D 2.1 – Report on the EM-TECH integrated electric motors, electric drives, and associated controllers

EM-TECH - Innovative e-motor technologies covering e-axles and e-corners vehicle architectures for high-efficient and sustainable e-mobility

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Abbreviations

Abbreviation	Long Version	Abbreviation	Long Version
ABS	anti-lock braking system	AFM	axial flux motor
AI	artificial intelligence	AWD	all-wheel drive
e-axle	electric axle	e-corner	electric corner
e-gear	electric gear	EHB	electro-hydraulic brake
EMB	electro-mechanical brake	FWD	front-wheel drive
HiL	hardware in loop	IWM	in-wheel motor
MiL	model in loop	NMPC	nonlinear model predictive control
NN	neural network	PM	permanent magnet
RWD	rear-wheel drive		

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1 Publishable Executive Summary

The Horizon Europe EM-TECH project brings together 10 participants from industry and academia to develop novel solutions to push the boundaries of electric machine technology for automotive traction. Target of this deliverable (related to Task T2.1) is to define the basic sizes (continuous and peak torque and power ratings, mass, expected available packaging envelopes) of the investigated components and systems for case studies. Furthermore, a set of integrated EM-TECH corner modules and on-board electric drive solutions for electric vehicles are defined to cover the widest possible range of vehicle segments. This deliverable also describes the associated machine control such as the cooling control and the inverter control for the new machines, and the vehicle controls to exploit the benefits to vehicle performance brought by the new machines, including the wheel slip control, the motor regenerative braking and braking blending, and the anti-jerk control.

2 Introduction

Motor providers ELA and VAI have already developed a series of in-wheel motor (IWM) and axial flux motor (AFM) products, respectively, and some use-cases for vehicle applications. In the EM-TECH project, ELA and VAI will continue their effort in new motor design for the enhanced motor performance and the applications for wide vehicle segments. In particular, ELA's electric corner (e-corner) drive solutions are discussed in Section 3, and VAI's electric axle (e-axle) drive solutions are discussed in Section 4.

The low-level motor control is discussed in Section 5.1. The expected benefits of new motor solutions to vehicle performance include the high torque responsiveness of ELA IWMs and the near-to-constant maximum torque over the whole speed range for VAI AFMs. In Section 5.2, the wheel slip control will investigate the actuation precision and the performance improvement of anti-lock brake function. In Section 5.3, the torque blending strategy will be studied for optimal energy recovery of the hybrid actuation of motor and vehicle brake. In Section 5.4, the anti-jerk control will study the improvement of driveability and ride comfort.

3 Set of integrated corner modules

In the EM-TECH project, the new design of e-corner drive and e-axle drive solutions will target applications for a wide range of vehicle segments. In order to align these vehicle applications to the production vehicles, we select example production vehicle models which cover passenger car segments A, B, C, D, M, small vans and heavy duty vehicles, as listed in Table 1. In our selections, both electric and conventional vehicle models are considered, and the powertrain layouts include front-wheel drive (FWD), rear-wheel drive (RWD) and all-wheel drive (AWD).

Table 1: Production vehicle segments in line with EM-TECH target vehicle applications.

	Fiat 500e [1]	Peugeot e-208 [2]	VW ID. 3 Style [3]	BMW 320i Sport Saloon 2L Petrol [4]	Audi Q4 Sport 50 e-tron Quattro [5]	Fiat E-DOBLÒ 2-seat van [6]	Mercedes-Benz eActros 300 4x2 [7]
Segment	A	B	C	D	M	Small van	HGV
Drive axle	FWD	FWD	RWD	RWD	AWD	FWD	RWD
Gross battery capacity [kWh]	24	50	58	-	82	50	336
Max. power [kW]	70	100	150	135 @ 5000 – 6500 RPM	70 (front) 150 (rear)	100	400
Max. torque [Nm]	220	260 @ 300 – 3674 RPM	310	300 @ 1350 – 4000 RPM	150 (front) 310 (rear)	260 @ 5500 RPM	970
Overall gear ratio (transmission and final reduction)	1-speed, 9.59:1	1-speed, 9.3:1	1-speed, 10:1	8-speed (5.25, 3.36, 2.172, 1.72, 1.316, 1, 0.822, 0.64), Final reduction 2.813	1-speed, 10:1 (front) and 11.5:1 (rear)	1-speed (ratio not available publicly)	2-speed (ratio not available publicly)
Max. axle torque [Nm]	2110	2418	3100	4430	1500 (front) 3565(rear)	Not available publicly	Not available publicly
0-100 acc. [s]	9.5	8.1	7.3	7.4	6.2	11.2	-
Top speed [km/h]	135	150	160	235	180	130	89
Gross weight [kg]	1665	1910	2270	2070	2720	2390	19’000
Unladen weight [kg]	1330	1530	1813	1590	2210	1665	8400
WLTP combined consumption [kWh/100km]	13	13	15.6	-	17.3	19.6	-

3.1 Target vehicle applications and in-wheel powertrains

ELA's current and future development of in-wheel or near-wheel radial flux permanent magnet (PM) synchronous motors aims for a wide range of applications, with specifications:

- Max. output torque up to 4000 Nm
- Cont. output torque up to 1750 Nm
- Peak power between 25 – 300 kW
- Cont. power between 15 – 100 kW
- Top output speed 2500 RPM
- Powertrain efficiency 96%
- Weight between 20 – 45 kg
- Torque density up to 60 Nm/kg

In the EM-TECH project, ELA and UBATH will develop a new series of e-corner modules, where the motors have an electric gear (e-gear) feature -- a technology realised by reconfiguring the stator windings according to the motor operation point. The e-gear enables the downsizing design of motor and power electronics, and thus improves the torque density, efficiency, implementation flexibility and reduces the use of rare earth magnets. Taking an 18' or 19' rim compatible IWM with torque density 45 Nm/kg and 180 Nm/L as baseline, the e-gear solution will increase the density beyond **the EM-TECH targets (>50 Nm/kg and >150 Nm/L).**

The wide power and torque ranges of EM-TECH e-corner solutions make them suitable for the vehicle segments listed in Table 1, with different powertrain architectures (two-wheel or four-wheel independent drive). In the EM-TECH project, the application of e-corner modules per vehicle segment will be assessed in terms of the reduced initial investment, time-to-market and cost, as well as the increased flexibility of chassis design. Detailed design and analysis, and prototyping will be carried out for a specific e-corner module (including novel colling solutions) and its applications in lower vehicle segments, e.g., segment B passenger cars and small vans.

