*EVS26*
*Los Angeles, California, May 6-9, 2012*

# *Plug-in Hybrids Made Easy – Selectable EV Drive using In-Wheel Motors*

Andrew Whitehead, Protean Electric Ltd, Farnham, UK,
andrew.whitehead@proteanelectric.com

**Abstract**

Policymakers, consumers and manufacturers are all agreed – the auto industry needs to adopt electrification to address climate change and dwindling natural resources – yet we still see very few hybrid and electric vehicles on the road today. Given the will is there, why the lack of adoption? In reality the main reason is not the technology, but rather the cost of developing the technology in these times of reduced profits and austerity. Using its revolutionary in-wheel motor technology Protean Electric has developed a plug-in hybrid vehicle architecture that can deliver a cost efficient solution to allow rapid electrification of the vehicles we all drive today. Simply put, by fitting a traction battery and a pair of Protean in-wheel motors to a conventional passenger vehicle, the vehicle can be given two additional selectable modes of driving, pure EV and hybrid, with little or no re-engineering of the base vehicle required. In conventional hybrids, to give the same functionality, the chassis system, body-in-white and base powertrain on every platform to be electrified would need to be significantly re-engineered to accept a centralised electric traction motor at substantial cost. It is this drastic reduction in engineering overhead cost that is the key to allowing this hybrid solution to produce cost efficient plug-in hybrids for the mass market. This paper will discuss the engineering involved in converting a conventional vehicle into a selectable drive plug-in hybrid and show how this can be simplified by harnessing Protean's unique in-wheel motor with integrated power electronics. The paper will cite Protean's previous work on hybridising a Vauxhall Vivaro LCV and Mercedes E-Class Saloon as examples of proof of concept hybrid conversions using identical in-wheel motors and related systems. The paper will look into all areas of these vehicle conversions, but will focus on 2 key areas of the conversion. Firstly the fitting of the in-wheel motor to the chassis and overcoming the challenges from packaging and friction brake integration will be discussed. Secondly the focus will fall on the development of the hybrid vehicle controller and its integration with the conventional power train and the battery system. The paper will also distil the real world results from these vehicles showing validation testing and in particular the fuel saving benefits found. The paper will go onto discuss the economics of vehicle hybridisation and attempt to show how this innovative solution, offered by Protean's in-wheel motor, can deliver a viable mass market business case for plug-in hybrids ahead of conventional solutions.

# 1 Introduction

One of the main advantages of in-wheel motors is the ease with which they can be packaged. Simply put – they go in the wheel. Making them work in the wheel is a challenging task, but once this is achieved a new paradigm in vehicle design open's up. Initially one thinks of the benefits for clean sheet electric vehicles. The much talked of 'skateboard' chassis with total freedom for the body shape or the ability to have E-segment space and comfort in a B-segment footprint all become possibilities. However in the short to medium term, when R&D budgets are being shrunk and automakers are being pushed to bring xEVs to the market, the in-wheel motor can offer a unique solution for a low cost, highly effective hybrid conversion. Merely fitting two in-wheel motors and a hybrid battery system to a conventional vehicle gives a pure EV 2WD mode and a hybrid 4WD or 2WD mode with very little re-engineering of the base platform thus minimising development time and cost.

This simple hybrid conversion architecture is made even easier with Protean Electric's in-wheel motor given its integrated power and control electronics and power/torque density. The Protean Drive™, developing over 80kW peak power and 800Nm peak torque, in a 16 litre, 31kg package that connects directly to the battery simplifies the vehicle conversion yet further. This technology allows two key benefits in the hybrid conversion:

1. The performance to give an adequate EV mode.
2. Maximises packaging volume for battery systems.

# 2 Vehicle Conversions

In support of its product development Protean Electric has taken part in a number of hybrid vehicle conversions, where its Protean Drive™ has been integrated onto a conventional platform to deliver a PHEV. The typical architecture of this conversion can be seen in Fig 1 below.

