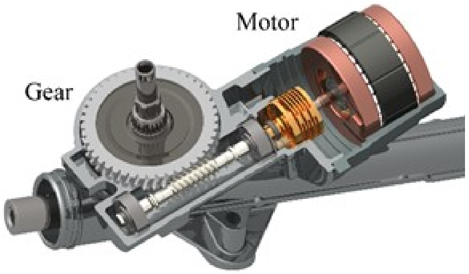
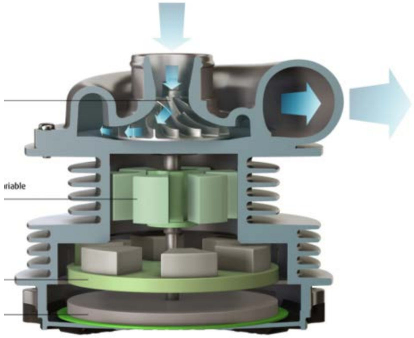
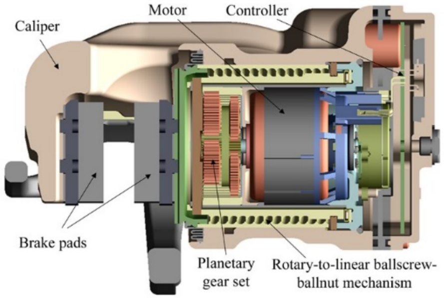
Fuel injector
Source: Bosch



Electric power steering
Source: Nexteer



Electric supercharger
Source: Valeo



Electric brake
Source: Delphi (IEEE IAS Mag, 2009)

Automotive Electrification:

The Non-Hybrid Story

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“Brief message from our sponsors”

IEEE Standard 11-2006(R) for Rotating Electric Machinery for Rail and Road Vehicles

- *Revision needed to include PM motors etc.*
- *Working Group just starting its work*
- *More volunteers welcome*
- *Working Group chair, Tim Burress (ORNL)*

- *More standard activity expected*
  - *Important avenue for IEEE-SAE collaboration*
  - *ITEC is the ideal meeting point*

IEEE STANDARDS ASSOCIATION ◆IEEE

IEEE Standard 11-2006(R) for Rotating Electric Machinery for Rail and Road Vehicles

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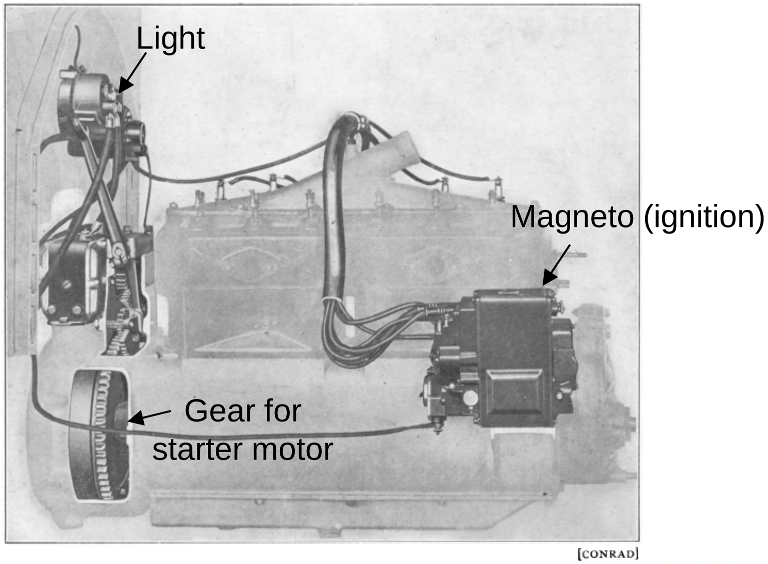
Introduction

- Hybrids and EVs get a lot of press – Well deserved, these are tremendous technical achievements

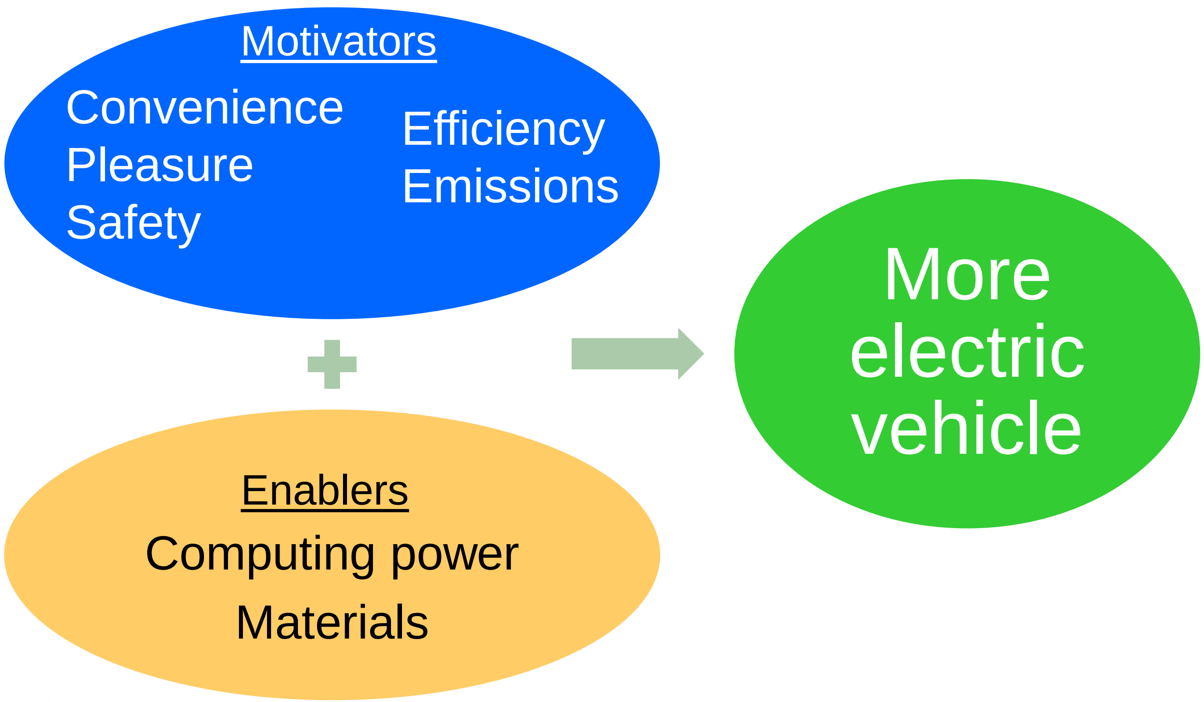
- There is however a much deeper groundswell of electrification throughout the automobile
  - Basics: Spark-plugs, lights, starter (1900-1915)
  - Radio (1950s)
  - Fuel injection (1960s)
  - Engine controllers (1970s)



