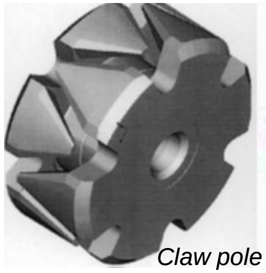
Claw pole


Cast copper rotor


Source: Teslamotors.com


LeTourneau


Toyota Prius

Electrification of transportation: Overview of the latest technical and market developments in e-mobility in North America and beyond

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www.emotorseng.com

CWIEME
October 1, 2014

eMOTORS Consulting, LLC

CWIEME

Who I am

- Electrical engineer, motors and electromagnetic expert, with 30 years of experience for automotive and transportation applications
  - GM Research, Delphi Research, Delphi Powertrain, Eaton
  - Worked on valvetrain electrification, power steering, electric brakes, throttle control, sensors, starter-generators and hybrid systems, etc.
  - 50 patents, number of publications in IEEE and SAE journals and conferences

- Now a consultant

GM

DELPHI

EATON
Powering Business Worldwide

Overview

- Introduction: Why automobile electrification?
- The less visible groundswell: The "not hybrid" story
  - Chassis and powertrain electrification
- The visible part: Hybrids and electric vehicles
- Impact on electric machine technology
- Market perspective and challenges ahead

Automotive electrification: Motivations

- Long history on gas-powered vehicles:
  - Starter motor (1911)
  - Radio (1950's)
  - Currently, some 30 motors per car
    - Mostly simple, low cost brushtype
- Motivation is very diverse:
  - Energy efficiency is only one factor
  - Reduced emissions
    - Smaller engine size with hybrids
  - Convenience and features:
    - Many gadgets require power or actuators
  - Performance
  - Image

Kettering demonstrating starter on a Buick (1913)

Source: ohiohistorycentral.org

- Key enablers:
  - Power electronics
  - Computer and controls

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Chassis electrification

- Chassis: Trilogy of steering, brake, suspension -> Vehicle handling
- All 3 can be electrified
  - Power steering: For fuel economy
  - Suspension: For variable suspension rates
  - Brakes: To eliminate brake fluids, and improve response time
  - All 3 for improved controllability

Image: melexis.com

Electric power steering (EPS)

Motivation:

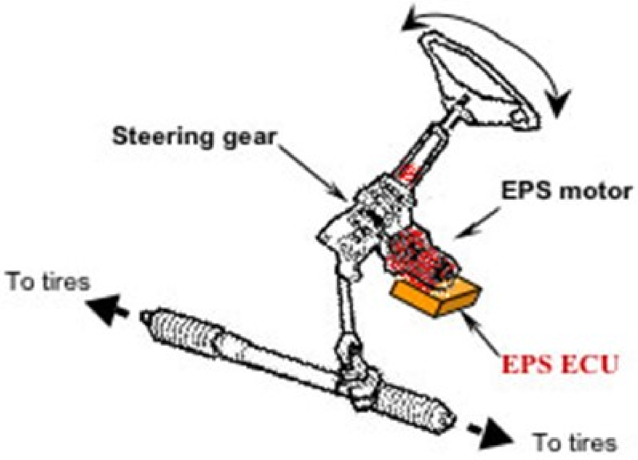
- Fuel economy, power on demand
- Hydraulic power steering requires the pump to be on all the time, a 1 mile/gallon penalty

History:

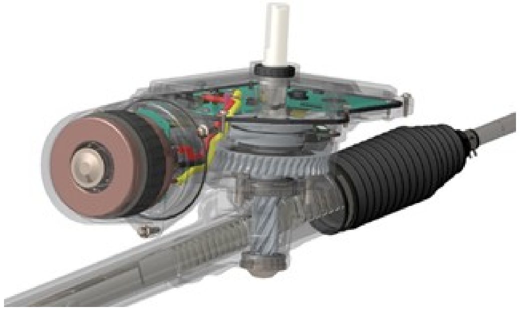
- Introduced on Susuki (1988), small Fiat car in 1999
- Becoming standard on passenger vehicles

Issues:

- Torque ripple (can be felt by driver)
- Need for fail safe features
- Cost:
  - Need for EPS to be almost on par with hydraulics



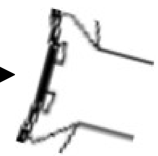
Denso EPS system
Source: globaldensoproducts.com



Nexteer EPS system
Source: motoren.wordpress.com

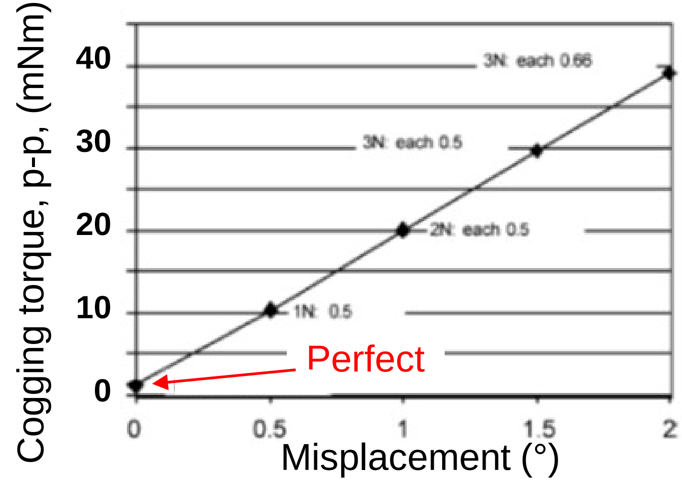
Electric power steering: Low torque ripple

- Approach:
  - Synchronous PM motor have no torque ripple
  - There are known ways to eliminate cogging
    - Slot/pole combinations
    - Skew
    - Phantom slots

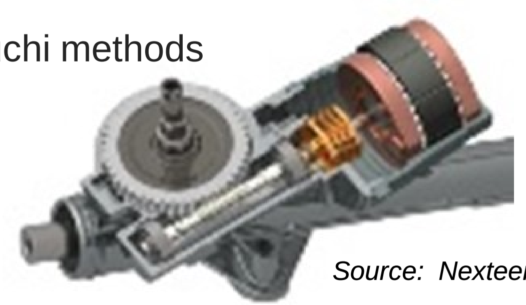


- When theory meets practice:
  - Manufacturing variations are critical!
    - Magnet magnetization pattern
    - Eccentricity
  - Required:
    - In-depth detailed understanding of impact of all variations on torque
    - Proper design: Six Sigma, Taguchi methods
    - Proper manufacturing

