

Source: Chargedevs.com
Photo by Windell Oskay



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



Source: IEMDC tutorial,
Hendershot and Bures, 2017

Electric machines for automotive propulsion: History and future

Bruno Lequesne, E-Motors Consulting, LLC
ITEC Asia-Pacific
Jeju, Korea, May 2019

Material can be used, with proper reference as follows:

*B. Lequesne, "Electric machines for automotive propulsion: History and future",
keynote presentation, IEEE ITEC-AP 2019, May 2019*

Available at: www.emotorseng.com

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
- Presentation will go over the changes and decisions made for production vehicles
 - Then extrapolate to the future
- Focus on electric machines

GM EV1



Toyota Prius Gen1



Source: Wikipedia

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, etc
- Machine location and integration
- Future and conclusions

Induction motors for propulsion: Tesla's choice

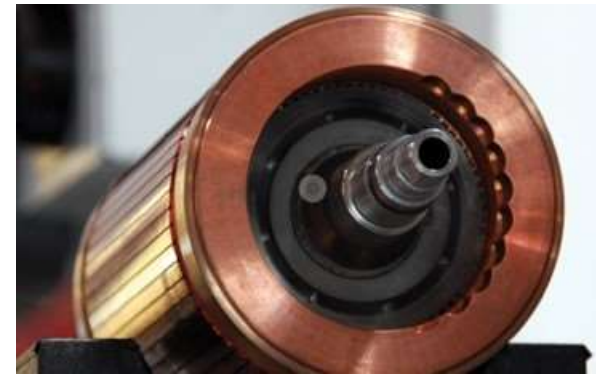
- Tesla is well known for using induction for propulsion
 - Roadster motor: 4-pole, induction 185kW / 270Nm (peak)
- Historical reasons:
 - People and companies behind the Tesla motor came from GM EV1

Tesla motor (2013)



Source: Chargedevs.com
Photo by Windell Oskay

Tesla rotor (2007)



Source: Chargedevs.com
Photo by Tinou Bao

Roots of Tesla's choice: GM EV1

- GM experiments with EV 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

Why did GM choose induction?

- 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 to succeed
- Nd magnets were young (risky)
- **Induction was a safer choice**
- Once PM technology matured, induction was displaced

Place for induction: Starter-generator

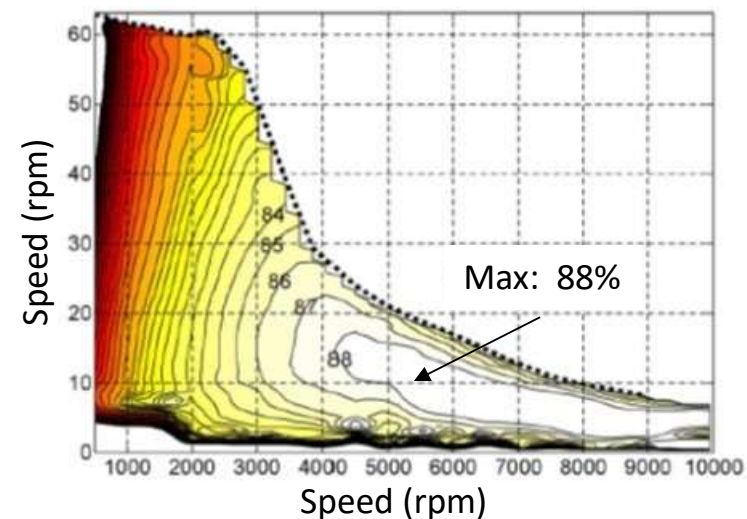
- Induction is used often for starter-generators
 - Example: GM BAS system (Buick)
- Reasons:
 - Sold to mainstream customers, not early hybrid adopters
 - Hence, cost sensitive, and induction is cheaper
 - Also, efficiency is not as critical as in full hybrid
- Induction choice not universal (Hyundai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

GM induction starter-generator



Source: hybridcar.com

Efficiency map



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

PM brushless: Early roots

- Toyota and Honda made a different choice: Use of PM technology
 - Surface permanent magnet (or near surface)
 - Honda: Motor mounted on flywheel
 - Prius: Inside transmission

