Transportation electrification: An overview with special considerations for commercial and off-road vehicles

Bruno Lequesne -
Consultant, E-Motors Consulting, LLC

Marquette University
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Who I am

- 30+ years in automotive research and advanced engineering
  - GM, Delphi (1984-2009), Eaton (2010-2014)
- Worked mostly on components:
  - Electric power steering, brakes, engine-valve systems
  - Stop-start systems
  - Sensors
  - At Eaton, on hybrid trucks / off-road vehicles, and industrial drives
- Now an independent consultant
  - Since 02/2014
- Past president, IEEE- Industry Applications Society (2011-2012)

Presentation overview

- Background: Motivators for electrification
- Hybrids: Different configurations
- Large systems
- Smaller systems add up
- Motor type
- Conclusions

Commercial and off-road vehicles

Buses

Construction

Off-road

Material handling

Trucks

Long haul

Utility

Mining

Farming

Delivery

Very diverse world
Variety of needs
Different duty cycles
Each with a low volume

Image source: eaton.com

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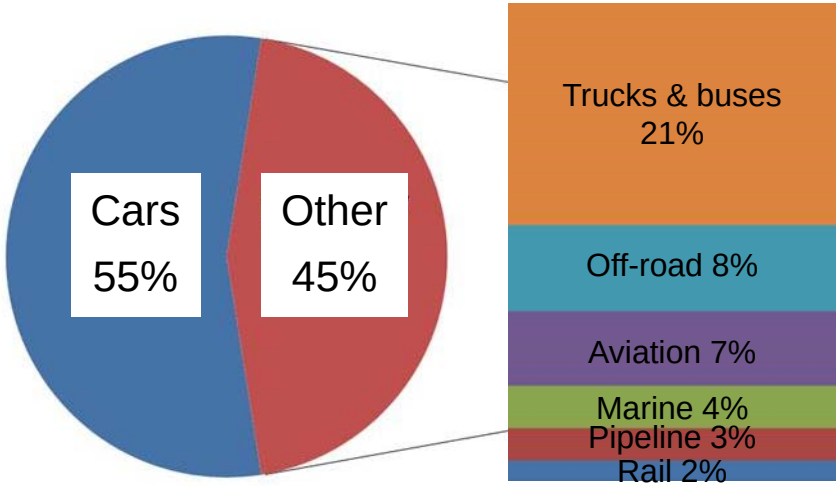
Energy impact of sector

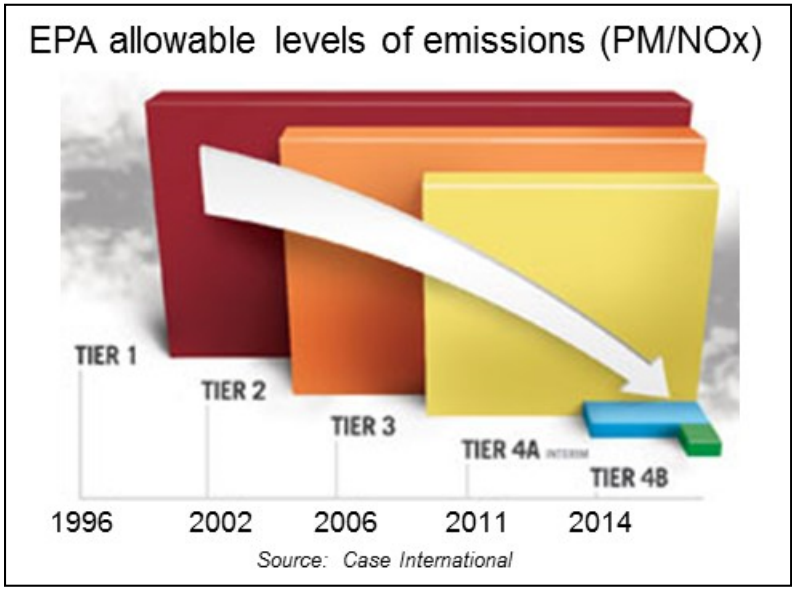
- Cars, trucks, and off-road vehicles use 30 quadrillion BTUs of energy (2011)
- Nearly 1/3 of all energy used
- Cars use only just over half of transportation energy



Source: Davis et al. 2011, cited by Argonne National Laboratories, 2013

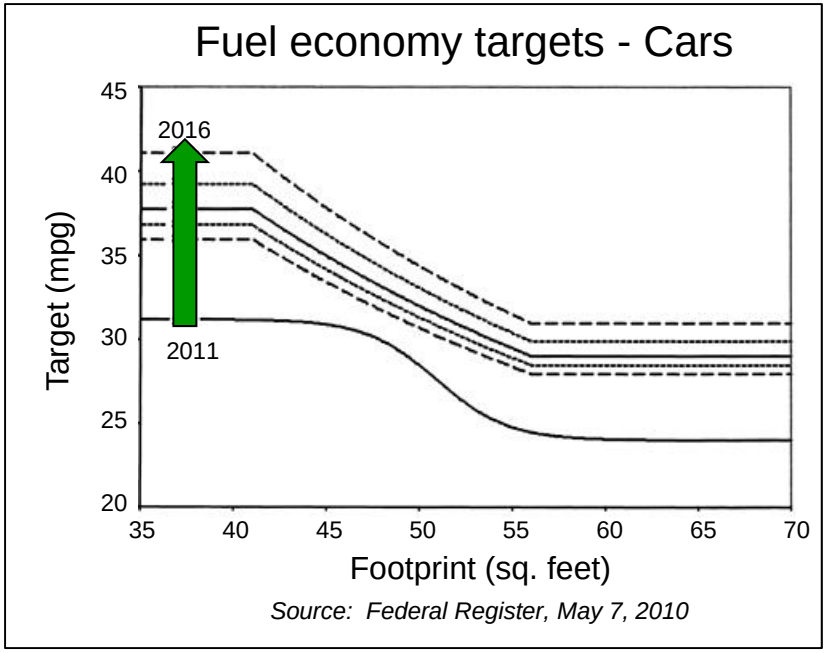
Electrification: Motivations

- Energy efficiency is only one factor
- Reduced mechanical complexity
- Emission reduction: Engine size reduction through hybridization



New CAFE Standard: Challenge for US market

- Goal: 35.5 mpg in 2016, cars / trucks combined
  - 39 mpg (cars) / 30 mpg (trucks)
  - Currently at 25.5 mpg ➔ +39% (5%/year)
- People still want their comfort, trucks, etc.
- Many technologies will need to contribute
  - Lighter weight
  - Lower friction
  - Tires
  - Aerodynamism
  - Dual clutch transmission
  - Electric cooling

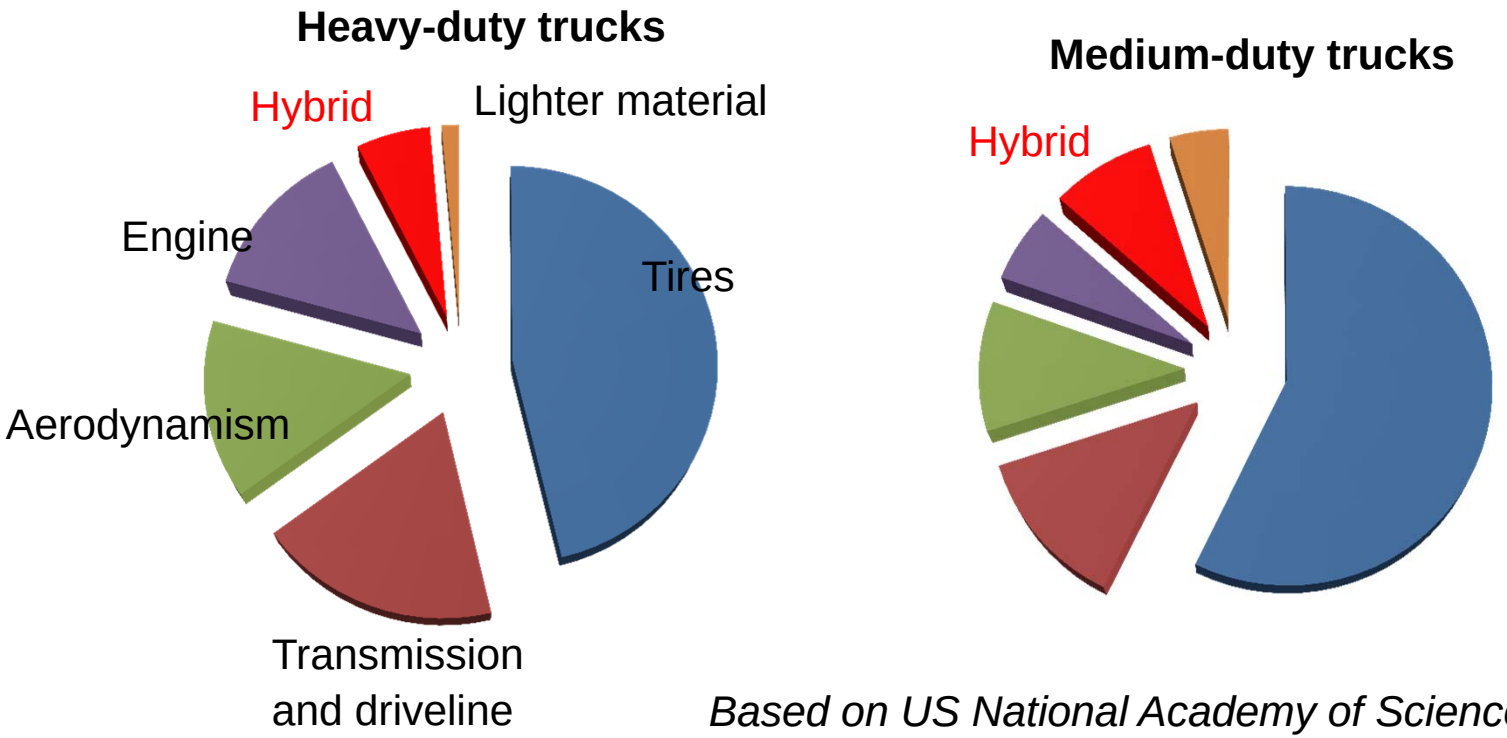


Source: Federal Register, May 7, 2010

Is electrification the best way to improve fuel economy?