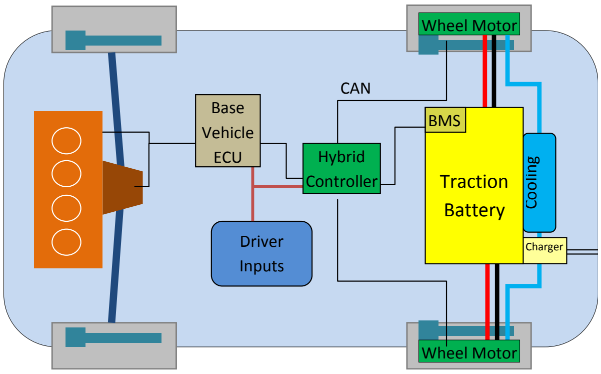


*Figure 1 - Diagram of a typical PHEV Architecture*

As we can see there is little impact on the base drive-train, requiring only CAN integration to the existing systems. The main engineering is the addition of the main three hybrid system: wheel motors, hybrid controller and battery system. Section 3 of this paper will discuss the wheel motor packaging the hybrid controller integration. The paper does not discuss battery integration, except to note that this style of conversion maximises the potential volume in which to package the battery. It should also be noted that additional cooling systems for battery and motors need to be added to the vehicle. In the author's experience these systems are relatively simple and well understood and as such this paper will not discuss them in detail.

## 2.1 Vauxhall Vivaro LCV PHEV

As previously noted Protean has taken part in a number of hybrid conversions using its motors. The first of these was the conversion of a Vauxhall Vivaro LCV when Protean worked with Millbrook Proving Ground Ltd to hybridise the vehicle. A picture of this vehicle can be seen in figure 2 below.

*Figure 2: Protean Millbrook Plug-in Hybrid Vivaro*

The vehicle retains the original ICE drive-train but in addition two Protean in-wheel motors are added to the rear axle with a battery system. This gives the vehicle a ‘pure EV’ mode as rear wheel drive, the performance of which can be seen from *Table 1*, and a 4WD hybrid mode that offers full vehicle functionality when required.

*Table 1 – Protean Millbrook TTR Plug-in Hybrid Vivaro vehicle parameters*

| | |
|---|---|
| Gross Vehicle Mass | 2800 kg |
| Drive System | 2 x PD18 Mtrs + 2.0l |
| 0-100 km/h | 16 s (EV only) |
| Continuous Grade @ GVW | 6% (EV mode) |
| Peak Grade at GVW | 12% (EV mode) |
| Top Speed | 130 km/h (EV only) |

In a large vehicle such as the Vivaro the physical integration of the motors is not complex, with the vehicle control, described in Section 4, of the two power-trains offering most challenges. Testing of vehicle handling and increased loading from the motors was carried out to assess the production feasibility of the concept. The results yielded data demonstrating that there are limits for rear wheel torque application, both in motoring and braking, but that they can be easily limited through the control system. Similarly strain gauging of suspension components shows higher stresses in those components from the added mass and torque. However this increase was not of an order that raised concern. It can be seen, by way of this example, that in-wheel motors offer a unique opportunity to convert a conventional vehicle to a parallel hybrid configuration with minimum disruption to the original vehicle, which has cost and engineering effort advantages.

### 2.2 Brabus E-Class PHEV

Protean’s newest and highest integrity vehicle conversion is a through-the-rear-axle Mercedes E-Class hybrid converted in partnership with Brabus GmbH. The aim of this project is a high performance hybrid with no compromise in passenger comfort. Clearly the packaging benefits and high performance afforded by in-wheel motors make them ideal for this challenge and have delivered a unique vehicle as shown below in *Figure 3*.


*Figure 3: Protean Brabus E-Class Hybrid*

*Table 2 – Protean Brabus E-Class 4WD BEV*

| | |
|---|---|
| Gross Vehicle Mass | 2300kg |
| Drive System | 2 x PD18 + 2.0l CDI |
| 0-100 km/h | 11 s (EV only) |
| Continuous Grade at | 11% (EV mode) |
| Peak Grade at GVW | 20% (EV mode) |
| Top Speed | 180 km/h (EV only) |

As can be noted from the performance in Table 2 above the vehicle has excellent performance in EV only mode and of course will beat the base vehicle in Hybrid mode (see section 4 for explanation). The integration of the motors themselves is complicated by the complex nature of the E-Class suspension and that, as noted in section 3, this vehicle also has friction brakes attached to the motor. The motors are therefore integral in this new corner assembly so are optimised for volume and mass to retain base vehicle handling performance.

The adaptability of the in-wheel motor solution is once more proved by these two real world cases. Both vehicles are significantly different however use the same base Protean Drive™ for the hybridisation.

## 3 Mechanical Integration

In all vehicle conversions cited in the previous section the mechanical integration of the motor was really the first significant challenge in the conversion.

