EARPA Position Paper

Component and system level development for clean and efficient powertrains – Gaps and Research needs

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About EARPA

Founded in 2002, EARPA is the association of automotive R&D organisations. It brings together the most prominent independent R&D providers in the automotive sector throughout Europe. At present its membership numbers 60, ranging from large and small commercial organisations to national institutes and universities.

Introduction

Advancements in electrical powertrains are driving the future of sustainable mobility, with innovations in power electronics and electrical machines – emphasizing durability, advanced materials, and comprehensive life cycle assessments (LCA). The development of hybrid configurations and attention to electromagnetic compatibility (EMC) ensure performance and reliability across diverse applications. Simultaneously, achieving CO_2 neutrality in internal combustion engines (ICEs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs) is being pursued through the integration of sustainable fuels, supporting a balanced transition toward cleaner transportation.

For this position paper reports and advisory documents from different associations and PPPs have been reviewed (ERTRAC, CCAM, 2ZERO, BATT4EU, Hydrogen Europe, IEA) [1-7] with additional input from the authors' network of propulsion and powertrain research groups in Europe.

On this basis gaps have been identified and formulated as research needs.

Electrical Powertrains

- **Power Electronics**

A research topic in the field of power electronics that is currently not addressed in the 2Zero SRIA is **advanced thermal management** - in particular, immersion cooling, especially for passive components. As we strive for higher energy densities, the cooling of inverters and DC/DC converters will become a major challenge in the coming years. In this context, **immersion cooling** or **hybrid cooling approaches** - such as water cooling for power components combined with oil immersion cooling for passive components - could represent promising research directions to effectively address this issue [8].

- **Electrical Machines**

The 2024 Electric Machines Technology Roadmap, developed by the Advanced Propulsion Centre UK, presents a detailed forecast of key technological trends, challenges, and opportunities for the mass adoption of electric machines within the global automotive industry [9]. It outlines a future where the acceleration of electric propulsion technologies will require coordinated advances in materials, manufacturing, control systems, and lifecycle management, supported by a strong emphasis on sustainability and innovation.

Central themes of the roadmap include: (1) **Machine Architectures**, where there is a push toward axial flux and transverse flux motors, radical designs enabled by simulation and additive manufacturing, and greater functional integration such as in-wheel motors and high-integration electric drive units (EDUs); (2) **Thermal Management**, where recommendations call for the adoption of phase change materials, direct liquid cooling techniques, and AI-driven design optimizations to improve thermal efficiency and enable higher power densities; (3) **Material Development**, which stresses the need to reduce heavy rare earth element dependence by developing high-performance alternatives like iron ferrite and polymer-bonded magnets, as well as exploring graphene-based and hollow conductors for improved electrical performance; (4) **Manufacturing Processes**, advocating for techniques like slinky stators, direct injection bonded magnets, and AI-optimized production methods to reduce waste, lower costs, and enhance component performance.

The roadmap also emphasizes **Noise, Vibration, and Harshness (NVH) Optimization**, recommending advanced control techniques beyond traditional PWM methods, AI-driven NVH modelling, and lightweight material developments.

In the area of **Software and Drive Controls**, there are strong calls for improvements in regenerative braking, enhanced drive dynamics using e-machines, predictive health management through AI, and sensor-less motor control technologies.

Finally, under **Life Cycle Management**, the report advocates for the early integration of Life Cycle Analysis (LCA) into design processes, the scaling up of closed-loop recycling, improved recovery of rare earth elements, and widespread adoption of end-of-life remanufacturing strategies.

- **Fuel Cell**

High energy density proton-exchange membrane fuel cells (PEMFCs) are an enabling technology for the development of hydrogen-powered electric vehicles. By directly converting energy from hydrogen to electricity via catalysed electrochemical reactions, PEMFCs offer efficiency for high power applications while producing only water and excess heat as by-products. Current challenges for PEMFCs are centered on production costs, durability of membranes and catalyst materials, system scaling for heavy-duty transport, and optimal control to balance lifetime and fuel efficiency [10].

The operation of PEMFCs is highly dependent on water balance throughout the stack, especially in the (e.g. Nafion) proton-exchange membrane which dominates the resistive losses. The water balance can also influence heat-transport and the reactant gas flows which must be maintained to maximize the electrochemical power output of the stack. Humidification, alternative membrane materials, and strategies to permit higher operating temperatures remain areas of interest.

The design of membrane electrode assemblies (MEAs) to produce unit cells with larger surface area increases the challenges of maintaining uniform conditions over the MEA. Larger MEAs exhibit greater pressure drop and variations in flow channel resistance which require more complex flow-field design to distribute reactant gases effectively. Statistical variation within the MEA materials also increases with its dimensions and also contributes to non-uniform current density, potentially impacting durability and system losses [11].

