Rare Earth Magnets for hybrid and electric cars

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August 2014
Introduction : VALEO Presentation

Motivation : why more hybrid and electric vehicles?

NdFeB magnet in automotive context?

Conclusion
Key figures 2013

Sales
12.1 Bn €

Employees
74,800

Countries
29

Order intake:
14.8 Bn €

Research & Development Centers
51

Platforms of distribution
12

Production Sites
124
Structure: 4 Business Groups

- **POWERTRAIN SYSTEMS**: Develops innovative powertrain solutions aimed at reducing fuel consumption and CO2 emissions.

- **THERMAL SYSTEMS**: Designs and produces systems, modules and components to manage the thermal energy of the powertrain and provide comfort inside the cabin for each passenger.

- **COMFORT & DRIVING ASSISTANCE SYSTEMS**: Develops interface systems between the driver, the vehicle, and the environment, which help to improve comfort and safety.

- **VISIBILITY SYSTEMS**: Develops innovative systems which offer the driver perfect visibility, thereby improving the safety of both driver and passengers.

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# 4 Product Groups within the Powertrain System

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<td>Hydraulic Clutch Actuation</td>
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<td>Belt Starter Generator</td>
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<td>Electric Motors</td>
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**System Engineering & Transversal Innovation**
- CO₂ Emission Reduction
- Pollutants Emission Reduction
- Hybrid and Electric
R&D focus

VALEO R&D

9,400 employees
35 development centers
16 research centers

R&D expenditure: 5.3% of sales

More than 300 in-house research projects
More than 786 patents filed
More than 45 PhD students

More than 50 are joint research projects

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Motivation: why more Hybrid and Electric vehicles?
Agenda

- Why reducing fuel consumption ?
- How is energy used in a vehicle ?
- Solutions to optimize energy consumption
- Conclusion
Why reducing fuel consumption?

3 main reasons to reduce fuel consumption:

- Finite nature of oil reserves
- Regulation due to climate change and emission
- Mutation of society
Oil reserves

- Oil reserves are a non-renewable energy:
  - high cost variation
  - growing demand due to vehicle fleet increase (>2 Billions cars in 2035)
  - Strategic: energetic dependency

![Diagram showing vehicle fleet and transport demand](image)

**Vehicle fleet**
- Billions

**Transport demand**
- Billion toe

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*BP energy outlook 2035 (2014)*
Stricter regulation applied to:

- Pollutant emissions (NOx, CO...) have been reduced to a tiny fraction of the levels in the 1970s, (fuel combustion, catalytic converters...)

=> Since 2004, emissions requirements for nitrogen oxides (NOx) and particulate matter (PM) have been reduced by 90%
Regulation on pollutant emissions (2)

- Greenhouse gaz (C0$_2$) : road transport is responsible for 16% of CO$_2$ emissions => in EU, CO$_2$ emissions diminution of 35% between 2015 and 2020 for a whole vehicle fleet

*Source: The International Council for Clean Transportation.*
Politics are multiplying incentives:

- Environmental policies and measures to promote energy transition (environmental bonus on cars in Europe and California)
- Road pricing to discourage use of certain classes of vehicle, fuel sources or more polluting vehicles (London, Berlin, Milan)
Society mutation (2)

- Urban mobility is mutating:
  - Increase of urban population (48.5% in 2005 and 69.6% in 2050) and also number of vehicles
  - Awareness of environmental issues due to pollution: fuel economy label on car, air quality information, eco driving behavior
  - Electric vehicle sharing scheme: bike-sharing scheme Velib’ and electric car-sharing system Autolib’ in France

![Fuel Economy Label](Image)
How energy is used in a vehicle?

- Estimation for a conventional vehicle

Only 18-25% of the fuel energy is used to propel the vehicle, (depending on the drive cycle)
Solutions to reduce fuel consumption

- Huge potential either by reducing weight or improving overall efficiency.

- 3 main categories:
  - Internal combustion engine (ICE) improvements
  - Progressive electrification: hybridization, electrical auxiliaries, battery ...
  - Advanced drive train: transmission, low friction tires, aerodynamics, chassis weight reduction ...
Internal combustion engine improvements

- Smaller (downsizing), lighter and more efficient engines:
  - Variable compression ratio engines, which can operate at higher compression ratios at lower load.
  - Variable valve lift and timing (VVL) systems to adjust valve opening time and lift.
  - Cylinder deactivation.
  - Turbocharger or supercharger (mechanical, electrical) to increase power at higher load.
  - Friction reduction: improved materials and piston ring design, camless valve actuation, synthetic lubricants …
  - Advanced thermal management and optimized engine mapping strategy.
  - New fuel with reduced emissions.

