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Electrification of powertrain and chassis components as opportunity for efficient and user-centric road transportation – Insights of the R&D projects HighScape, EM-TECH, and SmartCorners

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Executive Summary

During the last 15 years, the automotive domain has been subject to several disruptive transformations, impacting the full supply chain and enabling the uptake of new services and solutions around road-based passenger mobility and freight transportation. Electrification, CCAM, and SDV are leading to a total redesigning of the vehicle and its components, and very equally to a rethinking of how to deliver value. While software is playing a key role for value creation, it strongly relies on innovative mechatronics platforms and smart powertrain and chassis components as foundation for the SDV of the future. Target of this paper is to introduce the results of the three complementary research projects HighScape, EM-TECH, and SmartCorners, with the focus to deliver consistent innovation along the three following pillars: (a) electrified powertrain and chassis components, (b) vehicle platform and highly integrated corner solutions, and (c) novel control algorithms making use of smart components.

Keywords: Drive & Propulsion Systems, Chassis Systems for EVs, Power Electronics Systems, Advanced Control of EVs, Business Models for Vehicle Sales

1 Introduction

The automotive industry has faced disruptive changes for the last 15 years. The societal need to reduce greenhouse gas emissions (*"Paris Agreement"* [1], supported by the *"European Green Deal"* [2], and the *"Fit for 55"* legislative package [3], [4]) has led to an uptake of electrification in road transportation, strongly impacting the vehicles' components, architecture, and supply chain by replacing the internal combustion engine by an electric motor and a high-voltage traction battery, and adapting the auxiliaries accordingly. The target to reduce road fatalities and support mobility for all (*"Vision Zero"* [5]) is supported by the fast evolution of sensing technologies and computing platforms as well as from the uptake of driving automation systems [6]. This transformation has led to a better understanding of the vehicle surroundings (supported by e.g., radar, lidar, or video processing technologies) and a significant increase in processing power for analyzing different information streams in real-time and taking operational and strategic decisions about vehicle control. Moreover, this transformation is typically linked to Cooperative, Connected and Automated Mobility (CCAM) [7] to support the deployment of Cooperative Intelligent Transport Systems (C-ITS), allowing road users and traffic managers to share information between various entities and consequently creating a breeding ground for the growth of new mobility services.

All these transformations have led to a migration of the value creation from pure mechanical systems, toward mechatronic systems, and then finally to software systems. Following this trend, the software-defined vehicle (SDV) [8] transformation is focusing on the deployment of software development methodologies for vehicle development as well as on value delivery shift toward customers along the entire vehicle lifecycle. Evidently, innovative and flexible mechatronics platforms are the foundation of SDVs, providing a large range of actuators which can be reconfigured during vehicle lifetime for the optimization of existing functions, respectively for the emergence of new, customized services.

The migration toward high-voltage board-nets (400 V, 800 V, and above) paved the way for the migration of the powertrain and chassis components toward electro-mechanical counterparts, providing a higher degree of freedom (DoF), faster reaction, and more accurate control. This, in turn, is leading to over-actuated vehicle systems, where multiple actuators can influence the same vehicle dynamics state. Electrification of the powertrain and chassis actuators is a key enabling technology for SDVs.

Target of this paper is to present the complementary contributions of three European R&D projects in this context. Relying on innovations around power electronics (PE) (HighScape[1]), electric motors (EM-TECH[2]) and skateboard platform for user-centric mobility (SmartCorners[3]), this article introduces innovations related to electrified powertrain and chassis components in section 2, vehicle platform and highly integrated corner solutions in section 3, and novel control algorithms making use of smart components in section 4. Acknowledging the importance of mapping technology innovation with market and societal needs for impact creation, section 5 is discussing the stakeholders' segmentation and expected benefits.

2 Smart powertrain and chassis components taking advantage of electrification

Electrification is key to rethinking the components and providing accurate control of high power and high energy actuators. The introduction of new semiconductor materials like silicon carbide (SiC) or gallium nitride (GaN), capable of handling higher voltages, temperatures, and frequencies, makes wide bandgap (WBG)-based devices well-suited to a great range of applications, including the automotive domain [9]. In comparison to pure silicon semiconductors, the material properties of SiC and GaN semiconductors enable component size and weight reduction, improved reliability, and increased energy-efficiency, which is crucial for high-performance applications. These power devices open the way for redesigns providing new DoF for efficient and active control of the vehicle's powertrain and chassis.

2.1 In-wheel motors

Following approximately 20 years of research focused on mitigating the inherent challenges of direct-drive in-wheel motors (IWMs) – such as increased unsprung mass, durability, serviceability, packaging constraints, as well as noise, vibration, and harshness (NVH) – recent experimental validations and positive assessments from legacy automotive original equipment manufacturers (OEMs) have enabled a shift towards exploiting the distinct advantages offered by this technology.

Beyond the widely acknowledged benefits, including enhanced vehicle dynamics through individual wheel torque control, improved packaging efficiency via powertrain component elimination, potential gains in system efficiency, and powertrain's mechanical simplification, IWMs facilitate several less discussed but significant capabilities.