Cogging torque vs.
magnet misplacement



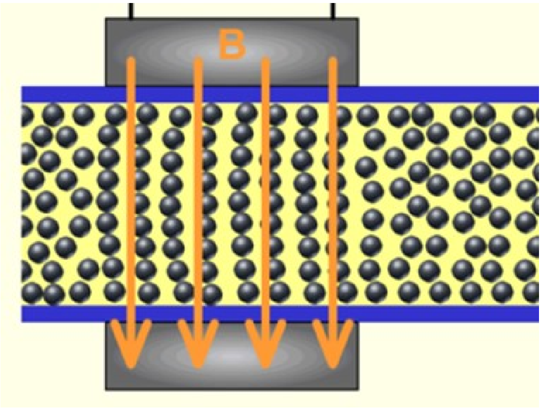
Islam, et. al. (Delphi/Nexteer)
T. Indus. Appl., 2004



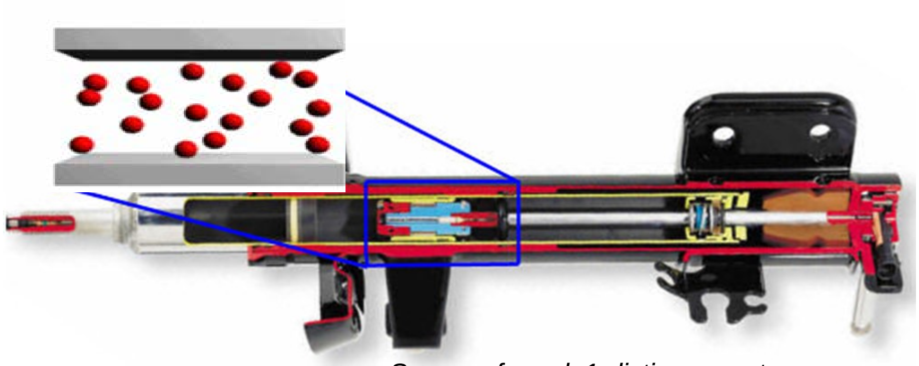
Source: Nexteer.com

Variable-rate suspensions

- Issues:
  - Conventional suspension have a fixed damping rate versus frequency
  - Accommodate various comfort levels: Plush versus sporty
- Solution #1:
  - Magnetorheological fluids: Oil filled with iron particles
  - Oil viscosity varies with applied magnetic field
  - Developed by GM/Delphi/Lord
  - Used on luxury vehicles: Cadillac, Corvette, Lexus, Ferrari
- Development hurdle:
  - Proper material with low sedimentation rate
- Limitation:
  - Only semi-active damping



Source: Wikipedia commons

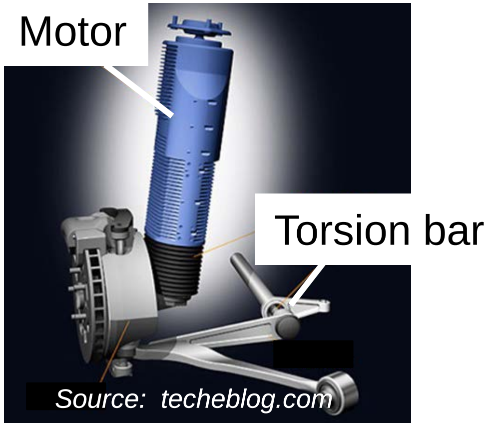


Source: formula1-dictionary.net

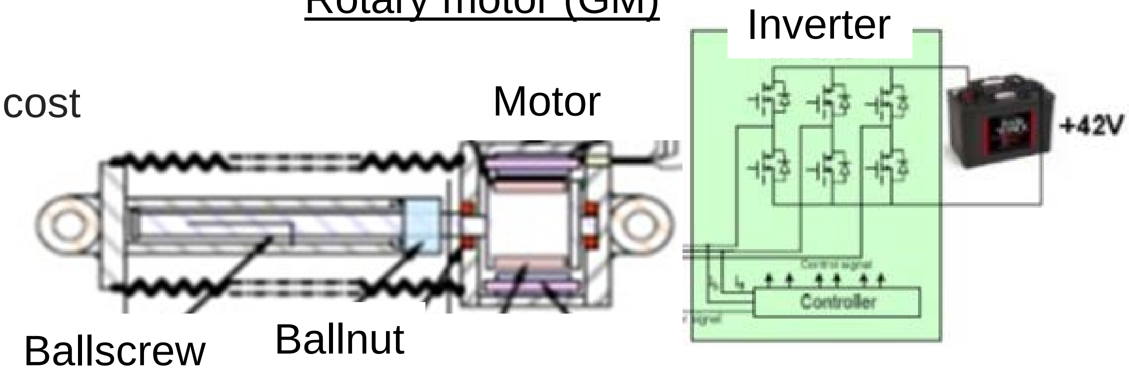
Active suspension systems

- Linear motors (Bose, etc)
- Motor with ballscrew-ballnut (GM)
- Advantages:
  - 100% controllable ride
  - Very minor energy harvesting
- Issues:
  - Size, energy consumption, cost

Linear motor (Bose)



Rotary motor (GM)



Source: Hao, et. al, (GM)
IEEE ECCE Conf. 2011

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Powertrain electrification

- Engines are no more mechanical…

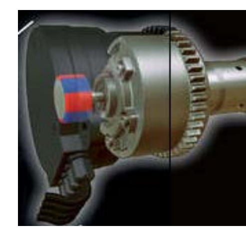
Engine controller
(Delphi)

Electronic throttle control
(Delphi)

Fuel injector
(Bosch)

Engine image: rouschperformance.com

Electric cam phaser
(Delphi)



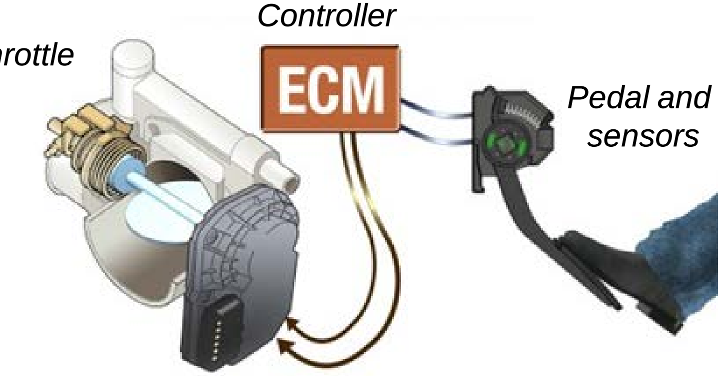
Electric water and oil pumps
(BMW, Alfa-Romeo)

Starter-generator
(Denso)

Throttle-by-wire

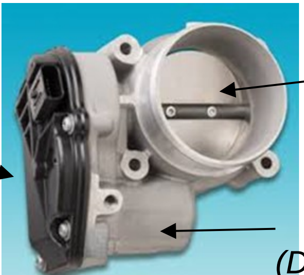
- Gas pedal system:
  - Linked to throttle by electric wires
  - Mechanical linkage disappeared 15 years ago
- Advantage:
  - Can manage input from driver AND steering, braking, etc (ABS system)
  - Less wear
- What about safety?
  - Toyota recall (2009)…
  - Electronic systems safer than mechanical systems
    - Redundancy
    - Sensors as fault observers
    - Fewer components, less wear
    - Not subject to human failures
    - Contributes to ABS and other safety functions

