


Total duration: 600 s

Max speed: 80.3 mph

Max acceleration: 8 mph/s^2

Driving Cycle: European Union



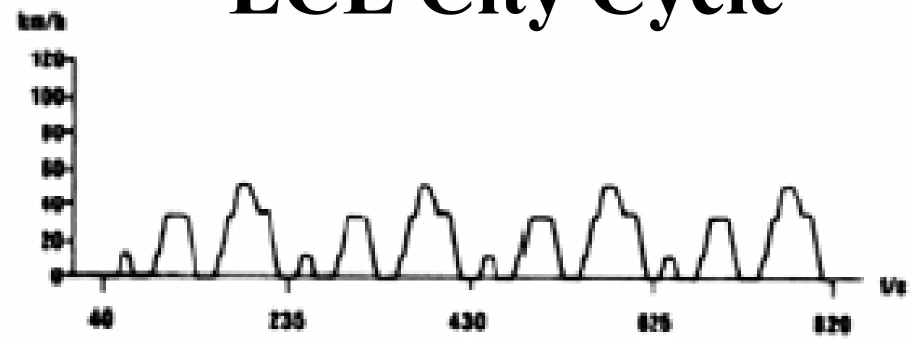
Part one (urban) (ECE) | Part two (extra-urban) (EUDC)

Length : 11.007 km Total duration : 1220 s
Max. speed : 120 km/h Average speed : 33.6 km/h

Planned lor EC 2000:
Modification of the start-up phase: Deletion of the 40 seconds idle period prior to bag sampling start. Simultaneous engine crank and bag sampling start.

NEDS (ECE + EUDS)

ECE City Cycle



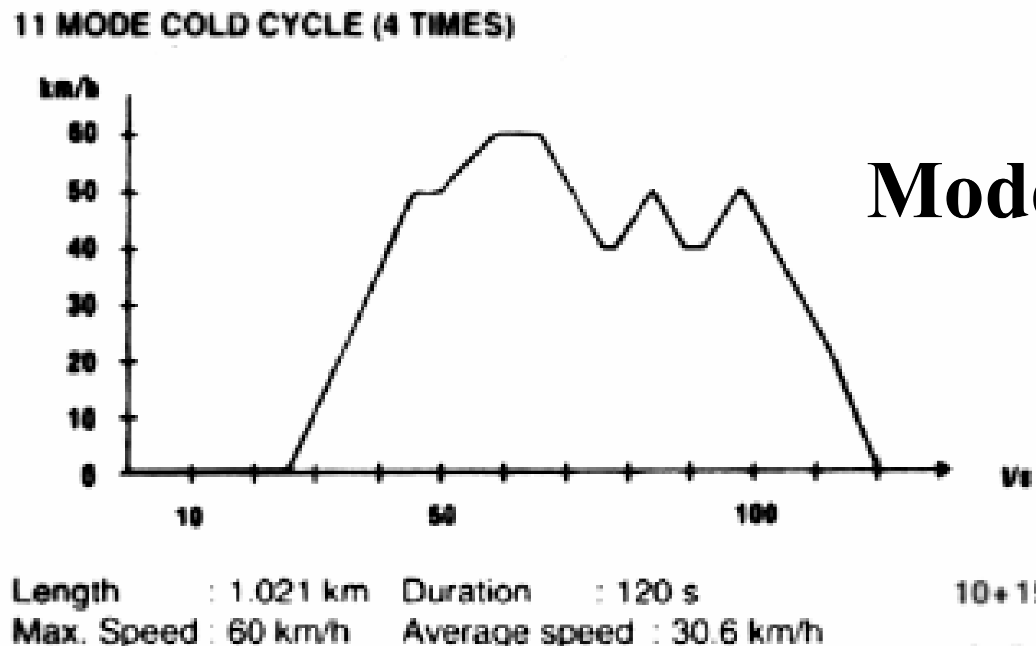
Length : 4.052 km Iotal duration : 820 s
Max. speed : 50 km/h .verage speed : 18.7 km/h

1) Also known as: MVEG A

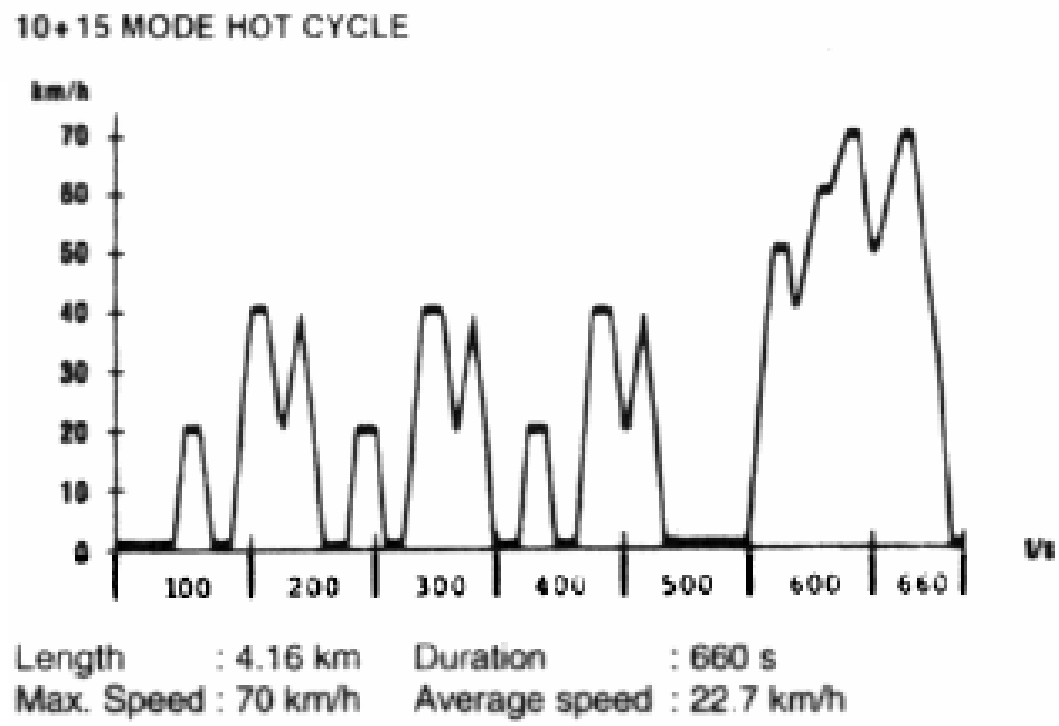
EU: European Union, formery called EEC or EC, ECE: Economic Commission lor Europe, European subgroup of United Nations, EUDC: Extra-urban driving cycle, MVEG: Motor Vehicle Emissions Group, advisory expert committee to .he European Commission

Driving Cycle: Japan

Mode 11

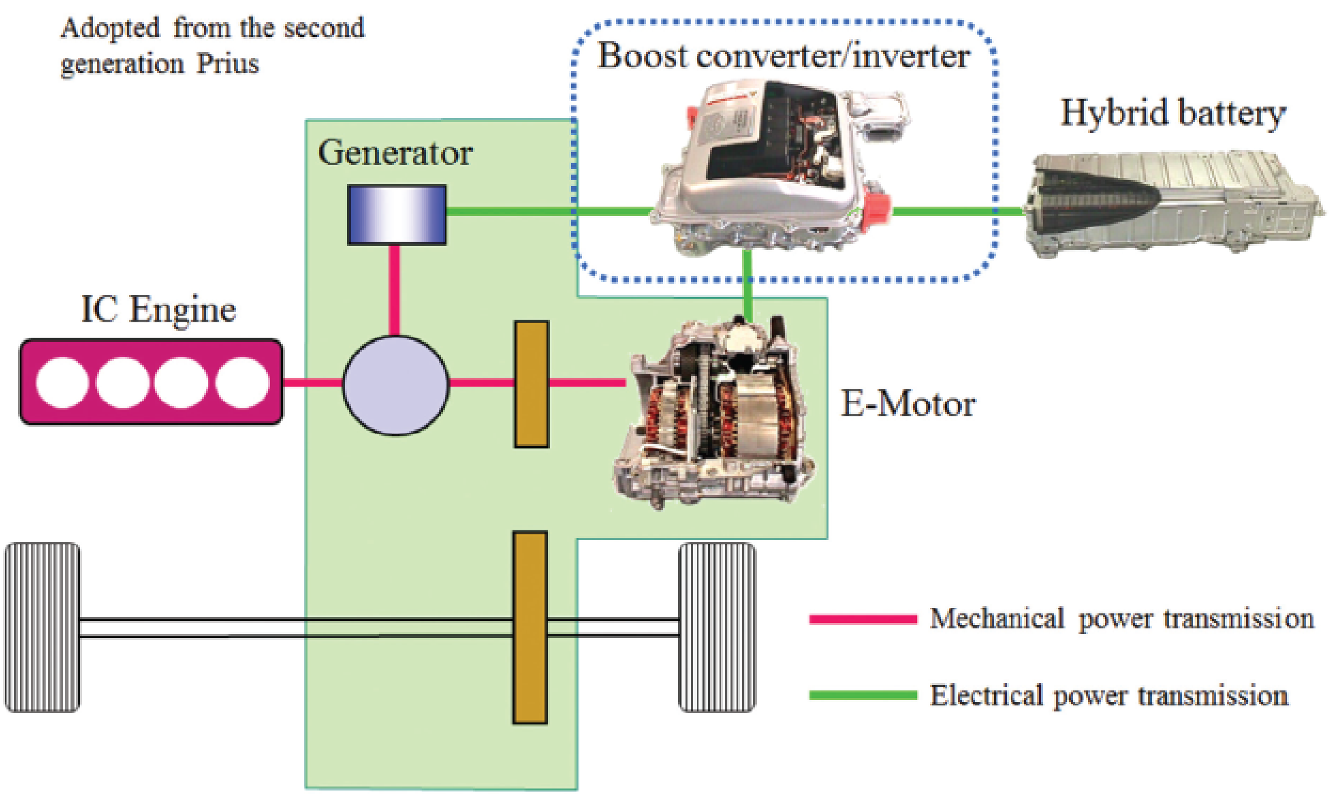


Mode 10 + 15

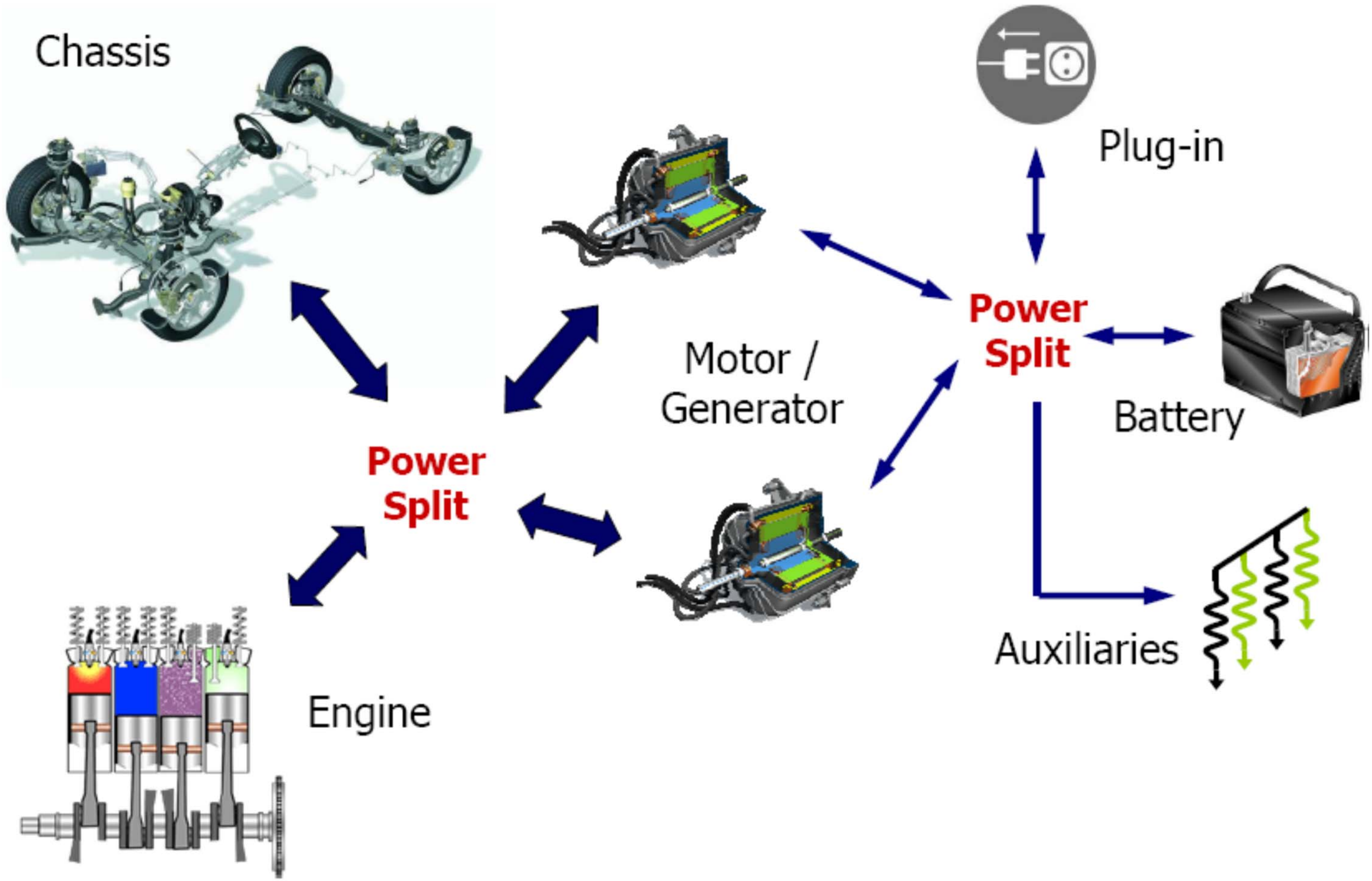


IV. Hybrid Powertrain Components

- Overview of IC Engine Efficiency
- Types of Transmissions used in HEVs
- Electric Propulsion Components
- On-Board Energy Storage
- Power Electronics and Electrical Architecture



Outline Electric-Drive Vehicle



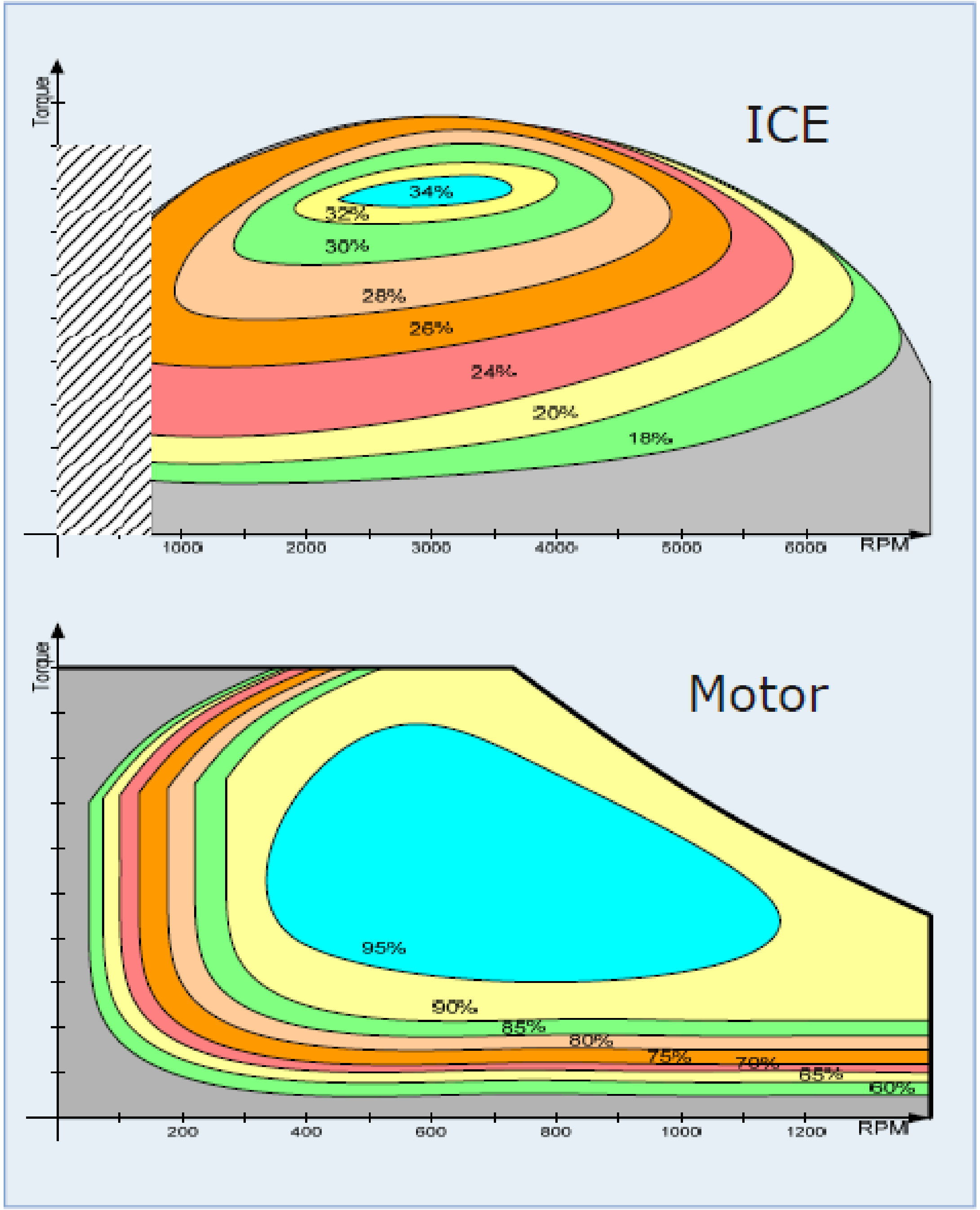
Major HEV Components

Drivetrain

The assembly of components permitting motion and mechanical transmission. It comprises the energy conversion system (engine, motor), coupling and mechanical transmission components, the differential and the wheels

On-board energy sources

The collection of energy storage systems (mechanical, electro-chemical and chemical). A hybrid is defined by multiple energy sources



Efficiency ICE vs Motor

- ICE Internal Combustion Engine
  - The sweet point is very small
  - 34% for Gasoline
  - 40% for Diesel
  - Requires complex transmission
- Motor
  - High efficiency wide area 95%
  - Torque at low speed
  - The Inverter efficiency must be included
  - Requires simple transmission
    - e.g. Low speed, high speed
  - The vehicle dynamic is very different
  - With Permanent Magnet the efficiency will change over lifetime
- Battery
  - The battery efficiency will change over lifetime
  - The battery capacity will change over lifetime

IV. Hybrid Powertrain Components

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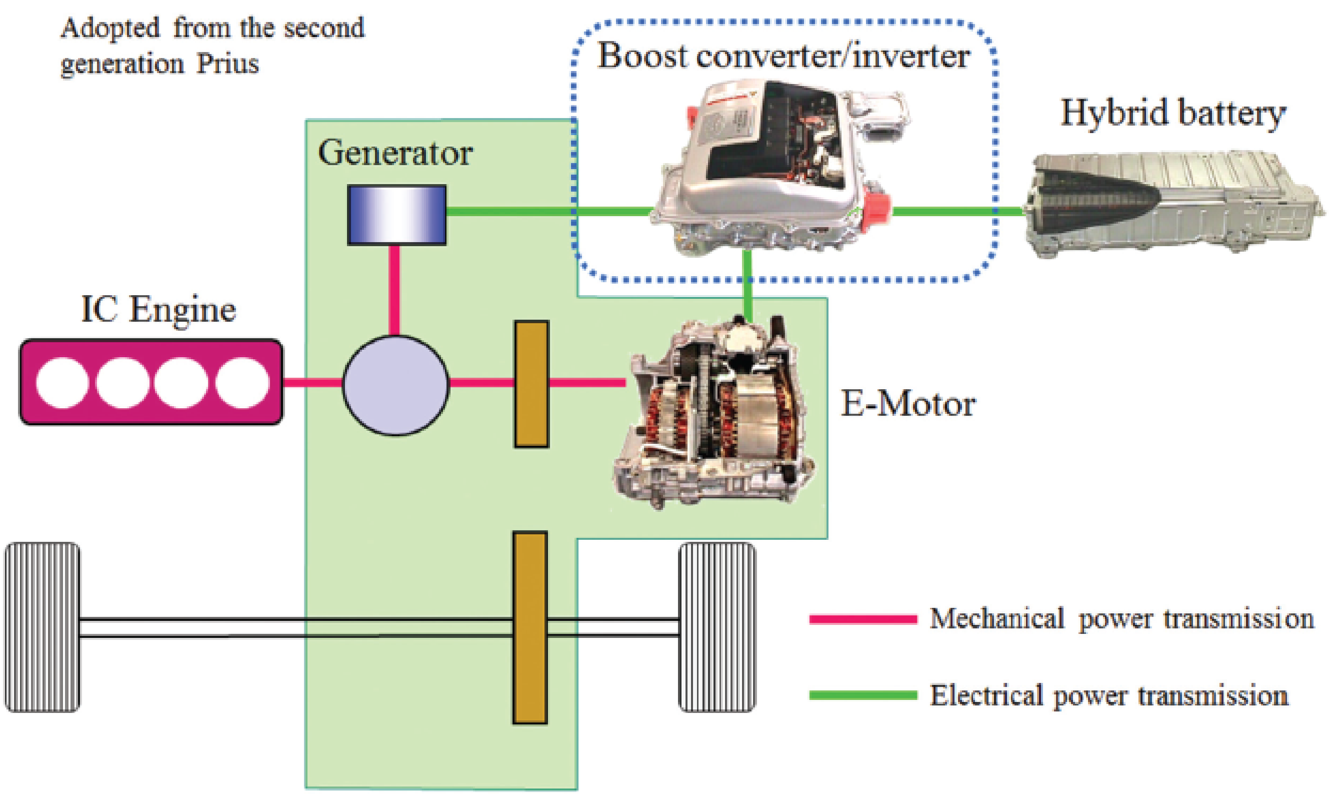


Electric Propulsion Components

Electric Machine: Motor/generator, Motor controller.

Energy Storage: Battery pack, Battery management systems, Ultracapacitor.

