RECENT TRENDS IN THE DEVELOPMENT OF SKATEBOARDS AND WHEEL CORNER MODULES IN ELECTRIC VEHICLES (EVS)

Fig 1. EV AUTOnomy Skateboard from General Motors (Ref. [1])

Electric Vehicles (EVs) have been going through disruption on multiple aspects including dedicated platform development, modularity and scalability, adaptation of multiple top-hats on the underlying platform leading to effective reuse and reduced costs of development, enabling faster deployment of autonomous technologies, and offering more cabin space and comfort to the passengers. An important disruption leading to Reinvention of the Automobile, in particular, Electric Vehicle, is the creation of the first Electric Skateboard platform AUTOnomy by the team at General Motors showcased at the January 2002 Detroit International Auto Show (Fig 1, Ref. [1]). The flat skateboard paved the way for increased application of x-by-wire (XBW) technologies such as Throttle by wire (TBW), Accelerate by wire (ABW), Steer by wire (SBW), and Brake by wire (BBW) thus improving drivability, braking, and manoeuvrability of the vehicle.

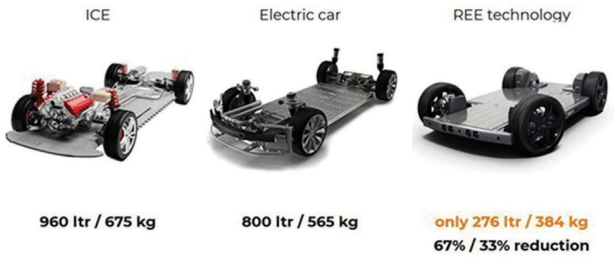

Fig 2. Weight Reduction from ICE to Electric Vehicle to Flat Skateboard with WCM (Ref. [2])

Over the last decade, another important disruption has been the emergence of Wheel Corner Modules (WCM) based on modular design around the geometric boundaries of a conventional wheel (Fig 2, Ref. [2]). The typical WCM, also sometimes called as “In-Wheel Motor (IWM), consists of a wheel containing an electrical in-wheel propulsion motor, a friction brake, a steering system and a suspension system. WCM is)”. WCMs (or IWMs) have been appealing to EVs due to a) Simplicity and b) Compact Packaging. The WCM design is simple because the motor requires no transmission or differential or constant-velocity (CV) joints to connect with the wheels, leading to much less energy losses to friction. The WCM design saves space because placing the motors in the wheels provides designers with greater freedom to develop multiple vehicle layouts with increased passenger space and storage. As per a recent estimate, additional weight savings of up to 33% are possible on flat skateboards with the usage of WCM over conventional suspension and steering systems (Fig 2, Ref. [2]).

1. Electric Vehicle Skateboards

For automotive OEMs in general, and EV start-ups in particular, the development of a vehicle platform

can demand millions of dollars in investment for design, development, build, and validation, not to mention the warranty and service liability costs. As EVs still struggle to catch up on volumes and stay price competitive compared to conventional vehicles, automotive OEMs find increasingly difficult to recoup millions of dollars of investment through vehicle pricing and sales volume and cost amortization per vehicle only add to erode the price competitiveness further.

Of late, OEMs and especially EV start-ups, have started jumping onto the bandwagon of a flat skateboard, first conceptualized by General Motors through the launch of AUTOnomy in 2002 (Fig 1, Ref. [1]). The advantage with a skateboard is that it accommodates a large flat traction battery with chassis integrating motors, steering, suspension, brakes, and controls. Fig 3 shows the collage of EV skateboard development over the last two decades.

Fig 4 (a). GM BEV3 Skateboard [Ref. 4]

Fig 4 (b). Ford-Rivian Skateboard [Ref. 3]

Fig 3. Collage of EV Skateboards developed over 20 years (Ref. [3])

Though manufacturers such as Rivian and Canoo have first developed vehicles, they have tweaked their business model to offer their EV platforms for other applications. Recent EV skateboards launched in 2020 include GM's BEV3 platform (and Ultium Traction Battery) and Ford Lincoln – Rivian joint venture as shown in Fig. 4 a and b.