System



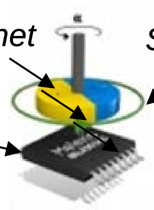
Source: Toyota.com

Actuator

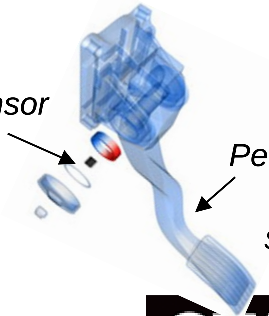


Source: Delphi.com

Pedal



Source: Melexis.com



Source: Melexis, ee-times.com

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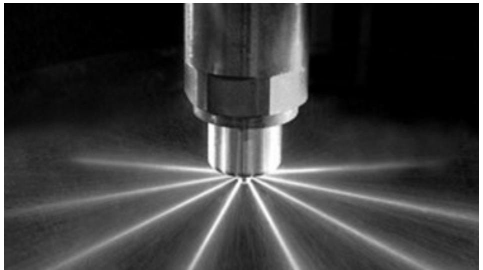
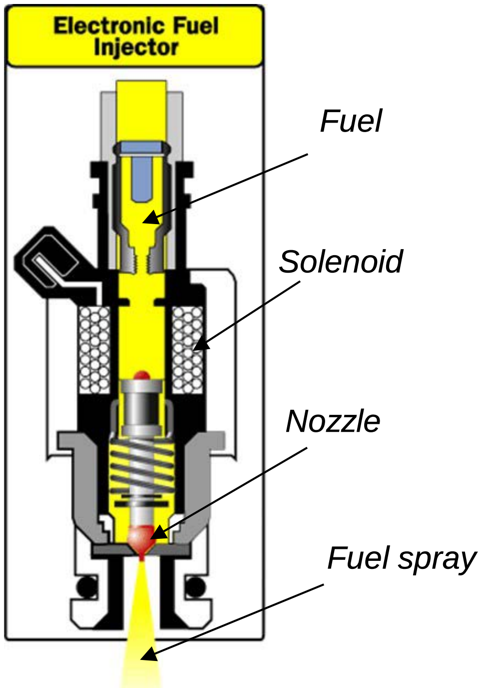
Fuel injectors – Faster, more precise

- Fuel injectors are just solenoids, right?
  - Fuel injectors led the development of FEA in linear motion (1980s)
  - Fuel injectors use piezo technology in mass production
- Why?
  - Move from carburetor to port to in-cylinder injection
  - Fuel dispersion and atomization key to clean burn
  - Precision and repeatability critical
  - Trend towards for multi injections per cycle

Source: atzonline.com



Source: marineinsight.com

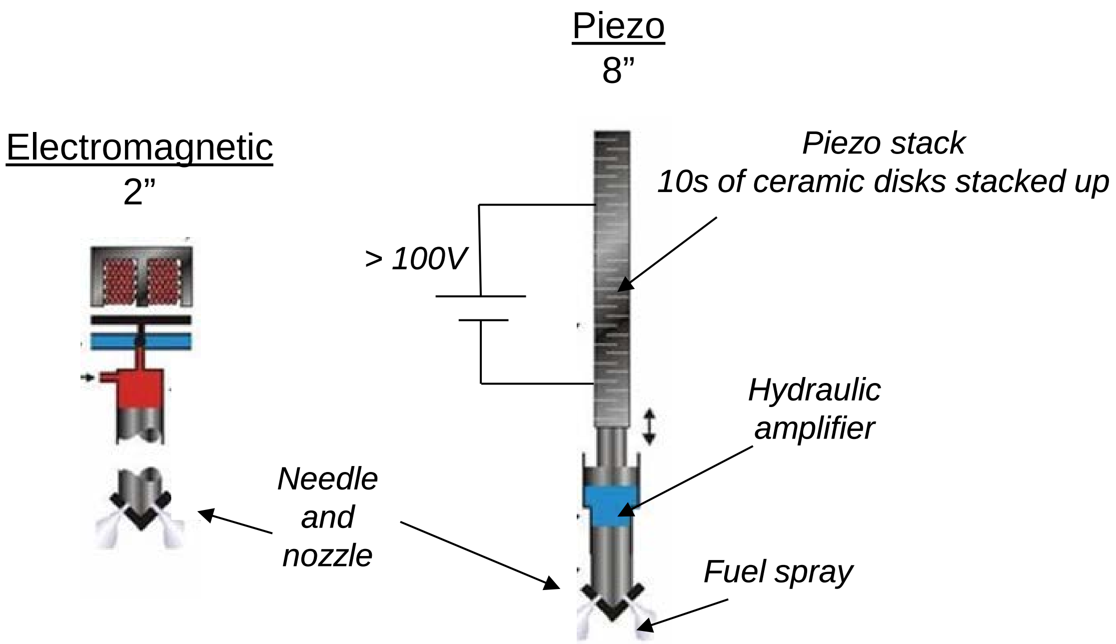


Source: howstuffworks.com

Fuel injectors – Electromagnetic versus piezo

- Piezo injectors making in-roads despite of cost, size, need for high voltage
  - May be as long as 8”
  - Need for high voltage supply
  - Stack may be immersed in pressurized fuel

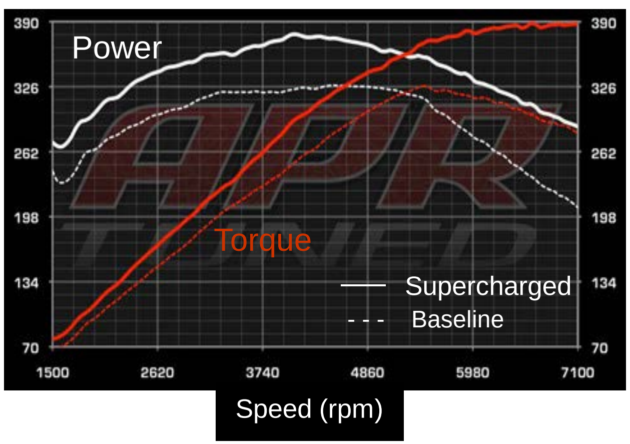
Not to scale!