[1] https://highscape.eu
[2] https://emtechproject.eu
[3] https://smartcorners.eu

A key enabler is the potential integration of high-accuracy, low-latency rotor position sensors suitable for mass-market application directly within the IWM. Given the direct coupling between the rotor and the wheel rim, this sensor configuration provides inherently superior wheel speed measurements in terms of both accuracy and latency compared to conventional anti-lock braking system (ABS) sensors. This high-fidelity sensing, combined with the exceptionally rapid torque response characteristic of responsive IWM designs (capable of slew rates approaching 500 Nm/ms), allows for unprecedentedly fast and accurate wheel speed control. The synergy between precise sensing and rapid actuation is particularly effective under variable surface conditions but also yields performance advantages on consistent surfaces, such as racetracks and off-road terrains, especially as motor torque capabilities increase. Consequently, torque vectoring algorithms can utilize direct wheel slip measurements for feedback, enabling a much faster and more accurate control loop for optimizing torque transmission at each wheel compared to reliance on slower vehicle-level inertial measurement unit (IMU) data.

Moreover, the potential of IWMs extends beyond advanced traction and stability control. A novel capability arises from the ability to generate active vertical forces at each wheel. This effect leverages the IWM's torque reaction acting through the suspension's instant center via the designed lever arm. Unlike conventional powertrains, IWMs can induce these vertical forces independently at each corner during both acceleration and braking phases, allowing modulation of vehicle pitch and roll without necessitating net changes in longitudinal velocity or acceleration. This rapid, controllable vertical force generation unlocks functionalities previously considered infeasible, such as active cancellation of road and tire noise at the source or providing haptic wheel vibration feedback related to grip limits or other advanced driver assistance system (ADAS) alerts.

Furthermore, IWMs can contribute to steering actuation, offering significant potential for autonomous vehicles and steer-by-wire architecture. By applying a precise torque difference between the steered wheels, a steering force can be generated at the steering rack due to the tire's scrub radius. This capability can serve as a redundant steering input or be used to augment the primary steering system, enhancing responsiveness without requiring an oversized steering actuator.

It is recognized that the deployment of all these functionalities is subject to constraints related to motor power density, vehicle power, and energy storage capacity. Therefore, effective integration and coordination with existing chassis control systems – such as active suspension, primary steering actuators, and friction brakes – are crucial. Current research initiatives, exemplified by the SmartCorners project, are focused on developing supervisory control strategies for such highly over-actuated vehicles. The central challenge is managing the interactions between multiple actuators to achieve common vehicle-level objectives safely and efficiently, avoiding conflicts and maximizing synergistic effects. Advanced methodologies, including complex system design platforms, are being explored to orchestrate these multi-actuator systems effectively. The projects EM-TECH and HighScape are focused on investigating innovative architectural solutions with respect to the IWM on the system level. Together with project partners, Elaphe is exploring the possibility of integrating system level components into the IWM structure to improve and enhance multiple motor key performance indicators (KPIs). Elaphe and University of Bath integrated the first mechanical e-gear of its kind into the Elaphe EM-TECH IWM, illustrated in Figure 1.

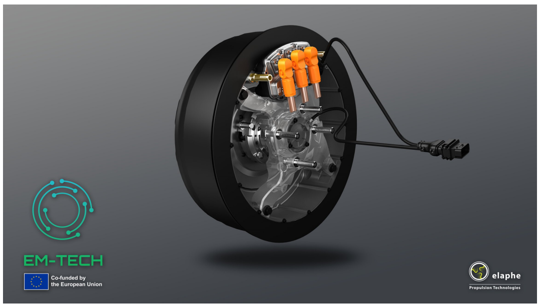

Figure 1: EM-TECH IWM design by Elaphe and University of Bath

A second innovative architectural improvement is the direct cooling solution developed by Elaphe and Politecnico di Torino. This solution not only influences motor operating temperatures but also affects the electric motor's design space, resulting in potentially increased design space and greater (efficiency) optimization possibilities for the IWM.

One of the more discussed advantages of the IWMs is their potential for improving the vehicle architecture and saving valuable space. The realized space savings can be utilized either for additional cargo space or passenger comfort, adding in both cases new value to the vehicle. With the integration of the PE components in the IWM housing the packaging is improved even more. This architectural IWM layout is investigated within the HighScape project by Elaphe and Bluways integrating the traction inverter to the IWM, system testing on the test bench as well as its integration to the test vehicle by Fiat Tofaş. The SiC traction inverter is intended to be seamlessly integrated into the housing of a wide range of IWMs up to 120 kW and is operating at 800V DC and optimized for low inductance and high thermal performance.

2.2 Active suspension

As the automotive industry is moving towards full vehicle electrification, many chassis systems are being replaced by their electrified counterparts like brake-by-wire or steer-by-wire. A special consideration is devoted to suspension actuators, since they strongly impact passenger comfort and vehicle handling. The former is ever more crucial since market trends highlight a large diffusion of premium and luxurious sport utility vehicles (SUVs). Moreover, the expected circulation of autonomous vehicles will require much higher comfort standards, as the vehicle cabin will become a multifunctional space for activities different from driving. Instead, handling strongly relates to safety as it depends on the tire-ground forces. For instance, proper control of the vehicle body motion improves the braking performance and rollover stability, as load transfers could be optimally controlled, and the coordinated control of suspensions, brakes, and steering could further enhance ride comfort, vehicle handling and performance. Currently, semi-active shock absorbers and slow-active actuators are state-of-the-art and already widespread in upper class vehicles. Hence, semi-active dampers rely on broad and fast damping control (30-40 Hz), they are still under the force-speed passivity constraint, at acceptable cost, complexity, and power demand (10-20 W). Contrarily, slow-active actuators can deploy forces in all the four quadrants of the force-speed working plane of the suspension, but with a bandwidth limited to 1-5 Hz. Hence, they can only control sprung mass low-frequency motion and at expenses of increased power consumption (1-5 kW) [10]. Full-active shock absorbers are cutting-edge technology as they can provide full force controllability, enabling optimal control of passengers' comfort and tire vertical dynamics. These modern systems are currently undergoing intensive development and are beginning to appear in prototype vehicles.