Another entrant to the EV space, with their luxury offerings and world-class styling, is Pininfarina (a subsidiary of Mahindra & Mahindra), which will launch different vehicle variants based

on the EV skateboard developed jointly with Bosch and Benteler (Fig 5, Ref [5]). The platform is highly flexible to offer variants ranging from sportscar to sedan to SUV.

Fig 5 (a). Bosch-Benteler Skateboard [Ref. 5]

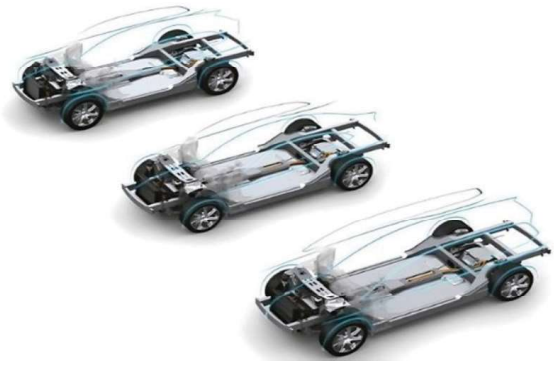

Fig 5 (b). Pininfarina Vehicle Variants [Ref. 5]

Though many organizations eventually started developing dedicated EV platforms, two start-ups have launched pure skateboards, namely AEV Robotics and REE (Fig 6, Ref [3]). These skateboards tout not only scalable and modular platforms for building "functional pods" for varying needs, but also boast advanced connectivity and ADAS technologies besides Wheel Corner Modules (WCM) that drive and manoeuvre the vehicles.

Fig 6 (a). AEV Robotics Skateboard [Ref. 3]

Fig 6 (b). REE Skateboard [Ref. 3]

1. Wheel Corner Modules (WCM)

A wheel corner module (WCM) is a Mechatronics-based modular design and implementation around the geometric boundaries of a conventional wheel for vehicular motion control. A typical WCM consists of a wheel containing an in-wheel propulsion motor, a friction brake, a steering system and a suspension system controlled by means of electrical actuators. A WCM is typically a complete system containing subsystems responsible for longitudinal, lateral and vertical motions of the vehicle. These subsystems comprise electro-mechanical actuators and linkages and are operated upon by inputs from a control system. The steering column may comprise a conventional steering wheel and pedals or an advanced system such as a joystick. The WCM is designed to easily attach to a vehicle platform by means of bolted connections and a power connector, which comes as an added advantage when combined with flat EV skateboards.

All functions of the WCM are electrically controlled based upon input from an operational device, in connection with one or several control units. It represents a pure x-by-wire based vehicle manoeuvring system. Mounted around the vehicle are several sensors that continuously supply the control units with information regarding the vehicle position and state. The sensors might include position sensors, velocity sensors, acceleration sensors, force and torque sensors, pressure sensors, flow meters, temperature sensors, etc. The information supplied by these sensors might be yaw rate, lateral acceleration, angular wheel velocity, steering angle and chassis velocity. The operational device comprises a conventional steering wheel and pedals, or any other feasible solution

such as e.g. a joystick. Few of the WCM designs are shown in Figures 7 and 8. These include Michelin's Active Wheel, Bridgestone's In-Wheel Motor Drive, and eCorner modules from Siemens VDO and Schaeffler.

An EV WCM may contain two or four WCMs and accordingly, the number of actuators may vary. WCM vehicles involve an increased number of actuators

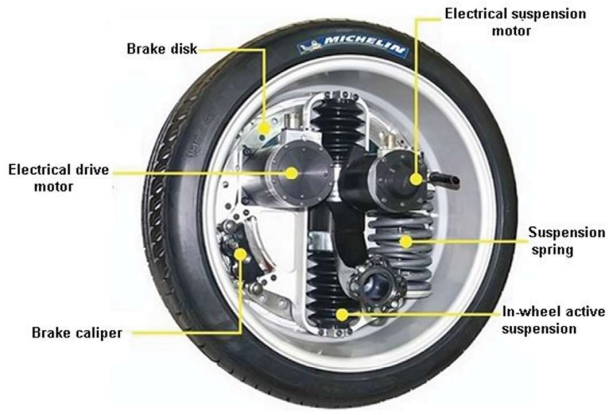

Fig 7 (a). Michelin's Active Wheel [Ref. 6]

