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

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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
- Trucks
- Long haul
- Material handling
- Utility
- Mining
- Farming

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

Image source: eaton.com
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

EPA allowable levels of emissions (PM/NOx)

Source: Case International
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
  - Aerodynamics
  - 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**

**Heavy-duty trucks**
- Hybrid
- Lighter material
- Tires
- Transmission and driveline
- Aerodynamics
- Engine

**Medium-duty trucks**
- Hybrid

*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

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

Hydraulic accessories
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
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**
- **Series**
  - Volt
  - Locomotives, tractors, etc

**Series-parallel**
- Allison
- GM/BMW/Chrysler/Daimler
- Toyota

**Parallel**
- Eaton
- Honda

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

*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

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

Source: thecarconnection.com

Chevy Volt
Parallel hybrids

- Engine and motor both drive wheels together

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

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

Conclusion:
- Best suited for mild hybrids

Source: Eaton
Honda Insight, 1999
Eaton truck
Combining series and parallel?

→ Let’s combine the two!

- Complex control
  - Must blend two power sources

Toyota system (SAE 2008)

Source: Wikipedia Commons

Toyota Prius
What is a “power-split device”?

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

**Planetary Gear Set**


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

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

**Drivetrain power diagram**

- Engine
- Machine 1 (generator)
- Machine 2 (motor)

*Only mechanical power paths shown*

**Note:**
- Machine 1 also starts the engine
- Machine 2 also performs regenerative braking
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*
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 (large vehicles)
- Energy efficiency
- Emission reduction
- More features
- Image (cars)

Key enablers:
- Computing power
- Power electronics
- Lithium-ion
- Telematics

Timeline:
- 1930
- 1950
- 1970
- 1990
- 2010
- 2030

Multi-energy systems

Marquette University Colloquium, 03/25/2014
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

Sources:
- 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)

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)

Source: deere.com

John Deere 944 wheel loader (2011)
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
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Accessories: Motivation

Energy efficiency
Emission reduction

More features

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

(*) US National Academy of Sciences, 2010

Source: Algrain, et. al., IAS Magazine, 2005
Cab electrification: Hotel loads

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

- Solutions:
  - Shore power: air, power, TV, internet
  - Auxiliary power unit: Fuel cell

Source: fleetequipmentmag.com, 2010
Source: idleair.com
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

Hydraulic schematic, backhoe/loader

Source: sauer-danfoss.com

Source: howstuffworks.com
Question: What to electrify?

Example: Backhoe

Upper body?
Arm and bucket?
Traction?

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

Specific Energy (Wh/kg)

Specific Power (W/kg)

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
  - Honda Insight

- **Induction**
  - Tesla Motors

- **Switched reluctance**
  - Emerson / Letourneau

Source: [wiki commons](https://commons.wikimedia.org), [teslamotors.com](https://www.teslamotors.com)
PM motor: Toyota

Data from ORNL reports

- 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
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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!