### 3.1 Packaging the Motor

When specifying the requirements for an in-wheel motor the key drivers are firstly the torque required to propel the vehicle adequately and secondly the space available to package the motor. A particular in-wheel motor technology has a characteristic torque density, measured in Nm/litre. In other words, the torque capability of a product based on a particular technology can be predicted approximately using the available packaging volume and multiplying by the characteristic torque density, assuming that the technology is sufficiently scalable. To define a product the motor designers need to consider whether their motor technology can provide the required torque in the space available in the wheel of a given vehicle.

*Figure 4* below highlights how vehicle torque requirements increase with vehicle mass, as does rim size. This effect clearly defines a minimum torque which a product has to deliver to service market segments, based upon a minimum 30% pull-away gradient and 22% continuous gradient.

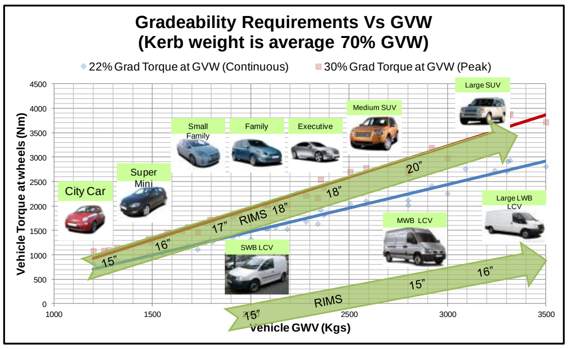


*Figure 4: Gradeability torque requirements for various vehicle classes with rim sizes overlaid.*

*Figure 5* below shows the volume available for an in-wheel motor within the rim. It can be seen that it is constrained by suspension, knuckle and steering components to be of a toroidal form towards the outer part of the wheel rim. packaging is complicated by fitting a brake, as discussed in section 3.2 of this paper, nevertheless it is clear that a larger rim means a greater volume available for the motor and in fact the volume available is approximately proportional to the square of the rim diameter.

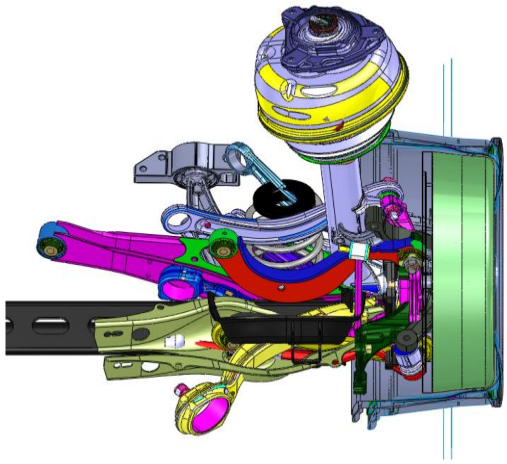

*Figure 5: CAD Collage of suspension systems, showing volume left for an in-wheel motor.*

Analysing the two key drivers of torque requirement and volume available as indicated above allows an in-wheel motor provider to determine the market segments that can be serviced. For Protean in-wheel motor technology the result is a “sweet spot” at a rim size of 18” diameter, at which size the Protean motor is capable of delivering a continuous torque of 700 Nm. Such a unit would be suitable for small family (C-segment) and family (D-segment) cars up to 2000 kg GVW in a 2WD pure EV configuration and for vehicles up to large SUVs with a GVW of 3500 kg in a 4WD pure EV configuration. In addition, in a parallel hybrid vehicle this motor unit could address the same wide market segment with a 2WD reduced EV or power assist performance.

It can also be seen in *Figure 5* above having a wheel that can accommodate the in-wheel motor is also an important factor in motor packaging. Clearly the wheel has to be nominally 18” to accept the motor but it is also important that the offset of the mounting flange allows the standard vehicle track and therefore steering geometry to be maintained. In general Protean have yet to find a vehicle where a suitable wheel could not be found however on some vehicles it was harder than others. On the Vauxhall Vivaro for example a tyre more common on 4x4 vehicles had to be used to fit the correct rim.

## 3.2 Friction Brakes

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 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. This section 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.

### 3.2.1 Brake Packaging

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 a Protean in-wheel motor is fitted, see *Figure 6* below.

