Rethinking transport
27–30 April 2020

TRA 2020 HELSINKI

Proceedings of 8th Transport Research Arena TRA 2020, April 27-30, 2020, Helsinki, Finland

EVC1000 – Integrated corner solution for innovative electric vehicles

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Abstract

E-mobility is a major automotive trend. With falling prices and recent technological advances, the second generation of electric vehicles (EVs) that is now in production makes electromobility an affordable and viable option for more and more people. To maintain this EV momentum, the latest edition of ERTRAC's European Roadmap for Electrification of Road Transport defines four big initiatives outlining the research and development needs. The EVC1000 project[†] targets the "user-friendly affordable EV passenger car + infrastructure" initiative and focus on in-wheel drivetrain layouts, as well as a wheel-centric integrated propulsion system and EV manager. Contribution of this paper is the introduction of the proposed integrated corner solution featuring in-wheel motor, distributed brake-by-wire and active suspensions, and presentation of the results achieved at project mid-time, especially in terms of performance and driveability.

Keywords: automotive; electric vehicle; e-mobility; in-wheel motor

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[†] Electric Vehicle Components for 1000 km daily trips. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824250, see www.evc1000.eu

1. Introduction

Smart transportation is a key industrial sector for Europe [1] by securing 13.8 million jobs, producing 20% of the vehicle worldwide (out of 98.1 million vehicles produced yearly worldwide), and generating a yearly trade balance over €134 billion. The automotive domain is currently facing two revolutions at a time: the shift towards electrification and towards autonomous driving. Both revolutions are tightly linked to societal challenges such as clean transportation [2], zero fatalities [3], mobility for an ageing population, as well as to customer needs towards more personalized mobility. Both revolutions are strongly supported or even enabled by information and communication technologies and consequently result to a shift in the value creation as well as required skills in the automotive domain. New regulations and incentives for e-mobility are published to support this trend [4]; parallel to this, new business models such as car sharing are emerging [5]; connected car [6] is a further important driver in this context. Summarizing, the automotive market is currently being revolutionized and reorganized, electrification and autonomous driving supported by key digital technologies playing a central role.

With falling prices and recent technological advances, the second generation of electric vehicles (EVs) that is now in production makes electromobility an affordable and viable option for more and more people. With the help of strong governmental support (e.g., see Norway [7]), it appears that electromobility is on the verge of major expansion in Europe and the rest of the world. To maintain this EV momentum, the latest edition of ERTRAC's European Roadmap for Electrification of Road Transport [8] defines four big initiatives outlining the research and development needs. Under the initiative of "user-friendly affordable EV passenger car + infrastructure" the topics include:

- Electric motors, power electronics and charging systems with high impact on powertrain efficiency as well as reduced needs for raw materials and rare earths.
- Energy efficient control of electric vehicle (EV) operation (vehicle, powertrain, passenger comfort, traffic flow, charging and energy management) with high impact on the integration of the EV in the traffic environment.

The EVC1000 project addresses these challenges by developing brand-independent components and systems, and demonstrates them through an integrated wheel-centric propulsion architecture and EV management approach implemented on two second generation EVs – from JAC and AUDI respectively. The goals of the EVC1000 components are to match/exceed the ERTRAC efficiency targets for EV2030+; to reduce cost by at least 20%; and to increase convenience and comfort of long-range travel.

2. The EVC 1000 project

At the core of EVC1000 is the in-wheel electric motor architecture because of its advantages in terms of active safety and drivability; and because of its unique benefits of packaging and modularity that will significantly enhance flexibility and adaptability of future EV architectures. For example, "design-for-purpose" vehicles built for dedicated usage models [8] can become reality more easily. At the same time, the EVC1000 participants acknowledge the perceived drawbacks of in-wheel motors – but the recent documented progress in terms of efficiency, durability, scalability and cost-reduction makes in-wheels motors a promising alternative to on-board motors. Also, the fact that two major car makers, AUDI and JAC, are investing resources here is a clear sign of the innovation potential of this technology.

To complement the in-wheel motor technology and exploit their full potential, EVC1000 provides new chassis components and integrated controllers. In particular, an efficient brake-by-wire system and electro-magnetic suspension paired with predictive controllers will be implemented to extend the driving range by up to 10%. What is more, the systems are selected to ensure relaxed, comfortable and safe driving on long journeys.

