

#### Electric Machines Roadmap



Updated by the Advanced Propulsion Centre in collaboration with and on behalf of the Automotive Council

#### **Executive summary –** *Electric machines*





- 2013 roadmap focused on a number of different motor architectures that could be applied for <40kW and >100kW electric machines.
- 2017 roadmap recognises that e-machine development is broadly focussed on both increasing technical performance and reducing cost in mass market products.
- **2017 roadmap has been built using a targets-based approach**, informed by consensus amongst a wide range of industry and academic experts. Key targets are cost and power density.
- More emphasis has been placed on materials and manufacturing processes reflecting their importance in delivering cost competitive and sustainable solutions.
- A number of technology evolutions occur after 2025 which reflects the immaturity of the current e-machine automotive mass market and the need for targeted R&D on future applications.
- The roadmap reflects greater alignment with the power electronics roadmap, recognising that future product developments will lead to greater compatibility and integration.



### **Update process:** The Electric Machine Roadmap was updated via a structured consensus-building process involving 46 experts



ADVANCED PROPULSION CENTRE UK

 A public workshop was held at the Advanced Propulsion Centre office in London, Stratford on the 25<sup>th</sup> January 2017

- The process was co-ordinated by the Advanced Propulsion Centre on behalf of Automotive Council
- The Advanced Propulsion Centre Electric Machine Spoke, supported by an expert Steering Group, helped to shape the roadmap before and after the workshop



Electric Machine Steering Committee and Workshop Attendees



Drivers of change	Passenger Car Traction	2017	2025
<ul> <li>CO<sub>2</sub> and air quality objectives challenge the universal application of ICE powertrains</li> </ul>	Cost (\$/kW) <sup>2</sup>	10	5.8
• Electrification features in product plans of almost every OEM across all sectors	Continuous power density (kW/kg)	2.5	7
<ul> <li>Electric machines feature in all xEV formats and larger ancillary machines used for steering and cooling</li> </ul>	Continuous power density (kW/I)	7	25
	Drive cycle efficiency (%) <sup>3</sup>	86.5	92.5
<ul> <li>Despite electric machines being used for over 100 years, innovations are still needed in electric machines specifically designed for vehicle traction</li> </ul>	Truck and Bus Traction Motor <sup>1</sup>	2017	2025
<ul> <li>In order to meet mainstream automotive demands</li> </ul>	Cost (\$/kW) <sup>2</sup>	60	15

- In order to meet mainstream automotive demands increased reliability, lower overall systems cost using widely available materials and higher performance are required
- In response to these challenges significant innovation is needed. Ambitious electric machine targets have been set which cannot be attained using existing designs.

Passenger Car Traction Motor <sup>1</sup>	2017	2025	2035
Cost (\$/kW)²	10	5.8	4.5
Continuous power density (kW/kg)	2.5	7	9
Continuous power density (kW/I)	7	25	30
Drive cycle efficiency (%) <sup>3</sup>	86.5	92.5	93
Truck and Bus Traction Motor <sup>1</sup>	2017	2025	2035
Truck and Bus Traction Motor <sup>1</sup> Cost (\$/kW) <sup>2</sup>	<b>2017</b> 60	<b>2025</b> 15	2035 12
Truck and Bus Traction Motor <sup>1</sup> Cost (\$/kW) <sup>2</sup> Continuous power density (kW/kg)	2017 60 1.5	2025 15 2	2035 12 2.5
Truck and Bus Traction Motor <sup>1</sup> Cost (\$/kW) <sup>2</sup> Continuous power density (kW/kg) Continuous power density (kW/l)	2017       60       1.5       4.5	2025 15 2 6	2035 12 2.5 7
Truck and Bus Traction Motor <sup>1</sup> Cost (\$/kW) <sup>2</sup> Continuous power density (kW/kg)         Continuous power density (kW/l)         Drive cycle efficiency (%) <sup>3</sup>	2017         60         1.5         4.5         83	2025 15 2 6 88	2035 12 2.5 7 90

1) All assume 350V / 450Amps @ 65degC inlet

2) Prices are 300% mark-up on material costs

3) Drive cycle based on WLTP



### **Technology categories:** Parallel technical developments are required in electric machine architecture, integration, materials and supporting areas

