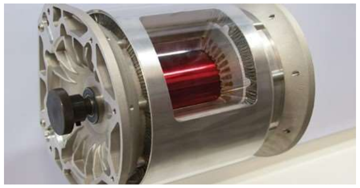

Source: Chargedevs.com
Photo by Windell Oskay

Source: IEEE IAS Magazine, 2017, Sarlioglu, et. al.

Source: IEMDC tutorial,
Hendershot and Buress, 2017

Electric machines for automotive propulsion: History and future

Bruno Lequesne, E-Motors Consulting, LLC
Marquette University, ECE Colloquium Series
October 29, 2019

Presentation available at: emotorseng.com

MOTORS Consulting, LLC

Background

- Modern hybrids and electrical vehicles (EV) are now over 20 years old: Adults!
  - GM EV1 (1996)
  - Toyota Prius (1997)
- We can start to see the evolution of some of the underlying technologies, from these first two models to current ones
- Focus on electric machines, and on commercial (production) designs
- Presentation will go over the changes and decisions made for production vehicles
  - Then extrapolate to the future

GM EV1

Toyota Prius Gen1

Source: Wikipedia

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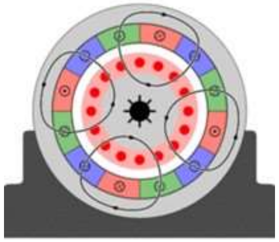
Personal introduction

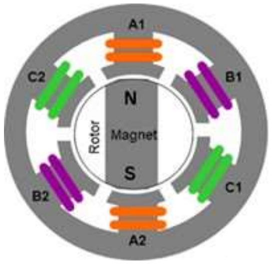
- General Motors Research Labs: 1984-1999
- Delphi Research, Delphi Advanced Powertrain Group: 1999-2009
- Eaton: 2010-2014 (hybrid commercial vehicles)
- Independent consultant (E-Motors Consulting, LLC): 2014
- Chair, IEEE Transportation Electrification Community (2019-2020)
- President, IEEE- Industry Applications Society (2011-2012)

Presentation outline

- Induction motor: From EV1 to Tesla to belt-driven
- Permanent Magnet (PM) machines:
  - Configurations
  - Magnet usage and material
  - Other attributes: Speed, windings, efficiency, etc
- Machine location and integration (for hybrids)
- Future and conclusions



Induction motor:
Currents are induced in rotor bars

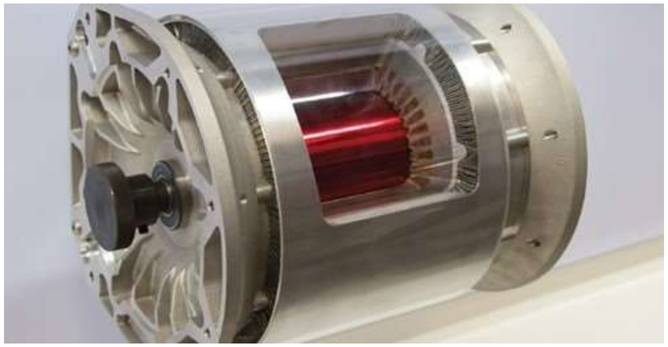


PM (brushless) motor:
Magnets in rotor

Induction motors for propulsion: Tesla's choice

- Tesla is well known for using induction for propulsion (until recently)
  - Roadster motor: 4-pole, induction 185kW / 270Nm (peak)
- Historical reasons:
  - People and companies behind the Tesla motor came from GM EV1
    - Wally Rippel with AC Propulsion then Tesla

Tesla motor (2013)



Source: Chargedevs.com
Photo by Windell Oskay

Tesla rotor (2007)

Source: Chargedevs.com
Photo by Tinou Bao

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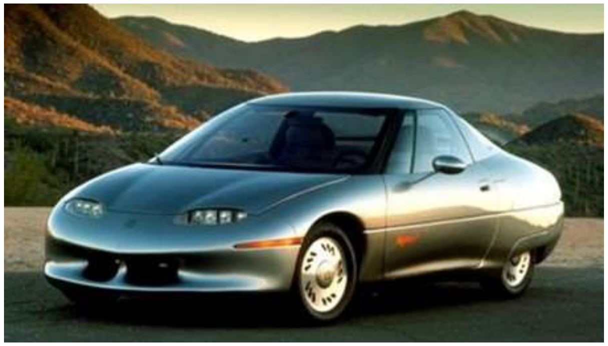
Roots of Tesla's choice: GM EV1

- GM experiments with EVs in early 90s was based on induction motor
  - With copper rotor for higher efficiency / longer range
  - Features were retained for the Tesla

GM Impact
Concept car (1990)



Source: Wikipedia

GM EV1
Production (1996)

Source: Wikipedia
Photo by C. Ableiter, Museum Autovision, Altlußheim, Germany

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Why did GM choose induction for the EV1?

