WORDS: **JOHN THORNTON**

For the past decade, in-wheel electric motors have been widely touted as the alternative propulsion system for future powertrains, but with the adoption of battery electric vehicles and the rebirth of hydrogen fuel cells, *E&H* examines whether this conceptual technology will ever make it to the fore

Depending on who is asked the question, the use of in-wheel electric motors as a production-ready propulsion system in future electric and hybrid passenger cars is either just around corner, five years away, or simply too technologically flawed to make it past the testing lab.

There's no denying that the technology promises much – and most agree with that statement – but whether in-wheel motors (also referred to by some as hub motors) will ever make an impact on production vehicles is a question that really divides opinion in all quarters of the automotive industry.

The list of manufacturers working on the technology reads nearly as long as the amount of time being taken to develop it, with the likes of TM4, Schaeffler, Protean Electric, Siemens, Michelin and several Japanese suppliers and OEMs, including Mitsubishi and Sim-Drive, privately cultivating their own products and tech demonstrators for at least the past decade.

# Circular precision

The Honda Air concept vehicle was created as part of the design challenge at the LA Auto Show. It shows how a vehicle with hub motor technology could look like in the future

And each organization is quick to extol the virtues of in-wheel motors – especially versus IC engines – regarding power and efficiency gains, improved packaging options and environmental friendliness.

"A permanent magnet motor can be placed anywhere in a vehicle, and if the design is correct it will always provide around 97% or 98% mechanical power efficiency, while IC engines achieve only around 30%," states Christian Pronovost, senior product manager at TM4, a Canadian company that has invested over 20 years in optimizing the technology. "With a typical in-board electric motor on the market today – in a Nissan Leaf, for example – the motor goes through a gearbox and then a differential before getting to the wheel. As much as 8% efficiency can be lost when power passes through all those components. With in-wheel electric motors directly connected to the wheel, the 98% efficiency is going right to the wheel, with no loss. You can't get better than that."

### Slow burner

As impressive as that sounds, the technology has so far only been deployed in a raft of demonstrator/concept cars, and been put into production only in certain applications, such as bicycles and buses. Subsequently, a perceived slowness-to-market of the technology has led to a growing number of critical voices casting doubts over the reliability, safety and durability of in-wheel motors, as well as concerns regarding the detrimental effects of increased unsprung mass on vehicle performance dynamics.

So what exactly is taking so long and when can the market expect to see production-ready in-wheel motors?

According to Dave Greenwood, head of hybrid and electric systems at automotive engineering consultancy Ricardo, the hold-up stems from technological immaturity. "The penetration of electric vehicles is generally still quite low, and hub motors aren't necessarily the easiest form to create," he says. "Typically, organizations that have moved to market with electric vehicles have tended to do so with a single-traction motor because they tend to be lower cost and lower risk. There are also challenges in physically packing a motor inside a wheel along with a good-quality braking system and a good-quality suspension system, as well as having a vehicle with good performance and good ride characteristics at the end of that."

For OEMs specializing in developing high-performance vehicles, such as McLaren Automotive, cost and lack of testing with high


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1. Protean Electric's production-version of its in-wheel electric drive system debuted this year in a Mercedes Brabus sedan

2. The 2008 Protean Ford F-150 all electric pickup truck used four in-wheel motors, offering 454ps combined power

3. Rear view of the Protean drive in-wheel motor with a mechanical braking system

specific outputs mean they're not jumping to install in-wheel motors in their vehicles anytime soon. "It's definitely a technology for the future, in terms of the architecture it brings to the car. But for us at the moment, the penalties outweigh the advantages," says Mark Vinnels, program director for new vehicle projects at McLaren Automotive. "At the price point for which we operate, cost is still an important factor. And so, although we can probably – in terms of the technologies that are appropriate for our cars – push the commercial aspect of some of the components, at the moment the overall costs are still relatively high. Also, some of the questions we've asked of the technology, particularly in relation to the durability of bearings and brushes, is something that we would need to have more confidence in before

