European Initiatives for User-Centric Design of Electric Vehicles

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Abstract

E-mobility is revolutionizing the automotive industry by improving energy-efficiency, lowering CO_2 and non-exhaust emissions, innovating driving and propulsion technologies, redefining the hardware-software-ratio in the vehicle development, facilitating new business models, and transforming the market circumstances for electric vehicles (EVs) in passenger mobility and freight transportation.

Ongoing R&D action is leading to an uptake of affordable and more energy-efficient EVs for the public at large through the development of innovative and user-centric solutions, optimized system concepts and components sizing, and increased passenger safety. Moreover, technological EV optimizations and investigations on thermal and energy management systems as well as the modularization of multiple EV functionalities result in driving range maximization, driving comfort improvement, and greater user-centricity.

This paper presents the latest advancements of multiple EU-funded research projects under the Horizon Europe framework and showcases their complementarities to address the European priorities as identified in the 2Zero SRIA, namely EFFEREST, MINDED, and SmartCorners. EFFEREST targets energy efficiency, comfort, safety, and affordability of EVs through considering knowledge from real-fleet behavior and personalization of data. MINDED aims to maximize EV's driving range by improving the thermal- and energy management of an electric minibus to reduce energy consumption while optimizing thermal comfort, and therefore directly impacting the user acceptance. SmartCorners provides scalable, flexible, and user-centric smart corner systems including e-axles and e-corners based on in-wheel powertrains. SmartCorners aims at introducing smart corner systems based on in-wheel powertrains as underlaying technology toward software-defined vehicles, enabling rightsizing, holistic optimization, innovative fault mitigation and actuator allocation strategies as well as more efficient, adaptive, predictive, and personalized system operation.

Introduction

The simultaneously ongoing shifts towards e-mobility and automated driving are challenging the automotive industry and expecting to result in a massive CO_2 emission reduction [1], a decline of non-exhaust emissions [2], an increase of energy-efficiency [3], and numerous technological EV optimizations. Both trends are in accordance with the following announced roadmaps from the European Commission: (a) the *"Towards zero emission road transport"* (2Zero) partnership and its Strategic Research and Innovation Agenda (SRIA) [4], striving for zero tailpipe emissions for road transport in Europe, (b) the *"European Green Deal"* [5], a bundle of policy initiatives including *"Fit for 55"* [6], aiming to reduce greenhouse gas emissions by at least 55 % by 2030, (c) the *"Paris Agreement"* [7], an international climate treaty to limit global warming, and (d) the Road Safety Initiative *"Vision Zero"* [8], with the ambition to achieve on European roads as close to zero fatalities as possible by 2050.

The E-VOLVE cluster is a platform for mutual promotion, synergy creation, and impact increasement of several EU-funded R&D projects with a focus on EV transportation, such as the three presented projects EFFEREST, MINDED, and SmartCorners. The term E-VOLVE stands for EV Optimized for Life, Value and Efficiency. Eight of the 14 projects that E-VOLVE currently has are active members. The cluster's aim is to gain synergies among the cluster members, conduct joint dissemination, exploitation, and standardization activities, boost the projects with increased (scientific) impact and visibility gained through E-VOLVE actions, and support the industrialization process of the various project's achievements. [9]

Therefore, E-VOLVE enables networking and know-how/experience exchange opportunities along with access to specialized associations, organizations, and scientific platforms, with the target to broaden the project's communication channels. One of E-VOLVE's key success factors is the diversity of the involved 139 project partners from 22 countries in 20 R&D projects, as of October, 2024: academia, industry, research centers, small and medium-sized enterprises (SMEs), and automotive original equipment manufacturers (OEMs) come together every 3 months with opposite viewpoints, different problem solutions and methodological approaches, discussing new ideas and pathways to reach the defined goals. [9]

In the last years, a sustainability-driven shift of the mobility system from traditional private car ownership toward EVs, shared mobility, mobility systems, and automated driving has gained momentum [10, 11, 12, 13]. Due to technological achievements and changing user expectations OEM's former mainly goods-oriented business models (BMs) are gradually changing and increasingly contain at least aspects of service-oriented BMs, which are grounded on the service-dominant logic (SDL) [14]. SDL considers goods, resp. EVs, being means of services and the users as the focal point of value creation [15]. A user-centered BM design approach tends to result in a more sustainable BM [16] and can lead to advantages for both, companies and user, as trust is built and user needs and wishes considered more thoroughly [17].