Beyond typical performance enhancements, active suspensions can support additional functionalities such as an “easy entry” mode, “tilt while cornering” mode, and even “dance” or “show” modes, which have already been demonstrated by some manufacturers. Modern active suspension systems have peak power ratings that can reach 10 kW, making their energy consumption a non-negligible factor. Vehicle electrification acts as a key enabler by providing a high-voltage architecture, which improves both efficiency and power density of the electrical components. Building on these improvements and PE developments by Bluways in the HighScape project, recent advancements have enabled higher force outputs and broader operational bandwidths. Since power demand still represents the main concern and suspension systems must dissipate energy during operation, energy harvesting approaches are leading to very low net power consumption.

Within the SmartCorners project Politecnico di Torino is investigating the innovative corner module, embedding an electro-mechanical shock absorber to propose an oil-free suspension [11]. The actuator features a surface permanent magnet (SPM) motor as rotary electric machines show higher power and torque density than linear ones. However, a rotary-to-linear conversion mechanism is mandatory to comply with the linear suspension motion. To this end, a linkage mechanism is employed: a connecting rod transmits the movement of the suspension lower arm to a crank lever, which rotates the actuator output shaft. Indeed, a mechanical speed reducer matches the force-speed requirements at the suspension level with the motor output to avoid a bulky system. All in all, the design procedure involves a global optimization methodology to respect both performance and packaging requirements. As this kind of actuator is fully reversible in motion, both active and passive forces can be generated, thus enabling power regeneration. Peak total conversion efficiencies of about 70 % and 60 % are usually achieved in active and regenerative modes, respectively. The full mechanical layout guarantees a force bandwidth higher than 40 Hz, enabling full-active functionalities.

Another critical area of development is the control system design, particularly the integration of active suspension with other chassis systems, including brakes and powertrain, is executed in the HighScape project by Tenneco. These systems also induce body motion through kinematics-driven force reactions, which must be accounted for in coordinated fault-tolerant control strategies developed by University of Surrey in the HighScape project using an integrated chassis controller. Moreover, the design of suspension kinematics itself is being reconsidered for vehicles equipped with active suspension. For example, traditional kinematics-induced effects such as roll steer – deliberately designed into passive systems – must be revisited when the suspension system actively maintains a level body under all driving conditions.

2.3 Electro-mechanical brakes

Electro-mechanical brakes (EMBs) consist of an electric motor, a transmission, PE components, and electronic control unit (ECU) and can be divided into different classes by their actuation principles [12]. All these components are broadly available already, but by today only a few suppliers have released EMBs for rear axle applications, since the higher available space in the wheel hub allows bigger brake calipers. For the front axle, the packaging must be improved to (a) fit into the rims, (b) guarantee full steerability, and (c) avoid collisions with the wheel lifting kinematics. The increasing vehicle mass of EVs and the trend to bigger vehicles such as SUVs lead to higher braking forces. With conventional 12 V DC motors, these forces cannot be generated or only with very big transmission ratios, which worsens the packaging challenges again.

Despite aspects of technical readiness, legal issues are another important point. Generally, the release of full brake-by-wire systems is possible by law, but the systems must provide a "safety state", in which the system can return in case of any failure and providing a sufficient brake power [13] to slow down the vehicle without unreasonable risk of harm [14]. So far, decoupled systems use a hydraulic fallback level, since it is fully operational even in case of total loss of electrical energy. For the broad introduction of EMB systems, fail-safety must turn into fault-tolerance, which means that the system is able to react on partial failures without system degradation. In HighScape, the project partners Bluways and Technische Universitaet Ilmenau are investigating fault-tolerant architectures for the PEs and actuators of EMBs, providing redundancy at low necessity of doubled components as shown by, e.g. Heydrich et al. [15].

Besides the challenges, EMBs are a promising technology from the perspective of vehicle dynamics control. As power-on-demand systems, they have a very low impact on energy consumption and their dynamics are generally higher than for (electro-)hydraulic ones. In combination with the shift from microprocessors to microcontrollers, this offers potential for highly integrated actuators with easy access to other sensors and control systems, capable of high-performant control algorithms, such as innovative electronic brake force distribution, automated emergency braking (AEB), ABS, electronic stability control (ESC) etc. Additionally, their high positioning precision leads to a very high accuracy in clamping force modulation, but reduces the drag torques too and therefore causes less passive brake wear. This is crucial regarding the new EURO 7 regulation, which includes limits for emissions of brake and tire wear particles (non-exhaust emissions) for the first time.

In summary, EMBs are a groundbreaking and necessary technology for future ground vehicles and dynamics control, that will evolve in the future. From the economic perspective, the demand for EVs and SDVs will lead to a growing market penetration of EMBs at constant growth in the next decade.

2.4 Half-track width variation & independent wheel positioning

Active chassis systems have long been fundamental to enhance vehicle dynamics and improve maneuverability, ride comfort, and safety. Traditionally, such systems manipulate key suspension and steering parameters – such as camber angle, toe angle, and rear-wheel steering – to optimize tire contact and overall dynamic response. However, a less explored yet highly promising concept is the active control of half-track width – the lateral distance from the vehicle's centerline to each wheel. In conventional setups, this dimension is fixed by the suspension design. When combined with independent wheel positioning, however, it becomes a new controllable DoF that can be dynamically adjusted in real-time.