Insight



Source: Wikipedia
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Honda

2005 Accord rotor



Source:
ORNL Report TM-2006-535

Toyota Prius

2004 motor



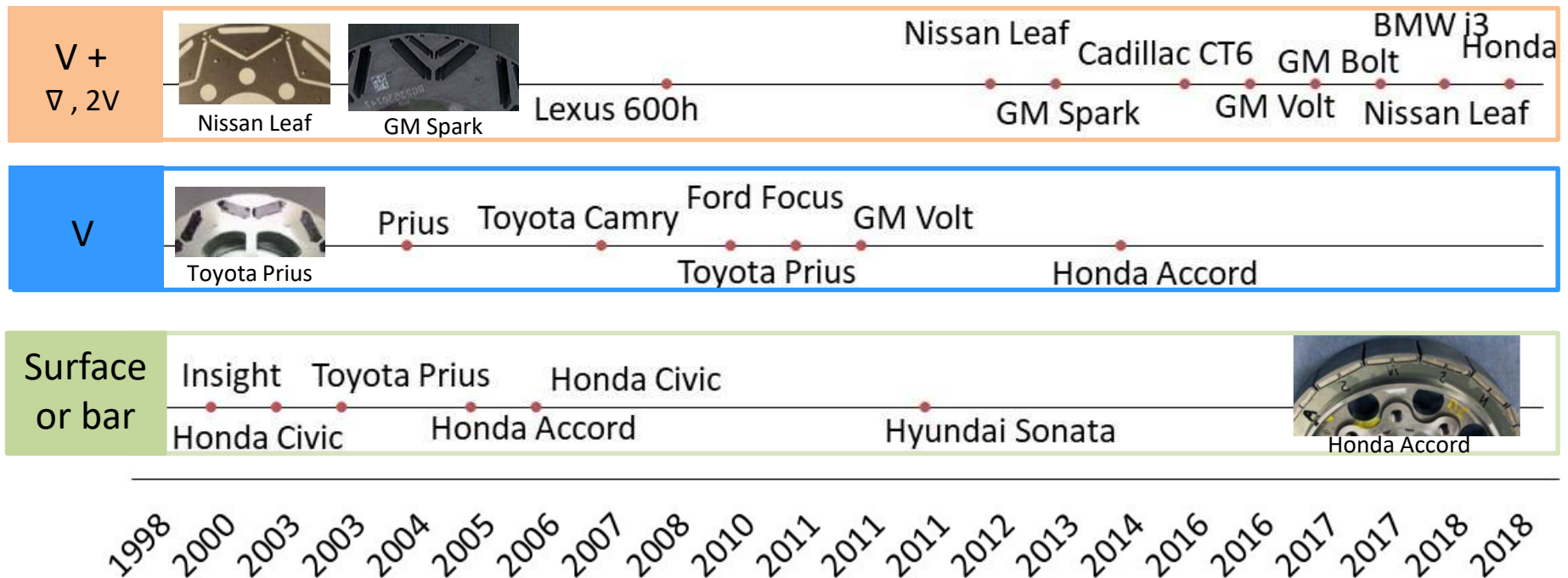
Source: ORNL Report TM-2006-423

2003 rotor



Magnet configuration

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



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

2005 Accord rotor

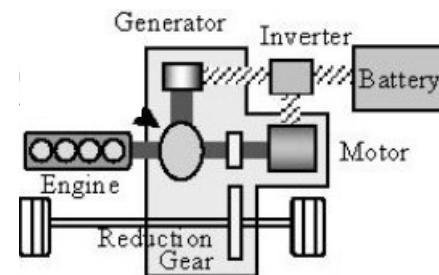


Magnets

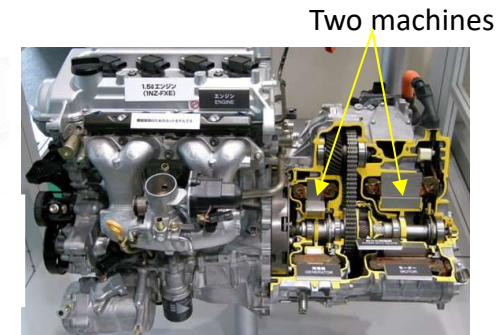
Source:
ORNL Report TM-2006-535

Source: Wikipedia CC BY-SA 2.0 de

Transmission (Toyota)



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



Source: Wikipedia

Buried magnets: Still PM motor, or reluctance machine?

