Wheel corner design for multi-actuated electric vehicles

Viktar Skrickij [1)] **Paulius Kojis** [2)] **Valentin Ivanov** [3)]

1) Vilnius Gediminas Technical University, Vilnius, Lithuania

E-mail: viktor.skrickij@vilniustech.lt

3) Vilnius Gediminas Technical University, Vilnius, Lithuania

E-mail: paulius.kojis@vilniustech.lt

2) Technical University of Ilmenau, Ilmenau, Thuringia, Germany

E-mail: valentin.ivanov@tu-ilmenau.de

ABSTRACT: A wheel corner concept is proposed to realize more efficient and capable electric vehicle motion control. In this framework, each wheel is highly integrated and equipped with an in-wheel motor alongside multiple actuators, such as active suspension, active camber, active toe, and brake-by-wire system. This provides a high degree of freedom for controlling the vehicle dynamics, thus leading to higher redundancy and better fail-safety. The proposed chassis control is designed with the use of AI-based methods, contributing to software-defined vehicles capable of efficient, adaptive and predictive operation. The development process also includes an X-in-the-loop approach, where multiple digital twins, component hardware and test facilities are connected to a master hub and being operated in real-time, accelerating the development process and reducing the costs simultaneously. The proposed wheel corner concept aims for scalability and replicability to a wide range of vehicle segments.

KEY WORDS: electric vehicles, in-wheel motor, motion control, x-by-wire

1. INTRODUCTION

Important trends in automotive engineering towards electric vehicles (EV), automated driving, and software-defined vehicles (SDV) enable new functionalities for advanced driving assistance and motion control and demonstrate demand for revisiting the classical chassis architecture [1]. To reflect this demand, serious innovations were recently proposed for the vehicle topology with individual wheel corners as promising user-centered mobility concepts, e.g. Hyundai Mobis e-Corner system, 180° Corner Module from Continental, Deep Drive, Michelin active wheel; Siemens VDO eCorner; Protean 360+, Volvo's WCM, Bridgestone's WCM [2, 3, 4, 5, 6, 7, 8].

A corresponding key element, wheel corner, is a vehicle chassis item that transfers tire-road contact forces to the vehicle body and enables multi-actuation for each wheel's independent rolling, driving, braking, steering, and riding. It provides massive redundancy and fail-safety, simplified zonal electronic control unit (ECU) design, and increased on-board connection in the SDV domain.

Generally, a pod car with four independent wheel corners can represent the resulting vehicle architecture. In this case, no vehicle axles are required, and the powertrain with the central motor and axial motor topologies is also out of scope. Therefore, the wheel corner solutions can usually use (i) direct-drive in-wheel motors (IWMs) or (ii) near-the-wheel geared traction motors. The second option can be more beneficial for the optimal packaging of actuators inside the wheel hub, e.g., brake-by-wire (BBW); however, it can limit the maximum possible suspension travel and steering angle, thus reducing the advantage in the motion flexibility that is expected from the wheel corner design.

Concerning the chassis systems, the wheel corners can integrate BBW, steer-by-wire, active suspension, active camber and active toe control. It enables multi-actuated vehicle motion control, improving maneuverability, handling, and redundancy. However, it also requires comprehensive control logic and challenging implementation methods.

The analysis of research literature outlines increased interest in the wheel corner concepts, but known studies are mainly focused on specific problems of the integrated control for selected powertrain and chassis systems [9]. Many aspects, such as optimal design on the component and system level, validation procedures, and fail-safety and redundancy, are still insufficiently covered. To address these questions, the wheel corner design is also being studied within the scope of the European Projects OWHEEL [10], SmartCorners and MOCO, the results of which and future steps are discussed in the presented paper. This study systematically analyses all main corner components, focusing on active systems that may positively affect EV dynamics. The investigation of proof of a concept is based on tests performed using the X-in-the-loop approach, which analyzes the handling and ride comfort maneuvers with the specially defined Key Performance Indicators (KPI).