- Study for commercial vehicles: No, but everything helps
  - Break even with fuel at $0.30/liter (heavy duty) and $1.10/liter (medium duty)

Measure of fuel economy gain per dollar spent



Based on US National Academy of Sciences report, 2010

Accessories can be central motivators

- Examples:
  - Refrigerated trucks now use 2 engines (1 to drive and 1 to cool)
  - Power take-off
  - Electric drives can cut on extended engine idling
  - Lower maintenance (brakes, etc)
  - Low noise

Refrigeration: > 20kW, 3-phase

Source: www.communityfoodbank.com

Power take-off:
120V/240V, 1- or 3-phase

Source: www.freightlinertrucks.com

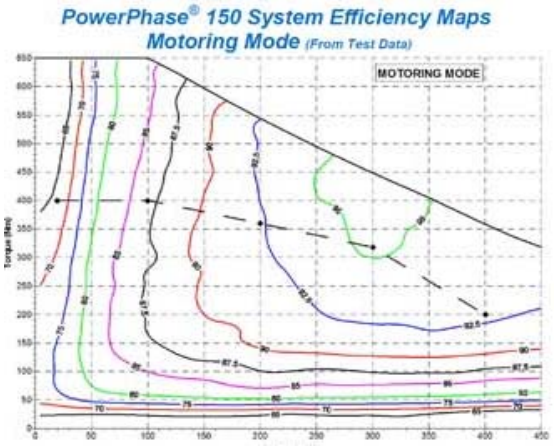
Hydraulic accessories

Source: www.elp.com

Hybrids: Performance advantage

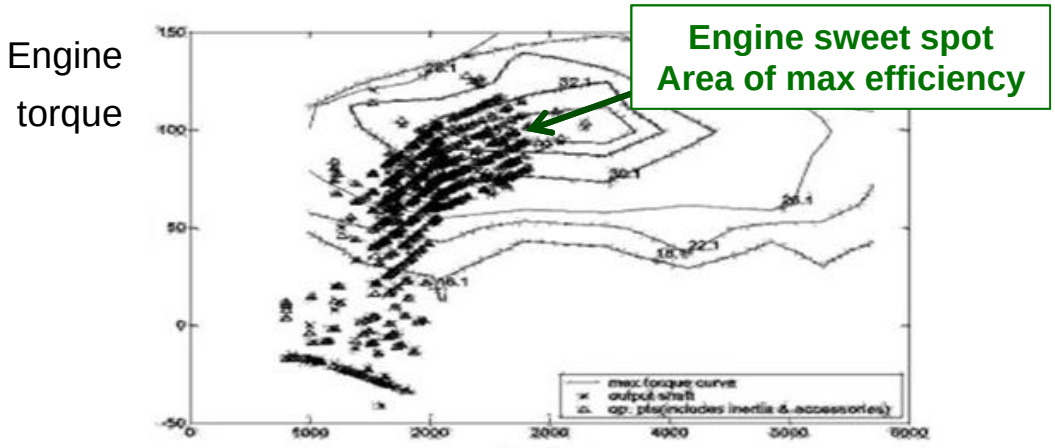
- Electric motor and engine *complement* one another
  - Electric motors have strong torque at zero speed
  - Engine cannot start on their own, and require a transmission

Electric motor



Source: UQM

Engine operating points



Source: Emadi (2006)

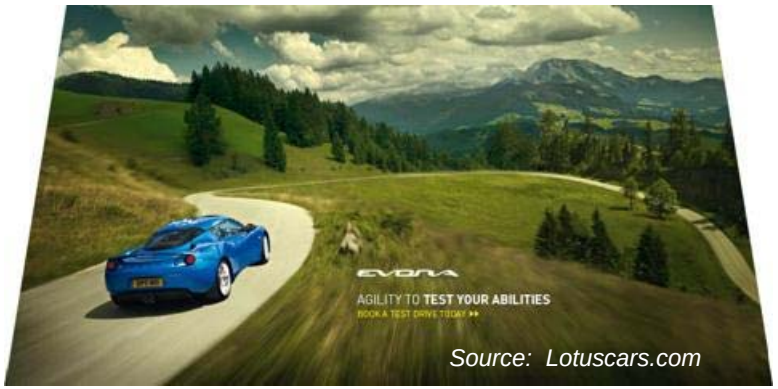
Performance of electrics/hybrid

- Performance of electric/hybrid cars is excellent – On par with traditional

Tesla:

248 hp (185 kW) motor
0–60 in 3.9 s

Lotus Elise:



163 kW supercharged engine
6-speed transmission
0-60 in 4.3 s

- Some cars (Lexus, Acura for instance) are hybridized for performance, not fuel economy

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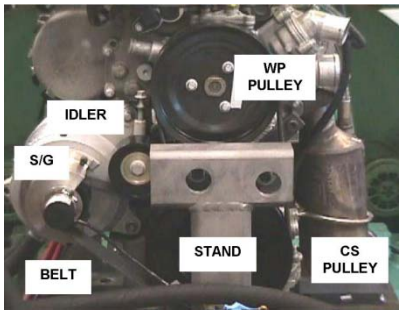
Hybrids: So many choices!

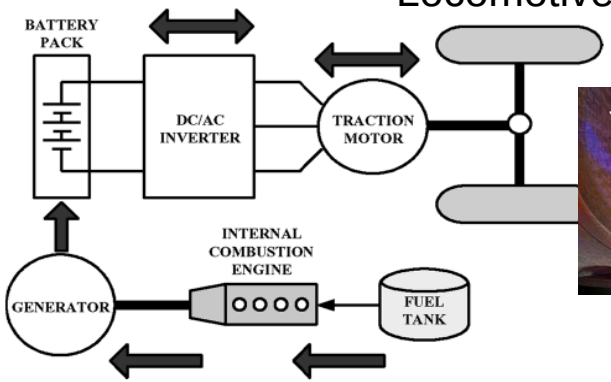
Belt driven



Source: Henry, et al (Delphi), SAE 2001

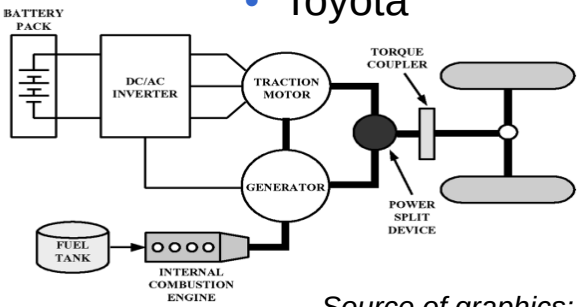
Series

- Volt
- Locomotives, tractors, etc



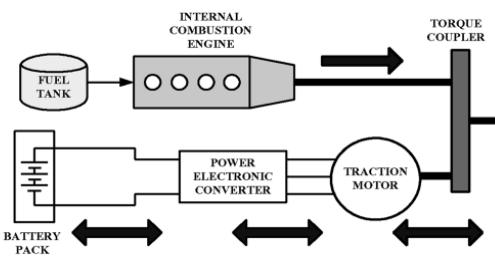
Series-parallel

- Allison
- GM/BMW/Chrysler/Daimler
- Toyota



Parallel

- Eaton
- Honda

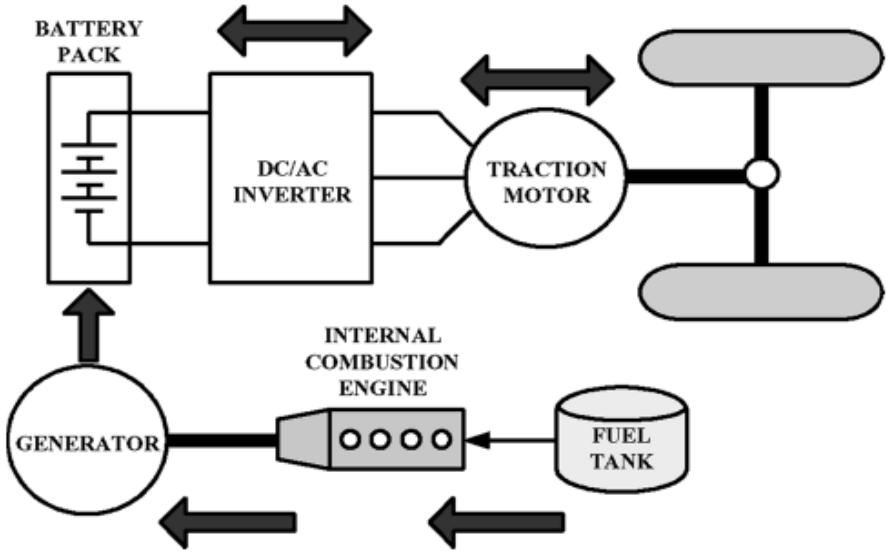


Honda Insight, 1999

Source of graphics: Emadi, et. al., IEEE, 2005

Series hybrids

- Engine drives generator
- Generator charges battery
- Electric motor drives wheels