Source: Conrad, AIEE, 1913

Introduction

- Everything is the car is getting electrified
  - Chassis
  - Engine and powertrain
- Degree of electrification paced by speed of cost reduction



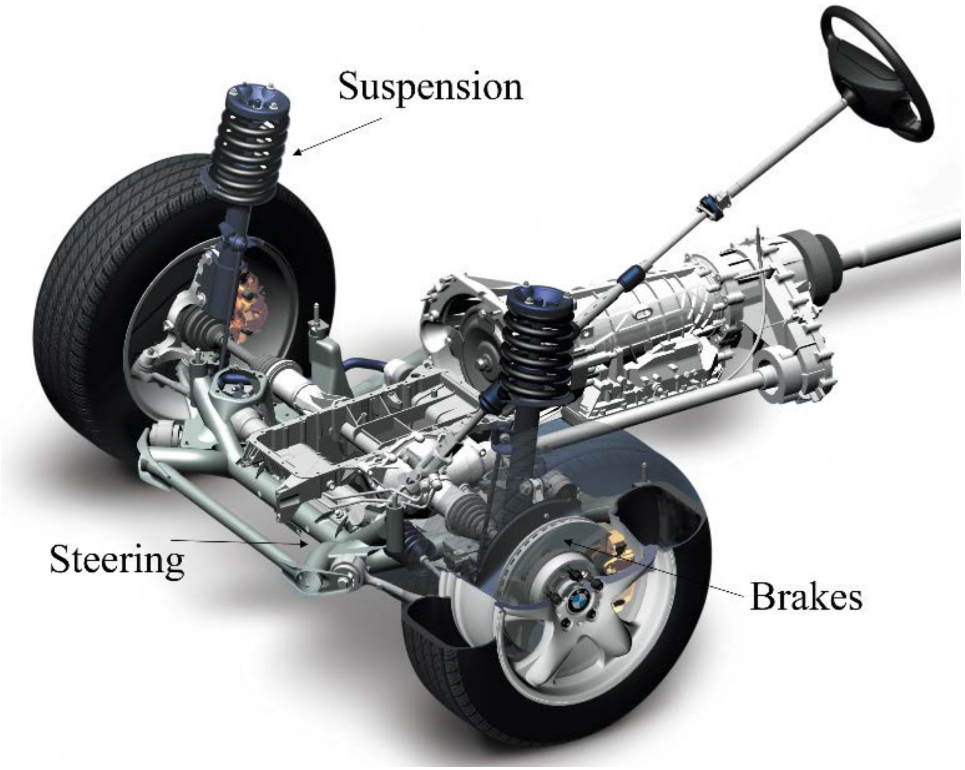
Presentation outline

- Chassis
  - Power steering
  - Suspension

- *Focus on energy conversion and systems*
- *Will not cover communications, algorithms, controls*

- Engines and powertrain
  - Fuel injectors
  - Valvetrains
  - Throttle control and fuel pump
  - Turbo- and super-chargers
  - Starter-generators as pathway to hybrids

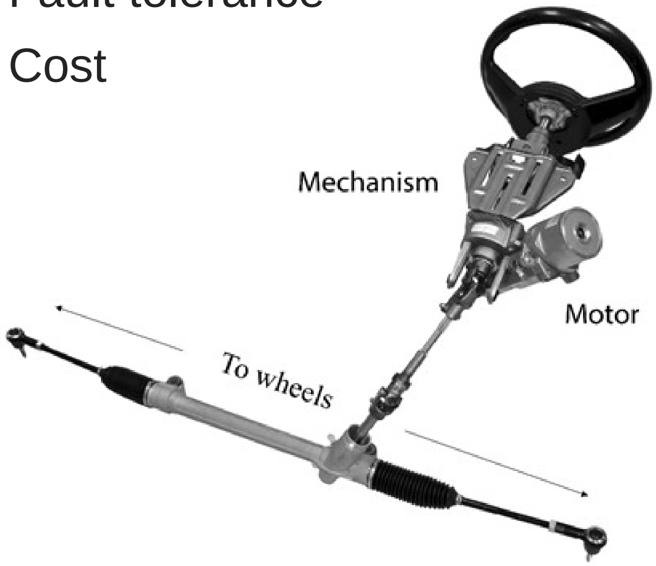
Chassis electrification

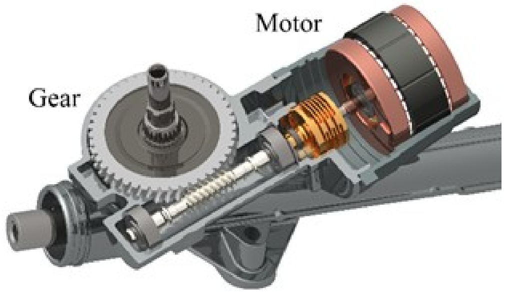


Source: BMW

Steering

- Best (recent) success story in automotive electrification
  - Electric power steering becoming standard
  - Provides power on demand: Significant fuel economy benefit (4%)
- Issues:
  - Torque ripple
  - Fault tolerance
  - Cost

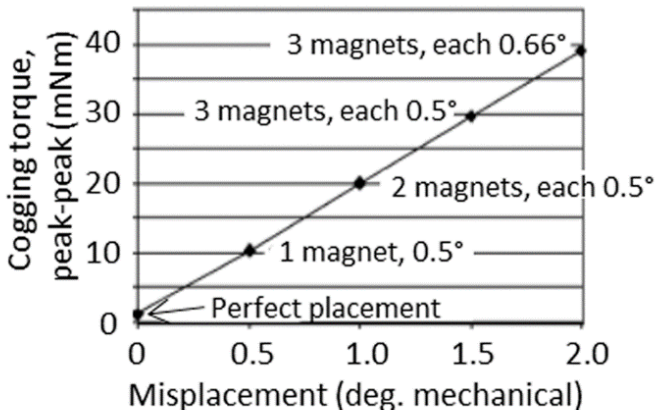




Source: Nexteer

Steering: Torque ripple

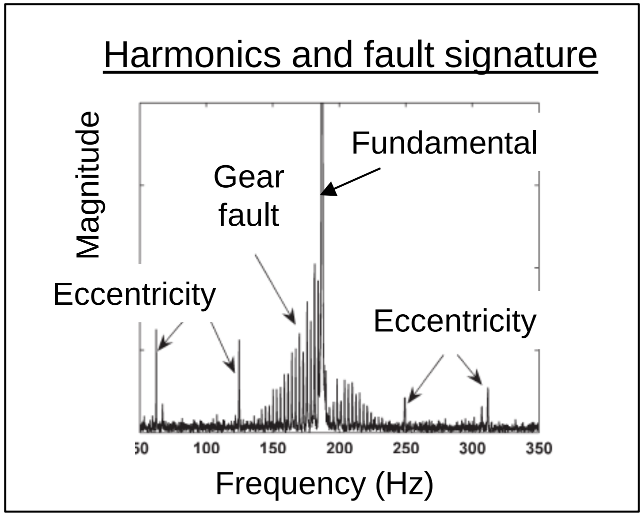
- Torque ripple felt by the driver on the steering wheel
  - Marketing issue (more than technical issue)
- Solution involved ***all*** aspects of motor and controller design and manufacturing:
  - Motor:
    - Matching of magnet back-emf with current excitation (magnet shape, etc)
    - Magnet skewing, pole/slot design, etc
  - Controller:
    - Sensor positioning and accuracy
    - Switching frequency, delays
  - Manufacturing:
    - Importance of Six Sigma methods to understand impact of build variations on performance