The system illustrated in Figure 2 is mounted on each corner and it is composed by the main actuator (MA, 1), steering actuator (SA, 2), swingarm (3), ring holder (4), wheel hub (5), link (6), three chassis hinges (7-9), wheel (10), air suspension (11), and camber actuator (12). The main and steering actuators are variable in length and built with two concentric cylinders. The relative movement between the two cylinders allows the variation of the steering angle and the half-track width with kinematic limitations and dependencies shown in Figure 3.

The core innovation, developed in conjunction with the SmartCorners project from HERONsports, is an integrated chassis control strategy that simultaneously manages both steering angles and half-track width variation. By dynamically adjusting the half-track width during tight maneuvers, the system minimizes wheel-to-body interference, enabling greater steering angles – ideal for urban driving, U-turns, or automated parking. Moreover, independent wheel positioning control allows for real-time optimization of inner and outer wheel angles, surpassing the constraints of traditional Ackermann geometry, to enhance grip, minimize slip, and improve overall handling performance. These capabilities are made possible by advanced PE, which provide the necessary infrastructure for high-speed actuation, low-latency signal processing, efficient energy conversion, and coordinated control of multiple electro-mechanical actuators. As a result, the system enhances vehicle dynamics across various driving scenarios, delivering a user-centered experience with improved vehicle efficiency and performance.

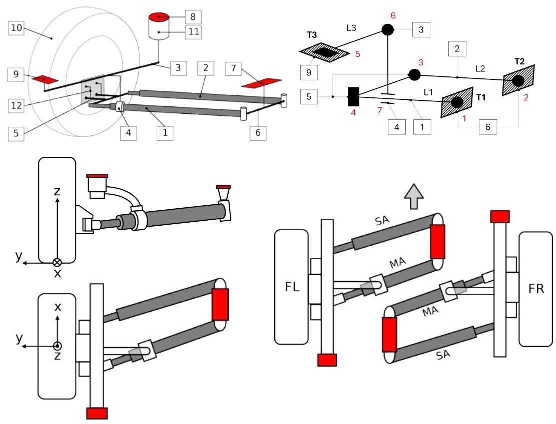

Figure 2: Conceptual visualization of the active suspension kinematics system

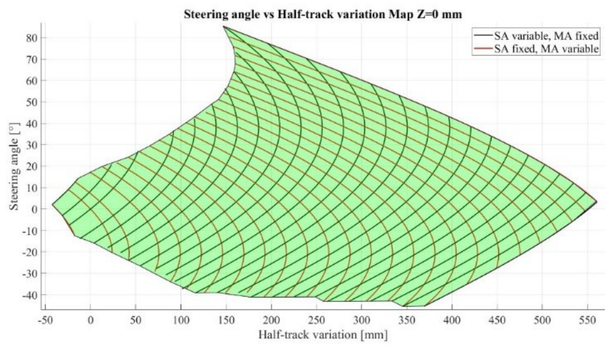

Figure 3: Working area in terms of steering angle and half-track width variation

3 Highly integrated corner solution

The integrated corner architecture represents a significant innovation for an increasingly electrified automotive market, unlocking a wide range of opportunities. In this context, the main output of the SmartCorners project is a single, compact corner module incorporating all key subsystems (powertrain, steering, braking, and chassis control). This design offers flexibility and supports the implementation of advanced functionalities that improve both performance and passenger comfort. The objective of implementing such highly integrated systems is to achieve maximum functional integration by developing a design that ensures cooperation among them. This approach from Politecnico di Torino not only optimizes packaging and energy consumption but also allows for a performance-based mechanical design that exploits component synergy. Due to the higher design freedom allowed by the corner approach, even the suspension architecture can be optimized to reach the best possible elasto-kinematic characteristics, guarantee the integration of the key subsystems, and add structural monitoring. Its modular and scalable nature facilitates easy integration into various vehicle classes, accommodating a wide range of dimensional and performance requirements. The system modularity also simplifies significantly the assembling and manufacturing processes, allowing cost reductions. The vehicle's maintenance would also benefit from the modular design, since the independent systems would allow higher levels of safety while at the same time reducing the efforts necessary for disassembly and repair. Additionally, the available luggage and passenger compartment space of the vehicle is expected to increase by 15-20 %, leading to comfort improvement of everyday usage of the EV. More in detail, the powertrain is totally removed from the engine compartment and the removal of the hydraulic shock absorber permits the design of a more compact architecture e.g., a low-type double wishbone.

The corner module is designed for direct compatibility with a skateboard platform, further enhancing flexibility. The skateboard vehicle chassis configuration is a structural approach used in the vehicle platform of EVs, which simplifies vehicle development by creating a self-contained platform that integrates the traction battery, electronic systems, and driving components. Additional components can be directly mounted on the platform, significantly reducing the assembly efforts and costs. Furthermore, the full system is completely scalable and able to be integrated within very different vehicle bodies, enabling high versatility and optimized design processes. An additional key advantage of the highly integrated corner concept lies in its potential to be involved in SDV development processes. Through the creation of accurate digital twins (DTs) of the components of the corner module, it is possible to improve the precision of the vehicle model, taking the dynamic behavior of each element into account. The obtained model can be rescaled for representing different classes and sizes of EVs, allowing for the development of a design methodology that is applicable to multiple cases and requirements. This approach leads to significant reductions in development costs and system complexity, while also bringing better reliability by minimizing variability across digital models employed during testing and validation phases.