Despite the high level of integration within EVC1000, full flexibility in the commercialisation of the individual components will be retained. This will facilitate the widespread introduction of the EVC1000 outputs on the automotive market in short term, and overcome the limitations of some of the previous integrated electric corner solutions. In summary, the main components/systems developed in EVC1000 (see Figure 1) are:

- New components for in-wheel powertrains: i) Efficient, scalable, reliable, low-cost and production-ready in-wheel motors suitable for a wide range of torque and power levels; and ii) Compact centralised drive for in-wheel motor axles, based on Silicon Carbide technology, targeting superior levels of functional integration and failsafe operation – so called, eWD[2]. The designs consider electro-magnetic compatibility aspects, and include prognostics and health monitoring techniques of the electronic components.

- New components for electrified chassis control with in-wheel motors: i) Brake-by-wire system, consisting of front electro-hydraulic brakes and rear electro-mechanical brakes for seamless brake blending, high regeneration capability and enhanced anti-lock braking system performance; and ii) Electro-magnetic and electro-pneumatic suspension actuators, targeting increased comfort and EV efficiency, e.g., through the optimal control of the ride height depending on the driving conditions.
- Controllers for the novel EVC1000 components and new functionalities, exploiting the benefits of functional integration, vehicle connectivity and driving automation for advanced energy management, based on the results of previous projects and initiatives.

EVC1000 will assess the energy efficiency benefits of the new technologies compared to existing EVs. This will include demonstration of long-distance daily trips of up to 1000 km across different Member States with no more than 90 minutes additional travel time due to charging, and without additional degradation of the components.

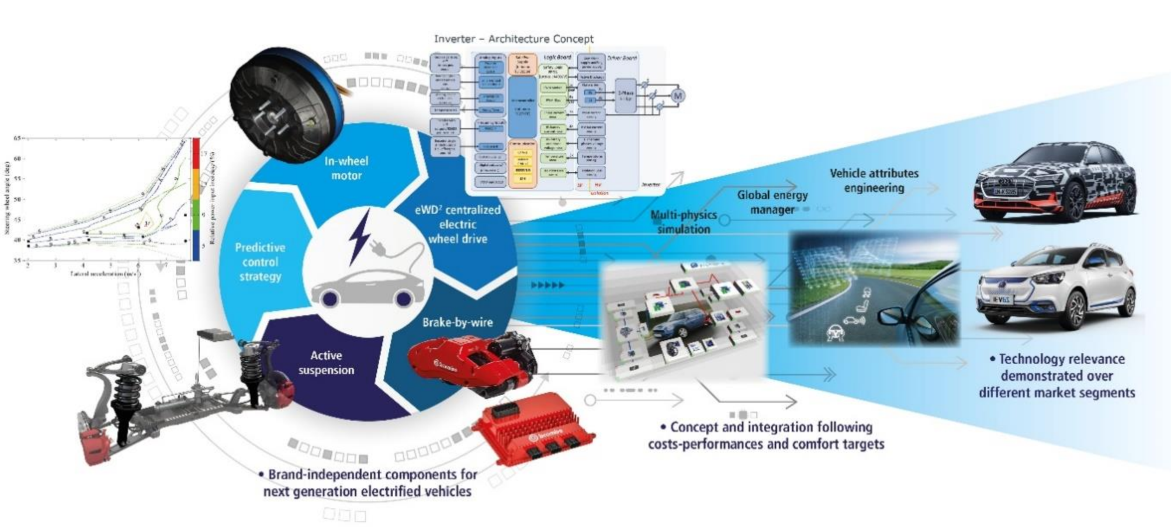

Figure 1: EVC1000 project at a glance

3. The corner components

3.1. Brake-by-Wire components

The overview of Brembo Brake-by-Wire (BbW)system for EVC-1000 application with its NO and NC valves to switch from BbW mode to hydraulic backup mode is provided in Figure *2* (left).
The system consists of the following components:

Brake control units - BCU (Figure *2*): Two BCUs, one for each axle, process an external braking request coming from the vehicle control unit and control the braking torque on the corners. Each corner is independent and can be controlled individually to the desired torque value. The BCUs are responsible for the low-level actuator control and provide feedback of the braking torque to the vehicle control unit.

Driver Braking Interface DBI (Figure *2*): The brake pedal is connected to the push-rod which moves the master cylinder. The fluid displaced by the master cylinder can either flow:

a) To the pedal simulator, which provides the desired pedal feel to the driver through elastic elements, during BbW mode (normal operating mode), or

b) Directly to the hydraulic calipers (passing through the actuators which are open in the rest position), during the hydraulic back-up mode (safe state).