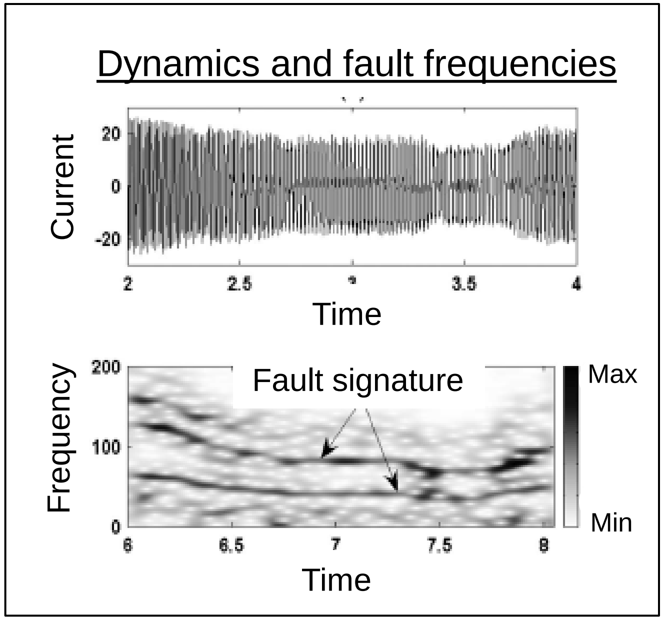


Source: Islam, et. al., IEEE T. IA, 2004

Steering: Fault tolerance

- Mechanical link to wheels kept, just in case
  - Last resort option
- Hardware solutions:
  - Minimize impact of fault (e.g., short circuit current)
  - Redundancy: Enough to be effective, not too much (FMEA)
- Software solutions:
  - Many faults have signatures in the current waveform
  - But, motor is always in dynamic situation
  - Alternatives to Fourier analysis needed
    - Wavelet, Wagnerville, windowed-Fourier…

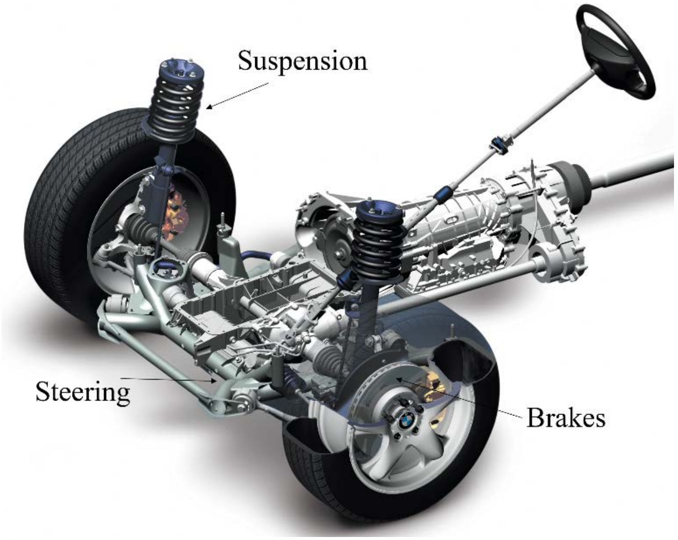




Source: Rajagopalan, et. al., IEEE T. IA, 2006

Suspension: Background

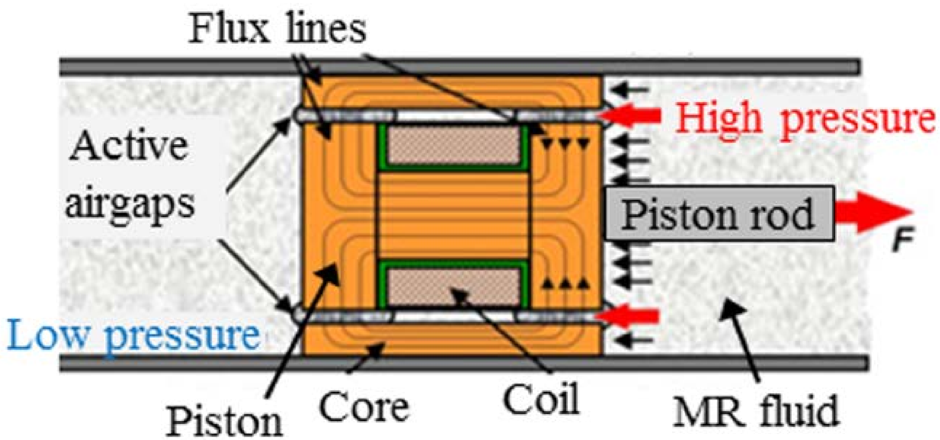
- Suspension (spring and damper) filter road noise
  - Passenger comfort, body durability
- Adaptive filter better suited (semi-active suspension)
  - Active suspension expands control range, adds car vertical positioning



Source: BMW

Suspension: Magnetorheological fluids

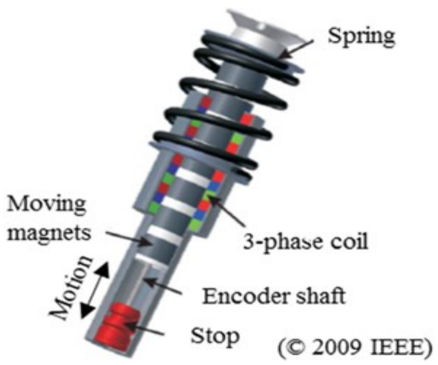
- Magnetorheological fluids: Oil with iron particle in suspension
  - Magnetic field stiffen the oil
- Issues:
  - Material: Develop particles and oil to prevent sedimentation of the iron
  - Magnetics:
    - Optimization for linearity
    - Issue with hysteresis: Iron particle cannot be annealed, leading to large hysteresis



Suspension: Fully active (and electric)