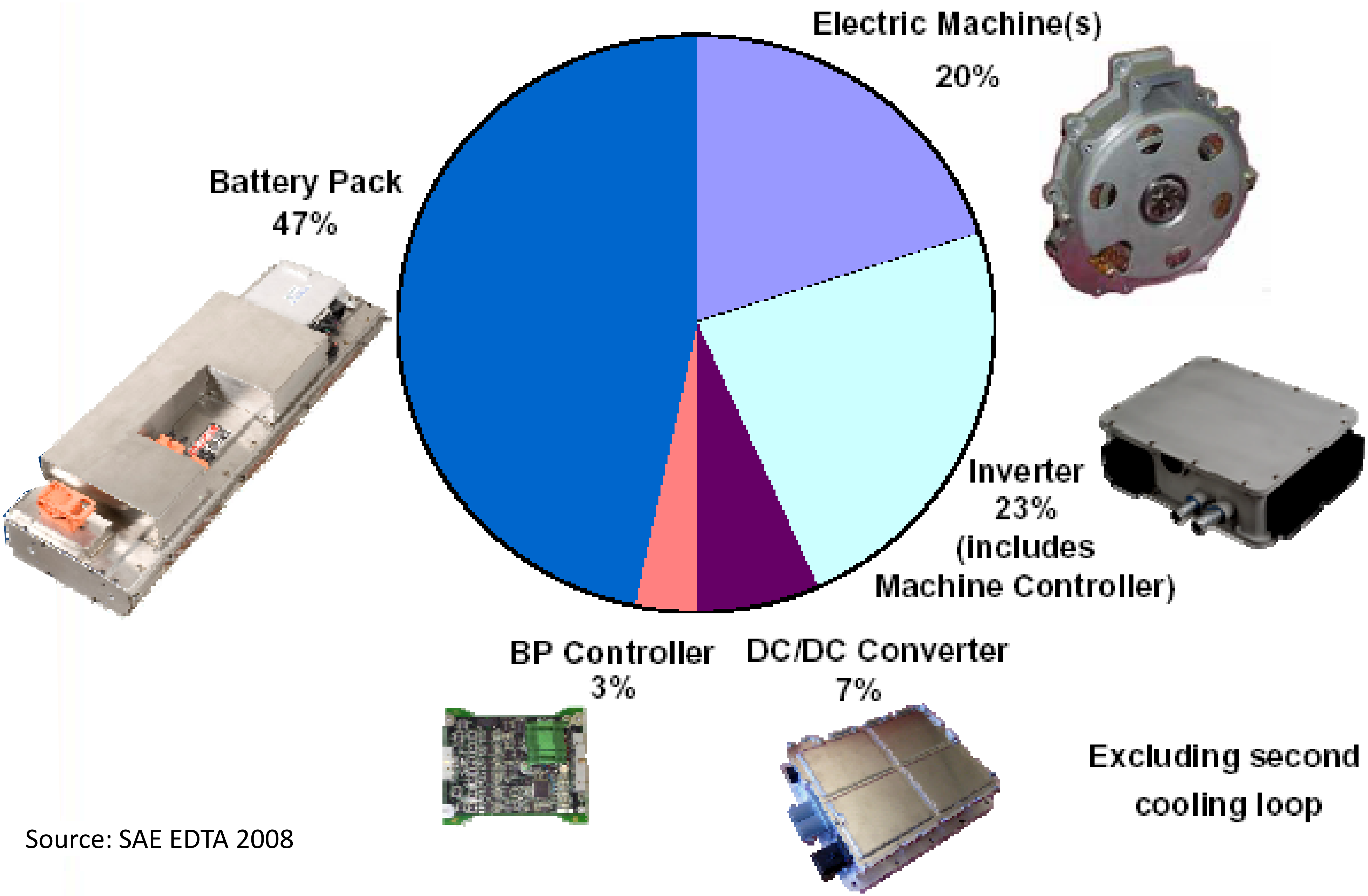
Power Electronics: Converters, Inverters, Power semiconductor devices.

Safety Components: Circuit breakers, Ignition key main contactor, potbox, Fusible link.

Instrumentation: Gauges, Ammeter, State-of-charge gauge, High-voltage gauge, Low-voltage meter.

Main Auxiliaries: Charger, Relays, Terminal blocks, Fuse block, Thermal management, Cooling, Cable grommets, Connector, Adaptors, Vacuum power brake, etc.

Component Costs in Electric Propulsion



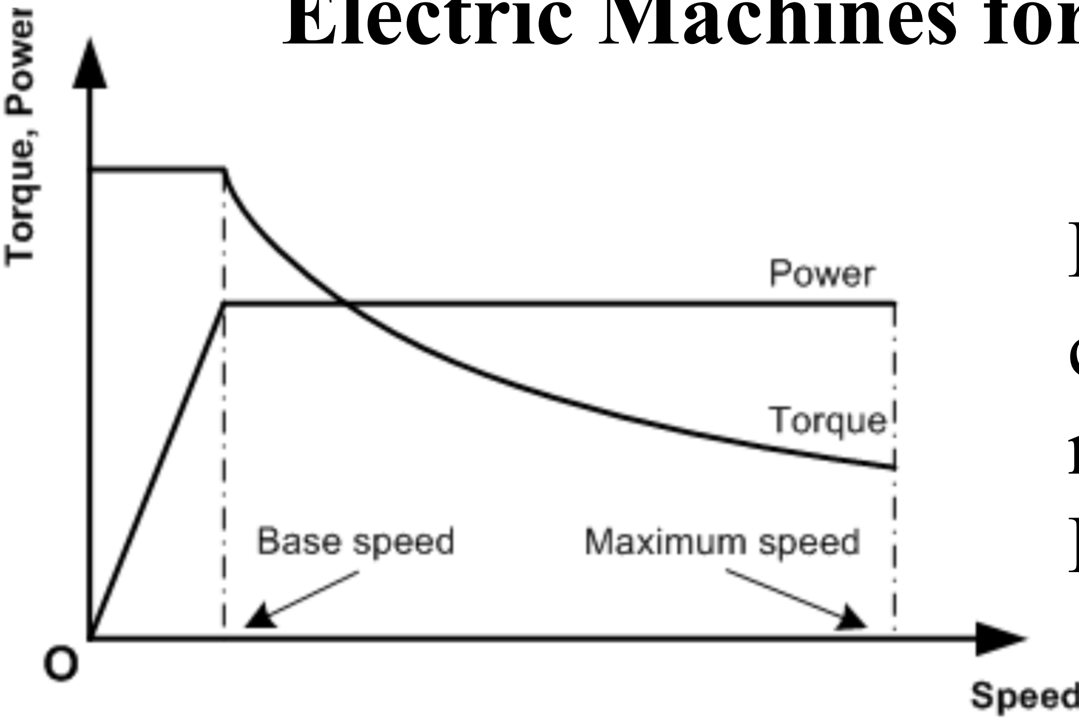
Source: SAE EDTA 2008

Electric Machines for HEV/PHEV/EV

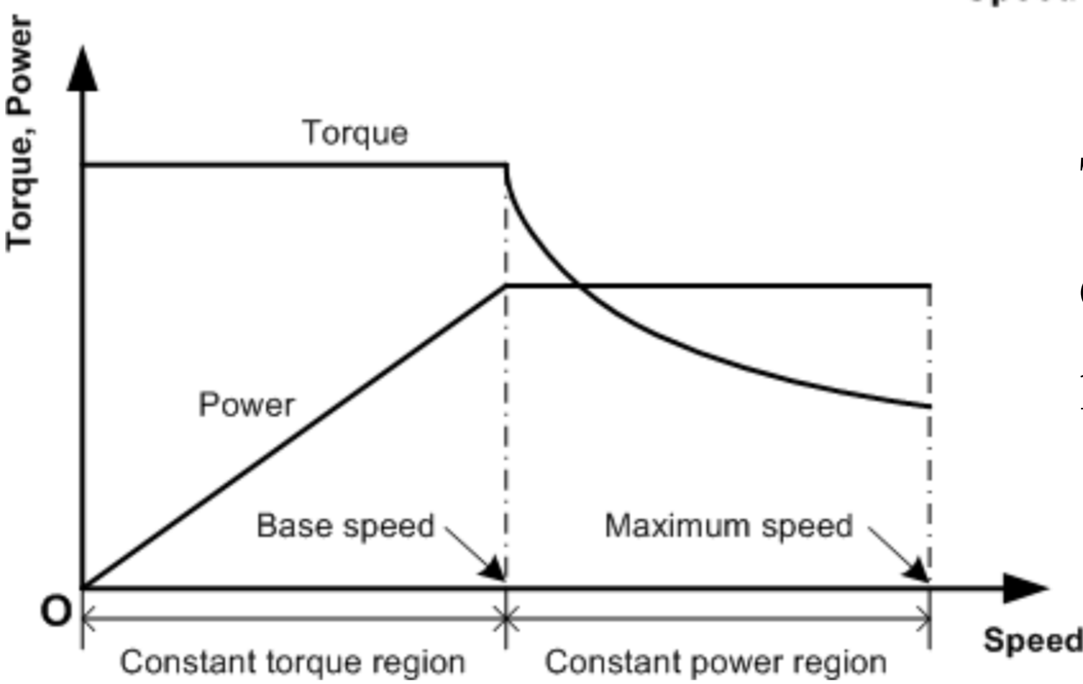
Motor Drive Needs:

- High instant power and a high power density
- High torque at low speed for starting, climbing, and acceleration
- Fast torque response
- High power at high speed for cruising
- Very wide speed range with constant power region
- High efficiency over the wide speed range with constant torque and constant power regions
- Frequently stop and start
- High efficiency for regenerative braking
- Downsizing, weight reduction, and lower moment of inertia.

Electric Machines for HEV/PHEV/EV

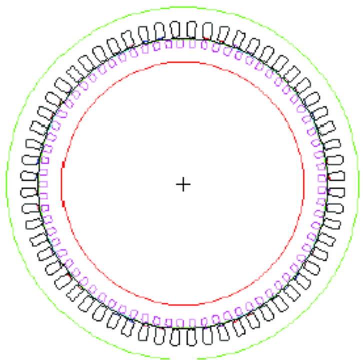


Desired output characteristics of electric motor drives in HEV/PHEV/EVs

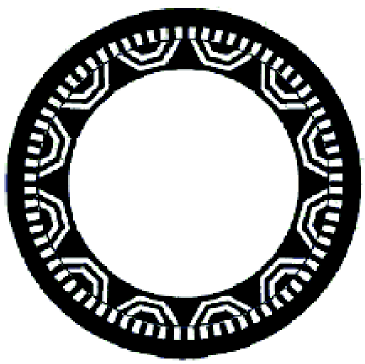


Typical performances of electric motor drives in industrial application

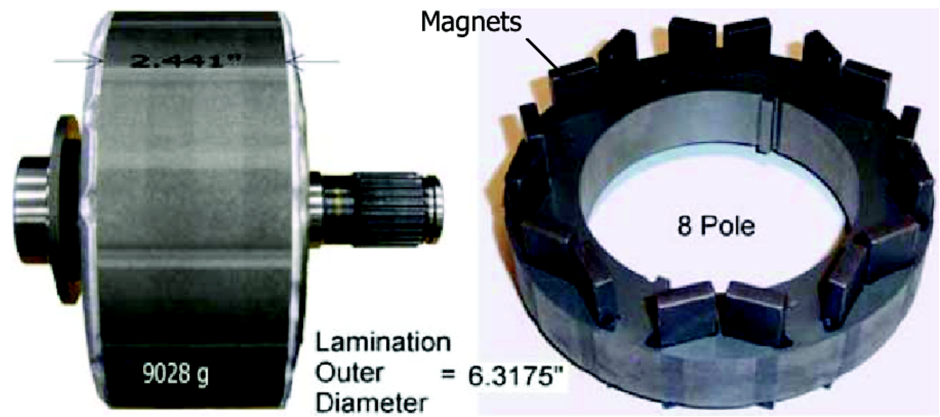
Electric Machines Suitable for Traction Applications

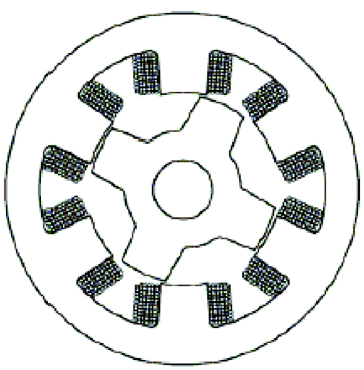


Induction Machine

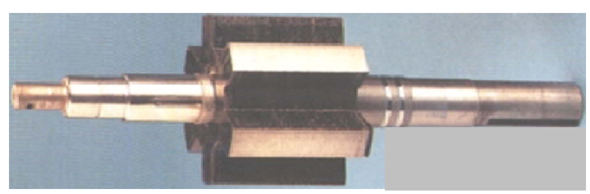


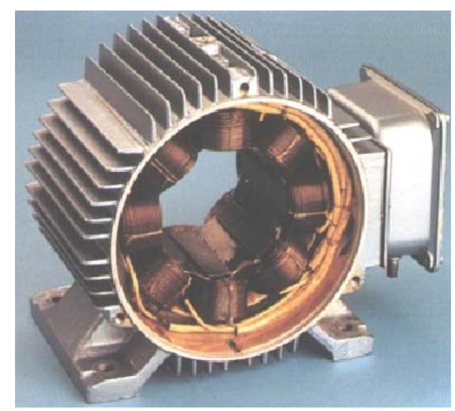
Permanent Magnet Machine





Switched Reluctance Machine





Fundamentals of Regenerative Braking

Studies show that, in urban driving, about one third to a half of the energy of the engine is consumed in braking.

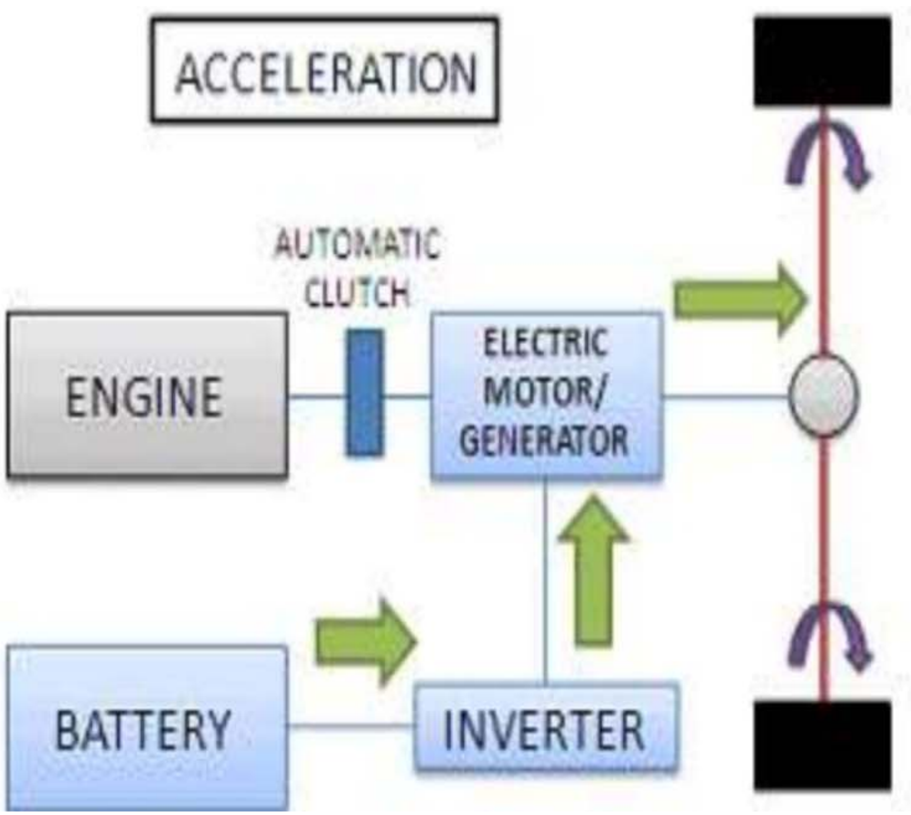
$$K.E. = \frac{1}{2} M_{eff} \left[V_f^2 - V_i^2 \right]$$

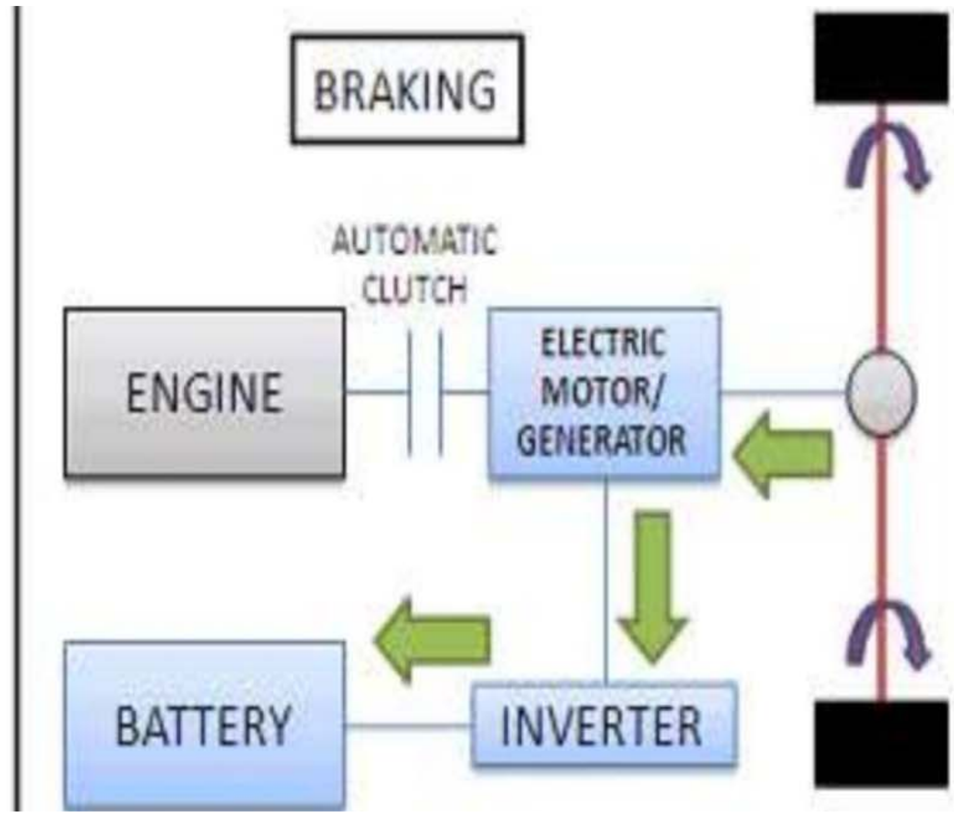
V_i Initial velocity

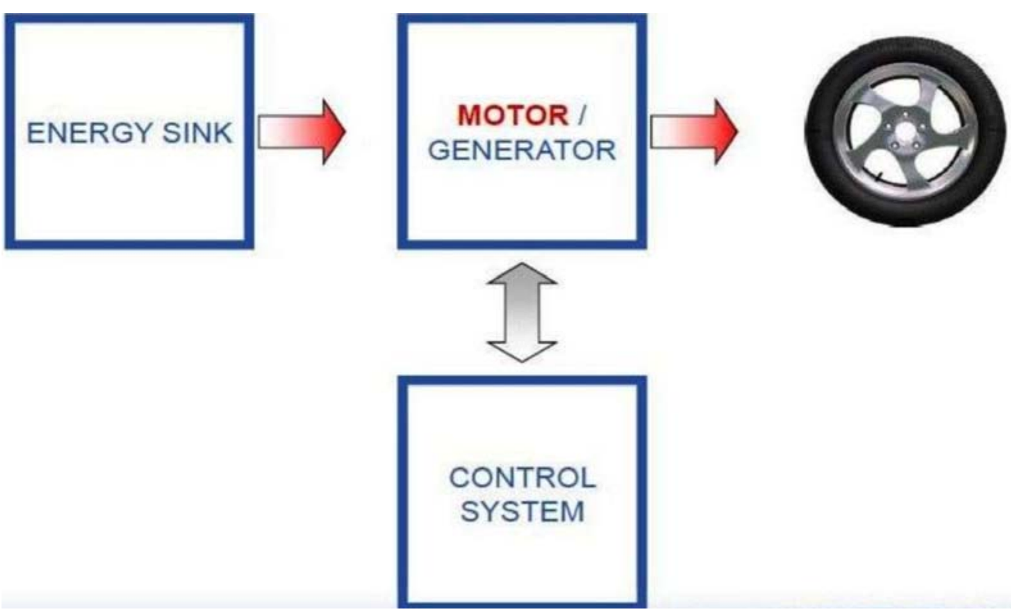
V_f Final velocity

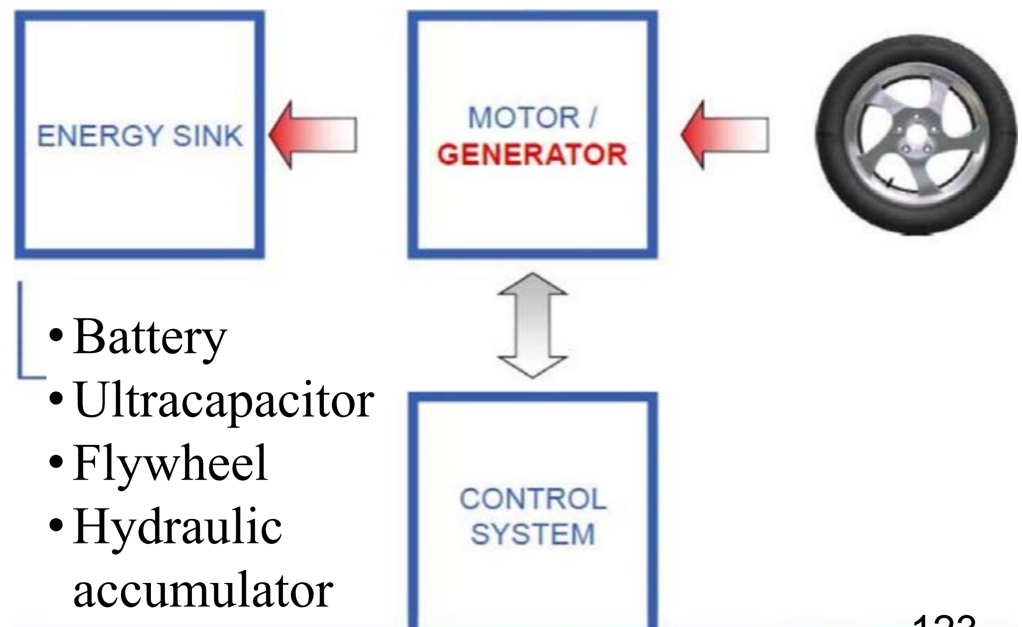
M_{eff} Effective vehicle mass

- During acceleration, the powertrain must supply this kinetic energy to vehicle (plus the energy lost to dissipative forces and through the overall inefficiencies of the powertrain from fuel/electricity to wheel.
- During deceleration, this kinetic energy (minus the energy lost to dissipative forces) must be either dissipated as heat in the brakes or converted back to useful energy (mechanical, electrical, etc.) through "regeneration" system.