Fig 7 (b). Bridgestone In-Wheel Motor Drive [Ref. 7]

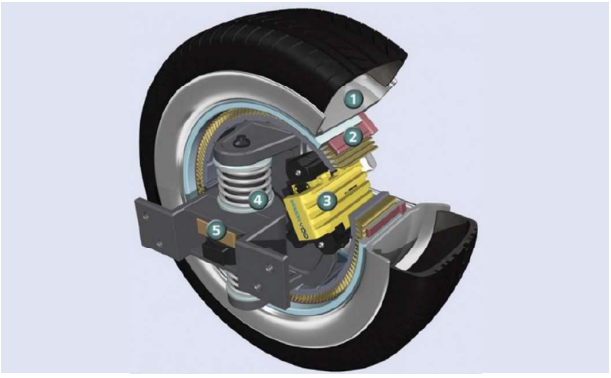

Fig 8 (a). Siemens VDO eCorner Module [Ref. 8]

Fig 8 (b). Schaeffler eCorner Module [Ref. 9]

compared to conventional automotive vehicles, with a number of actuators exceeding the degrees of freedom (DOF), thereby forming an over actuated system and thus enabling improved vehicular motion control. WCM vehicles, compared to conventional vehicles, are evaluated based on different vehicular aspects such as Handling, Comfort, Safety, Ride Quality, Environmental aspects, and Economical impact.

Protean360+ Wheel Corner Module (WCM)

Protean Electric has developed a new corner module concept that integrates electric drivetrain, steering and suspension in a single product that claims to offer a limitless 360-degree steering capability (Fig. 9, Ref [10]). The product has an in-wheel electric motor, an innovative suspension design, and pneumatic ride-height control. Owing to the module's compact packaging, it can fit well with flat EV skateboards offering large interior space and provide adequate lateral access to offer wheelchair ingress and egress via front, rear and side doors. High-degree steering capability also enables the vehicle to park front-, rear-, or side-on to the kerb. With adjustable ride height and kneeling capability, the vehicle offers stepless and virtually gapless ingress and egress straight onto the pavement even for passengers with impaired mobility.

The 360-degree Steering by Wire (SBW) capability is made possible by a rotating interface that sits above the corner module's main arm. The top of the rotating interface is fixed to the vehicle; the lower interface is fixed to the module arm. From the lower rotational interface, control cables for the motor, hydraulics, and pneumatic

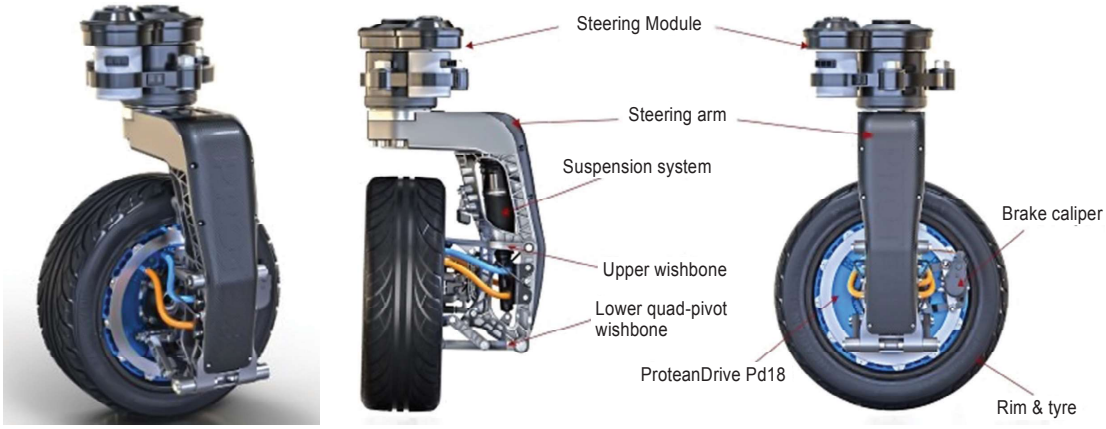

Fig 9. Protean Electric's Wheel Corner Module [Ref. 10]