Two valves, one normally closed (NC) and the other normally open (NO), ensure the switch between BbW and hydraulic backup mode if a failure is detected and even during lack of electrical power. Pressure and stroke sensors are integrated in the DBI and are responsible to acquire the driver braking request and provide it to the vehicle control unit (VCU), which compute the desired torques on the four corners and sends them to the BCUs.

Corner components: The four corners are responsible for generating the braking pressure/force in the calipers when requested by the system. In particular, each front corner is composed by Electro-Hydraulic actuators with hydraulic calipers, while each rear corner is composed by an Electro-Mechanical actuator integrated into a sliding caliper together with an EPB (electrical parking brake) device. The rear corners are "dry" corners, as there is no use of brake fluid.

The Electro-Hydraulic actuators – EHA (Figure 2) are responsible to apply the braking pressure on the front hydraulic calipers. The pressure is applied through an electric motor coupled to a mechanical system which translates the rotational movement into a linear displacement of a piston which in turn displaces the fluid through the hydraulic calipers. The actuated pressure is monitored by a pressure sensor and the information is used by the BCU as a feedback to actuate the control. The Electro-Mechanical sliding caliper (Figure 2) is responsible for the application of the clamping force on the rear brake discs. The braking force is applied through an electric motor which transmits the torque to a floating caliper which applies the force to the disc. The actuated force is monitored by a force sensor and the information is used by the BCU as a feedback to actuate the control. After the target clamping force is reached by the service brake, the EPB Device (integrated in the rear calipers) locks the clamping force and allows to maintain it even without power supply, for the parking brake function.

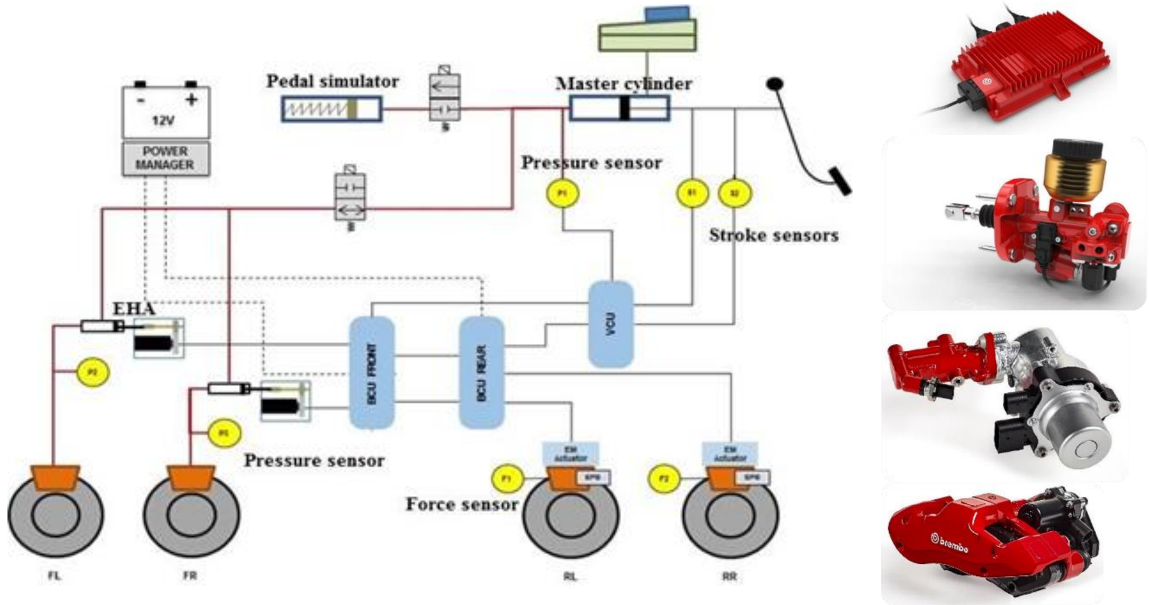

Figure 2: (left) Scheme of Brembo Brake-by-Wire system for EVC-1000 application, (right) Brake-by-Wire components: (a) brake control unit, (b) driver brake interface, (c) electro-hydraulic actuator (d) dry electro-mechanical sliding caliper

3.2. Advanced suspensions

3.2.1. Linear electro-magnetic suspension actuators

A first system will be experimentally assessed on the rear of JAC demonstrator. This will be in parallel to a conventional damper and coil springs. In the front, the compartment central electric motor will be removed together with gear box and inverter. Battery will be added in the space that will be made available. With EM (Electro Magnetic) suspension, Tenneco targets to lower the auto power density spectrum of the body acceleration, in particular challenging due to the higher unsprung mass by the in-wheel motors.