3.2 Commercially available ELA in-wheel motor solutions

The e-gear integrated e-corner modules proposed by ELA for the EM-TECH project are advanced development of its high torque density IWM products. ELA has already developed a series of available direct-drive IWM products as listed in Table 2, and found applications in micro or small EVs, SUVs, people movers and light commercial vehicles. The state-of-the-art ELA IWM efficiency map is shown in Figure 1. A concept of e-gear integrated IWMs is shown in Figure 2. A use-case of ELA L1500 IWMs can be found in EVC1000 project [8] for an Audi e-tron based demonstrator (independent two rear wheel drive, unladen weight 2660 kg, rim size 20'', 0-100 acceleration 7s, top speed 180km/h). The rim-integrated motor and brake assembly is illustrated in Figure 3.

Table 2: ELA available IWM product series [9].

	S400	M700	M1100	L1500
Nominal voltage (V)	100	300	370	370
Peak torque (Nm)	400	700	1100	1500
Continuous torque (Nm)	-	400	700	650
Top speed (RPM)	1565	1500	1160	1480
Peak power (kW)	40	75	90	110
Continuous power (kW)	23	50	70	77
Weight (kg)	17.6	23	40	34.8

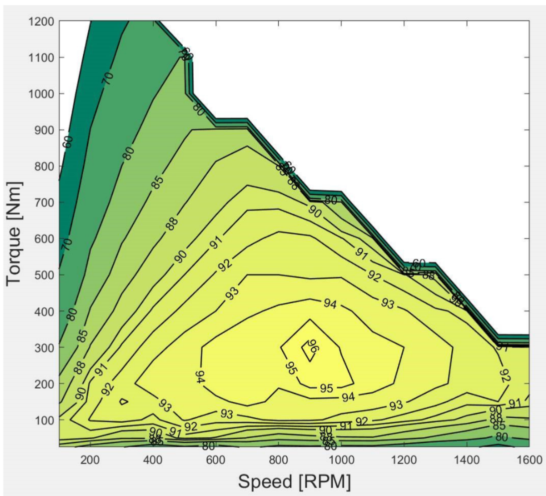


Figure 1: State of the art ELA IWM efficiency map.

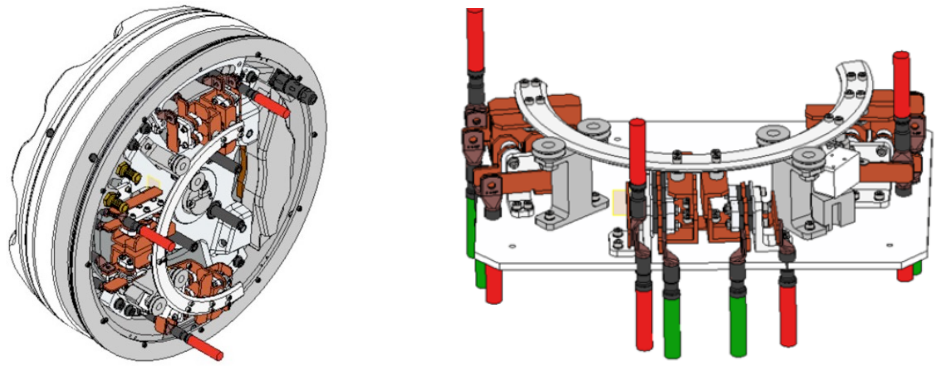


Figure 2: E-gearing concept of the mechanical switching mechanism integrated with the ELA L1500 IWM.

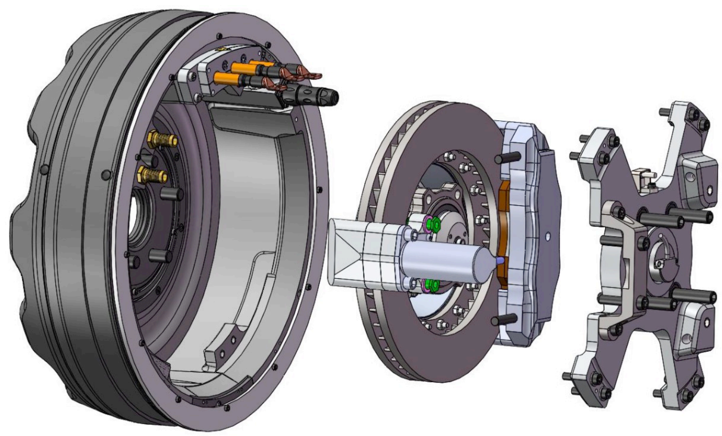


Figure 3: ELA L1500 IWM assembly including brake components [8].

4 Set of on-board electric drive solutions for electric vehicles

4.1 Target vehicle applications and on-board powertrains

In the EM-TECH project, VAI will develop a new series of on-board AFMs for e-axle drive solutions. These AFMs have high power density and efficiency. They adopt a modular structure for scalability and thus reduce the implementation cost. The proposed unit module (single-stator-double-rotor) will provide 100 kW continuous power and 52 Nm continuous torque for speed up to 20k RPM. By scaling-up, the standard 2-module configuration (2 stators/3 rotors) and the maximum 5-module configuration (5 stators/6 rotors) will achieve continuous power and torque at 200 kW & 104 Nm and 500 kW & 260 Nm, respectively. The power density also increases alongside the module scaling-up, as listed in Table 3, **achieving the EM-TECH targets (>10 kW/kg and >30 kW/L)**. The EM-TECH e-axle solutions are suitable for the applications for the vehicle segments listed in Table 1. Regarding the exploitation strategy, VAI will first focus on the heavy commercial vehicle sector, where the modular design of the AFM is providing the highest benefits. Based on this success story, the passenger car market will be addressed. Accordingly, AVL will assess the high gear ratio transmission systems. Depending on the drivetrain layout, the drive shaft could have big impact on the torsional oscillations.