The three R&D projects, EFFEREST [18], MINDED [19], and SmartCorners [20], presented in this paper belong to the 2023 call in Horizon Europe's cluster 5 *"Climate, Energy & Mobility"* and part of pillar II *"Global Challenges & European Industrial Competitiveness"*, dealing with the topic *"User-centric design and operation of EV for optimized energy efficiency"* [21]. The introduced R&D projects deal with user-centricity and pursue the following ambitions:

EFFEREST: With the goal of increased sustainability and user acceptance EFFEREST has the ambition of using digital twins (DTs) at a level of systematicity never attempted before for design and control of EV powertrains and thermal management. With the availability of powerful computing units and a wide range of on-board sensors, DTs have become a hot topic in several engineering areas. The review of recent advancements in DT technology applied to EVs in Bhatti et al. [22] provides a detailed workflow for constructing a complex DT of an EV system. Given the large amount of data that an EV generates through sensors, DTs are more suitable than other technologies, such as Hardware-in-the-Loop (HiL), to develop and/or assess innovative components and controllers. In EFFEREST this approach is applied in a holistic way to accelerate the design process and increase cost-efficiency. The application of DTs in the model-based predictive control approach will lead to improved overall efficiency and optimized passenger comfort.

MINDED: In 2022 the transport sector accounted for approx. 23.8 % of all CO2 equivalent emissions. Of this, approx. 26.2 % were produced by buses and heavy-duty vehicles [23]. This calls for a massive shift in this sector to deliver tangible benefits: reduced pollutant emission and noise, cleaner air, more livable urban and peri-urban spaces. In the same year 7 % of the EU passenger transport on land was made by buses and coaches, with 327 billion passenger-kilometers per year, making transport by bus the most widely used form of public transport. However, in 2022 only 1.4 % of the total European bus fleet was zero-emission [24], indicating a huge potential for the transport sector transformation to zero-emission buses for reaching carbon neutrality by 2050. The challenge hereby is to provide vehicles with suitable driving ranges while preserving or even increasing passenger comfort, which is to be done by improving the performance of the existing technologies in the MINDED project.

SmartCorners: The innovative smart e-corner design aims to reach new levels of flexibility, electric drive performance, suspension kinematics control capabilities, and steering functions. The vehicle's energy management system is optimized to decrease energy consumption and increase mileage. Several HiL platforms or component test rigs are networked enabling synchronized real-time experiments at geographically distributed test sites to reduce vehicle development time.

FIGURE 1   Project's complementarity to the 2Zero SRIA priorities

FIGURE 2   Project overview of EFFEREST

The three EU-funded projects are complementary to each other and arise from the same European call, and thus, pursuing the same call objectives. The 2Zero SRIA is composed of four pillars: (1) *"vehicle technologies and vehicle propulsion solutions for battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV)"*, (2) *"integration of BEV into the energy system and related charging infrastructure"*, (3) *"innovative concepts, solutions and services for the zero-tailpipe emission mobility of people and goods"*, and (4) *"life cycle assessment (LCA) approaches and circular economy aspects for sustainable and innovative road mobility solutions"*. [4] In Figure 1 the linkage of the projects EFFEREST, MINDED, and SmartCorners to the 2Zero SRIA research needs and its pillars is provided.
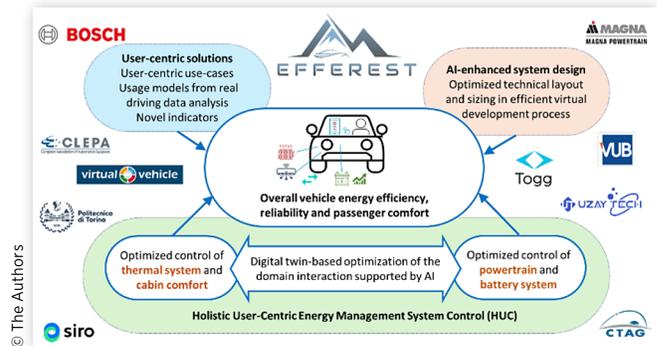
All projects have their research focus on the first pillar, addressing the topics *"conceptual vehicle design"*, *"energy-efficient and user-centric interiors"*, and *"thermal management"*. Moreover, investigations are performed to reduce the emissions and the environmental impact of next-gen EVs and in SmartCorners methods, tools, and processes for circular economy are applied. The three R&D projects tackle 3 out of the 4 2Zero SRIA pillars and are introduced in the upcoming sections.

EFFEREST (Efficient User-Centric Energy Management Systems for Optimized EVs)

Project Overview

EFFEREST targets a decisive leap forward in the novel use of data to achieve energy-efficient EV designs, matching enhanced user acceptance with efficient vehicle operation. By leveraging insights from real-world fleet behavior, the project seeks to deliver substantial improvements. Users will benefit from personalized data and the ability to choose different vehicle performance modes,

allowing them to experience tailored eco-functionality that meets their everyday needs. This will encourage long-term energy-saving behavior. To achieve its goals, EFFEREST brings together 11 partners from both industry and academia, representing the entire EV value chain. In Figure 2 a schematic overview of the EFFEREST project is given including all participating partners.

