IN-WHEEL ELECTRIC MOTORS

The Packaging and Integration Challenges

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ABSTRACT

One of the fundamental advantages of in-wheel motors is that they free up packaging space on the vehicle platform. From retrofits to new vehicle designs, the freedom to add batteries, range extenders, or simply preserve cargo and passenger space is a major competitive advantage for all styles of in-wheel motor over more conventional electrical machines.

This advantage needs to be preserved by not having to re-locate the friction brake to a position on the sprung mass of the vehicle, so both motors and brakes must be accommodated inside the wheels of a vehicle. To preserve as much of the retrofit market as possible, it must be ensured that the packaging solution inside the wheel does not require significant platform tear-up. In addition, the whole system must be safe, reliable, and provide credible vehicle performance. This has led to some radically different in-wheel motor concepts being developed by various organisations around the world.

Protean's unique solution to this packaging problem was, on the face of it, a bold one for a start-up company; displace the brake to provide space for a motor, and develop a new packaging philosophy for the unsprung assembly incorporating both brake and motor. By working with an expert partner on the braking side, this, we believe, results in a much more harmonious use of the valuable space inside the wheel than other in-wheel solutions, and meets or exceeds all the requirements outlined above.

This presentation will provide details of the process that resulted in the Protean design, as well as highlight the engineering of the solution fitted to the front axle of the high performance Protean/Brabus E-Class vehicle.

Figure 1: Unsprung assembly, Protean/Brabus E-class front-left corner.

TARGET MARKETS AND REQUIREMENTS OVERVIEW

Protean Electric is targeting both passenger vehicles and light commercials with a blank sheet electric motor design wholly dedicated to in-wheel applications. Principally, the motor must be capable of being the sole source of tractive power for an electric vehicle or series hybrid, but must also work alongside conventional internal combustion powertrains to enable parallel hybrid architectures. To keep costs down, 2WD is an absolute must on smaller vehicles and hybrids, and 4WD should lend credible performance to larger, heavier executive saloons and SUVs. The performance of these vehicles should be able to squarely address the market segment the vehicle is in with the performance, range and interior space that a demanding customer requires.

A key requirement that drives the Protean motor design is retro-fit ability. Clearly an in-wheel motor equipped powertrain opens up so many possibilities for sprung mass packaging and design changes that any vehicles that are designed from the ground-up around in-wheel motors will have their own protracted development cycles measured on the scale of several years. Balanced against this, OEMs need to remove significant amounts of carbon emissions from their entire fleet right now, and a handful of compromised niche vehicles will not achieve this. The ability to engineer a hybrid or full EV on an existing platform, with minimal tear-up of existing hardware or intrusion into passenger, storage or accident-vulnerable space cannot be underestimated and is one of the main advantages of choosing an in-wheel motor to propel a vehicle. It is therefore highly desirable for an in-wheel motor to be able to be fitted to a car without requiring any special wheel design or requiring risky suspension modifications, and this played a large part in the development of the requirements for the Protean motor.

Regardless of the general architecture and form of an in-wheel motor, the unsprung environment is a harsh one compared with the on-body requirements for a motor. The wading requirements of the vehicle mean that the motor needs to operate whilst essentially submerged, and the wheelhouse is subject to great extremes of temperature thanks to the friction brake and rejected heat from any on-body ICE powertrain. For a road vehicle the motor must survive repeated shock loads of up to 50g with continuous vibration spectra of up to 20g RMS for severe rough roads. Stones are expected to impact any exposed face of the device and the cabling to the motor must be able to survive repeated bending and articulation with suspension and steering movement at temperatures well below zero.[1]

The main challenge however will always be package space, especially with a retro-fittable design. In appreciating this, it is clear that Nm/litre and kW/litre have to be maximised. It is already well known that the best motor technology for volume specific performance is liquid-cooled brushless permanent magnet, and so early-on in the programme the decision was made to focus on this technology for the first high volume production motor that Protean is developing.

TORQUE AND POWER REQUIREMENTS

The principal purpose of the drivetrain is to deliver tractive motoring effort to the tyre-road interface. As a free bonus, an electric drivetrain has the potential to apply similar tractive effort in the braking domain and hand a sizeable chunk of the vehicle’s kinetic energy back into the battery. Safety and/or regulatory concerns aside, on first consideration it is tempting to believe that friction brakes can be replaced entirely with the electric drivetrain but a few simple calculations show the cost of such a move.

Take for example a relatively light 2WD passenger vehicle at 1500kg. Assuming a certain few key parameters it is quickly shown that the torque and power requirements are much greater in the braking domain than they are in motoring for a given wheel:

- Torque
  - Motoring - Pull-away torque for 30% grade = 650Nm (per motor)
  - Motoring - Maintaining 100mph at 6% grade =300Nm (per motor)
  - Braking - 1g braking = 1800Nm (per front wheel)
- Power
  - Motoring - Maintaining 100mph at 6% grade = 40kW (per motor)
  - Braking - Deceleration at a rate of 1g at 100mph = 250kW (per front wheel)

Fundamentally this is because the vehicle is always 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 forward vehicle performance. A universal truth of passenger vehicles is that the most powerful actuator on the vehicle is not the power-train, it is the brake system.

It is important to note that the majority of this braking effort is carried out by the front wheels. In targeting 4WD applications, and not discerning (at the requirements level) between RWD or FWD in the case of a 2WD drivetrain, Protean clearly has to cater for, or not prevent, the provision of these levels of braking power and torque in its motor design

If the motor were designed to be able to create the levels of retarding torque required in braking, it is shown by the example above that the motor would need to produce around three to four times more wheel torque and over five times more wheel power than if it were sized for even sporty forward performance. By inspecting Figure 2 below it can also be seen that, further to the above design difficulties, an emergency stop is very rarely conducted and so motors which are sized for full braking performance are very rarely of any use, and reclaim practically no extra regenerative energy than a drivetrain sized to regenerate up to 0.3g. The information displayed in Figure 2 was collated during initial developments on braking systems in conjunction with Alcon Components Ltd. Clearly, sizing the motor to meet emergency braking requirements will result in large implications for the cost, size and mass of the motor that are of little use.