Table 3: Power density of EM-TECH modular AFMs

	1-startor module	2-stator module	3-stator module	4-stator module	5-stator module
Power density (kW/L)	32.9	51.5	63.7	70.5	77.9
Power density (kW/kg)	8.7	13.4	16.4	18.4	19.9

4.2 Commercially available VAI on-board motor solutions

The new e-axle drive solutions in the EM-TECH project are VAI's continuous effort in the enhancement of energy efficiency performance and circularity characteristics of its available products. VAI has already developed its modular AFMs for many generations, with significant improvement in the energy efficiency and the power density. Thanks to the modular design, as illustrated in Figure 4, it is easy to scale for applications for different vehicle segments, and/or different drivetrain layouts (e.g., one motor per axle or two motors per axle). In a simulation use case, the latest 7th-gen modular AFM has reported the following features: 29 kg weight, 300 kW power, 20k RPM speed, >10 kW/kg power density and >97% benchmark efficiency. It also presents a nearly constant torque for whole speed operation range, as demonstrated in Figure 5. The AVL tool (Figure 6) can be employed to assess the efficiency of the transmission systems for specific drive cycles.

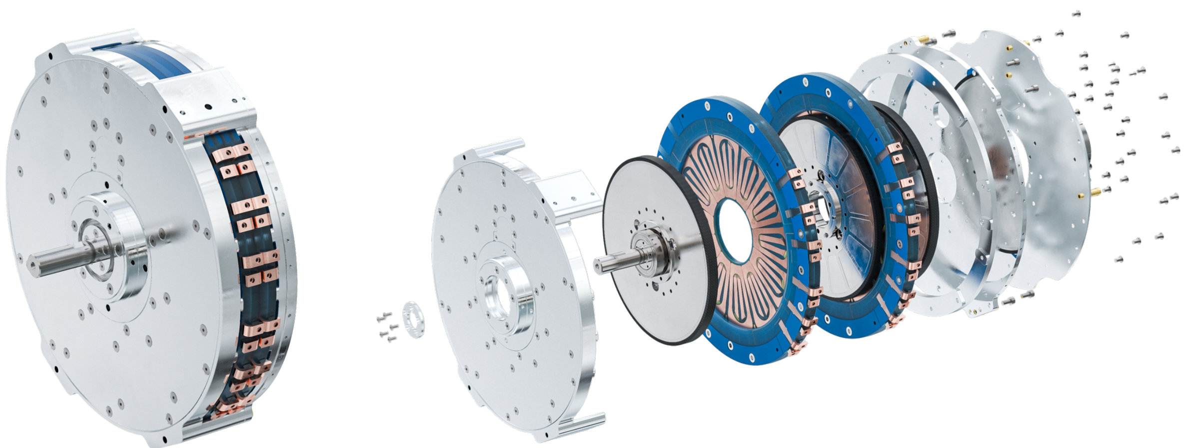


Figure 4: VAI modular AFM structure.

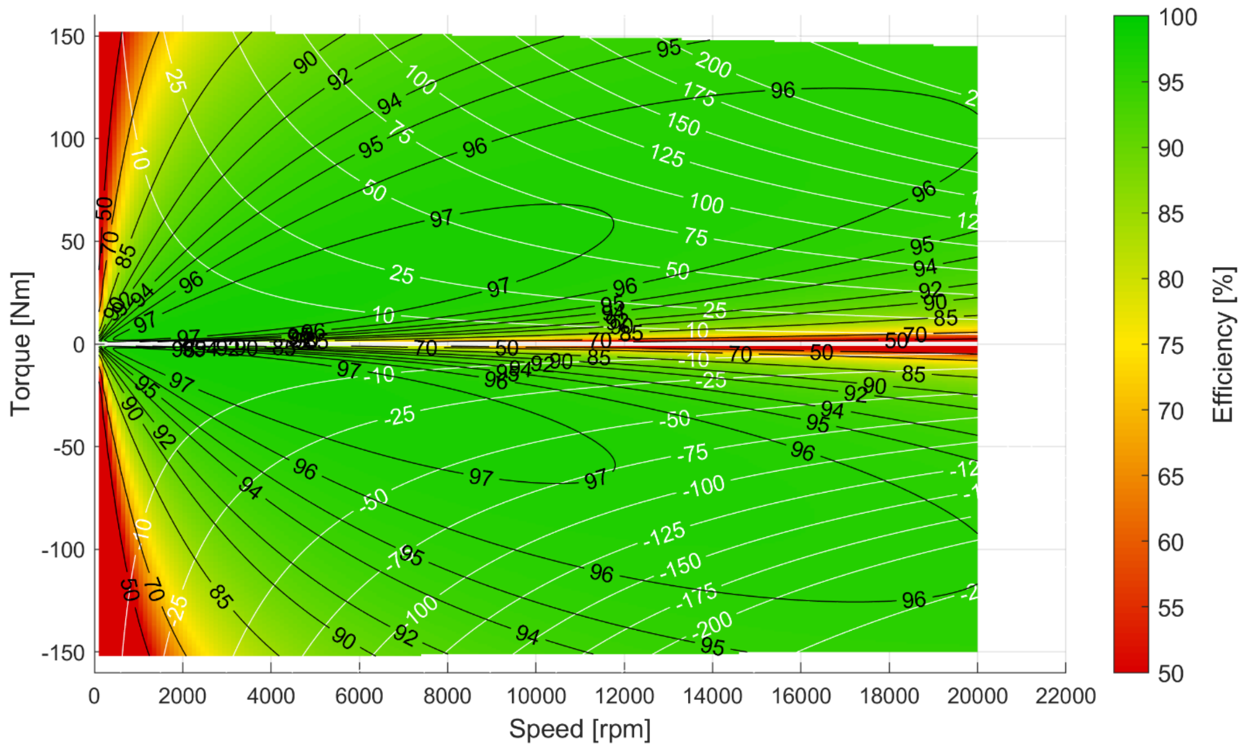


Figure 5: VAI modular AFM torque-speed characteristics and efficiency map.