- GM co-discovered Nd magnets (with Sumitomo), 1984
- GM used Nd magnets in SunRaycer – Winner of solar car race (1987)
  - SunRaycer was a publicity stunt
  - Showcase GM as high tech
  - Publicity for Nd magnets…

SunRaycer

Source: cleantechnica.com

Surface PM motor
Similar to SunRaycer's

Source: Naidu, et.al., IEEE TIA 1997

- Possible answer: Impact and EV1 were under a lot pressure from management to succeed
- Nd magnets were young (risky)
- **Induction was a safe management choice**

- Once PM technology matured, induction was displaced and debate ended

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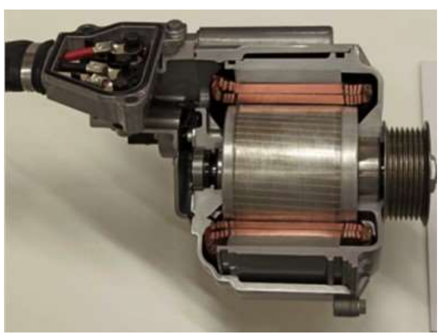
Place for induction: 1) Starter-generator

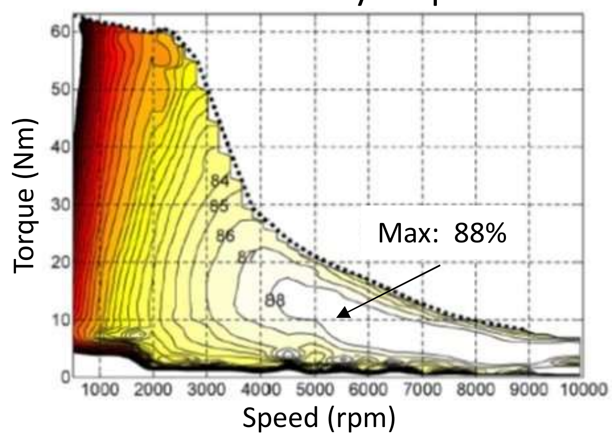
- Induction is used often belt-driven for starter-generators
  - Example: GM BAS system (Buick)
- Reasons:
  - Sold to mainstream customers, not early hybrid adopters
  - Hence, cost sensitive, and induction is cheaper
  - Also, efficiency is not as critical as in full hybrid
- Induction choice not universal (Hyundai Sonata 2012 uses PM)

GM induction starter-generator



Source: hybridcar.com

Efficiency map



Source: IEEE TIA, 2015, Jurkovic, et. al.

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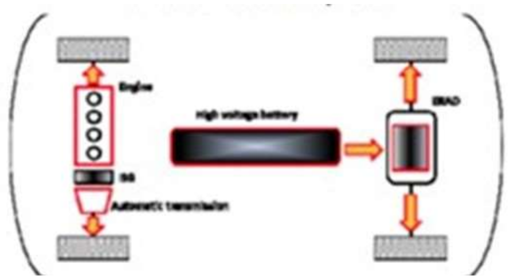
Place for induction: 2) 4-wheel drive (through-the-road hybrid)

- Engine on front axle, electric motor on back axle
  - Mechanically simple (but control challenge)
  - Provides on demand 4-wheel drive
  - Peugeot, Volvo V60, BMW i8, etc
  - Marketed by Siemens, Valeo, Magna, JinJin, BorgWarner, etc
- Problem with PM motors: Losses at zero torque
  - Magnets induce losses if motor rotates at no load
  - Takes place when motor is not active (2WD operation)
- Two solutions
  - Clutch or induction motor



Source: www.greencarcongress.com /2015/05/20150517-xc90.html.

Volvo / Siemens

Siemens SIVETEC

Induction (MRI) Synchronous (PM) (MRS)

Source: w3.siemens.com/topics/global/en/electromobility/pages/powertrain-ecar.aspx

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PM brushless: Early roots

- Toyota and Honda chose PM technology early on (1990s)
  - Surface permanent magnet (or near surface)
  - Honda: Motor mounted on flywheel
  - Prius: Inside transmission

Honda

Insight

Source: Wikipedia
CC BY-SA 2.0 de

2005 Accord rotor

Source:
ORNL Report TM-2006-535

Toyota Prius

2004 motor

2003 rotor

Source: ORNL Report TM-2006-423

eMOTORS Consulting, LLC

Magnet configuration: Surface or interior (buried) magnet?

- Buried magnets design increasingly complex: Double V, inverted Delta, …

Surface
(or near surface)