DRIVERS	xEV uptake, $CO_2$ limits, air quality regulation, ULEZs, $\alpha$	charging access	Very low CO2, zero emission zones, LCA, materials security, r	apid/opportunity charging infrastructure	
TARGETS*	Current status	2025 targets		2035 targets	
Cost (\$/kW)	<b>10</b> \$/kW	<b>5.8</b> \$/kW		<b>4.5</b> \$/kW	
Power Density (kW/kg)	2.5 kW/kg	7 kW/kg		9 kW/kg	
Power Density (kW/l)	7 kW/l 25 kW/l			30 kW/l	
MACHINE ARCHITECTURE	Machine architectures and topologies influences the performance and cost of electric machines				
MACHINE INTEGRATION	How the electric machine is integrated powertrain components is key to over	all system efficiency			
MATERIALS & MANUFACTURING Windings and insulation	Materials and manufacturing methods are closely related, both are fundamental to cost and performance				
Soft magnetics					
Permanent magnets					
ENABLERS	Several other technical aspects are required to support improvement				
2	015 2020	2025	2030	2035	

# **Machine architecture:** *Current machine architecture can be improved but new designs will be needed to meet longer term targets*

DRIVERS	xEV uptake, CO <sub>2</sub> limits, air quality regulation, ULEZs, charg	ging access Very low CO2, zero em	ission zones, LCA, materials security,	, rapid/opportunity charging infrastructure
TARGETS * Cost (\$/kW)	Current status 10 \$/kW	2025 targets <b>5.8</b> \$/kW		2035 targets <b>4.5</b> \$/kW
Power Density (kW/kg)	<b>2.5</b> kW/kg	7 kW/kg		9 kW/kg
Power Density (kW/l)	7 kW/l	25 kW/l		30 kW/l
MACHINE ARCHITECTURE	Evolution of existing high performance architectures Adv. architectures (e.g. i Lower cost architectures (e.g. inducti	s (e.g. higher speeds, targeted cooling, improv n-wheel, axial flux, transverse flux) on wound rotor and switched reluctance mot Safety and fault tolerance me	ed materials) Radical architectures ors) Radical architectures e echanisms for electric machines (e.c	enabling a step change in performance mabling a step change in cost reduction g. for CAVs)
MACHINE INTEGRATION MATERIALS & MANUFACTURING Windings and insulation	Machine architectures can be designed for high performance or for lower cost applications. Existing high performance architectures can be advanced by better thermal management (e.g. internal rotor cooling, oil cooling, heat recovery, targeted cooling of printed stators) and higher speed capabilities (e.g. ceramic/air bearings,	Advanced high performance machine architecture concepts, that have not traditionally been used for automotive, could be introduced to improve performance for specialist applications. These advanced	As connected and autonomous vehicles emerge, better fault prediction and fault tolerance mechanisms are required.	Radical new machines designs will be needed for both high performance and low cost machines. For lower cost machines, advanced manufacturing methods will drive down cost whereas higher performance machines could be:
Soft magnetics Permanent magnets ENABLERS	more compact motors and faster inverter switching frequencies). Lower cost machines require reducing copper and iron losses (eddy & hysteresis), cheaper motor housing solutions and reducing costly material content with a move to replace costly materials (such as permanent magnets and copper windings) with	architectures can be defined by how they are integrated into the vehicle (e.g. distributed machines such as wheel-hub motors) or their novel magnetic/mechanical design (i.e. axial, radial and transverse		aggressively cooled, contain advanced materials in the stator, rotor and windings or be novel designs leveraged from other sectors
2	lower cost alternatives.	flux motors).	2030	2035

## **Machine integration:** Integrating an electric machine effectively into the vehicle powertrain is essential to overall system efficiency

DRIVERS	xEV uptake, CO <sub>2</sub> limits, air quality reg	gulation, ULEZs, charging access Very low CO2, zero emissi	on zones, LCA, materials security, rapid/opportunity charging infrastructure
TARGETS*	Current status	2025 targets	2035 targets
Cost (\$/kW)	<b>10</b> \$/kW	5.8 \$/kW	<b>4.5</b> \$/kW
Power Density (kW/kg)	2.5 kW/kg	7 kW/kg	9 kW/kg
Power Density (kW/l)	7 kW/l	<b>25</b> kW/l	<b>30</b> kW/l
MACHINE ARCHITECTURE	As mild hybrids become more p near term emissions legislation, require closer coupling with the engines to deliver the optimum	For the next generation mild developed with the thermal p enable downsizing, potential	hybrids, e-machines will be co- ropulsion system and transmissions to y requiring a larger machine.
MACHINE INTEGRATION	Close coupling with transmissions	and TPS (i.e. xHEV) Co-developed machine, TPS a	ion) Motors with fully embedded PE
MATERIALS & MANUFACTURING			
		Integrated drives are a potential option for OEMs, howe challenges include: manufacturability; integrated coolin	A fully-integrated manufacturing route to integrated drives - where the power
		systems; graceful failsafe mechanisms; drives for multi & distributed machines; achieving higher switching frequencies to support high frequency (smaller) electric	ophaseelectronics and machine are fabricated together - has the potential for dramatic cost reductions
Permanent magnets		machines and adoption of switched reluctance drives.	
ENABLERS			
2	▲ ▲ ▲ ▲ ▲ 2020	2025	2030 2035