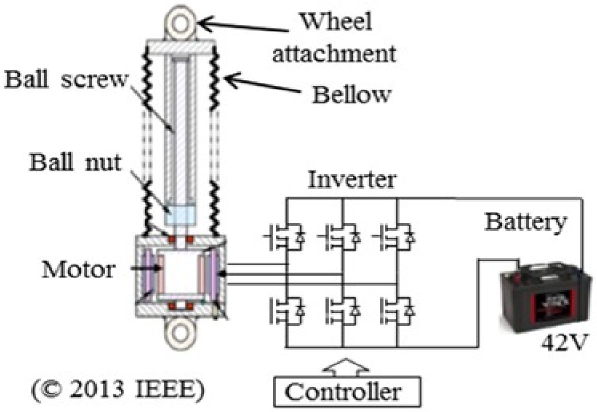
- Electric machine:
  - As a motor, to drive the wheel up/down and position the body
  - As a generator, to absorb energy
- Linear machine (Bose, Un. of Eindhoven)
  - Simpler (no gear)
- Regular brushless machine with ballnut-ballscrew (GM)
  - Possibly smaller, cheaper motor (thanks to gear)
  - Need to compare force/torque per volume, response time, etc

Linear motor (Eindhoven Un.)



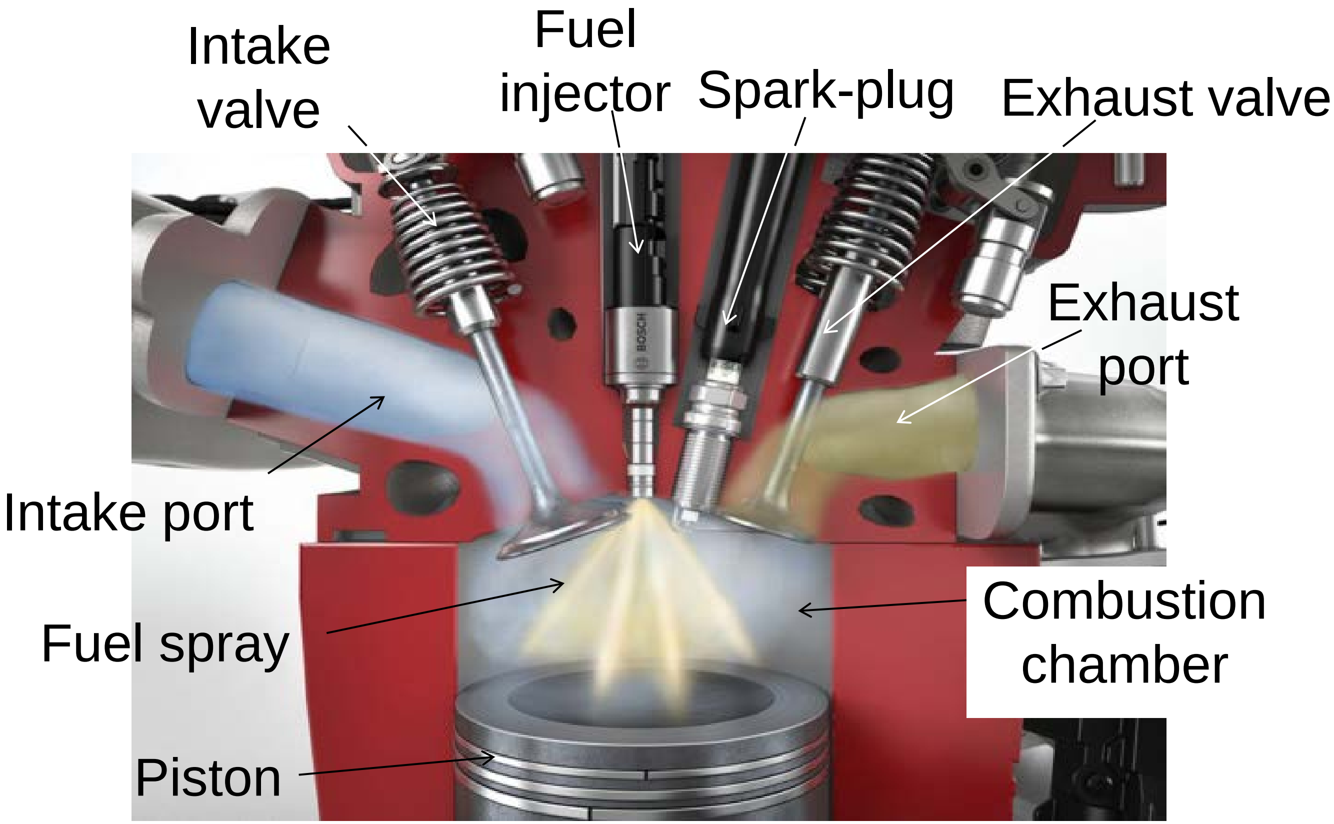
Source: Gysen, et. al., IEEE T. IA 2009

Rotating motor with ballnut/ballscrew (GM)