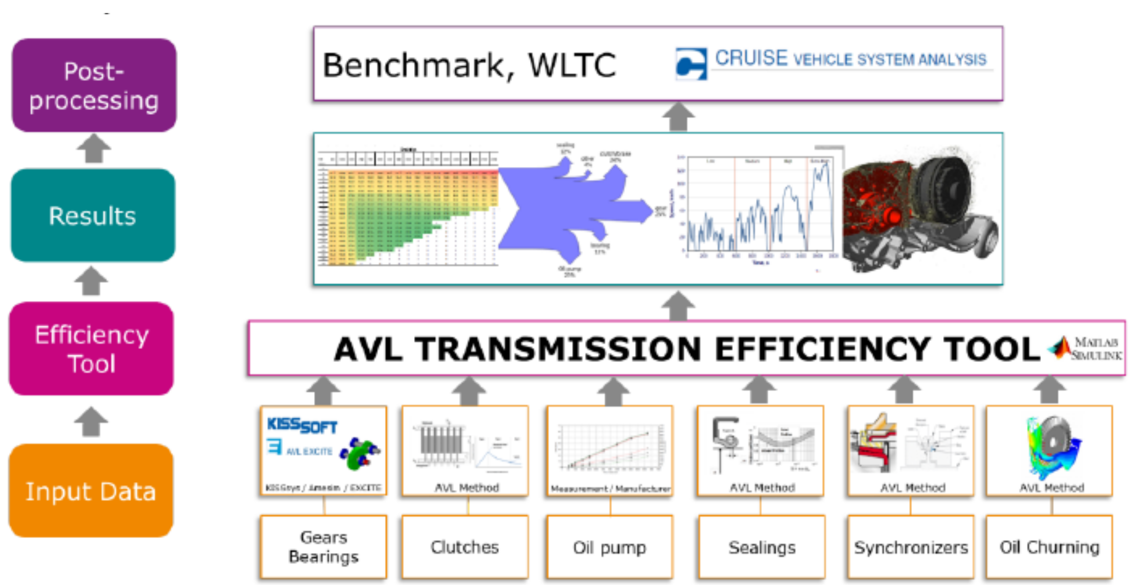


Figure 6: AVL transmission efficiency model structure.

5 Control functionalities for EM-TECH solutions

Model-in-the-loop (MiL) or Hardware-in-the-loop (HiL) simulation will be carried out to validate the new motor solutions. In the simulation, the low-level motor control functions include the inverter control, e-gear control and temperature monitoring. At the high level, the wheel slip control, the braking torque blending and the anti-jerk control will investigate the vehicle performance brought by the new developed e-corner and e-axle drive solutions.

5.1 Machine control

Real-time measurements and estimates of key electrical and mechanical quantities, voltage commands, phase currents and DC-link voltage signals, estimated back electromotive force (back-EMF), torque and speed, together with temperatures in key stator points, will be used for the real-time monitoring of the temperature distribution within the PMs. The impacts are strong as i) the accurate estimation of PM temperature allows for a more effective use of the material in limit conditions; ii) timely derating can be applied, and safety factors will be limited to a minimum, thus enabling the possibility of using lower PMs temperature grade, or recycled PMs. Take into account that lower PMs temperature grade corresponds to reduce the % of Dysprosium which means increase the residual induction (Figure 7).

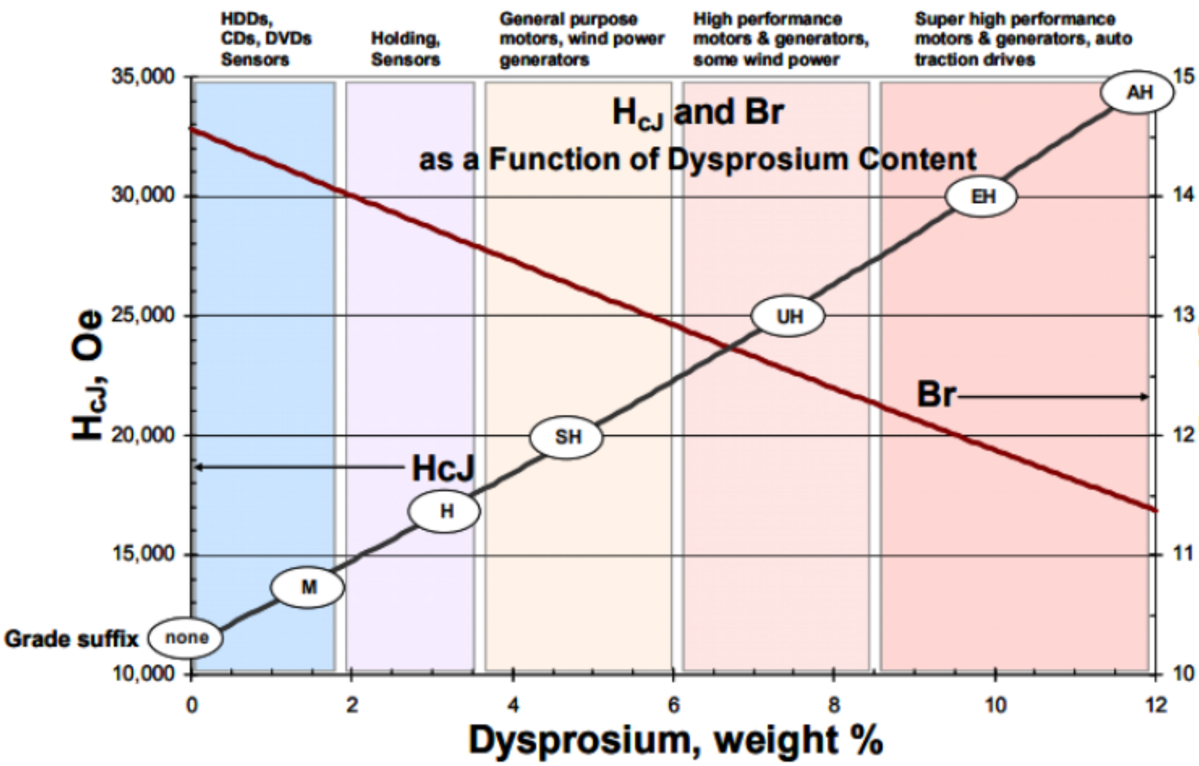


Figure 7: Intrinsic Coercitivity (HcJ) and residual Inductance (Br) as a function of dysprosium content [10].