The solution proposed by Tenneco is coming from a patented solution (EFS ID: 35170917) claiming an "active damper system actuator arrangement" [9], where a conventional damper is placed in parallel with an electro-magnetic actuator. This could provide the trade-off of hydraulic systems between primary body control (large damping forces) and secondary comfort (low damping forces), by applying in real-time an active force to the piston rod that is independent from the damping force generated by the compression and rebound valving. The system is illustrated in Figure *3*: (a) the full system with a conventional (passive) and EM dampers in parallel and a coil spring, similar to the rear JAC configuration; (b) the conventional damper with piston assembly (compression/rebound valves) and piston rod and (c, d) the EM actuator with a stator and magnetized armature slidably disposed within the stator. From an electric current input, an electro-magnetic field is generated in the coils that will interact with the armature and create an active force to the body of the vehicle.

The electromagnetic system consists of an electromagnetic damper (linear actuator), a power extraction circuit, and a controller. The EM damper is shaped as a cylindrical sleeve, and located in parallel with the passive damper, with the suspension coil spring. Packaging and angle according to the center point of the car needs to be adjusted. Following sections details the EM damper.

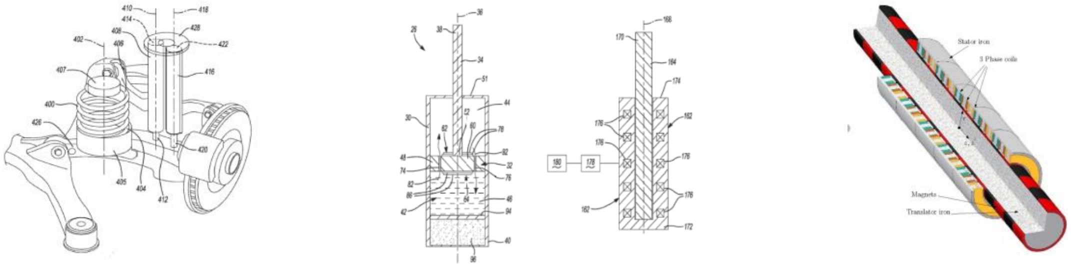

Figure 3: (a) complete system, (b) conventional damper, (c) and (d) electromagnetic actuator [9]

3.2.2. Electro-hydraulic suspension

A second system will be assessed on the Audi E-tron for front and rear. It consists of Tenneco CVSA2 (Continuously Variable Semi-Active generation 2) air dampers connected with hydraulic lines between left and right and controlled via ECU. With this advanced suspension, Tenneco targets to improve handling and energy consumption compared to a full hydraulic active system reference. The generic design is presented in Figure *4* (left). The complete concept with key elements is presented in Figure *4* (right). They can be grouped in module with dampers, valve blocks and accumulators, and powerpack with tank and pump.

Proposed CVSA2 dampers consists of air spring modules with integrated yoke. A commercial electromagnetic commanded pump is ensuring oil flow between left and right corners. It consist in a tank and a bidirectional pump (working pressure 320 bars) with the following characteristics: 3,2kW AC motor smart pump; 12V (reduced power) / 48VDC power line.

An E / E concept is proposed with a central control unit as the derivation of an existing VDP control unit as well as 4 actuator-related control units, which are interconnected by means of a bus system (CAN or FlexRay). The individual actuators receive the control information via a bus system. There is a central 12- or 48V power supply. The actuator-related control units are operated with 12V and the active power electronics with 12 or 48V. Between the 12V and the 48V side there is a galvanic isolation on the corner modules. The sensor concept envisages a full sensor concept in the first development stage, consisting of 4 level sensors, 4 wheel acceleration sensors, as well as yaw rate and vertical acceleration in the center of gravity of the vehicle.

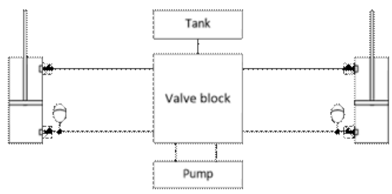

Figure 4: (left) Generic design for the electro-hydraulic suspension, (right) Electro-hydraulic concept

3.3. E-Axle components

The e-axle integrates the latest ELAPHE in-wheel motor technology and the electric wheel dual drive (eWD²) provided by I&M, see Figure *5*. The eWD² is based on wide band gap switches, perfectly matching the requirements of the proposed in-wheel motors.