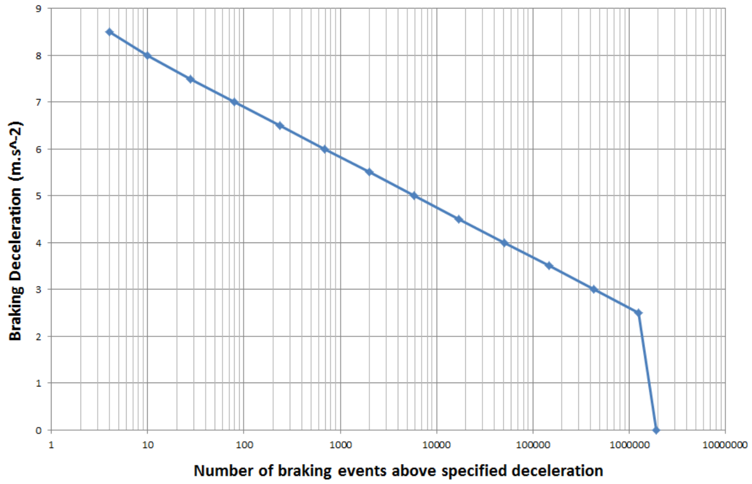

Figure 2: Brake utilisation curve for 2 million brake applications

There are also some other show-stopping constraints – you need somewhere to put this energy you are generating with your motors. This will require either a much higher performance battery or other energy storage/dissipation devices which will add to the cost of the vehicle. Managing the failure modes of such a high performance motor will require some very restrictive safety requirements to be applied at both motor and vehicle levels, further increasing cost.

The conclusion to this section is that Protean believes in-wheel motor driven cars still need friction brakes and one of the major requirements on our motor is that it is sized for forward performance only, and a friction brake is used to “top up” the braking torque when under rare demanding braking circumstances, or when the battery has restricted charge current. By making the vehicle perform adequately in the motoring domain, almost all of the available regenerative energy is captured over the majority of real-world drive cycles anyway, especially on front-drive applications where higher regenerative brake torque can be applied without stability concerns. There is optimism within Protean Electric that the present motor design will enable the safe removal of friction brakes from the rear axle in future applications, but this is not currently permissible under present road vehicle legislation.

So this leaves us to set torque and power requirements based on forward performance. When deriving torque requirements it is tempting to base the motor requirements from existing ICE-driven vehicles. This would go along the lines of matching the torque at-the-wheels of the target vehicles when in a low gear. However these low gear ratios (especially 1^{st}) are sized more around the limitations of the powertrain and clutch life – for example allowing low-speed crawling in traffic or around cark parks without having to “ride the clutch” constantly. Second or third gear would be a more realistic target, but then an electric motor torque curve is substantially different to an ICE, and the torque of an in-wheel motor can be changed on the scale of single milliseconds, as opposed to hundreds of milliseconds in the case of a suspended powertrain on driveshafts, giving a much greater “performance feel” [1] . When also considering automatic transmissions, the torque converter ratio introduces further uncertainty, and it rapidly becomes far easier and more consistent to size the torque requirement for grade-ability at GVW. Figure 3 shows the requirements for whole-vehicle torque requirements for 22% and 30% gradients over a large range of GVW values. Protean are aiming to make a single motor cover as many market segments as possible in 2WD and 4WD, so it can be seen, for example, that a motor that can propel a 1500kg car (torque-wise) in 2WD requires 500Nm continuous and 650Nm peak torque capability respectively, and this motor will also serve up to a 2500kg car in 4WD. These drivetrains will of course also propel lighter vehicles with greater performance if so wished.

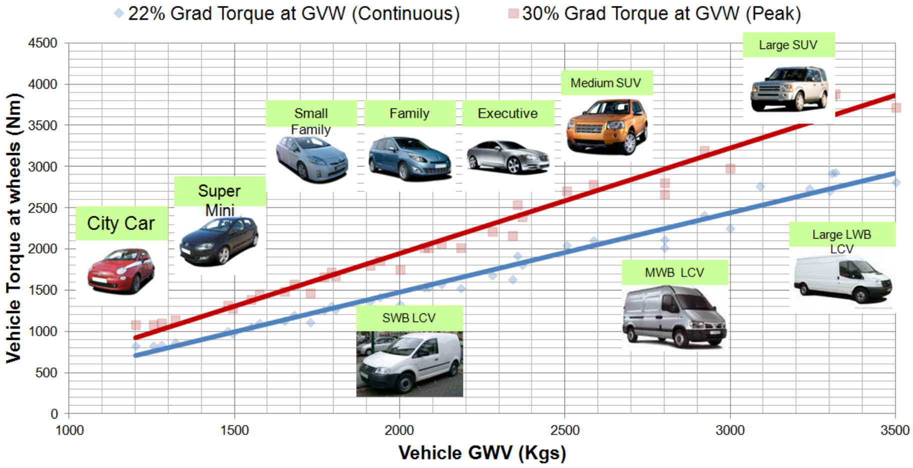

Figure 3: Vehicle GVW vs. torque requirements for 22% (continuous) and 30% (peak) grade

Power requirements for motoring a vehicle however, can easily be derived directly from the target vehicle and its original powertrain. Although naturally Protean took great care to derive requirements from first principles also, it was quickly found that the same power-at-the-wheels figure was broadly arrived at across a range of cases. The original powertrain must of course lend adequate top-speed and overtaking performance to the vehicle and these are power-limited driving scenarios. If an electric drivetrain can match this power then the performance will generally be, both subjectively and qualitatively, much better, as the motor will have a much broader power peak and much quicker dynamic responses than the outgoing ICE powertrain.
Figure 4 shows wheel power requirements for a range of vehicles up to 3500kg GVW. Using the same example of a 1500kg 2WD vehicle, this would require each motor to give 30kW continuous power performance. Again this covers up to around 2500kg in 4WD configuration so complements the torque requirements well.

