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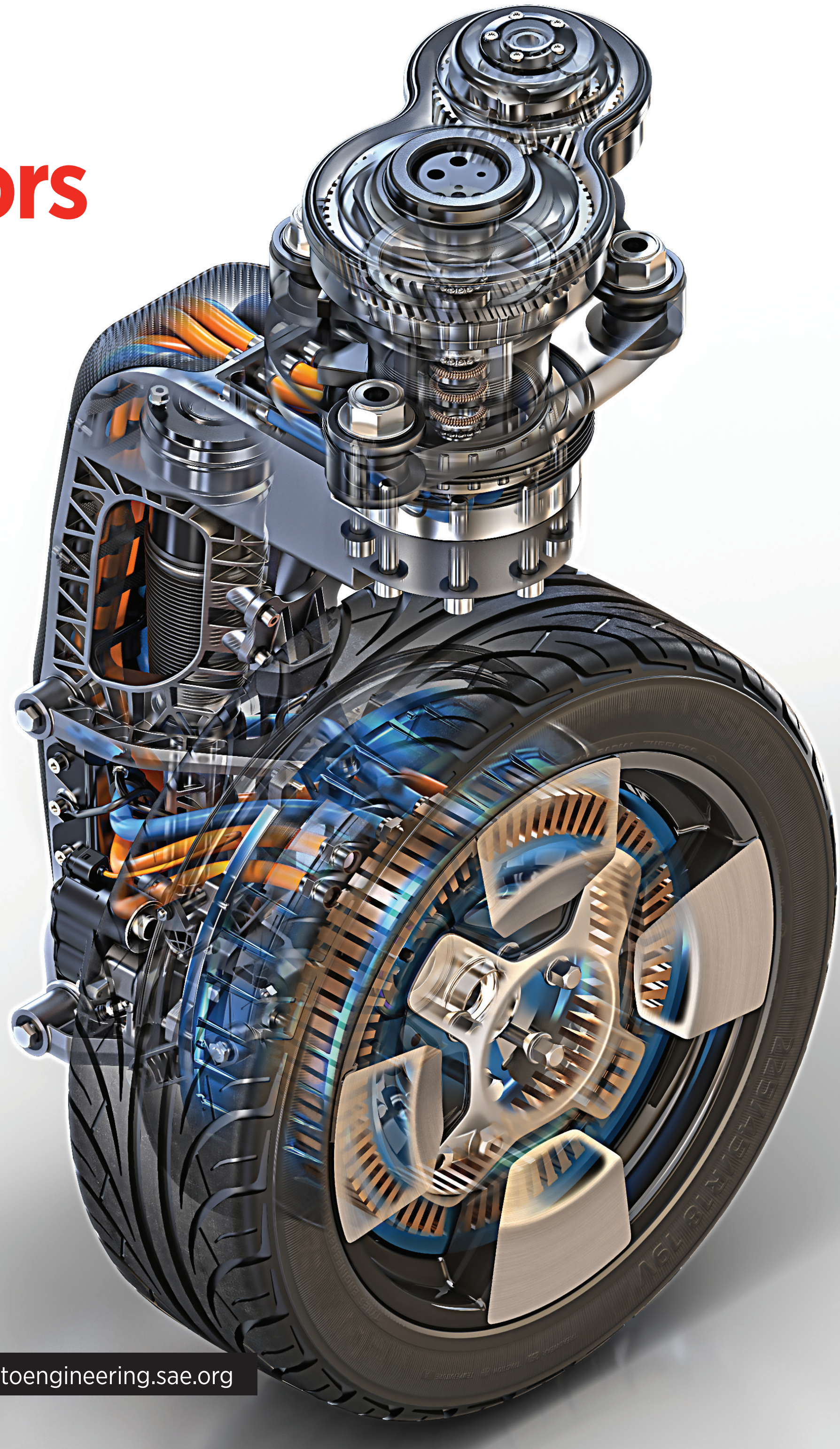
Integrated Wheel Motors

Rethinking the corner module for EVs



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COVER STORY

Making the case for IN-WHEEL MOTORS

IWMs offer many benefits in packaging, vehicle dynamics, safety and potentially lower cost for urban shuttle and delivery vehicles, among others.