Honda Accord 2005

Sources: ORNL Reports
Staton & Goss, CWIEME 2017

Interior

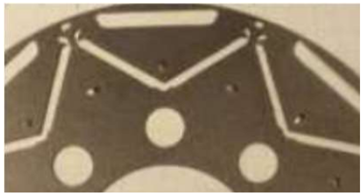
V

Toyota Prius 2004

Double V

GM Spark 2013

Inverted Δ



Nissan Leaf 2010

Double U

BMW i3 2013

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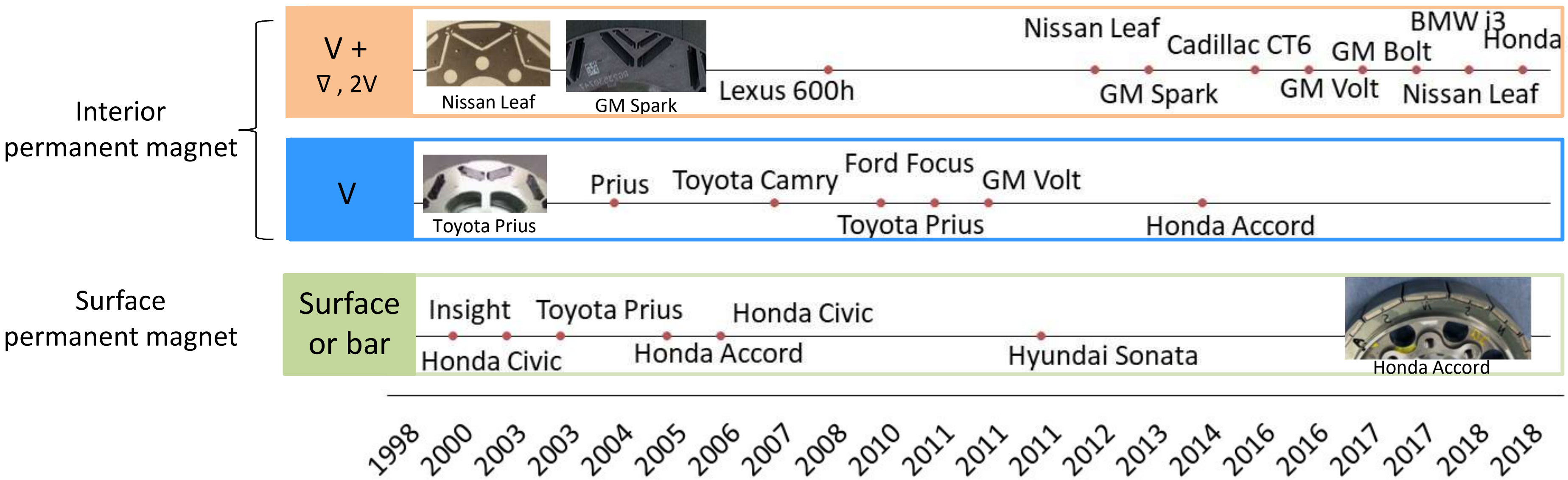
Magnet configuration: Surface or interior (buried) magnet?

- Early on, two approaches:
  - Surface (or bar) layout, mostly on flywheel - Honda
  - Buried magnets, V shape – Toyota Prius (2004)
- Surface magnet motors on flywheel have fallen out of favor



Surface versus buried magnets = Flywheel versus transmission location

- **Surface magnets** ⇔ flywheel location
  - Speed limited to that of engine (6,000 rpm), hence less need for flux weakening and wide speed range
  - Short length makes concentrated winding useful
    - Provides some reluctance from stator side

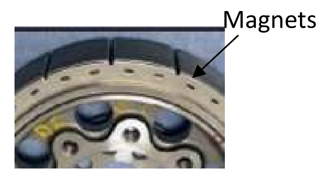
- **Buried magnets** ⇔ with other locations: Inside transmission, etc.
  - Better for motor design:
    - Better length/diameter ratio
    - Full use of reluctance torque
    - Wide flux weakening / speed range
    - Resistance to demagnetization
  - Full hybrids use 2 motors (Toyota Synergy, GM 2-mode): good system design of power flow from/to battery or gas tank

Flywheel (Honda)

Insight

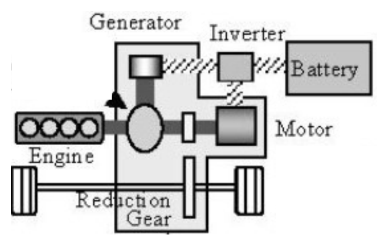
Source: Wikipedia CC BY-SA 2.0 de

2005 Accord rotor

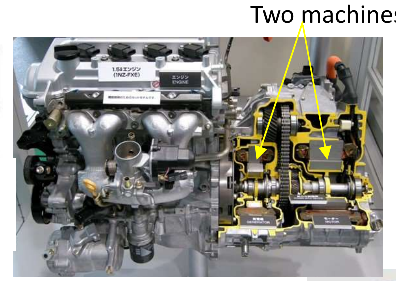


Source: ORNL Report TM-2006-535

Transmission (Toyota)



Source: IEEE PCC Conf. 2007 Asano, et. al.



Source: Wikipedia

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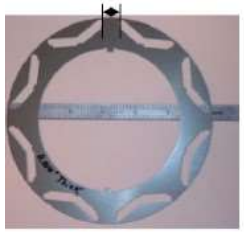
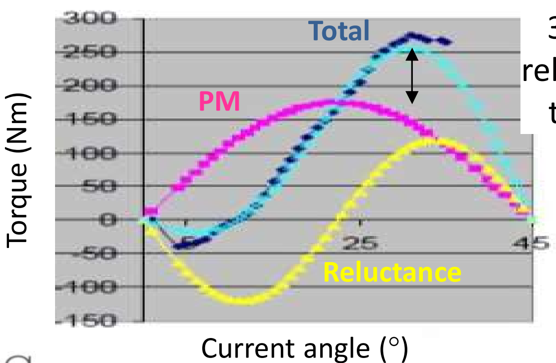
Buried magnets:
Still PM motor, or reluctance machine?