In this regard the state of the art is lacking and represents an important opportunity area for disruption. Research efforts have been focusing on state observers [11]. To overcome the drawbacks of model-based techniques, novel artificial-intelligence (AI-based) approaches will be developed and implemented to guarantee fast execution times and proper adaptability to multiple input signal combinations. Unsupervised and supervised learning approaches will be compared to yield robust solutions able to respond to multiple working conditions (also transient conditions for electrical, mechanical and thermal variables). At the same time, the efficient integration of these tools onto conventional digital signal processors for motor control will be addressed. Previous experiences from POLITO, based on the use of

AI techniques for the estimation of vehicle dynamic variables, such as the sideslip angle and the vehicle speed, battery state of charge and state of health, will be used as reference [12].

The developed multi-physics model will serve as a dataset creation tool to start establishing proper real-time virtual sensing algorithms. An initial implementation step of these techniques for PM e-machines will exploit code generation tools, such as MATLAB/Simulink and dedicated microcontroller toolboxes. More efficient implementation in low level languages will also be possible on subsequent stages. To test virtual sensing, the full-scale machine developed for prototyping experimentation will be equipped with self-powered temperature sensors embedded in the rotor. These measurements will validate virtual sensing estimates. Advantages will be quantified in terms of the relevant metrics specified in EM-TECH project. The new generations of on-board AFMs, IWMs (together with the double shift e-Gear), and the associated technical contents of new cooling system and virtual sensing, will be subject to extensive validation against automotive requirements through component-level and system-level tests or simulations.

5.2 Wheel slip control

Considering the maximum grip force that the tyre can provide at a driving situation, the wheel slip control regulates the torque applied on the wheel to prevent it from spinning during traction operations or from locking during braking operations. This control is the fundamental of vehicle's active safety functions such as ABS and ESC, so that it requires the control action to be actuated accurately and timely.

- **Dynamics feature of different braking actuators.** The slow dynamic response of conventional hydraulic brakes limits the improvement of slip control performances (e.g., oscillations, stopping distance) albeit the effort in advanced slip controller design. The electro-hydraulic brake (EHB) or electro-mechanical brake (EMB) (e.g., ZF-TRW [13], Brembo [8]), devices facilitating the brake-by-wire system, has quicker dynamics and thus also benefits the slip control. Thanks to the nature of motor's fast dynamic response, especially the IWM for direct drive, the actuation using motor braking has the potential to significantly improve the anti-lock braking performances. ELA estimates less than 10 ms (depending on different torque ratings and the winding reconfiguration by e-gearing) rising time of step torque response for their IWM solutions in EM-TECH project. Figure 8 compares the typical bandwidth of different types of braking actuators. For on-board multi-motor driven situation, the motor torque response is compromised when it is transmitted to the wheel due to the dynamics of mechanical transmission, half shaft and constant-velocity joint. The feature of near-to-constant maximum torque for the whole speed range of VAI's on-board AFM solutions for EM-TECH project expands the feasibility of motor braking actuation at high speed where the general motor has reduced maximum torque due to the field weakening.

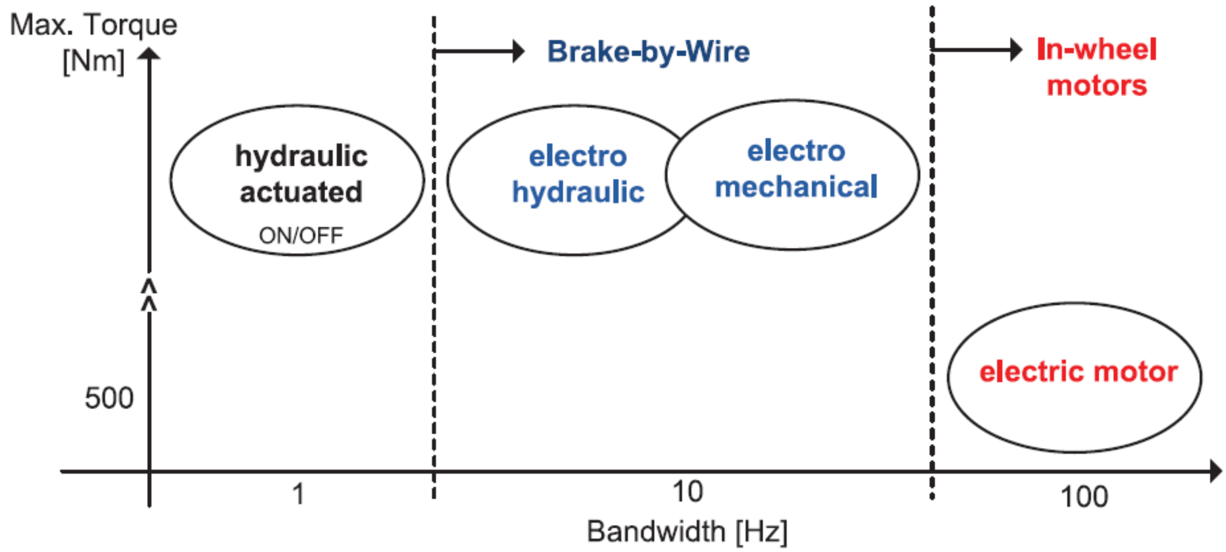
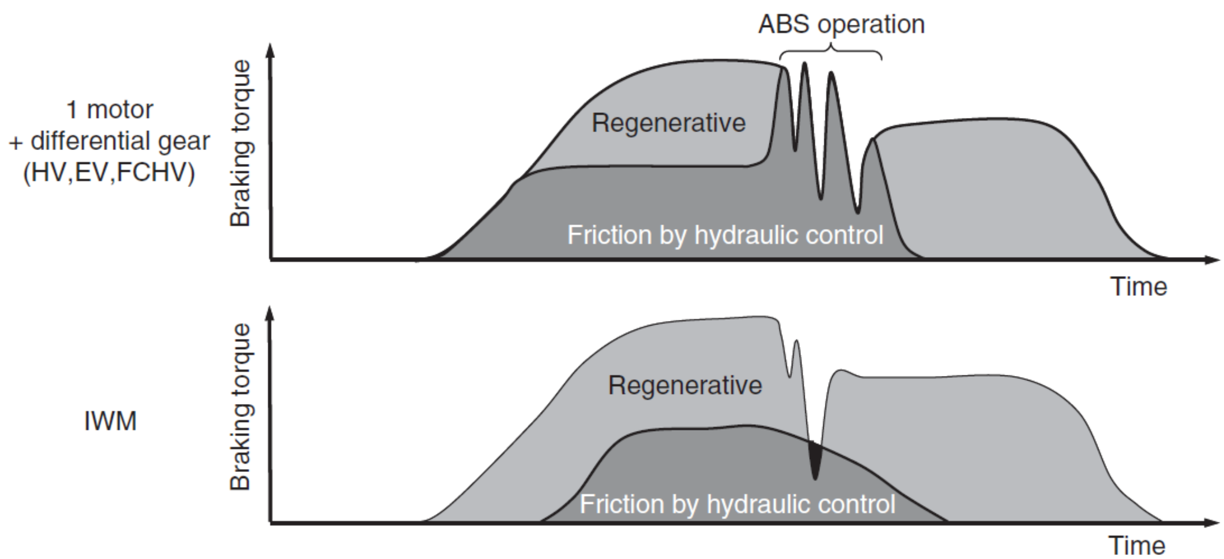
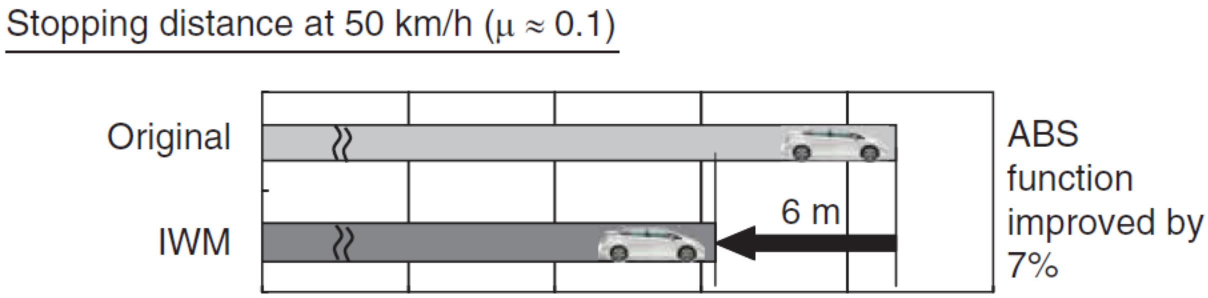