Example: VW 1.8L TSI is estimated to provide 16% better fuel economy than the 2.5L engine that it replaces (on 2014 Jetta with 6-speed automatic) (source Volkswagen)

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Progressive electrification (1)

- More electrified components:
  - water pump,
  - electric air conditioning compressor
  - drive by wire: electro-hydraulic brake, throttle by wire, steer by wire…

- Energy storage components:
  - Battery (lithium ion polymer or NiMH): Increase specific power and specific energy
  - Battery: Maintain capability at high depth-of-discharge
  - Others: supercapacitor, flywheel…
Progressive electrification (2)

- Hybridization: complement ICE with electrical power (hybrid vehicle) or replace it (electric vehicle EV)
  - Motor / generator device
  - Power and control electronics (inverter) with associated software
  - Electrical energy storage (batteries, super capacitors, flywheel....)

VALEO Hybrid4All 15 kW 12/48 Vdc solution
Progressive electrification (3)

Different types of Hybrid vehicles:

- **Micro Hybrid (~1-3 kW)**
  - Automatic start / stop of ICE: prevents wasted energy from idling
  - Regenerative Braking: converts energy normally wasted during coasting and braking into electricity
  - Torque Assist: additional power to assist the engine in accelerating, passing, or hill climbing.

- **Mild Hybrid (~3-15 kW)**
  - Electric drive: propels vehicle without combustion engine

- **Full Hybrid (>15 kW)**
  - Recharge from the electricity grid

- **Plug in (PHEV)**
  - Conventional alternator mode sometimes
Progressive electrification (4)

Machine location

Front end
- Electric motor on Combustion Engine (Buick LaCrosse)

Transmission
- Electric motor in transmission (Toyota PRIUS)

Rear / Wheel
- Electric motor on the rear-axle (PSA 3008 HY4)
Progressive electrification (5)

Different types of Electric vehicles:

- **Full electric drive**
  - Motor mode: starter, torque
  - Generator mode
  - Regenerative Braking: converts energy normally wasted during coasting and braking into electricity

- **Extended range**
  - Gasoline engine + electrical generator to produce electricity only

EV

EREV
Progressive electrification (6)

Machine location

- **Back axle**
  - Electric motor on rear axle (BMW i3)

- **Range extender**
  - Range extender (BMW i3)

- **Front axle**
  - Electric motor on front axle (Nissan leaf)
Advanced Drivetrain

- Advanced transmission with higher gear ratios:
  - Enables engine to operate at most efficient speed
  - Optimized shifting
  - Optimized efficiency with low friction clutch parts, bearings, gear sealing elements...

- Weight reduction (chassis and body ~50% of a vehicle mass is in chassis and body): aluminum closure, high stress steel, carbon fiber ....

- Low rolling resistance tires

- Aerodynamics drag optimization: shape optimization grills shutters, underbody shields.

Material composition of the average automobile in the U.S., [Ward’s 2006]
Conclusion: Breakthroughs are a necessity

- Drastic improvement on ICEs needed, at least 5% fuel eco
- Hybrids are mandatory to reach at least 38% efficiency
- Even with limited numbers, EVs (with 100% FE) bring significant benefit

To reach 95g, ICE and transmissions efficiency is not enough, Hybrids and EVs will be necessary
Conclusion : (2)

Summary :
- Environmental, regulatory (EU 95g/km CO2 2020), society incitements
- Improved efficiency and reduce weight of vehicle
- Downsizing of ICE + boosting devices
- Affordable hybridization: micro, mild hybrid
- Multispeed transmissions
- Reduced parasitic

Trends to 2020 :
- ICE still predominant but with more and more micro hybrid solutions
- Grow of various hybrid solutions: from mild to full and plug in hybrid
- A few percent of EV
NdFeB magnet in automotive context?
Agenda

- Magnets in vehicle
- What kind of magnet for HEV/EV?
- Specification of a typical HEV/EV motor
- Which magnets are available?
- Challenges and Solutions?
Magnets in vehicles

- In typical car, between 70 and 150 individual magnets mainly ceramic or rare earth (NdFeB, SmCo) for:
  - Electric motors
  - Sensing
  - Actuators
  - Loudspeakers

Electric power steering (EPS)
Crank angle sensor
Electrically operated inlet valves
Ignition coil
Electric compressor (0 to 0.3 kg NdFeB)
Motor generator (HEV, EV) (0 to 2 kg NdFeB)
Alternator
Water pump
EGR valve
Electric brake
Loudspeaker
Gear shift

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NdFeB Magnets in vehicles

- In conventional car average estimation of 250 g of NdFeB and 10-20g of SmCo mainly in small motors and sensors (according to magnet manufacturers):
  - with 80 M conventional units sales in 2013 => 20 kt (kilotons) of NdFeB

- In HEV vehicle, ~1.25 kg
  - with ~3 M HEV units sales in 2013 => 3.7 kt of NdFeB that should increase

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>Magnet weight (g)</th>
</tr>
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<tbody>
<tr>
<td>Prius (traction motor) 2010</td>
<td>770</td>
</tr>
<tr>
<td>Yaris (traction motor)</td>
<td>620</td>
</tr>
<tr>
<td>Yaris (generator motor)</td>
<td>300</td>
</tr>
<tr>
<td>Honda accord 2005</td>
<td>800</td>
</tr>
<tr>
<td>Camry 2007</td>
<td>930</td>
</tr>
</tbody>
</table>
What kind of NdFeB magnet for EV/HEV? (1)