Moreover, the advanced control capabilities of the integrated corner modules, enabled by independent actuators and X-by-wire systems, make the resulting EV an ideal platform for autonomous driving technologies. The solution is specifically optimized to provide smart, precise, and individual wheel force control, both in the case of four-wheel drive and two-wheel drive configurations. This level of controllability allows for the safe and efficient implementation of advanced motion planning and control strategies, accelerating the transition toward highly automated and intelligent mobility systems.

4 Vehicle control

4.1 Integrated methodology for the development of vehicle control

Realizing the full potential of a vehicle’s different components necessitates their effective integration and coordination with existing and future chassis control systems, such as active suspension, primary steering actuators, and vehicle motion control. This integration results in highly over-actuated vehicle systems, where multiple actuators can influence the same vehicle dynamics state. While offering enhanced vehicle performance possibilities, this complexity presents a significant challenge for control system design. Traditional control strategies often rely on rule-based activation thresholds or mode-switching logic, which can limit performance by failing to exploit potential synergies or resolve conflicting actuator demands optimally. The central challenge, as identified in the SmartCorners project, lies in developing supervisory control strategies capable of managing the intricate interactions between these multiple actuators to achieve common vehicle-level objectives such as stability, handling, path following, ride comfort, and energy efficiency safely and effectively, while avoiding conflicts and maximizing synergistic effects.

Independent control authority over each wheel enables direct influence on vehicle yaw and side-slip dynamics (torque vectoring), vertical force modulation for body roll and pitch management, active damping of high-frequency road-induced vibrations and noise, enhanced traction and braking performance through high-frequency slip control (potentially synergizing with friction brakes), and improved steering response. This expanded actuation capability opens possibilities for advanced integrated motion control (IMC) beyond conventional e-axle traction and regeneration capabilities, potentially addressing simultaneous control over all six DoF of the vehicle's sprung mass, see Figure 4. A critical consideration, often overlooked in studies focusing solely on vehicle dynamics performance, is the potential negative impact on overall energy consumption, which must be managed concurrently.

To address the complexity of designing and implementing such advanced IMC strategies for highly over-actuated vehicles, a novel platform is proposed utilizing advanced methodologies, including AI, inspired by complex system design frameworks. This platform is architected to facilitate the development of sophisticated, multi-objective control systems capable of orchestrating multi-actuator systems effectively.

The key design objectives for this platform mirror the requirements for modern complex system development, enabling the seamless aggregation of domain knowledge from various experts, such as those in powertrain, chassis dynamics, and control theory, without demanding exhaustive system-wide understanding from each contributor. Additionally, the platform aims to ensure that the generated control algorithms are predictable, robust, and human-interpretable, moving beyond opaque ”black-box“ approaches towards trustworthiness and explainability. It must also allow direct incorporation of various constraints, encompassing regulatory standards, physical hardware limitations like motor power density and energy storage capacity, and specific performance targets such as minimizing energy consumption or component wear. Finally, a crucial objective is to facilitate incremental inclusion and refinement of knowledge derived from diverse data sources, ranging from component-level tests and hardware-in-the-loop simulations to full vehicle simulations and data gathered from physical test vehicles.

The proposed solution architecture aligns with the framework comprising an offline learning pipeline and the resulting on-vehicle software. The core components are as follows. Firstly, a central knowledge repository, representing vehicle models, environmental contexts, physical laws, and control logic in a structured, verifiable, and human- and machine-understandable format across multiple abstraction layers. Secondly, a Human-Machine Interface (HMI), allows experts to intuitively view, edit, and augment information. Lastly, a compiler translates the symbolic rules, equations, models etc. into executable code.

The compiled software constitutes the second major element, given by the on-vehicle DT, which executes control actions from the software code and generates real-time feedback during operation or testing, which is used as feedback for offline optimization, creating a continuous loop of refinement and adaptation. This iterative process bridges offline analysis and design with real-world applications, aiming to accelerate the development cycle and optimize the overall performance, safety, and efficiency of the integrated powertrain and chassis control system.

4.2 Control strategies for the improvement of propulsion and brake efficiency

The desire for sustainable, climate-friendly and affordable mobility accelerated the development of zero-emission powertrain systems in recent years. New propulsion systems, such as BEVs are interesting trends, but they come at a price: A traction battery for energy storage is heavy and increases the vehicles' total mass by hundreds of kilograms compared to conventional powertrains. One the other hand, the new components – such as electric machines – are fast and precise in actuation, twice more efficient than the best combustion engines and able to recover energy, offering new potentials in operating a modern vehicle, but it requires new approaches of cooperative vehicle motion control due to new DoF in the manipulation of vehicle states, see Figure 4. Modern EVs are already capable of changing vehicle states by using combined operation different actuators in combination. Therefore, they are often referred to as over-actuated. One prominent use case is the cooperative operation of regenerative and friction brake systems. The regenerative brake system refers to the electric machines in generator mode, whereat they generate an electro-magnetic force that decelerates the vehicle. In parallel, the induction recovers electrical energy that can be stored in the traction battery. This control is beneficial in several ways, since (a) most daily braking maneuvers can be covered by regenerative braking solely, (b) brake wear is reduced and (c) the recovered energy extends EVs' range by up to 30 % [16]. To provide an optimal performance, the friction brake system should feature a decoupled architecture, but best results are expected by using EMBs.