Figure 8: Qualitative features of the braking devices in the EVs [14].

- **Hybrid actuation.** Considering the motor torque limitation, it is natural of combining both friction braking and motor braking to form a hybrid wheel slip control to cover the full range of braking operations. Figure 9 a) demonstrates that during ABS actuation, for vehicles equipped with IWMs (bottom plot), the braking torque reduction is mainly actuated by the motor and results in less fluctuations; on the contrary, the conventional ABS actuation method (top plot) has severe oscillations. Figure 9 b) shows that the IWM-based ABS function corresponds to a significant reduction of the stopping distance (7% in very low tyre-road friction conditions).



a)



b)

Figure 9: a) Braking torque fluctuations achieved through friction brakes and IWM torque modulation; and b) potential stopping distance reduction compared to a vehicle with a conventional ABS [15].

- **Slip control methods.** Threshold-based or rule-based slip control is widely used in conventional ABS, mainly due to the slow dynamics of hydraulic actuators and the low-cost computing demand of control algorithms. With advances in on-board computing capability, more and more advanced control methods have been developed to exploit the potentials brought by EHB, EMB and motor braking (see a survey in [16]). The optimal reference slip ratio, the high nonlinearity and uncertainty in the wheel slip dynamics and the actuator dynamics are three important aspects that an effective slip control design needs to address. In [17], the optimal slip ratio is identified via a tyre brake force observer, a tyre adhesion coefficient estimation and a map characterising the tyre's slip-adhesion feature. For this aspect, the neural network (NN) technology might be adopted to improve the tyre model accuracy. In [18], the explicit nonlinear predictive control (NMPC) is employed for an EHB actuation, where the EHB's deadtime is compensated. In the case study given in [16], the EHB's dynamics is characterised as a constraint in the formation of NMPC. Some cascade control structures can be found in [14, 19, 20] for on-board motor or in-wheel motor and hydraulic hybrid applications, where the slip controller and the control allocator are decoupled. The slip controller (e.g., PID, sliding mode control, nonlinear control) modifies the braking torque demand whenever necessary, and the control allocator splits the demand between the friction brake and the motor, with the actuator dynamics considered in the splitting mechanism.

5.3 Brake blending and regenerative braking

The ability of permanent magnet motors to operate as a generator makes it possible to recover energy from the vehicle during braking and returns it to the battery. However, electric motor braking cannot completely replace the vehicle's braking system, so it is necessary to design and implement a brake blending controller to combine the two systems and use the energy as efficiently as possible.

As part of the XILforEV [21] project, several conventional brake blending control strategies were tested on a distributed network of test benches, and the behaviour of each component was studied in detail (Figure 10).

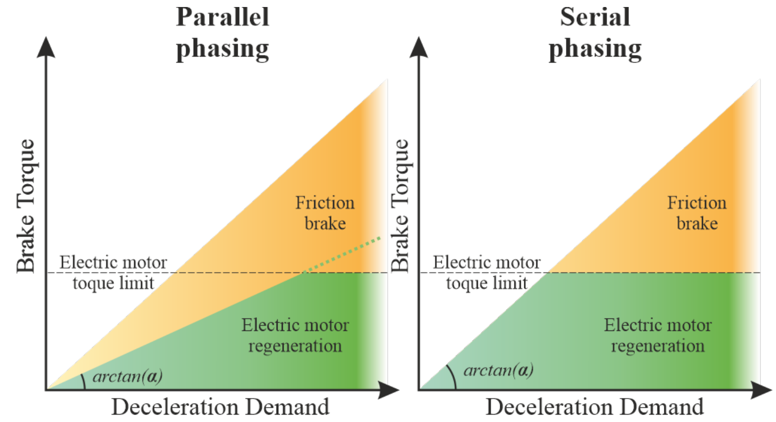


Figure 10: Brake blending controller architectures, which was compared in XiLforEV project [22].