Source: Hao & Namuduri, IEEE T. IA 2013

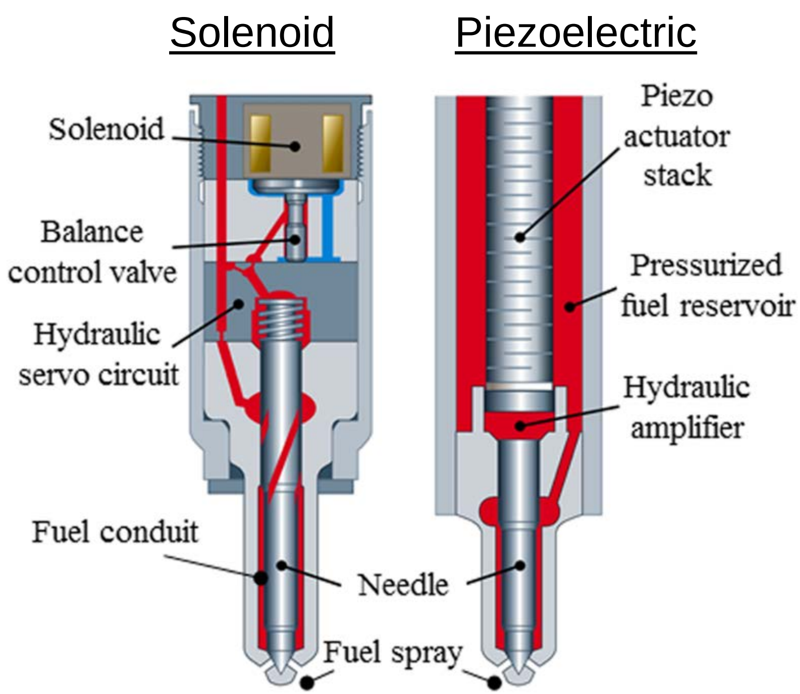
Engine electrification



Source: Bosch

Fuel injection: Background

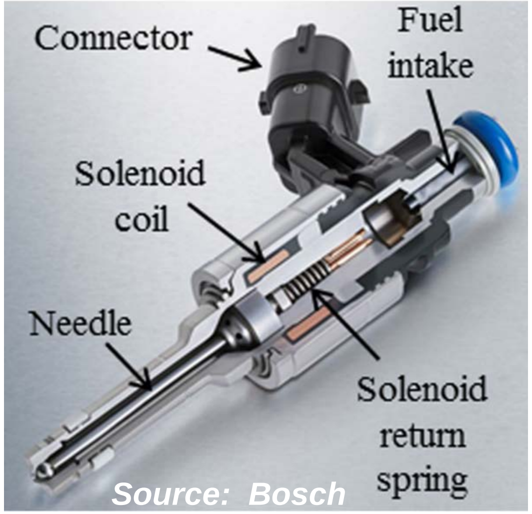
- Fuel injection has moved closer and closer to combustion
  - Direct injection is increasingly the norm
- Issues: Fast, precise, repeatable motion
- Piezo actuators are great but large and more expensive

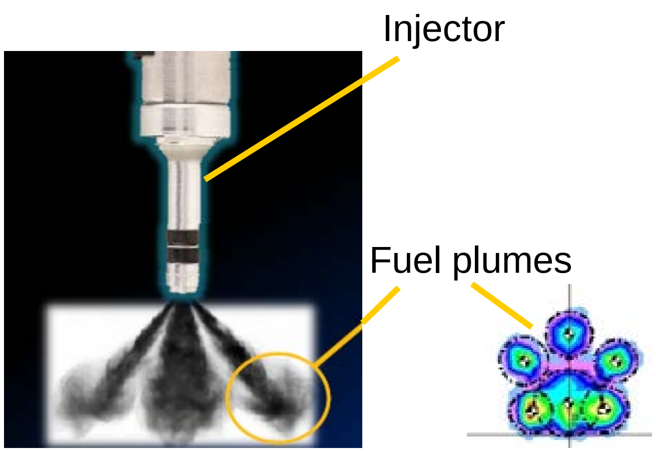


Source: Delphi

Solenoid fuel injectors

- Look simple, but:
  - Requirement of fast and repeatable motion has pushed technology
  - Solid parts (eddy currents)
  - Tiny motion (< fraction of a millimeter)
  - Fuel variety: Fossil, bio, natural gas
  - Recent trend of multiple injections per engine cycle
    - Repeatability means starting from same point – No lingering bounces, eddy currents



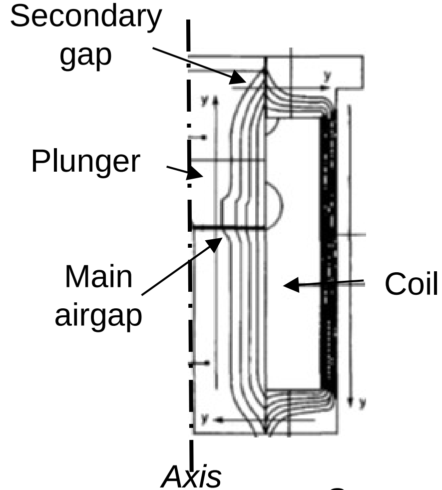


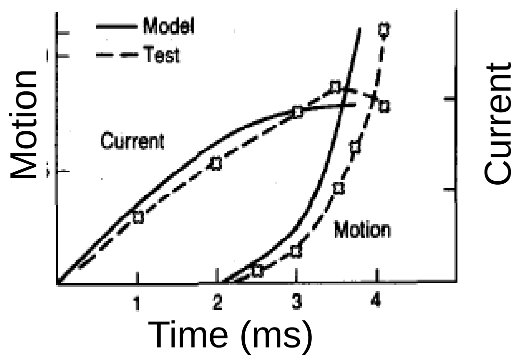
Source: Rivera and Kirwan, Delphi, 2014

Injectors: Modeling

- Fuel injector has driven modeling tools
  - First motion-compatible FEA models developed for this application
  - FEA solves for magnetic flux density over entire space
    - What matters is travel time, i.e. double integral of force, i.e. square of local flux density in airgap
    - FEA solves for global flux density in space
  - Simpler models: Depth models developed for eddy currents
  - Multi-physics to include magnetics, fluid dynamics, and thermal