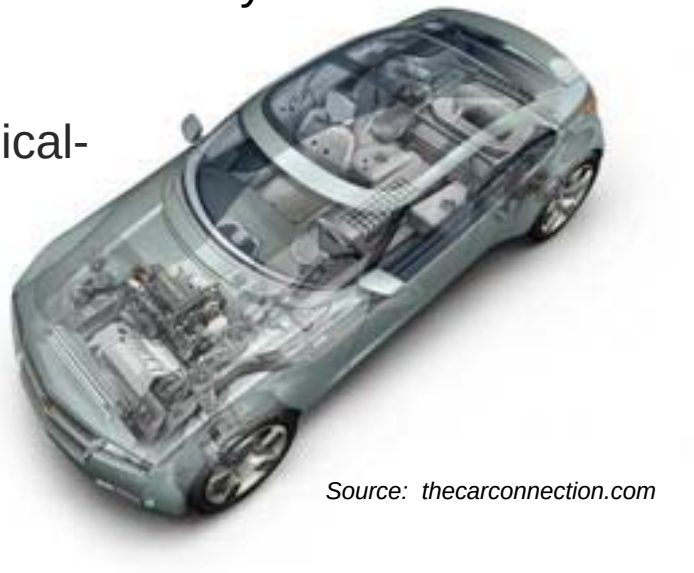
Source: Emadi, et. al., IEEE, 2005

Series hybrids: Pros and Cons

Advantage:

- Design flexibility

Chevy Volt



Source: thecarconnection.com

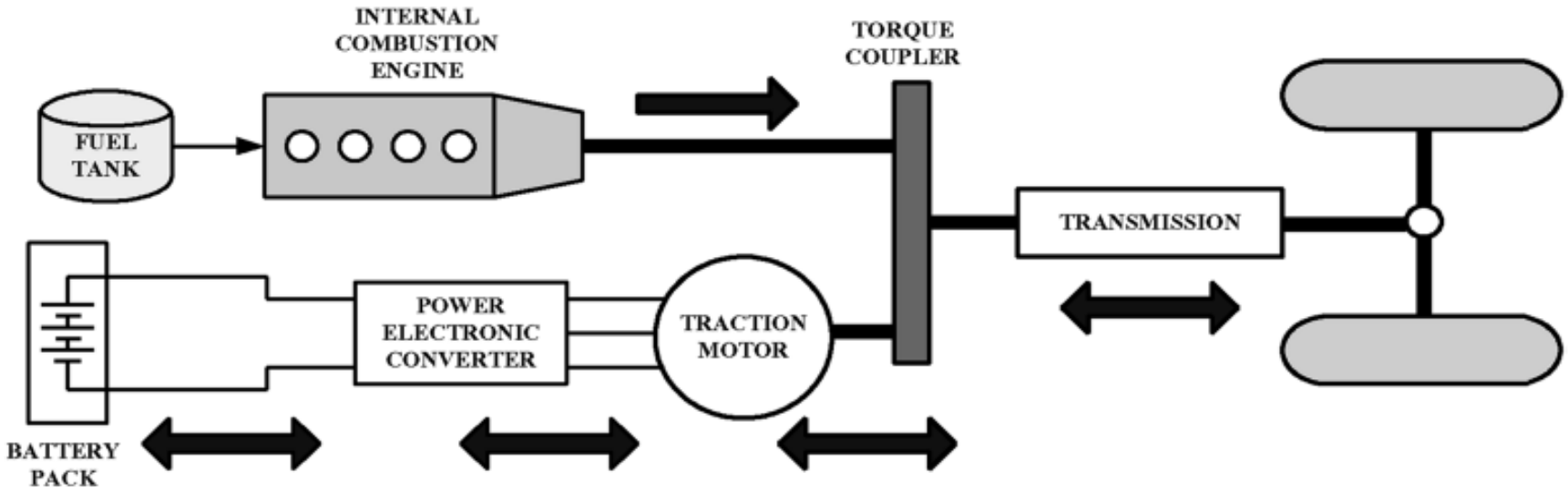
Disadvantages:

- Efficiency: Double energy conversion mechanical-electrical-mechanical
- Size (weight) and cost:
  - Two electric drives
  - Motor drive must be designed for peak power
  - Engine sized for average maximum power
  - Large, expensive drive train
- Battery must be good at deep discharge (energy) and power

Conclusion:

- Good solution if vehicle operates mostly on electric power

Parallel hybrids



Source: Emadi, et. Al., IEEE, 2005

- Engine and motor both drive wheels together

Parallel hybrids: Pros and Cons

Advantages:

- Motor drive and battery smaller, cheaper:
  - Never designed for full power
  - Battery sized for power, charge remains in narrow band
- Engine drive can use standard parts
- Controls can take full advantage of both power sources

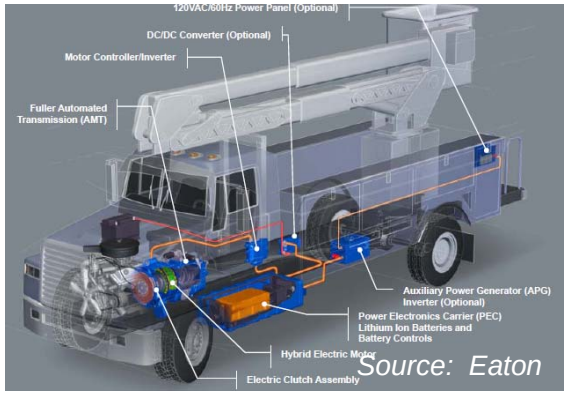
Honda Insight, 1999

Disadvantages:

- Complex control: Must blend two power sources
- Motor speed = engine speed

Conclusion:

- Best suited for mild hybrids

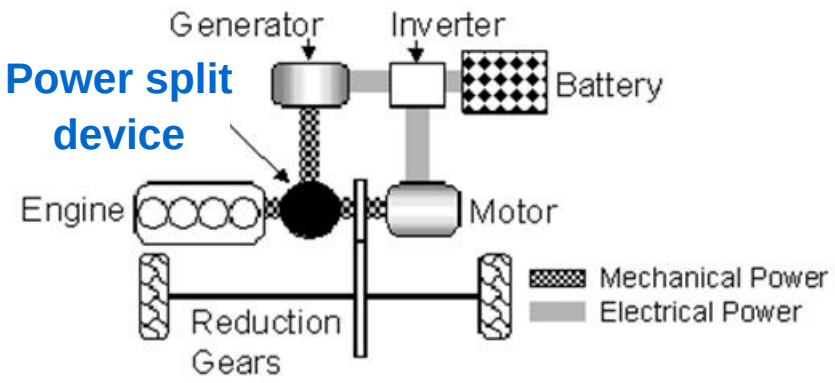


Eaton truck

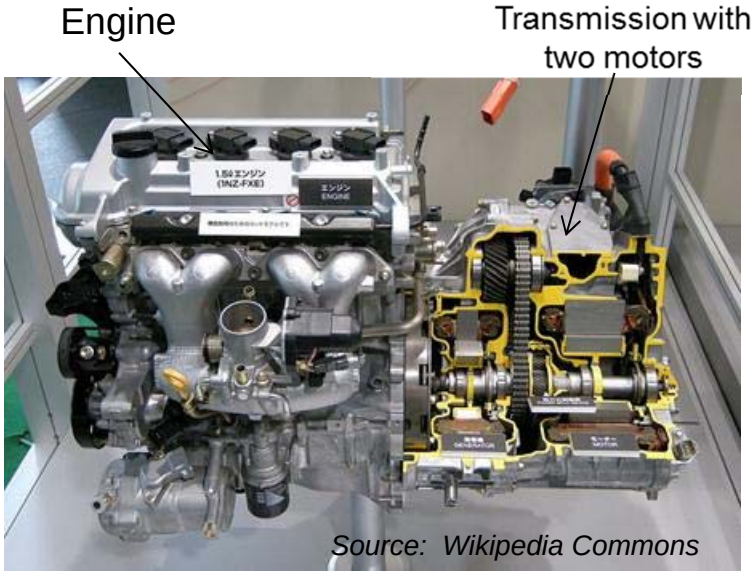
Combining series and parallel?

→ Let's combine the two!