ACCELERATION
AUTOMATIC CLUTCH
ENGINE
ELECTRIC MOTOR/ GENERATOR
BATTERY
INVERTER


BRAKING
AUTOMATIC CLUTCH
ENGINE
ELECTRIC MOTOR/ GENERATOR
BATTERY
INVERTER

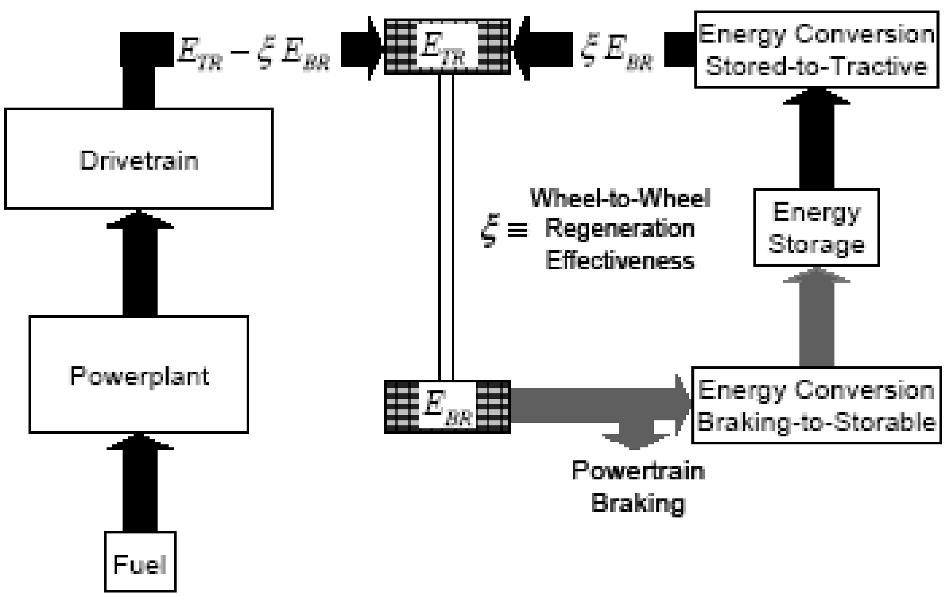

ENERGY SINK
MOTOR / GENERATOR
CONTROL SYSTEM

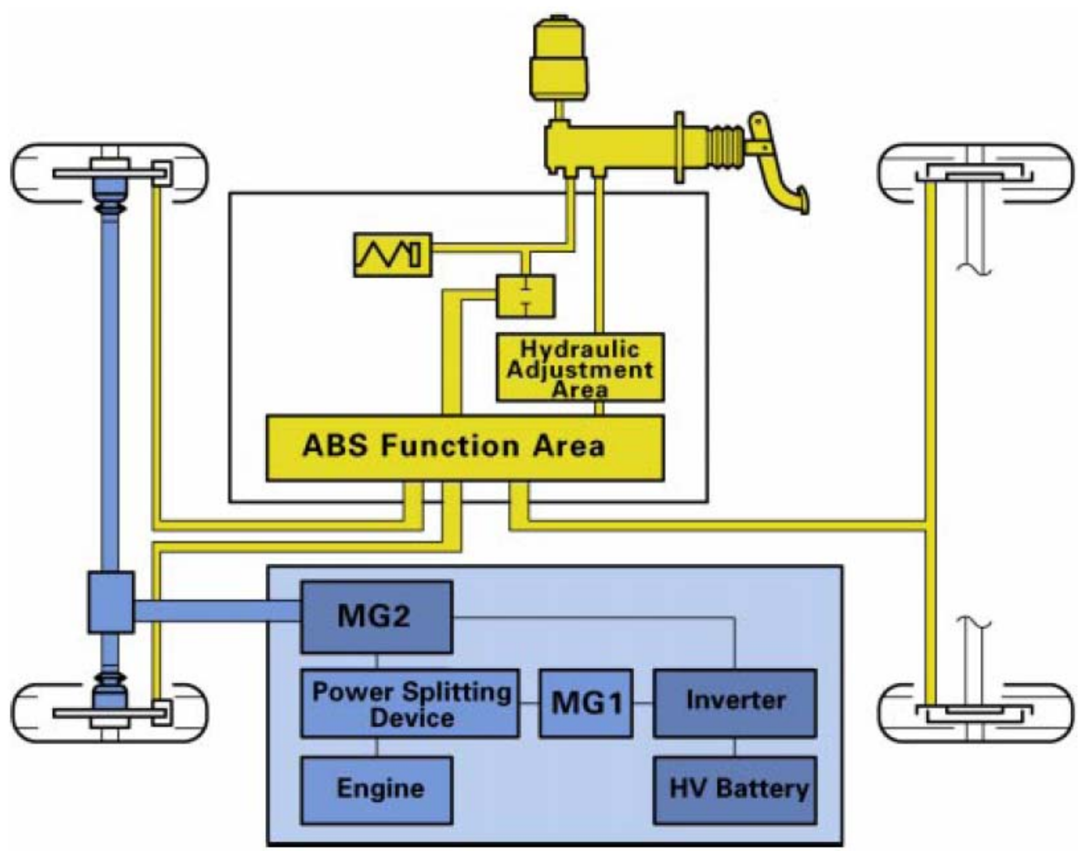

ENERGY SINK
MOTOR / GENERATOR
CONTROL SYSTEM
• Battery
• Ultracapacitor
• Flywheel
• Hydraulic accumulator

In HEV/PHEV/EV:

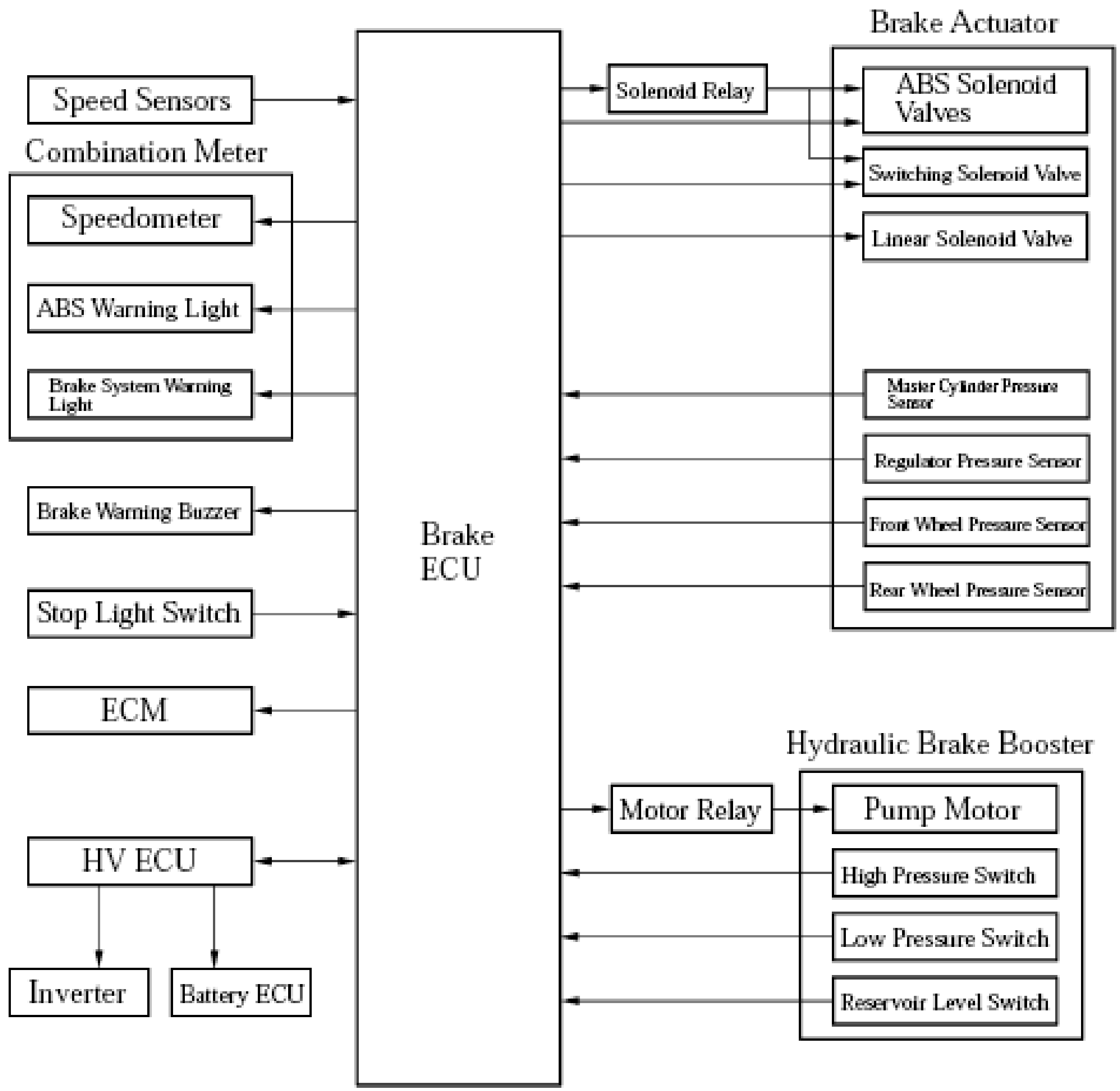
- Recovery of vehicle kinetic energy becomes possible through regenerative braking.
- The design and control target is not only to achieve a good braking performance, but also recover braking energy as much as possible.
- A portion of the vehicle kinetic energy that must be removed during the decelerations of wheel braking. With regenerative braking, however, the retarding force is the reaction to that used to drive an energy converter.
- Consequently, some of this braking energy can be converted, stored, and made available for later use.

- Traction motor of a HEV can be easily controlled to function as a generator, in which the kinetic or potential energy of the vehicle can be converted into electrical energy and stored into electric energy storage (usually chemical batteries).
- The recovered electric energy can be used for later propulsion. Thus the vehicle energy efficiency can be greatly enhanced





Based on the signals received from the sensors, the communication it maintains with the HV ECU, the brake ECU effects conventional brake control, ABS control, and regenerative brake cooperative control.



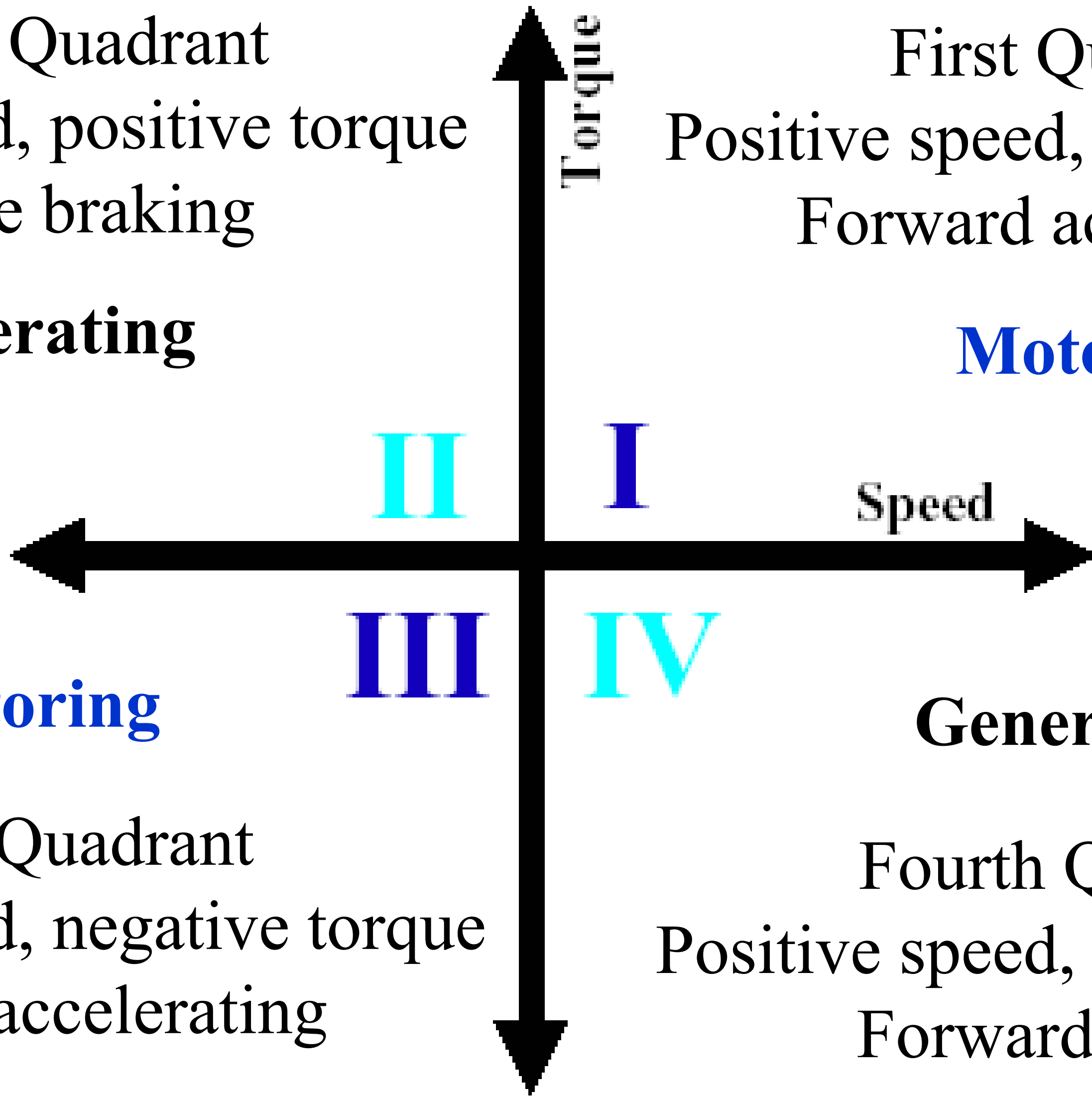
Quadrants of Operation in Electric Machine

Second Quadrant
Negative speed, positive torque
Reverse braking

Generating

First Quadrant
Positive speed, positive torque
Forward accelerating

Motoring



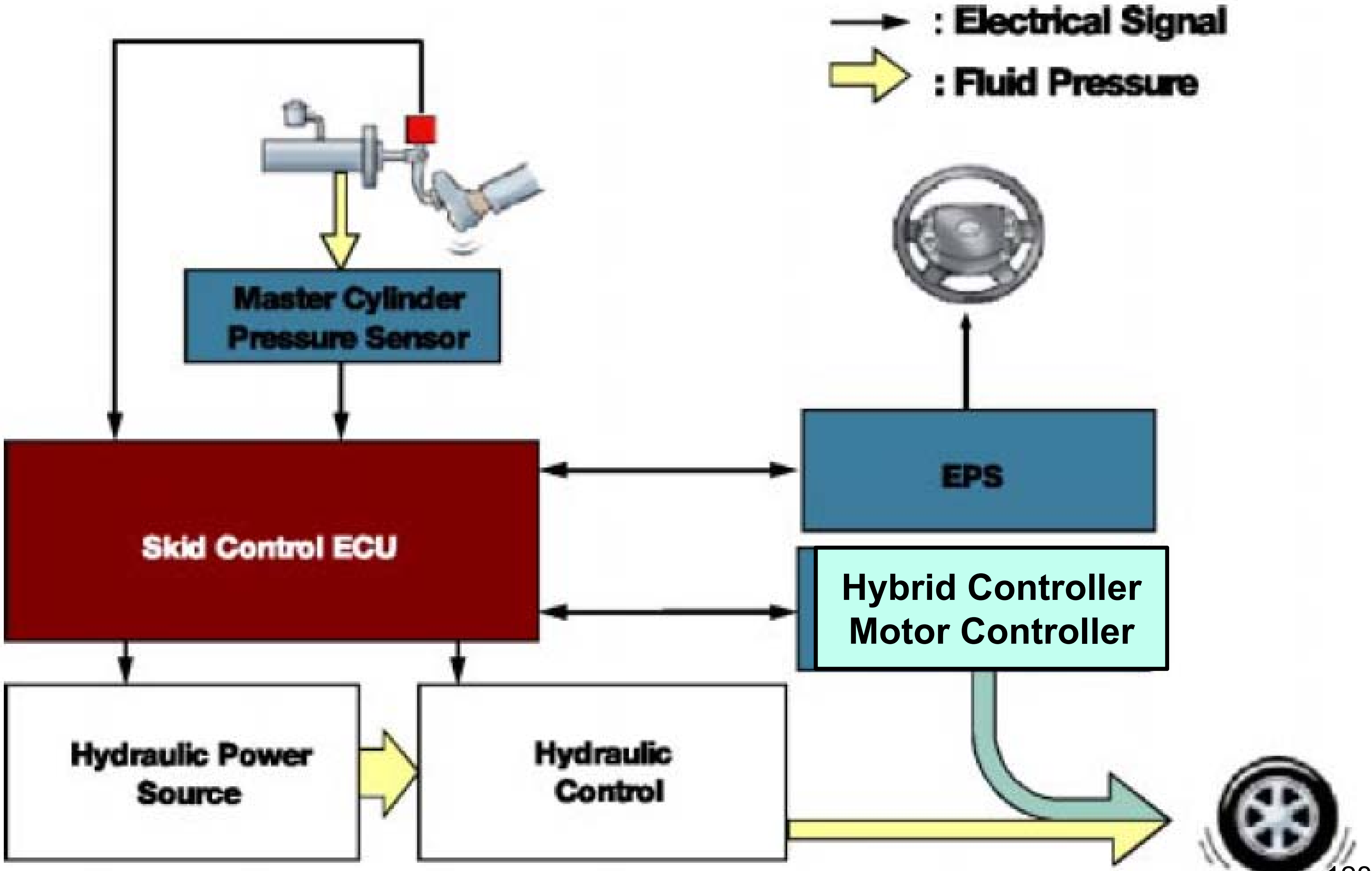
Motoring

Third Quadrant
Negative speed, negative torque
Reverse accelerating

Generating

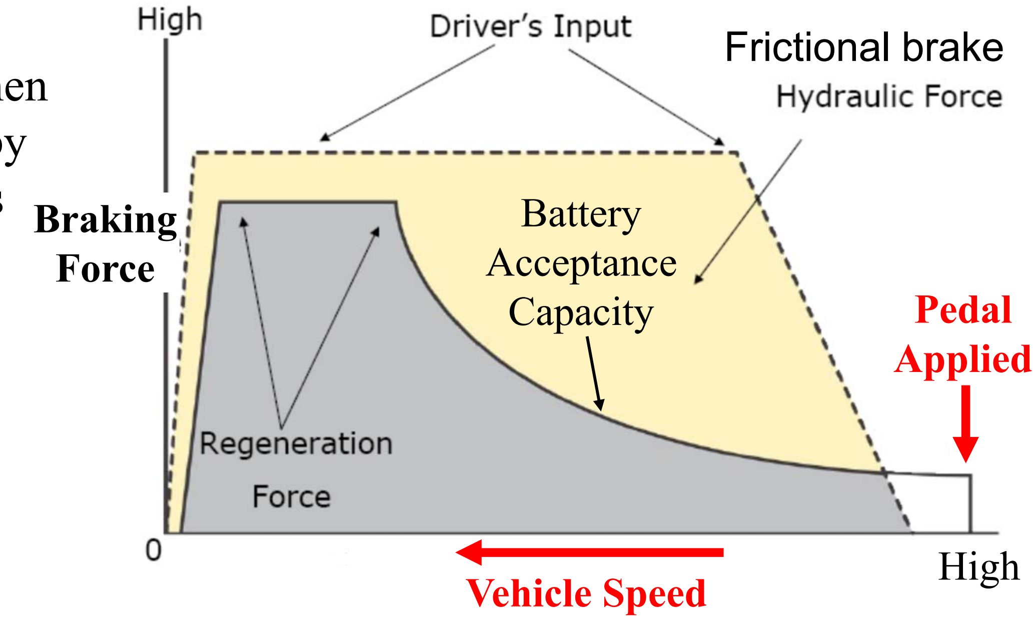
Fourth Quadrant
Positive speed, negative torque
Forward braking

Blending Brake Torque: Regenerative + Hydraulic (Frictional) Brakes

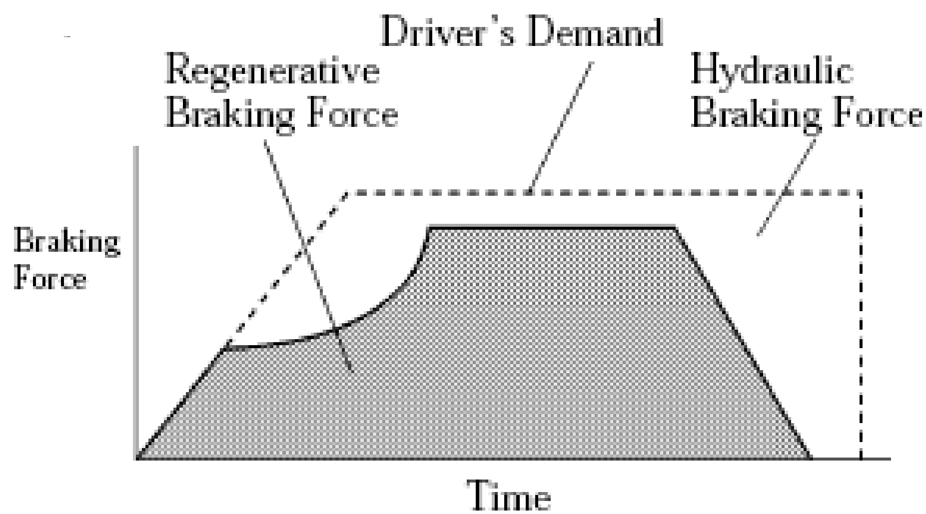


Blending Regenerative Brake – Blending Torque

- The master cylinder pressure that is generated when the driver presses on the brake pedal is detected by the pressure sensor, and the brake ECU calculates the brake force request factor.
- A portion of the brake force request factor is transmitted to the HV ECU in the form of a regenerative brake activation request factor.
- The HV ECU executes generative braking by commanding the electric motor to generate negative torque.
- The brake ECU controls the opening of the **linear solenoid valves**, which are used for increasing/ decreasing the hydraulic pressure, to regulate the wheel cylinder hydraulic pressure in relation to the master cylinder hydraulic pressure, thus compensating for the brake force that is not provided sufficiently by the regenerative brake.
- While the regenerative brake cooperative control is being prohibited due to an abnormality in the system, the regenerative braking force is not generated. At this time, only the hydraulic braking force is applied by turning ON (opening) **the linear solenoid valve SLA** and turning OFF (closing) the **SLR**.