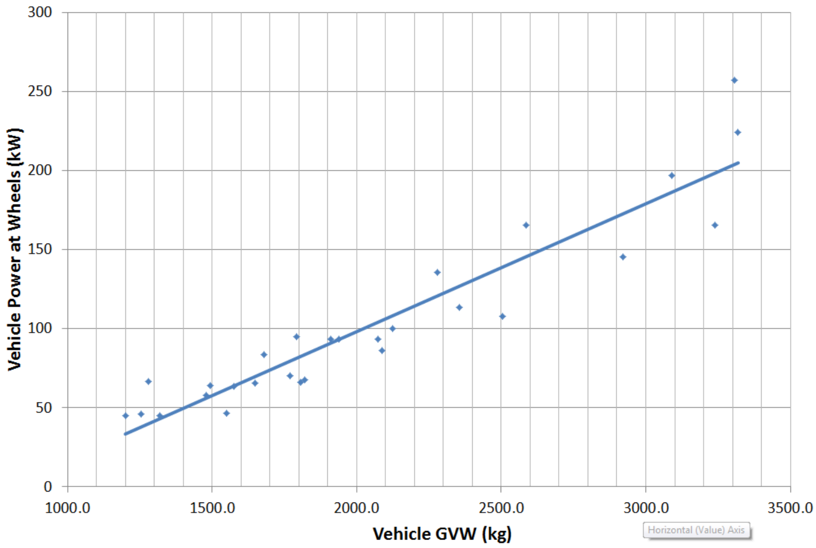

Figure 4: Vehicle GVW –vs– Power requirements as derived from standard vehicle powertrain

Now targets have been set for a range of performance requirements for the motor, the principles of the motor design and actual scalable performance characteristics of any particular motor layout must be well understood before settling on sizing for a single motor, which this paper shall now go on to describe in detail.

THE SAFETY GOALS AND REQUIREMENTS FOR AN IN-WHEEL MOTOR

Without question any vehicle drivetrain must be safe, and any drivetrain that has individually driven wheels presents a unique problem in this respect. A key safety goal for Protean's in-wheel motor design derived directly from ISO26262 [3] - "no single fault shall prevent the driver from retaining control". This safety goal, when applied to an individually electrically driven wheel, essentially boils down to a limit on the wheel torque error that the electric machine can cause through a single or random fault condition. This safety goal, along with many others, was defined through following a process defined in ISO26262, which is the de facto standard for automotive functional safety.

Any unintended single wheel torque will cause both an unintended acceleration/deceleration of the vehicle and also an unintended yaw moment and vehicle course deviation. Whatever the response of the vehicle is to this torque, the driver must be able to respond with "reasonable" inputs to the controls, with a "reasonable" reaction time, and the car must not depart from its intended course more than a "reasonable" amount. The subject of driver modelling, the reasonable limits on control inputs and vehicle responses, and other specifics of Protean's safety concept formulation are well outside the scope of this paper but are covered extensively in [4]

The single most effective way of addressing this issue for a broad range of motor faults is to use several separate motors to drive a single wheel. This requirement applies directly to the control and power electronics, and the stator electromagnetics of the machine. Note the rotor assembly and stator mechanicals are comparatively benign objects safety-wise and all sub-motors can share these components without safety concerns. Following analyses covered in [4] Protean have settled on four sub-motors, each with ¼ of the full motor performance, as being required for safe vehicle operation in its present design, although the architecture is inherently scalable for different levels of subdivision.

This means that many, normally potentially catastrophic failure modes can be mitigated locally inside the in-wheel motor, often with no net torque change at the wheel. Take, for example, a so-called "line-to-line" motor short, which would normally present a major safety concern as this would have the potential to produce a large uncontrolled braking torque in a single large permanent magnet machine. By subdividing the motor by four, not only is the fault torque quartered, but also three healthy motors remain with which to compensate for this braking torque through applying a motoring torque.

Of course some failure modes, such as a HV cable failure, cannot be mitigated by the motor and these effects must be managed at the vehicle level. What the sub-division of the motor achieves is a drastic reduction in the amount of single-point and random failures that result in net torque change at the wheel or require mitigation at the vehicle level, removing these roadblocks from widespread adoption.

The subdivision of the Protean motor is one of the key aspects of the technology and several patents have been awarded surrounding this architecture.

THE ARGUMENT FOR DIRECT DRIVE

One of the fundamental requirements Protean imposed on its in-wheel motor design from the outset was to completely remove any mechanical gearing from the motor, along with all the required bearings, lubricants and seals for such a device. This was done for several reasons:

- Reliability/Safety
  - The reliability of the motor is fundamental to its success. Simply put, there is no reliability cost to making a higher torque/lower speed motor but there is associated with the addition of gearbox components, especially considering that four separate gearboxes will be required for many vehicles.
  - A gearbox would be a single point of failure with the potential to lock a single wheel and create huge yaw moments on the vehicle with the associated safety/control issues of this. There is no vehicle level mitigation for such a failure mode without introducing a clutch in each wheel.
  - Making a high reliability motor will enable regenerative-only braking on future platform rear axles, removing cost from the vehicle BOM.
- Transient performance
  - By removing the back-lash from gears and mechanical compliance, direct drive will give the absolute best transient torque rate (torque change per unit time) and therefore control fidelity for use in slip control situations.
- Bearing deflection
  - The drive torque needs to be reacted between the vehicle suspension knuckle and the wheel. In between these two components is a surprisingly flexible element – the wheelbearing. Flexible drive elements, deflection-tolerant gears and/or even more bearings would be required in order to mitigate these effects, complicating the design.
- Package size
  - Although gearing will allow the motor to be located off-axis to the wheel, this is not necessarily an advantage and can result in heavily restricted motor diameter in order to allow retro-fit capability, as well as also having to locate a gearbox into the wheel assembly.