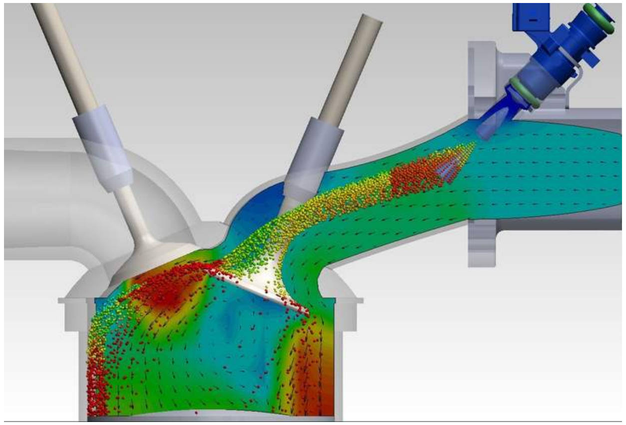
$$F = \frac{1}{2\mu_0} B^2 S$$





Source: Lequesne, IEEE T. IA, 1990

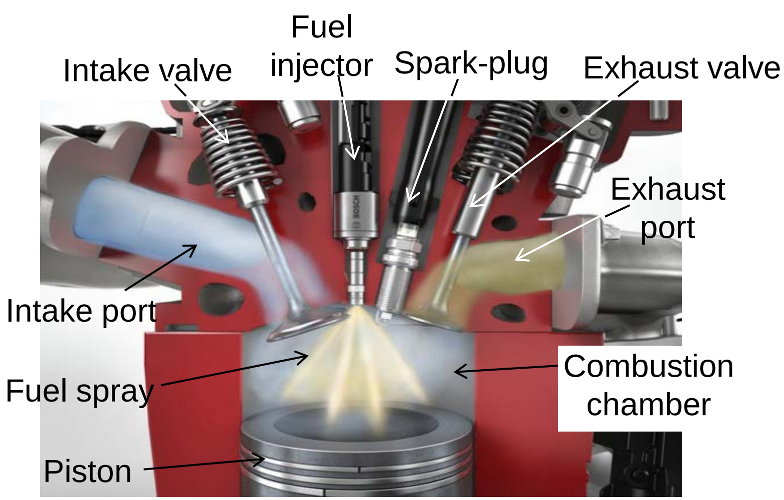
Multiphysics



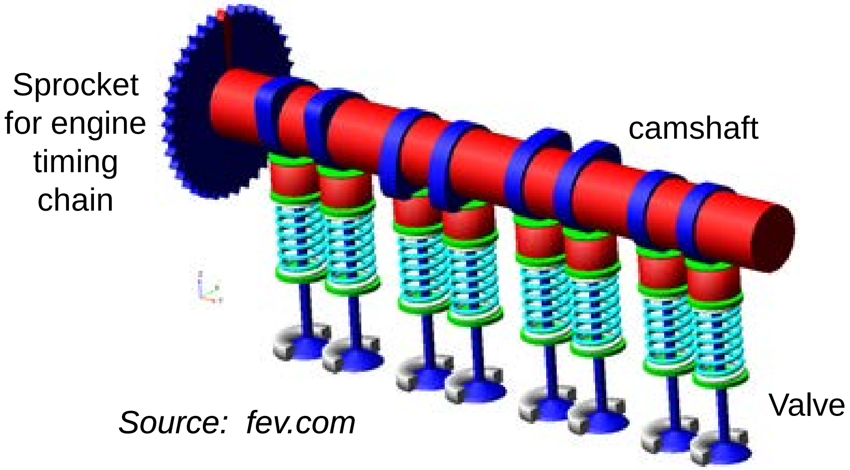
Source: ferrarilife.com

Valvetrain: Background

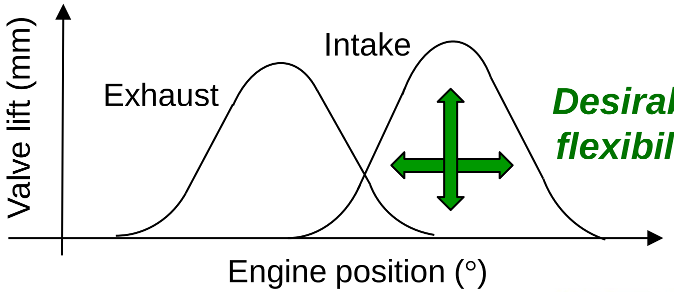
- Valve train bring air into engine, takes burnt gases out
- Conventionally run by a camshaft at half engine speed
  - Valve opening is constant in lift (mm) and span (degrees)
  - Desirable to vary both as function of speed, load, etc



Source: Bosch



Source: fev.com



Solution 1: Direct electrical actuation

- Challenges:
  - Long travel (10mm in 3 ms)
  - Energy use

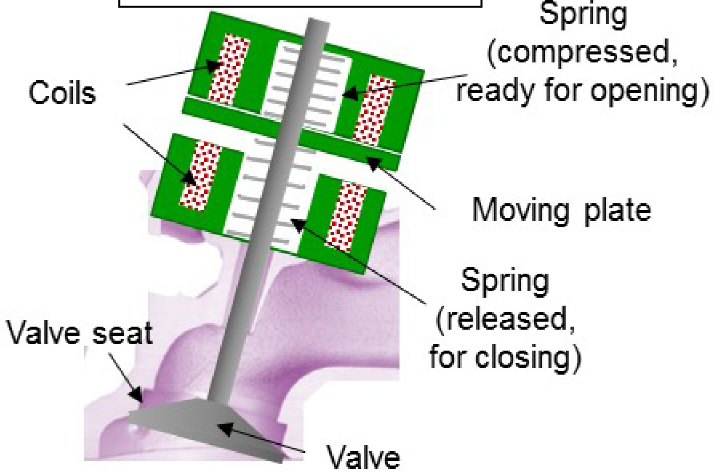
  Solved with 2-spring actuation:
  Two springs work like a swing controlled by 2 coils

  - Seating velocity
  - Repeatability
  - Durability

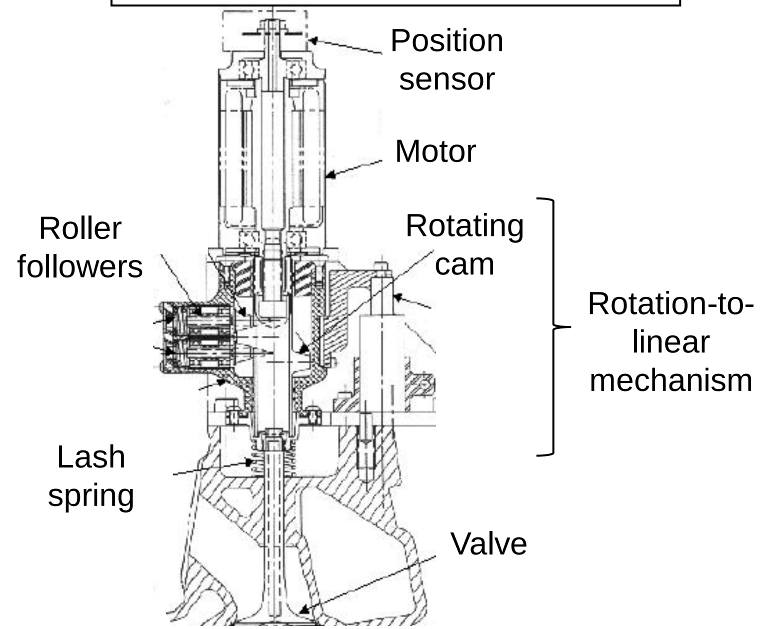
  Worked in experimental cars (FEV, Valeo)