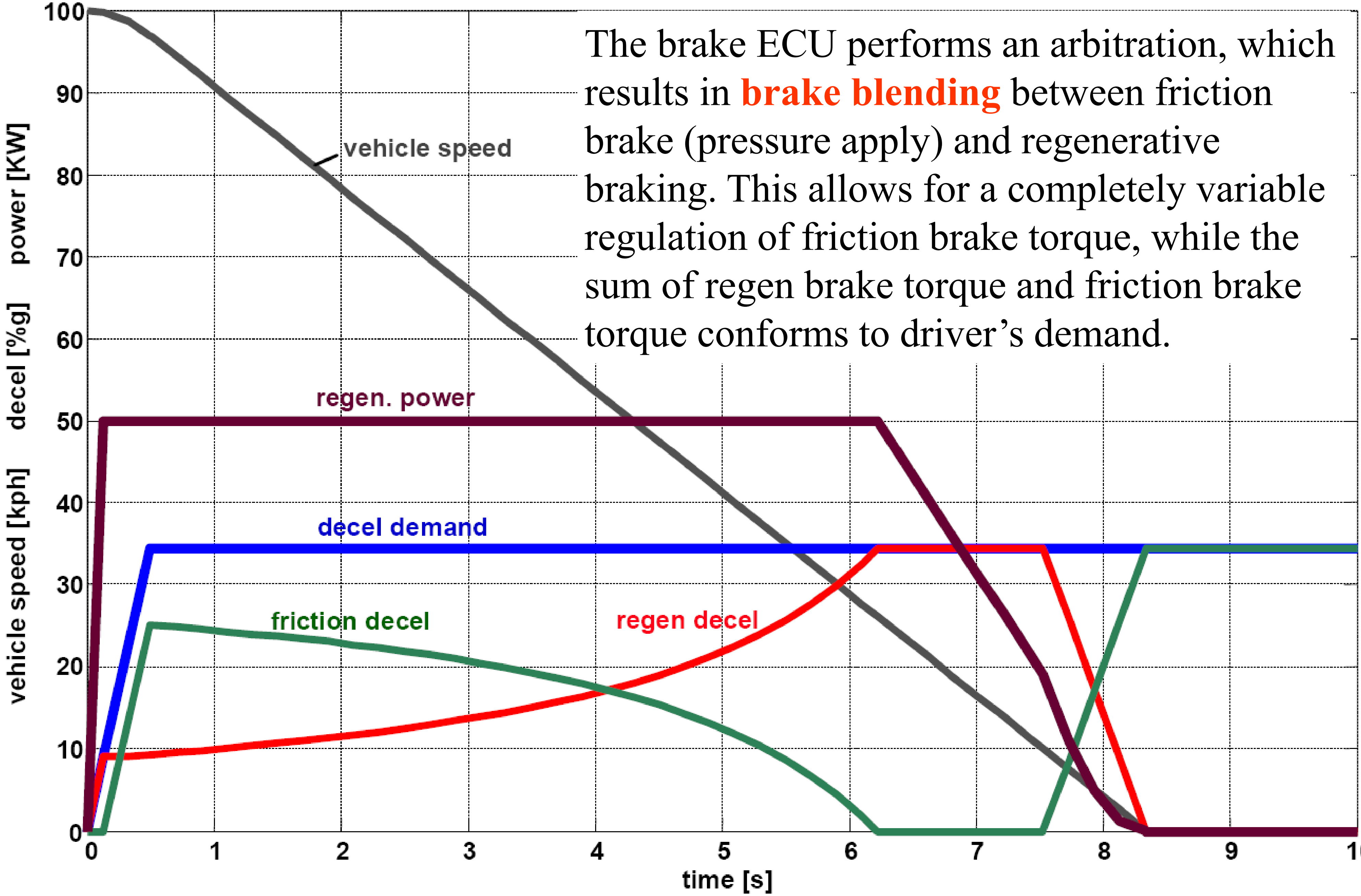


Changes in Regenerative Braking Force

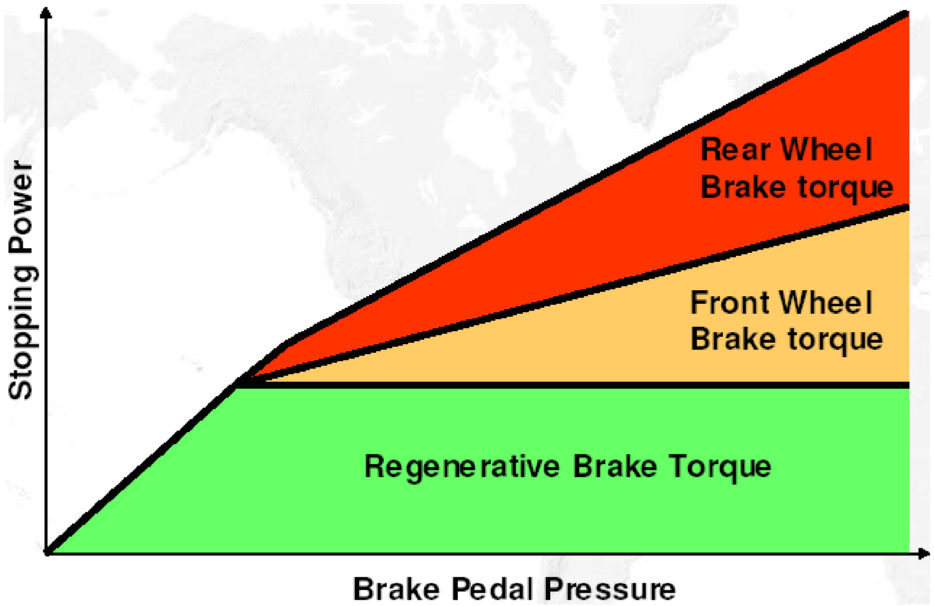


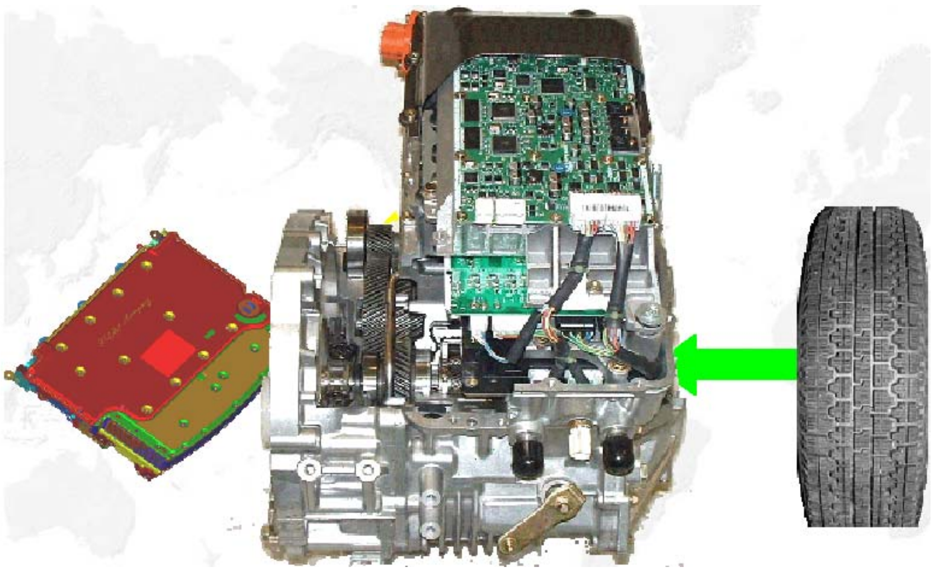
Changes in Braking Force Apportionment

Blending Regenerative Brake (Basic Interaction)

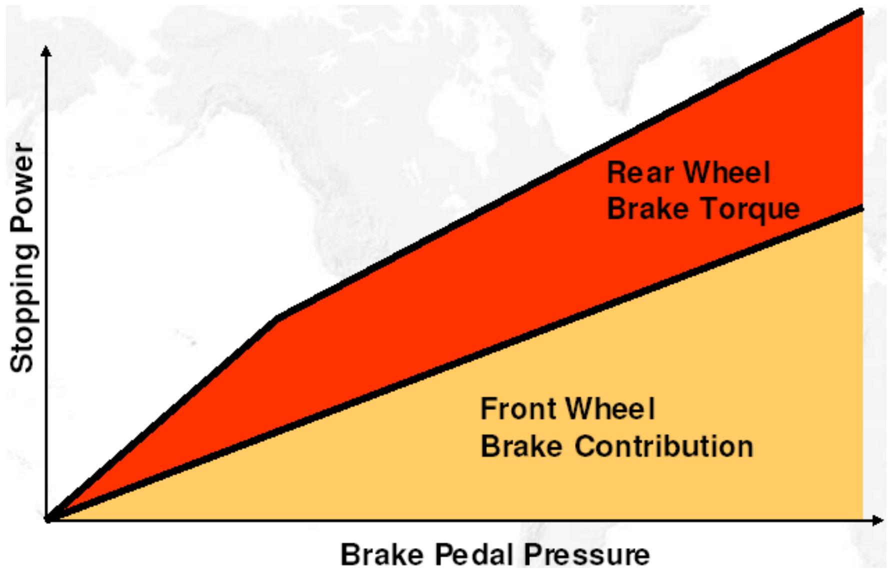


The brake ECU performs an arbitration, which results in **brake blending** between friction brake (pressure apply) and regenerative braking. This allows for a completely variable regulation of friction brake torque, while the sum of regen brake torque and friction brake torque conforms to driver's demand.





Regenerative Braking



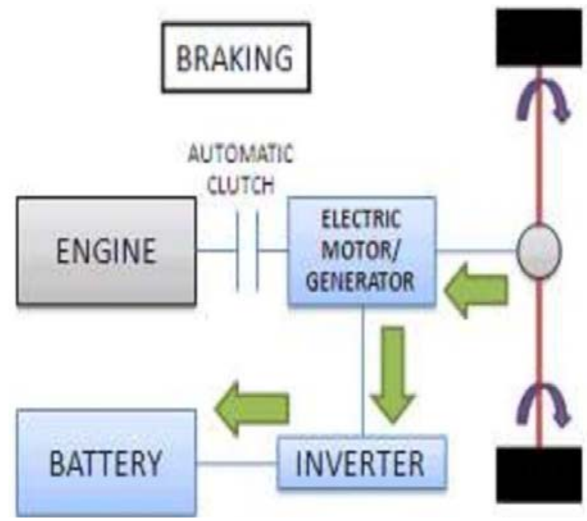
Conventional Braking

Regenerative Braking and Batteries (1)

- The electric motor becomes a generator when the brake pedal is applied. The vehicle kinetic energy is used to generate electricity that is then used to recharge the batteries. Traditional frictional brakes (hydraulic) must also be used to ensure that the vehicle slows down as necessary – Blending Brake (Blending Torque).
- Calibration of regenerative brake – regenerative brake control algorithm needs to consider driverability (not to create driver panic).
- Not all of the vehicle kinetic energy can be used for the batteries because some of it is "lost" to waste heat. Some energy is also lost to resistance/friction as the energy travels from the wheel/axle, through the drivetrain and electric motor, and into the battery.

Regenerative Braking and Batteries (2)

- What is regenerative efficiency? Need to consider Wheel-to-Wheel (W2W) efficiency – the kinetic (mechanical) energy captured from vehicle wheels, regenerative electric energy stored in the battery, will be used back to the vehicle wheels for traction (mechanical energy).



- The regenerative efficiency depends upon:
  - Regenerative brake calibration
  - Driving cycles
  - Efficiency of battery charging/discharging; EM efficiency, PE efficiency.
  - With a NiMH battery pack, the maximum overall efficiency of reuse is about 46.2 %. In practice, Toyota Prius could reach 36% in UDDS. The average efficiency of regenerative is about 20%.

Regenerative Braking and Supercapcaitor

Advantages relative to batteries

- Very high rates of charge and discharge.
- Little degradation over hundreds of thousands of cycles.
- Good reversibility
- Light weight
- Low toxicity of materials used.
- High cycle efficiency (95% or more)

Disadvantages

- The amount of energy stored per unit weight is considerably lower than that of an electrochemical battery (3-5 W.h/kg for a UC compared to 30-40 W.h/kg for a battery).
- The voltage varies with the energy stored. To effectively store and recover energy requires sophisticated electronic control and switching equipment.

Advantages of Regenerative Braking

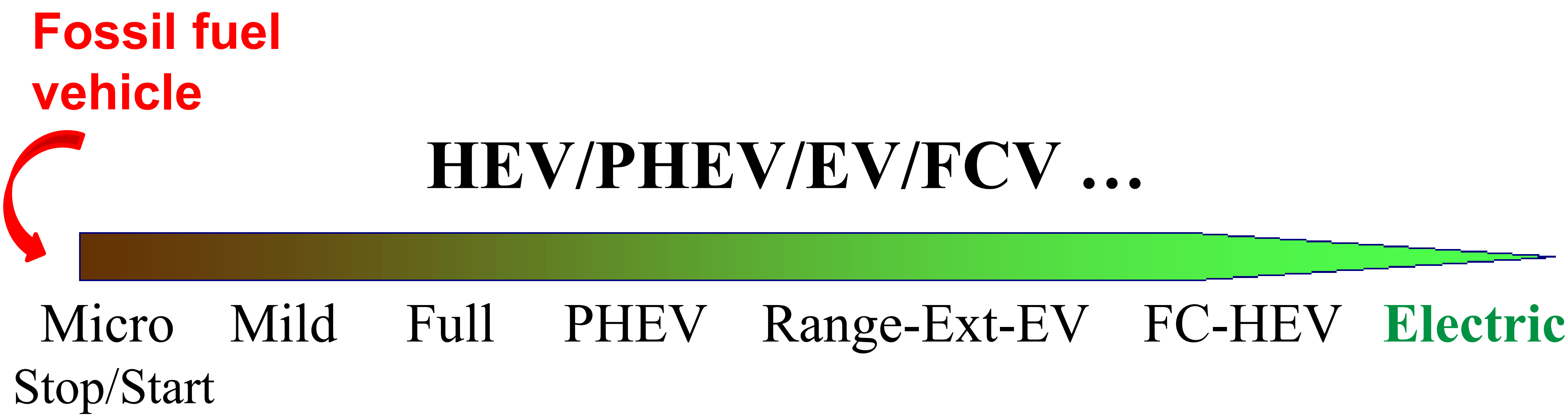
- Provide greater fuel economy
- Reduce emission
- Save energy: energy conversion is carefully controlled in the interest of maximum regenerative brake efficiency (W2W, a closed loop) and driveability.
- Provide ample drive power and power for sudden acceleration.
- Increase the lifespan of frictional (hydraulic) braking system

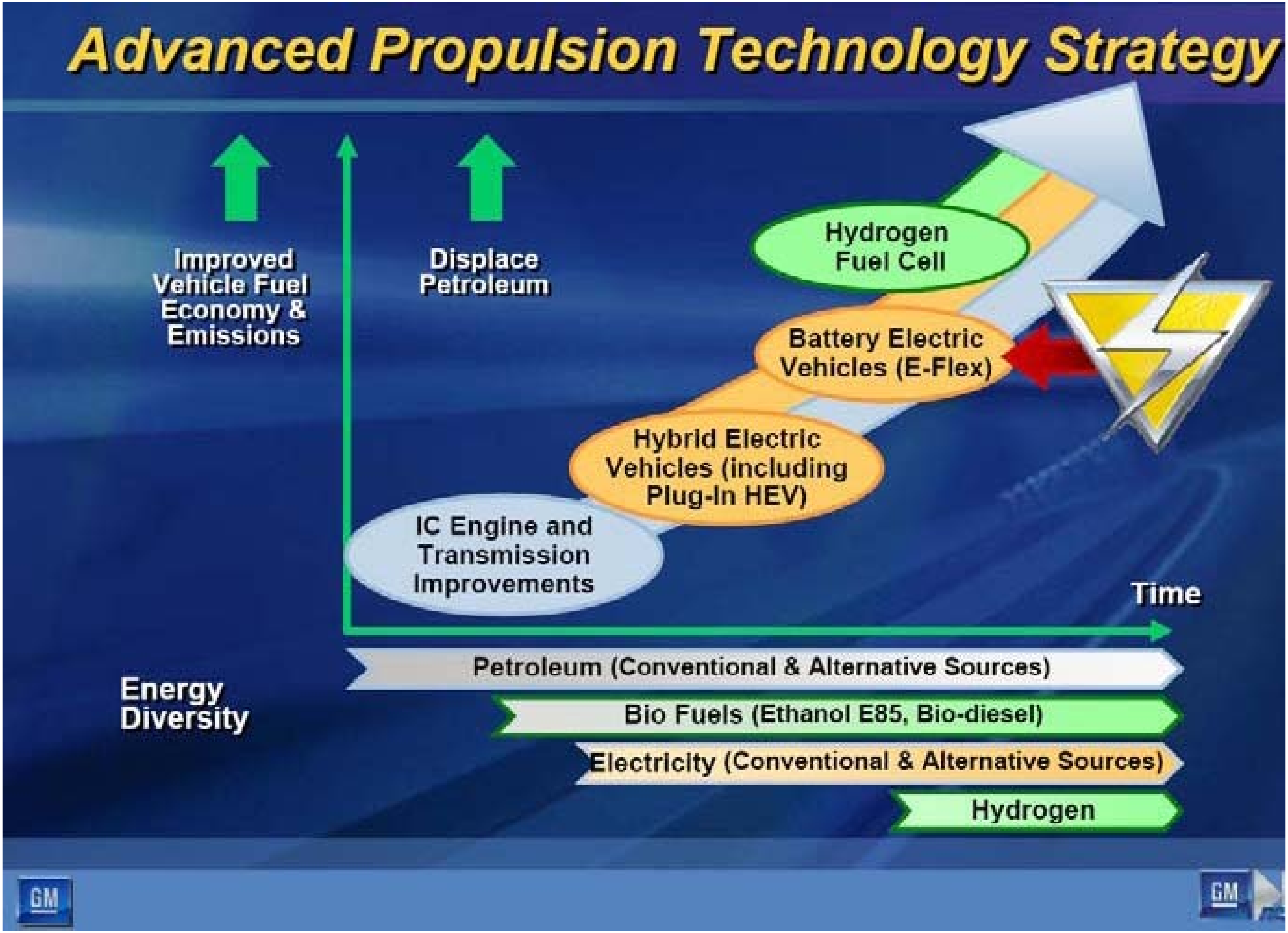
Disadvantages of Regenerative Braking

- Need to control the voltage and current frequency closely match the electricity generated
- Increase control complexity
- Add weight
- Increase cost of components, engineering, manufacturing, and installation.
- Still need frictional (hydraulic) braking system
- Safety concerns with on-board energy storage system

Future Trends for Ground Vehicles

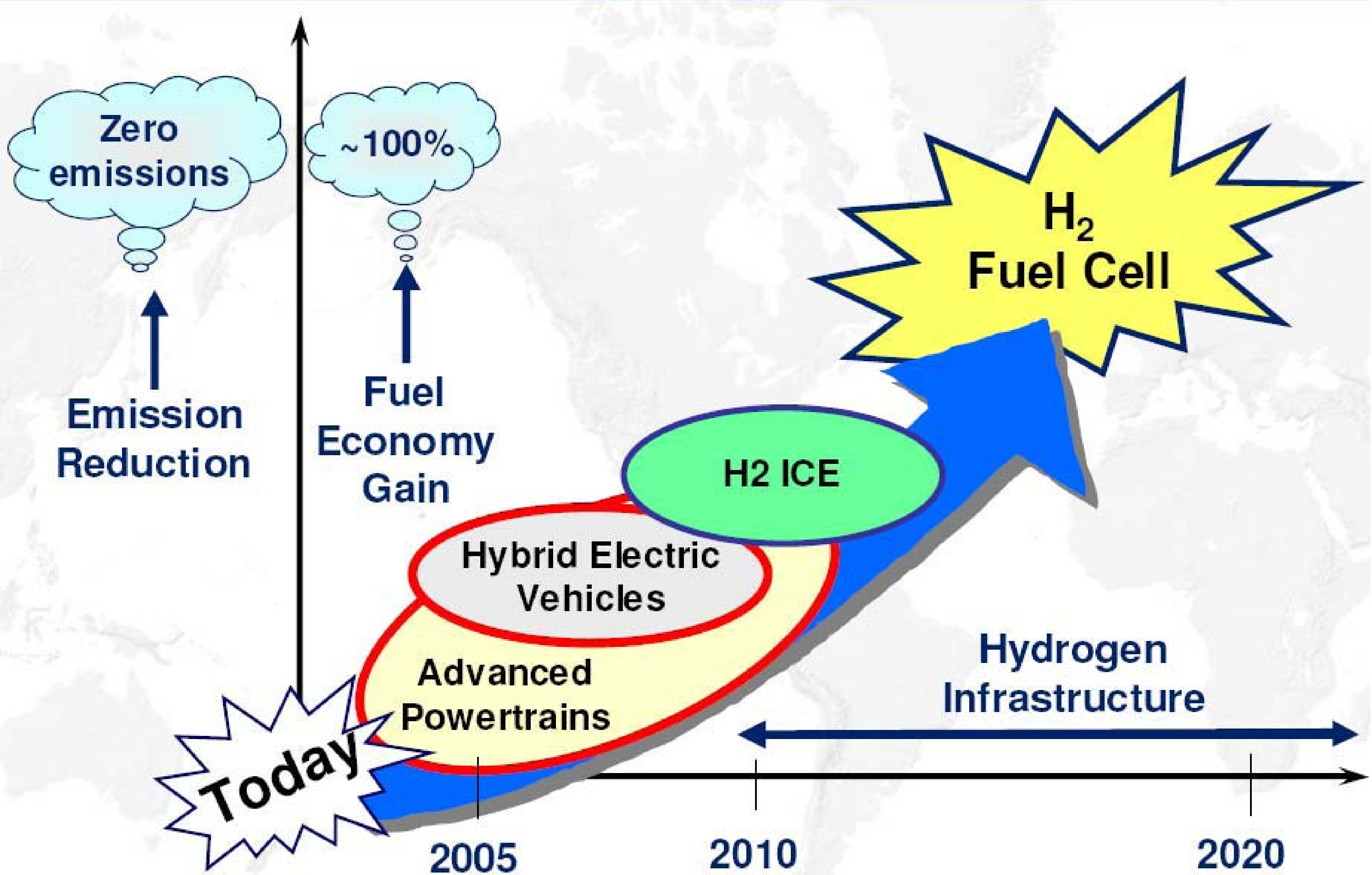
- Hybrid vehicles present medium-term solution
- Long-term solution: **Single** On-board Energy Source/Storage (**Electricity** or ??) for ground vehicles
- How is the electricity supplied by single on-board energy source/storage? From **Battery**, **Fuel Cell**, or ??

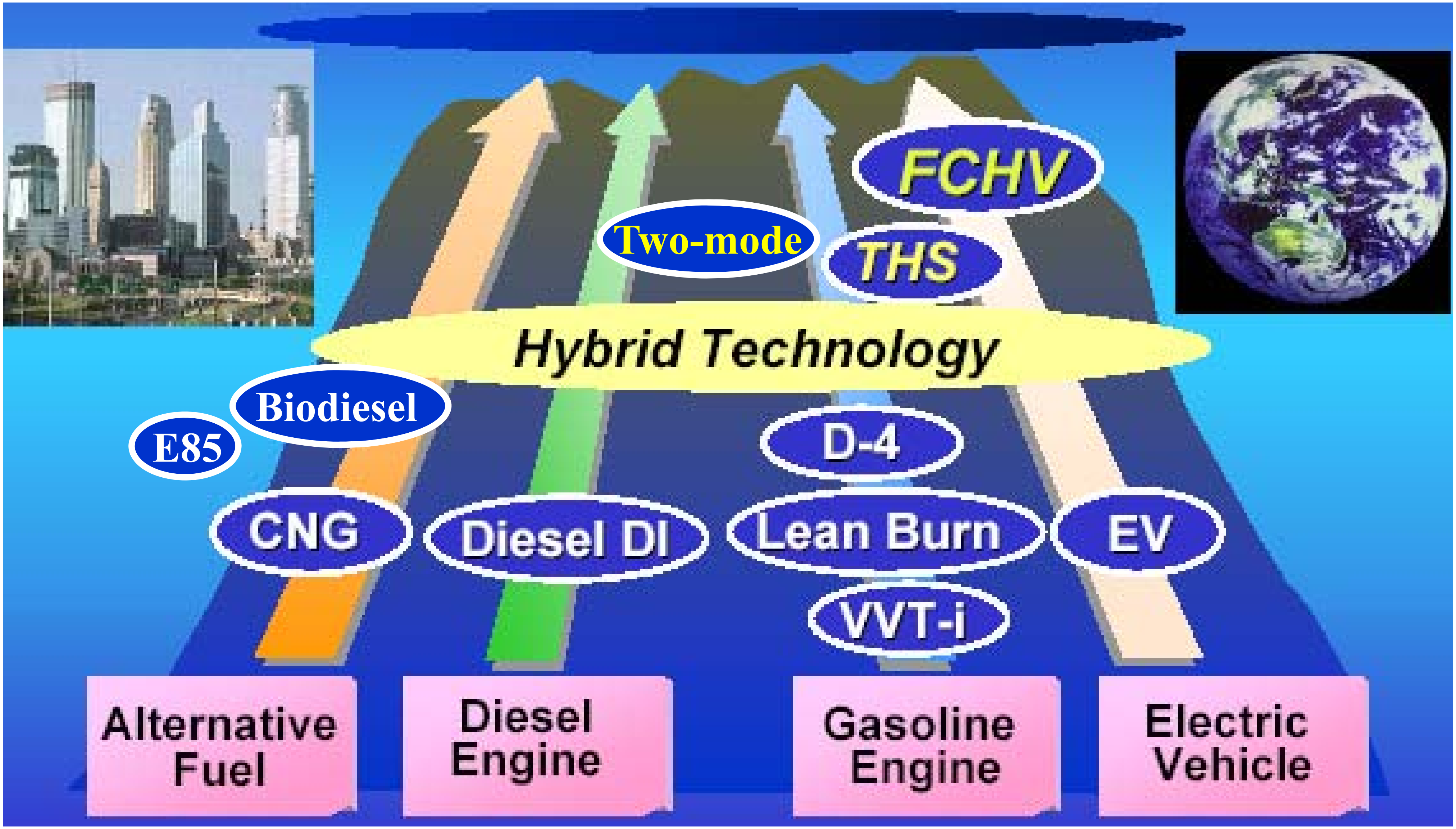




Advanced Propulsion Technology Strategy
Improved Vehicle Fuel Economy & Emissions
Displace Petroleum
Hydrogen Fuel Cell
Battery Electric Vehicles (E-Flex)
Hybrid Electric Vehicles (including Plug-In HEV)
IC Engine and Transmission Improvements
Time
Energy Diversity
Petroleum (Conventional & Alternative Sources)
Bio Fuels (Ethanol E85, Bio-diesel)
Electricity (Conventional & Alternative Sources)
Hydrogen
GM
GM

Technology Strategy





Continuously improved combustion engine, EM, battery, and alternative fuel.

