

Integrating In-Wheel Motors into Vehicles - Real-World Experiences

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ABSTRACT

Compact direct drive in-wheel motors with integrated inverters, control and brakes offer a number of distinct advantages compared to conventional electric drive systems. The most obvious being that the drive-train is now packaged within the wheel freeing up space elsewhere, in addition many driveline components and their associated losses are eliminated and the vehicle efficiency, response and handling can be improved. In new vehicle applications this allows complete freedom for designers to optimize the vehicle layout, have more usable space inside the vehicle body and enables revolutionary vehicle concepts (which will become more important as road space becomes scarce and taxation measures migrate towards vehicle size). In retrofit applications the compact package allows an electric drive to be added to any existing vehicle without requiring any significant disruption to the vehicle platform to keep integration costs down. This represents an opportunity for OEM's to hybridize their existing vehicle portfolio in order to address more stringent fleet-average emissions legislation.

Protean has retrofitted its Protean Drive™ in-wheel motors to a variety of different vehicles in both pure EV and hybrid configurations and has collated its findings over three years of track and road testing. This paper will distil the practical experience gained from these vehicle programs and illustrate some of the challenges and solutions associated with in-wheel motor integration. In doing so the paper deals with many of the key vehicle level topics, such as the CAN interface, vehicle control strategy, and brake integration.

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INTRODUCTION

In-wheel motors offer a way to revolutionize the automotive industry through a technology that can add electric drive to any conventional vehicle, without affecting the existing drive-train thereby maximizing design reuse. In order to achieve this, several practical hurdles have to be overcome regarding the integration of these motors. Protean's real-world experience gained over a wide variety of vehicle retrofit programs illustrates some of these challenges and gives practical examples of the measures taken to overcome them. Examples cited will include a sub-compact 3-door C segment vehicle, a mid-size luxury car and a full size pick-up truck in pure electric format, plus a mid-size commercial van and a luxury 4-door sedan in a parallel hybrid configuration.

When an in-wheel motor is referred to in this document it is assumed to be one having the optimum characteristics of being of a direct drive design with the power electronics

mounted inside the motors themselves. An example of this type of motor is the Protean Drive™ from Protean Electric.

The braking, control and high voltage systems are treated in detail and the issue of added unsprung mass is discussed. Functional safety is treated in the context of the ISO 26262 standard. Finally the in-wheel motor requirements, particularly relating to torque and packaging, are explained with reference to specific vehicles.

The paper is organized as follows:

1. Brake Integration

1.1. Do We Need Brakes?

1.2. Do We Have to Change the Brakes?

1.3. Diameter is Key

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1. BRAKE INTEGRATION

The Protean in-wheel motor concept occupies a package volume in the wheel which was previously occupied by the friction braking components of the vehicle. On a little closer inspection and calculation it is also clear that the Protean in-wheel motor, although a highly capable regenerative braking actuator, is not sized to produce the high levels of brake torque and power that is required during an emergency stop, particularly on the front wheels of a vehicle.

It is clear then that the friction brake that previously resided in the wheel has been displaced and needs to be repackaged as part of a Protean motor retrofit. Understandably this is one of the very first conversation topics that emerges during discussions with customers and partners when a new vehicle is being discussed. Protean has been working with an expert braking partner, Alcon Components Ltd, to develop a suitable braking concept for the sole purpose of braking a vehicle with Protean motors and the performance of this highly integrated set-up is proving very successful in initial dynamometer and field trials.

The decision to displace the brakes is evidently a bold move, however this part of the paper sets out to explain why, when considering both a motor and brake in the context of

the package inside a standard car wheel, it no longer makes sense to package the brake in the normally accepted manner. It goes on to explain how the packaging of the brake system works with the general design philosophy of the Protean motor and allows a highly effective retrofit solution which has recently been implemented on the Brabus/Protean E-class vehicle.