- Complex control
  - Must blend two power sources



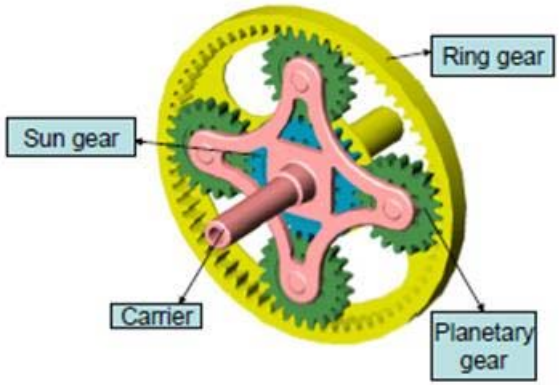
Toyota system (SAE 2008)



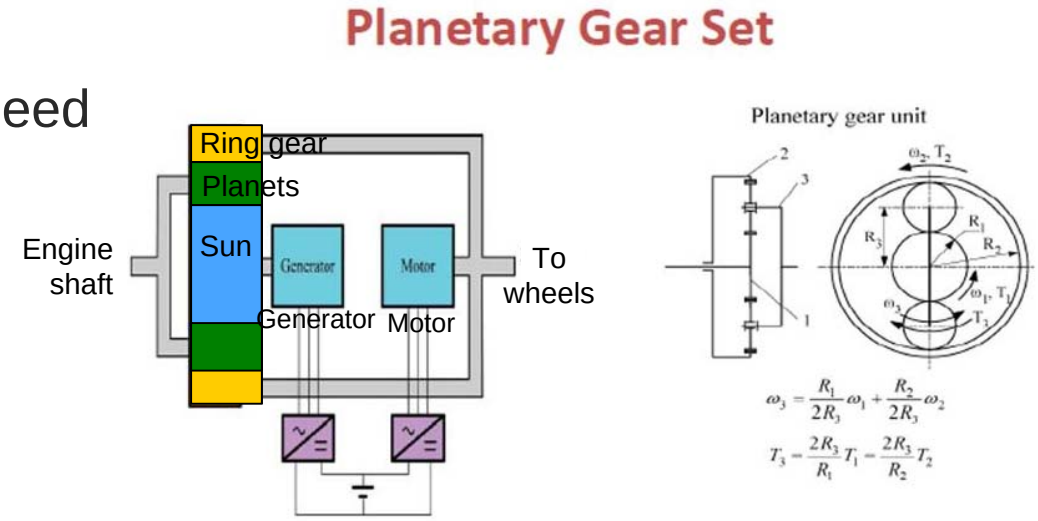
Toyota Prius

What is a “power-split device”?

- Example: Planetary gear set
- Adds or subtracts torque or speed

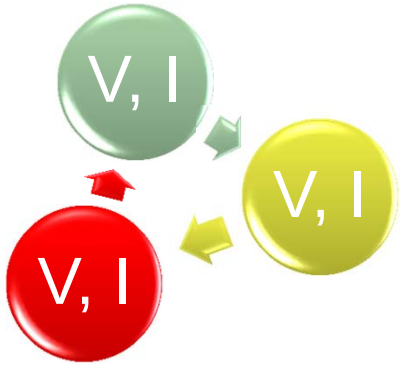


Source: IC Engine for HEV (Hybrid Benzinmotor), RWTH Aachen, Head: Prof. Dr.-Ing. Stefan Pischinger, 2007



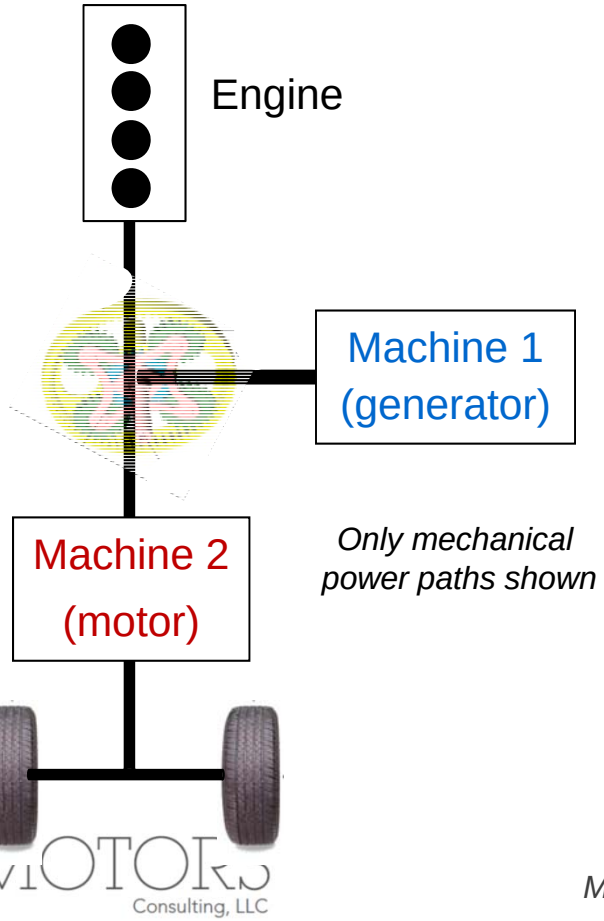
Source: Ehsani, et al, Proc. of the IEEE, 2007

- Electrical engineering equivalent:
  - Three power elements
  - 2 sources/1 sink or 1 source/ 2 sinks

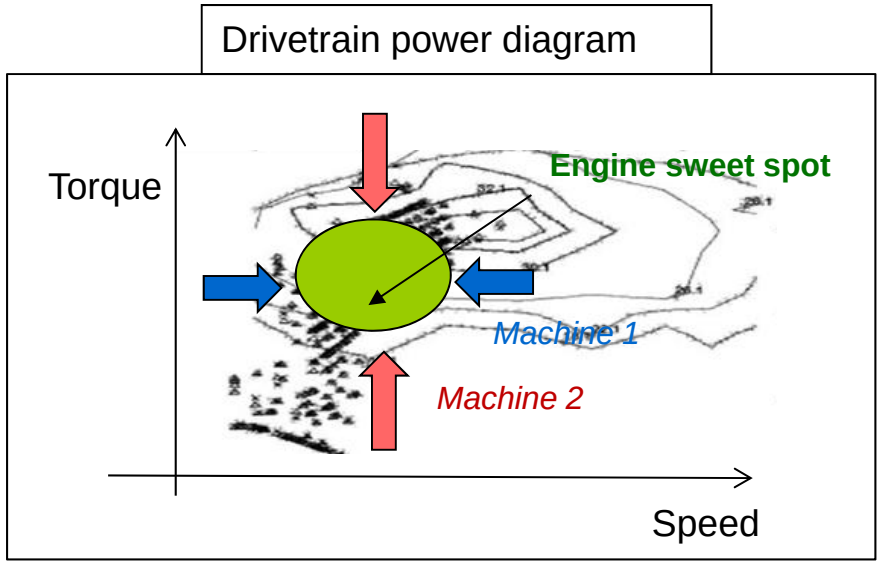


Series-parallel hybrids: Effect on transmissions

- Machine 2 (motor) can add torque to wheels
- Machine 1 (generator) allows to adjust engine speed
- → Result, an “eCVT”: Electric continuously variable transmission



Only mechanical power paths shown



Note:
Machine 1 also starts the engine
Machine 2 also performs regenerative braking

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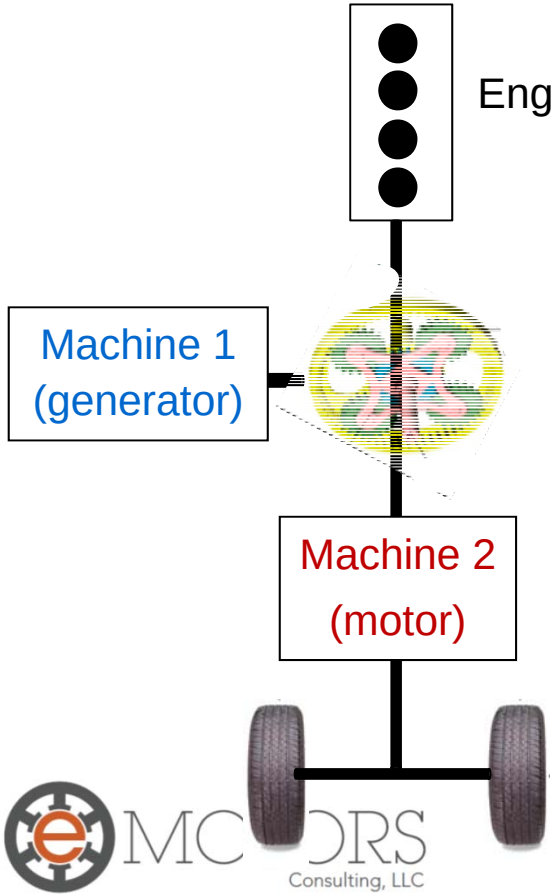
There is more than one kind of series/parallel!!

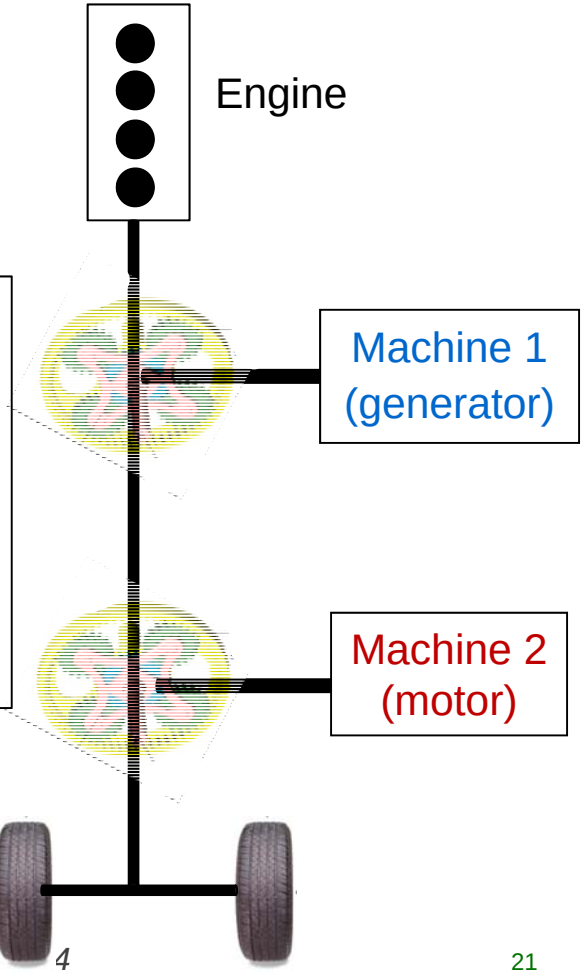
Toyota versus GM/Daimler/Chrysler/BMW

- Toyota first to implement a power-split system, but GM, et. al. introduced a more sophisticated version

- Toyota "THS": Simple series-parallel



- GM/Daimler/Chrysler/BMW: Dual-mode (or compound system)



Why?