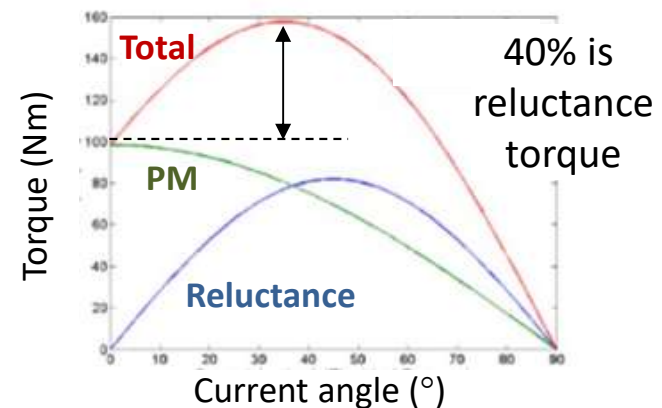
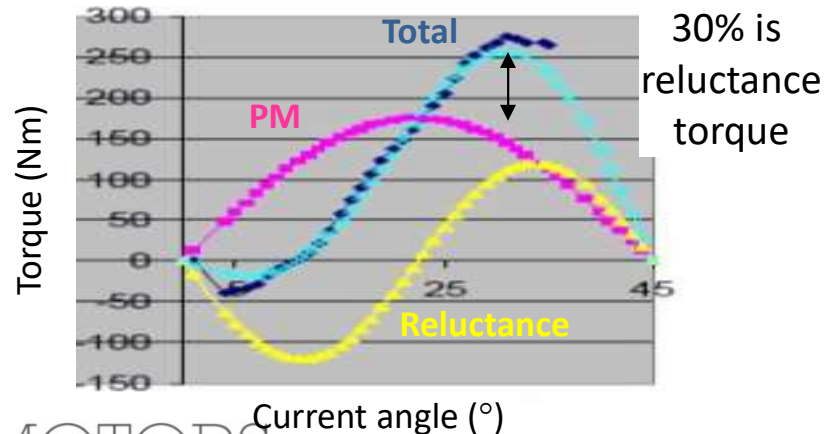
- Modern interior PM machines get almost half their torque from reluctance (synchronous reluctance specifically)
 - Great achievement from PM motor technology
 - V shape provides two benefits: Flux concentration, and different direct/quadrature inductance, for reluctance



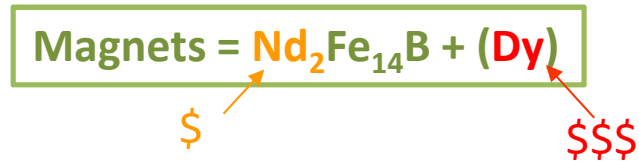
Prius 2004



Prius 2010

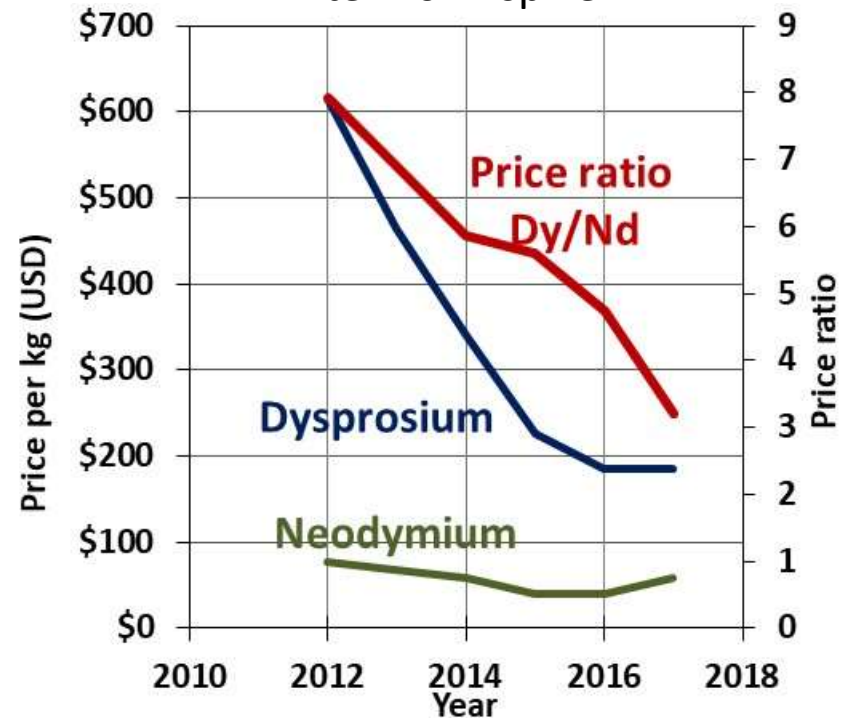


Magnet (rare-earth) cost



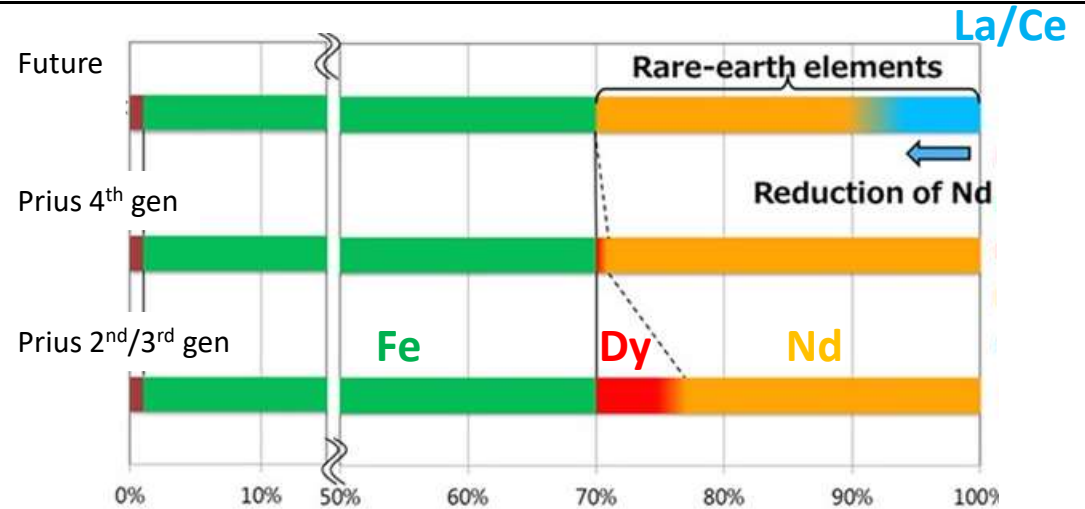
- Spike in raw rare earth prices in 2011 scared the market
- Magnet cost due in part to additives, like heavy rare earth (Dysprosium)
- Dysprosium needed to resist demagnetization
- Prices have stabilized, AND Dysprosium not as expensive (in relative terms)
- Still, magnet cost can be 4 times Cu + Fe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