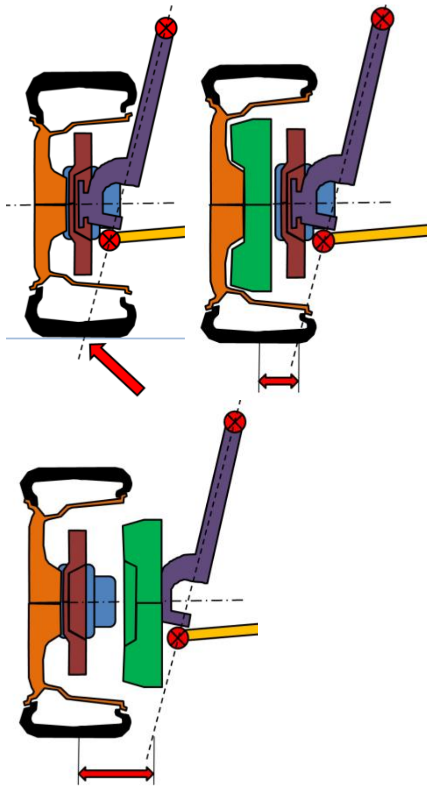

*Figure 6: Options for packaging an in-wheel motor with a standard disc brake.*

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.

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 positions. See *Figure 7* for clarity on the location of this volume and how this enables the track width of the vehicle to be maintained

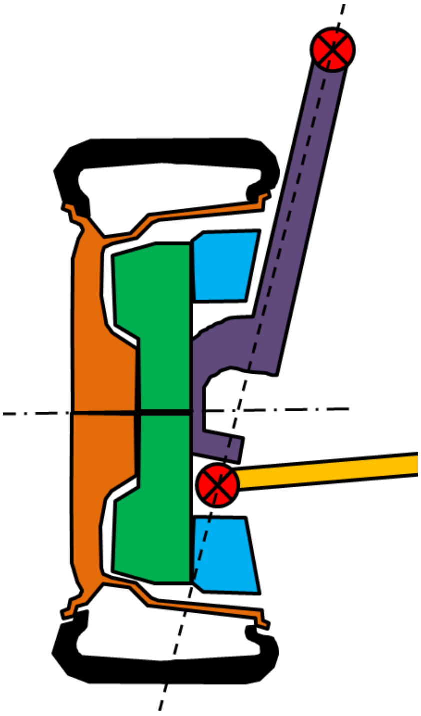

*Figure 7: Toroidal volume available for rotating brake hardware in blue*

### 3.2.2 The brakes in detail

*Figures 8 and 9* below show the braking system as fitted to the Mercedes E class.

*Figure 8: Left motor and brake assembly*

*Figure 9: Right motor and brake assembly with wheel*

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.

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 10* 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.

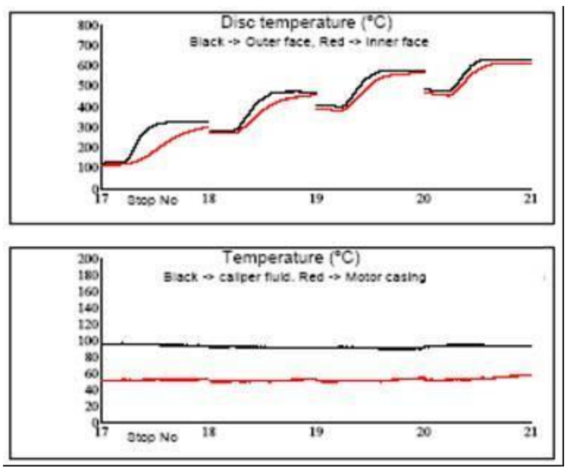


*Figure 10: Disc and rotor thermal traces during a series of disc cracking tests*

### 3.3 Connections

As one can also note from *Figures 8 and 9* above the provision of adequate connections to the motor is an important area. The motor requires effectively 6 connections to the vehicle:

a) 1 x mechanical to the suspension
b) 2 x electrical power (DC+ and -)
c) 2 x coolant connections (inlet and outlet)
d) 1 x control cable (CAN, 12v etc)

These 6 connections are really a minimum for a wheel motor given its requirements. Especially regarding the power connections having 2 DC connections versus a minimum of 3 AC connections for a conventional three phase motor is a significant advantage both in terms of routing but also EMC.

Given that a) is mainly covered in section 3.1 the effort involved in providing the remaining 5 connections is based on finding a path for the cables/pipes that is not obstructed and provides a route onto the sprung part of the vehicle ensuring no excessive strain, either static or dynamic. On the vehicle conversions to date Protean has found adequate connection routings even on complex suspension systems such as the E-Class.

## 4 Control System Integration

### 4.1 The EDM

The Protean control system, referred to as the Electric Drive-train Manager (EDM), is a generic, flexible and tuneable system for controlling a vehicle fitted with up to four electric motors. It has been developed using a modular generic approach to suit any format or size of vehicle and can be applied to pure electric (EV) and parallel hybrid (PHEV) architectures.

