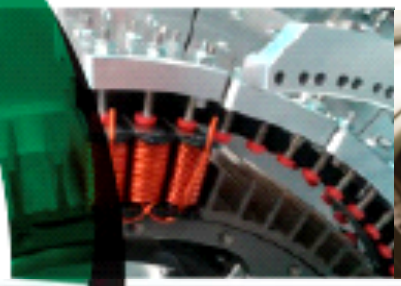
Protean ELECTRIC

Visionary Design. Practical Solution.




Understanding the Challenges of Integrating In-Wheel Motors

Apr. 2016

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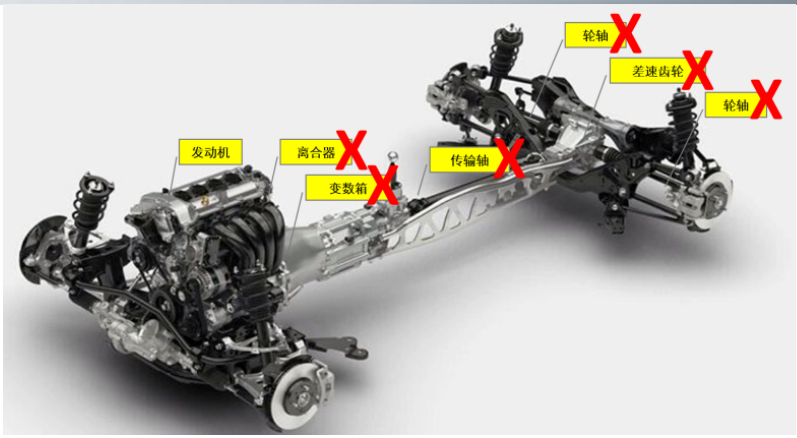
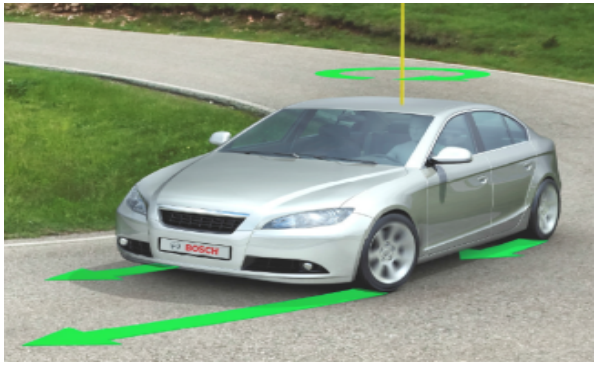
In-Wheel Motor Benefits

Wheel Motors can offer the following key benefits:

- Drive-train efficiency gains through removal of transmission system losses and regen braking optimization
- Removal of centrally mounted driveline to reduce vehicle mass and increase occupant volume
- Vehicle BOM count reduction to reduce fixed tooling and assembly costs
- Optimal application of torque vectoring to maximize linear driving region
- ABS response and stopping distance improvement
- Paradigm shift in vehicle design facilitated





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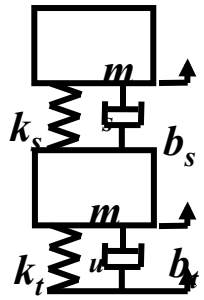
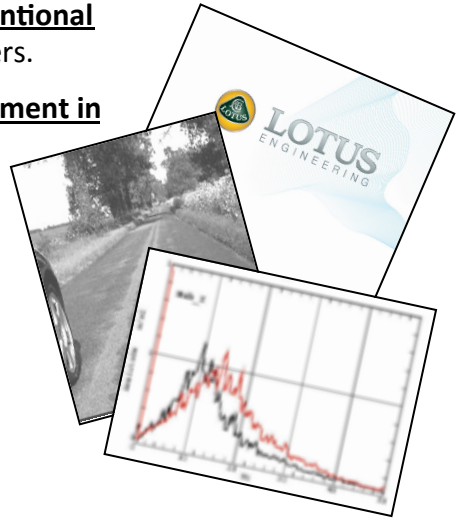
Impact of Unsprung Mass

- Protean has completed extensive work with Lotus Engineering and Damian Harty (Coventry University, now Polaris) to test the effect of unsprung mass on vehicle behavior.
  - Full DoE using ¼ and ½ car models used to simulate u/s mass increase
  - A Ford Focus was modified to add ~30kg of mass to each corner
  - Subjective and objective testing was completed
  - Practical and Theoretical projects merged
  - Suggested improvements tested on car to validate hypothesise (Phase 2)