Source: Delphi

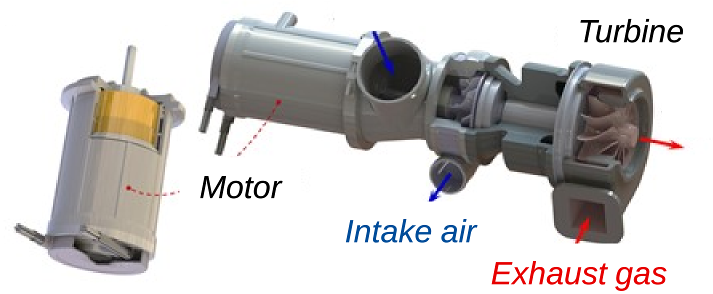
Superchargers and turbochargers

- Engine downsizing by intake air pressurization
  - Significant fuel economy
  - Turbocharging: Powered by exhaust gas
  - Supercharging: Mechanical or electric actuation



Source: goapr.com

- Example: Electric turbo compounding
  - Exhaust gas drives turbine to compress air
  - Electric motor mounted coaxially:
    - Drives system when exhaust pressure is low
    - Can generate power when plenty of exhaust pressure



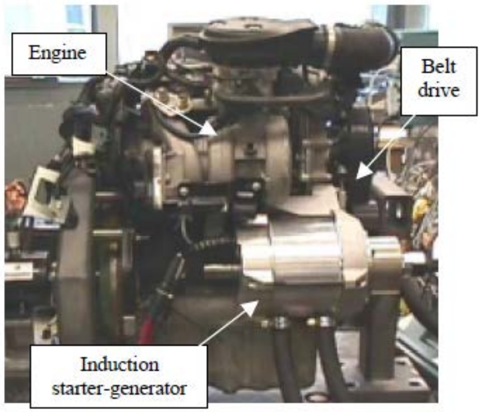
Source: mts.com

Stop-start systems

- Stop-start = Engine off at idle
  - Can save up to 4% in fuel
- Two types:
  - Regular system with stronger starter motor
  - Belt-driven combined starter-generator

Source: green.autoblog.com

Engine test stand



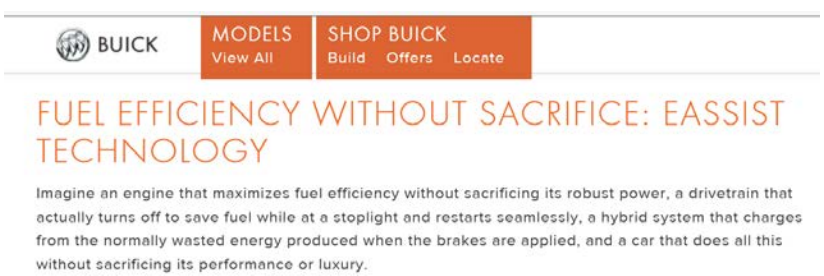
Source: Chen, Lequesne, Henry (Delphi), IEMDC 2001

Induction starter-generator

Source: AC Delco Training (archives online)

Stop-start systems or micro hybrid?

- Stop-start systems are also called micro hybrids
  - Depends on marketing strategy
    - GM calls it “eAssist” – Does not want to scare off traditional customers
    - Others taunt environmental friendliness (Peugeot’s “ecologique”)
  - Stop-start becoming standard, starting with Europe



Source: Buick.com

Source: Peugeot.com

Overview

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Performance of electrics/hybrid

- Performance of electric/hybrid cars is excellent – On par with traditional
- Some cars (Lexus, Acura for instance) are hybridized for performance, not fuel economy

Tesla:

Source: Teslamotors.com

248 hp (185 kW) motor
0–60 in 3.9 s

Lotus Elise:

Source: Lotuscars.com

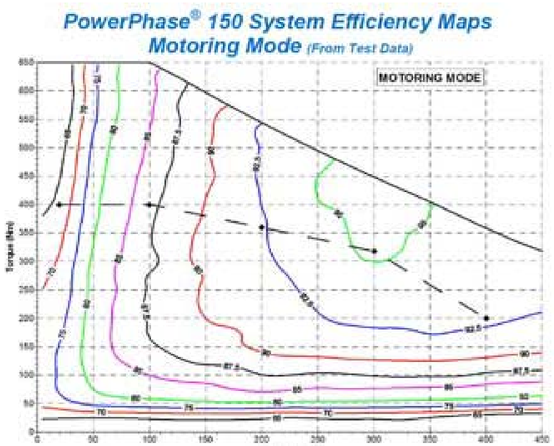
163 kW supercharged engine
6-speed transmission
0-60 in 4.3 s

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

Torque

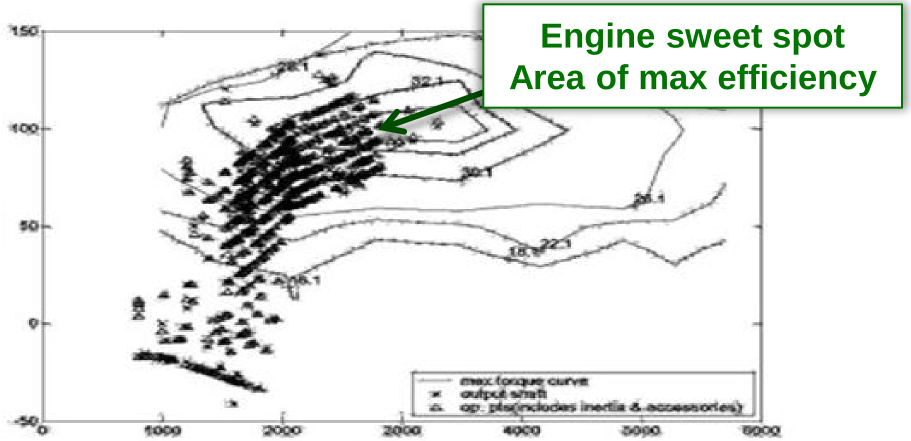


Speed

Source: UQM

Engine operating points

Engine torque



Speed

Source: Emadi (2006)

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Propulsion systems

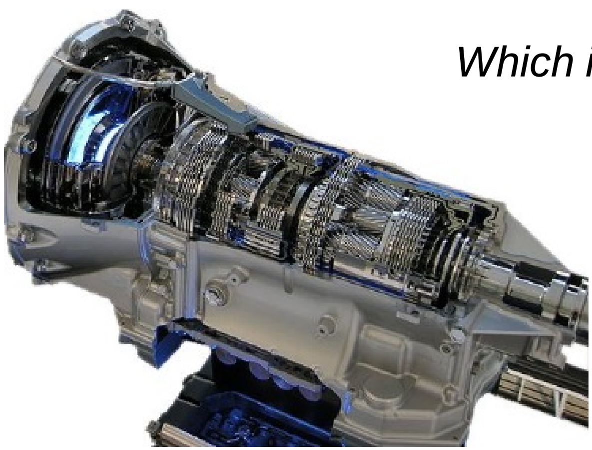
- Electric vehicles and plug-in hybrids:
  - Electric system needs to meet most traction torque/speed points

Electric engine

- Hybrids:
  - Electric system simply aids the engine
  - Better defined as an electrified transmission?

Electric transmission

Which is more complex?