Contrary to classical brake torque blending as presented previously, the approach does not primary aim for energy-efficiency improvement but uses the high actuation dynamics of the electric machines to track optimal wheel slip very quickly, which is necessary in severe conditions.

The Pulse and Glide (PnG) driving technique investigated by from University of Surrey is widely recognized as an effective strategy for improving the energy-efficiency of vehicles [17], particularly when compared to conventional cruise control, which maintains a constant torque command to sustain a target speed. PnG alternates between a pulse phase, where the vehicle accelerates using higher torque, and a glide phase, where the vehicle coasts with minimal or zero torque. In terms of EVs, this alternating control strategy enables the electric motor to operate more frequently within its high-efficiency region during the pulse phase while reducing power consumption during the glide phase. As a result, the PnG method can reduce overall energy consumption. To systematically realize the PnG strategy, a Linear Programming (LP)-based controller is developed to minimize energy consumption by optimizing the torque levels and their respective duty cycles within each pulse-glide period, based on the motor's power loss characteristics. The reconfigurability allows different powertrain configurations: (a) on-board with constant gear ratios for front and rear axles, (b) on-board with different gear ratios for front and rear axles, or (c) in-wheel.

Beyond energy optimization, the PnG strategy is also extended to determine the optimal gear usage for EVs equipped with an e-gear system in the EM-TECH project. The e-gear exploits a newly developed dual winding IWM architecture which enables the IWM to operate with two modes, leading to higher continuous power and improved efficiency: Mode 1 (series winding connection) and mode 2 (parallel winding connection), each offering distinct efficiency characteristics depending on the operating conditions. The LP optimization framework is utilized not only to determine the optimal pulsing and gliding sequences but also to identify the most energy-efficient gear selection based on the current vehicle speed and desired average motor torque, illustrated by Figure 5.

Additionally, a nonlinear model predictive controller (NMPC)-based ABS was developed, that uses combined brake torque control between the EM-TECH motors and the friction brakes, to prevent wheel lock-up and enhance vehicle stability are presented. The NMPC incorporates actuator dynamics, nonlinear tire models, and powertrain effects (e.g., torsional oscillation) within a predictive framework. Simulations compare IWMs and on-board axial flux motor (AFMs), showing improved braking performance and responsiveness. IWMs offer fast torque actuation without powertrain delay, while on-board AFMs provide improved torque regeneration during hard braking maneuvers. Across both layouts, the NMPC enhances braking efficiency and safety, outperforming conventional passive brake systems based on KPIs under various driving scenarios.

The EM-TECH project introduces a ride comfort control strategy using a NMPC enhanced with road profile preview to actively suppress longitudinal acceleration oscillations induced by road irregularities. Departing from conventional suspension-based methods focused on lateral acceleration compensation, the approach targets longitudinal dynamics by modulating electric powertrain torque, demonstrating that both IWMs and on-board AFMs with torsional half-shaft dynamics can enhance ride comfort. By anticipating disturbances via road preview, the NMPC optimizes torque adjustments to preemptively mitigate impacts. Validated through high-fidelity simulations of an all-wheel-drive EV across three configurations (four IWMs, four on-board AFMs, two on-board AFMs), the strategy is assessed using comfort-focused KPIs in diverse driving scenarios, proving computational feasibility for real-time deployment. Preliminary experimental trials with University of Surrey's ZEBRA EV further confirm its efficacy in reducing comfort-critical oscillation amplitudes [18].

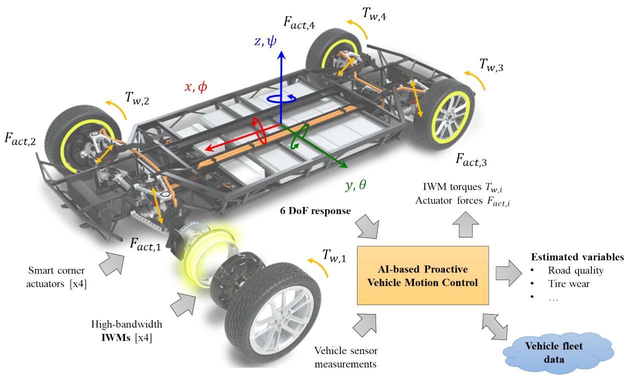

Figure 4: AI-based proactive vehicle motion control concept

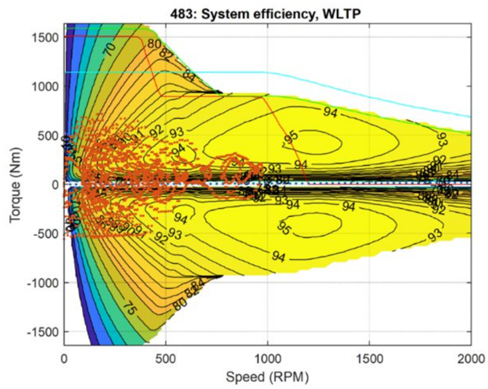

Figure 5: IWM DT efficiency map with mechanical e-gear

5 Stakeholder benefits

The overarching objective of European research programs is to "*strengthen its scientific and technological bases by achieving a European research area in which researchers, scientific knowledge and technology circulate freely, and encouraging it to become more competitive, including in its industry, while promoting all the research activities deemed necessary by virtue of other Chapters of the Treaties*", see [19], article 179. As such, the mission for European programs is to develop knowledge and technologies able to create an impact on our society – respectively creating benefits for the different stakeholders. The expected impacts for the three projects discussed in this paper are the following:

- **HighScape:** New designs of WBG-based PE, especially for BEV, and utilization for different powertrains and chassis applications. Key developments include integrated IWMs with PE, integrated PE (e.g., DC/DC converters) in the high-voltage traction battery, OBC sharing power devices with the IWMs, PE driven active suspension and brake systems. The development targets to reduce costs of e-powertrains, and to increase vehicle performances especially focusing on energy efficiency and vehicle dynamics.
- **EM-TECH:** Two complementary technologies of energy-efficient, affordable and eco-friendly electric motors addressing high-torque density radial flux IWMs and high-power density on-board AFMs. The

development aims to decrease energy losses along driving cycles and reduce production costs as well as the usage of rare earth content.