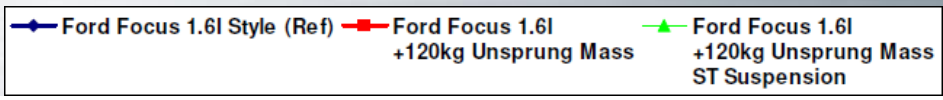


- Results:
  - Adding the equivalent mass of the Protean Drive™ system to the vehicle's existing unsprung mass showed **some adverse changes in the vehicle behavior that were not unexpected and did not drastically alter the vehicle**.
  - **The vehicle ride performance could be recovered on most vehicles with the use of conventional tuning methods** (optimizing dampers, bushings etc.) available to vehicle dynamics engineers.
  - **Potential benefits of independent torque control should far outweigh any marginal detriment in handling from increased unsprung.**

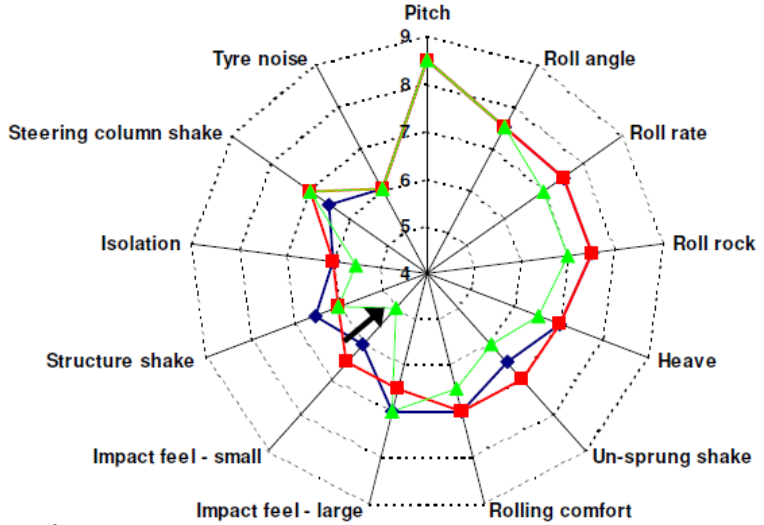


- The independent authors of this report are happy to speak to interested parties
- Full unsprung Mass reports and publications will be supplied:
  - AVEC10_Paper__144 Anderson Harty.pdf (English and Chinese)
  - Lotus Reports (Phase 1 and 2) and Harty report
  - SAE presentations, joint and Harty