- Several type of permanent magnet synchronous machine using NdFeB. They differ first with their stators:

  - Distributed (Camry, i3, Volt)
  - Concentrated (Honda)
  - Round wire
  - Rectangular wire
What kind of NdFeB magnet for EV/HEV? (2)

- And the rotor shape (a few examples):

**V shape (single or double layer)**

- Toyota Camry and Lexus
- Toyota Prius III
- Chevy Spark

**I “flat” shape**

- Toyota Prius I
- BMW i3
Specification of a typical HEV/EV motor (1)

- Typical needs:
  - Low machine size (and weight) according to location in HEV:
    - same size as conventional alternator for front end
    - integrated in transmission or between the combustion engine and the gear box

- Cooling through 3 ways:
  - Engine Under hood Air temperature from -30°C to 130°C
  - Glycol water temperature from 60°C to 110°C
  - Oil cooling up to 120°C

Magnet temperature from -30°C to >150°C depending on application.
→ Need for magnets with high temperature stability
Specification of a typical HEV/EV motor (2)

- Torque / speed request with two areas in motor and/or generator mode:
  - Constant torque area => high torque with limited inverter current => **high remanent flux density at requested temperature**
  - Constant power area => voltage limitation of the inverter, magnet flux must be controlled with stator demagnetizing current up to short circuit => **High magnet Hcj, magnet must not demagnetize**

- Good corrosion resistance (oil, salt...)
  - **Appropriate coating**

- Efficiency: low rotor losses
  - **high resistivity**

→ High Br for high torque
→ High Hcj not to demagnetize
→ Good corrosion resistance
→ High resistivity
Which magnets are available?

- UH EH grades with:
  - Rare earth: Nd (and Pr) insure the magnet Br magnetic flux density, with ~31% mass content
  - Heavy rare earth: Tb or Dy, increase of the Coercive Force (Hcj) to prevent magnet demagnetization but decrease magnetic flux density, for Dy content ~5.5%

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What are the challenges? (1)

- Finite heavy rare earth resources

Most of production is located in China and since 2005 China has decided to limit their exports by quotas policy to:

- Control their resources (limit illegal exports, control mining licenses, creation of stockpile…)
- Promote their downstream production

Consequence in 2010: -40% quota → major crisis.
What are the challenges? (2)

- Long term availability and access of heavy rare earth (Nd, Tb) for NdFeB magnet production => supply must be reliable

- Environmental impact of magnet extraction

- Cost instability due to:
  - Scarcity (time lag between production and growing demand)
  - Higher complexity of extraction (diminution of mineral rare earth content ….)
  - Political issues

Satellite view of China's Baotou rare earths complex. Mines are at top right, waste lakes are at left.
What are the solutions?

Solutions will involve tradeoffs (no single solution for all applications):

- Remanence
- Hcj
- Temperature stability
- Weight
- Efficiency
- Magnet
- Electrical machine
- Availability
- Cost
- Size
- Torque
- Speed

2 ways of improvement:

- Magnet properties and associated process
- Electrical machine design
What are the possible solutions: magnet side?

- Develop/improve magnet material with properties at least equal to current NdFeB magnet with:
  - Combination of material from different geographic regions with fewer heavy rare earth content, a few possible examples:
    => reducing Dy diffusion by optimized grain size for instance
    => other disruptive technologies (new magnet)

- Easily manufactured to final shape and size
  => increase magnet yield rate by limiting machining

- Recycling magnet material
What are the possible solutions, machine side? (1)

- Electrical machine design trade off, to use less magnets:
  - Thermal environment with better cooling solution like air to water or water to oil spray... => reduce magnet temperature effect
  - Improve iron silicon material => for instance less flux leakage in iron silicon bridge with higher yield strength iron silicon material
  - Optimize magnet shape (I,V,...) : increase reluctant torque instead of hybrid (magnet flux x current torque)
  - Inverter : current (more torque) or voltage (more power)

- Substitutions based on alternative electric motor designs

![2003 Prius](image1.png)  ![2004 Prius](image2.png)  ![2010 Prius](image3.png)
What are the possible solutions, machine side? (2)

<table>
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<tr>
<th>Rotor structure</th>
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<th>Induction</th>
<th>Wound rotor assisted with magnet (claw pole)</th>
<th>Switched reluctance</th>
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<td>Cost</td>
<td>Noise</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+++</td>
<td>- (variable)</td>
<td>+</td>
<td>++</td>
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</table>

Permanent magnet machines offer smaller size but at high cost. Wound rotor (claw pole structure) or Induction Motor could be an alternative solution depending on the application requirements.
Conclusion
Due to finite nature of oil reserves, regulation due to climate change and mutation of society, HEV (micro mild or full) will progressively replace conventional vehicles.

Permanent rare earth machines are a good candidate for HEV vehicle owing to their low weight and size compared with other topologies.

But the availability and cost of heavy rare earth is a key challenge of these machines.

That can be solved by combining improvement on magnet material and associated electromagnetic design.
Thank you for your attention!