- Changing speed/torque combinations provides flexibility
- Smaller electrical drive rating offsets additional hardware

Only mechanical power paths shown

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Series, parallel, and combined

- Series best suited to “mostly electric drive”
- Parallel good fit for mild hybrids
- Combined mode brings about great performance:
  - But requires special transmission, complex controls, etc
  - Configuration of choice for large-volume automakers

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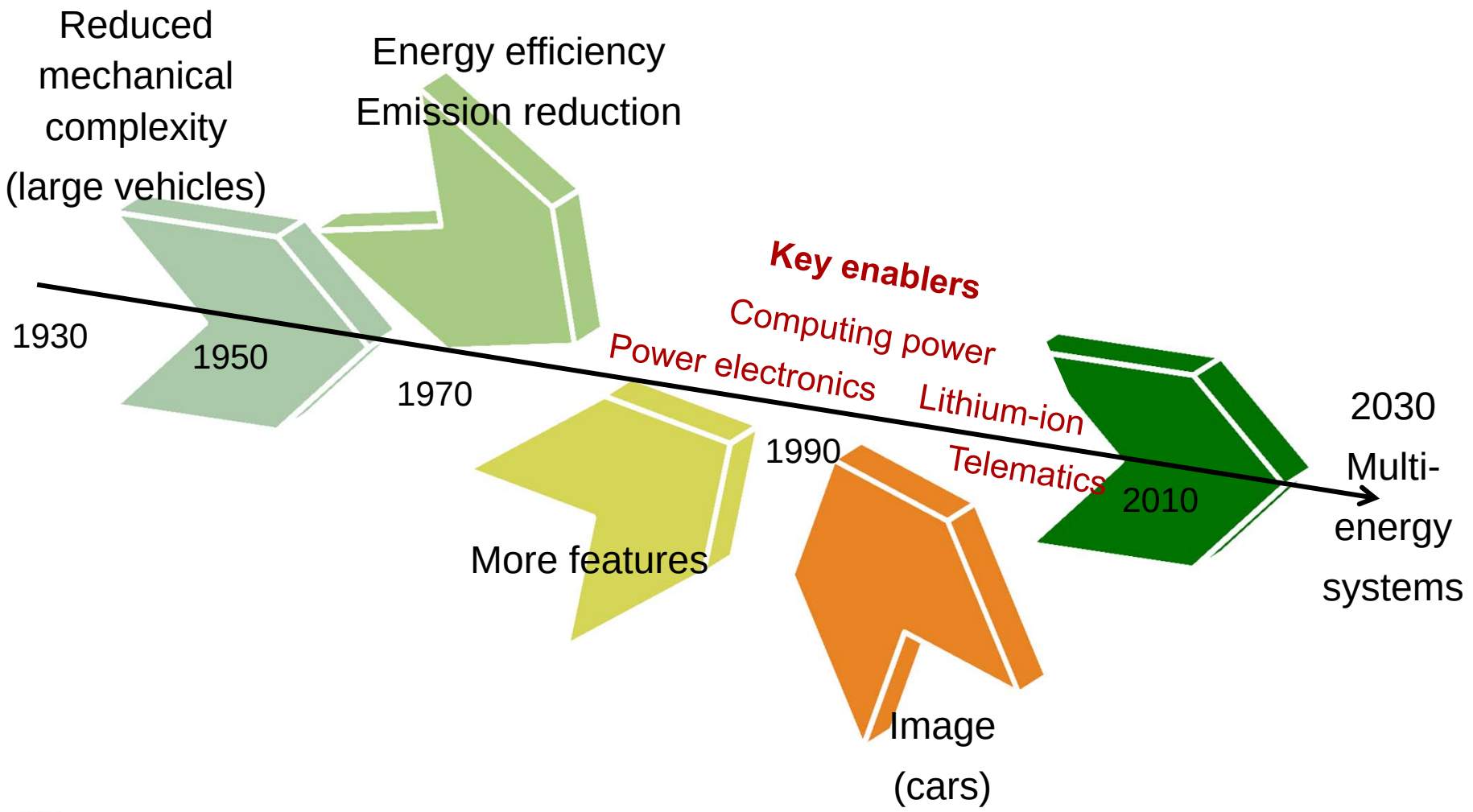
Motivators seen from historical perspective



Reduced mechanical complexity: Long history, for very large vehicles

- Best packaging flexibility
  - Locomotives: With 4 traction axles, transmission would be too complex
  - Ships: Motor can be located anywhere, including in the pod
- All electric range:
  - Mining
  - Submarines (since 1900!)
- All series

Burlington-Zephir (1934)

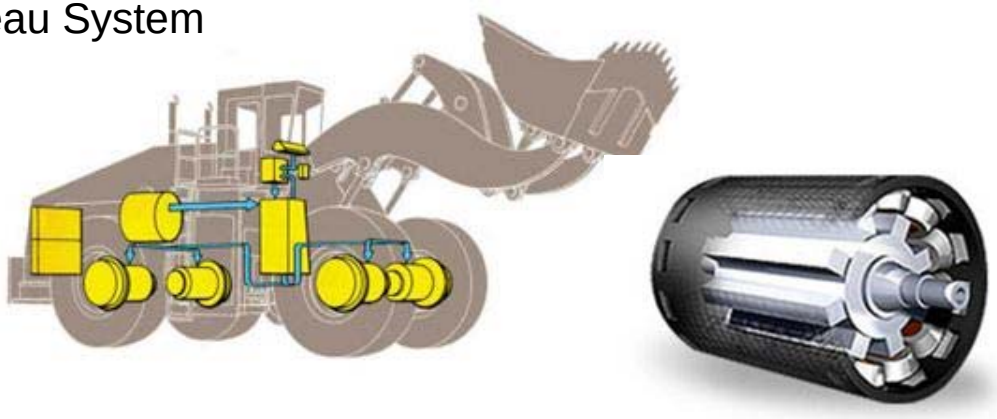
USS Plunger (1902)

Siemens azimuthal ship pods

Mining equipment

- Large mining equipment has had wheel motors since 1950's
  - DC brushtype for many years
  - Now replaced by brushless:
    - Switched reluctance: LeTourneau/Emerson (1.7 MW engine)
    - Synchronous generator and induction motors: Komatsu/GE (2.6 MW engine)
      - This will be remote controlled… from 1,000 km away (Rio Tinto 9/2013)

LeTourneau System



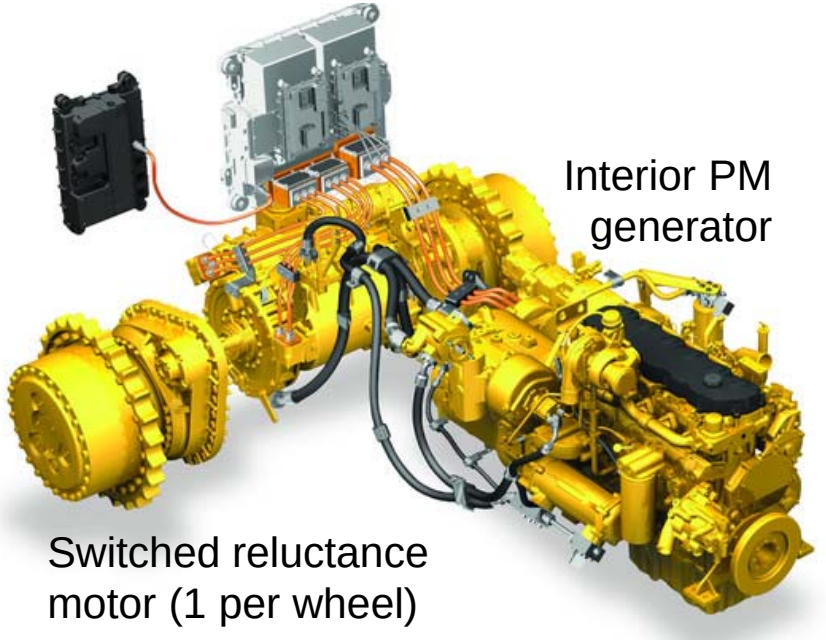
1 switched-reluctance generator

4 switched-reluctance wheel motors (300 kW)

Source: letourneau-inc.com and Emerson.com

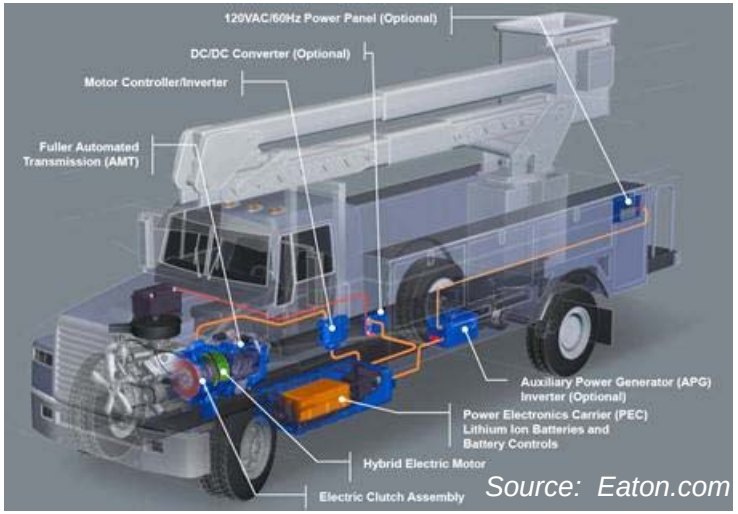
Penetration in other sectors: Construction