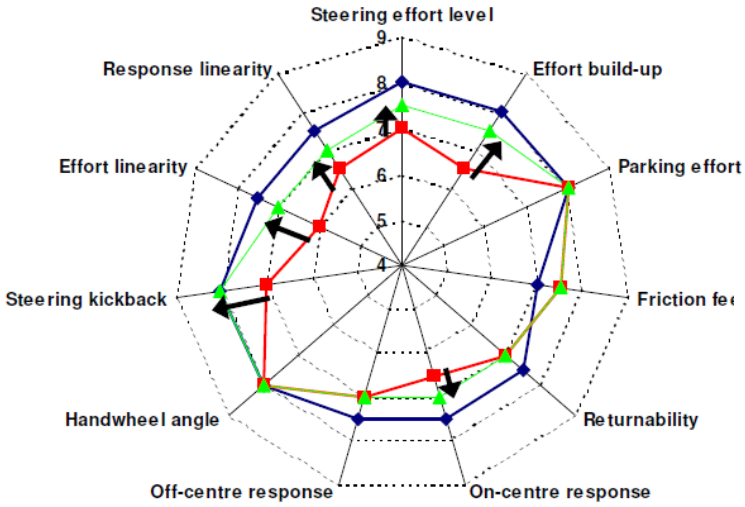
Summary of Phase 2 Results



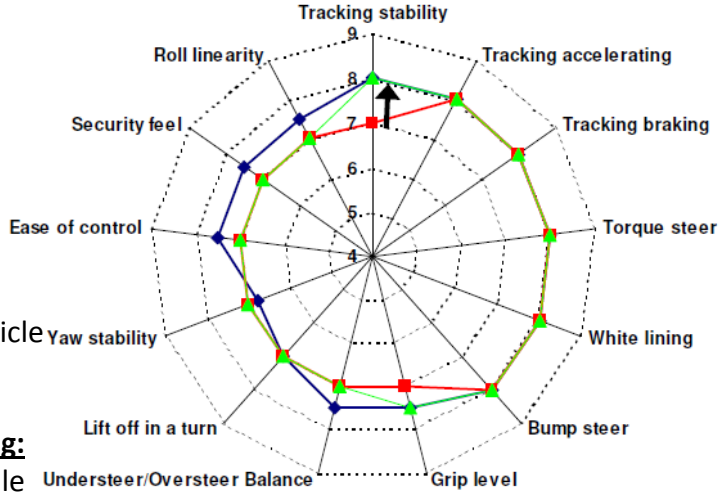
- The 2nd phase of the project looked to recover some of the lost performance in the Ford Focus with add U/S mass
- The results below show the impact of simple suspension tuning (dampers, bush stiffness etc) via fitting of replacement parts from other versions of the Ford Focus (ST version etc)



Ride:
Ability for the vehicle to soak up road imperfections



Steering:
Ability for the operator to feel connected to the vehicle



Handling:
Ability for the vehicle to remain stable and usable

Note:
1. Steering system was unaltered
2. Steering would not be impacted if U/S mass was only added to rear axle

Independent analysis by:

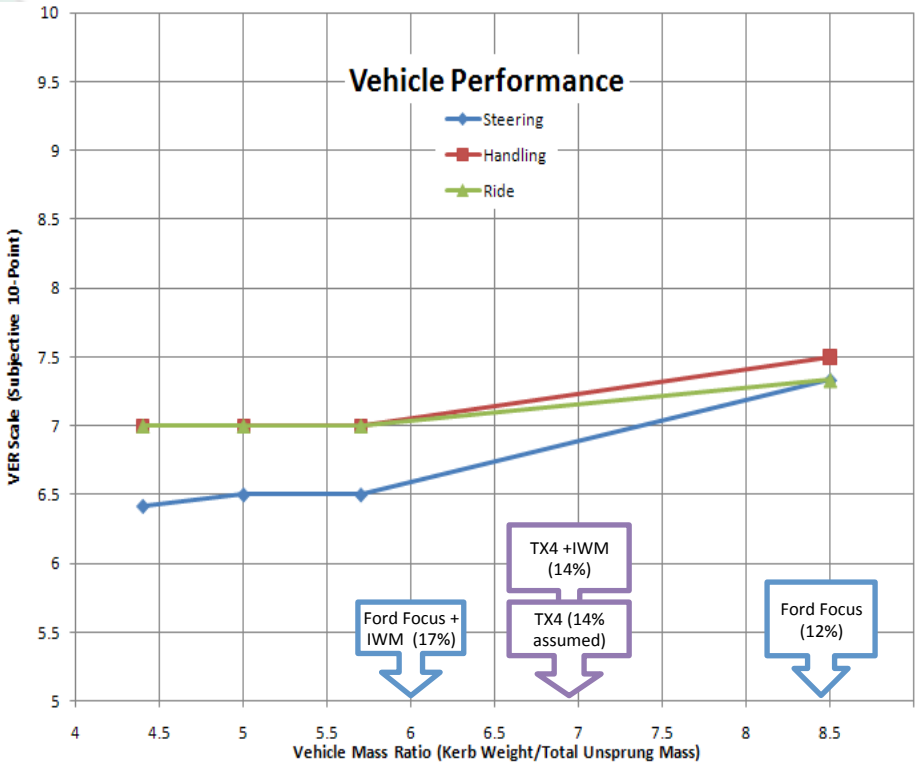
LOTUS ENGINEERING

Ratio of Sprung to Unsprung Mass

- **Specifically the ratio of Sprung to Unsprung mass was looked at by Harty/Anderson**
- **The graph below summarises the impacts *S:U/S* on a composite set of KPIs**
- **Additionally data points for Ford Focus, and LTI TX4 are added:**
  - Focus shows absolute worst case for IWM integration (See noted below)
- **Data suggests that the addition of IWM will keep the *S:U/S* within reasonable limits**

Ford Focus Case Worst as:

1. Lightest possible U/S mass starting point in PD18 addressable market
2. U/S mass of 4 wheel motors added, whereas only 2 needed for adequate performance
3. No additional mass savings estimates (eg removal of driveshafts etc)



Excellence beyond the requirements of the market; a cost reduction opportunity?