1.1. DO WE NEED BRAKES?

Safety and regulatory concerns aside, an understanding of the different vehicle performance requirements for motoring and braking highlights why the brakes cannot be deleted entirely with the current technology. Take for example a relatively light passenger vehicle of 1500kg. It is quickly shown that the torque and power requirements are much greater for braking than for motoring.

- Torque
 - Pull-away torque for 30% grade $\approx 1300\text{Nm}$ (Whole vehicle)
 - Maintaining 100mph at 6% grade $\approx 600\text{Nm}$ (Whole vehicle)
 - 1g braking $\approx 5000\text{Nm}$ (Whole vehicle)
- Power
 - Maintaining 100mph at 6% grade = 80kW
 - Braking power required to decelerate at 1g at 100mph = 700kW

Fundamentally the reason for this difference is that the vehicle is required to be able to perform an emergency stop from all speeds during normal operation, but forward tractive forces do not need to be anywhere near as large as braking forces in order to provide credible or even sporty vehicle performance. The most powerful actuator in any vehicle is not the power-train, it is the brakes.

If the motor were designed to be able to create the levels of retarding torque required in braking then it would need to produce around three times more wheel torque than if it were sized for even sporty forward performance. For an in-wheel motor that potentially means three times heavier, three times bigger and higher cost. Being able to produce this torque at speed while meeting the braking power requirements has large implications on the electronic and electromagnetic design which, although outside the scope of this section, would require large design compromises. The negative effects of unsprung mass will be quite obvious at this point (see section 3) and there is no practical way to retrofit such a large motor to an existing vehicle platform.

And there are other significant constraints - firstly the energy the motor is generating needs to be dissipated somewhere. This will either require a much higher performance battery or other energy storage/dissipation devices which will add to the vehicle cost. There is also the safety aspect of the motor control: a single-point failure may

result in an unacceptably large torque disturbance unless the motor is sub-divided into many independent modules.

From Figure 1 it can be seen that, in addition to the above design difficulties, an emergency stop is very rarely conducted and so the capability of a motor sized for full braking performance would be very rarely used.

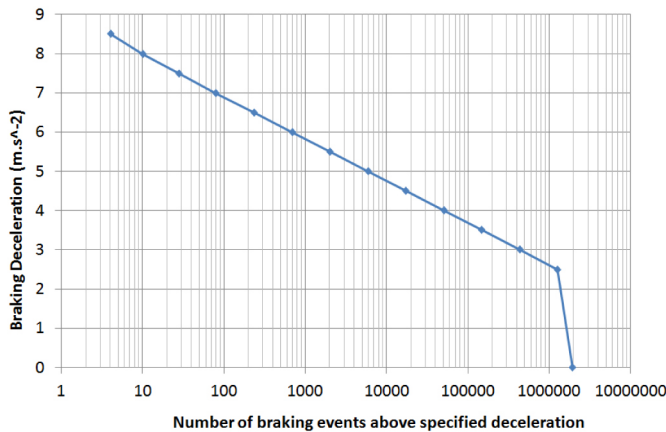


Figure 1. Typical braking utilisation curve.

In conclusion, when considering vehicle braking requirements, friction brakes are fundamentally better actuators in terms of volume and mass specific torque and power than an in-wheel motor. Also given that maximum braking force is so rarely used, other than in an emergency, it makes little sense to size the motor to deliver such a maximum. Therefore, even cars with in-wheel motors need friction brakes (at least on the front axle - see section 1.5). Inevitably it will almost always be more feasible to size the motor for forward performance and use a friction brake to “top up” the braking torque required. As can be seen from Figure 1, the overwhelming majority of braking events are below 0.3g which in-wheel motors can generally cover with regenerative braking quite readily.