In order to accelerate the electric vehicle (EV), the e-axle system employs two electric motors directly coupled with the vehicle wheels to generate torque by converting electric energy into mechanical. The process is reversed during regenerative braking, when energy is recovered with braking torque that decelerates the vehicle. Total requested torque represents a reference for the propulsion system control and is obtained from the driver over the accelerator and brake pedal positions. The in-wheel propulsion system enables an independent torque control for each driving wheel, whereas distribution of the torque between the driving wheels can be fixed or dynamic. The latter is used in the case of active propulsion systems with yaw control functions (torque vectoring) and/or anti-slip function. Active systems also employ steering wheel data as an additional reference for intended lateral motion from the driver.

Figure 5: e-Axle concept

The eWD² control board is based on latest Infineon 32-bit TriCore™ AURIX™ providing a top level computing performance and offering best in class features in term of safety. Main microcontroller consists of different cores: two of them are fully dedicated to the motors control, the remaining cores are available to integrate application dependent control strategies. The EVC1000 E/E architecture has been designed to be flexible enough to guarantee a two steps approach during the development of the application. In the experimental phase an external rapid prototyping unit is used in order to be faster in application update and tuning. Once the control algorithms will be stable enough the same application software will be synthesized. The resulting source code will be integrated directly on the eWD² control board.

3.3.1. L1500 In-Wheel motor

For EVC1000 an efficiency optimized variation of the L1500 in-wheel motor has been developed. General project constraints are:

- 19-inch rims;
- Nominal Battery voltage 396 V;
- Peek current from the inverter 400 A_{rms};
- SiC inverter switching frequency will be 50kHz;
- Two-wheel drive on rear axle.

Within motor design, electromagnetic part of the motor is developed through an extensive optimization process, which is focused to deliver efficient and high torque direct drive, with minimal mass and volume footprint within the wheel integration space.

In the first step electromagnetic design is optimized through genetic algorithms based on semi-analytical approach, which enable extensive number of motor design evaluations and rapid convergence of motor design to within few percent of final performance. Within this phase not only electromagnetic but also NVH (Noise, vibration and harshness), including airborne noise, and thermal motor characteristics are taken into consideration. Also coupling to inverter for system wide performance is accounted for. In the second step, performance of promising designs from the first step is confirmed by more extensive numerical simulations, also fine tuning of the models is done within this phase. In the final step the selected design is fully characterised by detailed numerical simulations. Also coupling to mechanical models for detailed NVH, thermal and structural analysis is performed.

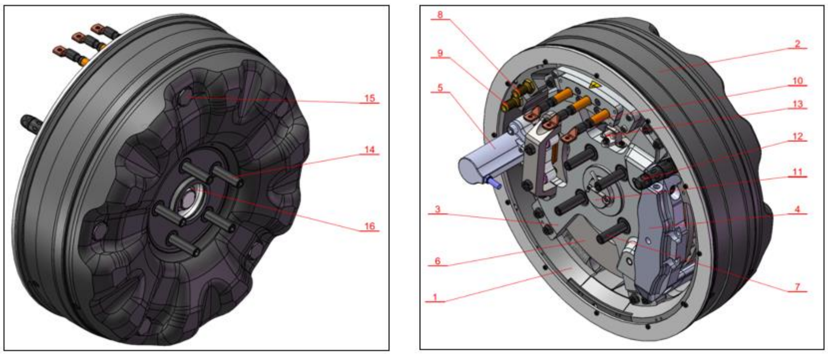

Figure 6: Front view (left) and rear view (right) of the L1500. 1 – Stator, 2 – Rotor, 3 – Stator Plate, 4 – Main Calliper, 5 – EPB, 6 – Brake Disc, 7 – Stud Bolts for vehicle mounting, 8 – Coolant - Inlet, 9 – Coolant - Outlet, 10 – Phase Cable, 11 –

3.3.2. DIDIMO Dual-Inverter

DIDIMO is a dual inverter developed by Ideas & Motion aimed at integrating functionalities available on two separate inverters into a single unit. Integrating two inverters in the same box helps in sharing hardware resources, facilitating also software development and system control. DIDIMO is the acronym for Dual Inverter Developed at Ideas & Motion but also an Italian male name deriving from Greek, didymos (δίδυμος), meaning twin. Since its internal architecture is based on two equivalent inverters, both origins perfectly fitting the device.

The idea is to target those applications where a pair of inverters is required and the two devices need to communicate to synchronize their activity (e.g., in-wheel motors; engine and turbo compound electrification; benches for driveline testing; six-phase motors...).