Hydrogen Fuel Cell Vehicle (FCV)

- Efficiency
  - More efficient than ICE and gas turbines
  - Can be as efficient for small systems than large ones
- No/low emissions (in principle)
  - True starting from hydrogen
  - Emissions from hydrogen production
- Simplicity, Reliability
  - No moving parts in stack
  - Not true for balance of plant
- Silence
  - True for fuel cell stack
  - Balance of plant
- Dual use technology (stationary power generation and transportation)

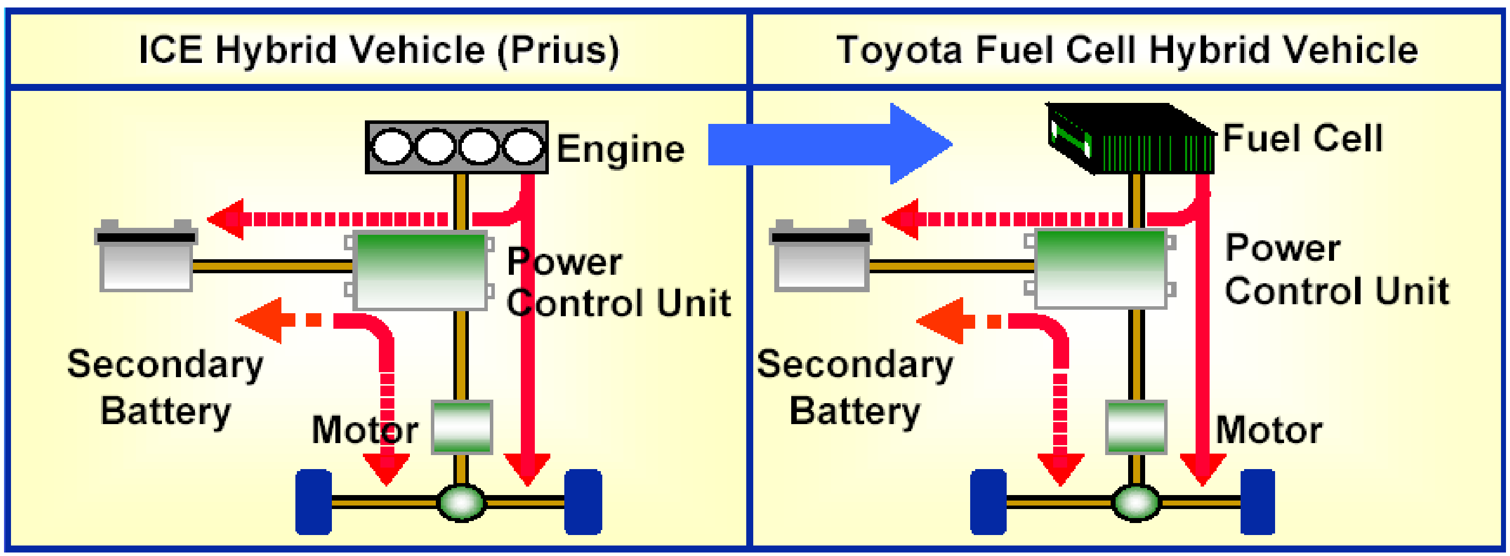
Hybrid Vehicle

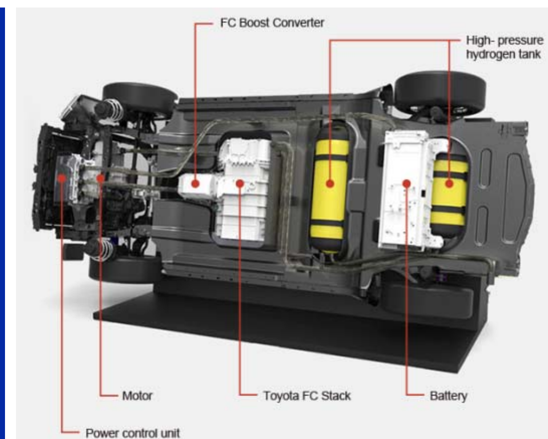
Fuel Cell Vehicle

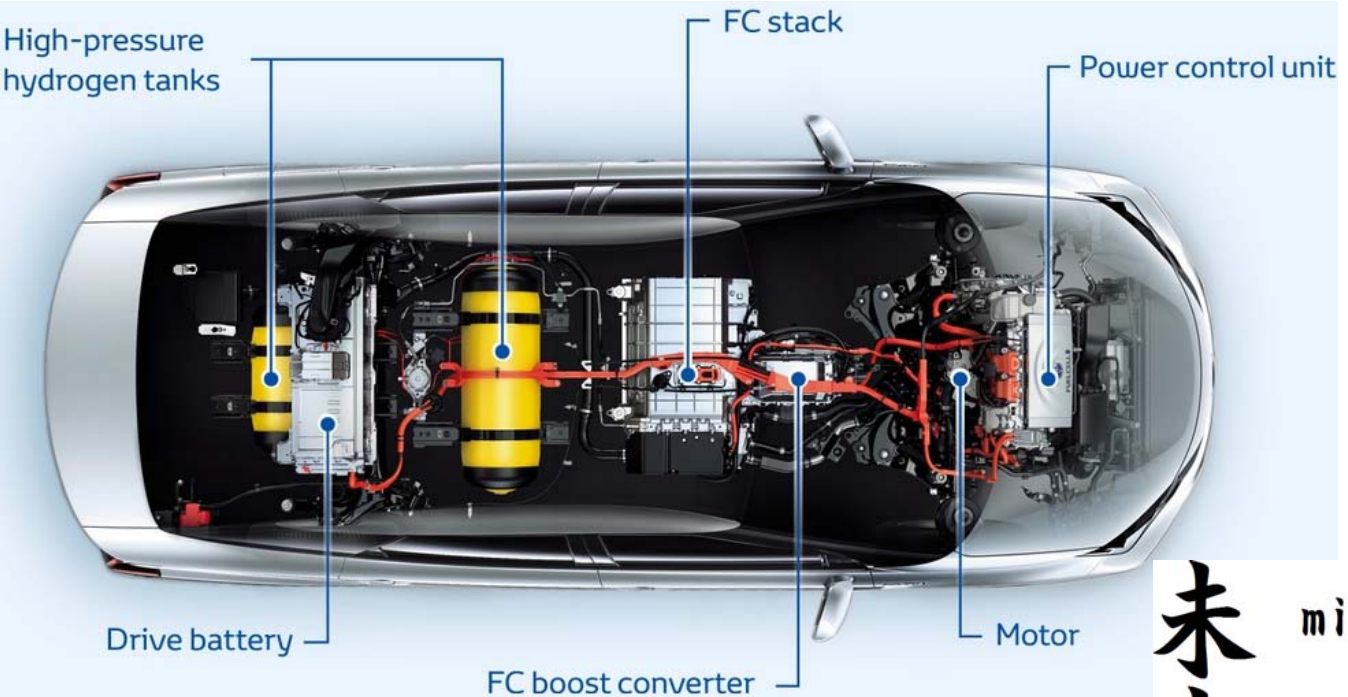
Engine Tech. ⟷ Good Competitor ⟷ FC Tech.

Common Tech.

- >Motor
- >Inverter
- >Battery
- >Vehicle power management
- >Regeneration brake

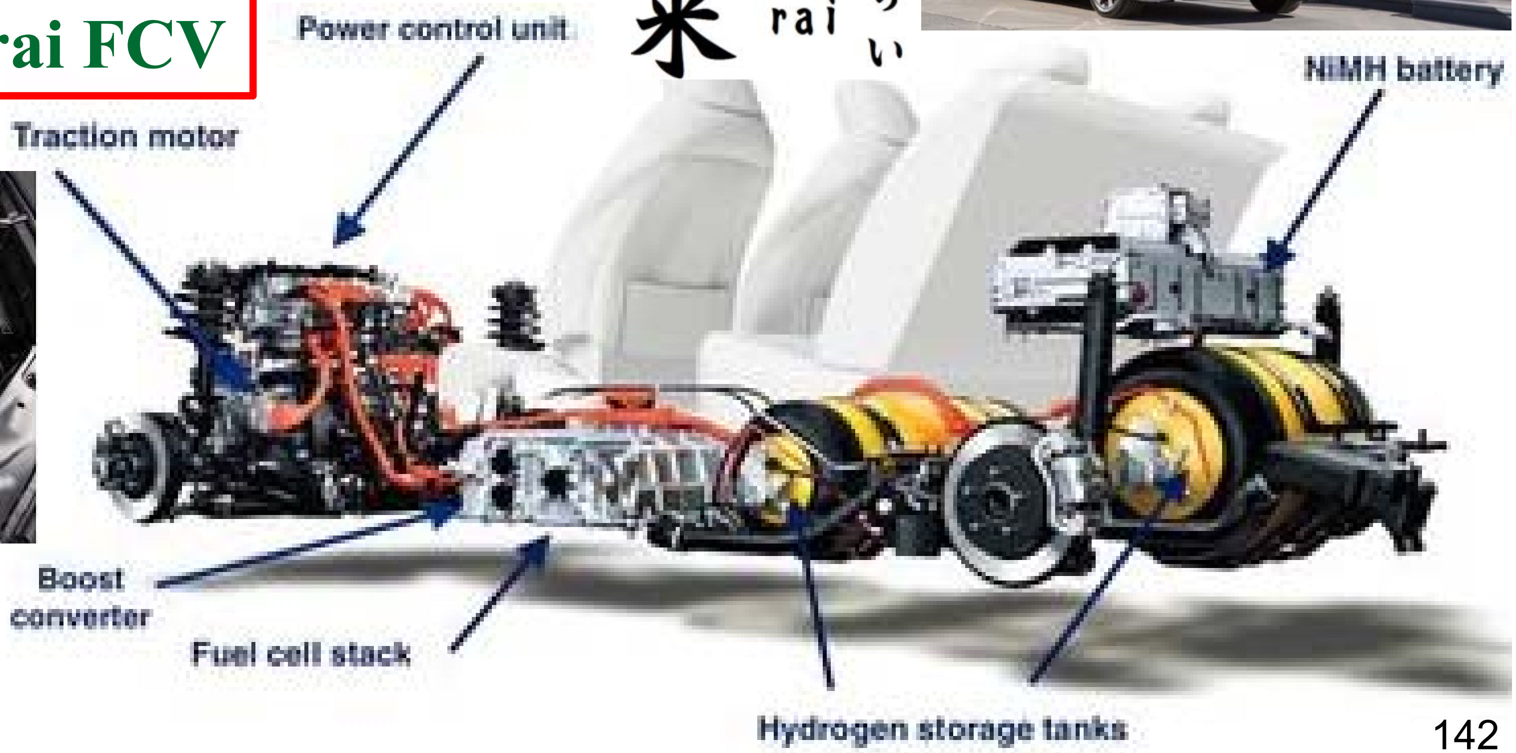




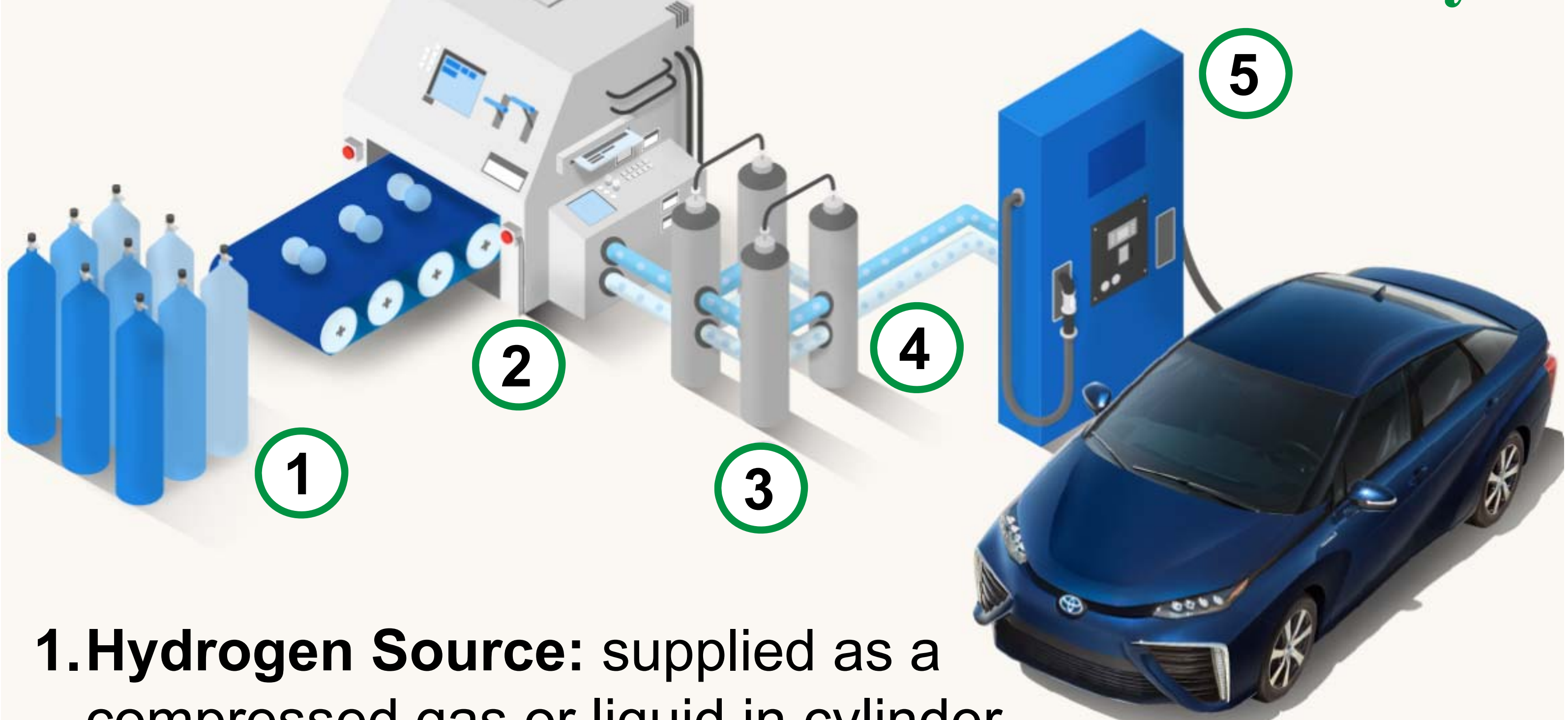


未来 mi rai みらい

2016 Toyota Mirai FCV



2016 Toyota Mirai FCV



1. **Hydrogen Source:** supplied as a compressed gas or liquid in cylinder racks
2. **Compression:** H_2 is compressed
3. **Buffers:** the pressurized H2 is then stored in tubes
4. **Exchanger:** H_2 is cooled in a heat exchanger, enabling for quick fueling
5. **The Dispenser:** the cooled H_2 is transferred to FCV

The Hydrogen Economy

Definition

The Hydrogen Economy is a hypothetical large-scale system in which elemental hydrogen (H_2) is the primary form of energy storage

- Fuel cells would be the primary method of conversion of hydrogen to electrical energy - Efficient and clean; scalable.
- In particular, hydrogen (usually) plays a central role in transportation.

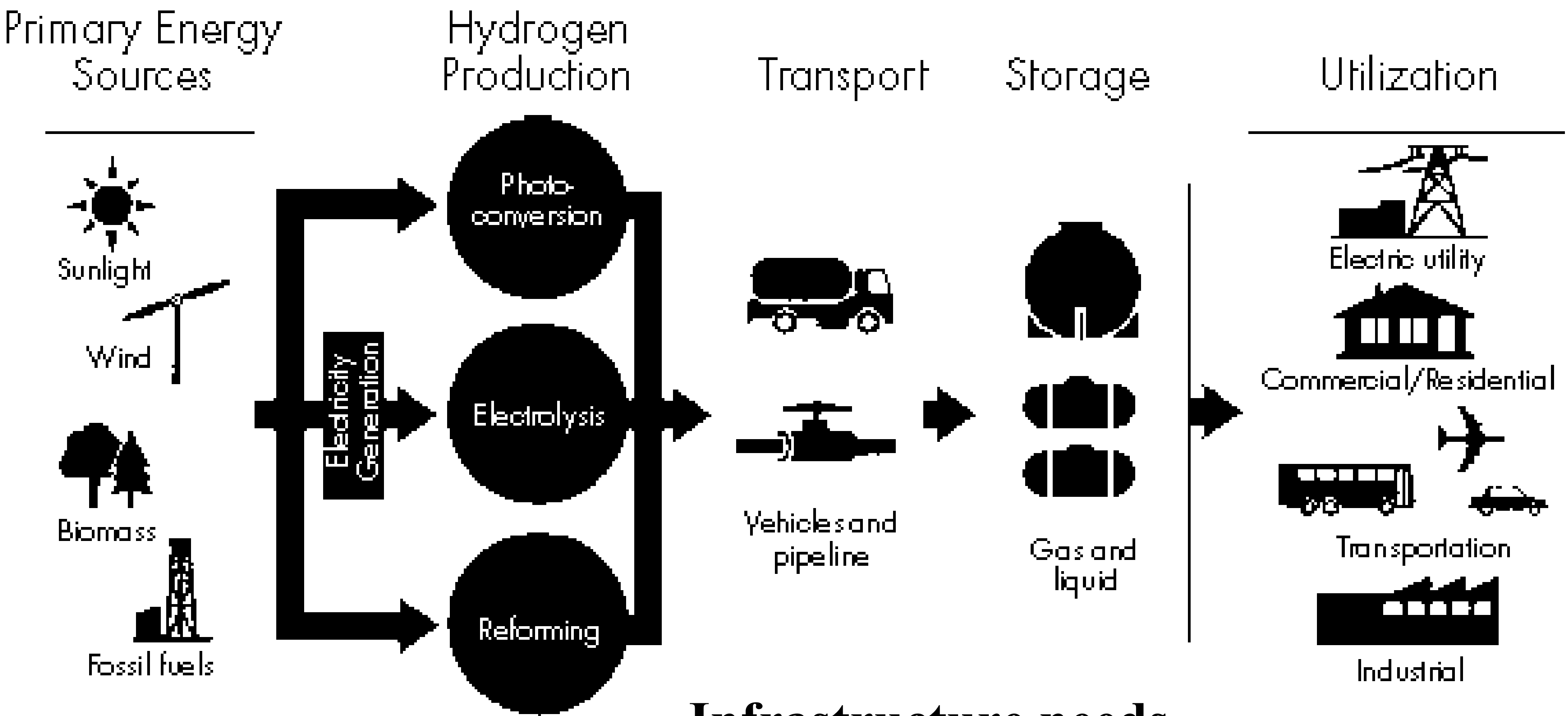
Potential Advantages

- Clean, renewable
- Potentially more reliable (using distributed generation)

BUT many roadblocks *including potential showstoppers*

- Poses great technological challenges for efficient hydrogen production, storage, and transport.

Components of the Hydrogen Economy



Infrastructure needs

- **Production**
- **Storage**
- **Delivery**
- **End use**

Hydrogen Production

Fossil Fuels

- Steam Reforming of Natural Gas
  - Combination of methane and steam produces hydrogen gas
    - Carbon monoxide is also produced
    - The “water gas shift” reaction can produce further hydrogen from the carbon monoxide. *Carbon dioxide is produced too*.
  - Most economical; main current method
    - Carbon sequestration one method to reduce CO_2 emission
- Partial Oxidation (POX) of Hydrocarbons
  - HC partially oxidized to produce hydrogen and carbon monoxide
- Coal Gasification
  - Gasified at high temps, then processed
  - Can also be used to get hydrogen from biomass

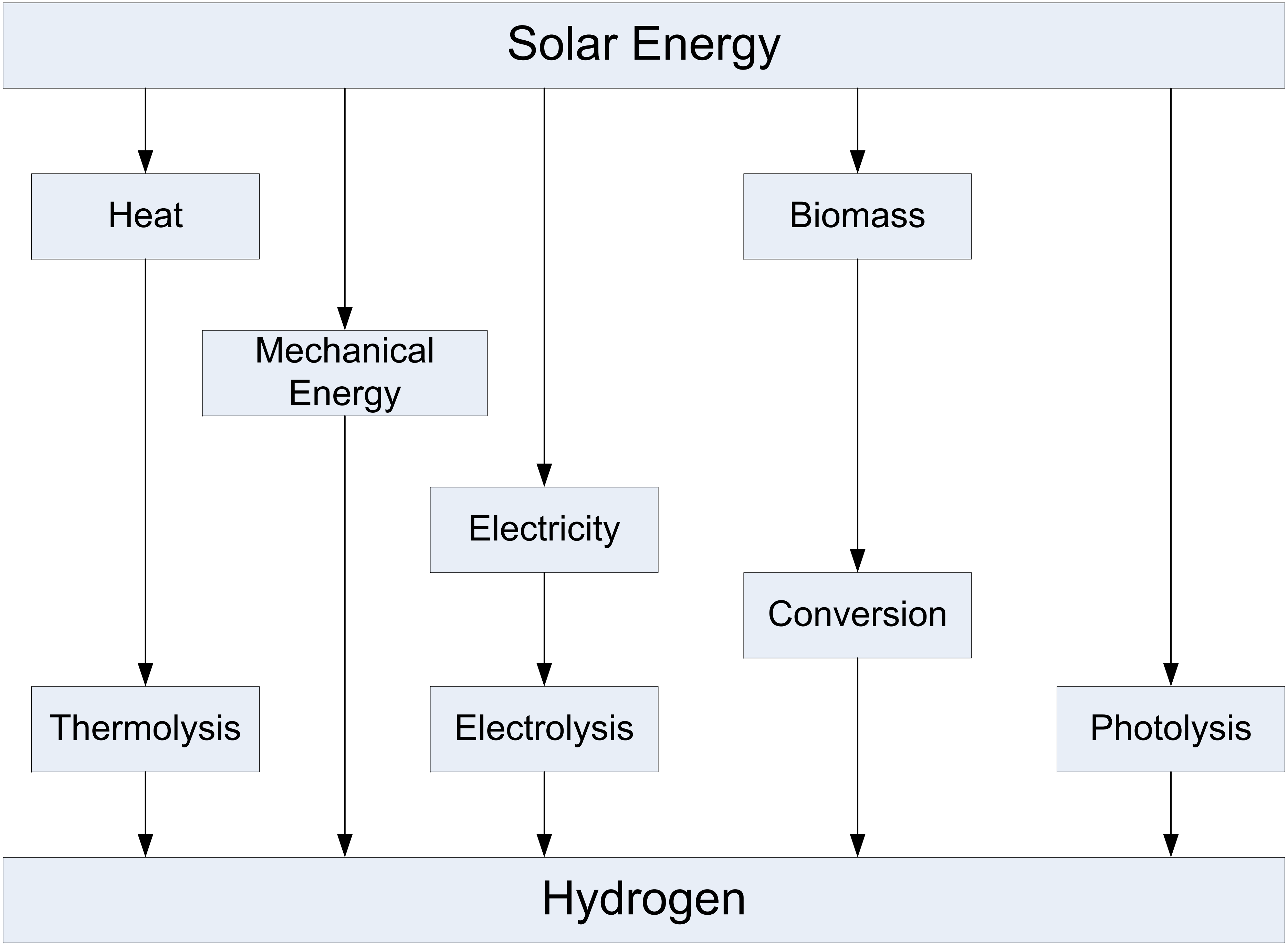
Electrolysis

- Efficiencies 70-85%
- Produces highest purity of hydrogen
- Currently, the electricity consumed is usually worth more than the hydrogen produced