1.2. DO WE HAVE TO CHANGE THE BRAKES?

Given that friction brakes must remain, vehicle manufacturers would consider it desirable to leave the brakes alone and package the motor in a location where braking changes are not necessary or at least re-use braking components during the retrofit. In targeting the retrofit market, consideration must be given to the structural modifications required to the vehicle in order to integrate the motor. To reduce the risks and re-validation resulting from the retrofit it was decided that minimum modification should be required to the suspension of the vehicle. With the suspension design as a given, and with a large variety of suspension architectures, there becomes only limited places that an in-wheel motor can be packaged. Without changing the braking components, the track width of the vehicle would be unacceptable when an in-wheel motor is fitted, see Figure 2 below.

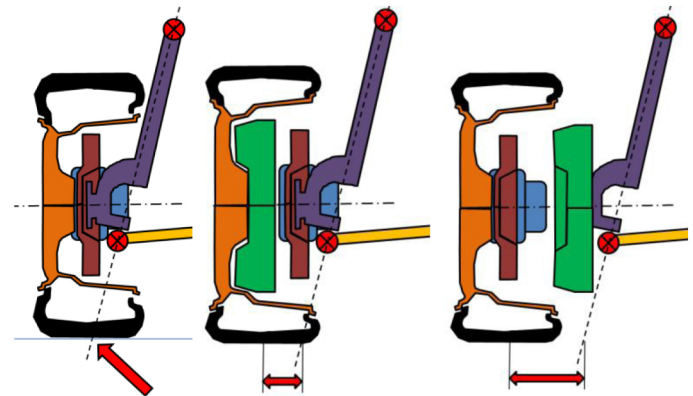


Figure 2. Options for packaging an in-wheel motor with a standard disc brake.

Besides the detrimental effect that the increased track has on ride and handling, how one physically connects the various rotating and static parts together in a reliable and structurally sound manner is not straightforward. Consequently, the vehicle's original brakes must be replaced during the in-wheel motor integration in order to preserve the track width and structural integrity of the suspension system.

1.3. DIAMETER IS KEY

As the Protean motor is direct drive, best mass specific torque (and therefore power) is achieved with a larger radius machine. Both machine continuous and peak torque are largely proportional to the product of the machine axial length and square of the machine diameter, commonly denoted $D^2.l$. This provides maximum cross sectional printed circuit board area and cooling potential for the internal inverters. Therefore the motor was designed to fit inside an 18 inch wheel, the largest wheel most commonly used across the target vehicle platforms (see section 6 for more information on the market requirements). Using the largest wheel available on a given platform maximizes the space available to integrate an effective braking system.

For example, the recent Protean/Brabus E-Class prototype vehicles, the Mercedes W212 E-class platform, can be purchased with a range of wheels from 16" to 19" as standard factory options. Of course, the standard vehicle suspension must fit inside the smallest rim as it would be impractical to offer a bespoke suspension design for each wheel size. As the larger wheels patently have a greater internal volume, and the smaller wheels will see most of their useable volume occupied by suspension components (a point particularly prevalent on complex 5-link and virtual pivot suspension such as that the E-class employs), the largest size wheel available on that platform is used for the in-wheel motor retro-fit. With the previous brake volume now occupied by the in-wheel motor, the extra diameter leaves a clear toroidal volume, located around the suspension links, and inboard of the motor position, which is freely available space that has guaranteed clearance through all suspension articulation