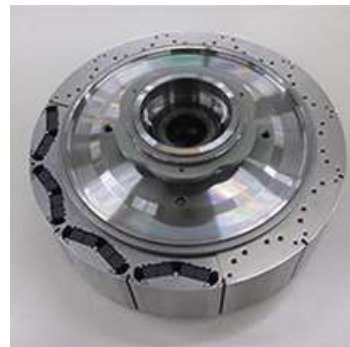
Material development: No heavy rare earth (Dy)

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

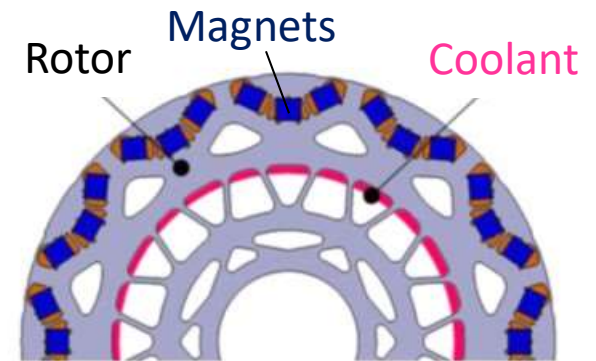


Source: Toyota newsroom, 2018

- Honda/Daido
 - Announced 2016
 - Motor design for Honda i-MMD (SAE 2019)
 - Uses rotor cooling



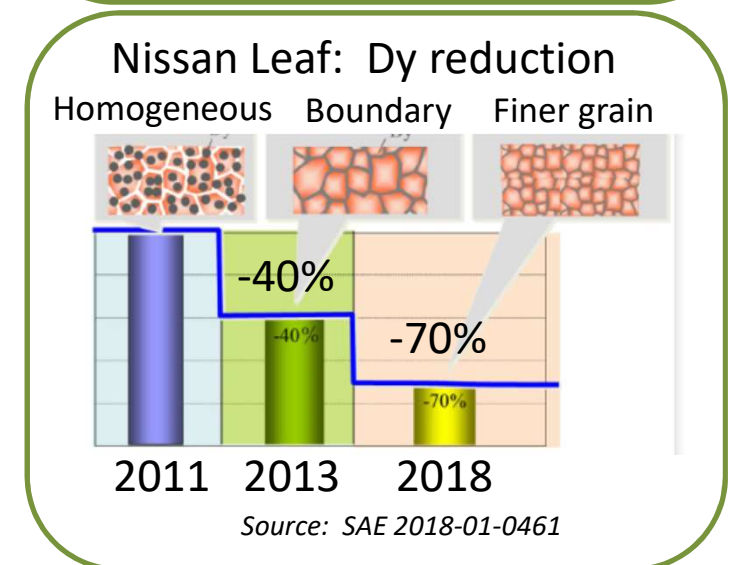
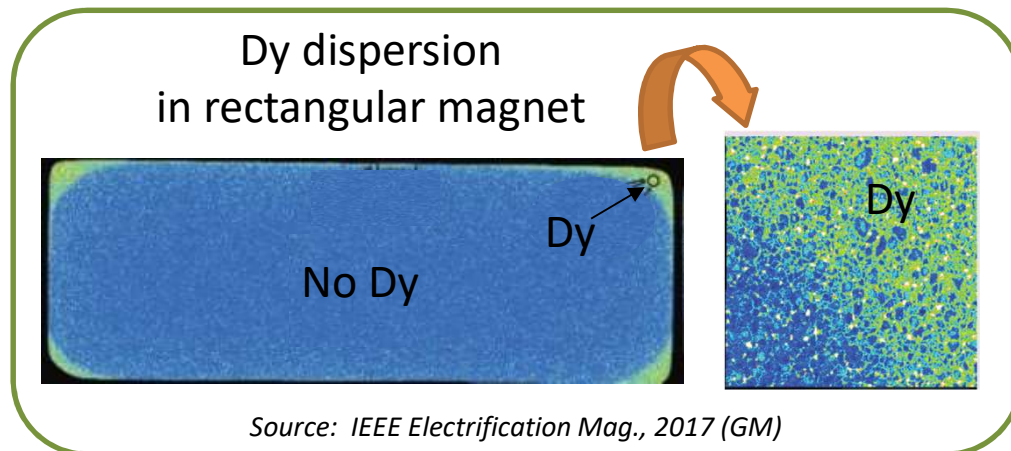
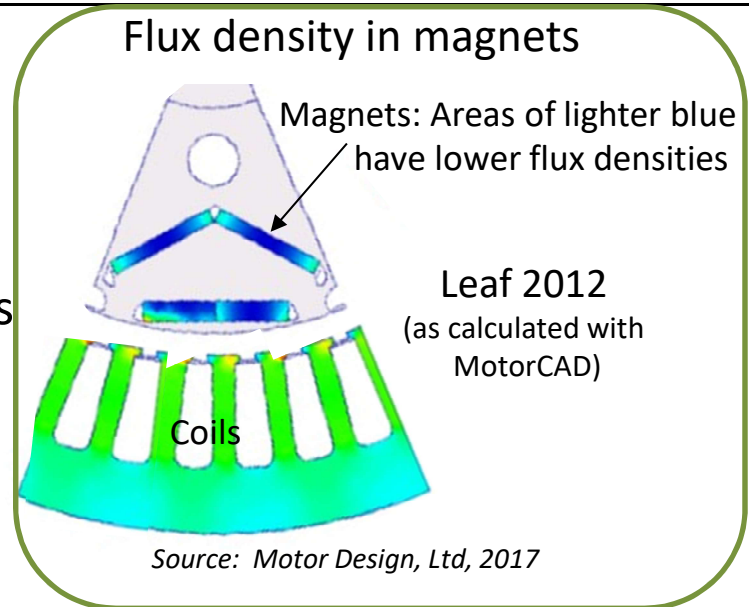
Source: daido.com, 2016