ride height controls are channelled down the module arm and are connected to a second static interface within the hub and into the wheel motor unit. As the arm module rotates through 360 degrees, the full component set rotates with it. As a result, the connections and cables are not twisted or stressed.

Protean360+ WCM comprises a novel twin-knuckle multi-link suspension design with an additional lower wishbone pivot to offer compact packaging and facilitate improved access to passengers. The quad-pivot double-wishbone spider movement enables high-strength force transfer with both compact packaging and full-range suspension travel, which in turn allows optimum geometry and additional articulation in the lower suspension arm for improved Kinematics & Compliance (K&C) capabilities. Additionally, a single common module design is optimized for all four corners of the vehicle, thereby reducing development and production costs.

Protean360+ WCM comprises fully integrated in-wheel Permanent Magnet Synchronous Motor (PMSM) and inverter with liquid cooling that offers higher efficiency and flexibility and greater dynamic control of the overall power and torque delivery. The system offers a high level of redundancy with in-wheel motor in each WCM. A friction brake disc and caliper are packaged in the wheel along with the motor complementing its regenerative braking capability. The rotor of the electric motor connects directly to the hub, delivering torque from the motor to the wheel and removing losses in power transfer. The motor features an outer rotor configuration to maximise torque which also allows rare earth-magnets to be surface-mounted without retention features that would otherwise compromise performance. The in-wheel motor offers direct torque transfer, high efficiency, and improved performance of ESC, ABS, and traction control systems, thus providing improved stability and safety through shorter stopping distance.

REE Wheel Corner Module

REE is an EV start-up from Israel that has developed a flat skateboard and a new integrated wheel module concept that houses X-by-wire (XBW) braking and steering systems along with suspension, electric motor, sensors and electronic controllers into each wheel well as shown in Fig. 10 a and b.

This design provides a low C.G. for better vehicle stability and manoeuvrability and improved energy efficiency along with agile responses to driver inputs. Efficient packaging of electric actuators and controllers in the wheel wells also enables flat floor, ample interior space, and large battery pack for longer range. In-wheel motors enable the option of torque vectoring to improve safety and handling. The use of X-by-wire, quad gearbox, and an integrated suspension with ride height adjustment improves passenger comfort and ride handling. The flexible platform offered by REE to vehicle manufacturers

Fig 10 (a). REE Flat EV Skateboard [Ref. 11]

Fig 10 (b). REE Wheel Corner Module [Ref. 11]

gives them the option to develop multiple top hats (body configurations) ranging from high-performance sportscars to off-road SUVs with active suspension and adjustable ride height to light & heavy-duty trucks.

Summary

WCM vehicles enable significantly improved handling performance, safety and ride comfort compared to conventional vehicles, owing to the x-by-wire technology and an additional number of actuators related to motion control. Longitudinal, vertical and lateral motions can be individually set for each corner module. Implementation of in-wheel motors is likely to cause an increased unsprung mass in terms of the WCM vehicle, compared to a conventional equivalent. Recent research indicates that an increased unsprung mass involves deteriorated handling performance, regardless of the vehicle velocity or road disturbance profile. At disturbance frequencies above the eigenfrequency of the unsprung mass, a significant ride comfort improvement is however indicated. Hence, the mass of in-wheel motors must be kept to a minimum, or an individual motor suspension along with ride height control may be required, which is the recent trend observed.

In conclusion, this article presented an overview of recent trends in EV platforms and Wheel Corner Modules with specific case studies to illustrate advanced technologies anticipated on vehicles in foreseeable future that augment well for Autonomous Vehicles.

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