IWMs can improve EV efficiency, dynamics, safety, and manufacturability – when unsprung mass is addressed in their design.

by Chris Borroni-Bird

Much of an IC engine-powered vehicle's ride, handling, sound and overall character derives from the engine. Some believe that electric vehicles (EVs), propelled by electric motors with no intake or exhaust sound and less gearing and NVH, limit the opportunity for vehicle differentiation. They argue that the powertrain will become a commodity and that competitive advantage will need to be achieved through other areas, such as styling and infotainment.

I contend that the exception to this view is the in-wheel motor (IWM), a technology that enables quantum improvements in propulsion efficiency, ride dynamics, active safety, and vehicle design. IWMs enable "turn-on-a-dime" operation, a relevant feature for dense urban environments and safe vehicle entry/egress from the sidewalk. Moreover, the IWM has the potential to extend the revolution – started by the now-ubiquitous EV "skateboard" architecture – in how vehicles are developed, manufactured and serviced.

IWMs are increasingly being developed and tested by OEMs and suppliers as part of the corner module. A growing number of advocates in the mobility-engineering community believe they are an inevitable solution for future EVs. Therefore, it is useful to understand what has prevented IWM commercialization so far, beginning with the commonly cited concern: unsprung mass.

PROTEAN ELECTRIC

Challenges and barriers

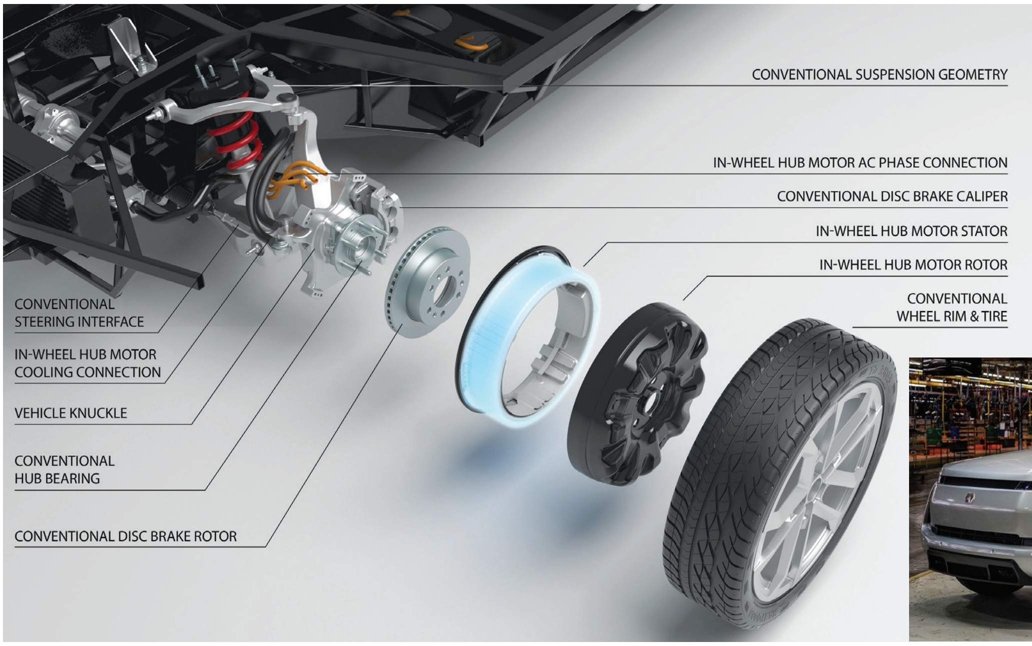
IWM can be integrated into the vehicle in various ways as shown in the accompanying images. They illustrate how IWMs can increase the unsprung mass – the components between the suspension system and the road surface, which includes wheels, tires, brakes and parts of the suspension system itself.