- Trend is for power level to be coming down
  - Mechanical simplicity meets efficiency
- Large construction equipment
  - Superior handling, improved productivity are important factors
  - Fewer moving parts, simpler transmission (better reliability)



Truck and buses

- Motivation efficiency and emissions
- Penetration based so far on government incentives and purchases
  - Private business are risk adverse as trucks are a production tool
  - Purchases by government entities (utilities, cities) critical to further development of technology



Eaton utility truck

Yutong city bus

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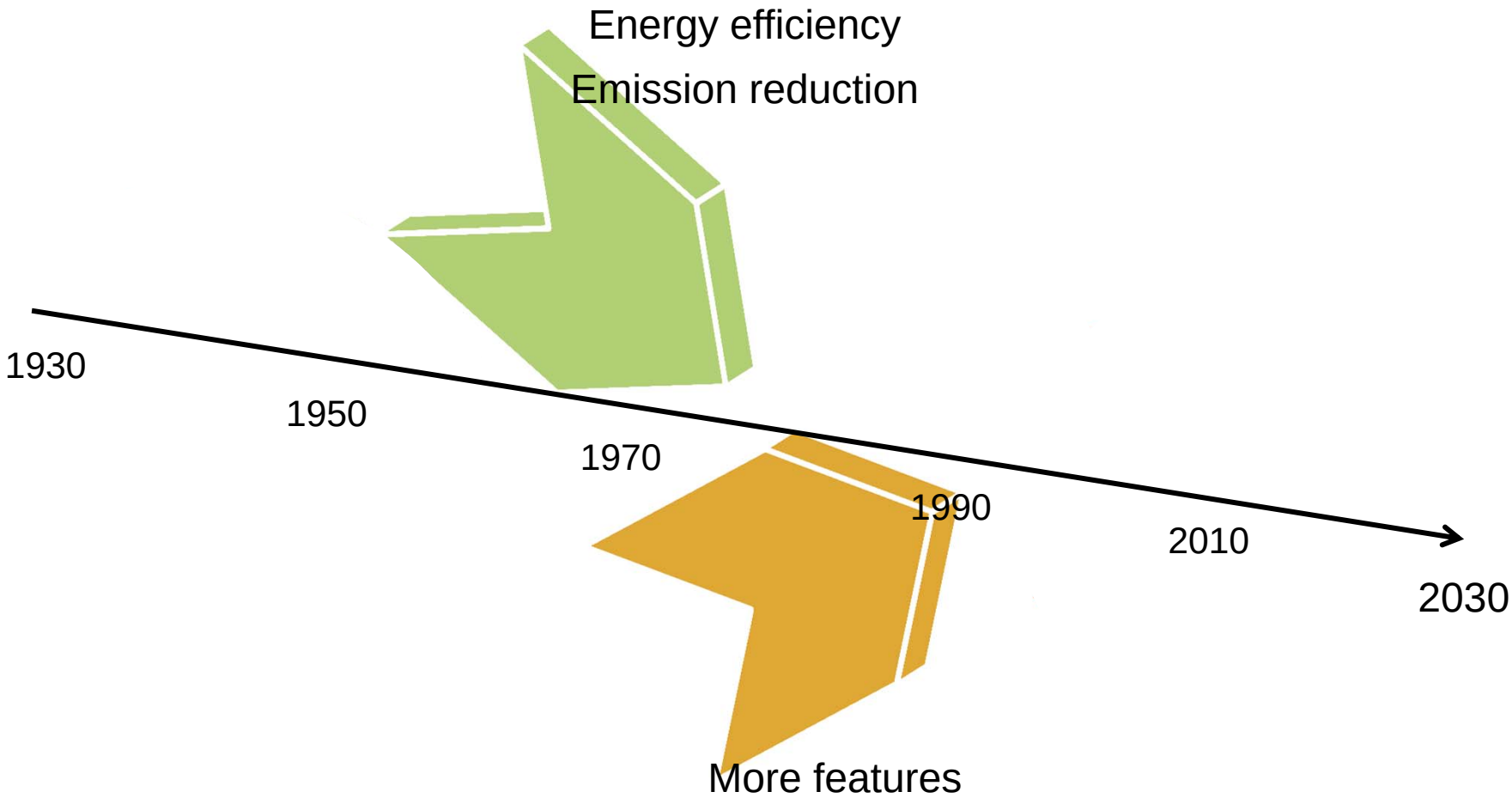
Accessories: Motivation



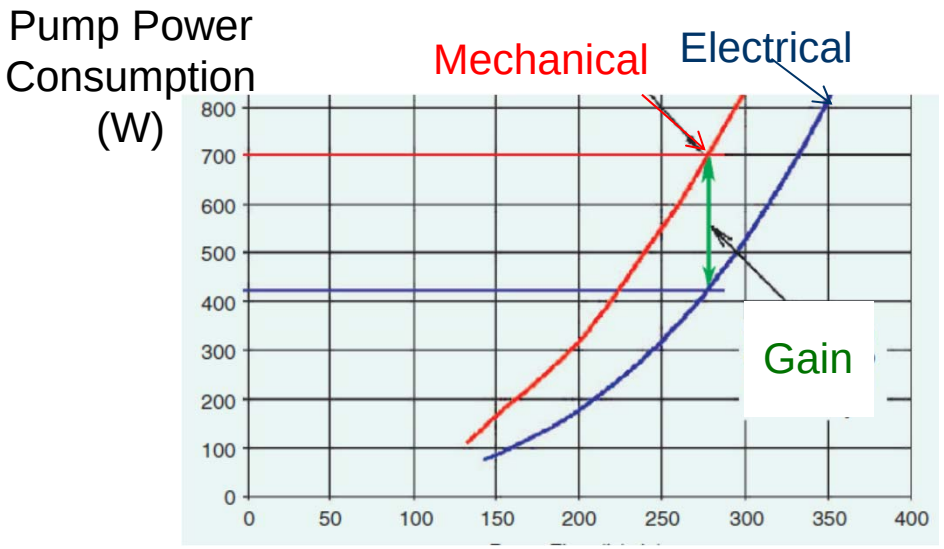
Electric accessories are everywhere

Engine accessory electrification

- Many accessories are engine (belt) driven:
  - Fans, water cooling pump, air conditioning, power steering
  - Accessory is therefore always on, and output is a function of engine speed

- Electrification brings:
  - Run on demand
  - Output controllable
  - 2% to 5% fuel economy expected (*)

- Example: Engine cooling pump
  - Flow should be a function of temperature, not engine speed



Source: Algrain, et. al., IAS Magazine, 2005

(*) US National Academy of Sciences, 2010

Cab electrification: Hotel loads

- Additional 6 to 8 conventional batteries (12V lead acid) may be needed

Source: fleetequipmentmag.com, 2010

- Solutions:

Shore power: air, power, TV, internet

Source: idleair.com

Auxiliary power unit: Fuel cell

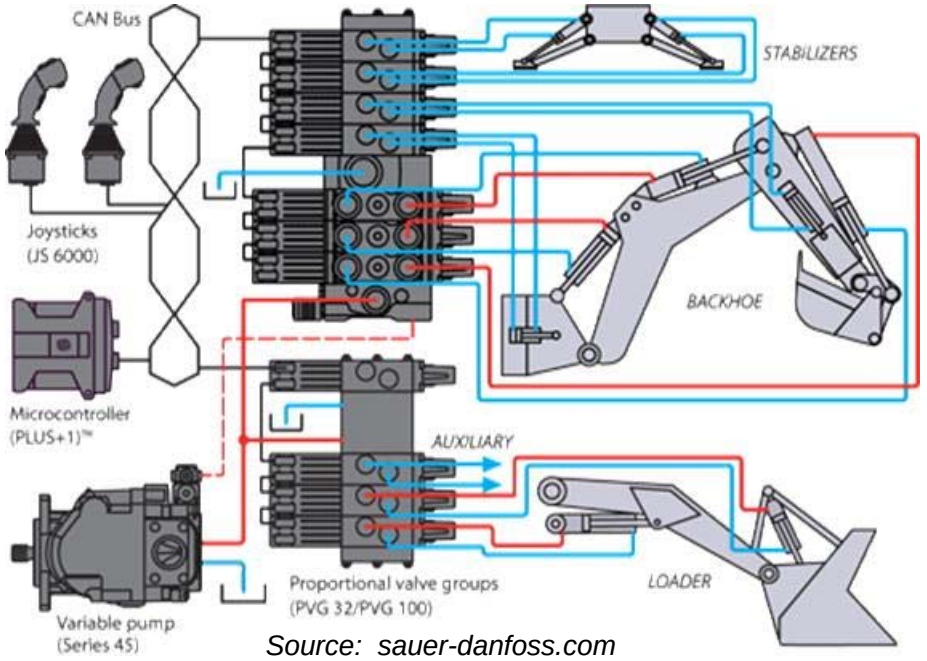
Source: delphi.com

Load electrification: Off-road vehicles

- Off-road vehicles include many high-power functions
- Hydraulically actuated now, for power density
- Motion can be repetitive (up-down, etc), good for electrification

Source: howstuffworks.com

Hydraulic schematic, backhoe/loader

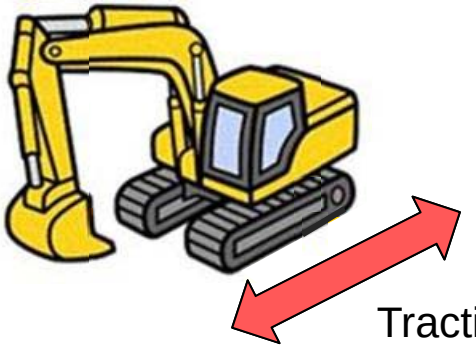


Source: sauer-danfoss.com

Question: What to electrify?