DIDIMO has a symmetric structure and the two parts composing it are equivalent: this helps optimizing size and room thanks to the sharing of some hardware components. Moreover coordination of the two motors is much easier than having two separate inverters, making this device more suitable for applications where reaction time between the two electric machines is important and safety has to be taken into account.

Total achievable power is 300kW (peak for 10s). Wide-bandgap power devices will be evaluated to provide high efficiency, a crucial point for e-mobility requirements. Its control unit is shared between the two inverters and it is able to coordinate the two electric machines connected with a high time resolution.

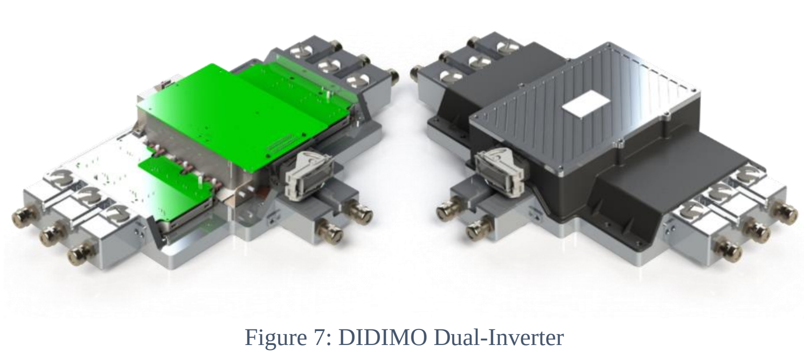

Figure 7: DIDIMO Dual-Inverter

The main target applications of DIDIMO dual inverter are Electric Vehicles (EV), but it may be adopted as well in Hybrid Electric Vehicle (HEV) or in Plug-in Hybrid Electric Vehicle (PHEV). The drive and management of the two in-wheels motors of an electrified axle has very strict requirements in terms of safety. Indeed, a failure might cause an abrupt change of torque delivered by a single wheel or, in the worst case, a change of its direction. This could lead to a momentum on the yaw angle of the vehicle, making the vehicle instable and hard be controlled for the driver. To overcome similar situation, I&M developed the idea of a fail-safe dual inverter.

3.4. Wheel slip control

The wheel slip control (WSC) functions in the target EVC1000 vehicle are realized for a braking mode with the combined use of three different actuators: four in-wheel motors, electro-hydraulic brake-by-wire system actuating front friction brakes, and electro-mechanical brake-by-wire system actuating rear friction brakes. Such a configuration makes possible different brake blending options to be used in WSC including pure regenerative ABS braking, pure friction ABS braking as well as several hybrid variants with regenerative / friction ABS braking.

A general WSC architecture, Figure 8, consists of several parts as follows. The value of the slip foreach wheel for given manoeuvre and road conditions is defined by the *reference slip generator*. The difference between the reference slip and the actual slip is processed by the *wheel slip controller* producing the limitation to the traction or braking torque demanded by the driver. For a traction mode, the WSC is working as the *traction controller* operating in-wheel motors only. For a braking mode, the WSC includes the *brake blending controller* defining the share of the brake demand to be realized by both electric motors and friction brakes. To compensate undesired difference between the dynamics of wheels and in-wheel motors, the *active vibration control* functions are also included into the overall architecture. In addition, to calculate vehicle velocity and derive the actual vehicle slip, a corresponding vehicle state estimator is also an inherent WSC part.

The qualitative WSC targets in the EVC1000 project are (i) to ensure smooth tracking of the reference wheel slip, also for severe road conditions, with maximizing the tyre friction utilization, (ii) to reduce essentially the vehicle jerk by braking or harsh accelerating, and (iii) to guarantee the control robustness in the presence of uncertainties caused by the road conditions and actuator dynamics. These targets are addressed through the meaningful selection of the control methods. Based on previous studies of the consortium participants, the proposed WSC is being realized as the combination of PI and sliding mode control methods, which demonstrated required performance by applying to the SUV with electro-hydraulic brake-by-wire system [10] and to the AWD vehicle with in-wheel motors [11].