It is accepted that a direct drive motor will have a lower mass specific power than if one were to design a high speed motor with gear. However the route that Protean took was to accept this mass increase for the above reasons and conduct research into the real-world effects that unsprung mass has on the ride and handling of a given vehicle [5] . In addition it is found that by increasing the diameter/length ratio of the machine it starts to bring about significant gains in terms of Nm/litre and Nm/kg as shall be discussed further on.

CABLING REQUIREMENTS AND INTERNAL INVERTERS.

As mentioned in the introduction, cabling requirements for an in wheel motor are very challenging and could quite easily prevent the motor from successful adoption if not addressed. It has already been shown that the motor must be subdivided with both four sub-motors and four sub-inverters. If the inverters were packaged on the vehicle body this would require 12 fully EMC-shielded flexible phase cables to be routed along suspension members to make the connection between the inverter and motor coils.

These long phase wires would have to carry high AC currents in operation as a function of the torque and efficiency of the machine. In order that the resistive losses are minimised the cable diameter must be made as large as possible. However, the vehicle suspension will clearly articulate and all 12 cables must be routed without exceeding their minimum bend radius or leaving the cables subject to fatigue through repeated flexing, particularly on steered wheels. This requires that the cables be as small in diameter as possible. The cables would also have to be routed without resorting to one large bundle, as the temperature of the inner cables will present a particular concern, so they will all have to take different routes. Coupled with the danger of cables being severed by road debris, and the need to also route two coolant pipes, a brake pipe, and two other multi-core cables (for redundant rotor position and motor temperature information) the integration challenges soon add up to a very difficult proposition that pushes many requirements up to the vehicle level.

The alternative to this is to package the inverters in the in-wheel motor itself. This obviously places challenging requirements on the electronic design, but reduces the cabling requirements drastically. Instead of 12 shielded phase cables, only 2 shielded DC cables are required. The integration proposition is now much more palatable, and furthermore this frees up yet another package volume on the sprung mass, further increasing the packaging flexibility on the body offered by the in-wheel motor concept.

The placing of the inverter inside the motor however does imply that the motor must have sufficient cross-sectional area in order that the electronics can be packaged on robust rigid boards and that there will be sufficient surface area for drawing thermal losses from the power devices into the coolant. Of course it is clear that cross sectional area of a cylindrical machine scales proportional to outer diameter squared, so larger diameter machines are patently at an advantage from this perspective. The following section will go on to discuss other aspects of the geometry of the Protean machine.

THE SIZING OF A DIRECT DRIVE MACHINE – “RULES OF THUMB”

In choosing to build a direct drive machine, Protean have had to ensure that it is optimised to produce the required torque from a minimum volume and mass. In ensuring that the speed range of the vehicle is met, the power of such a motor will essentially “come out in the wash” through electronics and winding design. Electric machine manufacturers often quote machine performance in terms of specific torque and power, with figures given for both volume and mass specific performance. Clearly in a crowded unsprung environment where torque is the driving performance requirement, both Nm/kg and Nm/litre are going to be of paramount importance. This section is present to provide a much simplified, but relevant overview of the dimensional factors that affect a motor design without delving into the depths of machine design specifics. The arguments are not absolute but are aimed to provide insight into the decisions that led to the form of the Protean machine.

Brushless permanent magnet electric machines create torque by sequentially energising electromagnets on a stator which creates a rotating electromagnetic field. This field is synchronised with the rotor speed and is aligned to interact with the traction magnets on the rotor, resulting in a tangential force reacted across the machine “air-gap” – and the sum of these tangential forces results in a torque around the machine rotational axis. For a given air gap shear area, the amount of magnetic flux that can be permeated through air, magnet or electrical steel is a limiting factor in the peak forces that can be developed across that air-gap. The maximum total tangential force divided by the effective air gap area is frequently termed the “air gap shear stress” and is broadly similar across different sizes of the same class of electrical machine for a given air gap, with permanent magnet machines being at the top of the pile, giving them superior volume and mass specific performance.

The continuous performance of the machine is solely limited by the temperature/life characteristics of the active parts, and to meet challenging continuous torque requirements means that every effort must be put into minimising the thermal losses from these components and optimising the thermal paths that are to draw the heat out of the machine and ultimately dissipate this to the ambient air.

Speaking generally, for a given air gap shear area and maximum air gap shear stress, greatest torque will clearly be produced when the air gap is located at the greatest radius. Similarly, a given torque will require

a lower field strength when the airgap is located at a larger radius, and energising this field will therefore require less current in the windings of the stator, giving lower thermal loss, better efficiency and greater continuous performance.
For the above reasons, best peak and continuous torque can be achieved for a given field strength by positioning the air-gap against the assumed largely cylindrical outer surface of the machine. This immediately drives the design towards a radial flux, outer-rotor layout as being most likely to meet the peak and continuous requirements with minimum package size and mass.
Consider equation 1:

$$(1) Torque \propto (Diameter_{AG}{}^{2} \cdot Length)$$

For a given machine design, torque scales approximately to the above rule, where $Diameter_{AG}$ is the airgap diameter. In simple terms this is brought about by considering the basic mechanics and geometry of the machine. By doubling the diameter of the machine, you have both doubled the lever arm at which the tangential forces are reacted, and also doubled the airgap shear area, resulting in a doubling of the tangential forces also – hence torque is quadrupled. In doubling only the length of the machine, you are simply doubling the airgap shear area, which doubles the tangential forces and torque only. Note that both continuous torque and peak torque scale closely to this relationship, in the case of continuous torque then the limiting factor is heat flux and not magnetic flux, but the principle is broadly similar.
By assuming a cylindrical machine, see equation 2:

$$(2)\ Volume_{cylinder} \propto (Diameter_{O}{}^{2} \cdot Length)$$

Where $Diameter_{O}$ is the outer diameter of the machine package. By accepting that $Diameter_{AG} \approx Diameter_{O}$ for an outer-rotor radial flux machine, dividing (1) by (2) gives the following approximate relationship:

$$(3) \frac{Torque}{Volume_{cylinder}} \propto \sim Constant$$

So fundamentally no matter whether the designer plays with the diameter or the length of a cylindrical, outer-rotor, radial flux machine, it will still need to take up approximately the same amount of litres of valuable wheel space in order to produce the required torque[1].
However, energising the airgap requires only a certain radial depth to the machine, and once the machine reaches a diameter where the inner diameter of the active components is large enough, the motor can essentially take on a toroidal form and the rules that govern the occupied volume change subtly.
Assuming that the radial depth of the active motor components is kept constant, and the diameter and length of this machine concept are free to be scaled, then the volume of these components follows known rules for a toroid, proportional to that shown in equation (4):

$$(4)\ Volume_{toroid} \propto (Diameter_{C} \cdot Length)$$

Where $Diameter_{C}$ is the diameter of the centroid of the toroid section. By accepting $Diameter_{C} \approx Diameter_{AG}$ it can be shown that in general, for a toroidal motor, dividing (1) by (4) gives:

$$(5)\ \frac{Torque}{Volume_{toroid}} \propto \sim Diameter$$

So, as the outer diameter of the machine increases, at some point it can transition from a cylindrical to a toroidal machine, and the Nm/litre performance potential begins to rise from an essentially constant value to being approximately linearly proportional to the machine diameter, see Figure 5 and Figure 6.

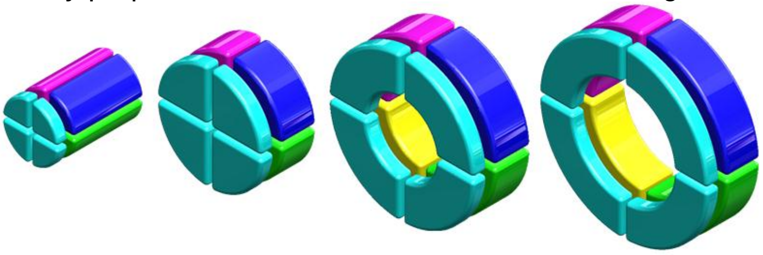

Figure 5: Quad-subdivided motor transitioning from cylindrical to toroidal form for better volume specific torque

[1] Note that for interior rotor, smaller diameter machines, or other machines where the airgap diameter is often significantly smaller than the outer diameter of the machine, this results in a Nm/l performance that is proportional to the square of $Diameter_{AG}$ over $Diameter_{O}$, however further discussion on this particular architecture is outside the scope of this paper.

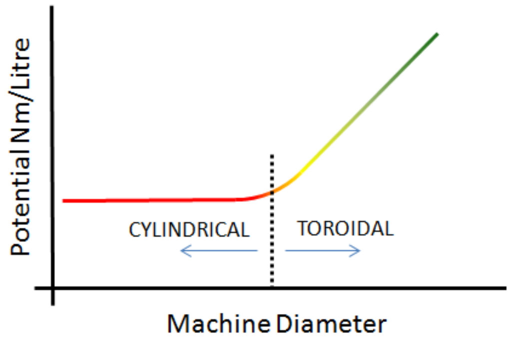

Figure 6: A plot to demonstrate the diameter "break-point" where Nm/litre begins to climb

This gives an interesting characteristic and a diameter "break-point", above which there is good potential for better volume specific performance. The use of the word "potential" here is paramount to this concept however. In order to realise the gains, it must be possible to package another component inside the toroid, where this component serves some other useful purpose in the context of the final machine assembly. In the context of an in-wheel motor, this means a toroidal motor having a large enough internal diameter to surround, for example, the vehicle wheel bearing or part of the suspension system – i.e. parts that have clear functions and take up volume for other purposes in the wheel assembly.
Since the major fraction of the mass of a machine is concentrated in the iron, copper and magnets, and these components keep an essentially toroidal form even at lower diameters, it can also be approximated that for a constant radial depth of the active components:

$$(6) Mass \propto Volume_{\ toroid} \propto (Diameter_C \cdot Length)$$

So again by neglecting the slight difference in diameter terms, dividing (1) by (6) shows that:

$$(7) \frac{Torque}{Mass} \propto \sim Diameter$$

So for a direct drive motor to give the best use of space, and minimum mass, some approximate geometric and known simple machine scaling factors can be used to show that a large diameter, minimum axial length, toroidal form machine that can accommodate a bearing or other suspension components in the centre will give the greatest chance of meeting the performance requirements in the given space. Of course the situation when considering a detailed motor design is much more complex than that outlined here with numerous other effects that are neglected here for simplicity – but it is critical to show that maximising diameter is absolutely key to meeting the torque requirements with reasonable motor mass and volume with a direct drive machine.

THE PROTEAN DRIVE VERSUS THE BRAKES – PACKAGE DEVELOPMENT

So, at this stage the designers are faced with the challenging situation where the following "shopping list" of components must be packaged in the standard volume that the unsprung assembly occupied:

- 4 sub-motors
- 4 sub-inverters
- Stator water cooling jacket
- A friction brake
- Mechanical housings and mountings
- A driveshaft (in the case of many hybrids) and
- Standard vehicle components - suspension, wheel bearing, wheel and tyre

As alluded to in the introduction, enabling retrofits with minimal platform tear-up is a large part of the Protean strategy. Interfering with the load path between the tyre and the vehicle body, or the torque path back to the engine in the case of a parallel hybrid, would be an undesirable modification for the OEM or integrator to make, driving a motor design that results in minimal changes to these components
By consideration of the basic machine design principles it has been shown that a larger diameter toroidal form will give better mass and volume specific torque output. A larger diameter also gives more cross-sectional area on which to package and cool electronics boards and radial flux is preferred given an assumed cylindrical machine shape. The machine is direct drive and therefore must be packaged co-axial with the wheel axis
It is only now, with the above information as given, that the mechanical concepts can begin in earnest and the merits of the differing layouts compared, which essentially boils down to three competing layouts:

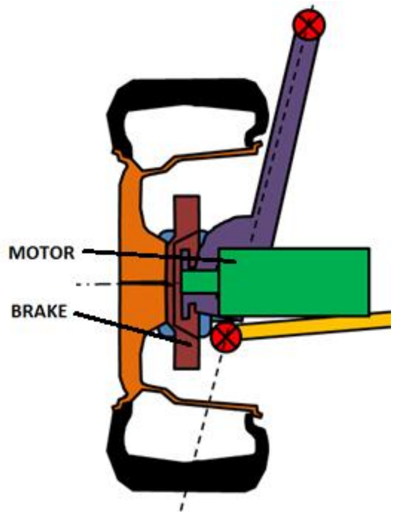

Figure 7: A "traditional" machine

Figure 7 shows what could be a termed a "traditional" machine layout applied to an in-wheel setting. The rotor would drive through a splined shaft onto a driven-style wheel bearing. The advantages of such are layout is principally that the brake and wheel are standard – in particular the wheel does not even need to be increased in diameter. The downsides to such a layout are crippling to its success though. It will clearly have to be low diameter in order to fit between suspension links, thus giving poor Nm/kg and Nm/litre performance. There is very little room for an internal inverter and one would have to consist of many board layers with the reliability cost of the many interconnects between these boards. Furthermore it would not be possible to fit the standard car's driveshaft should this be a driven wheel on a parallel hybrid, it would not be compatible with many suspension types and the length of the machine would interfere with the metalwork of the wheelhouse of the vehicle.

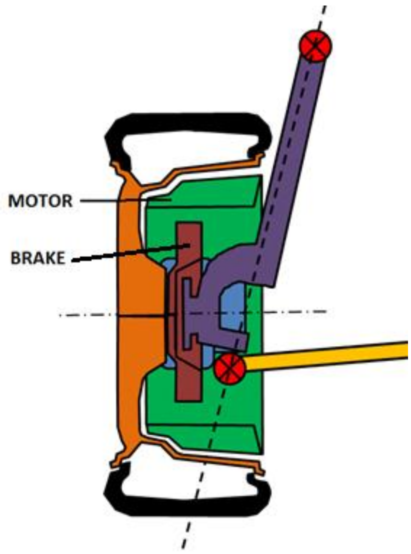

Figure 8: A "halo" style machine

Figure 8 shows a motor volume disposed around the suspension system in a "halo" form. This has the advantage that this is the largest possible diameter that could be achieved inside a given wheel diameter so should potentially be much smaller and lighter compared to a "traditional" machine. This layout would require the wheel diameter to be increased to the maximum size on a given platform, and there is a good chance the standard friction brakes would be able to be retained. The need to have an internal diameter that can be packaged around suspension links is the downfall of this concept however. Typically there will only be a range of around 3" in the available wheel diameters that are offered on a given platform (e.g. Mercedes W212 E-Class is offered with 16" to 19" wheels). For a given platform the suspension will generally be configured to occupy most of the diameter available inside the smallest wheel. To design a motor to fit around suspension designed for a minimum of, for example, a 14" wheel would very likely mean that this same motor would not fit on a platform designed to accept a minimum wheel larger than this, as the suspension system will be physically larger. In this 14" example, this would preclude most retro-fits above a C-segment vehicle in size. In addition, the outer diameter of such a motor would have to be constrained by the smallest wheel that is the maximum diameter specified across the cars left in the market you have available. An A-segment vehicle typically has a maximum wheel size of 16", a B-segment

typically 17” and a C-segment typically 18”, leaving very little radial depth to physically package the motor if the motor is to address all these markets. Although the specific performance of such a machine may be potentially good, the absolute performance will not - the volume is physically not available to cover many market segments with minimum motor variants. This will result in many expensive redesigns and repackaging exercises to create new motor variants for different combinations of suspension and wheel size. In addition this concept will likely require large diameter support bearings, and the connections to the wheel and suspension knuckle will enclose the brake within the motor, encumbering its heat rejection and giving many potential thermal transfer problems into the motor.
When analysing the “halo” layout for a variety of vehicles, it becomes clear that the brake system is effectively occupying more volume inside the wheel than is left for the electric machine. The de facto form for a friction brake has evolved to perform very well in a package environment where this is no motor, however, when a motor is also added into the unsprung package, this format is no longer a logical way to package the brake and motor together in a coherent manner. In terms of both Nm and kW per litre of friction brakes and motors, and also the absolute available space and performance requirements of both, this clearly suggests the brake should occupy the lesser volume of the two.