  - Cost *Unresolved*

2-spring actuator



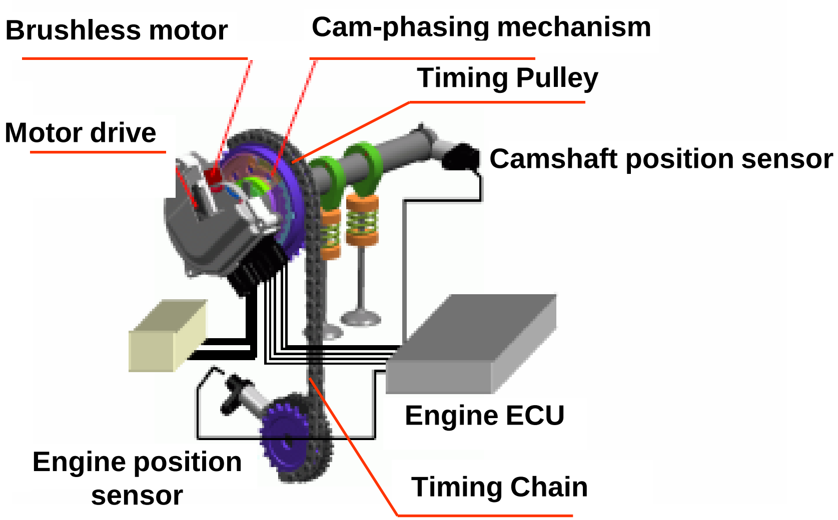
Motor actuated cam system



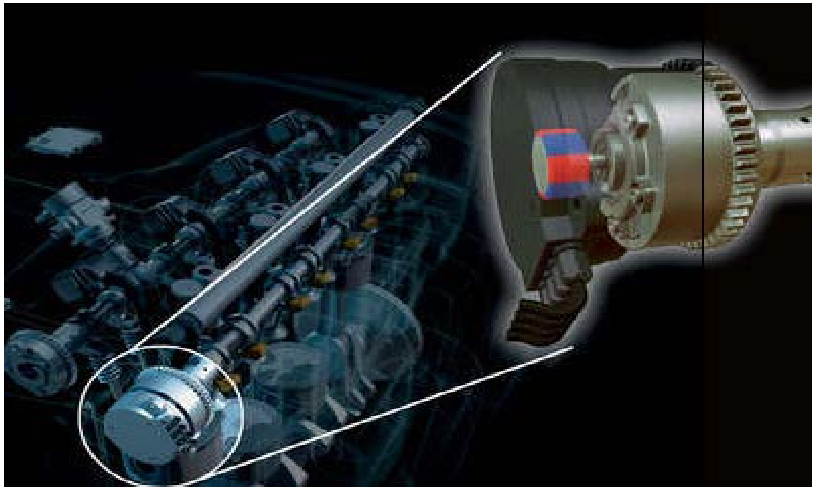
Source: Henry, SAE 2001-01-0241

Solution 2: Motor-controlled camshaft

- Motor (DC brushless) controls a mechanism that adjusts the camshaft
  - BMW (Vavetronics), Hitachi
  - Electric cam phaser shifts (phases) camshaft with respect to engine
    - Cam phasers standard now, but generally hydraulic
    - Electrical actuation broadens phase range, prepositions for cold starts
    - System uses harmonic drive (gear) and axial motor (for space)



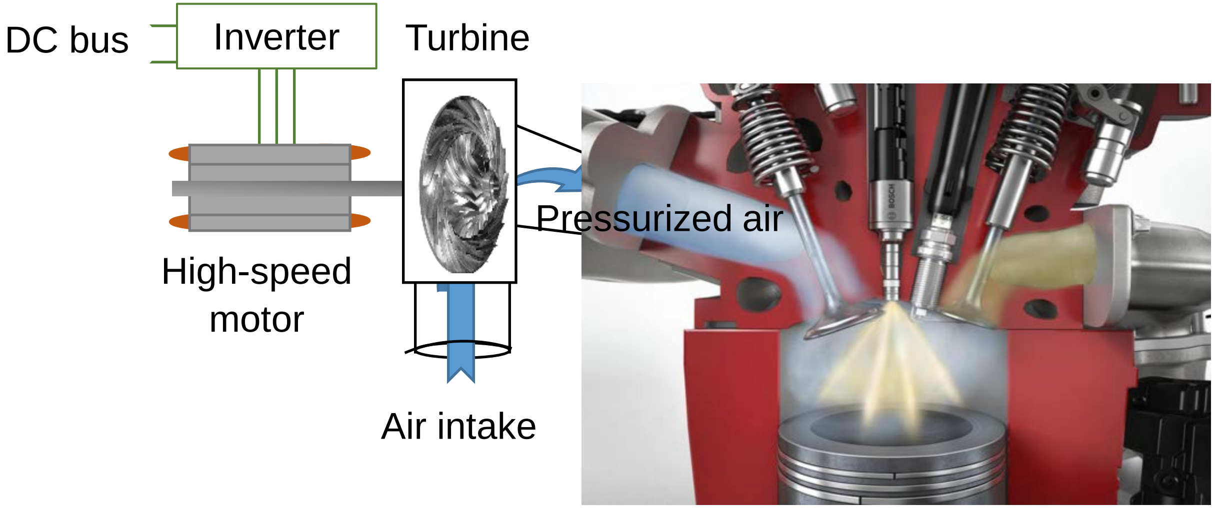
Source: Denso



Source: Jacque, et. al., MTZ Zeitschtrift, 2012 (Delphi)

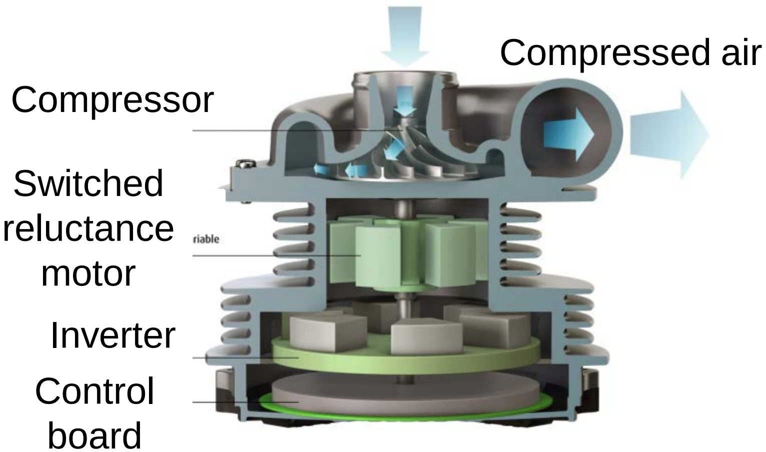
Turbo- and super-chargers: Background

- Basic concept: Pressurize intake air to expand engine output
- Turbocharger: Uses exhaust pressure to run a turbine
  - Uses waste energy, but suffers from lag
- Supercharger: Direct actuation of pressurizing turbine
  - Mechanical (belt driven): Cheaper, simple, but limited speed not ideal for turbine
  - Electrical



Electric super-chargers

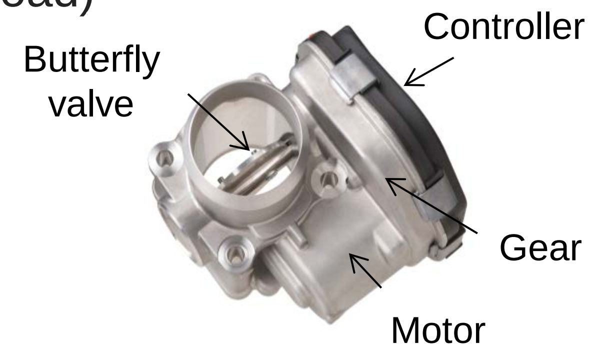
- Can go to very high speed (70 to 150 krpm for 1-2 kW)
  - Good for turbine
  - Can be done with motors, but a first for automotive
    - Issues of cost, controls, motor design from 12V
- First production-ready system (Valeo) uses switched reluctance motor
  - 70 krpm