- Modern interior PM machines get almost half their torque from reluctance
  - Great achievement from PM motor technology
  - V shape provides two benefits: Flux concentration, and different direct/quadrature inductance, for reluctance

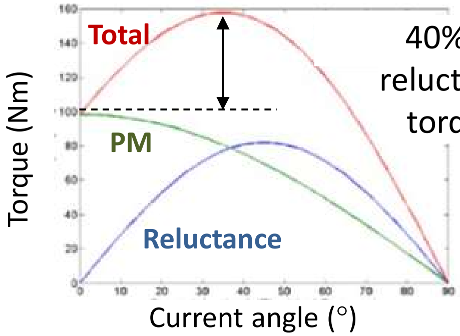


Prius 2004



30% is reluctance torque

Prius 2010



40% is reluctance torque

Source: ORNL reports

Magnet (rare-earth) cost

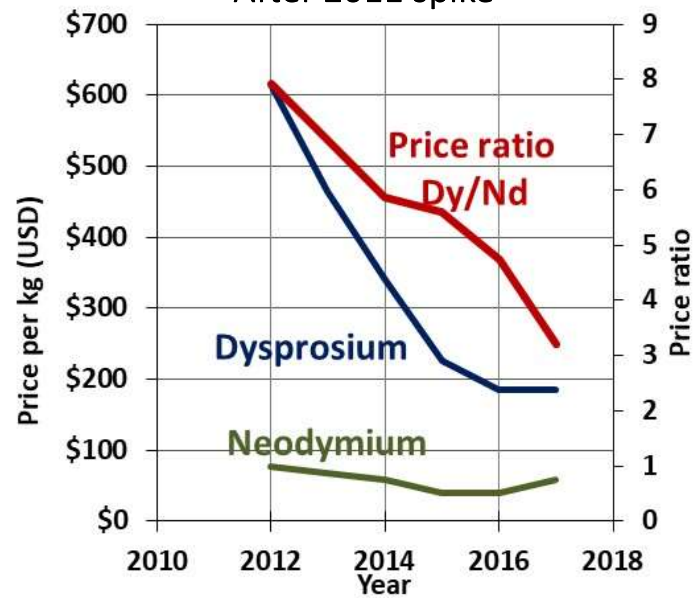
Magnets = $Nd_2Fe_{14}B$ + (Dy)

\$ \$\$\$

- Spike in raw rare earth prices in 2011 spooked the market
- Magnet cost due in part to additives, like heavy rare earth (Dysprosium)
- Dysprosium needed to resist demagnetization
- Prices have stabilized, AND Dysprosium not as expensive (in relative terms)
- Still, magnet cost can be 4 times Cu + Fe
  (Burwell, Goss, Popescu, Tokyo, 2013)

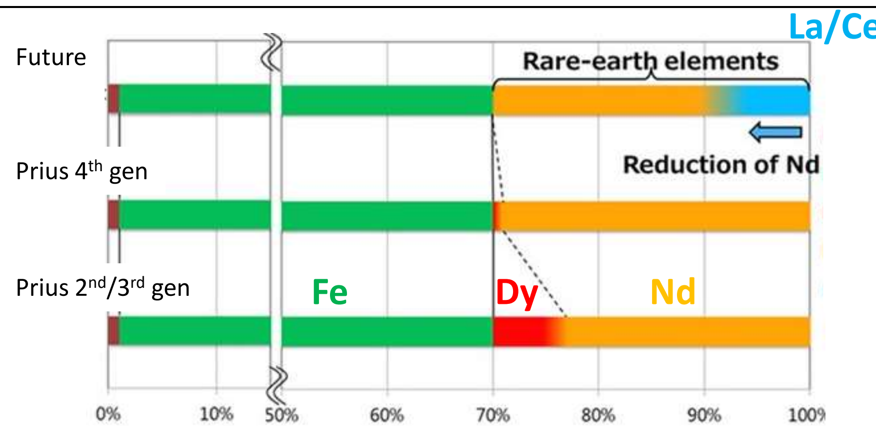
- Material and design development:
  - Reduce heavy rare-earth content
  - Reduce magnet volume (?)

Price of raw material
(US Geological Survey)
After 2011 spike



Material development: No heavy rare earth (Dy)

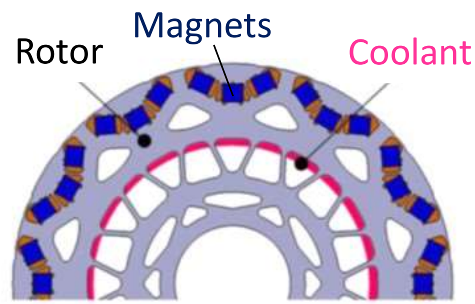
- Toyota (2018):
  - Eliminate heavy rare earth
  - Replace Nd with La/Ce
  - May reach production in 2020 in power steering motors



Source: Toyota newsroom, 2018

- Honda/Daido
  - Announced 2016: Magnets with no Dy
  - Motor design for Honda i-MMD (SAE 2019)
    - Uses rotor cooling