Excellence well targeted to market requirements

Target customers may notice performance not as good as rivals

Majority of customers will find performance unacceptable; return-to-dealer or warranty issues may result; unwise to approve for production

Conclusions – “The Realities”

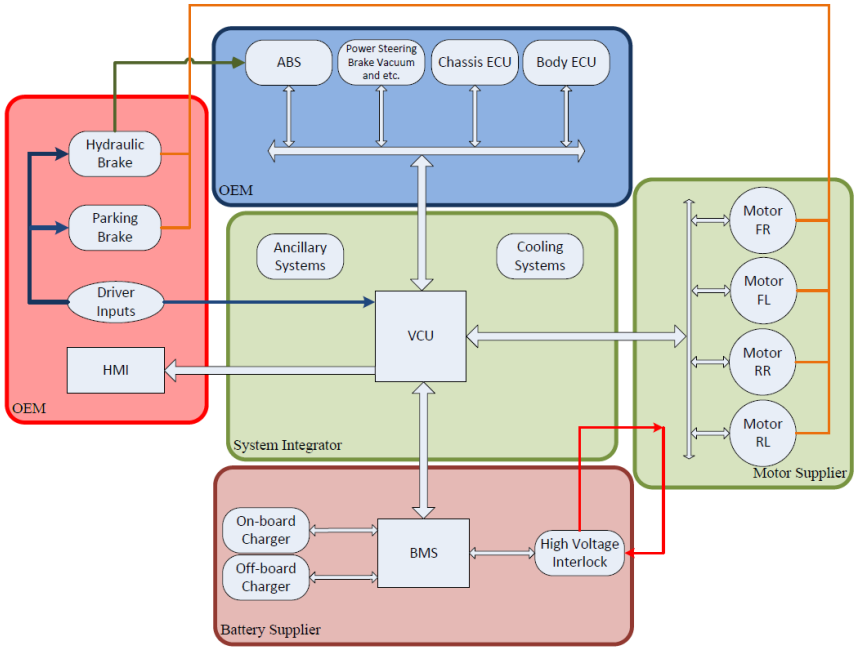
- No obvious “break point” for safety, ride or refinement
- Analysis indicates that road surface variation and tyre quality are greater factors than unsprung mass
- Tuning is containable with normal development techniques for the average customer perception.
  - e.g. tyres, bushes, springs, dampers, arb’s and top mounts
- The opportunities far outweigh the slight negative changes to vehicle character
- Lotus quotes:
  - “The understanding gained from this study has led Lotus to believe that the small performance deficit could be largely recovered through design changes to suspension compliance bushings, top mounts, PAS characteristics, springs, arb’s and damping, all part of a typical new vehicle tuning program”
  - “Add the powerful benefits of active torque control and Lotus’s findings make a strong argument for the vehicle dynamic benefits of hub motors as an EV drivetrain”

Contents

Vehicle Controls and Dynamics

- **The Protean Drive™ IWM control systems are similar to other New Electric Vehicle (NEV) systems and such switching to IWM is not a big step:**
  - Additional e-drive components (e.g. battery, motor, inverter)
  - Electrical ancillary components (e.g. DC/DC, power steering, charger)
  - Interface to standard components (e.g. ECU, ABS, cooling)

- **Key topics of the control system on a vehicle with In Wheel Motors:**
  - Differential Performance
  - Regen Braking
  - Torque Vectoring