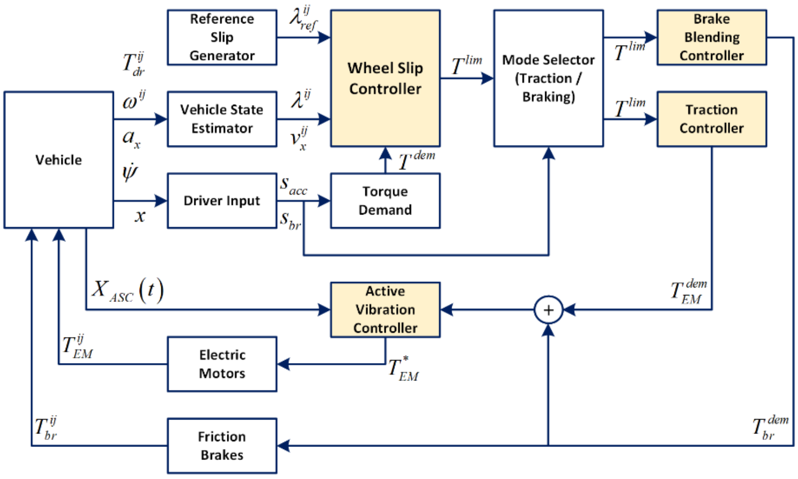

Figure 8: WSC Architecture (by M. Heydrich, TU Ilmenau)

x – longitudinal vehicle position; *i, j* – wheel indices; λ - actual wheel slip; λ_{ref} - reference wheel slip; T_{dem} – overall torque demand; T_{lim} – slip-limited torque; v_x – vehicle velocity; ω – wheel rotational velocity; ψ - yaw; T_{dr} – driving torque; a_x – longitudinal acceleration; *s* – displacements of acceleration and brake pedals; T_{EM} – in-wheel motor torque; T_{br} – friction brake torque; $X_{ASC}(t)$ – input function of the active vibration controller.

3.5. Torque-vectoring and active suspension control

Within EVC1000, a torque-vectoring controller with the following features will be developed:

- Multi-layer control structure for ease of integration with other controllers, such as: i) the wheel slip controllers for traction and braking, based on the actuation of the in-wheel motors and friction brakes; and ii) advanced drivability controllers, using the in-wheel motors for the compensation of the longitudinal jerk induced by road irregularities
- Generation of a reference yaw rate that allows a safe vehicle cornering response while reducing the power losses in cornering. The off-line reference yaw rate generation process will account for the electric motor power losses as well as the longitudinal and lateral tyre slip power losses
- Variation of the reference yaw rate as a function of the estimated sideslip angle to keep stable cornering response
- Capability of varying the understeer characteristic, i.e., the graph of steering wheel angle as a function of lateral acceleration, depending on the driving mode selected by the user
- Increased yaw and sideslip angle damping in transient conditions, with respect to the same vehicle with even wheel torque distribution

- Seamless integration of torque-vectoring with the stability control function based on the actuation of the friction brakes (commercially known as Electronic Stability Program or Electronic Stability Control)
- Ease of integration with the active suspension system, through a multi-variable control structure to be developed in EVC1000. The suspension controller will vary the front-to-rear anti-roll moment distribution to facilitate the yaw rate tracking control action of the torque-vectoring system

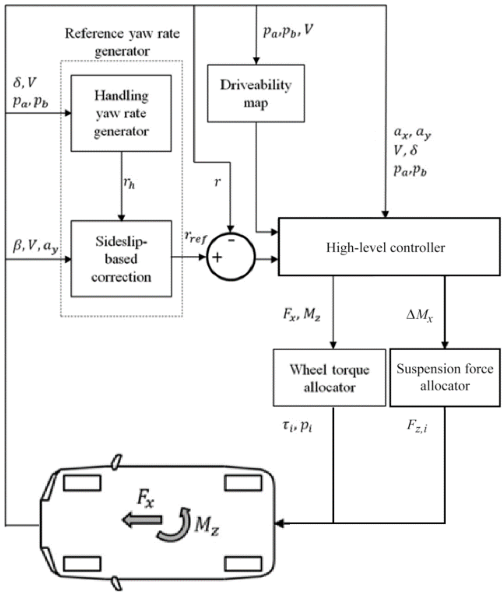

Figure 9: First approximation block diagram of the EVC1000 torque-vectoring and suspension control structure

Figure 9 shows a simplified block diagram of the torque-vectoring control structure, including its integration with the active suspension controller. The 'handling yaw rate generator' outputs a reference yaw rate suitable for the operation of the vehicle in high tyre-road friction conditions. The 'sideslip based correction' modifies the handling yaw rate as a function of the estimated sideslip angle, to account for variable tyre-road friction conditions. The 'high-level controller' is based on a multi-variable structure that outputs the total wheel torque demand, reference direct yaw moment and front-to-rear anti-roll moment distribution. Appropriate allocation blocks calculate the reference wheel torque and suspension force levels for the four corners.