One of the disadvantages that emerged from the carried-out experiments was the varying effect of different controller setups, with some controller configurations showing a higher effect at higher vehicle speeds at the start of braking, and others the opposite; see the right graph of Figure 11. The driver's commands are also very important, e.g., the more the driver presses the brake pedal, the less energy the motor can regenerate. This effect is presented in the left graph of Figure 11. The greater the torque demand from the motor on low velocity, the less efficiency the motor can provide. Therefore, with more intensive braking, a parallel brake force strategy is more advantageous than a series one.

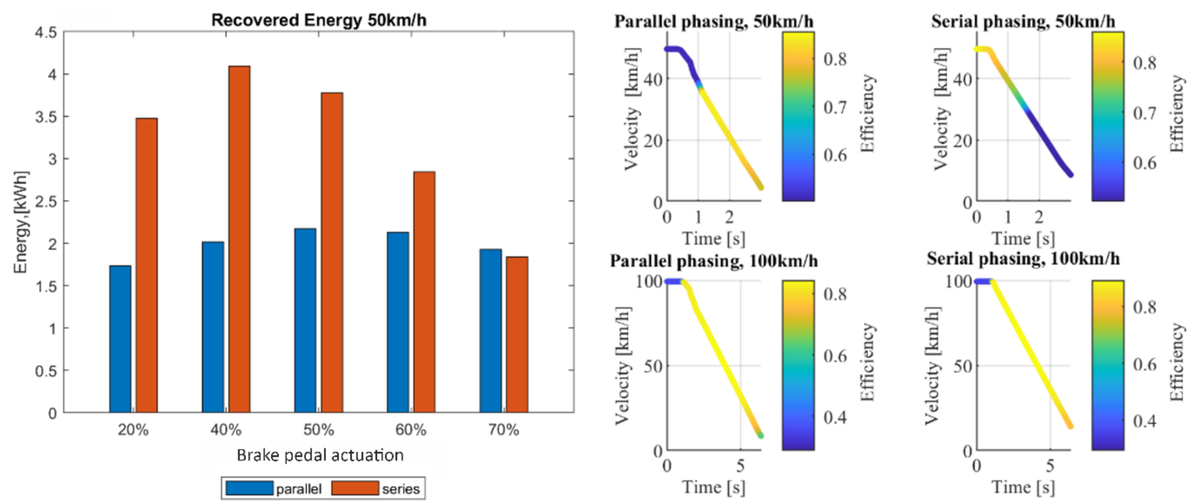


Figure 11: Brake Blending controller test results from XilforEV project [22].

Left: Recovered energy during braking for different brake pedal actuation.

Right: Electric motor efficiency during braking from different velocities.

These results encourage the implementation of a controller that is equally effective across the entire application range. Presumably, the controller will optimise the torque on the electric motor in real time, according to a predetermined efficiency map, Figure 12, and subsequently, allocate the rest of the braking force to the conventional braking system.

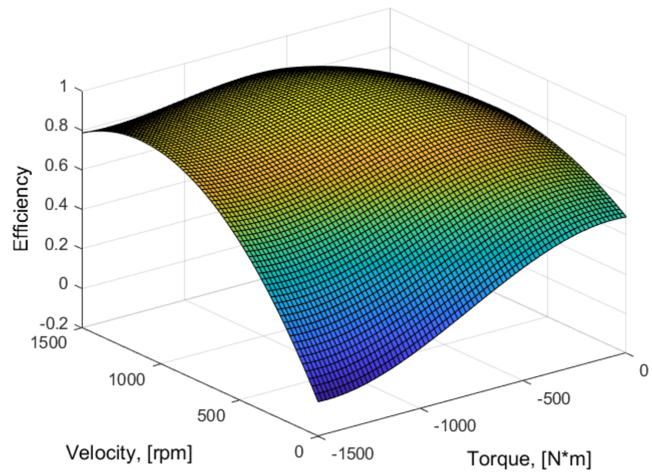


Figure 12: Approximation of efficiency map for ELA L1500D IWM for generator mode in XilforEV project [22].

Thus, the torque required from the IWM will depend on two parameters, the driver's request and the actual wheel speed of the vehicle. Once the IWM has optimised the braking torque request and the inverter has optimised the wheel torque, the driver's unfulfilled request will be sent to the friction braking system. This controller will improve the efficiency of regenerative braking and will also allow the brake torque redundancy to be realised by the two systems. The architecture is illustrated in Figure 13.

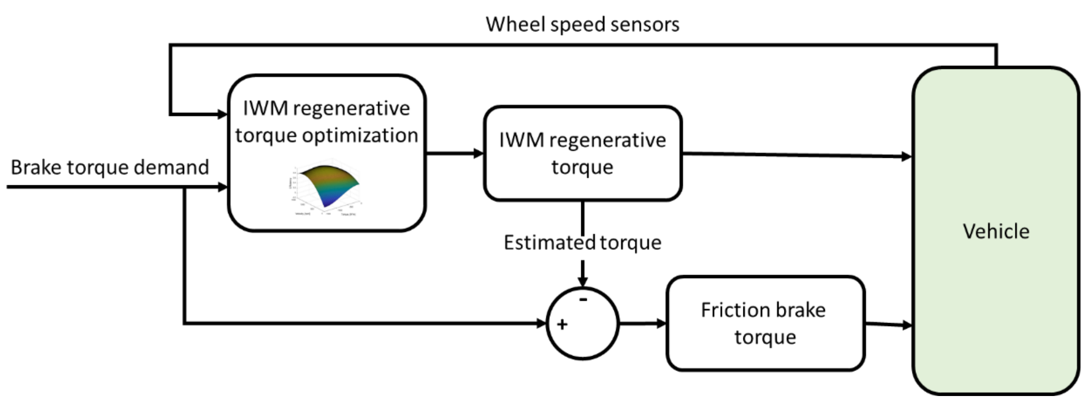


Figure 13: Proposed Brake blending controller architecture.