Source: daido.com, 2016



Source: SAE-2019-01-0600, Ito, et. al., Honda R&D

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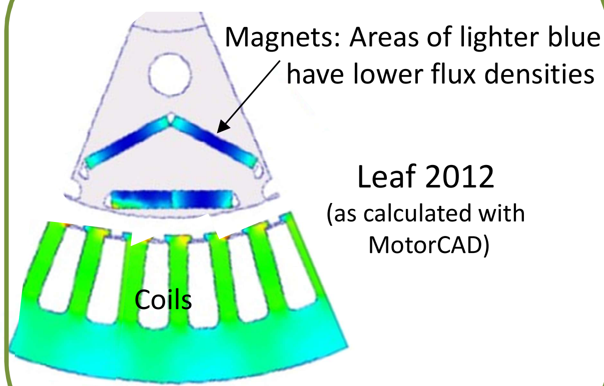
MARQUETTE

Material development: Grain-boundary diffusion

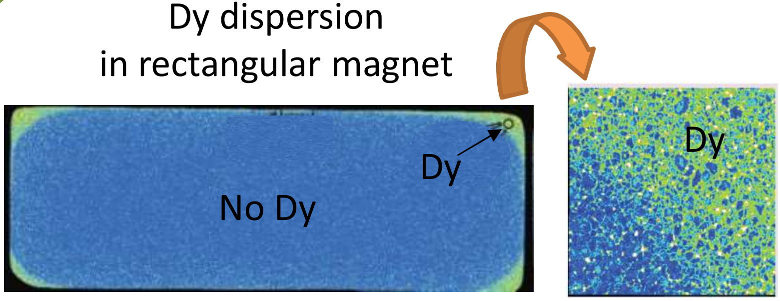
- Observation: The most likely part of a magnet to demagnetize is the surface and corners
- Development of magnets with Dy only near surface to resist demagnetization where it matters
  - Dy on grain boundary near surface
  - Finer grains
- Challenges: Balancing diffusion extent with need

Flux density in magnets



Source: Motor Design, Ltd, 2017

Dy dispersion in rectangular magnet



Source: IEEE Electrification Mag., 2017 (GM)

Nissan Leaf: Dy reduction

Source: SAE 2018-01-0461

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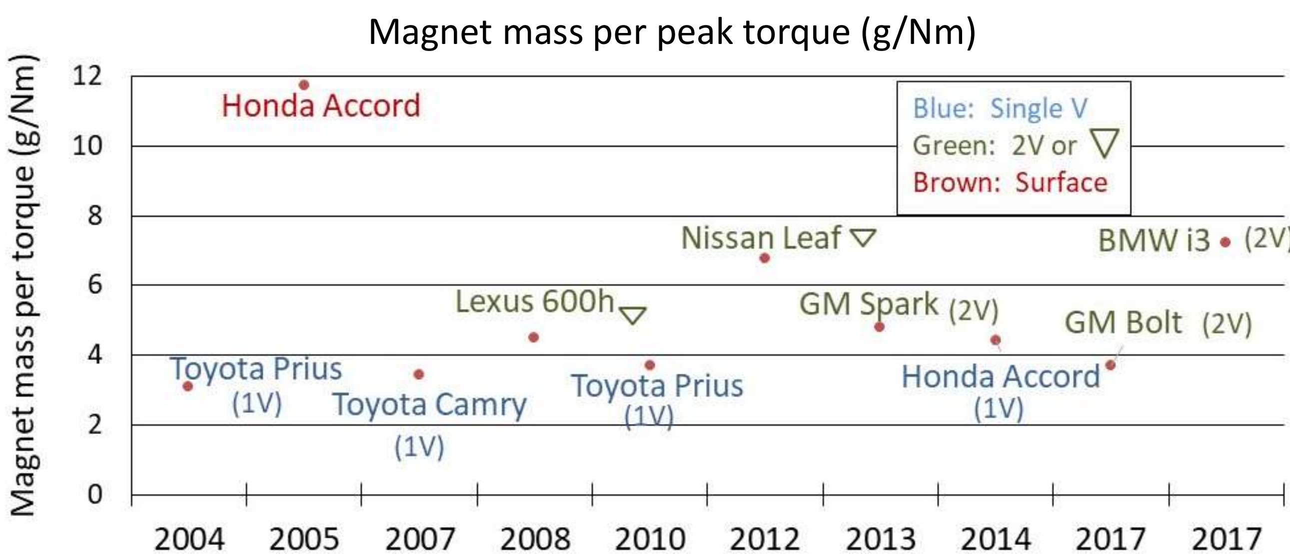
Are we using less magnet?

- Not really borne out by available data:
  - In fact, magnet weight (per torque) seems to increase with time
- Main differentiating factor appears to be magnet configuration:

  Single V motors use < 4 g/Nm versus 4 to 7 g/Nm for double Vs, ▽, etc

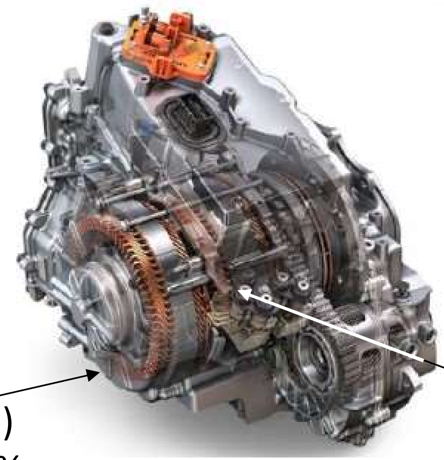


Way around using magnets: Combine motor types

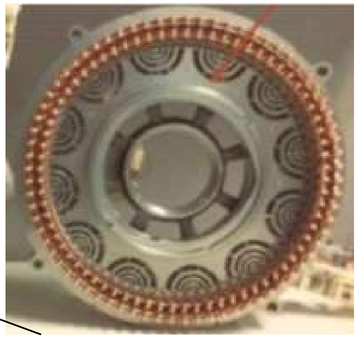
- For hybrid configurations with 2 motors:
  - One motor with Nd magnets, other with ferrite (or induction)
- Idea: Design motors and system such that each motor is used to its strength
  - Nd motor for efficiency (base), other machine as complement
  - Ferrite motor is actually more of a synchronous reluctance machine, with some magnets