The three key challenges and solutions in EFFEREST, namely a holistic user-centric approach, incorporating artificial intelligence (AI)-enhanced system design and operation, and demonstrating the project outcomes, are outlined in greater detail below.

The Holistic User-Centric Approach EFFEREST will develop user-centric design solutions and control functionalities for making EVs more affordable, energy-efficient, comfortable, safe, and tailored to the individual user needs. Novel indicators will be identified that more accurately and holistically represent the potential impact that such technical improvements have on user experience. This will help to derive development targets which balance user benefits and engineering effort. A holistic user-centric control (HUC) energy management system will be developed, integrating innovative, tailored vehicle control functions for thermal management and powertrain optimization. These functions will be designed to reduce energy consumption and/or extend vehicle's driving range while not compromising comfort. Rather than improving each function in isolation, they will be interconnected within the HUC framework for enhanced overall performance.

The HUC includes:

- Self-adaptive comfort controller (SACC) for efficient personalized thermal comfort.

- Predictive thermal control including preconditioning strategies, using information on the predicted mission profile and environmental conditions for holistic optimization of heating, ventilation and air conditioning (HVAC), refrigerant/coolant circuit, traction battery and powertrain operations.

- Novel control functions to enhance safety, e.g., automatic demisting and predictive health management.

- Virtual evaluation of intelligent controllers for novel energy management system layouts, e.g., embedding: i) vehicle integrated photovoltaics; ii) air conditioning systems with natural refrigerants.

AI-Enhanced System Design and Operation A stream-lined co-design framework for design and operation will be implemented based on adaptive DTs, which will be derived from high-fidelity physics-based simulation models and specific measurements with the help of AI and machine learning (ML) techniques. The system of interacting DTs allows for model-based optimization for component rightsizing and the development of an integrated predictive model-based control for the combined system of powertrain, thermal management, and cabin comfort system. The co-design framework will bring:

- Earlier implementation of control functions using model-based controllers and embedding adaptive DTs.

- Reduced HVAC design time using an enhanced thermal manikin, ANDI, and related comfort model to target highly asymmetric thermal conditions that are not covered by existing models.

- Reduced duration testing of samples and reduced involvement of human subjects through the systematic adoption and demonstration of the open vehicle powertrain platform.

- Reduced durability/fatigue testing of components and systems through the systematic application of the mission profile-oriented lifetime tool, to estimate the lifetime load-profiles on new powertrain components and optimize accordingly.

The EFFEREST combined vehicle control system will adapt to user specific characteristics and preferences during operation to further improve overall efficiency and user acceptance.

Demonstration of the Results EFFEREST will demonstrate its achievements in a series vehicle, which is specifically modified during the project and tested on test benches as well as under realistic driving conditions. In addition, virtual demonstrators will be used in a complementing way to assess EFFEREST developments in an extensive set of scenarios, representing the realistic vehicle usage in the EU. To derive those relevant testing scenarios real-fleet data from different sources is analyzed and characteristic vehicle use cases are derived during the project, which allows for the estimation of the effective impact of EFFEREST on the overall reduction of the vehicle's CO_2 footprint.

Latest Achievements

The main project achievements of the first year include, on the one hand, important steps to define more specifically the starting point, boundary conditions and the ambitions of the project. On the other hand, conceptual work was done to build the main architecture for the virtual development tools, the improved energy management layout, and the corresponding HUC system.

Data Analysis and Use Cases Through data analysis of real driving data relevant use cases are derived, which are used to assess vehicle systems in a virtual environment and partly on the testbench and in real-driving tests. The goal of the data analysis was not limited to derive single driving cycles for typical scenarios but instead to consider the usage of a car over a longer time. With this, the individual behavior of real people is considered and a human centered approach in the weighing of specific mobility tasks in the system assessment was established.

System Breakdown A detailed system breakdown helped to identify components which are in focus of the project and those who are not. The most important components relevant in achieving the project targets were identified. Components and sub-systems were differentiated according to whether they are redesigned, re-dimensioned inside the project or remain untouched. Components of interest were listed to formulate requirements on their functionality and performance in the next project step. Other components just need to be technically sufficiently specified to enable their correct consideration in the virtual vehicle model.

Requirements Definition The combination of the defined vehicle use cases and the description of the system under development on the one hand, with the overall project targets on the other hand, leads to the definition of requirements for the vehicle system, components, and functions. This includes basic functionality as well as performance characteristics, which are needed to achieve the project goals and to fulfill legislation rules.

Detailed requirements were also derived for the virtual demonstrator and the AI-based adaptive DTs, which are used online in the vehicle. These simulation models not only have to produce accurate results and work with the correct technical interfaces of the system component, but they also need to be executed on limited computational hardware, which is available in the vehicle.