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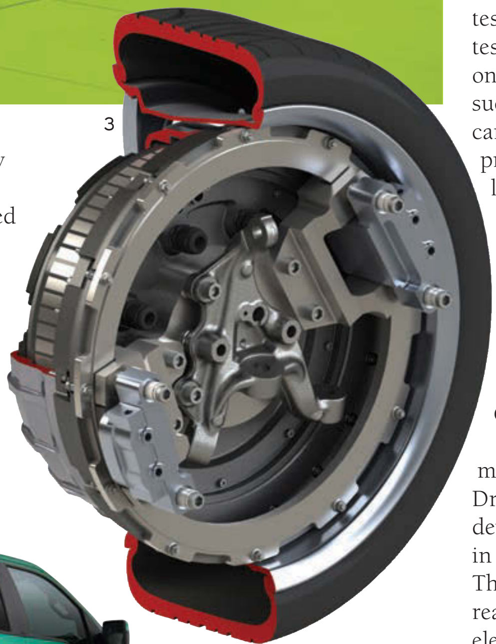

making in-wheel motors a fundamental part of any development program we begin."

With that in mind, it has become widely accepted that electric derivatives of bicycles and buses are easier to equip with a similar technology due to both types of applications enjoying better economies of scale. Compared with cars, bicycle wheel motors are low-tech, low power, have fewer safety implications, and are therefore more cost-effective to develop. Buses, meanwhile, tend to be manufactured in relatively smaller volumes per year than cars and are used in more controlled cycles by operators. Critically, buses aren't sold to the general public, and because of that, the depth of engineering required to validate the product isn't quite as much as that needed on a passenger car.

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### Driving force

One company that appears to be on the threshold of possibly changing this perception is Protean Electric. At Auto Shanghai 2013, the Michigan-headquartered company unveiled the production-version of its latest in-wheel electric drive system. Used as part of a hybrid powertrain system housed in a Mercedes Brabus sedan, the two rear-wheel motors are paired with a traditional IC engine and each offer 101ps peak power and 1,000Nm peak torque – representing a 25% increase in total torque compared with the previous generation's design. Weighing in at 31kg each, Protean claims the motors can improve fuel economy by up to 30% in hybrid configurations, compared with the existing vehicle, and depending on battery size. The company says the drive system also offers superior regenerative braking capabilities that allow up to 85% of the available kinetic energy to be recovered during braking.

"We are at the end of our concept validation phase and are about to go into design verification," reveals Andrew Whitehead, Protean Electric's director of strategic alliances. "We've carried out a multitude of testing, from subsystem tests to motor bench testing and motor unit testing, and also on-road vehicle testing at proving grounds such as Millbrook and Idiada. We're also carrying out an accelerated vehicle life testing process, where a multitude of surfaces and load conditions are used. The next step is to start putting it into tooled-up production toward the end of this year.

"So, no, I don't think 'immature' is the right word. Is the technology as mature as centralized drive systems on the market today? No, it's not, but is any electric and hybrid technology as mature as IC engines? Clearly, the answer is 'no'."

Slightly behind Protean in terms of market readiness is Schaeffler's E-Wheel Drive system. Now in its beta stage of development, the technology was presented in a new concept Ford Fiesta earlier this year. The compact vehicle is driven by two rear-wheel motors that house not only the electric motor but also the power electronics, controller, brake and cooling system. The wheel hubs provide an output of 111ps per drive, with a continuous output of 91ps, and deliver torque of up to 700Nm.

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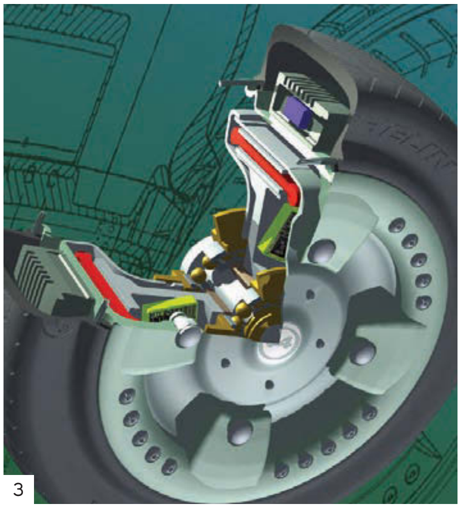

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Dr Raphael Fischer, director of the wheel hub drives product group in Schaeffler's e-mobility systems division, claims that with a weight of 53kg per wheel motor they were able to reduce vehicle weight thanks to integrating the components and thus omitting much complex wiring.