Experimental methods

- Biological hydrogen production
- Direct photolysis
- Thermolysis

Renewable Solar Paths to Hydrogen



Hydrogen Storage

Large-Scale Stationary Storage

– Underground in depleted oil/gas fields, aquifers, caverns

Intermediate- and Small-Scale Stationary/Mobile Storage

– The focus of most current research
– As a liquid
  - Advantage: higher energy density, cheaper transport
  - Disadvantage: economic/energy cost of liquefaction is significant
– As a compressed gas
  - Probably best short-term method, particularly with advanced materials to decrease weight
  - Advantages
    - Rapid charging/discharging
    - Lower costs than liquid storage
  - Disadvantages:
    - Low energy density, Probably still acceptable for ground vehicles
    - Safety (except for public perception)
– As a solid form, metal hydrides
  - Hydrogen is absorbed (into metal mesh) under pressure, released when heated.
  - Less filling pressure needed
  - Low energy density, long recharge time, expensive

Experimental Methods

– Improved hydrides; carbon nanotubes; many other materials (eg conversion to ammonia)

Types of Hydrogen Fuel Cells

- Proton Exchange Membrane (PEM) or Polymer Electrolyte Fuel Cell (PEFC)
  - ⇒ The technology of choice for FC vehicles, or certainly the most common
- Alkaline Fuel Cell (AFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)
  - ⇒ An alternate technology considered for FC vehicles

Types of Hydrogen Fuel Cells

Proton Exchange Membrane (PEM) or Polymer Electrolyte Fuel Cell (PEFC)

- Only liquid is water
- Electrodes are made a proton exchange membrane (polymer, such as fluorinated sulfuric acid polymer or equiv.)
- Water management in membrane is critical
- Low operating temperature (<120°C, typically 80-85 °C)
- Use hydrogen rich gas as fuel, with no or very low CO (poisoning)
- High catalyst loading (Pt usually) required at both electrodes

⇒ The technology of choice for FC vehicles

Alkaline Fuel Cell (AFC)

- Electrolyte is concentrated KOH (35 to 85%)
- Electrolyte in matrix (asbestos usually)
- Many catalysts used (Ag, Ni, etc.)
- Temperature range (120°C to 250°C)
- Very sensitive to CO poisoning as well as CO_2
- Technology is being phased-out, except for space applications

Phosphoric Acid Fuel Cell (PAFC)

- Electrolyte is pure phosphoric acid
- Electrolyte in matrix of silicon carbide
- Pt used as catalyst for both electrodes
- Temperature range (100°C to 220°C)
- Sensitive to CO poisoning

Molten Carbonate Fuel Cell (MCFC)

- Electrolytes are alkali carbonates (K, Na)
- Electrolyte in matrix of $LiAlO_2$
- Temperature Range (600°C to 700°C) for molten salts (carbonates)
- Usually Ni anode and Ni oxide cathode are used
- Usually no catalyst required

Solid Oxide Fuel Cell (SOFC)

- Electrolyte is solid, non-porous metal oxide (usually Y_2O_2-stabilized ZrO_2)
- Temperature range (650°C to 1000°C)
- Anode is Co-ZrO_2 and cathode is Sr-doped $LaMnO_3$

⇒ An alternate technology considered for FC vehicles

Types of Hydrogen Fuel Cells

Summary of Basic Chemical Reactions of Various Types of Fuel Cells

Fuel Cell	Anode Reaction	Cathode Reaction
Proton Exchange Membrane	$H_2 \rightarrow 2H^+ + 2e^-$	$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Alkaline	$H_2 + 2(OH)^- \rightarrow 2H_2O + 2e^-$	$\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$
Phosphoric Acid	$H_2 \rightarrow 2H^+ + 2e^-$	$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Molten Carbonate	$H_2 + CO_3^{=} \rightarrow H_2O + CO_2 + 2e^-$ $CO + CO_3^{=} \rightarrow 2CO_2 + 2e^-$	$\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^{=}$
Solid Oxide	$H_2 + O^{=} \rightarrow H_2O + 2e^-$ $CO + O^{=} \rightarrow CO_2 + 2e^-$ $CH_4 + 4O^{=} \rightarrow 2H_2O + CO_2 + 8e^-$	$\frac{1}{2} O_2 + 2e^- \rightarrow O^{=}$

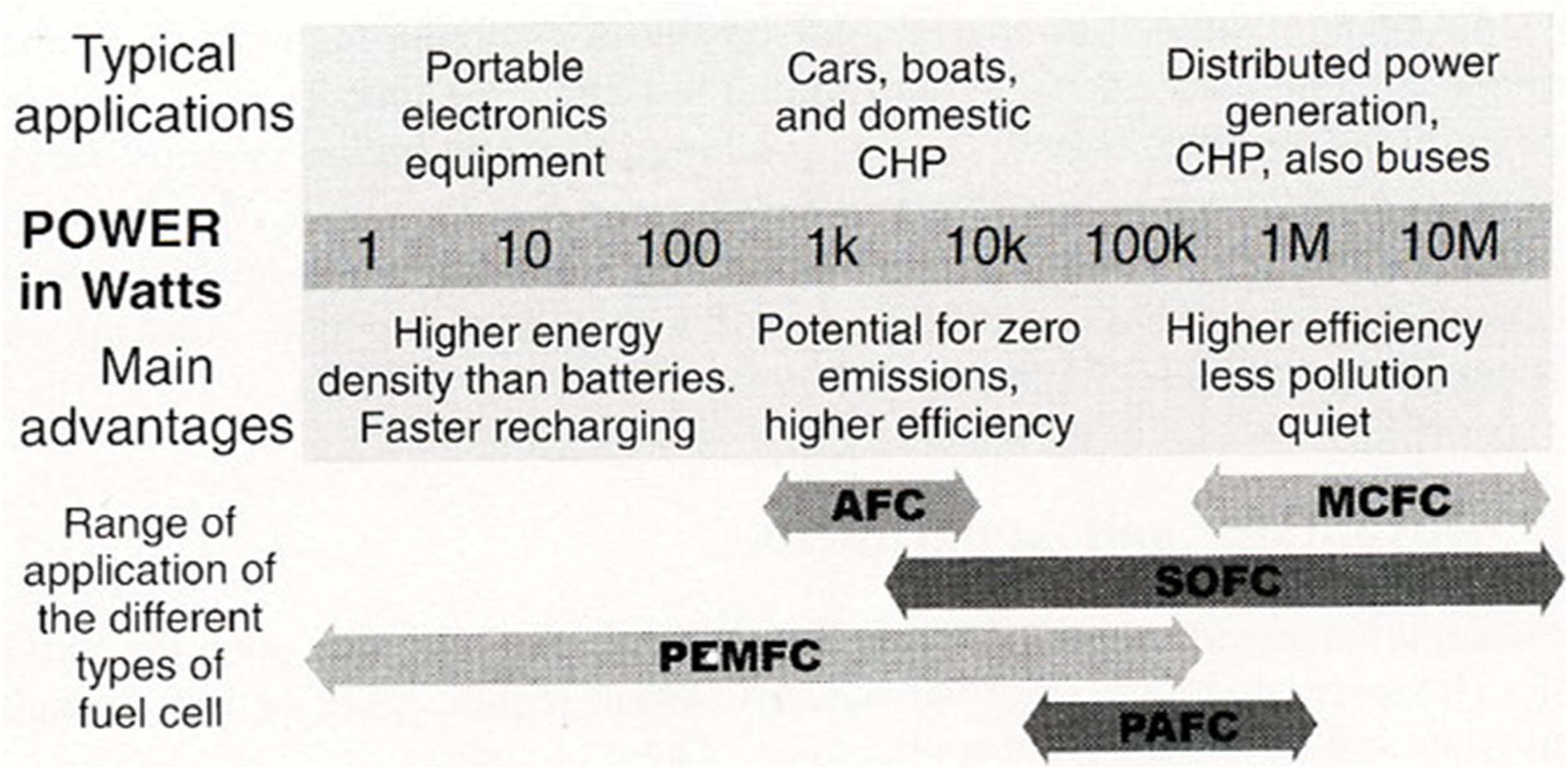
CO - carbon monoxide
CO_2 - carbon dioxide
$CO_3^{=}$ - carbonate ion
e^- - electron
H^+ - hydrogen ion
H_2 - hydrogen
H_2O - water
O_2 - oxygen
OH^- - hydroxyl ion

Types of Hydrogen Fuel Cells

Summary of Characteristics of Various Types of Fuel Cells

	PEFC	PAFC	MCFC	SOFC
Electrolyte	Ion Exchange Membrane	Immobilized Liquid Phosphoric Acid	Immobilized Liquid Molten Carbonate	Ceramic
Operating Temperature	80°C	205°C	650°C	800-1000°C now, 600-1000°C in 10 to 15 years
Charge Carrier	H^+	H^+	$CO3^=$	$O^=$
External Reformer for CH_4 (below)	Yes	Yes	No	No
Prime Cell Components	Carbon-based	Graphite-based	Stainless Steel	Ceramic
Catalyst	Platinum	Platinum	Nickel	Perovskites
Product Water Management	Evaporative	Evaporative	Gaseous Product	Gaseous Product
Product Heat Management	Process Gas + Independent Cooling Medium	Process Gas + Independent Cooling Medium	Internal Reforming + Process Gas	Internal Reforming + Process Gas

Types of Fuel Cells and Applications



Fuel Cell Types by Use (after Larminie and Dicks, 2000)

Fuels for Fuel Cell Systems

- Hydrogen
- Alcohols (methanol, ethanol, etc)
- Natural gas/gaseous hydrocarbons (methane, ethane, propane, butane, coal gas, syn-gas, etc.)
- Liquid hydrocarbons (gasoline, Diesel, kerosene, naphta, etc)
- Others (ammonia, hydrazine, etc.)

Fuel Sources

- Petroleum
- Natural gas
- Coal
- Bio-mass
- Electricity (fossil fuel, nuclear, hydro, solar…)

Gas species	PEM Fuel Cell	AFC	PAFC	MCFC	SOFC
H_2	Fuel	Fuel	Fuel	Fuel	Fuel
CO	Poison (>10ppm)	Poison	Poison (>0.5%)	Fuel [a]	Fuel [a]
CH_4	Diluent	Diluent	Diluent	Diluent [b]	Diluent [b]
CO_2 and H_2O	Diluent	Poison [c]	Diluent	Diluent	Diluent
S (as H_2S and COS)	Few studies, to date	Unknown	Poison (>50 ppm)	Poison (>0.5 ppm)	Poison (>1.0 ppm)

a – In reality CO reacts with H_2O producing H_2 and CO_2 via the shift reaction (7.3) and CH_4 with H_2O reforms to H_2 and CO faster than reacting as a fuel at the electrode.

b – A fuel in the internal reforming MCFC and SOFC.

c – The fact that CO_2 is a poison for the alkaline fuel cell more or less rules out its use with reformed fuels

(after Larminie and Dicks, 2000)

Hydrogen Storage for Fuel Cell

Methods

- Compressed in gas cylinders
- Cryogenic liquid
- Reversible metal hydrides
- Alkali metal hydrides

Requirements

- Safe to handle
- Require little energy to supply hydrogen
- Easy to supply hydrogen
- Gravimetric storage efficiency
- Volumetric storage efficiency

Name	Formula	Percent hydrogen	Specific gravity	Vol. (L) to store 1 kg H_2	Notes
Simple hydrides					
Liquid H_2	H_2	100	0.07	14	Cold, -252°C
Lithium hydride	LiH	12.68	0.82	6.5	Caustic
Beryllium hydride	BeH_2	18.28	0.67	8.2	Very toxic
Diborane	B_2H_6	21.86	0.417	11	Toxic
Liquid methane	CH_4	25.13	0.415	9.6	Cold –175°C
Ammonia	NH_4	17.76	0.817	6.7	Toxic, 100 ppm
Water	H_2O	11.19	1.0	8.9	
Sodium hydride	NaH	4.3	0.92	25.9	Caustic, but cheap
Calcium hydride	CaH_2	5.0	1.9	11	
Aluminium hydride	AlH_3	10.8	1.3	7.1	
Silane	SiH_4	12.55	0.68	12	Toxic 0.1 ppm
Potassium hydride	KH	2.51	1.47	27.1	Caustic
Titanium hydride	TiH_2	4.40	3.9	5.8	
Complex hydrides					
Lithium borohydride	$LiBH_4$	18.51	0.666	8.1	Mild toxicity
Aluminium borohydride	$Al(BH_4)_3$	16.91	0.545	11	Mild toxicity
Lithium aluminium hydride	$LiAlH_4$	10.62	0.917	10	
Hydrazine	N_2H_4	12.58	1.011	7.8	Toxic 10 ppm
Hydrogen absorbers					
Palladium hydride	Pd_2H	0.471	10.78	20	
Titanium iron hydride	$TiFeH_2$	1.87	5.47	9.8	

(after Larminie and Dicks, 2000)

Hydrogen Storage for Fuel Cell

Compressed Hydrogen

- Stored in metal cylinders at high pressures (340 bars [5000 psi] currently)
- Pressures increasing to 10,000 psi shortly
- Typically aluminum liner with epoxy composite shell
- Low storage efficiency (both volumetric and gravimetric)
- Limited to relatively small quantity to storage density:
  : A stretch to package in automobiles and meet range requirements!
- Unlimited storage time and no restrictions on purity
- Not very "user-friendly" at refueling station due to high pressure
- Safety is a concern due to high pressure (rather than hydrogen explosion risk, except in confined spaces)

	2 L steel, 200 bar	147 L composite, 300 bar
Mass of empty cylinder	3.0 kg	100 kg
Mass of hydrogen stored	0.036 kg	3.1 kg
Storage efficiency (% mass H_2)	1.2 %	3.1 %
Specific energy	0.47 $kWh.kg^{-1}$	1.2 $kWh.kg^{-1}$
Volume of tank (approx.)	2.2 L (0.0022 m^3)	220 L (0.22 m^3)
Mass of H_2 per litre	0.016 $kg.L^{-1}$	0.014 $kg.L^{-1}$

(after Larminie and Dicks, 2000)

Hydrogen Storage for Fuel Cell

Liquid Hydrogen – LH_2

- Cryogenically stored at about 22ºK
- Low pressure, typically 2-3 bars
- Vacuum double wall tanks
- "Slow" release of hydrogen gas
- Relatively "user-friendly" to refill
- Good volumetric and gravimetric storage efficiency
- Require ultra low temperature (-253ºC)
- Liquefaction is energy expensive (60% efficiency typically)
- Has received more attention in Europe

Mass of empty container	51.5 kg
Mass of hydrogen stored	8.5 kg
Storage efficiency (% mass H_2)	14.2 %
Specific energy	5.57 $kWh.kg^{-1}$
Volume of tank (approx.)	0.2 m^3
Mass of H_2 per litre	0.0425 $kg.L^{-1}$

(after Larminie and Dicks, 2000)

Hydrogen Storage for Fuel Cell

Alkali Metal Hydride

- Calcium or sodium hydride typically
- React with water to produce hydrogen
- Not easily reversible
- Liquid hydroxide by-product (caustic)
- Requires large excess water as hydroxides are hydrophylic
- Atmospheric pressure and temperature storage
- Storage efficiency comparable to other methods
- Safe except caustic liquid
- "Refilling" means disposal of by-product and replenishment
  – *Not desirable for automotive applications*

$$NaH + H_2O \rightarrow NaOH + H_2$$

$$CaH_2 + 2H_2O \rightarrow Ca(OH)_2 + 2H_2$$

Mass of container and all materials	45 kg
Mass of hydrogen stored	1.0 kg
Storage efficiency (% mass H2)	2.2 %
Specific energy	0.87 kWh.kg^{-1}
Volume of tank (approx.)	50 L
Mass of H_2 per litre	0.020 kg.L^{-1}

(after Larminie and Dicks, 2000)

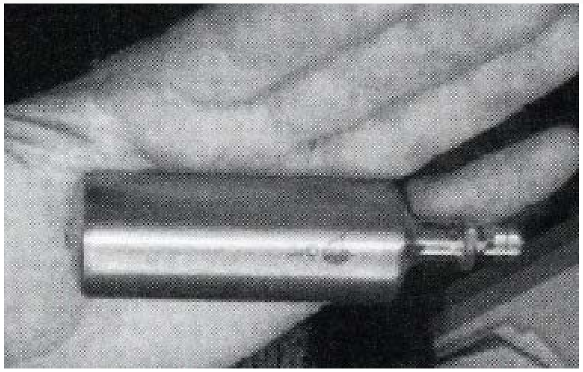
Hydrogen Storage for Fuel Cell

Reversible Metal Hydride - MH_2

- Metal (alloys) of titanium, iron, manganese, nickel, chromium, etc.
- Reversible reaction
- Well suited for low pressure (2 bar), room temperature storage
- Storage is mildly exothermic (rate limiting for refilling)
- Release is mildly endothermic, self limiting with pressure
- Capable of several hundreds of charge/discharge cycles (thermally managed)
- Storage affected by impurities
- Volumetric storage efficiency as good as LH2
- Gravimetric storage efficiency like compressed H2
- Very safe
- Slow refilling

Mass of empty container	0.26 kg
Mass of hydrogen stored	0.0017 kg
Storage efficiency (% mass H_2)	0.65 %
Specific energy	0.26 $kWh.kg^{-1}$
Volume of tank (approx.)	0.06 L
Mass of H_2 per litre	0.028 $kg.L^{-1}$

$$M + H_2 \leftrightarrow MH_2$$



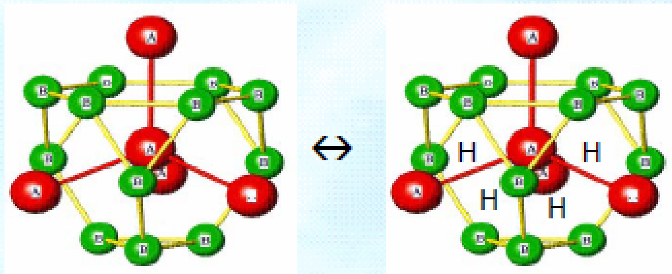
(after Larminie and Dicks, 2000)

Solid Hydrogen Storage System

Reversible

$$M + H_2 \leftrightharpoons MH + \Delta \mathcal{H}$$

Safe



Compact

Design Requirements:

- Suitable MH Alloy
- Efficient Heat Exchanger
- Proper Powder Packaging

H_2 Desorption Process

- Gaseous hydrogen withdrawn from the tank to operate the engine or fuel cell
- process absorbs heat
- MH powder cools to a point at which hydrogen desorption will stop
- External heat is required to sustain the desorption process

H_2 Absorption Process

- Hydrogen is chemically bonded to a host metal alloy that is contained in powder form within the storage tank.
- When gaseous hydrogen is introduced to the tank, it is chemically absorbed by the host metal, which is transformed into a metal hydride (MH)
- Heat is released

Applications

Features

- DOT approved
- CGA certified components
- >3300 units worldwide

Standard products

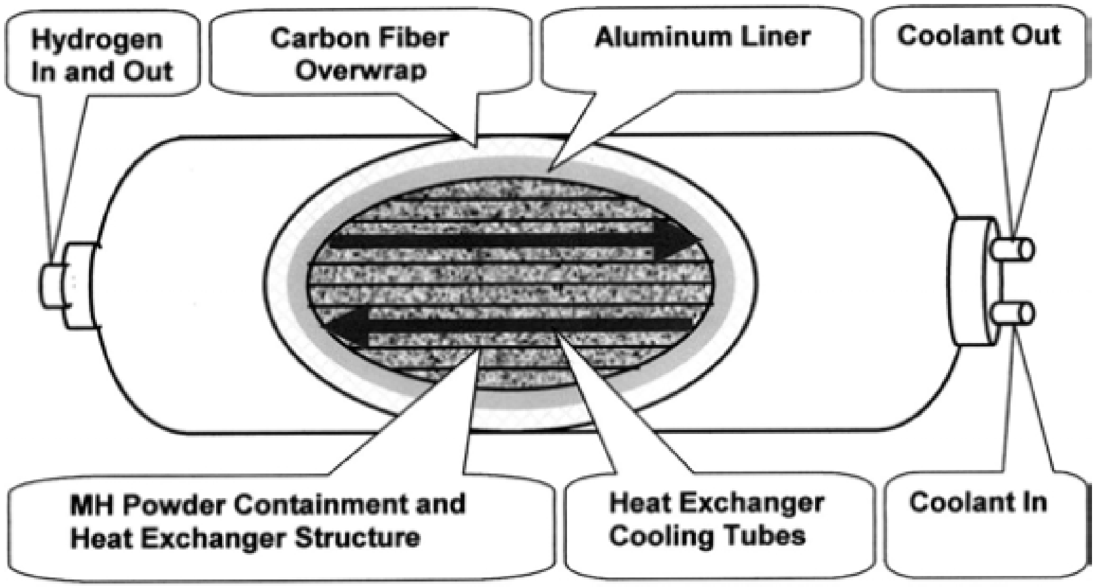
Model	diameter (in.)	length (in.)	weight (lbs.)	capacity (liters)
7G250	2.0	6	2	75
10G250	2.5	5	2	100
25G250	2.5	12	5	280
85G250	3.5	17	14.5	900