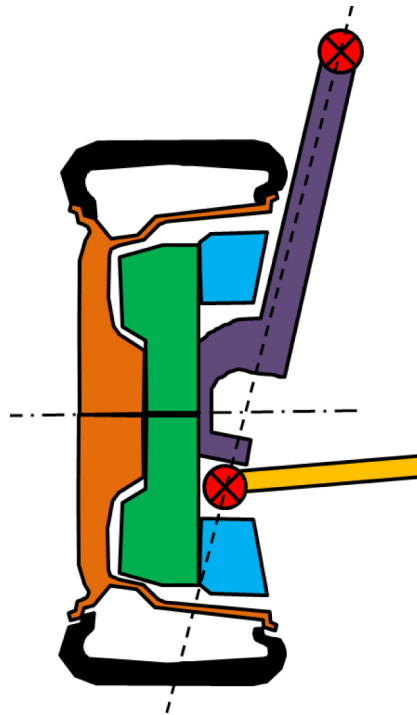


Figure 3. Toroidal volume available for rotating brake hardware in blue

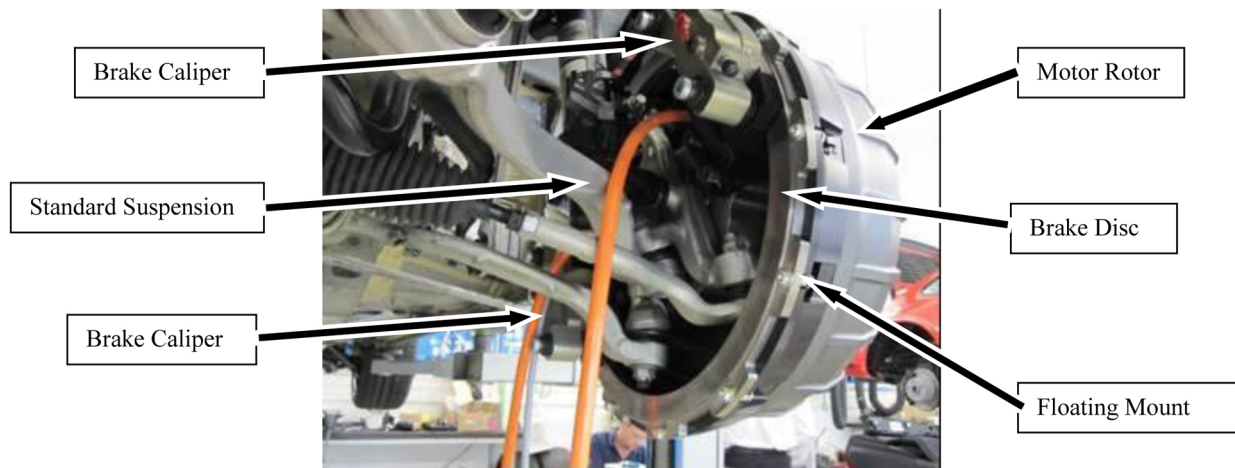


Figure 4. Left front motor and brake assembly

positions. See [Figure 3](#) for clarity on the location of this volume and how this enables the track width of the vehicle to be maintained

1.4. THE BRAKES IN DETAIL

[Figure 4](#) and [Figure 5](#) show the front braking system as fitted to the Mercedes E class front axle.

The system is based around an inside-out disc with twin piston sliding hydraulic calipers. The actual principle of operation is, in practical terms, identical to a normal vehicle brake and most of the critical parts used in the design are standard disc brake components that are well understood and

have been fitted into custom housings. The idea of an inside-out disc is not new and has been seen on production vehicles before, but prior to in-wheel motors there were very few good reasons to depart from the incumbent standard of vehicle brakes, as they make sense when there is no drive-train in the wheel along with them!

Besides the inside out disc, one of the obvious differences in the system to a standard car setup is the use of the twin calipers. The reason for the twin calipers is twofold. The first reason is that, in order to package the brakes in the given radial depth, the rubbing path of the brake disc is, compared to the OEM disc, quite small. To obtain the required pad area,

instead of trying to manufacture one long, thin pad, and actuating with a single four-piston hydraulic caliper, two dual piston calipers each actuate smaller pads. This gives a much better packaging proposition and de-risks the design by mimicking current brake pad aspect ratios.