FIGURE 3 ANDI comfort dummy with and without clothing for reference testing

Benchmark Testing Three reference vehicles were tested on a roller testbench at MAGNA in Austria: besides the C-Segment vehicle, which is the focus of the EFFEREST project regarding the implementation of newly developed features and improvements, two further state-of-the-art vehicles in the B- and D-segment are benchmarked. The test program includes selected drive-cycles and climatic boundary conditions to show the system efficiency under both typical and critical conditions. By using the ANDI thermal manikin, comfort relevant values are measured, and comfort indices are evaluated on state-of-the-art level.

Holistic User-Centric Control As an example of the conceptual work during the first project year, the first draft layout of the HUC system of the demonstrator vehicle should be mentioned. HUC is the hierarchical concept of an integrated control design which will be developed and implemented in EFFEREST. It does not replace completely the existing control system of the base vehicle. Instead, the border between the "system under development" and untouched functionality was clearly identified during the system breakdown phase of EFFEREST. The associated interface inside the control architecture was defined in the requirements definition phase. The HUC concept consists of two layers with different abstraction levels and time horizons in its corresponding control logics.

The lower level communicates directly to the technical components or sub-systems and provides them with the control inputs they need. The time horizon ranges between real-time applications and predictive control functions which consider the system behavior in the future minutes. In this layer the efficiency and comfort-oriented control functions for both the traction battery and powertrain side on the one side as well as for the thermal management and passenger comfort on the other side, are mainly unconnected.

The top-level control layer implements the holistic approach of the control concept by combining all control domains in global and more abstract control strategies. Considering a wider time horizon, ranging from several minutes to the length of a full planned trip, energy bottle-necks may be identified, and the usage of the available energy may be optimized, depending on trip characteristics like slope, speed limits or charging events. Adaptive DTs enable the efficient consideration of the individual driving behaviour as well as individual comfort preferences.

MINDED (Thermal and Energy Management for Increased Driving Range of an Electric Minibus Including Improved User-Centric Design and Thermal Comfort)

Project's Objective and Technology Bricks

The objective of MINDED is to deliver a battery-electric, zero-emission IVECO eDaily minibus with 20 % improved driving range at 0 °C. To reach this objective, the MINDED project is grouped in three AREAs consisting of ten technology bricks:

AREA I (Heating and Cooling System) dealing with the design and implementation of (1) infrared heating panels, (2) an improved thermal cabin insulation, (3) a thermal mannequin for measuring and evaluating the passenger comfort, (4) an optimized HVAC system layout with heat pump operation mode based on an oil-free e-compressor with gas bearing technology, (5) the development of necessary electronic control units, and (6) the design and implementation of user-centric designed driver and passenger HMIs for adjusting the thermal comfort.

AREA II (DT and Control Strategy) dealing with (7) the development of an entire DT model of the minibus, (8) an AI-based algorithm for prediction of the driving behavior to be fed into the overall control strategy of the vehicle, (9) the development of an overall predictive thermal and energy management (control) strategy, and (10) the development of a comfort control strategy for determining the best settings for optimum comfort.

The combination and interaction of all developments and simulations from AREA I and AREA II pave the way

to AREA III, for the successful integration and demonstration.

AREA III (Demonstration and Performance Evaluation) deals with the integration of the developed technology bricks into the vehicle demonstrator and the overall testing of the vehicle on the climatized chassis dynamometer at 0 °C ambient temperature at technology readiness level (TRL) 7. Furthermore, the optimized air conditioning system with improved performance in heat pump mode is demonstrated on the testbed under various operating conditions at TRL 6. All testing results will be fed to an overall DT model of the entire vehicle.

Heating System for Improved Thermal Comfort

The main focus of MINDED is the development of an energy-efficient heating system providing highest possible thermal comfort to the passengers in the field of passenger transport. Especially in EVs this is an important aspect since thermal energy for conditioning the passenger cabin must be supplied by the traction battery, which has a serious impact on energy consumption and thus on the vehicle's driving range. EVs currently on the market generally use conventional positive temperature coefficient (PTC) heaters to generate heat in the passenger compartment. These heaters are made of ceramic material and are based on PTC technology. The PTC material is characterized by the property of increasing its resistance as the temperature rises. However, this is accompanied by a significant energy requirement, which is drawn directly from the traction battery and therefore reduces the driving range. It is a well-known fact in the field of vehicle electrification that the driving range can be reduced by up to 50 % in adverse climatic conditions [25]. In commercial passenger transport, this factor can have an even more significant impact, since the state-of-the-art solutions using convective air conditioning of the cabin require the same heating power regardless of whether there are 3 or 19 passengers in the vehicle.

By introducing a highly efficient heating system for the driver and passengers based on infrared heating panels it is possible to reduce the cabins' interior temperature and therefore also reduce the power needed for convective heating. Since the heating panels are located close to the passengers, their needed energy consumption for radiative heating is rather low and is also only necessary when a seat is actually occupied. A thermal and energy management strategy controls the panels' temperatures while minimizing the overall heating system's energy consumption. An improved cabin insulation will add its benefits to the reduction of needed heating energy.