Applications

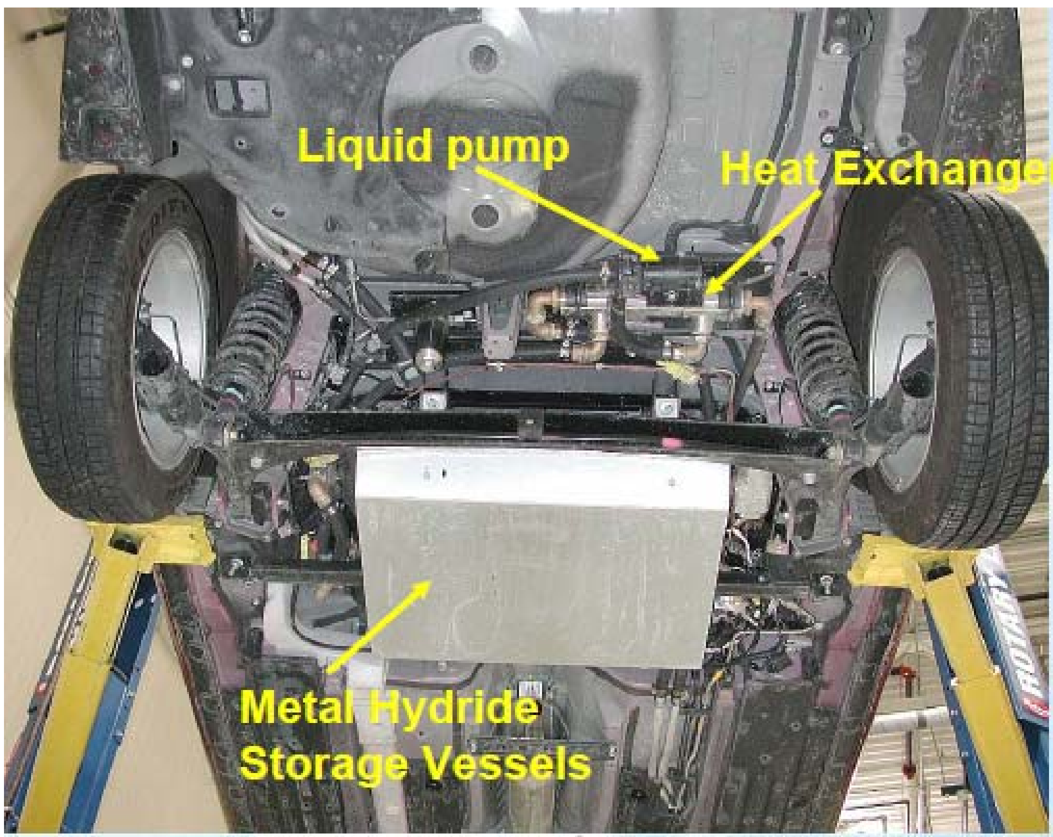
Portable power

Vehicular

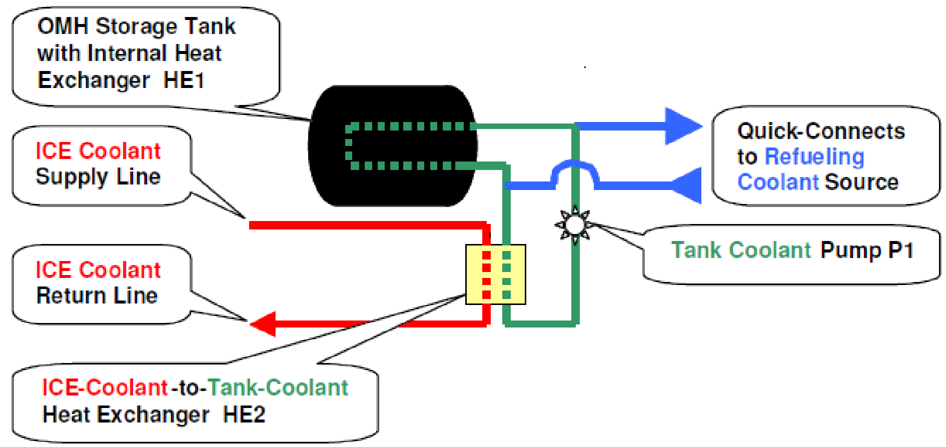
Stationary power



Hydrogen In and Out
Carbon Fiber Overwrap
Aluminum Liner
Coolant Out
MH Powder Containment and Heat Exchanger Structure
Heat Exchanger Cooling Tubes
Coolant In



Liquid pump
Heat Exchanger
Metal Hydride Storage Vessels



OMH Storage Tank with Internal Heat Exchanger HE1
ICE Coolant Supply Line
ICE Coolant Return Line
Quick-Connects to Refueling Coolant Source
Tank Coolant Pump P1
ICE-Coolant-to-Tank-Coolant Heat Exchanger HE2

2005 Model ▶
2004 Model ▼
2002 Model ▼

Fuel Cell Application: Electricity for Vehicle Auxiliary Power Unit (APU)

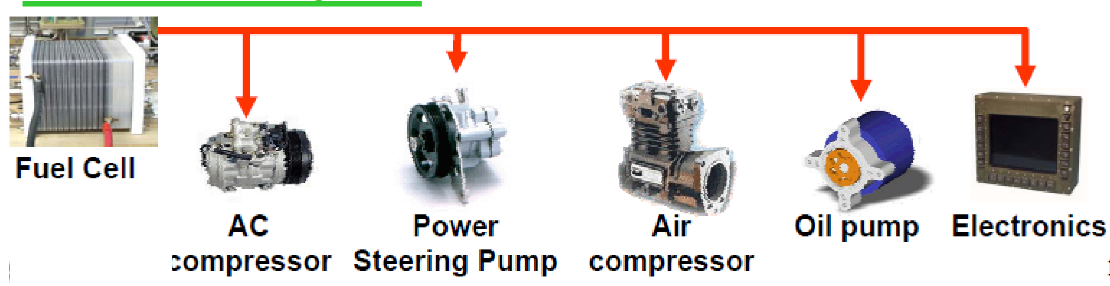
- Engine Idling (alternator power)
  - –Significant noise and heat generation
  - –Low Fuel Efficiency

- Battery
  - –Limited silent watch duration
    - 3 h @ 1kW, 1 h @ 2.4 kW with only one cranking
    - Needs 6.5 hours to recharge
    - Deep cycling reduces battery life

- Auxiliary Power Unit (APU)
  - –IC engine or gas turbine + generator
  - –*Fuel Cell*

- Mechanical coupling with engine speed
- High parasitic losses

Fuel Cell APU system



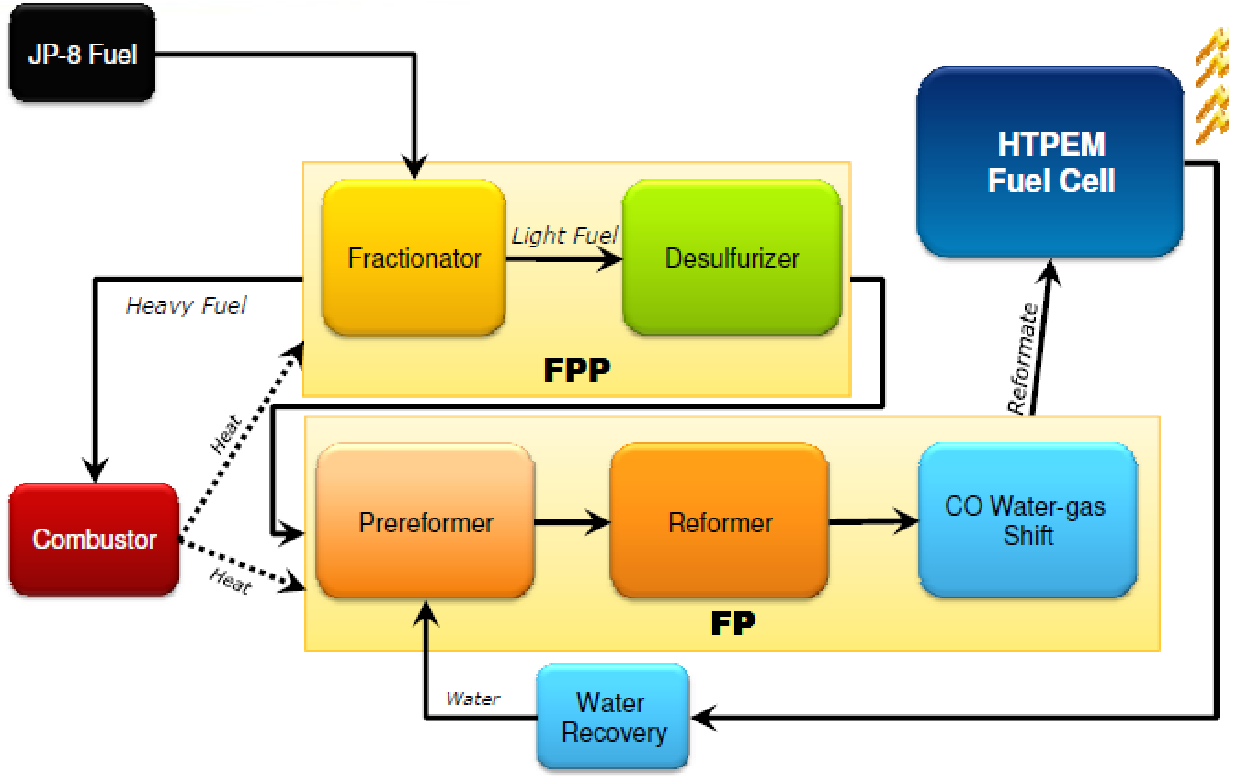
Heavy-Duty Vehicle Auxiliary Load Electrification

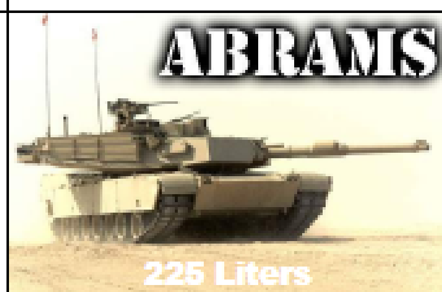
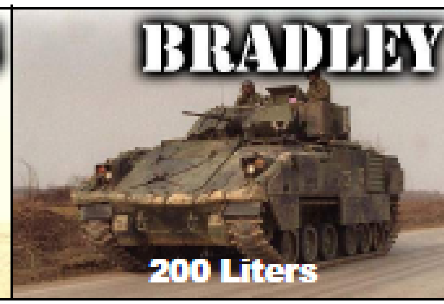
- Platform: Class 8 non-refrigerated tractor-trailer
  - future studies will examine Classes 3-8

- Aux. Components analyzed
  - engine cooling fan
  - engine oil pump
  - engine coolant pump
  - power steering pump
  - alternator
  - air compressor
  - air conditioning compressor

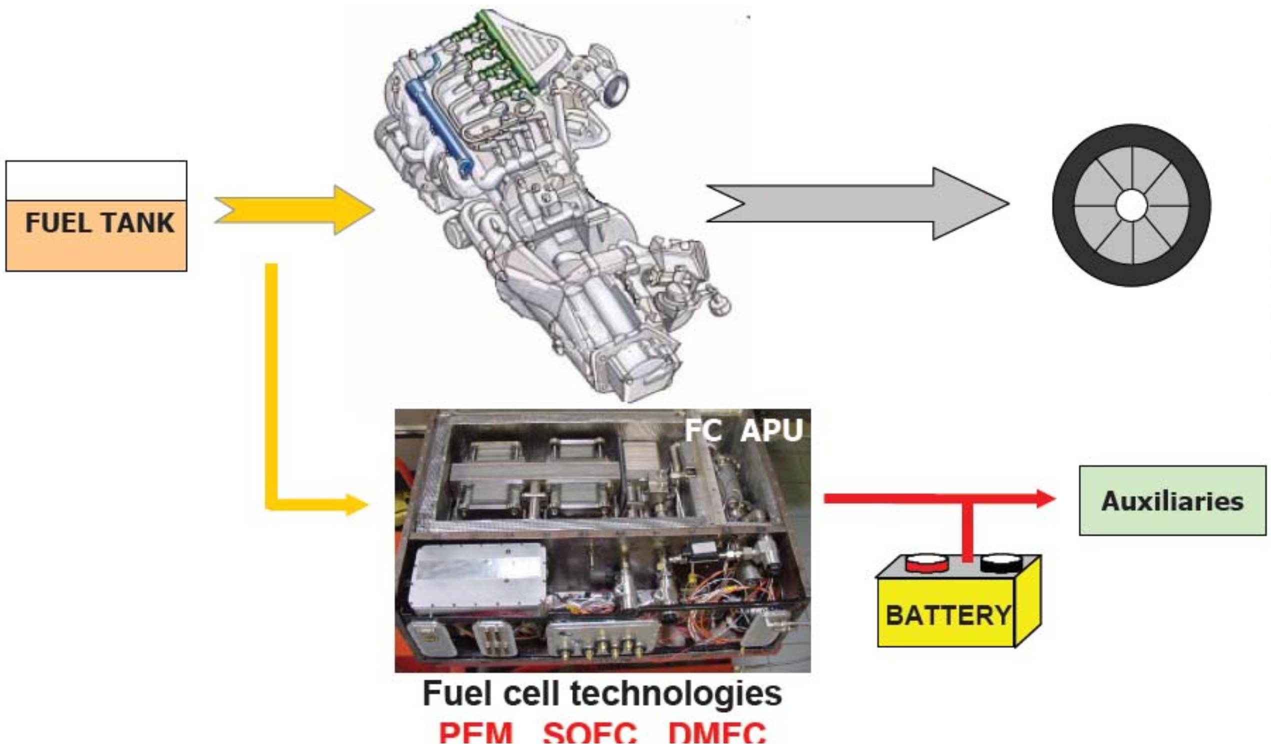
Fuel Cell Application: Silent Watch Support

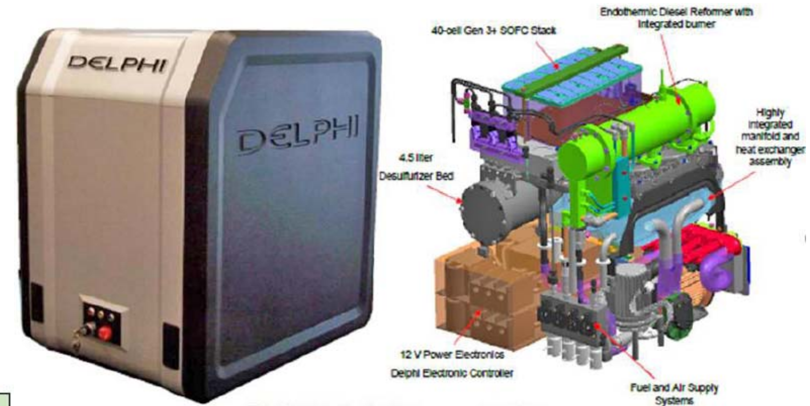
- Engine Idling (alternator power)
  - –Significant noise and heat generation
  - –Low Fuel Efficiency
- Battery
  - –Limited silent watch duration
    - 3 h @ 1kW, 1 h @ 2.4 kW with only one cranking
    - Needs 6.5 hours to recharge
    - Deep cycling reduces battery life
- Auxiliary Power Unit (APU)
  - –IC engine or gas turbine + generator
  - –*Fuel Cell*



Abrams, Bradley and Stryker APU Performance Requirements			
Continuous Power	8 kW (Threshold) / 10 kW (Objective)		
Mission Duration	> 12 hours		
Fuel Consumption	1.75 gal / hour (Threshold) / 1.5 gal / hour (Objective)		
NPS Volume			
NPS Weight	453 lbs. – Requires its own cooling system		254 lbs. - Can integrate into engine's cooling system
Procurement Cost	< $40K		

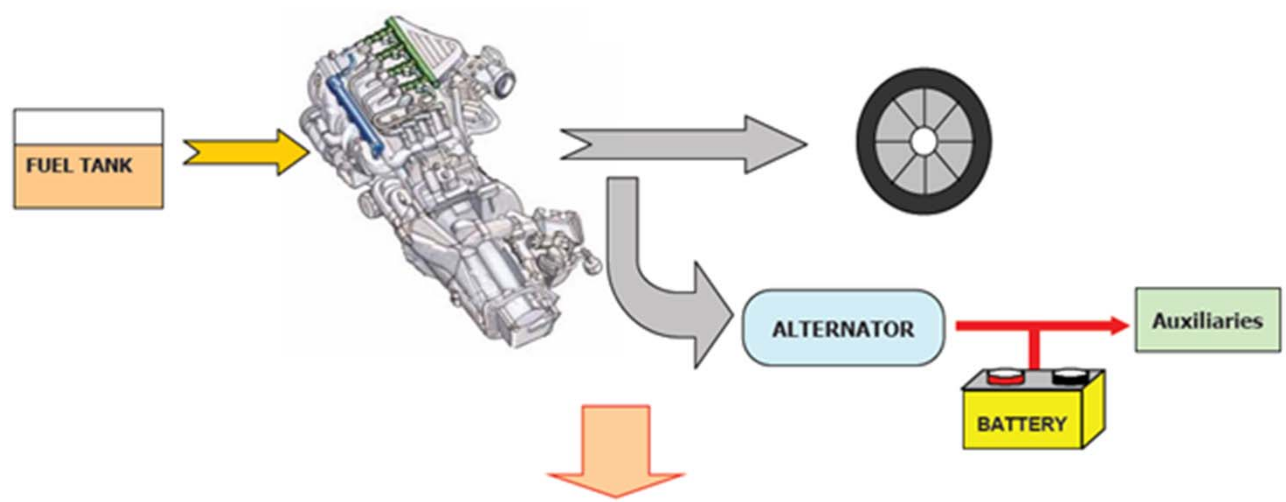
Fuel cell APU: On-board Reforming for H_2





DPS3000-D (244 Liters – 3.5 kW)

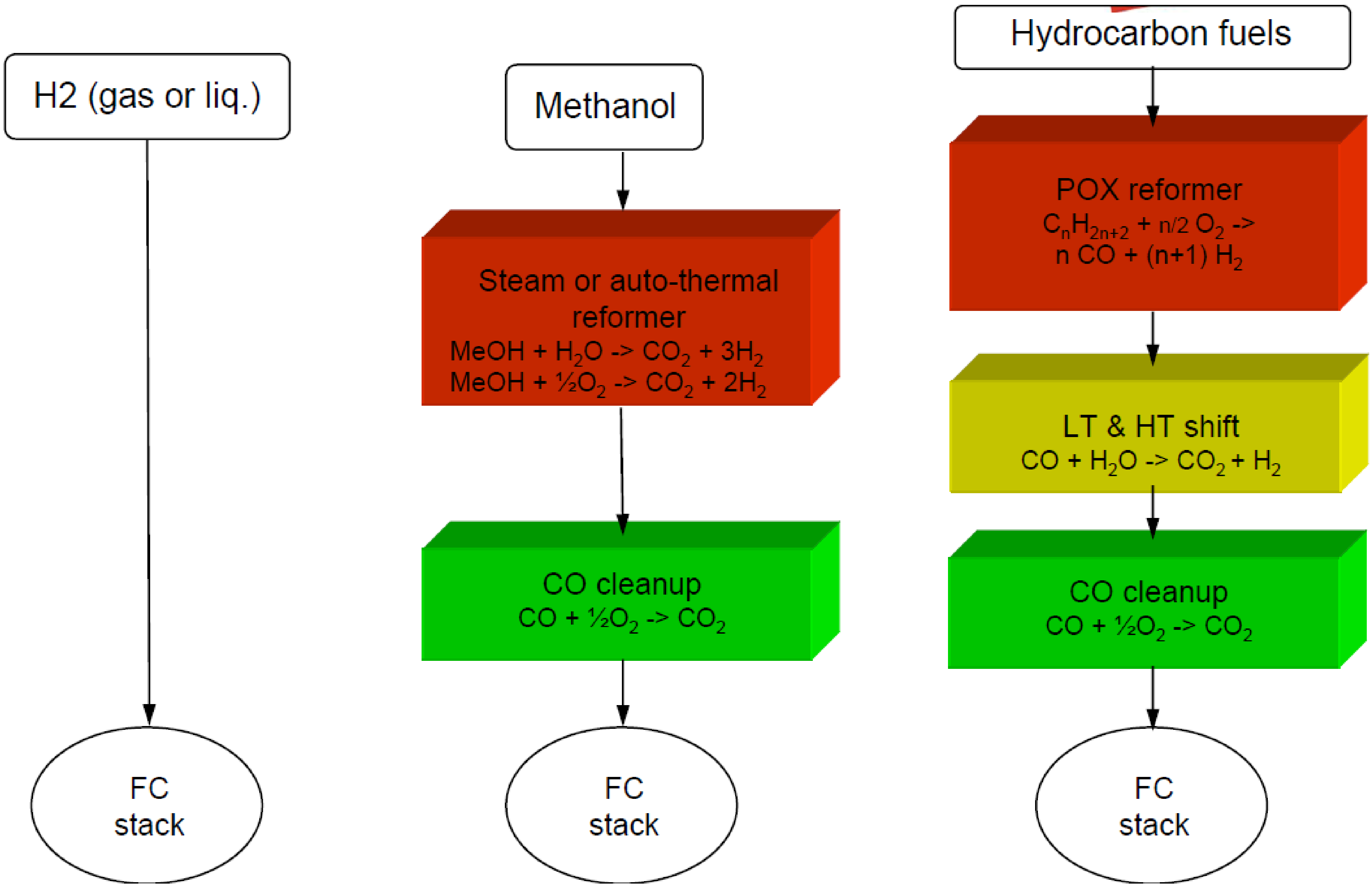
(25 in long x 22 in wide x 27 in tall)



Weak point: low efficiency running (<15%) idling (<5%)

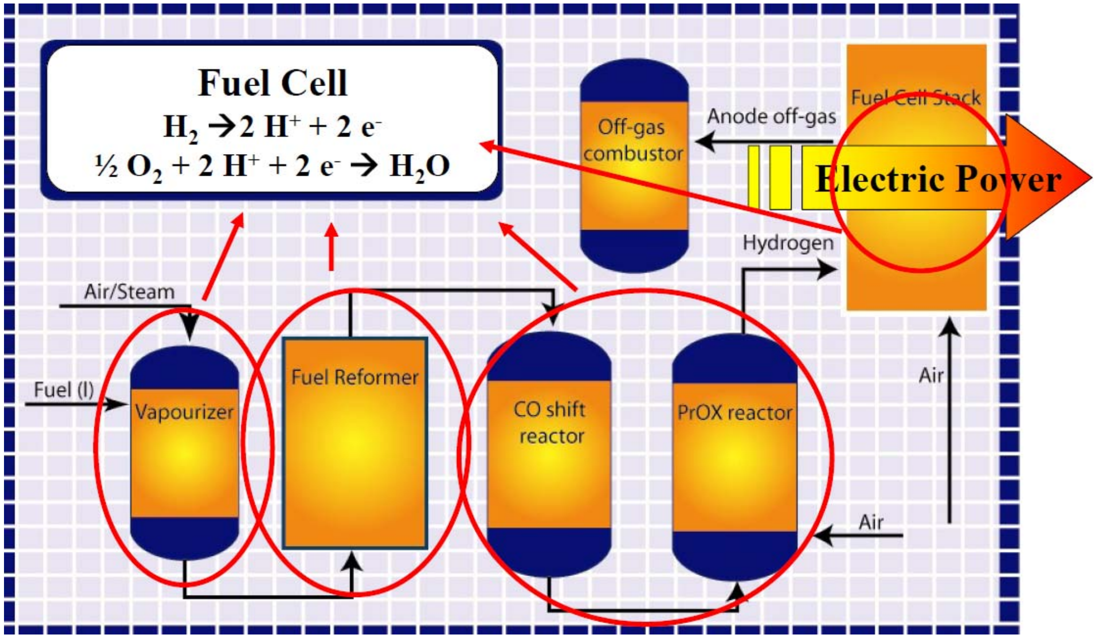
Strong point: simple, cheap and reliable