The EDM has the ability to be fully calibrated to provide the required driveability and handling characteristics. It also encompasses a safety critical subsystem responsible for maintaining the vehicle system under its safety constraints, the requirements of which were analysed from the ISO 26262 process adopted at Protean.

The EDM interfaces with the electric motors, the battery management system and other vehicle systems to provide the following key functions:

- Comprehensive torque mapping and limiting functions for the motors
- Centrally coordinated system state management
- Continuous system health monitoring
- Detailed motor protection algorithms
- Closed loop battery protection algorithms
- Regenerative brake force distribution
- Arbitrated torque management
- Failure detection on all inputs and actuators
- Integrated system management for all detected failures
- Battery system interfacing
- Battery limit control and multi string management
- Cooling systems control
- HV distribution control
- HV integrity and safety monitoring and control
- Safety/dependability monitoring of the main EDM functions leading to torque management

Note that the Protean in-wheel motor package includes the power electronics and motor control, so that the EDM can issue torque demands via CAN to the in-wheel motors. The translation from torque demand to currents in the coils of the electro-magnets is dealt with as part of the motor control and so is not part of the EDM functionality.

The EDM software has been generated using a model based approach in Matlab/SIMULINK. The modular approach for the various vehicle platforms was achieved using the SIMULINK model referencing attribute for easy configuration management. Initial builds have been realised using rapid prototype hardware (dSPACE MicroAutoBox). However, the EDM software architecture enables its deployment on a wide range of hardware options (ECU's). Furthermore, the EDM architecture is not constrained to the application of in-wheel motors but to any EV technology.

## 4.2 Vehicle Control Architecture

The vehicle control architecture incorporating the EDM for hybrid conversions is shown in *Figure 11*. The SIU (System Interface Unit) acts as a CAN gateway as well as a high voltage (HV) control unit to monitor the health and status of the HV components that interface to the EDM.

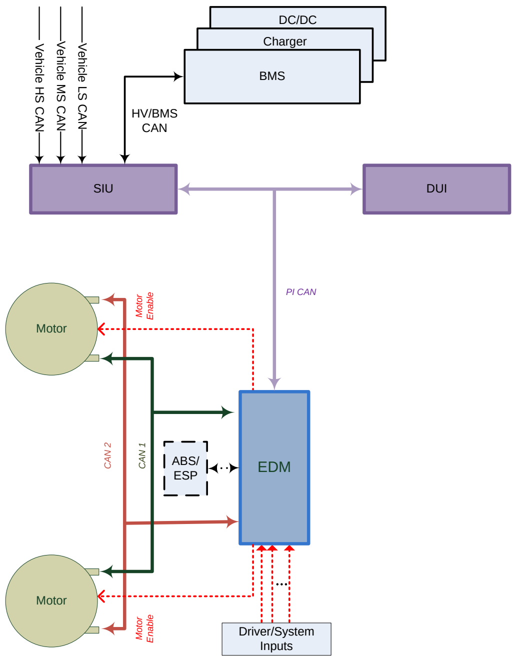


*Figure 11: 4WD vehicle architecture for a Vehicle Control System which includes the generic EDM*

The software functions that broadly describe the EDM are graphically illustrated in Figure 12.

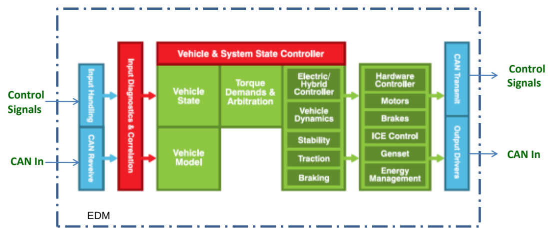


*Figure 12: High-level software functions of the EDM.*

## 4.3 Vehicle Systems Integration

### 4.3.1 Driver Controls

Clearly when introducing one or even two new modes of propulsion the driver control and interface must be considered. The areas to thought through include what inputs to give the driver and how to evaluate them, and also how to provide feedback to the driver.

In the case of driver inputs the parallel hybrid conversion offers some challenges. Initially one must know if the vehicle to be converted is manual or auto. Automatic transmission will offer a more refined system but a solution must also be sought for a manual transmission and in the vehicle conversions cited in Section 2 both vehicles were based upon manual transmissions. Once this is established the new modes of propulsion must be defined. Given the performance offered by only two Protean motors a ‘pure EV’ mode is generally available for economy driving and most gradients. But additionally there will be a hybrid mode when both ICE and Protean motors provide balanced tractive effort to offer full vehicle performance. There will be an ICE only mode with the final option of rapid charge mode if required.