Figure 5. Right front motor and brake assembly with wheel

The second reason for the adoption of twin calipers is that it reduces the bending moments applied around the rotor front face during a braking event. If a single caliper were used, the force couple would constitute the tangential friction force at the pad/disc interface and a radial reaction force equal in magnitude and opposite in direction to the friction force at the wheel-bearing. The reaction of these two forces through the rotor of the in-wheel motor creates an undesirable loading condition for the in-wheel motor - acting to close the machine airgap - and a stiffer, heavier rotor is required. The twin calipers allow two friction forces, diametrically opposite from each other, to create the force couple required to brake the vehicle. This means that although the motor rotor clearly has to carry the brake torque, it does not have to bear any large bending moments or airgap-closing forces, and a lighter rotor results.

Clearly an electric motor is a heat sensitive device, and effort has expended to ensure that the disc is thermally isolated from the motor rotor. The disc is mounted using a series of "floating" bobbins. These allow the transmission of tangential forces, with a limited amount of axial freedom (fractions of a mm) at each interface. This results in the radial direction being largely unconstrained at each interface point. This technology is in wide use today on high performance brakes, because it allows the disc to expand and contract readily as a function of temperature without significant disc coning or distortion. This system also gives a very poor conductive heat transfer path into the motor rotor, whilst by virtue of the disc diameter, giving a large amount of surface

area for the disc to be convectively cooled by ambient air. See [Figure 6](#) for an image of the braking system during a disc cracking test and [Figure 7](#) for a snapshot of the thermal results over several high energy stops. In these tests the brake disc temperature was in excess of 600°C and the rotor never exceeded 80°C over several cycles, thus demonstrating the effective thermal isolation of the bobbin mounting system.

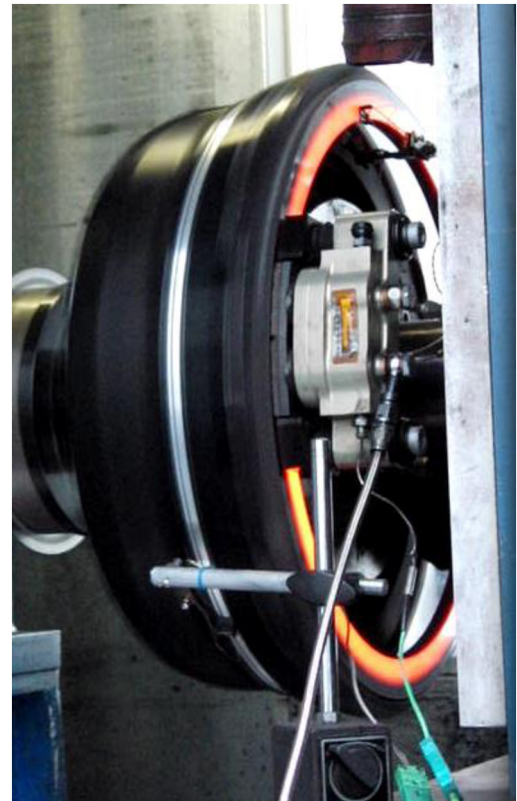


Figure 6. Rotor mounted brake concept during disc cracking test

1.5. FUTURE BRAKING OPPORTUNITIES

A major forward-looking opportunity is that Protean motor technology can be used to replace rear friction brakes entirely on many vehicles and a project on this topic with a major OEM is currently underway to validate this and show equivalent compliance to current volume regulatory standards. This ability is due to several key advantages:

- Protean PD18 braking torque capability exceeds the optimum braking torque requirements of almost all vehicles up to 2,000kg GVW and many more beyond that mass.
- The sub-motor architecture of Protean motors allows this level of total machine torque to without potentially destabilising fault torque under a single point or random failure - only a quarter of the machine can fail at any one time
- Rather than simply phasing out regenerative braking when a slip control event occurs, the motor can respond to new