Example: Backhoe

Upper body?



Traction?

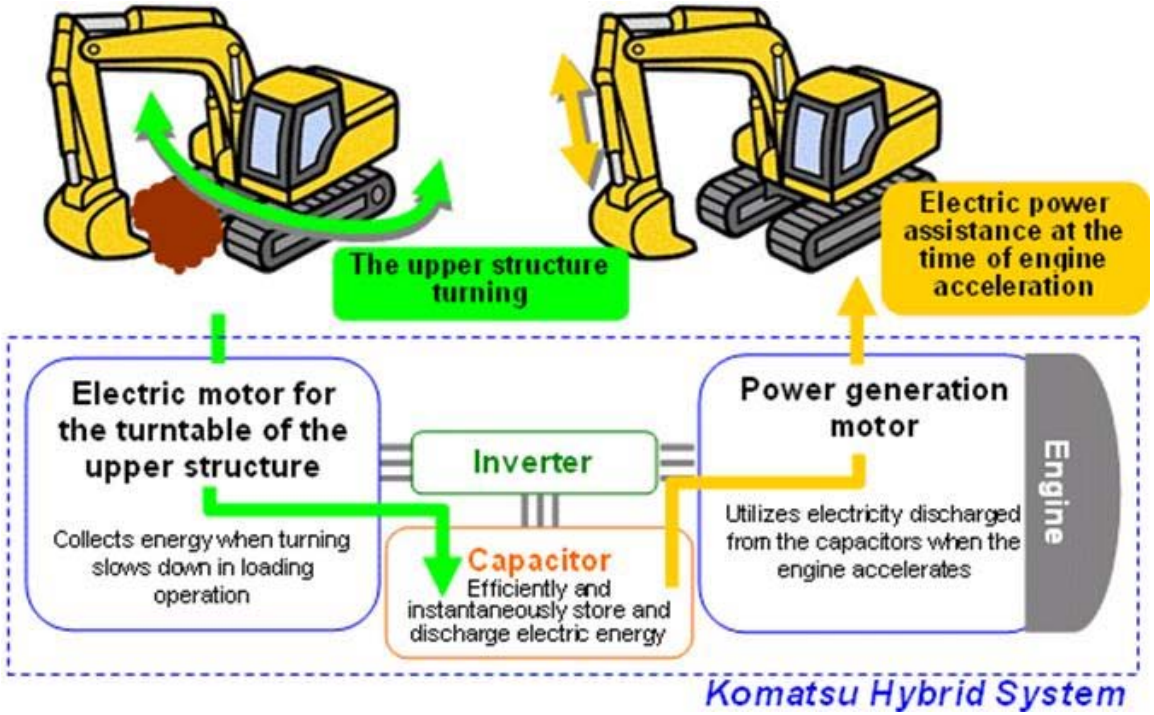
Arm and bucket?

Importance of cycle analysis to determine best gain/cost

Answer: Komatsu hybrid backhoe

- Komatsu backhoe:
  - Small parallel hybrid with super capacitors
  - Electrically-driven upper structure
  - Mild power assistance

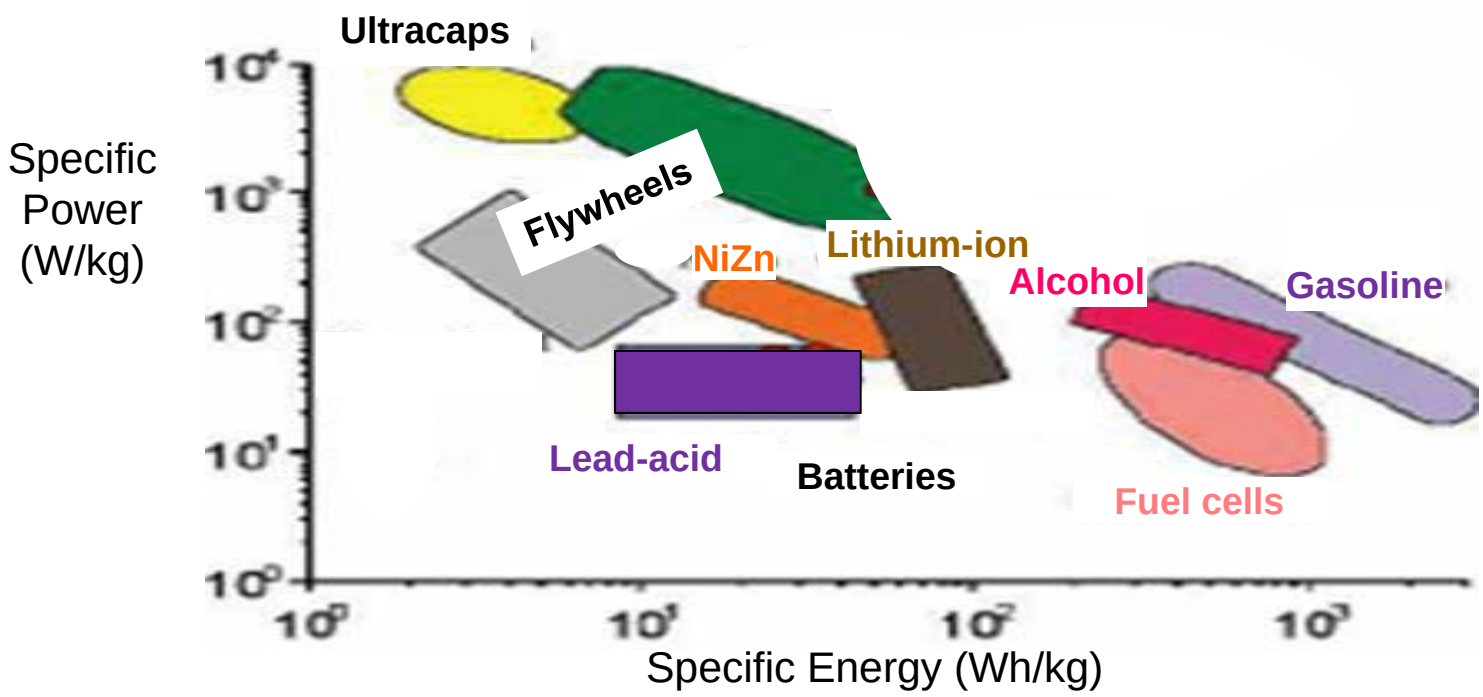
Main reason is upper structure electrification, because of back and forth motion



Energy storage

- Both energy density and power density are important

Power vs. energy Ragone plot



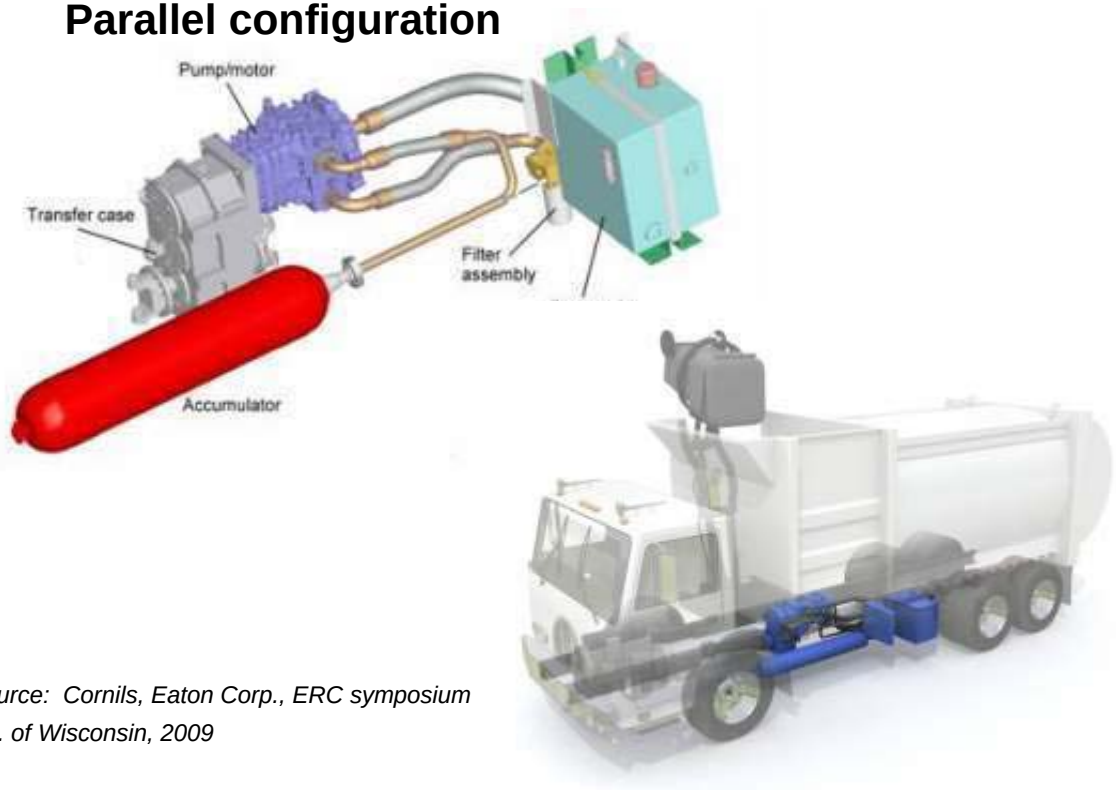
Source: SAE Vehicle Electrification, Aug. 2013