As the vehicles were proof of concepts it was defined that switching between modes would be driver controlled with little automation. To this end three modes were defined as:

1. ICE only (conventional powertrain)
2. EV and Blended mode (pure EV or EV + conventional powertrain)
3. Rapid Charge mode (Engineering mode where regen is applied to motor and ICE ‘pulls’ rear axle to rapidly charge the battery)

In all cases the vehicle has to be stationary to change mode except from EV to blended. These mode switches can be seen in *Figure 13* below:

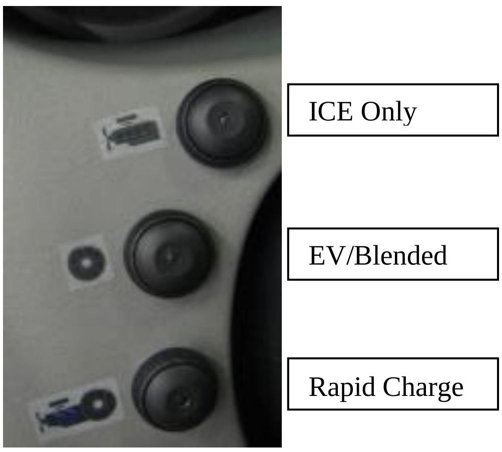


*Figure 13: Drive Mode Switches*

In the case of EV and blended mode the driver typically moves off in EV mode using normal automatic transmission logic switches – D (drive), N (neutral) and R (Reverse). Given the vehicle is a hybrid and not expect to meet all driving requirements in pure EV mode, where more performance in required the driver simply selects the appropriate gear for the speed and the vehicle switches seamlessly into blended mode with RWD EV and FWD ICE.

In addition to driver input new driver feedback is required to communicate appropriate data. To these ends Protean developed a bespoke DUI (Driver User Interface) which interprets CAN data and displays data per *Figure 14* below.

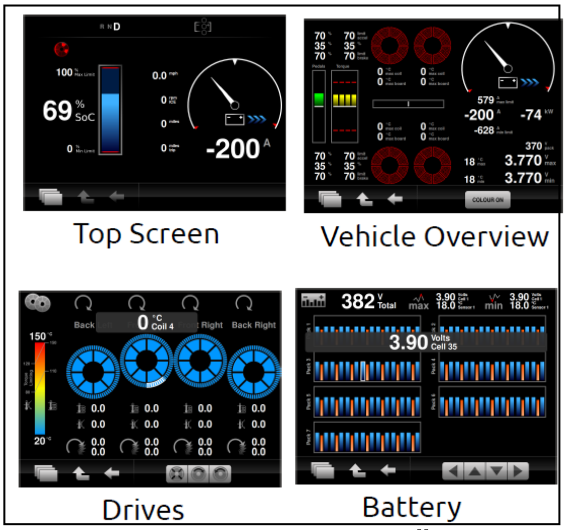


*Figure 14 – DUI Screen Collage*

The display is a touch screen and can be interrogated by the user to provide the data required. The display is mounted in the ‘double DIN slot’ originally provided for the infotainment system and is within easy view and reach of the driver. In the initial vehicles the screens provide significant data for engineering evaluation. It is clear however in production a more concise data set would be presented to the driver and may also come through the conventional instalment panel.

### 4.3.2 Systems Interface Unit (SIU)

This unit, as seen in *Figure 11* has 2 primary functions;

1. To Interface the additional hybrid systems with the base vehicle.
2. To interface the HV system with the EDM

In function 1 the unit operates as a CAN gateway providing inputs into the EDM such as engine speed, steering angle etc. It also provides some data to the vehicle systems from the EDM that are required to be present for the vehicle to run. In short it is the unit that ensure the base vehicle system operate as normal post hybridisation.

In function 2 the SIU provides a reasonable form of isolation and secondary functions if the EDM is unable to effectively control the HV system near its constraints. The electrical safety of the vehicle is also managed through a hardware interlock which manages the BMS and other HV components independently of the software monitor in the SIU, if required. Additionally, the interface with the charger and other ancillary HV systems can be achieved in the SIU.

The other system to be integrated but not covered by the SIU is integration to ABS/ESP systems. As noted in *Figure 11* this integration is carried out directly with the EDM and not via a gateway. This is to ensure the fastest possible response of the systems to ensure the integrity of these safety critical systems.