GM Volt 2016

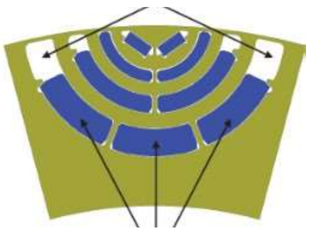
Motor (Nd)
Top eff: 96%



Powertrain



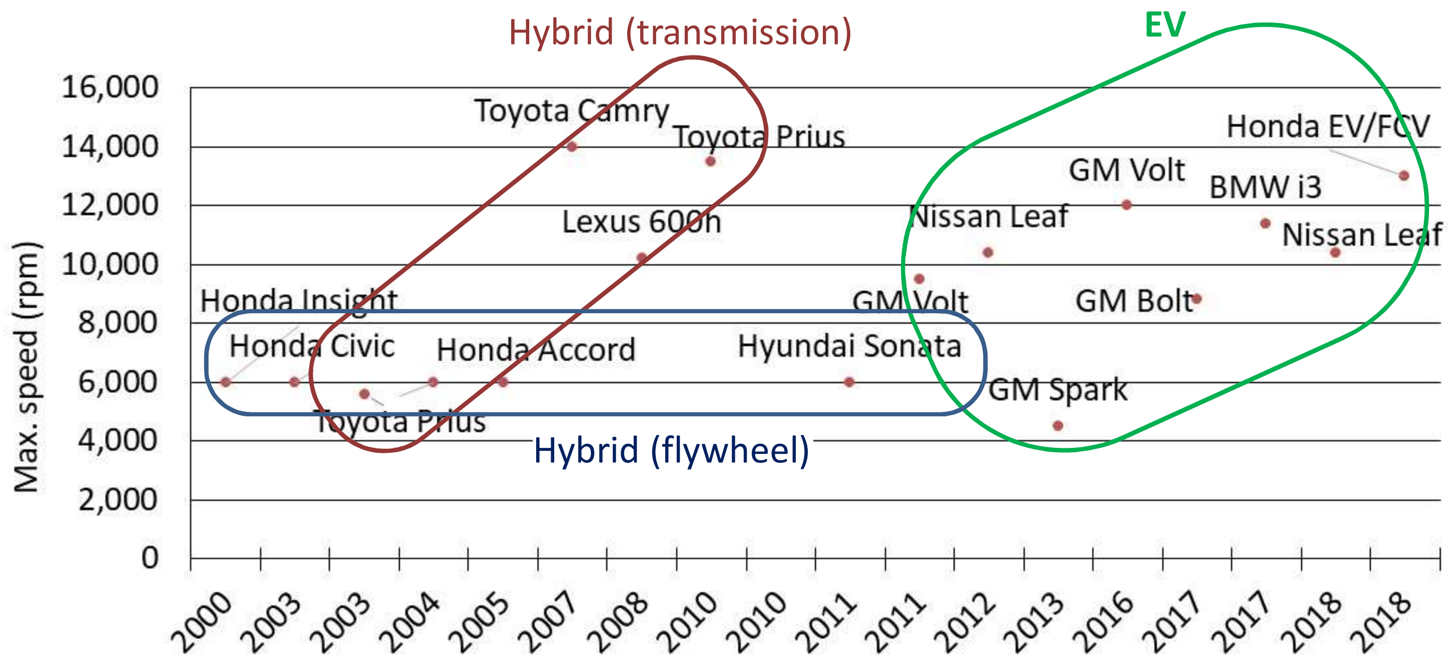
Generator (ferrite)
Top eff: 94%



Sources: Motor Design, Ltd, 2017 and IEEE ECCE, 2015, Jurkovic, et. al.

Maximum motor speed

- Plot of machine maximum speed over last 20 years
- The trend is definitely up
  - 14,000 to 20,000rpm is not that fast, but new to traction
  - Loss issues need to be addressed



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Winding configurations

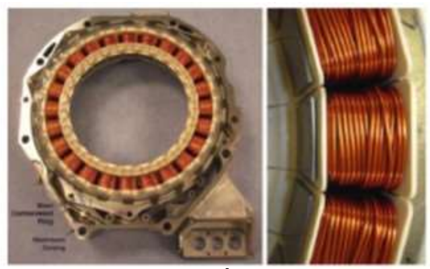
- Concentrated windings have made significant inroads in PM machines in general
  - Not that much for traction motors, except on flywheel (Honda)
- Significant development has been the bar (or hairpin) winding (Remy/GM, 2006)
  - Allows much better cooling of copper