2. FRAMEWORK FOR THE WHEEL CORNER CONCEPT

Four different classes of wheel corners can be considered in general as part of the global vehicle architecture:

- *Passive corner with specific wheel positioning* – the wheel corner has a design that allows for specific wheel positioning (e.g., with extra cambering) to provide targeted tire-road interaction dynamics; active chassis systems are not being explicitly included here;
- *Passive composite corner* – the wheel corner has conventional packaging (e.g., no extra cambering), but a specific design with composite materials is provided;
- *Active corner with ordinary ride dynamics control* – the wheel corner has only traditional active chassis systems as a (semi-)active suspension and brake-by-wire;
- *Active corner with integrated wheel positioning control* – the wheel corner is equipped with additional active chassis systems that enable, for instance, the cooperative control of the wheel camber, and toe angle through mechatronic actuators.

Fig. 1 introduces an example of the wheel corner packaging designed for an electric sport utility vehicle (SUV) with a typical mass of 2500 kg to 3000 kg. In the technical task, the nominal power of the propulsion system was defined in a range from 150 to 300 KW. This can be achieved by installing two or four IWMs. As a result, it significantly increases the vehicle's unsprung masses (UMs). The additional mass from the IWM, which generates about 75kW of nominal power, is about 35 kg. Additional actuators and redesigned corner parts increased the UM of the SUV in a range from 65% to 70%, depending on the SUV under investigation and if it is a front or rear corner.

For the proposed concept, the wheel corner design can totally have more than 20 actuators, influencing the tire forces and torques (6 actuators for one wheel: electric motor (EM) in traction and braking mode, friction brake in BBW, active suspension, active camber, active toe, and steer-by-wire). It provides a reliable selection of the EV topology by mitigating failures of braking, steering or stability control functions with simultaneous consideration of an appropriate energy-efficient combination of involved actuators. However, it requires a sophisticated integral motion control strategy. A corresponding example is outlined in Fig. 2 and is based on the previous work of authors [11].

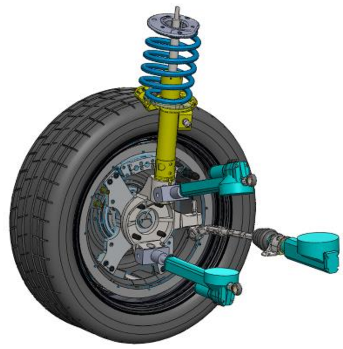

Figure 1: Active wheel corner design with the actuators for the suspension and wheel positioning control.

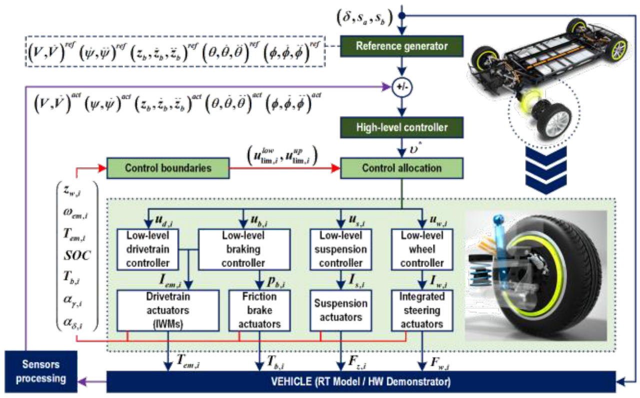

Figure 2: Active wheel corner design with the actuators for the suspension and wheel

The proposed configuration has been subject to feasibility studies using software-in-the-loop (SIL) simulations and hardware-in-the-loop (HIL) experiments. The procedures are discussed in the next sections.

2.1. Vehicle's mathematical model for SIL and HIL

Two vehicle high-fidelity mathematical models were developed; first, using MSC Adams simulation environment, second, on the IPG CarMaker simulation platform. The model has been parametrised based on mass-inertia parameters, suspension kinematics and compliance. The Delft-tire model was validated using test bench testing and used for simulation in IPG CarMaker, the experimentally validated Ftire model was used for simulation in MSC Adams. The vehicle's data is available in [12], the model has been validated using field test data from the proving ground [13], as described by [14].

The testing methodology, which includes handling and comfort tests, has been created to investigate how the new wheel corner design will impact vehicle dynamics. The comfort tests included driving on the road with Belgian pavement, bumps, and high-class (D-F) pavement irregularities at constant velocities in the range from 25 to 70 km/h. The testing methodology for handling includes different tests such as Acceleration and Braking, Skid Pad (ISO 7975:2019), Step Steering (ISO 7401:2011), Double-step Steering (ISO 17288-1:2011), Obstacle Avoidance (ISO 3888-2:2011), Sine-with-Dwell (ISO 19365:2016), and Sinusoidal Steering.