However, quantifying exactly how much vehicle weight electric in-wheel motors can save isn't so cut and dried. "You've got to look at it from a whole vehicle point of view," explains Phil Barker, chief engineer of hybrid and electric vehicles at Lotus Engineering. "If you're putting wheel motors in, then that suggests it's got to have an onboard electrical storage system of some sort, such as a battery – and a battery's going to be heavy. So, if you take out a conventional powertrain, which weighs around 200kg, maybe more, and replace it with a couple of in-wheel motors that weight around 30kg each, then you could say you're saving some number of kilograms, but what about the battery you're also adding in? The weight is probably going to go up."

### Weight matters

Greenwood at Ricardo concurs: "The issue isn't with the weight of the motors, it's the weight of the batteries. The challenge with electric vehicles is to package sufficient batteries to give an acceptable range, thus the mass of the battery is relatively high. The weight of four in-wheel motors compared with a single traction motor is probably slightly higher, but not dramatically so. But that's almost irrelevant in the context that there are going to be several hundred kilos of batteries on board the vehicle to enable it to have an acceptable range."

Another weighting issue, which has become something of an albatross for in-wheel motor manufacturers, is the

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1. The E-Wheel Drive wheel hub is small enough to fit inside a standard wheel rim

2. The concept Fiesta has undergone extensive winter testing in Scandinavia

3. TM4 began development of its 4-wheel motor system and control software in 1991

4. TM4 supplied four electric wheel motors to the Peugeot Quark quad-bike in 2004


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unsprung mass of the wheel. While there is no disputing that the weight of a wheel increases once a motor is added to it, the consequences of doing so are hotly contested. "If you increase the weight of the wheel too much, the wheel won't drop into the contours of the road as fast as it would do usually, meaning some traction is lost," states TM4's Pronovost. "You'll also lose grip when accelerating or cornering. If you're cornering on a bumpy road, the higher the weight of the wheel, the more the vehicle will skid on the sides. So, the main drawback is losing the patch to the ground."

However, the results of a six-month study into the dynamic implications and opportunities of an unsprung-mounted drivetrain, conducted by Lotus Engineering, Protean Electric and Dunamos in 2010, challenge such assertions. A 2007 1.6-liter Ford Focus was evaluated for ride, handling and performance around corners and over bumps. The vehicle was then modified with

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The 2006 Honda FCX has three electric motors: one front-drive motor with an output of up to 108ps, and two smaller motors with a maximum output of 34ps driving each of the rear wheels

added static and rotational mass to the front and the rear – to simulate the added weight of the wheel motors – and retested. According to Protean Electric and Lotus Engineering, there was a difference, but that difference was minimal and could be recovered with traditional ride and handling techniques.

"The myth surrounding the issue of unsprung mass is a pure misconception," states Barker. "There were some downsides to the vehicle dynamics behavior, but you'd have to be a specialist in vehicle dynamics to notice them. The average man in the street wouldn't notice the difference at all."

In fact, Whitehead even goes so far as to compare the effects of unsprung mass on the tested Focus to "a car in the middle of a development process, as opposed to a car that was undriveable or a car that needed new suspension geometry". The Protean Electric director suggests that "there are actually probably more benefits to using in-wheel motors in terms of ride and handling" once advancements such as torque vectoring are taken into account.

Ford has also undertaken testing in this area with the Fiesta E-Wheel Drive development vehicle. Roger Graaf, Ford Europe's project manager for research and advanced engineering, claims, "Test drives have clearly shown that the driving behavior of this test vehicle in terms of comfort and safety has remained at virtually the same level, despite the higher wheel-sprung masses compared with the conventional basic vehicle."