Lexus 8-gear transmission

Source: Wikipedia Commons

Toyota Prius

MOTORS Consulting, LLC

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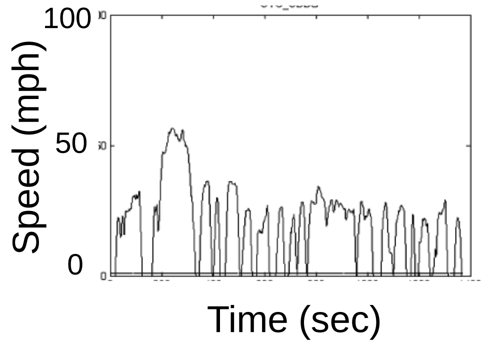
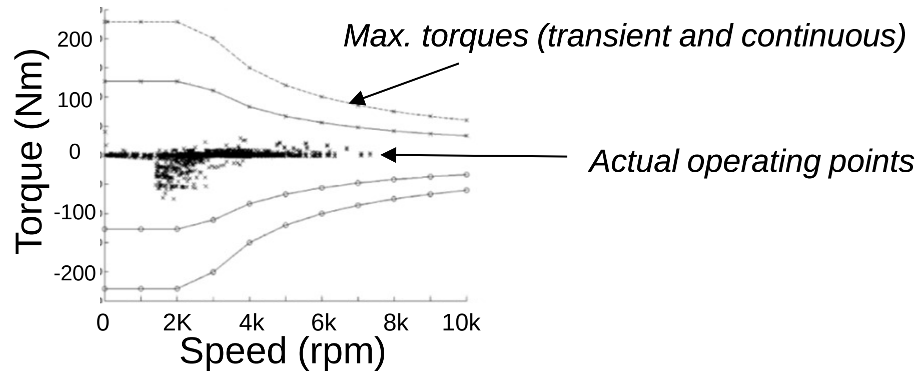
Propulsion and hybrid motors: Load cycle

- Importance of low-load points on overall efficiency

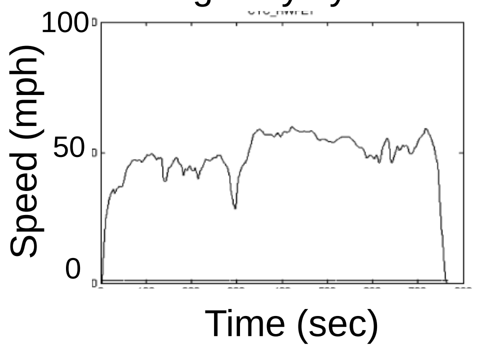
Urban cycle

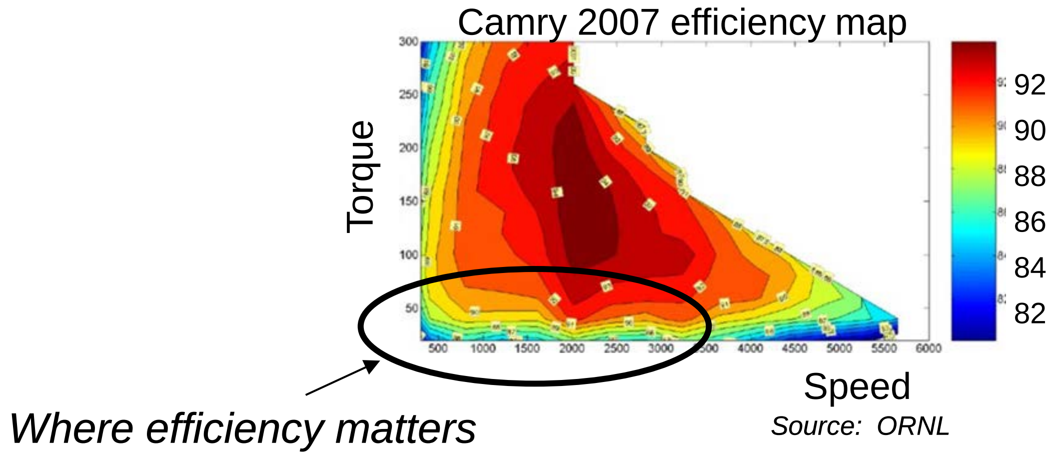




Source: Emadi, Trans. PEL, 2006

Highway cycle

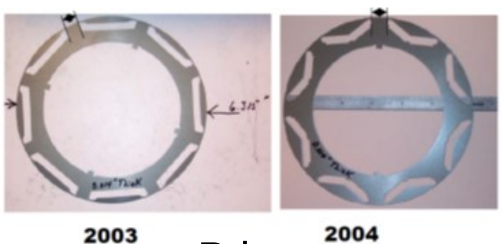




Source: ORNL

Propulsion motors: Which motor type?

- **Permanent magnet:**
  - Favored for **hybrid vehicles**: Honda, Toyota, GM, Ford
  - Buried magnet design, with more and more reluctance torque
    - Less magnet material, better resistance to demagnetization



Prius

Source: ORNL reports

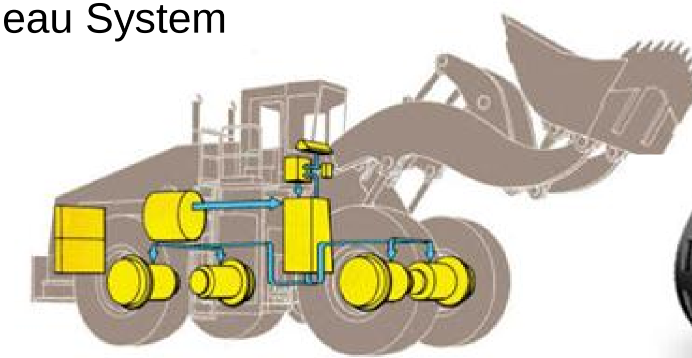
Camry 2007

- **Induction:**
  - Favored for **all-electric** (GM EV1, Tesla)
    - Lower efficiency means range, can be offset with bigger battery
  - And **belt-driven**

What about switched reluctance?

- Used for heavy equipment
  - LeTourneau, all switched reluctance
  - John Deere: PM generator, SR motors
- Noise and vibrations of little concern
- Ruggedness and fault tolerance important

LeTourneau System



1 switched-reluctance generator

4 switched-reluctance wheel motors (300 kW)

