

## EARPA Position Paper

### Vehicle Control - Future Challenges – 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 Europe's automotive sector. At present, its membership numbers 60, ranging from large and small commercial organisations to national institutes and universities.

#### Introduction

In the era of high-resolution data from onboard sensors, vehicle-to-everything communication, cloud-based services, and software-defined vehicle architectures, the role of vehicle control has shifted from performing conventional rule-based functions to executing complex decision-making processes at the system level. This requires new research on how such new data streams can be integrated, validated, and transformed into actionable inputs for component and system-level control.

As richer information becomes available, new research should focus on how vehicle components can be controlled through more adaptive, predictive decision-making processes. Advanced diagnostic and prognostic methods, combined with uncertainty-aware algorithms, have the potential to improve robustness and responsiveness<sup>1,2</sup>.

Control should also integrate functionalities for system-level optimization. Component-level decisions must increasingly account for heterogeneous interactions across subsystems and trade-offs (e.g., performance vs. NVH) as well as evolving operational requirements<sup>3</sup>. Developing such capabilities also demands research into coordination mechanisms, hierarchical control structures, and overall optimization frameworks.

Regulatory demands (homologation, safety standards, cybersecurity rules), high development and validation costs, and integration challenges with legacy vehicle architectures often slow the introduction of new component controls<sup>4</sup>. These barriers can be reduced by designing for compliance early, using modular and simulation-supported certification, including digital twins, adopting platform-based architectures to spread costs, collaborating closely with suppliers, and modernizing integration through clear interfaces and automated testing.

Substantial benefits can be reaped when combining such advances. Vehicle control strategies can become more precise and more adaptive. Design margins can be reduced, improving efficiency and reliability across a wider range of conditions and ultimately contributing to a safer, more sustainable, and better-performing vehicle platform.

EARPA members have identified six specific areas where the expertise of their members can help improve control functions to meet these targets, specifically (i) Energy management, (ii) environmental performance, (iii) safety, (iv) user experience, (v) diagnostics and predictive maintenance, and (vi) vehicle testing and training.

#### 1. Energy and Power Management

Energy management in vehicle control systems requires research on developing more efficient and intelligent energy distribution algorithms. This involves **creating advanced control strategies that optimize energy flow between powertrain components** (engine, battery, fuel cell, motors, and auxiliary systems)<sup>5</sup>. By integrating **hybrid algorithms that combine physical modeling with artificial intelligence** - such as physics-informed deep learning - vehicles can achieve predictive monitoring of component aging trajectories. These techniques enhance the ability to forecast degradation mechanisms, enabling proactive energy management that minimizes system wear and extends operational lifespan. **Aging-aware supervision** plays a crucial role in optimizing long-term efficiency, prioritizing energy strategies that limit wear while maximizing overall value extraction over an extended service life<sup>6</sup>. AI-driven, personalized usage prediction based on historical operational data can autonomously adjust vehicle pre-conditioning to optimize efficiency in line with anticipated mission profiles. Additionally,

exploring **innovations in battery technology**, such as solid-state batteries, requires adaptive control methodologies that support diverse charging and discharging profiles while accounting for aging characteristics. The integration of **vehicle-to-grid (V2G)**, **vehicle-to-building (V2B)** or **vehicle-to-home (V2H)** systems further necessitates bidirectional control mechanisms designed to maintain energy stability and efficiency on a larger scale. Developing modular algorithms that accommodate the evolving nature of powertrain components (ICEs, fuel cells, batteries, etc.) remains essential for creating adaptable, cost-effective solutions. A specific area of interest for control strategies is **heat management**, ensuring both component longevity and user comfort while minimizing total vehicle energy demand<sup>7</sup>.