The modular and flexible architecture allows the developments in MINDED being carried over also to other vehicle platforms like, for example, coaches.

User-Centric Designed HMIs

User-centric design is another crucial topic when it comes to the attractiveness, safety, and user acceptance of EVs. It has significant influence on many parts of the EV like thermal comfort, HMI, ergonomics, noise, and vibration, etc. An optimized and appealing user-centric design of the vehicle can raise the acceptance of EVs if, at the same time, the energy consumption can be reduced. The optimized HVAC system of MINDED together with an innovative and easy-to-use HMI, where the user can directly influence certain parts of the thermal management of the vehicle, shall raise the acceptance regarding thermal comfort.

Two different HMI designs will be developed: one for the driver and the other for the passengers, whereas the former will have extended functionality while the latter will have only restricted functionality. Each passenger will have their own display for controlling the target temperatures of the infrared heating panels assigned to their seat. Default comfort values will be set automatically by the thermal management strategy, but passengers can adjust the temperature using intuitive buttons labelled "Too COLD" or "Too HOT". The control strategy will automatically adjust the temperature based on the user's input, and a visual display will provide feedback on the heating intensity. This user-centric approach allows for a zonal and comfort-based climatization concept.

The HMI for the driver can be used to control the HVAC system and set target values for the heating and cooling system. It can also control the panel target temperatures for the infrared heating panels assigned to the driver's seat. Additionally, an overrule functionality will be established to enable the driver to also control the target temperatures for the heating panels of the passengers or to switch them off entirely, if required. An additional visualization provides the driver feedback about the use of the infrared heating panels for each passenger seat.

Latest Achievements

To determine the baseline values of the unmodified vehicle and therefore being able to determine the impact of the measures implemented, the minibus was first tested in its current (baseline) condition at 0 °C on the climatized dynamometer. This serves as the reference for the optimization measures during the project. The controller area network (CAN) bus of the vehicle was logged during the measurements and all relevant signals for developing the DT models and the subsequent analyzes were recorded. Additionally, the vehicle's thermal system circuits were equipped with mass flow and temperature sensors for determining the thermal behavior of the HVAC systems, as not all necessary signals could be found on the CAN bus. For analyzing the thermal comfort in the baseline vehicle, comfort measurement

FIGURE 4 IVECO eDaily minibus on the climatized roller dynamometer of the Automotive Test Center of TU Wien

these backrest panels have been produced, corresponding to the number of backrests available. On the other hand, heating panels for the floor have been produced which are placed in the foot area of the individual passengers. These floor heating systems emit radiant heat upwards onto the legs and feet of the sitting passengers. 19 heated floor heating panels were produced with different dimensions to be able to integrate them into the geometries corresponding to the vehicle. In addition, a floor heating panel was also produced for the driver.

FIGURE 5 Implemented infrared heating panels on the backrest of the seats and on the floor

dummies were placed on three seats distributed inside the passenger cabin. These dummies measured ambient temperature, humidity, mean radiant temperature and air velocity. With these values it was possible to determine the Predicted Mean Vote index, which serves as a measure for the comfort of a human being. The fully equipped minibus was then placed on the climatized dynamometer of the Automotive Test Center of TU Wien and the vehicle was tested under four different ambient conditions (-7 °C, 0 °C, +23 °C, and +40 °C) while being driven for a repeated number of worldwide harmonized light vehicle test procedure (WLTP) driving cycles.

To meet the abovementioned challenge of increasing the driving range by reducing the energy consumption of the vehicle for heating while increasing thermal comfort for the passengers, MINDED relies on the use of innovative infrared heating panels. The radiant heat emitted by these panels, which is perceived as very pleasant, leads to a reduction in the overall temperature requirement and therefore offers considerable potential for energy savings. The sophisticated placement of these panels enables the room temperature to be reduced by up to 5 °C while increasing thermal comfort. The reduction of ambient temperature leads to a reduced energy demand for heating up the cabin air and at the same time reduces the temperature difference to the outside temperature, which reduces thermal losses.

After the initial measurement the implementation of one of the core technology bricks of MINDED – the infrared heating system - began. The interior of the cabin was thoroughly analyzed, and a detailed measurement of the available geometries was performed. Then, individual infrared heating panels for each seat in the bus were produced by the project partner Villinger. The panels were on one hand attached to the seat backrests. These heaters provide infrared radiant heat to the passengers sitting behind the respective backrests. A total of 18 of

Outlook on the Next Steps to be Performed

In the upcoming subsequent series of measurements during the MINDED project different stages of vehicle configurations will be examined step by step, e.g. with new cabin insulation, installed infrared heating panels and a newly developed thermal and energy management system. Lastly, the optimized vehicle configuration will be tested, evaluated, and compared with the baseline vehicle in terms of thermal comfort, energy consumption, and driving range.