### **Materials and manufacturing:** New processes and materials for windings can significantly improve performance or lower cost

DRIVERS	xEV uptake, CO <sub>2</sub> limits, air qual	ity regulation, ULEZs, charging access Very low CO2, z	zero emission zones, LCA, materials security, rapid/opportunity charging infrastructure
TARGETS*	Current status	2025 targets	2035 targets
Cost (\$/kW)	<b>10</b> \$/kW	5.8 \$/kW	<b>4.5</b> \$/kW
Power Density (kW/kg)	2.5 kW/kg	7 kW/kg	9 kW/kg
Power Density (kW/l)	7 kW/l	<b>25</b> kW/l	<b>30</b> kW/l
MACHINE ARCHITECTURE	Winding strategies (e.g. d the performance and redu increasing material fill fac (e.g thin enamels, nano-n for coil encapsulation) im automating the manufactu	istributed, concentrated) are key to maximising ucing machine losses. Key challenges include: tor; improving insulation and isolation methods naterials, self-repairing insulation, better materials proved winding processes (e.g. litz wire) and fully uring process to enable lower cost machines.	Introducing advanced additive layer manufacturing can remove the requirement for winding processes if complex machine geometries can be manufactured at high volumes
MACHINE INTEGRATION			
MATERIALS & MANUFACTURING	Optimised winding tech	niques (e.g. increase material fill, hairpin windings)	Elimination of winding process (e.g. additive layer manu.)
Windings and insulation		Alterna	ative low cost windings (e.g. aluminium) Higher performance windings (e.g. carbon, HTS, nanomaterials)
Permanent magnets	Wi ch pe ter	nding materials offer the potential for dramatically low eaper, lighter and more readily recyclable with steel the rformance materials (e.g. carbon nanotubes embedde mperature superconductors) offer higher conductivity	ver costs or radically improved performance. Aluminium windings are han copper thus making it a potential replacement. Alternative higher ed in copper or on the surface, graphene; nano-materials; high and lower losses but currently command a price premium.
ENABLERS			
;	2015 2	2020 2025	2030 2035

### **Materials and manufacturing:** *Improvements in the material properties of electrical steels and soft magnetic composites can deliver cost and performance improvements*

DRIVERS	xEV uptake, C	CO <sub>2</sub> limits, air quality regulation, ULEZs, charging access	Very low CO2, zero emission	zones, LCA, materials security, rapid/oppor	rtunity charging infrastructure
TARGETS *	Current status	2025 targets		2035 targets	
Cost (\$/kW)	<b>10</b> \$/kW	5.8 \$/kW		<b>4.5</b> \$/kW	
Power Density (kW/kg)	2.5 kW/kg	7	kW/kg	9 kW/kg	
Power Density (kW/l)	7 kW/l	2	5 kW/l	<b>30</b> kW/l	
MACHINE ARCHITECTURE					
MACHINE INTEGRATION MATERIALS & MANUFACTURING		Advances in electrical steels magnetic and improving overall machine efficiency. Short methods and material models/characterisat coatings), achieving lower loss thinner grad Longer term challenges include utilising models (e.g. cobalt, manganese, vanadium, chromit	chemical properties can reduce of term challenges include: automo- ion, improved bonding and coating the steels, higher alloy content gra- ire grain orientated steels, cost er um) and developing tailored steels	eddy and hysteresis losses, otive relevant measurement ng technologies (i.e. self bonding ides for automotive volume. ffectively introducing other metals els with localised optimisation	
Windings and insulation					
Soft magnetics	Optimised	l e-steels (e.g. 6.5% Si steel, better bonding/coating, thi Optimised SMCs (e.g. lower losses, reduced	nner laminations)	Next gen. e-steels (e.g. improved allo Enhanced SMCs (e.g. improved mate	ys, localised properties) rials, smaller grain size)
Permanent magnets		Soft magnetic composites a	re less commonly used in automo	otive applications compared to	
ENABLERS		manufacturing. Challenges i smaller grain sizes and achi	nclude improvements in losses a eving significant cost reduction in	nd permeability, achieving the manufacturing processes.	
2	015	2020	2025 2	<b>0</b> 30 203	5 .