- **SmartCorners:** Introduction of user-centric smart corner systems (SCS) relying on IWMs, electro-mechanical brake systems, electro-mechanical active shock absorbers, active suspension kinematics with increased capabilities in terms of toe, camber, and track width control and higher suspension travels. Relying on predictive user-centric AI-based controllers, the development targets to provide a new series of flexible SCS for next-generation EVs, enabling rethinking of vehicle architecture.

In the course of these three R&D projects the following stakeholder segments and related expectations have been identified:

- **End users and general public:** Demand of private and business users for affordable and reliable EVs, well integrated in mobility platforms for additional services; getting benefits via affordable, safe, right-sized, and comfortable EVs by using the technology developed in the projects; increase awareness on the capabilities of the technology and performance of EVs and educate the market.
- **Automotive OEMs:** Increasing the market share of energy-efficient EVs with a high level of customer acceptance and a high economic and reputation value for a company; getting benefits via illustrating technological advances and the capability to tailor for the respective OEM's portfolio in order to create revenue through selling of a product and/or services.
- **Automotive suppliers / engineering partners:** Demand in rapid creation of innovations in EV systems and components as well as related technologies, engineering services, and data-driven services for e-mobility; getting benefits via illustrating technological advances and the capability to transfer IP and/or competences for revenue creation.
- **Technology providers / SMEs:** Increasing positions as a more agile and latitudinous driver of innovations in emerging EV components and EV-related services as compared to large companies; getting benefits via onboarding to promote the technologies developed in respective projects ("technology ambassador").
- **Research community:** Advancing design methods and proposing new technologies for EVs and their systems / components, which are beyond state-of-the-art; getting benefits via interacting with the R&D community to create an open innovation ecosystem, supported by high quality public deliverables and high ranked scientific publications.
- **Policy makers:** Developing policies and promoting strategies for eco-friendly road-based transport and smart mobility; getting benefits via challenging of new policies through technology evaluation and issuance of technological recommendations on policies under preparation.

Key aspects for impact creation are the capability to engage with the relevant stakeholders to support industrialization, replication, and uptake of the solutions created by the respective project. Important concepts in this context are the scale (number of individuals affected by an impact) and the significance (importance or value of the impact) as introduced by the European Commission. Evidently, evolutionary or incremental innovations are expected to have easier acceptance in the ecosystem since maintaining technical, functional, and business-related interfaces already exists. In the contrary, revolutionary or disruptive innovations are pivotal events for the respective ecosystems (either in terms of technology, supply chains, and/or in terms of business model), where the uptake and replication is expected to require more resources. To support engagement with the relevant stakeholder, Value Proposition Canvases and Business Model Canvases are created in collaboration with the projects' respective project partners as part of their exploitation strategy. Table 1 provides an overview of the expected benefits for the different stakeholders. The confirmation (and delivery) of these benefits will be the basis for the stakeholder engagement and exploitation strategy.

Table 1: Benefits of various stakeholders among the presented R&D projects

Stakeholder segment	**HighScape**	**EM-TECH**	**SmartCorners**
End users and general public	Affordable, safe, and comfortable EVs with increased range	Affordable, safe, comfortable, and more sustainable EVs with increased range	Right-sized, user-centric, and affordable EVs
Automotive OEMs	PE-enabled components to improve	IWMs and AFMs to improve	Scalable and flexible SCS to

	vehicle performances and energy-efficiency	vehicle performances and reduce environmental footprint	support the efficient development of right-sized EV solutions
Automotive suppliers / engineering partners	IPs for PE-enabled components and control strategy to be integrated in their respective portfolio	IPs for e-motors components and control strategy to be integrated in their respective portfolio	IPs for SCS to be integrated in their respective portfolio
Technology providers / SMEs	Ambassador of customized solutions relying on PE-enabled components	Ambassador of customized solutions relying on e-motors	Ambassador of customized solutions relying on SCS
Research community	Pushing forward research in the specific research field, aiming for high-quality publications, increased visibility, reputation within the academic community, and option on IP rights in case of interest		
Policy makers	Evidence-based policy making with real-world data, user insights, and technology assessment from the R&D projects, support of the strategic agendas in force, project results can influence EU-wide or global standardization or regulation, user-centric innovation from R&D projects reduces risk of public resistance and improves the acceptance of new transport regulations		

6 Summary/Conclusions

The availability of electric energy in excess through the introduction of high-voltage boardnet is a game changer for the EV architecture. Hence, it enables the migration of powertrain and chassis components toward electro-mechanical counterparts, leading to a more direct and accurate control, and a reduction of part numbers – respectively reduction of volume and mechanical interfaces required.