In parallel to these implementations and to further improve the performance of the IVECO eDaily minibus an overall predictive thermal and energy management strategy will be demonstrated in a DT model of the entire vehicle. The model considers the vehicle's powertrain, the implemented infrared heating system, the air conditioning system based on a highly efficient oil-free centrifugal e-compressor with gas bearing technology, which can also operate the system in heat pump mode, and a prediction of the driving behavior based on AI and advanced driver assistance systems sensors. Measurement results from the testbeds are incorporated to the DT and

the models are validated step by step. This enables a comprehensive evaluation of the thermal and energy-related operating strategy and will allow to show the 20 % driving range extension at the end of the project, as not all improvements in this project can be implemented in the bus directly.

SmartCorners (User-Centred Optimal Design of Electric Vehicle with Smart E-Corners)

Project Overview

SmartCorners aims to refine EV design and operation through user-centric, adaptable, and energy-efficient smart corner system (SCS), which incorporate in-wheel motors (IWMs) and advanced control technologies. The project aims to improve vehicle performance and efficiency while promoting the systemic transition to sustainable and decarbonized mobility. To fulfil the ambitions project objectives the SmartCorners consortium unites complementary skills and expertise of 11 project partners from 5 countries, covering the whole automotive supply chain and providing great and interconnected lab infrastructure. Figure 6 outlines the objectives, assets, available validation and key infrastructure, scaling and replication possibilities of SCS, and the targeted stakeholder groups.

The main objective of SmartCorners is to implement an adaptive, multilayer control strategy, which will forge a path for the future development of software-defined vehicles. ML and AI will be utilized to analyze both the historical and real-time data from the vehicle, its environment, and users, as well as relevant EV fleet information. The selected approach will enable rightsizing, holistic optimization, fault mitigation, and adaptive actuator allocation strategies, while enhancing system efficiency, adaptability, and personalization for user-centric design.

The vehicle architecture selected for further research in SmartCorners is the skateboard platform with 4 IWMs. This design increases the available space within the vehicle and trunk. The chosen vehicle class for the implementation of the SmartCorners hardware and software components are sports utility vehicles, based on the high-performance characteristics and higher cost tolerance of the market segment. Simulation testing will be conducted on high-fidelity B-segment EV models. SCS will be implemented for different users' categories, such as passenger car users, public transport users, and urban logistics operators with a focus on energy-efficiency aspects. Multiple EV demonstrators will allow for an early evaluation of the SmartCorners outcomes, demonstrating vehicle dynamics functions and thermal management aspects. The ambition of the SmartCorners SCS design is to achieve high levels of flexibility, enabling the integration of various actuator and component sizes across a wide range of EV segments. Practical functionalities for everyday use such as steering-on-the-spot and crab-walking will also be incorporated to improve maneuverability and usability.

By following a user-centric approach and employing the V-model development method, the project aims to achieve advancements in vehicle safety, comfort, and efficiency.

Asset 1 – Wheel Corner Design The foundation of SmartCorners is the IWM technology, which is emerging as a mature technology, highly suitable for the development of user-centric EVs, and shown in Figure 7. IWMs can be integrated into multi-functional, controllable modules that include the electric powertrain, friction braking, and suspension/steering actuation. These compact modules enable the consolidation of multiple vehicle functionalities, offering significant potential to improve EV design and operation.

FIGURE 6   Project overview of SmartCorners

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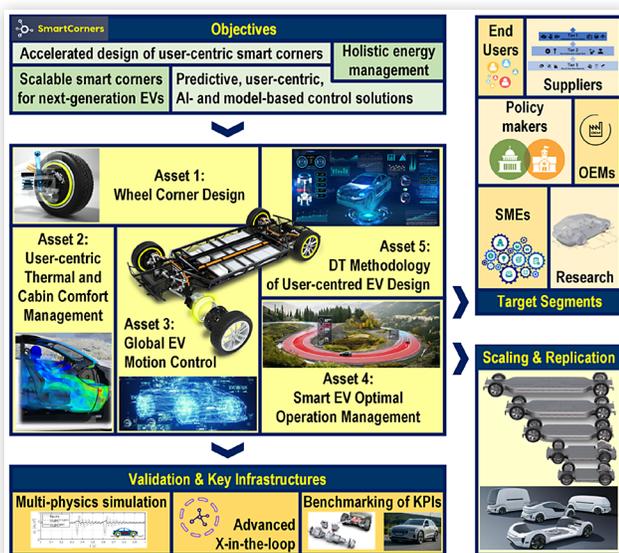
FIGURE 7   Integration layout of the Elaphe IWM