### 4.3.3 Motor Control

Communication with Protean's electric motors is via CAN with additional hardware enable signals. The EDM makes torque demands of the motors which report back with state-of-health information. This allows the 'intelligence' on the vehicle to remain in the EDM and for it to make decisions related to motor protection and vehicle functional safety with full knowledge of all vehicle systems.

This architecture has been chosen by Protean to align with industry standards for powertrain systems. This allows for relatively simple integration of existing systems, such as ESP, but also some more exotic systems, such as torque vectoring (TV), now possible to far greater limits with in-wheel motors. Protean motors now allow for full independent wheel control which has some very interesting benefits in the field of vehicle control and dynamics. Although not discussed in depth in this paper this area of development is of great interest to many vehicle engineers and dynamicists.

# 5 Economics

## 5.1 Market Environment

It is plain for all concerned to see that there is a current desire to push towards a more sustainable transportation system with a mosaic of technical solutions and that electric drive, both pure EV and hybrid will for a significant part of it. However current economics, both of scale and fuel cost, are not yet conducive enough to deliver the much maligned electric drive boom. There are many external factors (oil price, governmental regulation etc) that could drive the market however those involved in the industry must also deliver innovative solutions to drive the economic argument. It is to this end that the wheel motor hybrid conversions can significantly advance the electric drive market but driving down the ownership costs in the short to medium term.

## 5.2 Typical Fuel Savings

The main aim of a hybridisation is to reduce fuel consumption and $CO_2$ emissions of the vehicle. In this endeavour fuel savings offered by hybrid conversions are mainly dependent on the battery size used in the conversion in a typical charge-depleting drive mode. The energy stored in the battery does not add to tailpipe emissions and a hybrid vehicle in pure EV mode could be considered to have an infinite 'MPG' figure. This generally correlates linearly (to a limit) with a larger battery equating to increased EV only range and therefore reduced $CO_2$ emissions. On the flip side the battery adds mass and once empty may in some cases add to the fuel consumption of the vehicle. Therefore one can state the size of battery has to be considered carefully.

The other aspect that affects the overall fuel saving offered by the hybridisation is the design of the EV drive system. In this regard Protean believe that its motors, being in-wheel and direct drive offer the optimal hybrid solution. The motors deliver the battery's energy directly to the road with no transmission driveline losses and similarly recover regenerated energy with none of the losses associated with a conventional EV drive-train.

On the vehicles converted to date Protean have real world data for the Vivaro TTRH conversion and the sensitivity to battery size as demonstrated in Table 3 below.

*Table 3 – Fuel Savings for Vivaro Hybrid with differing Battery Sizes*

| Parameter | Option 1 | Option 2 | Option 3 |
|---|---|---|---|
| **Battery Energy (kWh Total)** | 25.4 | 16.9 | 8.5 |
| **EV only Range (miles)** | 41 | 27 | 14 |
| **Diesel only MPG*** | 26 | 27 | 27 |
| **Electric and Diesel MPGe** | 42 | 42 | 42 |

** Note this is not base vehicle MPG (28) as added system mass reduces diesel only consumption*

The data for battery options 2 and 3 is based upon the correlated model for option 1 as built into the demo vehicle. In all cases the same pack densities and internal resistances were used and the hybrid Drive-train remained constant.

The MPG and MPGe figures were calculated using the standard EPA model which is described as:

1. Simulate vehicle in charge depleting (CD) mode for UDDS drive cycle:
    - Calculate MPGe by using kWh to gallon conversion and adding diesel consumption
    - Calculate CD mode range
2. Simulate vehicle in charge sustaining (CS) mode for UDDS cycle
    - Calculate MPG
3. Apply "5 cycle correction" to get MPGe in CD, MPG in CS mode for city driving and CD mode range.
4. Repeat 1-3 using the HFET cycle to get fuel economy figures for highway driving.
5. Combine assuming 55% urban and 45% highway driving to give:
    - MPG in CD mode for a combined cycle
    - CD mode range for a combined cycle
    - MPG in CS mode for a combined cycle

It is clear from the table that significant fuel savings can be achieved by the hybridisation of the vehicle. Somewhat counterintuitively it does not appear that a larger battery results in greater fuel savings, however this is somewhat due to the EPA model and the longer pure EV range will have an impact on the vehicle running costs.

## 5.3 Business Case for Conversion

Once the potential fuel saving, and therefore payback, has been established the next step in understanding the economics of vehicle conversions is to understand the cost associated with the conversion itself.