Source: letourneau-inc.com and Emerson.com

Challenge: Cost

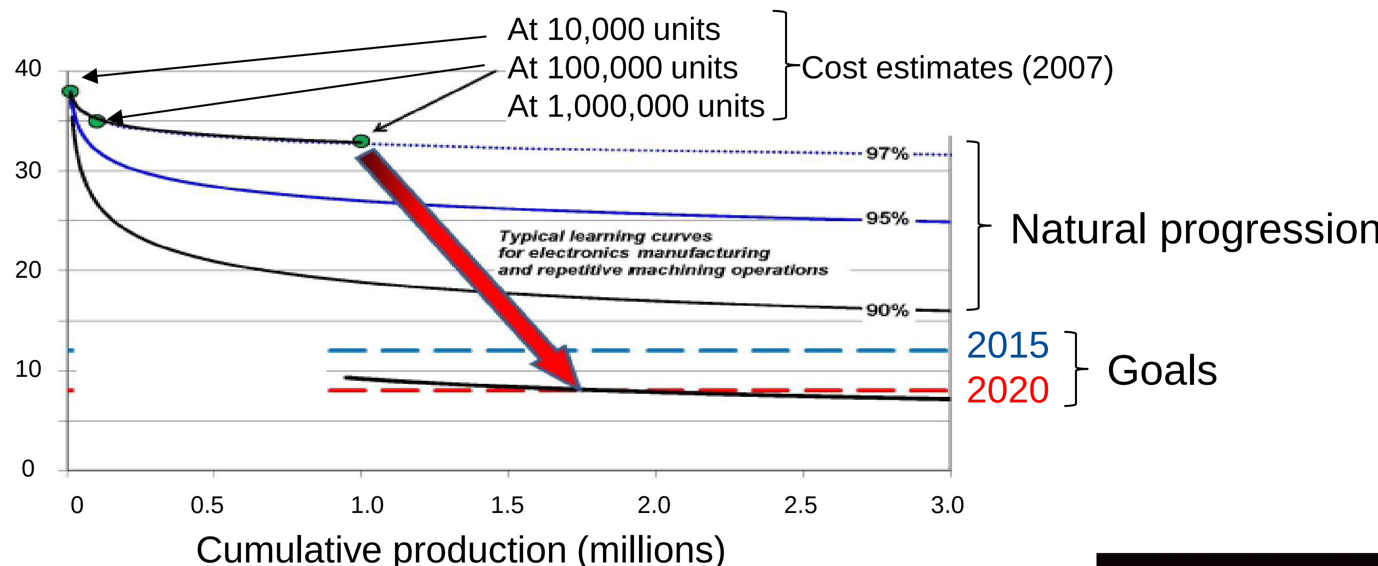
- DOE has established ambitious targets for cost and output
  - Requires more than just economies of scale

Electic traction system	2015	2020
Cost ($/kW)	< 12	< 8
Specific power (kW/kg)	> 1.2	> 1.4
Power density (kW/l)	> 3.5	> 4.0
Efficiency (10-100% speed at 20% tq.)	> 93%	> 94%

Motor	2015	2020
Cost ($/kW)	< 7.0	< 4.7
Specific power (kW/kg)	> 1.3	> 1.6
Power density (kW/l)	> 5.0	> 5.7

Electric traction system cost ($/kW)

DOE, 2007



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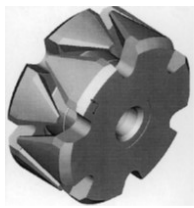
Impact on motor design: Examples

- Design for consistency:
  - Torque ripple, fuel injectors: Repeatability spec more critical than actual value
  - Taguchi method, design for 6 sigma
- Importance of design for load cycle (compound efficiency map)
- History of the modern generator as example of how to improve old technology competing with the new
- Motor construction and concentrated windings

Automotive generation

- Lundell alternator has reigned for 50 years:
  - Issues: Difficult to scale up, and low efficiency



DC generator

Lundell

Add permanent magnets (GM)

Windings as bars (Denso)

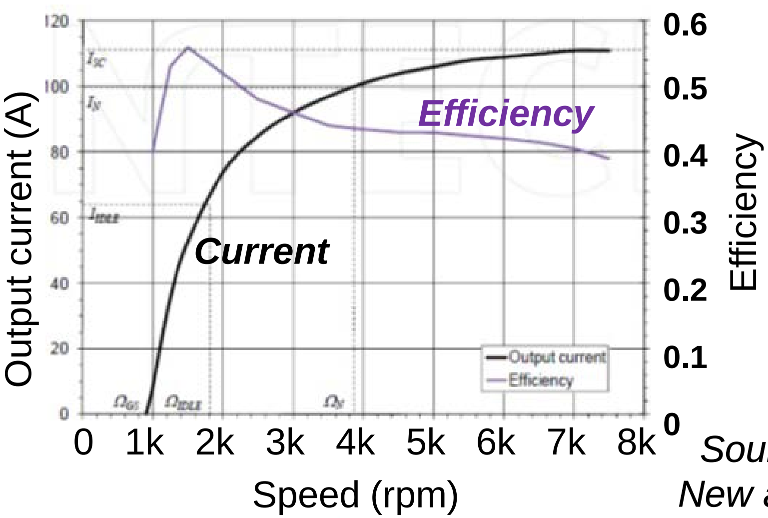
Water cooling (Bosch)

1960

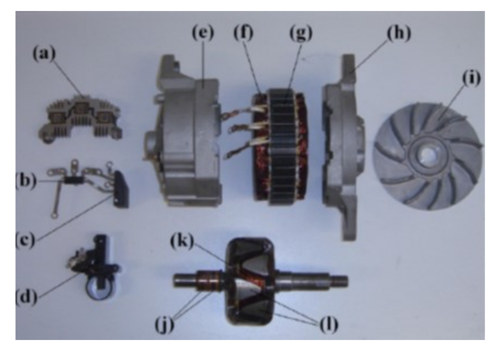
1990s

Active rectifier (Ford, MIT)

Twin rotors



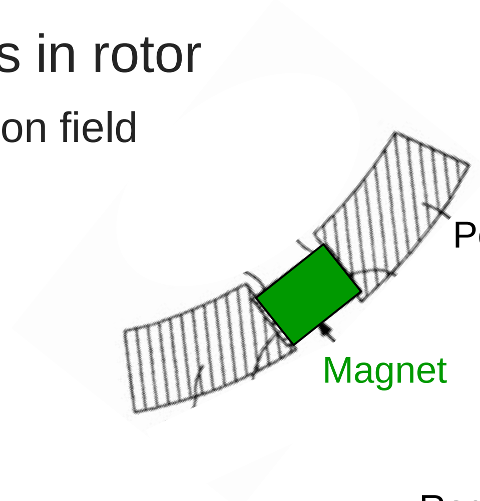
Source: Ivankovic, et. al., New advances in vehicular… InTech, 2002



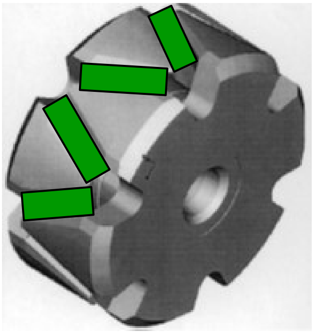
Source: Nexteer.com

Lundell improvements

- Permanent magnets in rotor
  - Boosts rotor excitation field
  - Reduces leakage