In EVC1000 energy-efficient understeer characteristics will be designed and implemented, based on the experimentally validated theory developed by the Centre for Automotive Engineering of the University of Surrey. The preliminary experimental results from the previous FP7 project iCOMPOSE show several percentage points of energy consumption reduction of the optimal configuration with respect to the same electric vehicle with even left-to-right wheel torque distribution [12].

4. Preliminary simulation results

The on-board powertrain layouts of the original baseline configurations of the two EVC1000 target vehicles (Audi e-tron and the JAC iEV7) have been modelled with the vehicle simulation software AVL VSM 4™[‡]. The vehicle models have been extensively experimentally validated with data from: i) vehicle dynamics tests in steady-state and transient conditions (Figure 10); and ii) driving cycle tests carried out on a rolling road facility (Figure 11).
The validated simulation models for the two baseline vehicles have been further upgraded to the in-wheel motor driven powertrain proposed by the project. The energy consumption of the upgraded powertrains has been evaluated using the WLTP driving cycle. The results have demonstrated that the upgraded Audi e-tron with in-wheel motors could save up to 12.56% of energy, and the upgraded JAC iEV7 with in-wheel motors could save up to 9.1% of energy.

5. Conclusion

Success factors for the large-scale deployment of e-mobility are linked to vehicle range and component performances, affordability and user friendliness (e.g., comfort). The European project EVC1000 introduces an integrated corner solution featuring in-wheel motor, brake-by-wire and active suspensions. The approach relies on innovations both at component level - electrified chassis components, e-axle – and at system level with the use of advanced control strategies taking advantage of the new controllability of the introduced components. Hence, the in-wheel motors with their invertors, the brake-by-wire systems and the active suspensions provide new degree of freedoms that can be efficiently combined through advanced and tightly integrated wheel slip control, torque vectoring and active suspension control strategies. Preliminary results already indicate a significant increase of energy efficiency.

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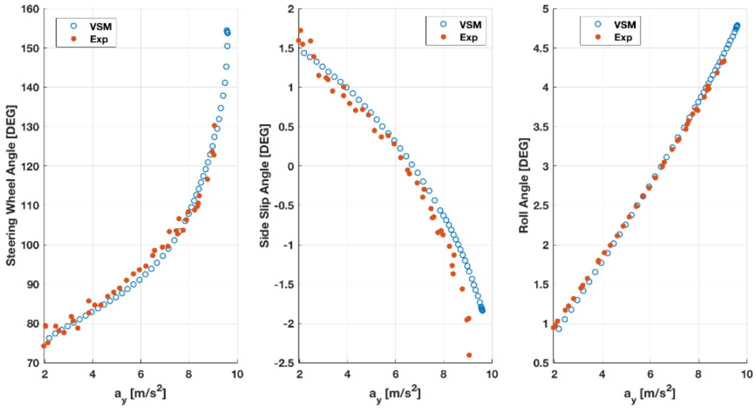

Figure 10: Example of model validation results along a skid pad test for the baseline Audi e-tron (VSM: simulation results; Exp: experimental results)

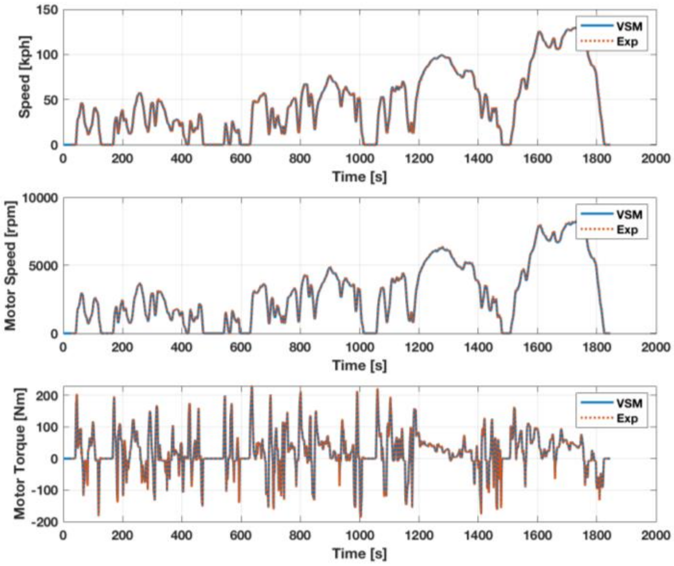

Figure 11: Example of model validation results along the WLTP for the baseline Audi e-tron (VSM: simulation results; Exp: experimental results)

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