From a vehicle-dynamics perspective, it is useful to consider a vehicle's mass as a combination of sprung and unsprung mass. A vehicle's primary resonance mode (~1 Hz) is mainly caused by the vehicle's sprung mass bouncing on the suspension system. Unsprung mass, however, adversely affects ride comfort because it creates a more pronounced secondary resonance mode (~7-10 Hz, due to its inertial lag bouncing on the tire). It also makes handling more difficult because the suspension must work harder to keep the tires in contact with the ground.

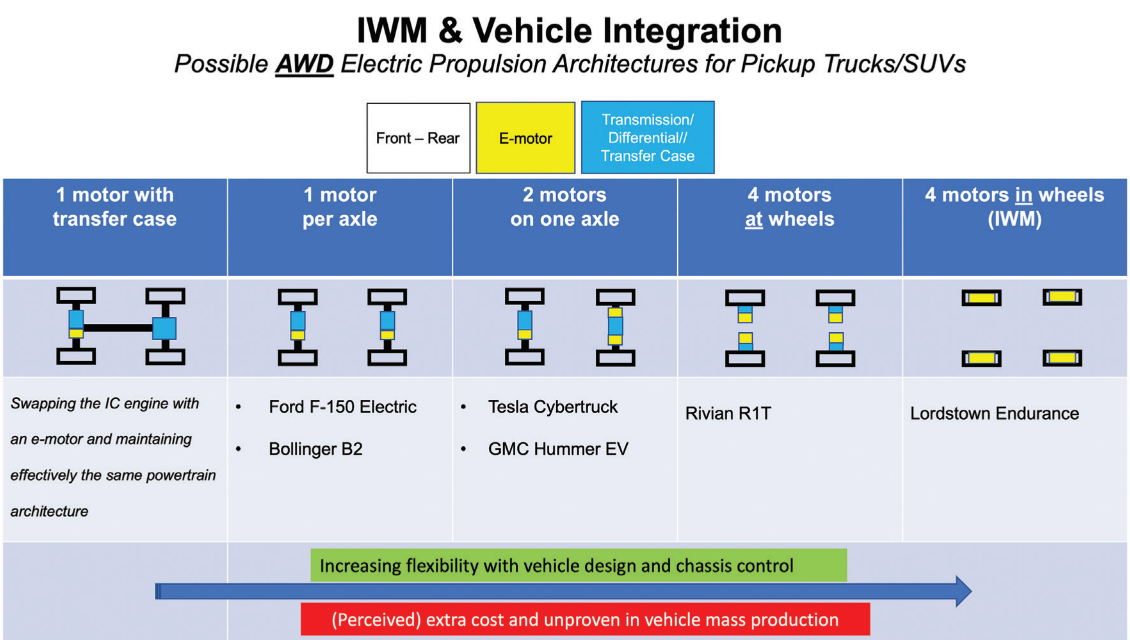
IWMs at each corner might perhaps double the vehicle's unsprung mass. But the consequences can be mitigated by tuning the suspension shock absorbers and reinforcing the shock-mount structure (to manage increased loads into the body structure). Moreover, ride deterioration is less perceptible for certain types of vehicles, like trucks and SUVs, that have a higher sprung:unsprung mass ratio (which drives the magnitude of this secondary resonance). Passenger expectations for ride comfort also may be less demanding for these vehicles.

In 2010, Lotus Engineering modified a 2007 Ford Focus by adding 30 kg to each wheel to simulate the effect of adding Protean's IWM unsprung mass. Data comparing ride and handling characteristics before and after the modification showed that increased unsprung mass can be addressed with typical ride-and-handling optimization techniques.

Other concerns with IWM include durability, thermal management and electrical safety. Although there is no mass-produced automotive IWM yet, development activity is expanding. Substantial mileage is being accumulated in the lab and on test vehicles. Lessons learned



Elaphe IWM at left. Lordstown Endurance electric pickup (below) uses one per corner.