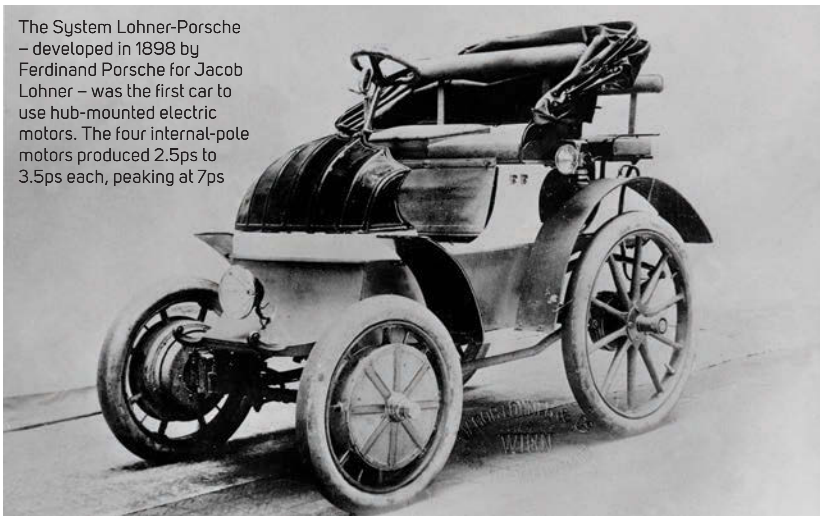
## Applying the brake

However, while the ability to independently control the amount of torque at each wheel can improve the maneuverability, driving dynamics and active safety of the vehicle, the lack of friction braking associated with in-wheel motors continues to leave some within the industry skeptical. Jon Hilton, co-owner and co-founding director of Flybrid Automotive, is a staunch critic of in-wheel motors. "I can't see the technology taking off, to be honest. I've seen people offer wheel motors in packages that appear not to have friction brakes, which I don't know how you'll get past the DFMEA [design failure mode and effects analysis]. The brake itself is very hot, and magnets in motors can't stand very high temperatures – 180°C will kill most magnets. You'd be better off with a pancake style motor, mounted on the inboard end of the driveshaft by the differential. Or back-to-back pancake motors with no diff."

Likewise, Barker believes supporters of the technology will fall short on a regulatory and technical basis. "Current braking regulations do not allow completely non-friction braking systems, and regulations take time to catch up with technology," he says. "To change the actual regulations is probably a three-year process. There's a customer expectation as to how quickly the vehicle can slow down, and regenerative braking simply cannot move the energy around quickly enough. We're talking about megajoules of energy in a 1g deceleration. A standard vehicle decelerating from 1g at 100mph [160km/h] has to get rid of 1.8 megajoules of energy, and 75% of that is at the front wheels because of the weight transference. So it might be possible not to have friction braking from the rear axle, but certainly with current and near-term technology you'll still need friction braking on the front."

Despite such drawbacks, a huge perceived benefit of all electric motors, including in-wheel variants, is the environmental gains that the technology realizes, but even this issue is being debated. While vehicles that run on an EU-average electricity mix will show somewhere between 20% and 30% net $CO_2$ benefits over IC vehicles, the way in which the electricity itself is sourced ultimately determines how green the technology truly is. "If we can get to a point where the electricity we use is genuinely zero carbon, then clearly our form of transport becomes zero carbon," says Greenwood. And while Pronovost cites that 90% of Canada's electricity is sourced from clean hydroelectricity, Barker says that in the UK, "the tailpipe equivalent grams per kilometer of $CO_2$ for a pure EV is around 70-80g just because electricity is generated in a dirty way. In France it's far less because a lot of their electricity generation is nuclear. So, you can't just say that a pure EV emits fewer emissions than a combustion vehicle – you've got to look at the bigger picture."

So, it would seem in-wheel electric motor technology still has much to prove, not only to OEMs potentially interested in adopting it, but also to the suppliers developing the technology. What's certain, however, is that in-wheel motors will one day become a legitimate method of propulsion in light passenger vehicles. When that day will arrive is yet to be determined.



The System Lohner-Porsche – developed in 1898 by Ferdinand Porsche for Jacob Lohner – was the first car to use hub-mounted electric motors. The four internal-pole motors produced 2.5ps to 3.5ps each, peaking at 7ps