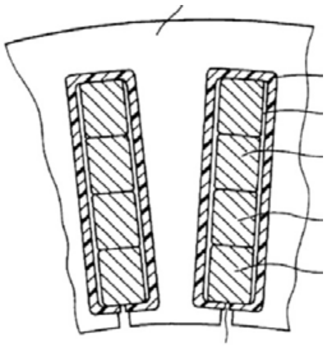


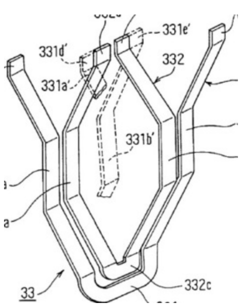
Lundell rotor



Radomski (GM), US 4,959,577

- Coil windings for better slot fill





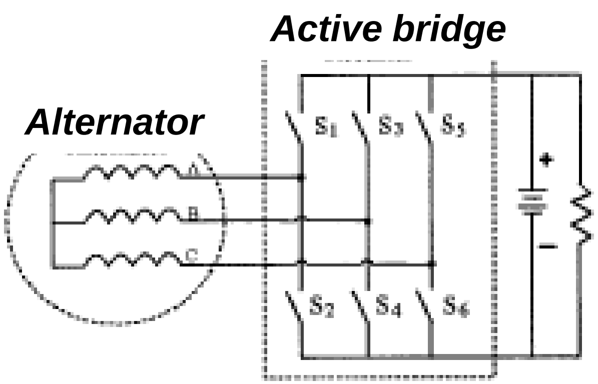
Umeda, et. al. (Denso), US 5,982,068

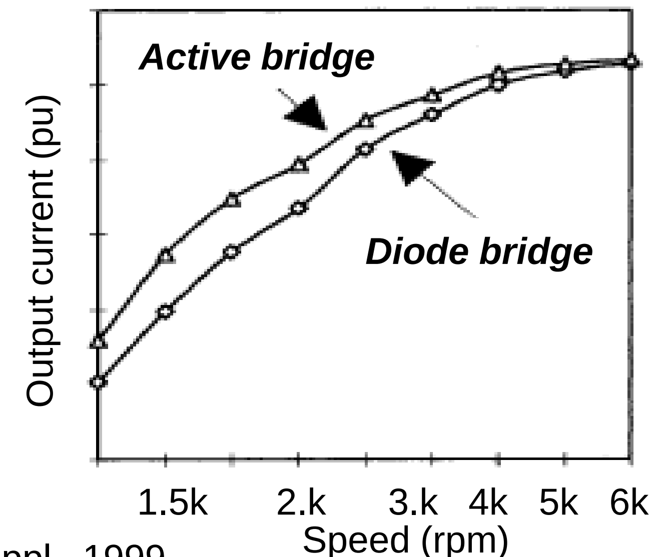
Lundell improvements

- Active rectifier
  - Lower losses (resistive drop better than diode voltage drop)
  - Control of phase angle

$$P = \frac{3\,E\,V}{X}\sin\theta$$

V is output voltage
E is back-emf
Θ is angle (V,E)
X is reactance





Liang, Miller, Xu (Ford), T. Ind. Appl., 1999

Motor construction

- Emergence of concentrated-coil windings
  - Obvious choice for flywheel-mounted motors
  - Simpler construction, better fill factor
  - Development of segmented stators

Honda Insight

Honda Accord

(Source ORNL report on motor technologies, 2011)

Fractional hp motor

(Source movingmagnet.com)

Full integration/modularity

(Brown, Jahns, Lorenz, IAM 2007)

Future needs

- Higher speed motors
  - Needs advances in motor and gear technology
- Thermal / Electromagnetic modeling integration
- Modularity
  - Especially non-automotive, to increase volume
- Higher temperature power electronics (to reduce number of cooling loops) and motor
- Materials:
  - Cast copper rotor (Tesla)
  - Laminations
- Voltage: 48V come back?

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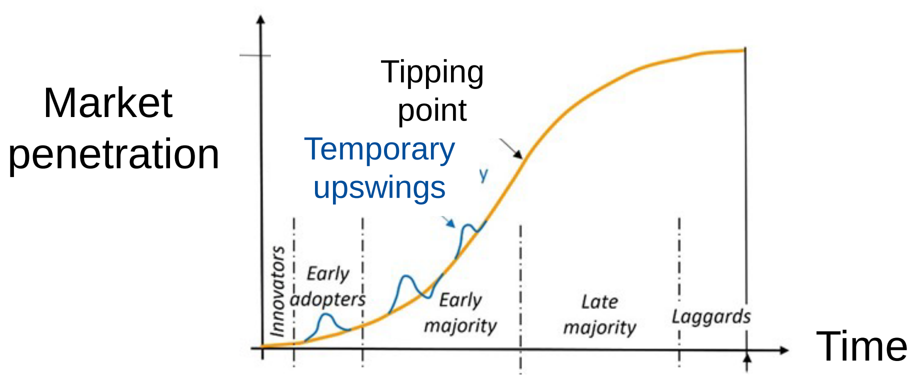
Market penetration

- Electrification is a slow but unrelenting process:
  - Example, electric power steering:
    - Worldwide deployment will skyrocket 72 % to 79M vehicles in 2018 from 46M in 2013 (NSK, 8/2014)
  - True across the board: Automotive, off-road, ships, more-electric aircraft, etc.