## 2. Environmental performance

Advanced vehicle controls can also significantly enhance a vehicle's environmental performance, going beyond simply optimizing energy use. Controls for **regenerative braking** facilitate energy recuperation but can also be tuned to decrease brake wear particles<sup>8</sup>. **Advanced traction and stability controls** help maintain optimal tire-to-road contact. By precisely managing acceleration, braking, and steering inputs, these systems reduce unnecessary tyre slippage and abrasion. Adaptive cruise control and eco-driving modes can predict upcoming traffic conditions and eliminate the need for harsh braking or cornering, which are known to cause most non-exhaust particle emissions<sup>9</sup>. Moreover, such control can also regulate the vehicle's noise, benefiting passengers and the surrounding environment. For powertrains, including engines, especially those with often-interrupted operation (e.g., plug-in hybrid vehicles), advanced **engine and aftertreatment control** is required to achieve optimal engine performance and low emissions during frequent transient start/stop events.

## 3. Safety

Enhancing safety through vehicle control systems requires research into robust sensor fusion techniques that integrate data from LiDAR, radar, cameras, and ultrasonic sensors to provide a comprehensive understanding of the vehicle's surroundings<sup>10</sup>. Improvements on **pedestrian safety** beyond compliance with UN ECE R152 highlight research needs for overall safety improvements in road transport. Control of vehicle motion, including chassis control and suspension, improves passenger comfort and vehicle safety, e.g., in slippery conditions. Developing algorithms for real-time object detection, classification, and prediction is crucial, especially across a wide range of environmental and weather conditions. There's a need to explore **fail-operational system architectures** that ensure safety-critical functions remain operational even in the event of partial system failures. Research into **cybersecurity measures** is essential to protect control systems from malicious attacks, which could compromise safety. Human factors engineering is another key area, investigating how drivers interact with automation and designing **intuitive warnings and intervention strategies** that enhance overall safety without causing confusion or overload.

## 4. User Experience and Well-being

Improving the user experience involves researching adaptive human-machine interfaces (HMIs) that personalize the driving environment, including augmented reality and hazard identification capabilities. Investigating **natural language processing (NLP)** for voice-controlled systems can make interactions more intuitive, thereby enhancing driving comfort and safety by reducing driver distraction. Research into **emotion-detection algorithms could enable the vehicle to respond to the driver's mood, adjusting settings such as music and lighting** to enhance comfort or improve the driver's awareness, condition, and agility. In terms of well-being, vehicle controls **improve thermal comfort in conjunction with energy management and NVH parameters, e.g.**, through suspension adjustment or vehicle speed regulation. Finally, **over-the-air (OTA) updates** within SDV platforms can improve vehicle functionality.

## 5. Diagnostics and Predictive Maintenance

Advancing diagnostics and predictive maintenance requires research into **advanced sensor networks** and **edge computing** within the vehicle to monitor the health of every component in real time. Implementing a **dual data processing framework** enhances efficiency by handling high-dynamic critical data at the edge, while slower-changing degradation and aging-related data are processed in the cloud. This cloud-based approach enables cross-referencing data from multiple vehicles, enriching AI methodologies through **federated learning techniques** to improve predictive accuracy and system-wide insights. Machine learning models can analyze sensor data patterns to anticipate failures before they occur, allowing for proactive maintenance scheduling. AI-driven diagnostics can also support root-cause identification and decision-making based on severity, enabling efficient fault resolution. **Enhanced pinpointing of failures** reduces costs and downtime and improves

environmental impact during a vehicle's in-use period. Research into **digital twin technology** enables virtual simulations that mirror real-world vehicle systems, allowing for detailed stress testing without physical wear<sup>12</sup>. Additionally, ensuring **secure and efficient data transmission** for remote diagnostics remains crucial, requiring robust cybersecurity measures to balance rich data exchange with privacy concerns.

## 6. Vehicle/control testing and training

Training vehicle control systems requires research into developing sophisticated algorithms that can create highly realistic virtual scenarios<sup>13</sup>. This involves generating detailed simulations that accurately mimic real-world driving conditions, including varied terrains, weather patterns, traffic dynamics, hazards, and unexpected obstacles. Research is needed to enhance machine learning models capable not only of replicating these complex environments but also of adapting to new situations through reinforcement learning, thereby improving the fidelity of the simulations. Such an approach can be **combined with HIL/SIL systems**, thus accelerating the testing process, reducing reliance on physical prototypes, and leading to more robust and reliable vehicle control systems in an economical way.

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