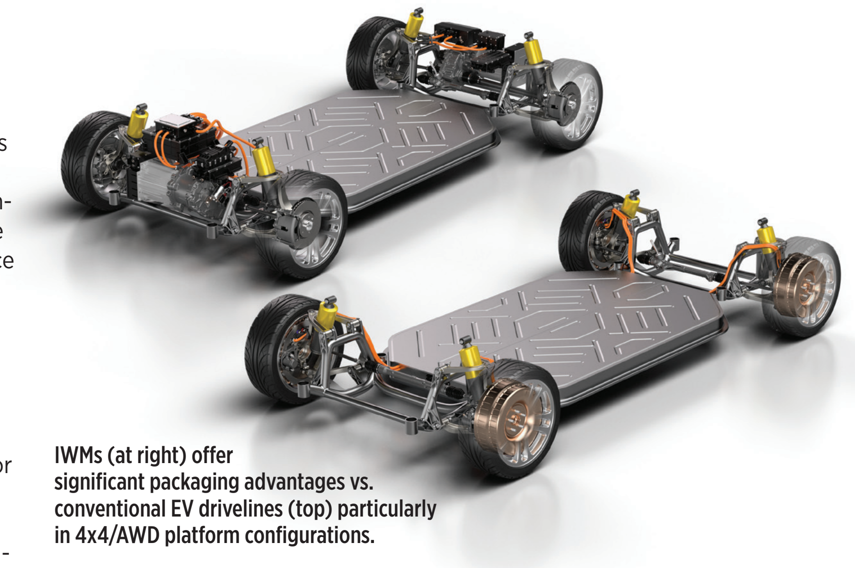
Some possible E-AWD architectures.

from this testing have been used to improve durability by ensuring adequate water sealing (and electrical isolation) and corrosion resistance.

Protection from road debris is also critical for the otherwise exposed high-power cabling and cooling lines. Liquid cooling is required to protect the IWM from excessive heating that is exacerbated by proximity to radiant brake-rotor heat in worst-case conditions (e.g., no regenerative braking, extreme hot weather, motors caked with mud). In terms of electrical safety, failure of one IWM must trigger a shutdown within milliseconds of the other side's motor to prevent adverse torque steer; loss of overall power could result in reduced speed, but this may only be noticeable under high-load conditions. Although IWMs provide new challenges for vehicle integration, there has been sufficient design, development and testing over the last 20 years to provide a solid basis for their consideration for vehicle production.

Beyond technical concerns, IWM adoption has been hindered by several other factors. For example, EVs are only now approaching cost-competitiveness with ICE-powered vehicles, so there has been little incentive to

FROM TOP LEFT: ELAPHE; LORDSTOWN MOTORS; CHRIS BORRONI-BIRD explore IWM. Even as EVs become fiscally attractive, however, the separate powertrain, chassis, safety and design silos of most product-development organizations make it harder to champion a technology such as IWM that offers benefits across the vehicle. For example, IWM costs likely are higher than for a more conventional electric propulsion system, but at the vehicle level, the cost of IWM may be attractive. However, since the choice of propulsion system typically is made by powertrain-development organizations, a comprehensive vehicle-level analysis may not be considered.



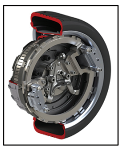
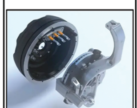
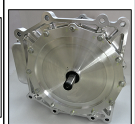
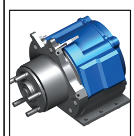
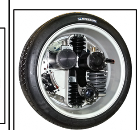
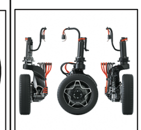
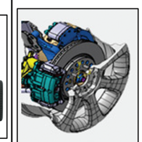
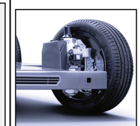
IWMs (at right) offer significant packaging advantages vs. conventional EV drivelines (top) particularly in 4x4/AWD platform configurations.

PROTEAN ELECTRIC

Near- and long-term advantages

Perhaps the best near-term automotive application for IWM is the full-size SUV or pickup truck segment, where low end torque is desirable and expectations for ride comfort, handling and speed are less demanding than for cars. Lordstown Motors is electrifying each corner of its Endurance electric pickup truck with Elaphe-designed IWMs, making it potentially the first commercialization of IWM in an automotive application – *if* the vehicle launches as planned in late 2021.