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

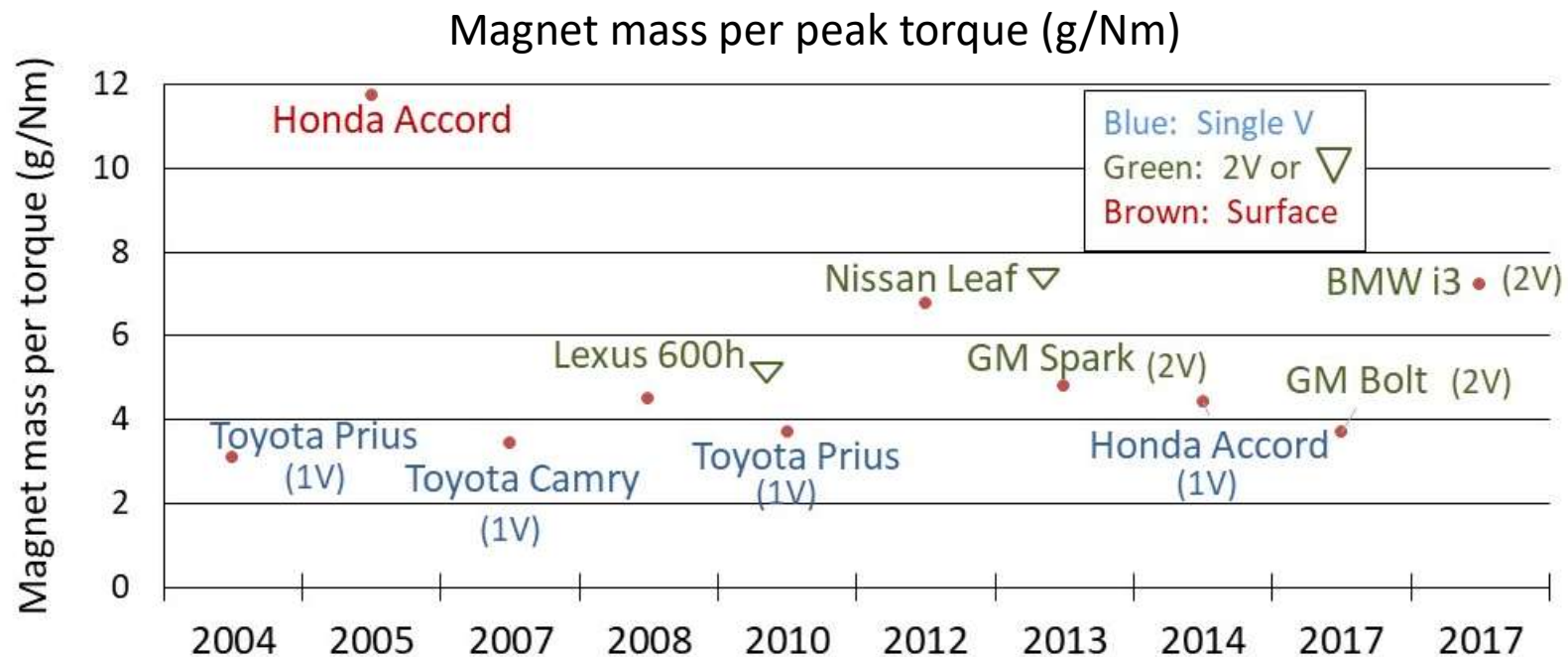
Material development: Grain-boundary diffusion