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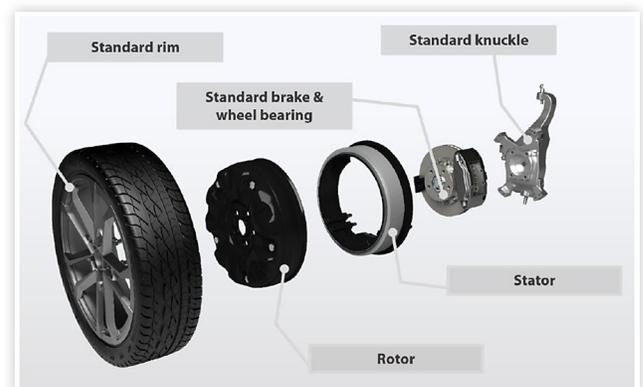
The integration of IWMs for propulsion results in increased unsprung mass, which can negatively impact the vehicle ride quality and handling. To address this, the implementation of active suspension actuators, particularly electromagnetic systems, provides advantages such as regenerative capabilities, sufficient actuation bandwidth, and high efficiency. Advanced control strategies can then be employed to optimize both comfort and road-holding performance. Furthermore, incorporating a composite lever mechanism with self-sensing capabilities, combined with AI-driven monitoring in rotary electromechanical actuators can enhance overall system performance and reliability. The use of fiber-reinforced polymer composites in suspension components will reduce the overall vehicle weight and will be enhanced with conductive particles for self-sensing capabilities and offers opportunities structural health monitoring. The combination of self-sensing materials, data acquisition systems, and AI algorithms will enable real-time damage detection and load assessment, further improving vehicle safety and performance.

Asset 2 – User-Centered Thermal and Cabin Comfort Management

Another important aspect of user-centric vehicle design is considering the user experience, so one of the objectives of the SmartCorners project is also holistic thermal and passenger comfort management. A holistic and predictive thermal management system is proposed to account for all thermal contributions, with improved adaptation to varying environmental conditions. This system includes pre-conditioning functions for key powertrain components and the cabin, optimizing the balance between user experience and energy consumption across different climates.

Asset 3 – Global EV Motion Control

Integrating IWMs with advanced torque vectoring and slip control alongside friction braking and suspension/steering actuation significantly enhances vehicle performance and safety. Torque vectoring and slip control of IWMs allows precise distribution of torque to each wheel independently, improving traction and handling in various driving conditions. When combined with friction braking, this ensures more responsive and efficient deceleration. Additionally, incorporating suspension and steering actuation into the module enables real-time adjustments to road conditions, leading to improved ride comfort and stability, and enabling entirely new capabilities in control. Such a holistic integration not only streamlines the vehicle's architecture, but the combination of these actuators allows precise control over multiple degrees of freedom, optimizing vehicle functions and performance. With such a new SCS vehicle architecture, specific degrees of freedom can be controlled by novel actuation systems. This is an important step towards software-defined vehicles, which will be able to actively enhance the vehicle motion response through the advanced and holistic control of degrees of freedom that are traditionally characterized by response dynamics defined by the design features of passive components.

SmartCorners will utilize advanced control strategies enhanced by AI and DTs, to optimize system operation. Starting from the already well-known model predictive control (MPC) and nonlinear model predictive control (NMPC), more innovative control algorithms based on AI will be implemented, such as neural network-based model predictive control (NNMPC) and imitation learning (IL), leveraging deep neural networks (DNNs) trained through deep reinforcement learning (DRL).

Asset 4 – Smart EV Optimal Operation Management

SmartCorners aims to develop and integrate specialized virtual sensors that leverage corner-specific data to account for both energy consumption and vehicle dynamics. By considering the interactions between each corner's behavior and utilizing virtual sensor and cloud data, the system can generate context-aware insights and enable proactive control strategies.

Asset 5 – DT Methodology of User-Centered EV Design

In the vehicle design phase, efficiency, cost, weight, and powertrain space are key considerations. Due to the complexity of these design challenges, many researchers propose multi-objective optimization strategies. To reduce the computational demands of the optimization process, model reduction techniques are often recommended to simplify simulations. In this context, SmartCorners will integrate fast, scalable DTs of the system into a multi-objective optimization framework, accounting for the impact of self-adjusting control strategies and the vehicle's energy and thermal management.

Additionally, the project seeks to connect multiple HiL platforms, DTs, or component test benches remotely to enable real-time experimentation. This approach is called X-in-the-Loop (XiL), which is shown in Figure 8, and it accelerates the development and validation of the smart corner systems, further reducing development time and costs.