There are different ways to enable AWD for this platform. IWMs add motor mass to the vehicle and need additional HV cabling and multiple inverters (compared to a single- or dual-motor configuration offering AWD) as well as vehicle structure stiffening to compensate for greater shock loads. However, because the mass of parts not required by IWM (transmission, driveshaft, transfer

In-wheel motor suppliers		Electric motor suppliers		Driveline supplier	Bearings supplier	Tire supplier	Auto components supplier		Skateboard developer
Protean	**Elaphe**	**Nidec**	**Dana TM4**	**Neapco**	**NTN**	**Michelin**	**Schaeffler**	**Hyundai Mobis**	**REE**
									
• UK-based (Chinese-owned) • Supplier to Local Motors "Olli" AV shuttle	• Slovenia-based • Supplier to Lordstown Endurance • Aiming to be 1st production passenger vehicle with IWM	• 2023 production announced • 100 kW • 32 kg (20-in wheel)	• Joint Venture between Dana Inc. & Hydro-Quebec • Supplier of wheel motors (dual motor e-axle) for buses in China	• Under development • High torque demand • Can support smaller wheel diameters	• 30 kW, with parallel axial gear reducer • Can be used with existing steering & suspension • Air-cooled • Fits inside 17-in wheels	• 30-kW "active wheel" • 7 kg • Current status unclear	• Under development • Concepts include IWM, corner module & even skateboard / vehicle concepts	• Under development • Concepts include separate IWM corner modules for front & rear wheels	• Israel-based startup • Developing skateboard chassis with in-board wheelmotor corner modules • Aim to scale across passenger/ commercial vehicles

The number of IWM developers and their technology solutions in the global mobility industry is expanding.

INDUSTRY SOURCES

case, differential, rear axle, half shafts) can exceed 250 kg (551 lb.) the resulting mass balance can be favorable for IWM versus alternative e-AWD configurations.

The mass comparison becomes even more favorable for IWMs if their higher efficiency is considered. By eliminating the transmission, a direct-drive IWM can be a few percent more efficient under typical driving conditions. This can translate either into longer range or using a ~20 kg (~44 lb.) lighter battery for the same range. For low-speed urban vehicles, high IWM efficiency and distributed power at each corner could lead to a lighter, air-cooling solution.

Similar analysis needs to happen for cost at the vehicle level. Although four IWMs and associated power electronics will cost more than one- or two-motor solutions, at the vehicle level, the overall cost equation can be favorable for IWMs if elimination of drivetrain components and reduced battery energy requirements are considered.

For the customer, more obvious benefits of IWM may be in vehicle dynamics performance and vehicle design features. Compared with the 200-300ms needed for spooling up air intake, engine and driveline components, IWM can apply torque near-instantaneously and more precisely so that there is less pitch during braking and less roll when cornering. Eliminating the front center-mounted traction motor can provide a larger "frunk" (front trunk). Eliminating the rear axle offers the potential to lower the pickup bed or SUV trunk floor for easier loading/unloading; a loading area comprising the entire length of the vehicle also is possible. The absence of incompressible motor hardware in the load path can be exploited to manage impact forces into the structure and potentially improve passive safety.

Several future mobility trends are favorable to IWMs. Increased fleet ownership for shared vehicles and goods delivery will drive decisions based on lifecycle costs; elimination of gearboxes and driveshafts could improve reliability for IWM-driven vehicles. Urban mobility, where a greater portion of the world's vehicle-miles traveled (VMT) are generated, will place more importance on vehicle compactness: IWMs can enable shorter vehicles that still offer the same occupant and battery storage space. They can also enable relevant urban performance, even offering 90-degree articulation, to greatly enhance parkability.