- 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



Are we using less magnet?

- Not really born 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



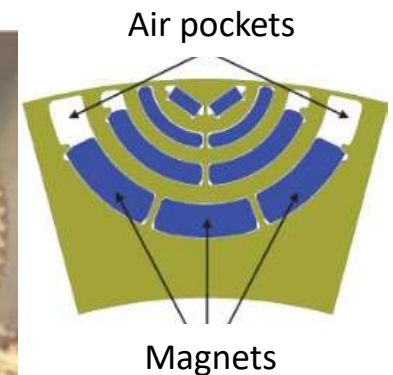
Motor (Nd)
Top eff: 96%



Powertrain



Generator (ferrite)
Top eff: 94%

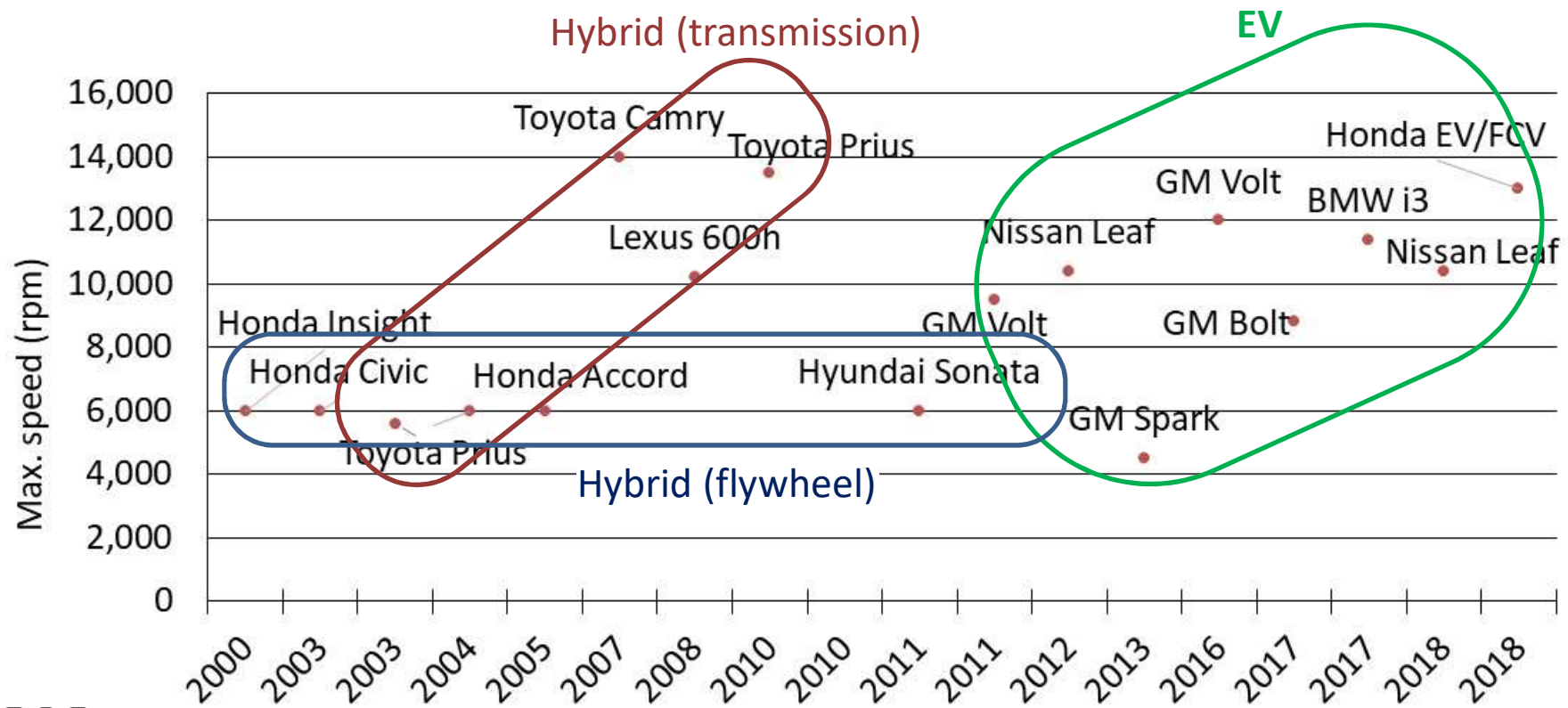


Air pockets

Magnets

Maximum motor speed

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



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
 - Allows much better cooling of copper