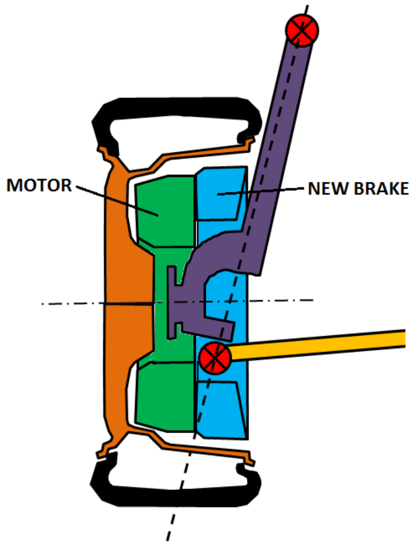

Figure 9: A “doughnut” shaped motor

Assuming then that the friction brake can be repackaged into a new form around the suspension, this leaves a clear volume on the inboard side of the spokes of the wheel for a “doughnut” shaped motor – a slightly smaller diameter toroid which can be pushed toward the outside of the wheel volume. This will still give much better volume specific performance than the “traditional” motor due to the large diameter, and since it is not packaged around the suspension, it does not have an internal diameter that is heavily constrained by the suspension type and size. This means there is space for internal inverters and a promising amount of radial depth to the active motor parts. There is an easy connection to the wheel and knuckle and the vehicle wheel bearing can be used as the motor bearing (thus saving cost and reliability aspects). Of course the major downside of this design is that it requires a new friction brake design, and this brake design will be subject to similar design constraints as the “halo” motor layout (although it does not need to clear a standard brake caliper), however of these two major components (brake and motor) the motor (and inverter) is by far the most expensive and time consuming to redesign for a particular application and so should be the carry-over part for multiple integrations, not the brake.
Of the above machine designs, it became clear that it is necessary to “bite the bullet” and repackage the brakes to make room for the in-wheel motor as a toroid around the wheelbearing where the brake previously existed. Protean believes this is the logical conclusion when one considers the path from performance, safety and packaging requirements.
The doughnut layout has an essentially cylindrical outer surface and so a radial flux machine is a practical proposition within this volume. It is possible to use the vehicle wheel-bearing as the only bearing structure in this design of motor and the radial flux layout also gives better tolerance to wheelbearing deflection than other layouts. An outer-rotor design, as well as maximising airgap diameter, is also the only practical way to provide a rotating brake interface, whilst also providing a large surface area from which to reject thermal losses from the rotor components, ultimately reducing magnet cost.
The design is at a stage now where the packaging dimensions need to be understood in order to model and prototype the technology to ascertain what can be achieved in a given wheel size. The internal forms of different wheels can vary dramatically and care was taken to ensure that the largest reasonable space was

given to the motor without overly constraining wheel choice. The target wheels were all off-the-shelf or OEM aluminium alloy wheels and were selected based on their design being suitable for large brake clearance whilst maintaining vehicle track width (not so-called “deep dish” designs). See Figure 10.

Figure 10: A “good” wheel (left) and a “bad” wheel (right) for in-wheel motor packaging and track width

The packaging volume the motor designers were set was based from a “collage“ of an assorted arrangement of suspension types and suitable wheels. The suspension systems all have the standard brake data removed and the form of the suspension limited the axial length of the motor without affecting the track width of the vehicle. Many of these datasets had to be reverse-engineered and setting a packaging volume was one of the lengthiest parts of the road to a complete set of technical requirements for the motor.

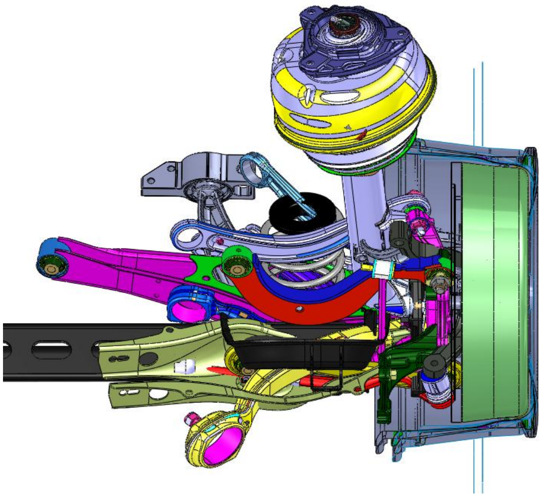

Figure 11: A suspension and wheel “collage” showing the space left for a wheelmotor

With the package situation understood for a range of vehicle sizes, and the performance requirements set also for those sizes, the detailed design of the motor can begin in earnest. There then ensued a period of modelling and prototyping to understand what can be achieved with this motor layout in various size wheels, and the impact on market coverage that has. The result of this is that Protean homed-in on 18” being the optimum size for an in-wheel motor to cover most market segments and also provide enough volume inside the wheel in order to physically move these vehicles with credible performance. Light commercial load-rated tyres are also available in 18”, but not in larger diameters. During prototyping, motors had been developed around projects such as the Volvo “ReCharge” concept and the Millbrook parallel hybrid Vivaro, which both utilised 18” wheels, so there was good historical data for this size of machine, and a raft of customer enquiries and further requirements to feed into the design.
By choosing an 18” wheel as the target, at present Protean cannot provide a retro-fittable solution to A-segment vehicles and most B-segment vehicles. The motor form can easily be housed in larger wheels to allow brake integration on larger vehicles resulting in the potential markets for this motor being from C-segment upwards. The motor should power a C-segment vehicle in 2WD and a J-segment in 4WD. Completing the loop and returning back to Figure 3 and Figure 4, this requires the following performance characteristics:

- 1000Nm peak
- 700Nm continuous
- 54kW continuous

A study similar to that shown in Figure 11 gives a toroidal package requirement of approximately:

- 420mm largest outer diameter
- 115mm maximum length.
- 190mm inner diameter

An in-depth review of the detailed solution to constructing a reliable motor that met these performance targets inside this packaging volume is outside the scope of this paper. However, the solution as fitted to the Brabus/Protean E-class vehicle is a perfect example of prototype in-wheel motors, realised from the above requirements setting process, in the setting of what is turning out to be a very successful prototype vehicle.