For robotaxi operators that need to maintain and store vehicles overnight, enhanced parkability converts into lower real estate costs (often in expensive cities), as well as faster passenger pickup and drop-off times, leading to more paid rides per day and increased profitability. The smoother ride quality enabled by IWMs can reduce the risk of motion sickness in autonomous vehicles and risk of freight damage for delivery vehicles. A lower load floor not only improves loading/unloading but can improve entry/egress for an increasingly aging population and for wheelchair users. Car-free centers, being proposed by several European cities, could stimulate new door systems, such as front entry with the requirement for a low step-in height and floor.

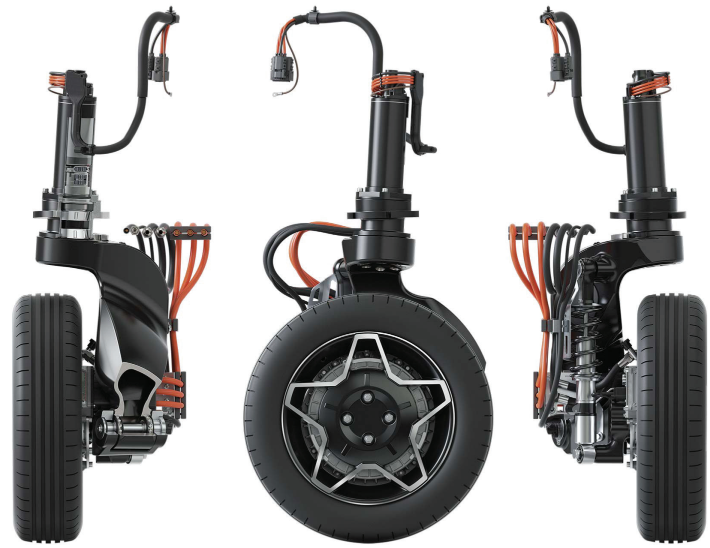
IWMs are being developed by a variety of companies (table above). The growing roster includes "pure play" IWM developers, like Protean and Elaphe, who have been refining their designs for more than a decade, as well as several automotive suppliers. Some have made production announcements and demonstrated IWM vehicle concepts, as they are seeing IWM as a natural extension to their current business. In addition, startup EV "skateboard" developers are integrating wheel motor corner modules into what they believe is the best "ground-up" EV platform solution. More technology developments and business announcements can be expected in the near future.

Reinventing vehicle development

IWMs will not only shape the form and function of future vehicles. As with the skateboard architecture, they will influence how automakers develop a product portfolio and how vehicles will be manufactured and serviced. Tier 1 supplier Schaeffler has envisioned an entire IWM-driven vehicle portfolio.

Independent corner modules that integrate braking, steering, suspension and propulsion with the wheel and tire assembly can make it easier to develop a wider variety of vehicles off the same architecture, because it becomes easier to change both track and wheelbase. It can also lead to a "plug-and-play" philosophy where the entire module is "bolted on" to the skateboard on the assembly line and quickly swapped out when repairs are needed. It is conceivable that a scalable module (with customization of power and torque) could support the entire vehicle portfolio, especially as software will increasingly be a primary method for vehicle differentiation.

Continuous improvement in power electronics, sealing, bearings and torque density have brought the IWM close to production-ready status. When combined with the future trends in mobility, the future looks promising for IWMs to revolutionize vehicle design, development, manufacturing and servicing. ■



SCHAEFFLER GROUP

Three views of a Schaeffler Group IWM corner module incorporating the supplier's e-motor and control technologies, and FAG bearings.

Dr. Chris Borroni-Bird is co-author of *Reinventing the Automobile: Personal Urban Mobility for the 21st Century*, with Dr. Larry Burns and the late Prof. Bill Mitchell (MIT Press, 2010). He has led advanced automotive-related activities at Chrysler, GM, Qualcomm and Waymo including the development of several IWM concepts at GM, including the 2002 Autonomy (the first "skateboard" concept) and the 2010 EN-V. He holds 50 patents and is the founder of Afreecar LLC (afreecar.org), where he consults on future mobility and has created a novel e-kit solution for the developing world.