FIGURE 8 XiL methodology with multiple connected test benches and DTs

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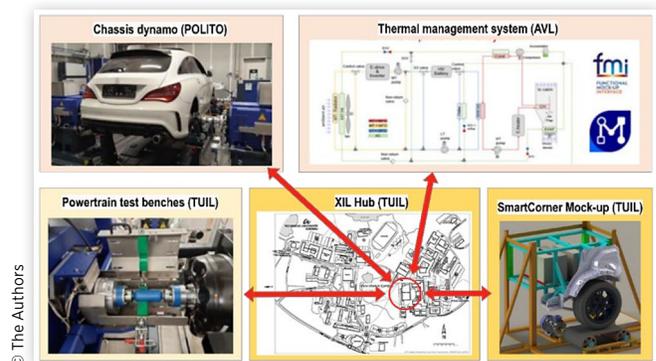
Latest Achievements

In SmartCorners an overview of the vehicle components, innovative control strategies, the available EVs for testing and demonstration, as well as the main stakeholder groups was provided. The systematic project approach to sustainable mobility through SCS was presented and includes: (1) SCS-equipped EVs to seamlessly complement and integrate with other modes of transportation, (2) user-centric design to raise the adoption rate of EVs and shared mobility services, and (3) the development of viable business models for shared mobility and mobility-as-a-service. The four main components of the SCS, namely the IWM, active shock absorber, suspension control arms, and chassis actuators were explained including their interaction and synergies. Moreover, an overview on the state-of-the-art of energy-efficient torque vectoring control was provided, together with innovative AI-based and user-centric control algorithms for thermal and cabin comfort, as well as for road preview-based vehicle dynamics control. Finally, a matrix was created displaying the impact of the four main SCS components on safety, comfort, handling, efficiency, and tire management.

Summary/Conclusions

The call HORIZON-CL5-2023-D5-01-01 and as a direct consequence, EFFEREST, MINDED, and SmartCorners likewise, are focusing on user-centric solutions and technologies, predictive control, and AI, aspiring for next-gen EVs that are more sustainable in terms of design and operation, more affordable for their users, and fulfilling to greater extend the changing user needs and expectations [12].

The EU has set itself the goal of reaching climate neutrality by 2050 and of cutting net greenhouse gas emissions by at least 55 % compared to 1990 levels by 2030, which means, that the share of zero-emission vehicles must drastically increase in the next years, which represents a major opportunity for developments in the MINDED project. As the MINDED concept is designed in a modular and flexible way, it can be re-used, transferred, and integrated into other vehicle types like intercity buses and coaches. This enables significant market potential for the developments in MINDED summing up to a notable potential of vehicles with this technology. This in turn generates a remarkable impact on the total fuel consumption and CO2 emissions of the transport sector.

EFFEREST shows the concept and application example to deal with three main key factors for the users' acceptance of cars: the total costs of running the vehicle, range limitation concerns and the user experience in terms of thermal comfort and general usability. The proposed technologies like holistic energy management, self-adapting comfort control, the innovative thermal system layout based on natural refrigerants and the streamlined co-design framework including the effective right-sizing methodology are all further developed to a higher level during the EFFEREST project. In combination, the future application of these technologies in industrial vehicle design has the potential to significantly improve the attractivity of EV to the customers and consequently to increase their market share to fulfill the 2030 goals of the EU.

The novel design and capabilities of the SCS enables different EV architectures among various vehicle segments. Moreover, this technology supports EU's defined greenhouse gas emissions reduction targets and increases EV acceptance due to the improved energy-efficiency and ride quality of SCS equipped EVs. The achievements in the project SmartCorners encounter huge market potential, address a wide stakeholder range, and support the uptake of innovative, energy-efficient, user-centric, and safe EVs.

The three presented EU-funded R&D projects address the outlined challenges by (a) utilization of DT methodologies (EFFEREST and SmartCorners), (b) application of optimized AI, data, and control strategies (EFFEREST, MINDED, SmartCorners), as well as (c) the consideration of a holistic and user-centric viewpoint (EFFEREST, MINDED, SmartCorners) for a large range of applications from electrified passenger cars to light-duty EVs.

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Definitions, Acronyms, Abbreviations

2Zero - Towards zero emission road transport

AI - Artificial Intelligence

BEV - Battery Electric Vehicle

CAN - Controller Area Network

DNN - Deep Neural Network

DRL - Deep Reinforcement Learning

DT - Digital Twin

EV - Electric Vehicle

FCEV - Fuel Cell Electric Vehicle

HiL - Hardware-in-the-Loop

HMI - Human Machine Interface

HUC - Holistic User-centric Control

HVAC - Heating, Ventilation and Air Conditioning

IL - Imitation Learning

IWM - In-wheel Motor

LCA - Life Cycle Assessment

ML - Machine Learning

MPC - Model Predictive Control

NNMPC - Neural Network-based Model Predictive Control

OEM - Original Equipment Manufacturer

PTC - Positive Temperature Coefficent

SACC - Self-adaptive Comfort Controller

SCS - Smart Corner Systems

SME - Small and Medium-sized Enterprise

SRIA - Strategic Research and Innovation Agenda

TRL - Technology Readiness Level

WLTP - Worldwide Harmonized Light Vehicle Test Procedure

XiL - X-in-the-Loop