Source: Valeo

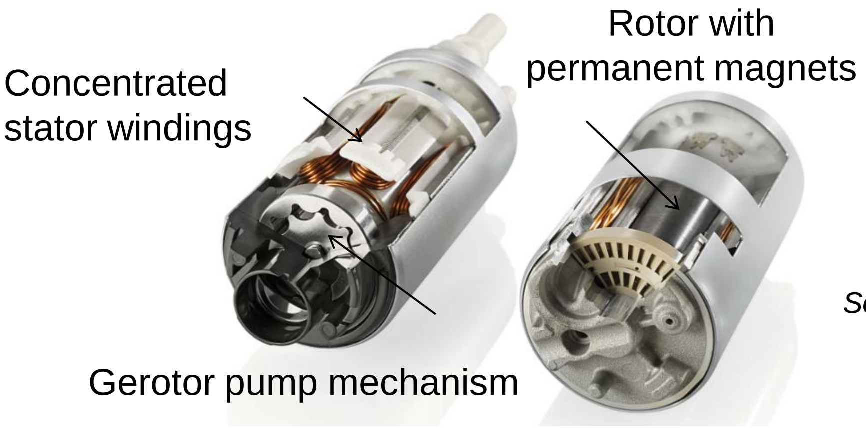
Throttle control and fuel pump

- Throttle controls air intake (acceleration and load)
  - Done "by-wire" for 20-30 years
  - Brushtype motor for low cost



Source: Delphi

- Fuel pump electric for decades
  - Moving from brushtype to brushless thanks to cost downward trend
  - Note concentrated windings
    - Lower cost

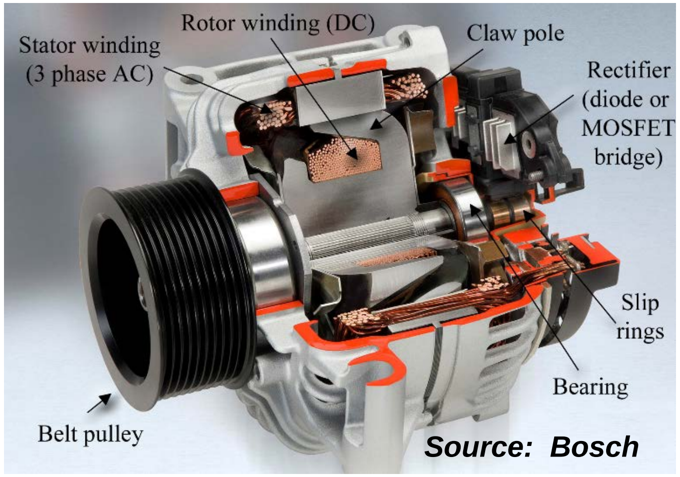


Source: Continental

Starter-generator

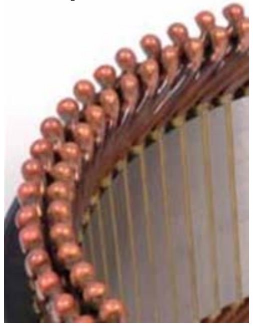
- Starter motors are used for 30 seconds then “dead weight” during regular driving
- Starting needs high torque at low speed (0 to 200 engine rpm), generation power over a wide engine speed range (800 to 6,000 rpm)
- Combination starting to occur (finally) due to:
  - More and more power demand (specs merging)
  - Idle-off (stop-start) feature (4% fuel economy benefit)
- Belt-driven system offer good packaging
  - PM: Research level
  - Induction: GM eAssist (no magnet, wide speed range)
  - Lundell: Toyota Lexus 2003, GM Saturn Vue 2005 (lowest cost solution)

Lundell motor



Source: Bosch

Hairpin winding



Source: Remy

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Starter-generator: Segway to hybridization

- Starter-generator can also be used for:
  - Transient acceleration support, to shave off some of the engine peak loads
  - Regenerative braking
    - Limited by power rating (braking is a lot of energy in a short time)

- Starter-generator is a micro- or mini-hybrid
  - Growing to ”regular” hybrid is a matter of ratings, controls
  - Or, cost/benefit trade-off

- Engine hybridization will therefore appear gradually as costs come down and technology improves
  - Part of gradual electrification of the car systems
  - Not as a “disruptive technology”

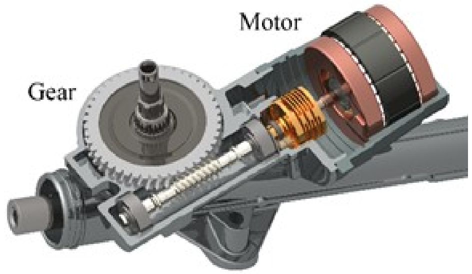
Conclusions (1)

- Most automotive sub-systems experiencing some degree of electrification
- Still room to grow:
  - Turbo- and super-chargers
  - Brakes and suspension
- Issues of immediate interest:
  - High speed motors (superchargers)
  - Improved cooling and packaging
    - Motor / power electronics integration
    - SiC
  - Modeling (fuel injectors)
  - Clever electromechanical integration and new materials

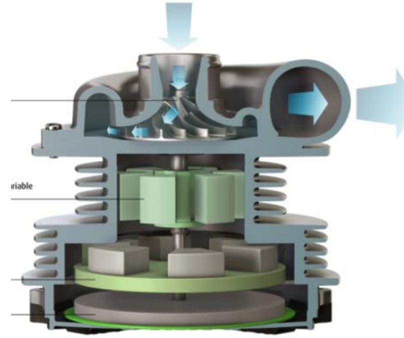
Conclusions (2)

- Electrification enabled by computing power, materials, and paced by progress in cost reduction
- Starter-generators as “backdoor” entry to general hybridization
  - Hybridization logical next step of a much deeper and longer historical trend
- Voltage?
  - A lot is possible at 12V
  - 48V will come as “happy medium” between high-voltage hybrids and low-voltage systems

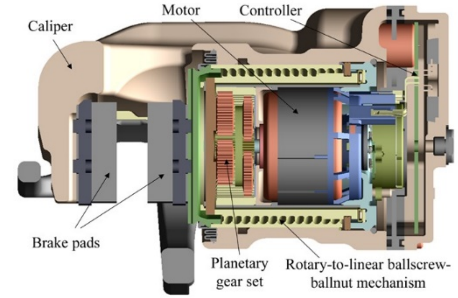
Fuel injector
Source: Bosch



Electric power steering
Source: Nexteer



Electric supercharger
Source: Valeo



Electric brake
Source: Delphi (IEEE IAS Mag, 2009)

Thank you!

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Bibliography

- See Lequesne, “Automotive Electrification: The Non-Hybrid Story”, IEEE Transactions on Transportation Electrification, 04 May 2015
- And references therein