### **Materials and manufacturing:** *Permanent magnet electric machines can be high cost so effective use of rare earth materials is needed*

DRIVERS	xEV uptake, CO <sub>2</sub> limits, air quality i	regulation, ULEZs, charging acces	s Very I	ow CO2, zero emission z	cones, LCA, materials security, rapid/op	portunity charging infrastructure
TARGETS*	Current status	2	025 targets		2035	targets
Cost (\$/kW)	<b>10</b> \$/kW		<b>5.8</b> \$/kW		4.5	\$/kW
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MACHINE ARCHITECTURE						
MACHINE INTEGRATION MATERIALS & MANUFACTURING Windings and insulation	Heavy rare earth materials su Dysprosium are added to imp temperature resistance of Ne expensive and strongly conce China. There is a desire that eliminated to reduce costs an	orove the odymium but are entrated in these should be od supply risks.	Light rare machines or alterna	e earth magnets (e.g s. Architectures that ative magnetic mate	g. Neodymium) are a significan do not use magnets (i.e. induc rials (i.e. ferrite magnets) are p	t cost to current electric ction and switched reluctance) otential solutions.
Soft magnetics						
Permanent magnets	Eliminate heavy rare Refine manu. processes for cons	e earths (e.g. Dy) sistent PM magnet attributes	$\rightarrow$	Eliminate rare ea Increased use of recycle	arth content (e.g. other magnetic mat ed rare earths (e.g. Nd)	erials or magnet free)
ENABLERS	New manufacturing processes laminations to reduce eddy curr strength, durability and high ten	are required to: allow thinn rent losses; produce PMs v nperature capability; manu	er vith improved facture new	Utilising recycled characteristics w the cost and envi	permanent magnets that main ill enable a closed-loop supply ironmental performance of perm	tain performance chain for rare earths improving manent magnet machines.
2	015 202		2025	20		

#### **Enablers:** A number of supporting innovations are essential to meet the performance and cost targets

DRIVERS	xEV uptake, CO <sub>2</sub> limits, air qualit	ty regulation, ULEZs, charging access	Very low CO2, zero emission zones, LCA, materials s	ecurity, rapid/opportunity charging infrastructure		
TARGETS*	Current status	2025 targets		2035 targets		
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Power Density (kW/l)	7 kW/l	25 kW/l		<b>30</b> kW/l		
MACHINE ARCHITECTURE MACHINE INTEGRATION	Refined manufacturing te higher volumes of existing topologies. Increased aut	chniques could improve performance, g machine topologies and the manufac omation (utilising tooling expertise from	enable sture of new n other	Machine will be designed and		
MATERIALS & MANUFACTURING Windings and insulation Soft magnetics	Sectors) could improve co	manage NVH, efficiency optimisation	Advanced data analytics V2V and self-learning software could enable electric machines to self adapt for high efficiency peak power or reliability	<ul> <li>manufactured with disassembly</li> <li>and end-of-life in mind. New</li> <li>recycling processes to enable</li> <li>sensing, sorting, separation,</li> <li>purification and reprocessing of</li> <li>materials will also improve the life</li> <li>cycle environmental sustainability</li> </ul>		
Permanent magnets ENABLERS	Advanced control software	e developed in collaboration with power electro	onics community Self l	earning software optimised for drive cycle		
2	015 20	Adv. designs for re	euse/recycling (e.g. easy extraction of PMs/conducto	Design for LCA		