When understanding the vehicle conversion costs one must look at the overall picture. The overall cost model or total cost of ownership(TCO) is mainly made up of the following parameters which are discussed below:

1. Engineering of the hybridisation, including all design and validation work.
2. Component costs
3. Cost of up-fitting/converting vehicle
4. Running and maintenance costs
5. Residual Value

Upfront engineering costs using a wheel motor conversion offer one of the most significant areas for cost savings. The ability to simply 'bolt on' a hybrid drive-train with little or no changes to the base vehicle drastically reduces both design and validation time and therefore cost. Only the additional systems require validation and in general even the warranty of the base vehicle systems can be honoured. For a centralised drive typically the engine and gearbox are significantly modified to accept hybrid drives, thus adding huge cost.

The actual component costs themselves are out with the scope of this paper. However it can be assumed that a hybrid vehicle will need many of the same components (charger, DC:DC convertor, battery, EV drive-train etc) and that on a $/kW basis one system cost will be largely similar to the other. What is also clear given current pricing is that the battery predominates in the cost model and anything that can be done to reduce its capacity will give an advantage. Given this the optimal efficiency of Protean's system may offer a slight advantage over others.

The conversion cost is another area where the a Protean conversion can look to reduce the TCO.

Given the fact that there are few changes to the base vehicle required the unfitting cost will be lower than a centralised EV drive-train hybrid. Hybridisation can now become a late configurable or post registration option and the idea of converting existing fleets also becomes a viable option. One could, in the longer term, even imagine a kit of parts supplied for 'dealer conversions'. Essentially the key benefit in this area of the TCO is more the increase in size of addressable market and thus the achievement of a volume market and associated economies of scale sooner.

Running costs are a key subject for many consumers and it is a huge factor in the financial models of large fleets customers who a prime first movers in this market. Clearly the fuel savings must give an eventual pay-back on the inevitable higher upfront costs, but other improvements in running costs can be significant and there should be no detriments. In this area the wheel motor conversion is as reliant on the battery pack for fuel savings as any other but again efficiency gains may lead to bigger fuel saving improvements. Additionally some benefits may also be derived from the reduction in brake wear from the high levels of regen available from having the actuators at the wheels.

Residual value (RV) is again a financial driver that is of substance, especially to large fleets. Their ownership models and those of the financing companies underwriting the vehicles place importance on the capital value of the vehicle once it has completed its useful life in the fleet. One of the big issues with current xEV vehicles is that the technology is so new that there is very little understanding of residual values. The battery again predominates in this discussion but also there is very limited data for the rest of the EV parts. Again Protean's EV drive parts have the same concerns placed upon them, however Protean's 'bolt-on' conversion can also be 'unbolted' such that the RV of the base vehicle is maintained as if unaltered. Indeed many of the base vehicle components (engine, transmission) will have meaningful extra life in them compared to a standard vehicle of the same age given the mileage under EV power. The ability to having an accurate RV to use in the financial models is another key advantage of the In-wheel motor hybrid conversion.

# 6 Conclusion

This paper has attempted to distil the practical experience of Protean Electric in the hybridisation of vehicles using its wheel motor system. The paper has demonstrated how Protean have overcome the packaging and control issues with the innovative design on their motor, brake solution and control system.

The paper has attempted to demonstrate that by using these innovative solutions the tough economic barriers can be overcome in the near term.

In general the will to 'go green' is there but the economics are not. Hybrid vehicles are in demand but due to costly engineering the demand cannot be met. Using its novel in-wheel motor with integrated power electronics Protean Electric have developed a selectable EV drive plug-in hybrid solution that can short cut much of the costly engineering that holds back vehicle electrification. Protean's real world experience shows this simple solution is viable and able to deliver the functional, economic and carbon reducing requirements of the mass market.

# Acknowledgments

The author would like to thank Dr Chris Hilton, Dr Sunoj George and Alexander Fraser for their assistance and support in writing the paper.

# References

[1] Alexander Fraser, IN-WHEEL ELECTRIC MOTORS, The Packaging and Integration Challenges. CTI Syposium, December 2011, Berlin

# Author

Andrew Whitehead graduated from the University of Strathclyde in 2000 with a BEng in Mechanical Engineering. Before joining Protean in 2009 his career had been focussed on Motoracing Engines and latterly worked in Honda's F1 Engine Programme. At Protean Electric Andrew is Business Development and Applications Manager and helps to span the gulf between Engineering and the Customer.