After reviewing the literature, two main KPIs were selected: root mean square (RMS) of sprung mass (SM) vertical acceleration as the main KPI for comfort and Dynamic Load Coefficient (DLC), which considers wheel loading change for handling. The use of the difference thresholds is proposed to evaluate comfort. Difference thresholds are the minimum change in the magnitude of the whole-body vibration required for the seat occupant to perceive the change in magnitude [11].

3. FEASIBILITY ANALYSIS OF WHEEL CORNER FUNCTIONALITY WITHOUT ACTIVE CHASSIS SYSTEMS

Firstly, the wheel corner configuration without active chassis actuators has been investigated. Results showed that increased UM due to using IWM negatively impacted vehicle dynamics. For performed tests regarding the comfort achieved, RMS change for worst cases was about twice as high as defined difference thresholds (Table 1).

Table 1. Results for sinusoidal excitation

	2.5 Hz	5 Hz	10 Hz	20 Hz
	RMS of SM vertical acceleration (Unweighted) $[m/s^2]$			
Reference vehicle	0.3979	0.5987	0.9665	0.4014
Vehicle with corner	0.4190	0.6644	1.101	0.2552
Absolute difference	0.021	0.066	0.135	0.146

Further critical issues were related to handling. Tire contact losses have been defined for roads with sinusoidal excitations when the excitation frequency was higher than 20 Hz. Also, the vehicle could not perform Obstacle Avoidance (Figure 3) and Sine-with-Dwell tests at specified high velocities of 80 km/h and above. These results pointed to the demand for active chassis systems.

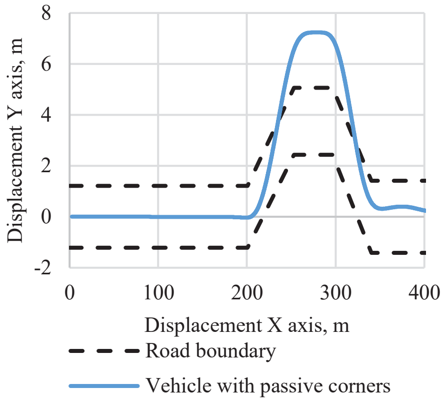

Figure 3. Obstacle avoidance maneuver with passive vehicle corner

4. FEASIBILITY ANALYSIS OF WHEEL CORNER FUNCTIONALITY WITH ACTIVE CHASSIS SYSTEMS

The introduction of the wheel corners influences the vehicle's kinematic & compliance (K&C). A K&C test of active wheel corners was performed in the SIL environment to investigate this aspect. By varying the camber angle (Figure 4), the lateral forces, steering angle, and lateral acceleration can be tuned, improving the handling and stability of the vehicle. However, this requires precise control and real-time adjustments.

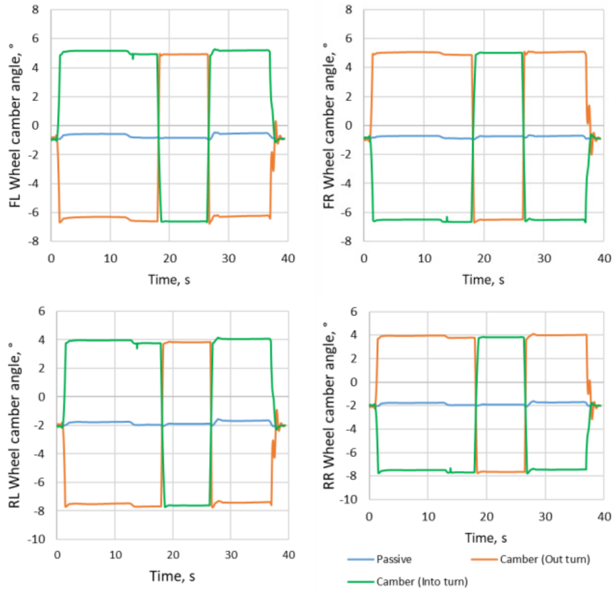

Figure 4. Example of active camber variation during cornering for all four wheels

It was found that active camber drastically impacts vehicle roll, and comfort level decreases significantly Figure 5.