#### **TECHNOLOGY ROADMAP 2017: ELECTRIC MACHINES**

Roadmap developed by the Automotive Council and the Advanced Propulsion Centre



DRIVERS	xEV uptake, CO <sub>2</sub> limits,	air quality regulation, ULEZs, charging acce	ss Very low CO2, zero emis	sion zones, LCA, materials security,	rapid/opportunity charging infrastructure
TARGETS*	Current status	;	2025 targets		2035 targets
Cost (\$/kW)	<b>10</b> \$/kW		5.8 \$/kW		4.5 \$/kW
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Power Density (kW/l)	7 kW/l		<b>25</b> kW/l		30 kW/l
			•		•
	Evolution of existin	g high performance architectures (e.g. hig	her speeds, targeted cooling, improve	d materials)	
		Adv. architectures (e.g. in-wheel,	axial flux, transverse flux) 💦 🔪	Radical architectures	enabling a step change in performance
MACHINE ARCHITECTURE	Low	er cost architectures (e.g. induction woun	d rotor and switched reluctance moto	rs)	
				Radical architectures e	nabling a step change in cost reduction
		$\rightarrow$	Safety and fault tolerance mec	hanisms for electric machines (e.g	g. for CAVs)
MACHINE INTEGRATION	Close coupling with tra	ansmissions and TPS (i.e. xHEV)	Co-developed machine, TPS	S and transmissions (i.e. xHEV)	$\rightarrow$
		Integrated xEV	drives (motor, PE, control and transmi	ssion)	Motors with fully embedded PE
MATERIALS & MANUFACTURING	Optimised windi	ng techniques (e.g. increase material fill, ha	airpin windings)	Elimination of winding	g process (e.g. additive layer manu.)
Windings and insulation			Alternative low	cost windings (e.g. aluminium)	
windings and insulation			$\rightarrow$ $\rightarrow$ $\rightarrow$	Higher performance wind	ings (e.g. carbon, HTS, nanomaterials)
Coff magnation	Optimised e-steels (	e.g. 6.5% Si steel, better bonding/coating,	thinner laminations)	Next gen. e-steels (e.g. in	nproved alloys, localised properties)
Sort magnetics	$\rightarrow$	Optimised SMCs (e.g. lower losses, reduc	ced saturation)	Enhanced SMCs (e.g. im	proved materials, smaller grain size)
Dermanent magnets	Eliminate	heavy rare earths (e.g. Dy)	Eliminate r	are earth content (e.g. other magr	netic materials or magnet free)
r ennanent magnets	Refine manu. process	es for consistent PM magnet attributes	Increased use of re	ecycled rare earths (e.g. Nd)	
	Advanced control	software developed in collaboration with	power electronics community	Self learning	software optimised for drive cycle
ENABLERS		Improved electric	c machine assembly processes with ne	ew manufacturing methods	
		Adv.	designs for reuse/recycling (e.g. easy e	extraction of PMs/conductors)	>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
	2015	2020	2025	2030	2035
	2013	2020	2025	2050	2055

1 chevron = some uncertainty around timing of mass market adoption or phase out 2 chevrons = considerable uncertainty around timing of mass market adoption or phase out

# **Glossary:** Explanation of acronyms and terms not described in the roadmap due to space constraints



- CAVs (Connected and autonomous vehicles) Connected and autonomous vehicles is an umbrella term to capture the varying levels of autonomy and technologies relating to self-driving vehicles.
- **Dy (Dysprosium) –** *Dysprosium is a heavy rare earth material that is used alongside Neodymium. Dy has been essential in making it possible to use NdFeB magnets in high power density applications such as vehicle traction*
- HTS (High temperature superconductors) Developmental conductor materials that are extremely conductive compared to copper but require low temperatures (between -240°C and -70°C) in order to conduct efficiently.
- LCA (Life cycle analysis) Identifying the total environmental impact of a given product.
- Nd (Neodymium) Neodymium is a light rare earth material that is widely used as a rare earth material in automotive electric machines. In order to make a usable magnet, Neodymium is usually alloyed with Iron and Boron to create NdFeB magnets.
- SMCs (Soft magnetic composites) Soft magnetic composites (SMC's) are an alternative to electrical steels. They are made of iron powder particles coated with an electrically insulating layer and they can be moulded into complex shape under high pressure in a die.
- **TPS (Thermal propulsion systems)** Thermal propulsion system is the Automotive Council's new term for internal combustion engines. It is a device that integrates an engine or fuel cell with thermal and / or electrical systems to manage power delivery to the wheels and recover waste energy to improved performance and efficiency. The key feature of a TPS is that the primary energy is stored chemically (rather than electrochemically like in a battery)
- V2X (Vehicle-to-X) Vehicle-to-X refers to an intelligent transport system where all vehicles and infrastructure systems are interconnected with each other.