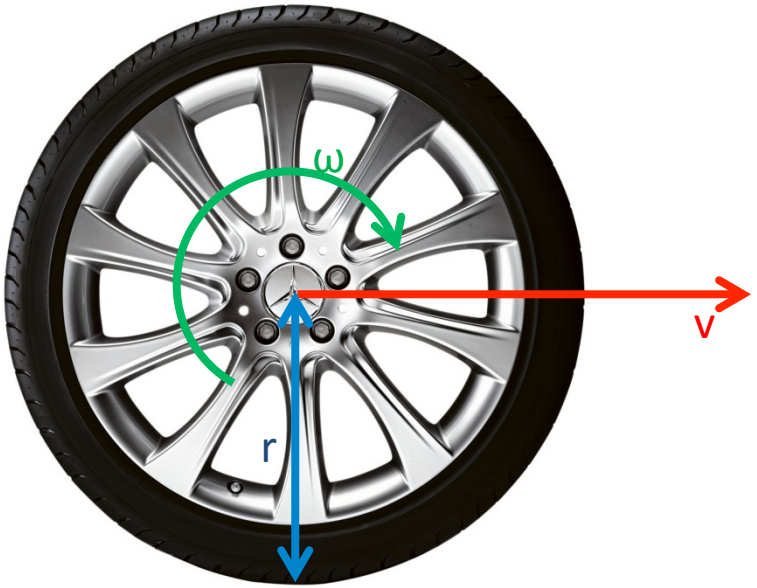


Vehicle Controls and Dynamics

1. Differential Performance

- **The equations are identical for a mechanical differential and in-wheel motors:**
  - By demanding equal torque from two independent IWM's the resulting wheel speeds are identical to those which result from a central motor with mechanical differential

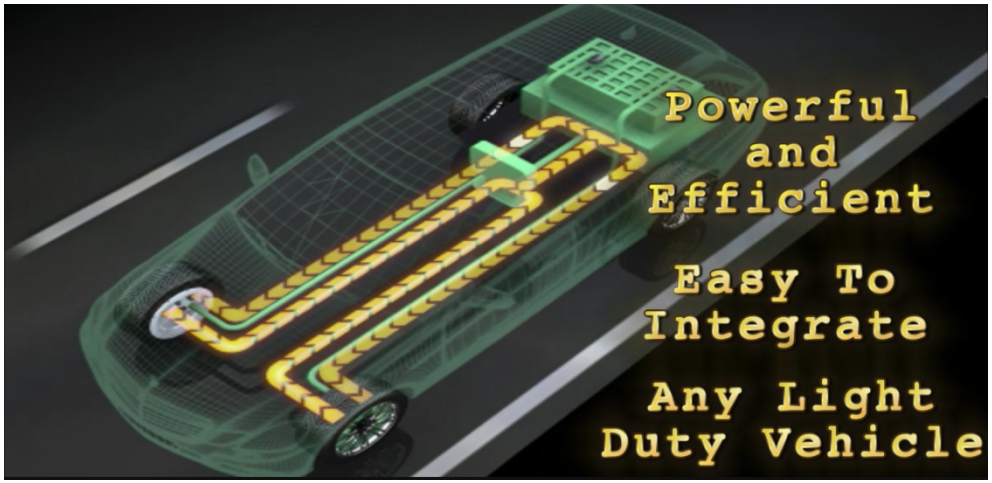
- **There are opportunities to improve vehicle dynamics with IWM's by taking advantage of the rapid torque response and ability to produce motoring and braking torque:**
  - Torque vectoring – asymmetric torque to improve cornering performance and vehicle stability and agility
  - Anti-slip – reduce torque on wheels which are losing traction and spinning up (ESC-like)
  - Anti-lock – modulate torque on wheels to avoid wheel lock-up (ABS-like)



Vehicle Controls and Dynamics

2. Regen Braking

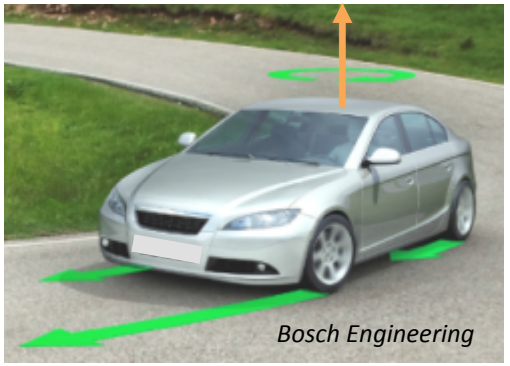
- **Regenerative braking is a key part of the overall efficiency strategy**
- **Optimisation of regenerative braking requires detailed study and is a trade-off between performance and cost/complexity**
- **Solutions can be classified by complexity**
- **In-wheel motor vehicles can have enhanced traction control, giving improved ABS and ESP function, taking advantage of**
  - Independent torque production at each wheel
  - Sub 5 ms response times
  - Positive and negative torque capability