Figure 5. The vehicle rolls during the cornering maneuver, with the wheel cambered into a turn.

The findings reveal that the impact of active camber angle adjustment is constrained by tire geometry, resulting in only marginal increases in lateral force. Additionally, implementing such adjustments would require substantial actuator displacement exceeding 200 mm for SUVs, potentially leading to packaging challenges. Conversely, toe angle adjustment yields a more substantial increase in tire lateral force and offers a broader range of tuning.

Simultaneously, active suspension components were developed, and a control strategy to reduce roll was tested. The control targets are to reduce the vehicle's roll angle effectively and keep it within an amplitude of 2° (Figure 6).

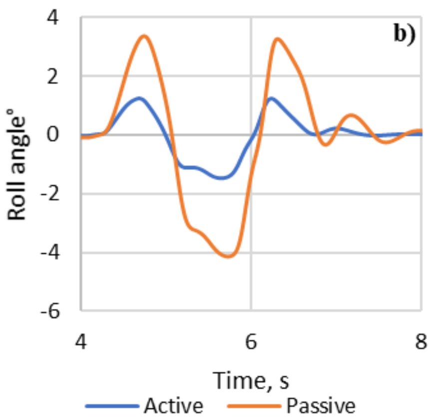

Figure 6. Active roll in the obstacle avoidance test

The proposed control strategy reduced the negative roll effect; however, the tires are overloaded, which increases tire wear. As a result, camber actuators do not provide significant improvement in vehicles with conventional suspension. The chassis can be redesigned additionally so the roll would not increase significantly during camber change.

To enhance direct yaw rate control, the integration of toe actuators has been proposed on both the front and rear axles. This approach can serve as a viable alternative to conventional dynamic control systems that rely on braking forces or be employed in conjunction with braking and powertrain systems. Results indicated that the vehicle successfully executed maneuvers with the proposed control strategy, exhibiting minimal trajectory and velocity deviations. Furthermore, the implementation significantly reduced the yaw rate in both scenarios, improving vehicle performance in regard to comfort and stability.

Notably, the active wheel positioning system led to reduced lateral and vertical accelerations during maneuvers. The essential decrease in the RMS of vertical acceleration surpasses the defined difference threshold, signifying a perceptible improvement in occupant comfort during extreme maneuvers.

Figure 7: HIL environment with installed wheel corner.

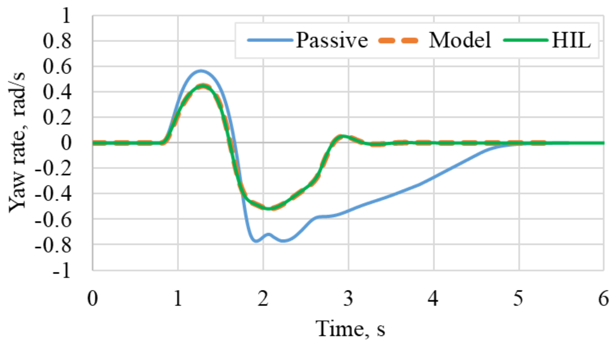

Figure 8: Example of HIL results: Active toe for Sine-with-dwell maneuver from 80 km/h

For further studies, the wheel corner has been prototyped and tested in the HIL environment, Figure 7. The relevant tests confirmed that the inclusion of new active chassis systems not only keeps the required ride comfort and provides efficient handling but also improves the vehicle stability. For example, as can be seen from Figure 8, the wheel corner with the active chassis systems supports driving during critical safety scenarios by reducing excessive yaw motion and enabling maneuver implementation on high velocities.

4. CONCLUSIONS

This investigation examined four distinct wheel corner designs: a passive corner with specific wheel positioning, a passive composite corner, an active corner featuring standard ride dynamics control with (semi-)active suspension, a BBW system, and IWM, an active corner integrated with an advanced wheel positioning system. This last design incorporates additional active systems that allow for cooperative control of IWM, BBW, (semi-)active suspension and wheel positioning, adjusting camber and toe angles through mechatronic actuators.