The resulting modular EV architecture is a key enabler for right-sized mobility solutions. Hence, the mechanical decoupling between powertrain and chassis components from the chassis leads to a redesign of the supply chain: in a long-term vision, the availability of scalable SCS that can be "plugged" to the chassis will lead to a significant decrease of complexity while designing new vehicles. This will in turn significantly reduce efforts and time to market to introduce new solutions on the market, opening the door for smaller entities to become car manufacturers for niche applications.

The more direct and accurate control – supported by high-speed networks, high performance computing units and the emergence of zone controllers – leads to a new level of functional integration. The availability of over-actuated vehicle systems, where multiple actuators can influence the same vehicle dynamics state, is a game changer to introduce new (AI-based) control strategies improving vehicle performances. Furthermore, this platform represents the mechatronic foundation for SDV, where the vehicle behavior can be modified by software updates during vehicle lifetime.

The three European research programs HighScape, EM-TECH, and SmartCorners are introducing components and solutions in this context. The technical targets are to develop solutions increasing performances, reducing costs and environmental footprint (with focus in reducing rare-earth for the magnets of the e-motors). The ecosystem's related target is to engage with the relevant stakeholder segments interested, to evaluate the proposed innovations, finally supporting replication and uptake. For that, light entry points both at business strategy level (value proposition canvas and business model canvas) and at technical level (comprehensive simulation models and testing environments) are provided to lower the entry barriers as much as possible.

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References

[1] United Nations Framework Convention on Climate Change (UNFCCC), 2015, *Paris Agreement*, https://unfccc.int/sites/default/files/english_paris_agreement.pdf, accessed on 2025-04-16.

[2] European Commission (EC), 2019, *The European Green Deal*, COM(2019), 640 final.

[3] EU, 2025, *European Climate Law*, https://eur-lex.europa.eu/legal-

content/EN/TXT/?uri=legissum:4536626, accessed on 2025-04-16.

[4] EC, 2021, *Fit for 55: delivering the EU's 2030 Climate Target on the way to climate neutrality*, COM(2021), 550 final.

[5] CINEA, 2022, *EU Road Safety: Towards Vision Zero*, https://cinea.ec.europa.eu/system/files/2023-02/H2020%20Transport-Road%20Safety%202022-web.pdf, accessed on 2025-04-24.

[6] SAE International, 2021, *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*, J3016_202104.

[7] EC, 2016, *A European strategy on Cooperative Intelligent Transport Systems, a milestone towards cooperative, connected and automated mobility*, COM(2016), 766 final.

[8] EC, 2023, *Concept paper on an open European software-defined vehicle platform for the vehicle of the future*, https://digital-strategy.ec.europa.eu/en/library/concept-paper-open-european-software-defined-vehicle-platform, accessed on 2025-04-24.

[9] *Infineon*, 2025, https://www.infineon.com/cms/de/product/technology/wide-bandgap-semiconductors-sic-gan/, accessed in 2025-04-23.

[10] Savaresi, S. M., Poussot-Vassal, C., Spelta, C., Sename, O., and Dugard, L., 2010, *Semi-active suspension control design for vehicles*, ISBN: 9780080966786, Amsterdam, Elsevier.

[11] Galluzzi, R., Circosta, S., Amati, N., and Tonoli, A., 2021, *Rotary regenerative shock absorbers for automotive suspensions*, Mechatronics, 77, 102580, https://doi.org/10.1016/j.mechatronics.2021.102580

[12] Yan, Z., Peng, H., Chen, X., and Yan, M., 2024, *Design, Modeling, and Control of Electronic Mechanical Brake System: A Review*, SAE Int. J. Veh. Dyn., Stab., and NVH, 8(4): 467-489, https://doi.org/10.4271/10-08-04-0026.

[13] EU, 2015, *ECE-R13H: Uniform Provision concerning the approval of vehicles of categories M, N and O with regard to braking*, https://eur-lex.europa.eu/eli/reg/2016/194/oj/eng, accessed on 2025-04-24.

[14] ISO, 2018, *Road vehicles – Functional Safety,* ISO 26262-1:2018.

[15] Heydrich, M., Lenz, M., Ivanov, V., Stoev, J., and Lecoutere, J., 2025, *Concept of an Electromechanical Brake-By-Wire System for Battery-Electric Vehicles*, SAE Technical Paper 2025-01-8804, https://doi.org/10.4271/2025-01-8804

[16] AUDI AG, 2017, *Fahrwerk - Elektrohydraulisch integriertes Bremsregelsystem*, https://www.audi-mediacenter.com/de/audi-technik-lexikon-7180/fahrwerk-7185, accessed on 2025-04.24.

[17] Li S E, Peng H., 2012, *Strategies to minimize the fuel consumption of passenger cars during car-following scenarios*, Proceedings of the Institution of Mechanical Engineers. Part D: Journal of Automobile Engineering, 226 (3): 419-429, https://doi.org/10.1109/ACC.2011.5990786.

[18] Stano P, Lazzarini D, Santoro S, Mihalkov M, Montanaro U, Vigliani A, Ferrara A, Dhaens M, Sorniotti A., 2024, *On-board electric powertrain control for the compensation of the longitudinal acceleration oscillations caused by road irregularities*. Mechanism and Machine Theory, 202:105759, https://doi.org/10.1016/j.mechmachtheory.2024.105759.

[19] Official Journal of the European Union, 2012, *Consolidated version of the threaty on the functioning of the European Union*, C326/47, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:12012E/TXT:en:PDF, accessed on 2025-04-26.

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