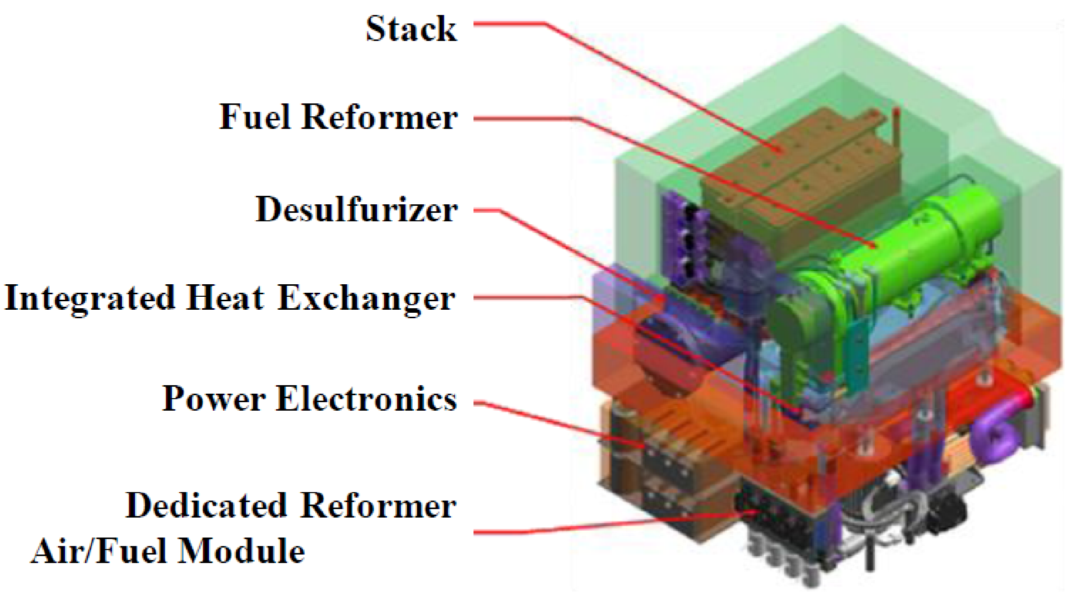
Choice of Fuel: On-board Reforming for H_2



P. Ekdunge, PEM fuel cells for automotive applications: auxiliary power, 2007

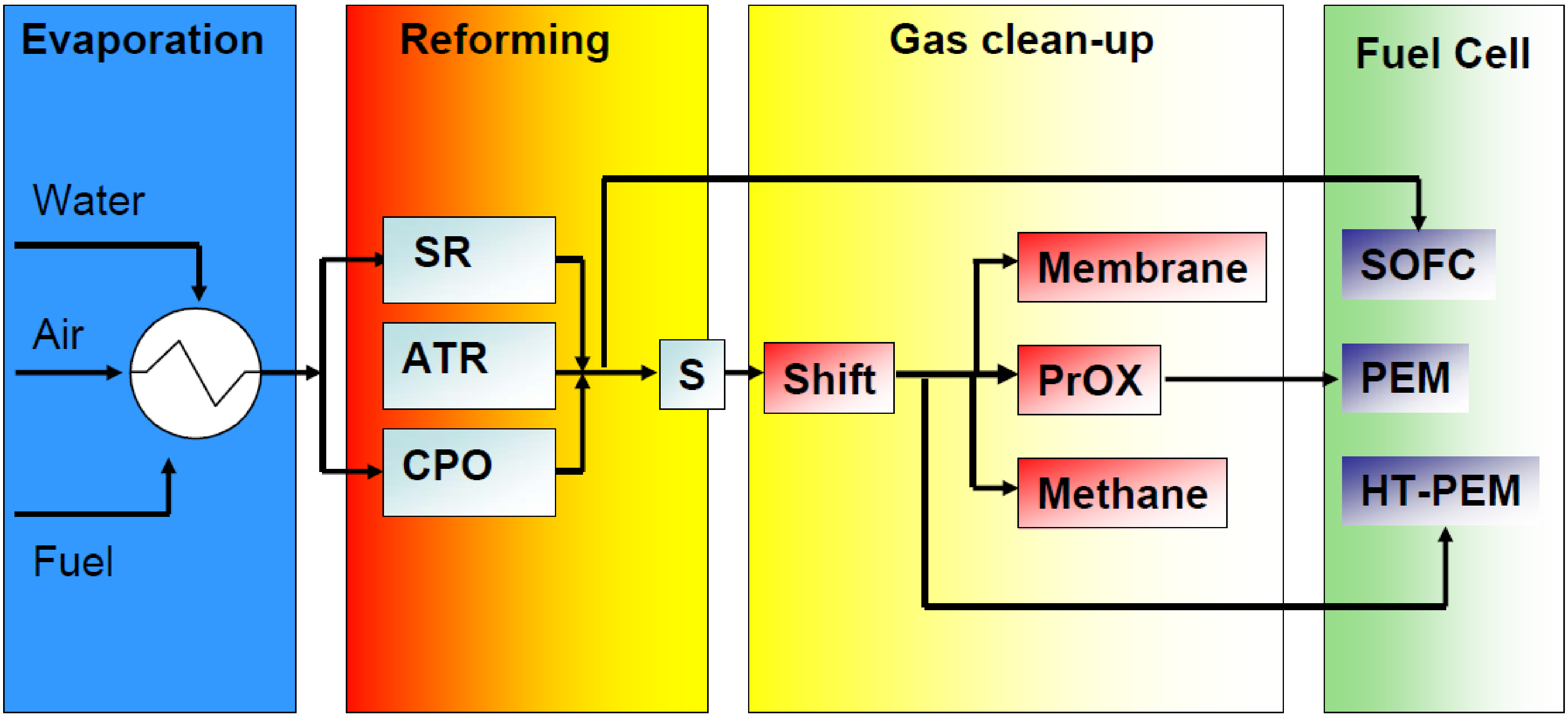
Reforming Process





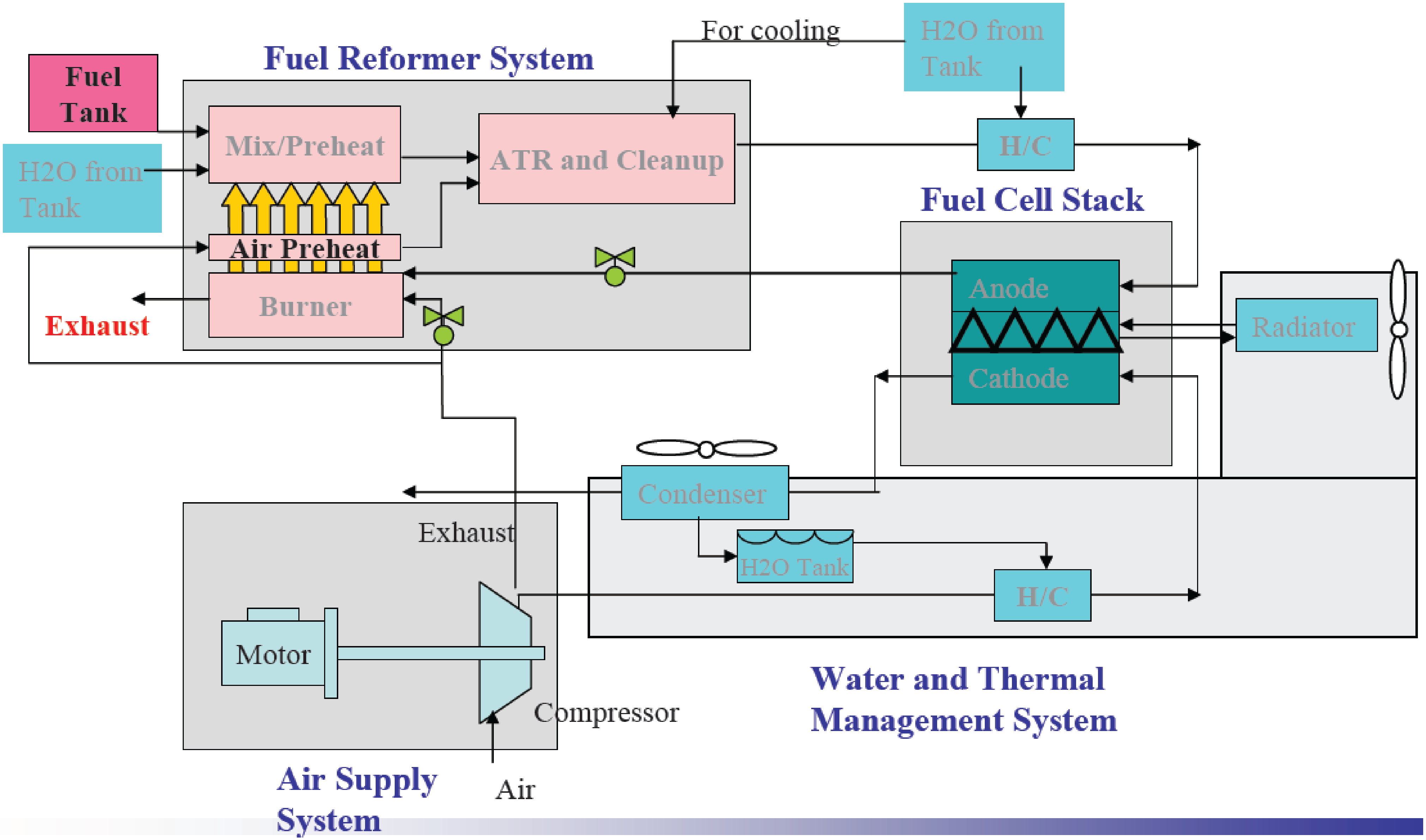
P. Ekdunge, PEM fuel cells for automotive applications: auxiliary power, 2007

Reforming Systems



P. Ekdunge, PEM fuel cells for automotive applications: auxiliary power, 2007

Reforming Process



P. Ekdunge, PEM fuel cells for automotive applications: auxiliary power, 2007

Well-to-Wheels (WTW) Energy and Emission Impacts of Vehicle/Fuel Systems

Other WTW: Wheels-to-Wheels in Regenerative Brake Efficiency

WTT – Well To Tank: Impacts associated with feedstock extraction, transport to processing, processing/refining, and distribution, expressed in per unit energy in the fuel. The term "fuel cycle" is sometimes used for WTT.

TTW – Tank To Wheels: Fuel consumption and emissions from vehicle refueling, evaporation, and operation expressed on a per mile basis. The term "vehicle cycle" is sometimes used for TTW.

WTW – Well To Wheels: WTT plus TTW impacts expressed as per mile driven with the split between the upstream (WTT) and vehicle (TTW) emissions indicated.

Well-to-Wheels Pathways

Resource

- Crude oil
- Coal
- Natural Gas
- Biomass
- Wind
- Nuclear

Fuels

- Conventional Gasoline/Diesel/Naphtha
- Synthetic Diesel
- CNG (inc. biogas)
- LPG
- MTBE/ETBE
- Hydrogen (compressed / liquid)
- Methanol
- DME
- Ethanol
- Bio-diesel (inc. FAEE)

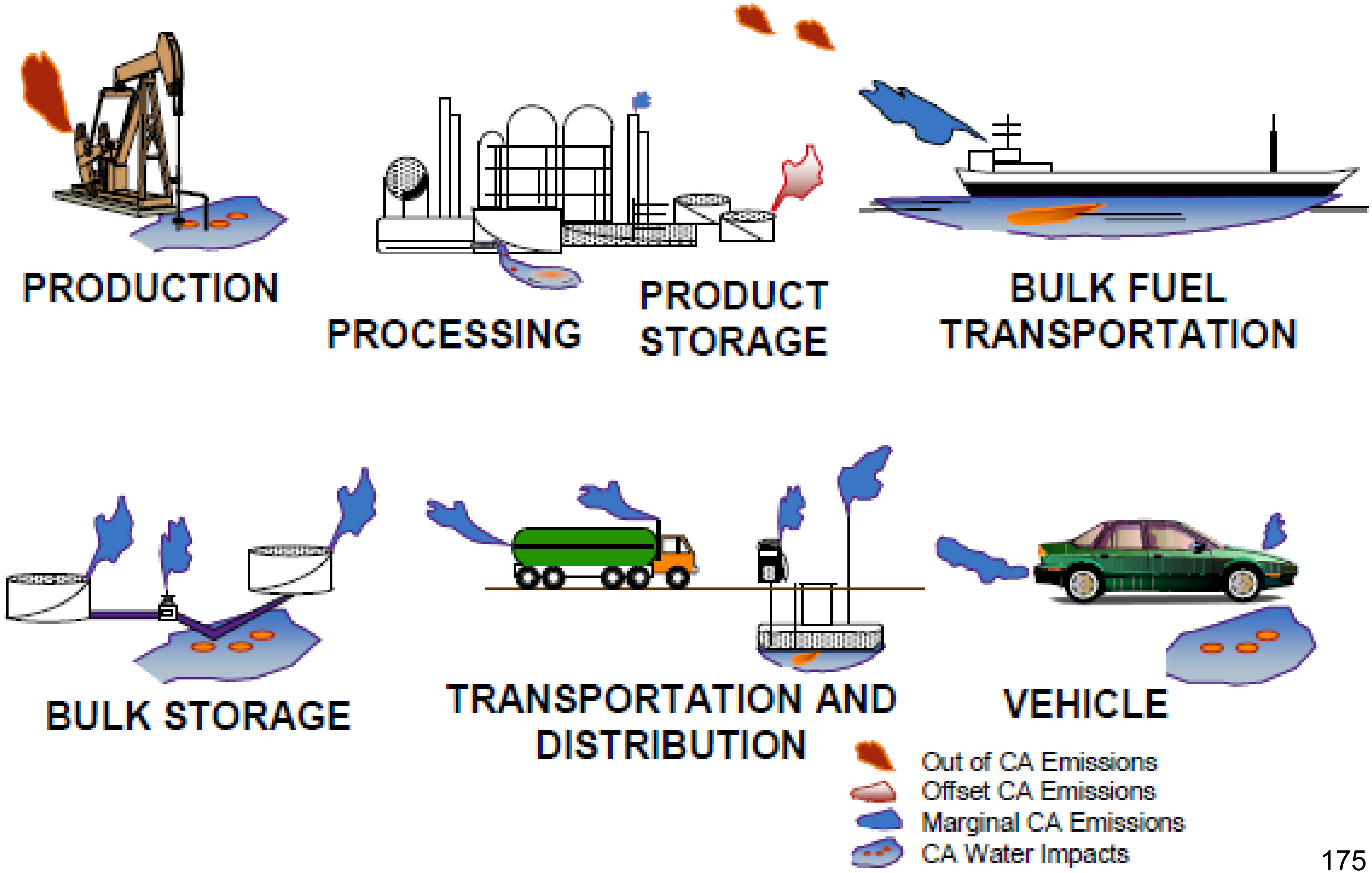
Powertrains

- Spark Ignition: *Gasoline, LPG, CNG, Ethanol, H_2*
- Compression Ignition: *Diesel, DME, Bio-diesel*
- Fuel Cell
- Hybrids: *SI*, *CI*, FC
- Hybrid Fuel Cell + Reformer

TTW: Tank To Wheels

WTT: Well To Tank

Emission Events Included in a Full Fuel Cycle Assessment



Total Vehicle Well-to-Wheels Energy Cycle

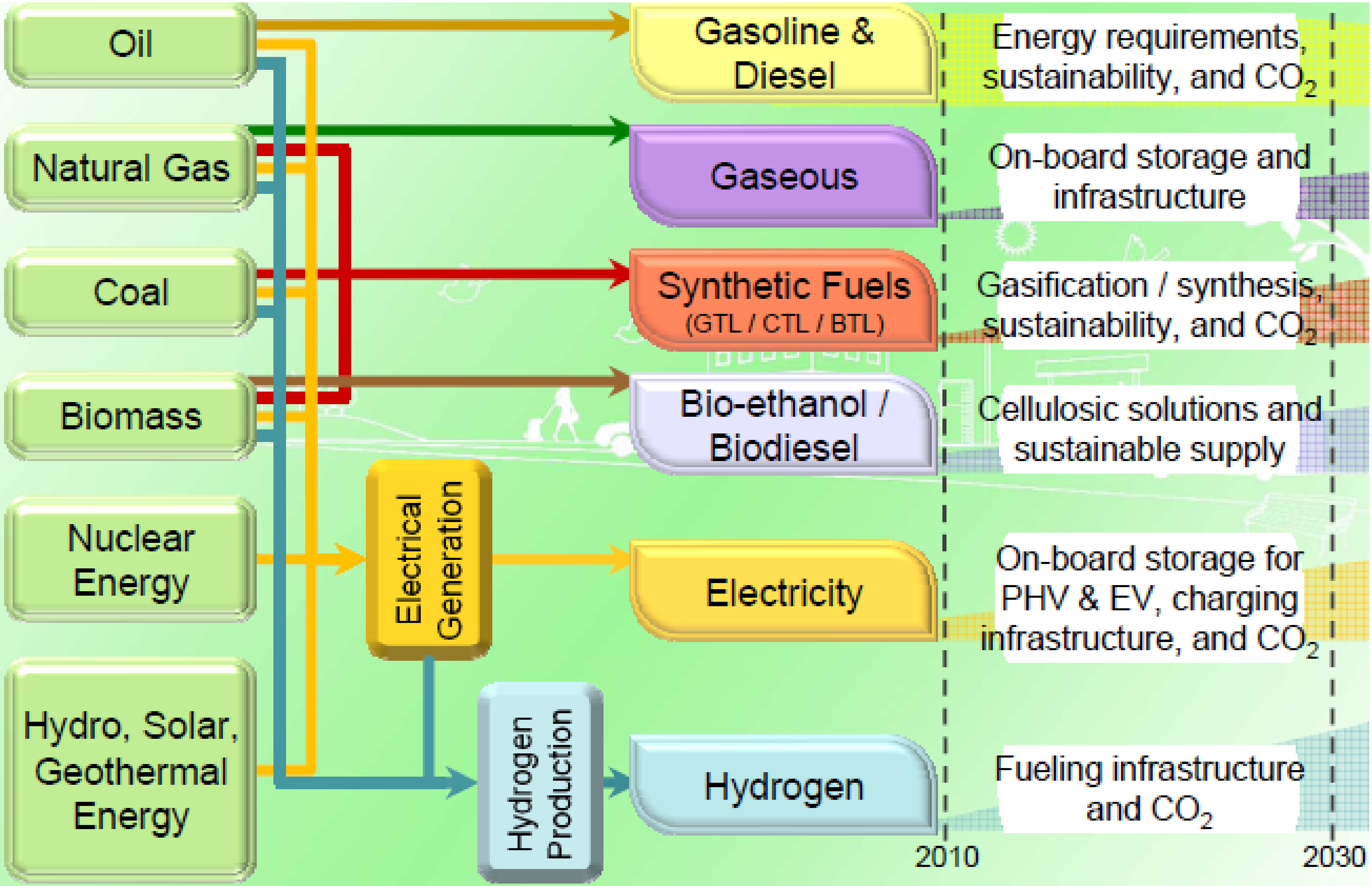
WTW Emissions gram/mi	=	WTT Finished Fuel Emissions gram/MJ	X	Vehicle Fuel Economy MJ/mile	+	Vehicle Emissions g/mile

For each finished fuel, each pollutant's WTT emission factor is multiplied by the vehicle's fuel economy and then added to the vehicle's emission factor.

*A **greenhouse gas (GHG)** is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range.*

This process is the fundamental cause of the greenhouse effect. The primary greenhouse gases in Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone.

Scenarios for Sustainability



Multiple Pathways Improve Efficiency

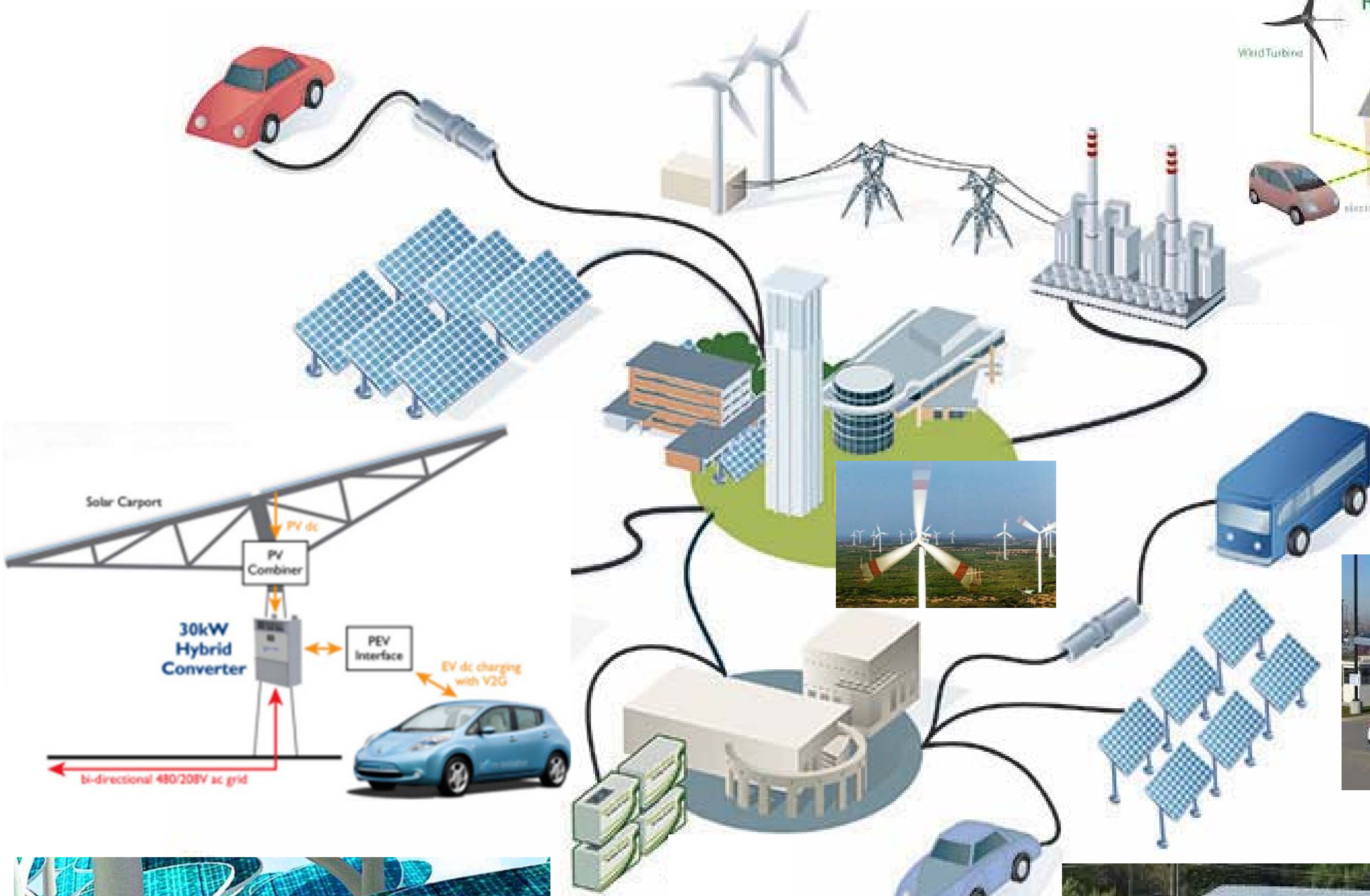
	Energy pathway	Well-to-Tank (0% – 50%)	Tank-to-Wheel (0% – 50%)	Well-to-Wheel *1 (0% – 20% – 40%)
Fuel Cell Vehicle (FCHV-adv)	Natural gas ↓ Membrane separation Hydrogen *3	67% *2	59%	40%
Electric Vehicle	Natural gas ↓ Gas-fired power gen. Electricity	39%	85%	33%
Gasoline Hybrid (Prius)	Crude oil ↓ Refine Gasoline	84%	40%	34%
Gasoline ICE	Crude oil ↓ Refine Gasoline	84%	23%	19%

(Toyota Calculation)

*1 Tank-to-Wheel efficiency: measured in the Japanese 10-15 test cycle
*2 Efficiency difference between 35MPa and 70MPa: approx. 2%
*3 Hydrogen at 70MPa



Dutch trains will start running on wind energy from next year and the country's entire rail network could be fully powered by green electricity by 2018.


Solar Carport
PV dc
PV
Combiner
30kW
Hybrid
Converter
PEV
Interface
EV dc charging
with V2G
bi-directional 480/208V ac grid


REbus™ DC Microgrid
Wind Turbine
solar panels
circuit panel
electric vehicle
conventional
AC infrastructure