THE BRABUS EV BASED ON THE MERCEDES-BENZ E-CLASS

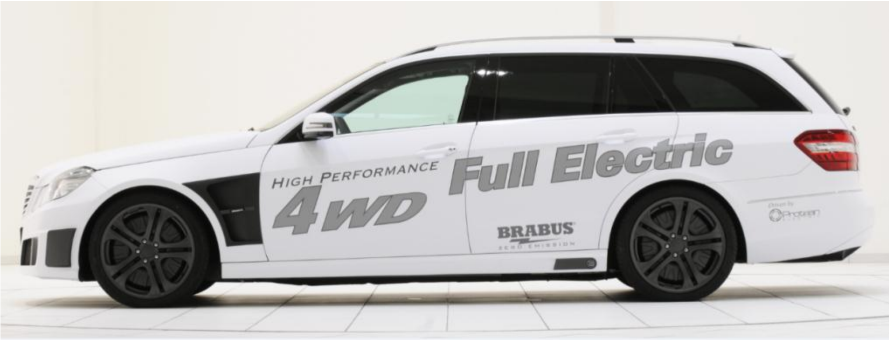

Figure 12: The BRABUS EV based on the Mercedes-Benz E-Class

The recent Mercedes E-Class EV to which Protean retro-fitted in-wheel motors, in conjunction with Brabus, is one of the most highly integrated vehicles Protean motors have powered to date. The vehicle is the quintessential example of a 4WD application of in-wheel motors, where it is difficult to conceive of how a centralised electric drivetrain could possibly be packaged on the body without intolerable compromises in other areas, as almost every spare space freed up by removal of the standard powertrain has been filled with batteries in order to give the vehicle the performance and range that customers would expect on a vehicle of this sort. Figure 13 shows the general packaging of the HV and motor system on the vehicle.

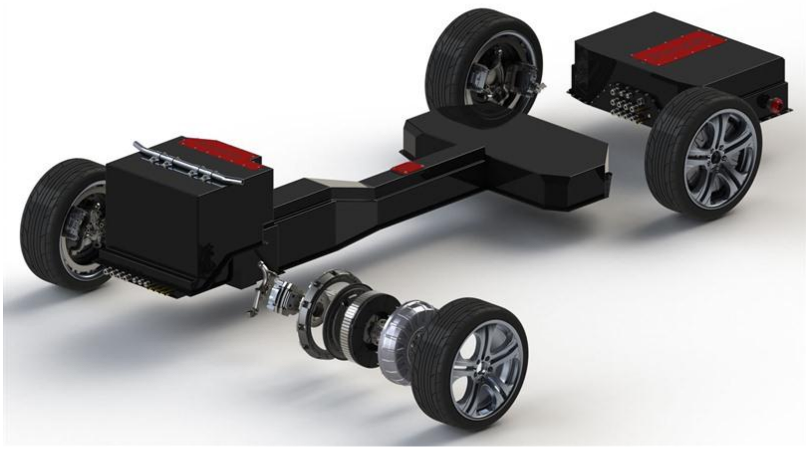

Figure 13: Layout view of the vehicle showing relative motor and battery packaging

The four-wheel bespoke braking system was designed and developed for this car by Alcon Components Ltd. In order to make space for the brakes, the maximum platform wheel size of 19” was selected at the start of the design. Figure 14 and Figure 15 show the motor and brake package as fitted to the vehicle. The brake 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 disc 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 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!

Figure 14: Left front motor and brake assembly

Figure 15: Right front motor and brake assembly with wheel

Besides the inside out disc, one of the obvious differences in the system to a standard car setup is the use of twin, diametrically-opposed 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.

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 wheel-motor creates an undesirable loading condition for the 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 still 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 much effort has expended to ensure that the brake 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 16 for an image of the braking system during a disc cracking test and Figure 17 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. In practice, thermal testing on the complete vehicle supports this conclusion well.

Figure 16: Rotor mounted brake concept during disc cracking test

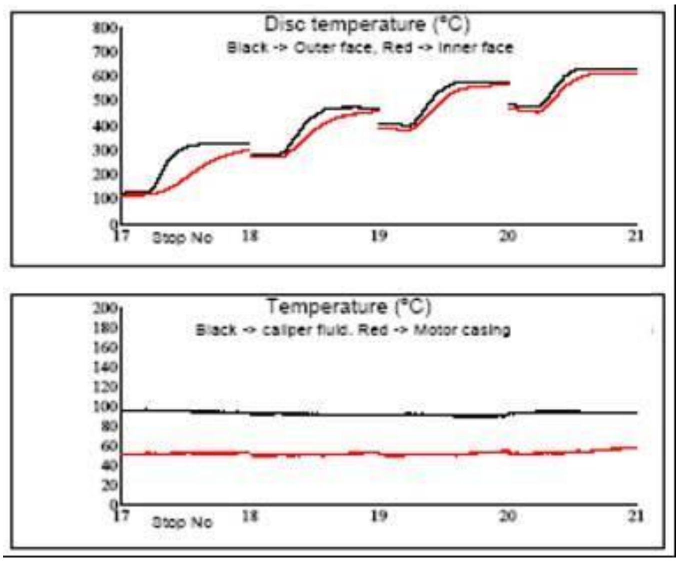

Figure 17: Disc and rotor thermal traces during a series of disc cracking tests

CONCLUSION

A viable high-volume in-wheel electric motor design is a highly anticipated enabler of many electric and hybrid-electric vehicle designs. It is often said that improving battery technology is the key to mainstream electric and hybrid vehicles, but the battery technology “gap” is large and significant on-body packaging restrictions can be relaxed in the absence of a centralised drivetrain. The adoption of in-wheel motors as a volume EV drivetrain will see the converging of battery and hybrid powertrain technology with available platform space much sooner than if we continue to restrict ourselves with a comparatively bulky centralised drivetrain. This principle is maintained regardless of the vehicle architecture –EV, series or parallel hybrid, retro-fit or new design.

This paper has provided an overview of the “logical path” behind Protean’s particular in-wheel motor design philosophy, explaining how fundamental technical requirements have affected the design and steered the development of Protean’s in-wheel motor to take the shape and have the performance that it does today, in a form ready for retro-fit integration onto many different classes of passenger and light commercial vehicle platforms.

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DEFINITIONS/ABBREVIATIONS

2WD Two Wheel Drive
4WD Four Wheel Drive
EV Electric Vehicle
FWD Front-Wheel Drive
OEM Original Equipment Manufacturer
GVW Gross Vehicle Weight
ICE Internal Combustion Engine
IWM In-Wheel Motor
RWD Rear-Wheel Drive
SUV Sports Utility Vehicle