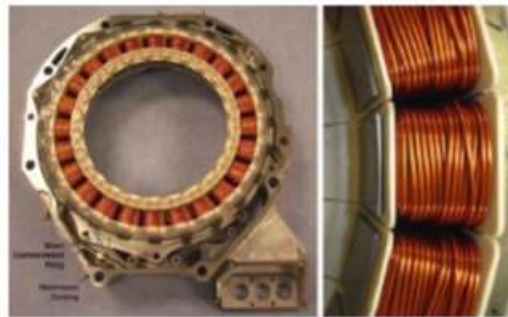
Distributed windings



Prius 2010

Source: ORNL-TM-2010-253

Concentrated windings

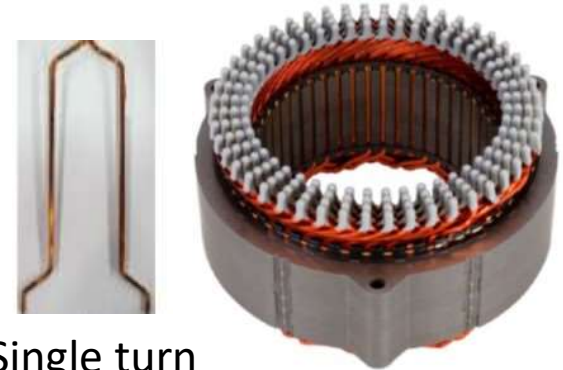


Accord 2005



Source: ORNL-TM-2006-535

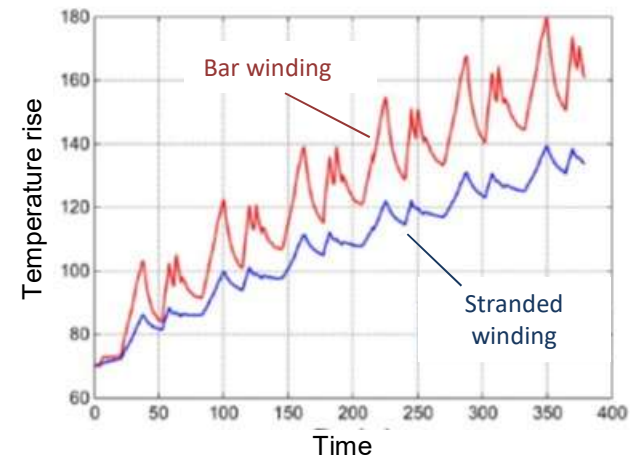
Hairpin (bar) windings



Single turn
GM 2006

Prius 2017

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

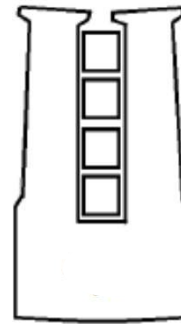


Source: Jurkovic, et. al, (GM) IEEE TIA 2015

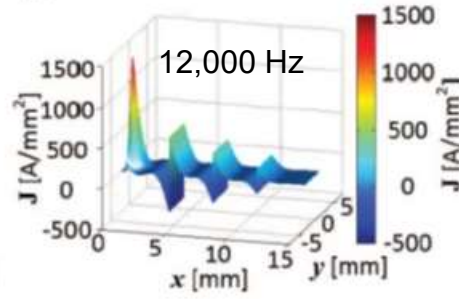
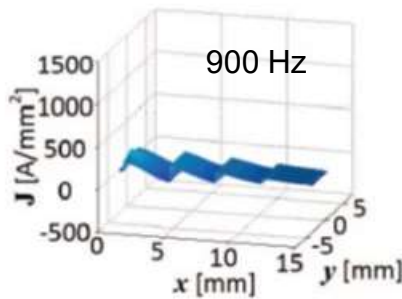
Bar winding: High speed