Distributed windings

Prius 2010

Source: ORNL-TM-2010-253

Concentrated windings

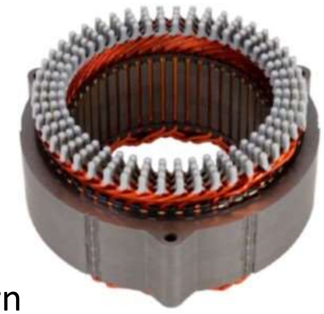


Accord 2005

Source: ORNL-TM-2006-535

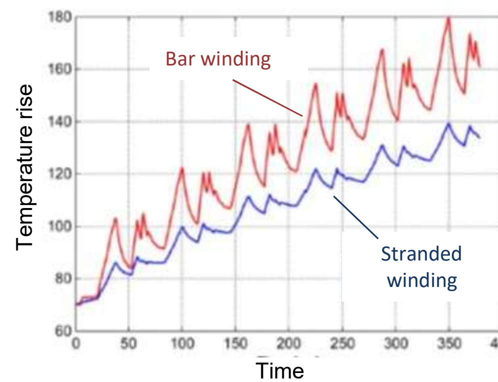
Hairpin (bar) windings

Single turn GM 2006



Prius 2017

Sources: IEEE ECCE Conf. (Rahman, et. al.) and IEMDC tutorial, Hendershot and Buress, 2017



Source: Jurkovic, et. al, (GM) IEEE TIA 2015

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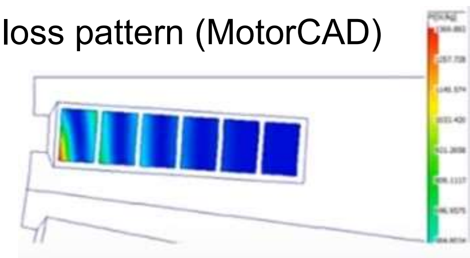
Bar winding: High speed

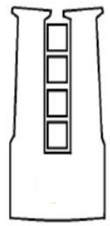
- Proximity losses in bar windings need careful consideration
  - AC resistance can be 10 times the DC resistance!
  - Zhang and Jahns, IEMDC 2015

AC loss pattern (MotorCAD)

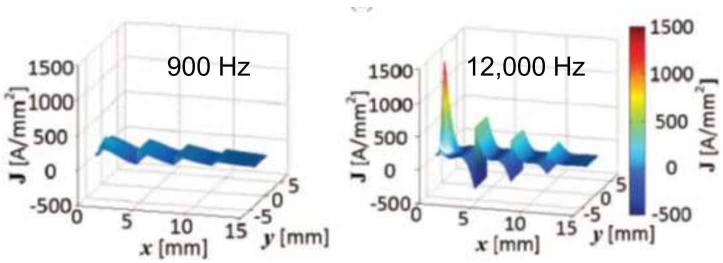


Source: motor-design.com)

4-bar winding



Current density versus position within slot

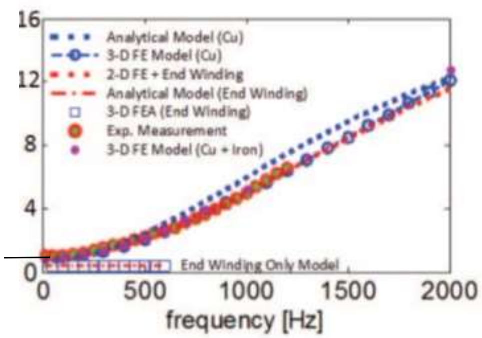


Source: IEEE IEMDC 2015 (Zhang and Jahns)

Resistance versus frequency

Base: DC

1



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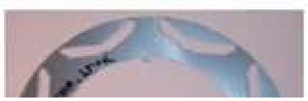
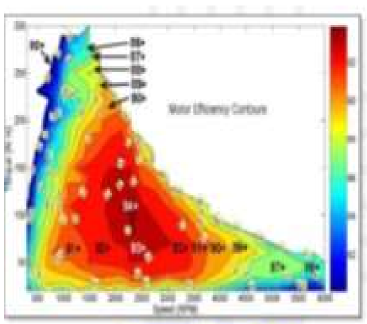
Efficiency: Progress?

- Peak efficiency in mid 90%
- Hard to discern much improvement over time
  - Progress from magnet material, reluctance torque, winding fill
- Best in sample below: Nissan Leaf (97%)
  - Efficiency more important for EVs than hybrids (higher motor efficiency = less battery for given range)
  - This indicates that designers trade off the last percent of efficiency for something else (cost, size, etc)

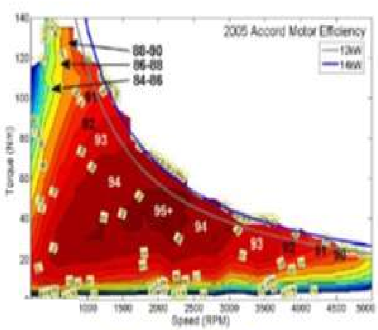
2004 Toyota Prius	2005 Honda Accord	2007 Toyota Camry	2012 Nissan Leaf	2014 Honda Accord
V shape	Flat	V shape	Inverted Δ	V shape
93%	95%	94%	**97%**	95%