5.4 Anti-Jerk control and pitch control

The jerk defines the rate of the longitudinal vehicle acceleration variation during the change of the driver's torque demand (traction or braking), which is an important aspect to assess the ride comfort. In general, an anti-jerk control aims to modify the profile of the torque demand and thus suppress excitations in the drivetrain torsional motion and in the vehicle longitudinal motion. The control usually needs to balance the drivability and the comfort. A recent review of anti-jerk controls can refer to [23].

- **For on-board motor EVs**, the fast-responded motor torque is subject to excitation by the half shaft stiffness and thus leads to torsional oscillations in the drivetrain. Several feedforward and feedback anti-jerk control strategies are compared in [24], where the drivetrain dynamics are included in the controller design. The combined control performance of the fourth power vibration dose value, the root-mean-square value, the degradation of acceleration, the responsiveness of motor torque request, and the integral of absolute value of control action, is illustrated in Figure 14. In [25], the drivability optimization is discussed for a hybrid on-board motor and hydraulic brake application. In [26], it studied the optimal torque distribution between motor and friction brake to suppress the oscillation due to the gear backlash during the transition from motor driving and motor braking.

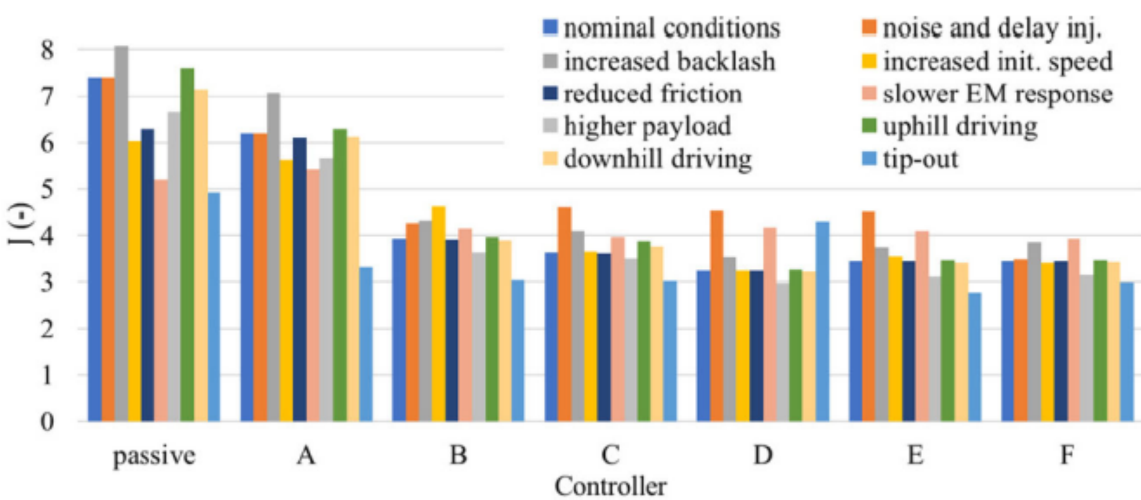


Figure 14: Performance comparison for different anti-jerk controllers and different uncertainties and driving situations [24].

(A – feedforward control; B – motor speed oscillation-based control; C – feedforward + motor speed disturbance observer; D – Tachometric controller; E – drivetrain torque based pole placement control; F – explicit NMPC)

- **For in-wheel motor EVs**, the absence of half shaft makes the conventional anti-jerk control unnecessary, but at the same time, the motor torque ripples are undamped and therefore they could cause significant rotational and longitudinal oscillations in the motions of rim, tyre, unsprung mass and sprung mass. Torque ripple reduction is often a subject of inverter control (e.g., through current injection). In [27], a modal frequency analysis is carried out for a multi-body model to identify the dominant frequency mode for individual motions, as listed in Table 4. Further publications regarding the attenuation of these oscillations by modifying motor torque are also available (e.g., see [28, 29, 30]).

Table 4: Multi-body modal frequency analysis [27].

(θ_a – rim rotation; θ_b – ring rotation; x_a – rim horizontal displacement; x_b – ring horizontal displacement; x_u – vehicle body horizontal displacement)

Order	Modal frequency/Hz	Modal damping ratio	Energy distribution on each degree of freedom (%)				
			θ_a	θ_b	x_b	x_a	x_u
1	0	–	1.26	2.2	1.74	7.56	87.24
2	4.1	0.1276	8.79	15.29	11.93	51.23	12.76
3	45.2	0.0522	43.05	28.03	0.26	28.65	0.003
4	95.4	0.0601	45.88	43.69	6.35	4.08	9.5×10^{-5}
5	136.4	0.0657	0.96	10.84	79.62	8.58	9.7×10^{-5}

EM-TECH will cover the AWD applications. For AWD, the activation of front axle drive is usually designed to minimise the power loss. On the other hand, to improve of pitch comfort it needs to optimise the front-to-rear torque distribution. Therefore, a strategy will be developed to achieve the balance between the power loss and pitch comfort. The pitch dynamics will be modelled, where the in-wheel drive and on-board drive are distinguished. The reference pitch should consider the driving experience.

6 Conclusion

In this deliverable, the basic ratings or sizes of the new e-corner and e-axle drive solutions is determined, and they can be applied for segment A, B, C, D, M passenger cars, small vans and heavy commercial vehicles, where the prototypes of new solutions will focus on segment B passenger cars and small vans for the e-corner applications, and heavy commercial vehicles for the e-axle applications. In Task 2.2, the accurate ratings and sizes will be determined when defining the technical requirements for the motors and integrated systems in detail, where key project objectives such as power density and torque density will also be derived. The associated control functions, including the low-level machine controls and the high-level vehicle controls, are described for MiL or HiL simulation study which will be carried out in Task 2.3 and 2.4.

6.1 Deviations, Impact and Recovery Actions

There is no deviation for this deliverable regarding the intended content. The final submission of this deliverable has been delayed by approx. one month to incorporate all the feedback from the review process.

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