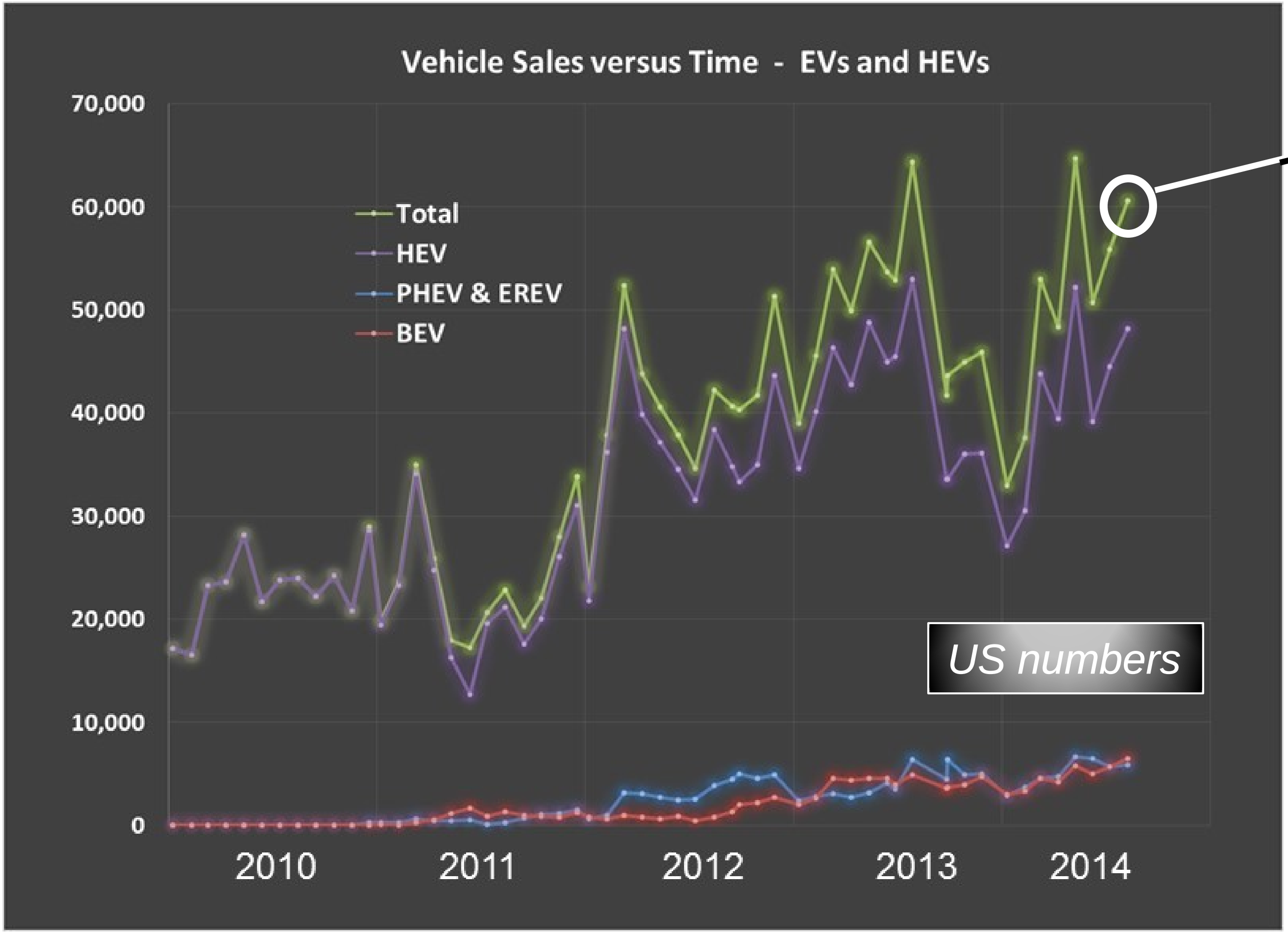
- Hybrids and EVs keep knocking at the door
  - Sales increasing steadily, with regular upticks in enthusiasm
  - But have not really reached a tipping point yet



Lequesne, Electrification Magazine, 2014

Sales of electric (EVs) and hybrid (HEVs) vehicles (US)

- Trend is up, but still a niche market

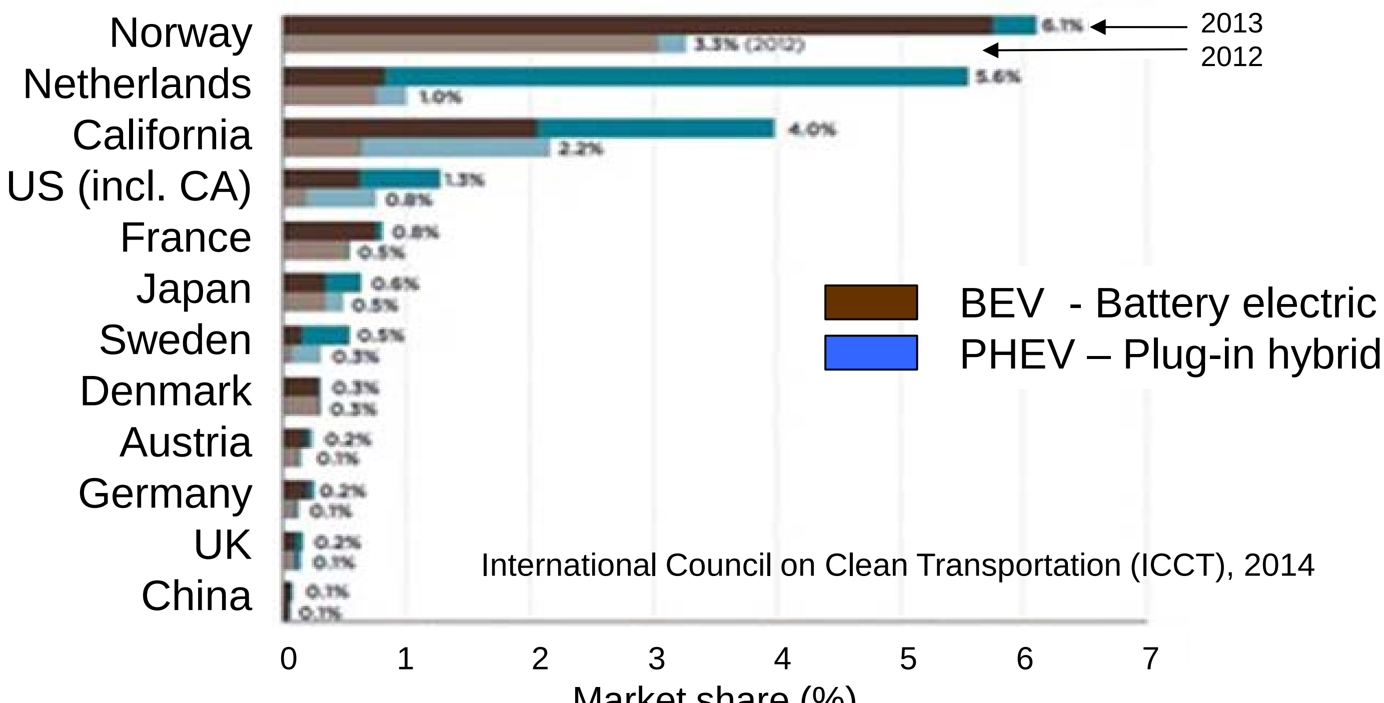


3.8% of total car sales

Source:
Electric Drive Transportation Association

World view

- Technology penetration world map shows large variations, mirroring incentives and the price of gas
- Gas and electric vehicles have a different economic model
  - Electric: High initial price, low energy cost
  - Gasoline: Opposite



China: Will it drive the technology?

- Very strong government incentives
  - Pollution mitigation
  - Economic independence
  - Leapfrog engine technology, and master the future

Source: chinae-vehicle.com

Source: Fleetsandfuel.com

Where are we going?

- So many contradictory announcements

Harley-Davidson announces its first electric motorcycle, LiveWire

LA Times, June 2014

Image?

Eaton Discontinues Diesel-Electric Hybrid Trucks

Truckinfo.com, September 2014

Dollars and cents?

Trends (personal opinion)

- Electrification is real, but a slow process
- Hybridization will happen, but through the back door:
  - Stop-start systems
  - Move to 48V
  - Stop-start systems will "grow up" over time: brake energy recovery, vehicle launch
- Full hybrids and electric will remain niche for a long time
  - EVs face a fundamental problem with battery cost and charging time
    - 1 gal of gasoline is 120 MJ of energy - a 3 minute refill is 13 MW rate
  - HEVs have the cost and complexity of two powertrains
- Only China can truly accelerate the trend, if government stays steady

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Source: komatsu.com.au

Work in progress!