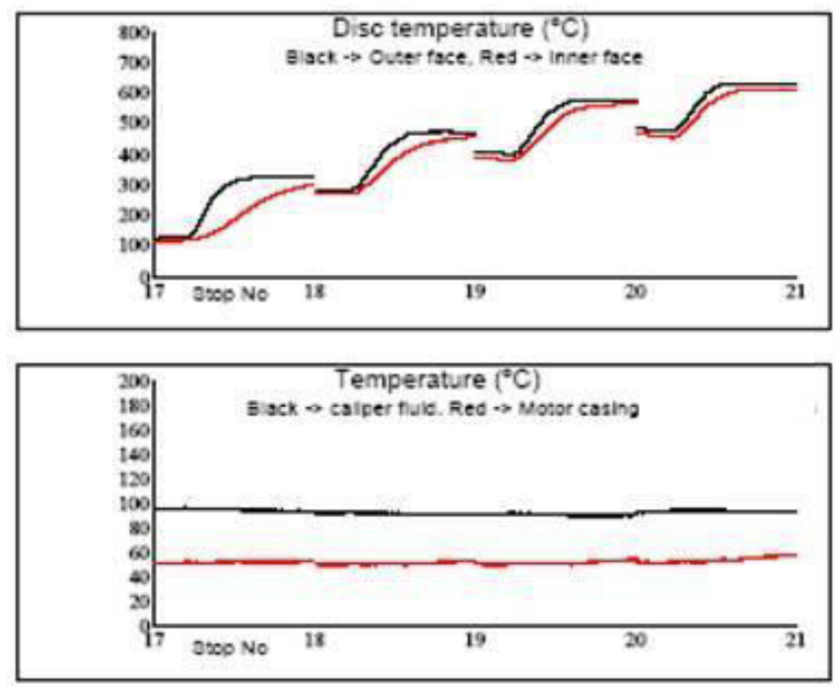


Figure 7. Disc and rotor thermal traces during a series of disc cracking tests

torque demands in both motoring and braking domains to the order of single milliseconds thus offering huge improvements to slip control algorithms.

This ability to delete the rear brakes from the vehicle bill of materials (BOM) will enable future integrations - both retrofits and new platform design - at significantly lower cost and lower mass.

brake energy sink cannot be provisioned. This brake operates on a very similar layout to that of the Brabus front brakes, but simply involves the use of one caliper not two. The brake torque requirements of rear axles are low enough to enable this solution without impacting the design of a generic rotor. CAD models of this braking arrangement are shown in [Figure 8](#) and [Figure 9](#).



Figure 8. Single caliper brake concept

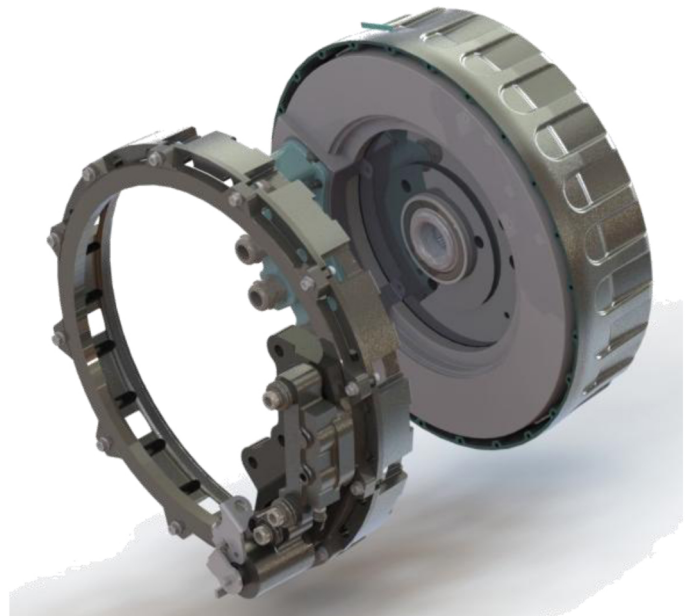


Figure 9. Single caliper brake concept

In the meantime, a “low torque” single caliper brake is in current development for those rear axle applications where road legality in volume is required, or where a guaranteed