The catalyst materials in PEMFCs are sensitive to contamination (e.g. by CO, H2S, SO2, NOx, Fe+, Cu+) and require high purity hydrogen. Mitigation of contaminants, design of contaminant-resistant materials, and optimizing PEMFC stack control to remove contaminants or alter cell conditions to enhance tolerance are areas of interest [12].

- **Battery**

Emerging battery chemistries such as sodium-ion (Na-ion) and lithium manganese iron phosphate (LMFP) are gaining attention, raising important questions about the applicability of existing algorithms and monitoring methods to these new technologies [13]. In parallel, the industry is preparing for the introduction of the **battery passport** in 2027, mandated by the new EU Battery Regulation. This initiative aims to enhance transparency by enabling the monitoring, tracking, and public disclosure of battery health data. Research efforts are focusing on the lessons learned from the initial implementation of the battery passport and exploring potential improvements for future implementations of the battery passport. Additionally, **second-life applications and recycling** remain key areas of investigation, particularly regarding the statistical viability and volume of second-life batteries originating from automotive powertrains—and how these may be influenced by the use of the battery passport. The shift toward Cell-to-Body (C2B) architecture also introduces new considerations for end-of-life strategies and recyclability.

Electromagnetic Compatibility (EMC) research is crucial in electric vehicles (EVs), as they contain complex electronic systems that generate electromagnetic fields. These fields can interfere with other devices EVs also produce high-voltage, high-frequency, and high-power signals that may cause electromagnetic interference (EMI) and radio frequency interference (RFI), affecting vehicle safety and reliability. EMC research ensures compliance with safety and regulatory standards by developing test methods, reducing interference, and designing systems to minimize emissions. Research is also needed where current testing equipment or environments are inadequate [14].

- **CO2 neutrality of HEVs (e-Fuels, ICEs with H2)**

Internal combustion engines (ICEs), including those embedded in hybrid electric vehicles (HEVs) and plug-in hybrids (PHEVs) and Range-Extended EVs, will continue to play a vital role in the transition to climate-neutral mobility. Ensuring the long-term sustainability of ICEs requires a multi-faceted R&D approach, focusing on carbon-neutral fuels, advanced combustion strategies, enabling technologies, and engine architectures tailored for hybridized powertrains in terms of maximized efficiency and minimized exhaust emissions.

- **New Low-Carbon and Carbon-Neutral Fuels (see also OTT1)**

Research into advanced synthetic fuels (e-fuels), hydrogen, ammonia, methanol, and other low-carbon energy carriers is critical. These fuels can be produced using renewable energy and carbon capture, enabling near-zero net CO_2 emissions. E-fuels, in particular, can be designed for compatibility with existing infrastructure, offering a drop-in solution for decarbonizing legacy fleets. Hydrogen ICEs (H_2ICEs) are emerging as a viable option, especially for heavy-duty and off-road applications, thanks to their high efficiency, potential use of impure hydrogen, and near zero criteria pollutant emissions focusing on cold start operation and on efficient nanoparticle filters also addressing non-volatile components [3].

- **Advanced Combustion Concepts**

To maximize efficiency and minimize emissions, ICE research must focus on new combustion strategies including dual-fuel modes, Reactivity Controlled Compression Ignition (RCCI), and High-Pressure Direct Injection (HPDI) [15]. Technologies such as lean or diluted combustion, pre-chamber ignition, and Miller cycles offer significant efficiency gains and lower pollutant formation. These combustion modes, combined with novel fuels, can reduce the need for complex after-treatment also through the development of sensor and OBM and/or OBD technologies to secure monitoring of vehicle performance under all driving conditions and over its entire useful life.

- **New Enabling Technologies**

Progress in ICE architecture must include high compression ratios, electrically assisted turbocharging, and intelligent control systems through advanced physical and/or virtual sensors. Electrified auxiliaries and advanced thermal management can further improve real-world efficiency. Digital twins, model-based control, and online diagnostics should be integrated to optimize operation and extend system life. Moreover, the synergy between ICEs and electric components in hybrids must be fully exploited to minimize transient emissions and fuel consumption.

- **Tailored Engines for HEVs and RE-EVs**

Developing ICEs specifically optimized for hybrid operation is essential. Range extenders (RE-EVs) and PHEVs offer a strategic bridge technology. Engines for such applications can operate in narrow, high-efficiency zones, enabling downsizing, simplification, and optimization for specific fuel types [16]. Future R&D should address combustion system design, catalyst thermal management and seamless integration with electric propulsion, to ensure ultra-low emissions in real-world operation also through new materials to reduce heat transfer and minimization of friction and wear.

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