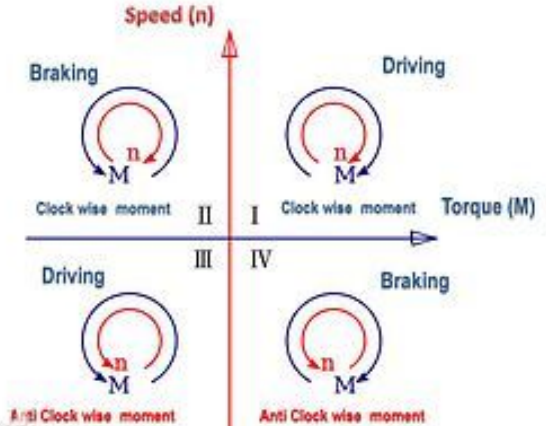
Vehicle Controls and Dynamics

3. Torque Vectoring

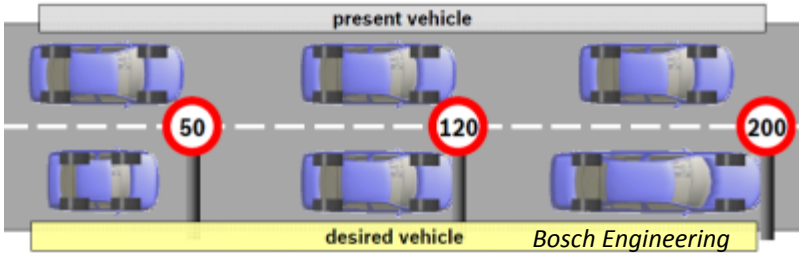
- **Torque vectoring is the application of different torques at different wheels to enhance dynamic performance of the vehicle**



- **In-wheel motors are the ideal actuators for torque vectoring**
  - Fast response
  - Entirely independent torque control at each wheel
  - Four quadrant operation of motors
    - Both directions of motion and torque



- **Torque vectoring is not necessary with in-wheel motors, but it represents a performance enhancement opportunity.**
  - Better Improves driver feel
  - Optimise vehicle handling
  - Consistent cornering feel



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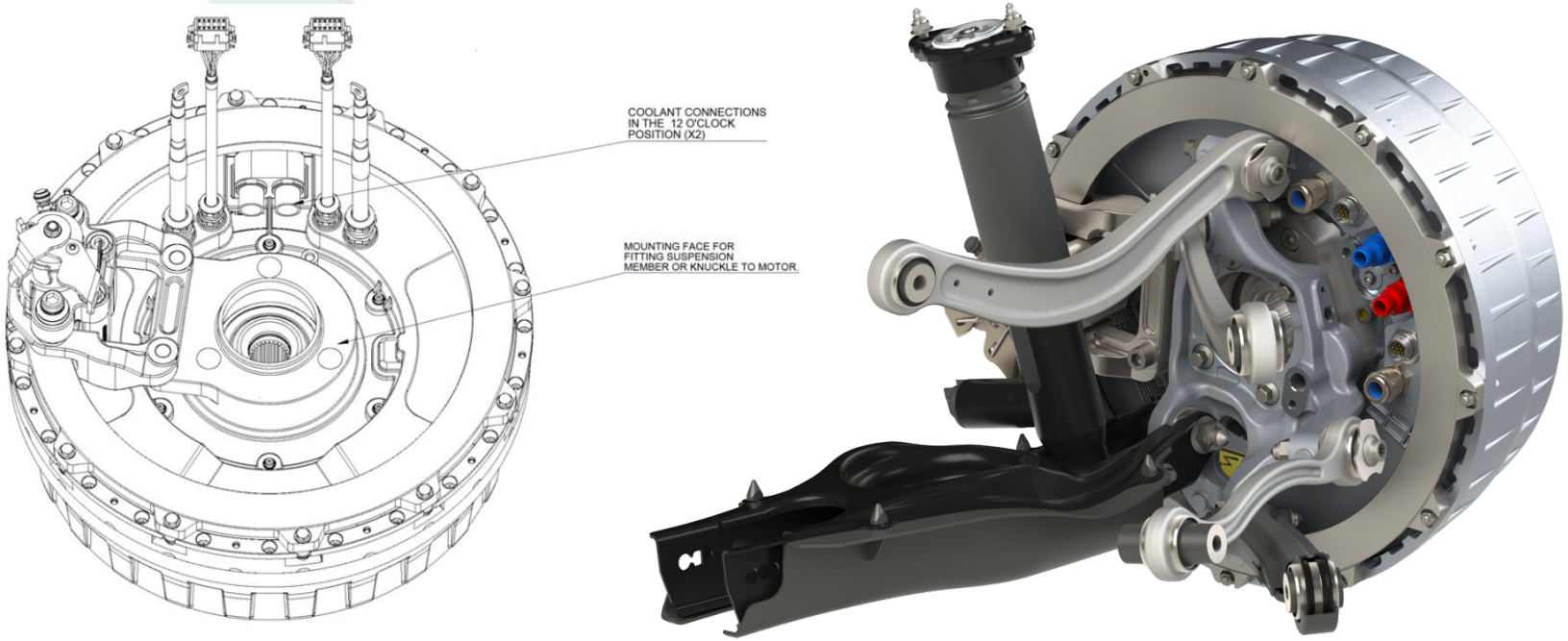
Suspension and Brake Design and Packaging