Findings indicate that an increase in UM adversely affects vehicle dynamics, particularly handling, while the impact on ride comfort is comparatively minor. Relying solely on lightweight solutions does not adequately address these concerns; thus, further exploration of innovative EM technologies to significantly reduce IWM weight is warranted.

The benefits of IWM and BBW systems have been acknowledged in previous research conducted by the authors. However, the introduction of camber actuators in conventional vehicles has presented challenges and failed to deliver the intended effects. Therefore, developing new pod car designs that explore alternative kinematic arrangements is essential. Conversely, toe actuators provide substantial benefits, enhancing vehicle handling and comfort without necessitating significant modifications to existing vehicles. Their effectiveness has been validated through both SIL and HIL testing. The greatest potential for active suspension innovation lies in the advancement of novel electromechanical actuators.

ACKNOWLEDGEMENT

Several parts of this research were funded from the European Union Horizon 2020 Framework Program, Marie Skłodowska-Curie actions, under grant agreement no. 872907. Further research on this topic will be conducted as part of the Horizon Europe projects Smart Corners and MOCO.

REFERENCES

(1) D. Slama, A. Nonnenmacher, T. Irawan, “The Software-defined Vehicle: A Digital-first Approach to Creating Next-generation Experiences,” 2023, p.60.

(2) https://www.hyundaimotorgroup.com/story/CONT0000000000105101

(3) https://www.continental-automotive.com/en/solutions/brake-system/from-drive-brake-unit-to-highly-integrated-corner-module.html

(4) P. Evans, “Michelin active wheel system to hit roads in hit roads,” 2010, https://newatlas.com/michelinactive-wheel-production-electric-car-by-2010/10489/

(5) M. Hanlon, “Siemens VDO visualises the electric wheel hub motor,” 2006, https://newatlas.com/go/5996/

(6) S. Brich, “Protean Electric aims for pirouetting autonomous EVs,” 2019, SAE International.

(7) M. Biček, D. Miljavec, G. Gotovac, S. Zupan, “Mechanical failure mode causes of in-wheel motors,” Strojniški vestnik – J. Mech. Eng., 2015, 61(1), pp. 74–85.

(8) G. Nagaya, “In-wheel motor system,” Patent US0 247 496A1 (2005). Bridgestone

(9) P. Kojis, A. Danilevičius, E. Šabanovič, V. Skrickij, “The second generation of electric vehicles: integrated corner solutions,” TRANSBALTICA XII: Transportation science and technology. Proceedings of the 12th international conference TRANSBALTICA, September 16-17, 2021, Vilnius, Lithuania. Cham: Springer, 2022. ISBN 9783030947736, pp. 87–100.

(10) C. Kat, V. Skrickij, B. Shyrokau, P. Kojis, P. et al., “Vibration-Induced Discomfort in Vehicles: A Comparative Evaluation Approach for Enhancing Comfort and Ride Quality,” SAE Int. J. Veh. Dyn., Stab., and NVH 2024, 8(2), pp. 139–153.

(11) V. Ivanov, V. Beliautsou, F Büchner, “Distributed Validation and Testing of EV Systems”, in Proc. of the 6th International Electric Vehicle Technology Conference (EVTeC), 2023, pp. 1–6.

(12) V. Skrickij, E. Šabanovič, P. Kojis, V. Žuraulis, V. Ivanov, B. Shyrokau, “Improving vehicle stability and comfort through active corner positioning,” SAE World Congress Experience, WCX 2024, 16–18 April, Detroit, USA. SAE International, 2024, pp. 1–9

(13) C. Vaseur, S. Van Aalst, “Test Results at Ford Lommel Proving Ground ESR 11 (Version Final),” [Data Set]; Interdisciplinary Training Network in Multi-Actuated Ground Vehicles: Geneva, Switzerland, 2019.

(14) E. Šabanovič, P. Kojis, Š. Šukevičius, B. Shyrokau, V. Ivanov, M. Dhaens, V. Skrickij, “Feasibility of a Neural Network-Based virtual sensor for vehicle unsprung mass relative velocity estimation,” Sensors. Basel: MDPI. ISSN 1424-8220, 2021, 21, pp. 1–17.