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

4-bar winding

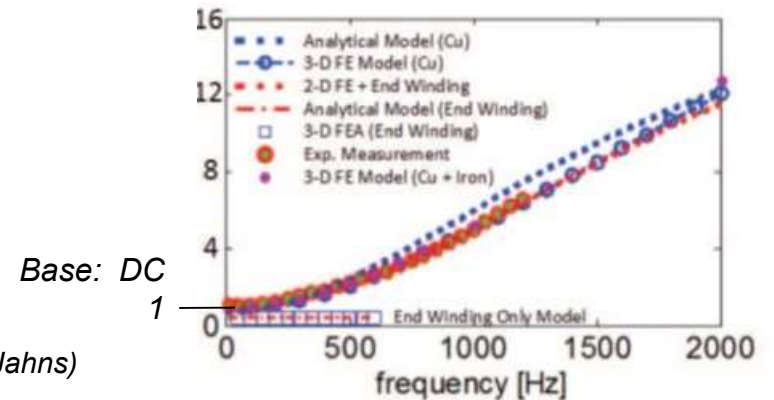


Current density versus position within slot



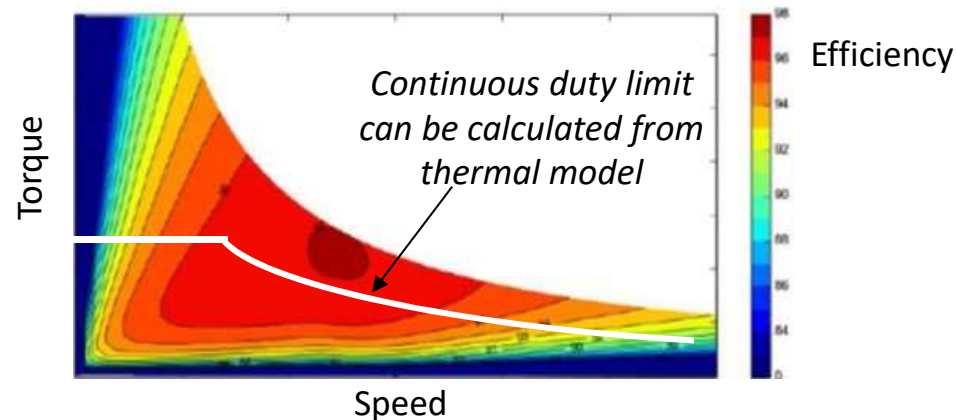
Source: IEEE IEMDC 2015 (Zhang and Jahns)

Resistance versus frequency



Machine modeling

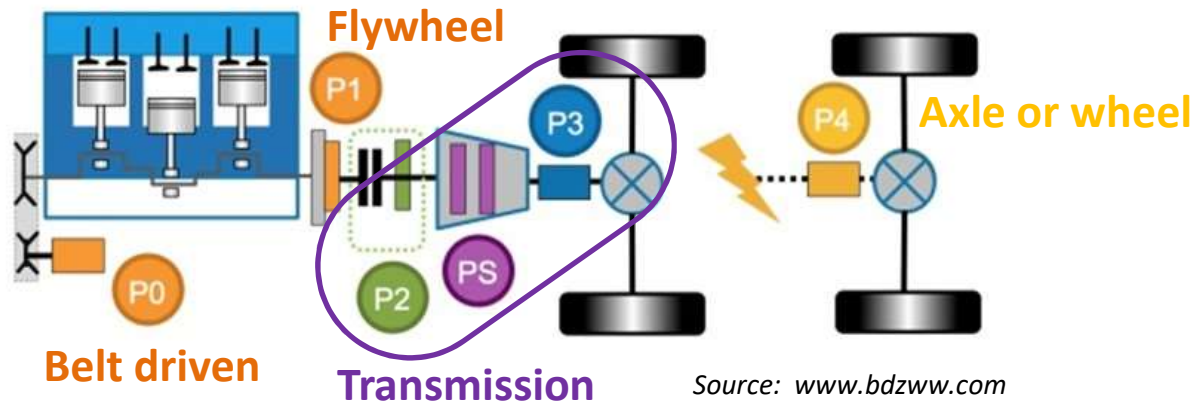
- Late 1990s, first breakthroughs in terms of modeling:
 - Finite element electromagnetics and SPEED software for machines
- Since 2010:
 - Complete automated efficiency map calculation
 - Multiphysics: Magnetics + Thermal (Motor Design Ltd., etc)
- Very significant as it allows:
 - Comprehensive optimization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



Source: Motor Design, Ltd, 2017

Electric machine location (hybrids)

- Electric machine can be located in various places, denoted P0, P1, P2/P3, P4



Electric machine location: Industry trends

- 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

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

Conclusions

- Motors are important, 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

Thank you!

Presentation (with bibliography) available at:

www.emotorseng.com

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B. Lequesne, “Electric machines for automotive propulsion: History and future”, keynote presentation, IEEE ITEC-AP 2019, May 2019, Available at: www.emotorseng.com

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- The data behind the figure on slide 13 came from: J. Giambogi, US Geological Survey, “Mineral commodities summary”, pp. 132-133, Feb. 2019. Available at: <https://www.usgs.gov/centers/nmic/mineral-commodity-summaries>.
- The Oak Ridge National Laboratory has conducted a number of teardown studies of foreign (non-US) hybrid and electric drivetrains. The reports are available at: https://info.ornl.gov/sites/publications/_layouts/15/start.aspx#/SitePages/Home.aspx.