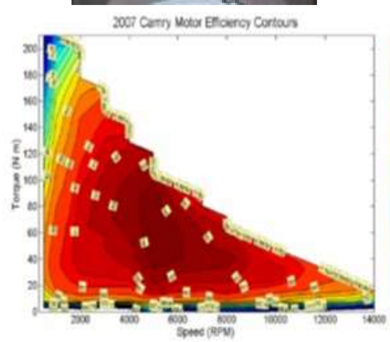


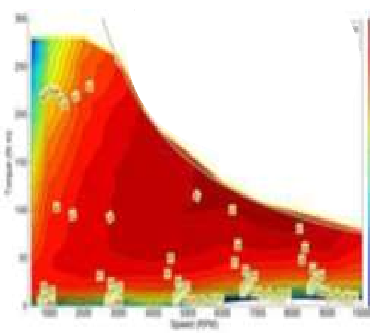
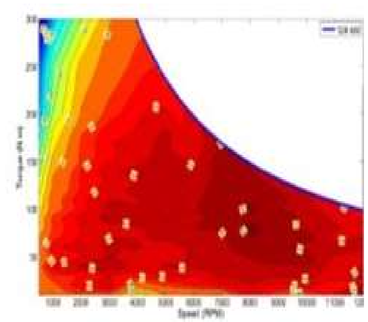


Measured Efficiency Map



Measured Efficiency Map

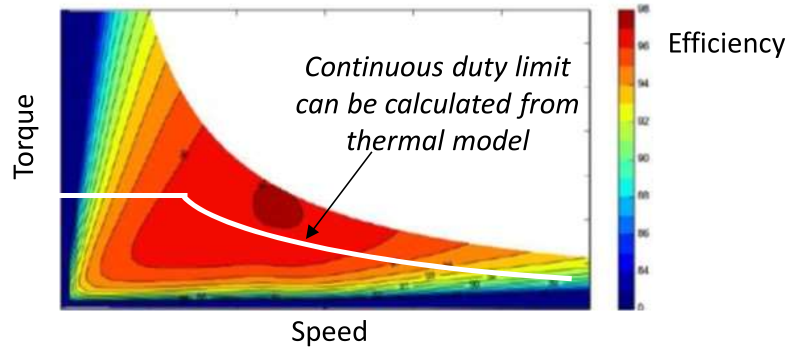


Sources: ORNL and Staton and Goss, 2017 CWIEME

Machine modeling

- Late 1990s, first breakthroughs in terms of modeling:
  - Finite element electromagnetics and SPEED software for machines
- Since 2010:
  - Complete automated efficiency map calculation
  - Multiphysics: Magnetics + Thermal (Motor Design Ltd., etc)
- Very significant as it allows:
  - Comprehensive optimization of entire torque-speed map
  - Reduce design safety margins



Source: Motor Design, Ltd, 2017

Electric machine location: Motor + Gear integration

- News from corporate world:
  - Borg-Warner (gears) acquires Remy (motors) (2016)
  - American Axle "is developing an electric rear-drive unit" (Wardsauto.com, May 2017)
  - Dana (axles and transmissions) acquires TM4 (motors) (2018)
- Possible reasons:
  - With hybrids and EVs, fewer gears: Gear manufacturers looking at other revenues
  - Gear integration provides system benefits:
    - With transmission, smooth continuous power flow, single oil cooling
    - With axle: 4-wheel drive and torque vectoring of the two wheels
  - Makes even more sense for EVs: Group all main mechanical components together

EV integrated motor + gear
(Borg-Warner, 2017)

Source: www.borgwarner.com

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MARQUETTE

Can we extrapolate and read the future?

- Efficiency is already high (peak at 96%), hard to do better
- Lower cost:
  - Trends are contradictory:
    - Reduce cost by using less magnet, and less heavy rare-earth
    - But magnet content is not really decreasing
    - Market is accepting magnet cost, or system optimization makes magnet cost acceptable
  - Nd magnets, interior PM machines are here to stay
- Higher speeds:
  - Reduces machine size (and cost)
- Better cooling, integrated cooling
- Improved modeling will lead to better optimization
- Integrated design: Motor + gear/transmission

Pininfarina design
Source: www.designboom.com

eMOTORS Consulting, LLC

Conclusions

- Motors are important to EVs and hybrids, but not the star (batteries are)
- In the last 20 years:
  - Efficiency is very high and hard to improve
  - Motor moved from flywheel to transmission or axle
  - The interior permanent magnet motor has increased its market dominance, despite material concerns
    - Evolution from single V pattern to more complex patterns (double V, etc)
  - Bar windings are gaining in importance
- Expected trends:
  - Higher motor speeds for reduced size and cost
  - Material development: Steel and possibly magnets
  - Further refinements in models, especially thermal and combined electromagnetic/thermal/mechanical
  - Integration, with transmission or axle

Source: Wikipedia

Rivian EV pick-up truck
Source: SAE Automotive Engineering, 01-2019

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Thank you!

Presentation (with bibliography) available at:

www.emotorseng.com

Material can be used, with proper reference as follows:

B. Lequesne, "Electric machines for automotive propulsion: History and future", Marquette University Colloquium, Oct. 2019, Available at: www.emotorseng.com

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