Based on study by Ricardo

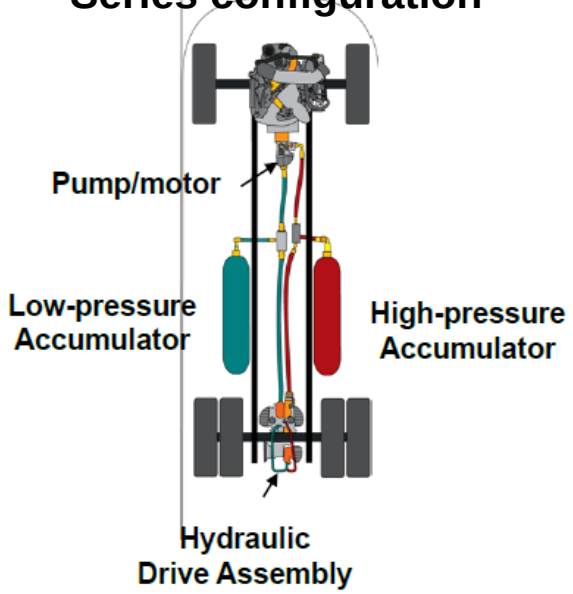
Alternatives to electrification: Hydraulic hybrids

- Hydraulic hybrids excellent in terms of power
  - Solution for frequent stop/starts

Parallel configuration



Series configuration



Source: Cornils, Eaton Corp., ERC symposium Un. of Wisconsin, 2009

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- Challenges and conclusions

Motor type: So many choices!

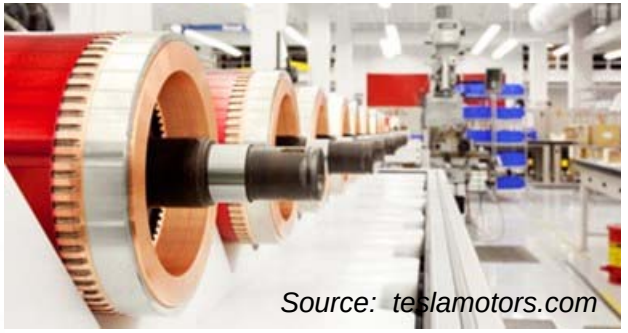
Permanent magnet brushless

Toyota Prius

Source: wiki commons

Honda Insight

Induction



Tesla Motors

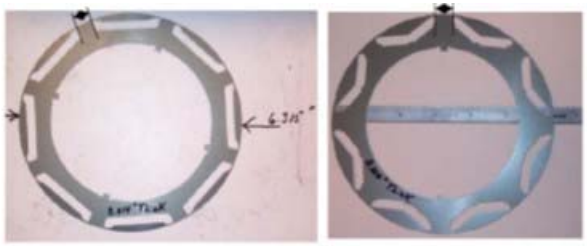
Switched reluctance

Emerson / Letourneau

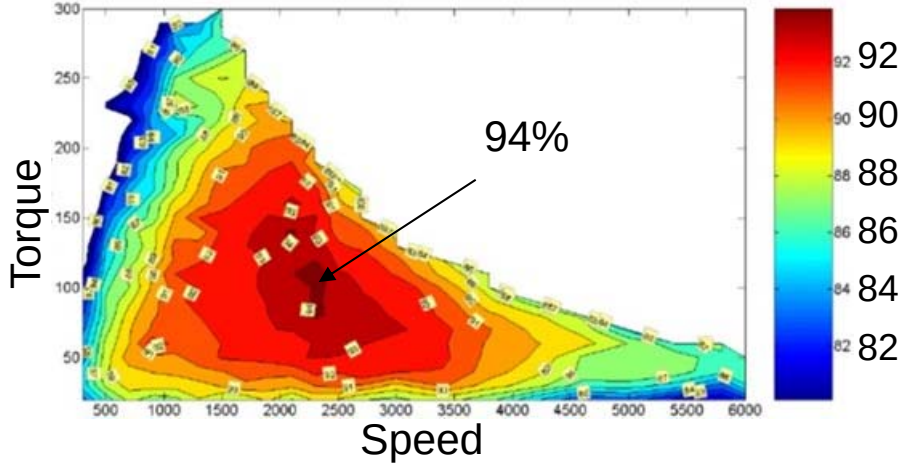
eMOTORS Consulting, LLC

PM motor: Toyota

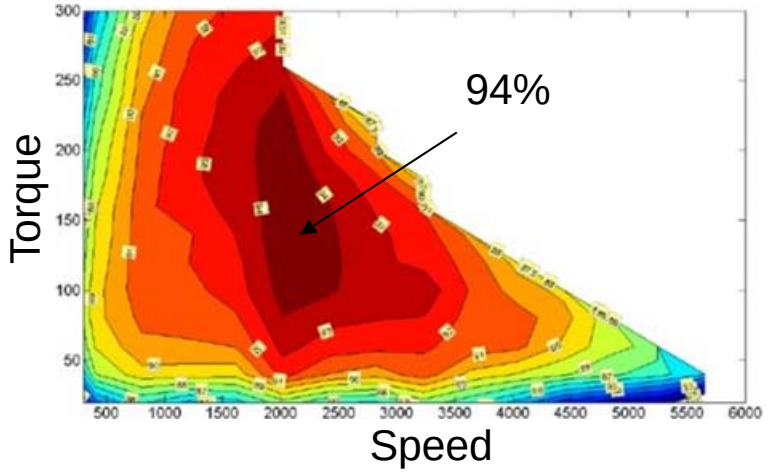
Data from ORNL reports



Prius 2004 efficiency map

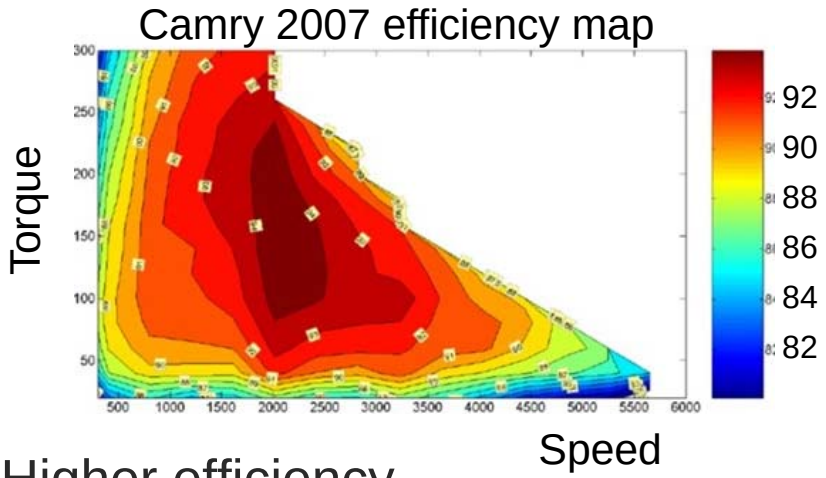


Camry 2007 efficiency map



- Steady effort to increase efficiency and reduce size
  - V-shape magnets, 2004: Reluctance torque added
  - In 2007, note effort to increase efficiency at low speeds

Comparison



- PM strength: Higher efficiency
  - Critical in hybrid design where sticker mpg is point of pride
- PM weaknesses:
  - Price: Induction can overcome PM in EVs (Tesla) where a bit of efficiency loss can be compensated by a bit more battery
  - Speed range: If you need to weaken the field, why have it in the first place?
    - Belt driven starter generators are induction
- SR strengths: Large speed range, ruggedness:
  - Chosen for construction equipment

Presentation overview

- Background: Motivators for electrification
- Hybrids: Different configurations
- Large systems
- Smaller systems add up
- Motor type
- Challenges and conclusions

Challenges (1)

- Cost/benefit ratio (payback time):
  - Selection of applications with good payback time critical
  - Cutting cost
    - Automotive: Large engineering effort to draw cost down
    - Commercial/off-road: Create volume from disparate applications
- Reliability and durability:
  - Electronics have proven themselves even in harsh environments
  - However, this is a special expertise
  - Customers need to be convinced

Challenges (2)

- Cooling:
  - Too many cooling loops: Engine, cab, power electronics, battery
  - Key to higher power density
- EMI:
  - Issue at component and system level
- Safety:
  - Higher voltage, dual voltage, broad public exposure
  - Complexity both asset (lots of sensors and computing power) and impediment
- Energy/ power storage:
  - Lithium-ion has enabled many recent developments, but still limited

Conclusions

- Electrification is much more than “green”
  - High performance, emissions, new features
- Significant progress to date enabled by advances in:
  - Power electronics, motors, computing power
  - More importantly, batteries
- Remaining challenges are, in that order:
  - Cost, cost, and cost

Work in progress!