1. Suspension

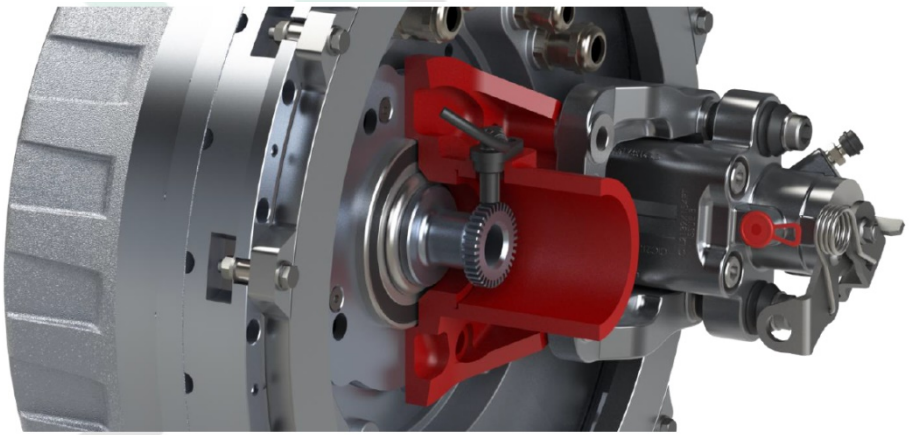
- Small axle mounting modifications may be required, such as using an adapter plate.
- The **Protean Drive™** motor can be configured to accept customer-specific bearings and adapter plates. Refer to below picture for the concept of using an adapter that attaches to both the motor and to a vertical suspension member on your vehicle (if necessary).
- In its standard form the **Protean Drive™** motor is supplied with an adapter plate that attaches the motor to the vehicle via the mounting face as indicated in the diagram below.

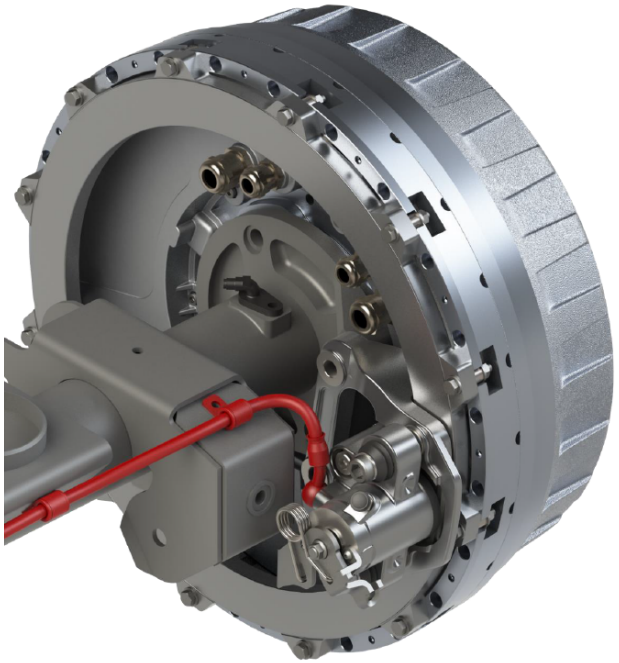


Suspension and Brake Design and Packaging

2. Brake Design

- The **Protean Drive™** motor is available with an integrated friction brake which has been developed in conjunction with Alcon Components Ltd.
- The solution re-packages the brake disc onto the rotor of the in-wheel motor and thus transfers its torque via the rotor into the wheel.
- The axle design would accommodate mounting bosses for ABS sensors on each rear wheel. A small shaft with a toothed wheel would be mounted in the centre of the wheel bearing to provide the speed signal.

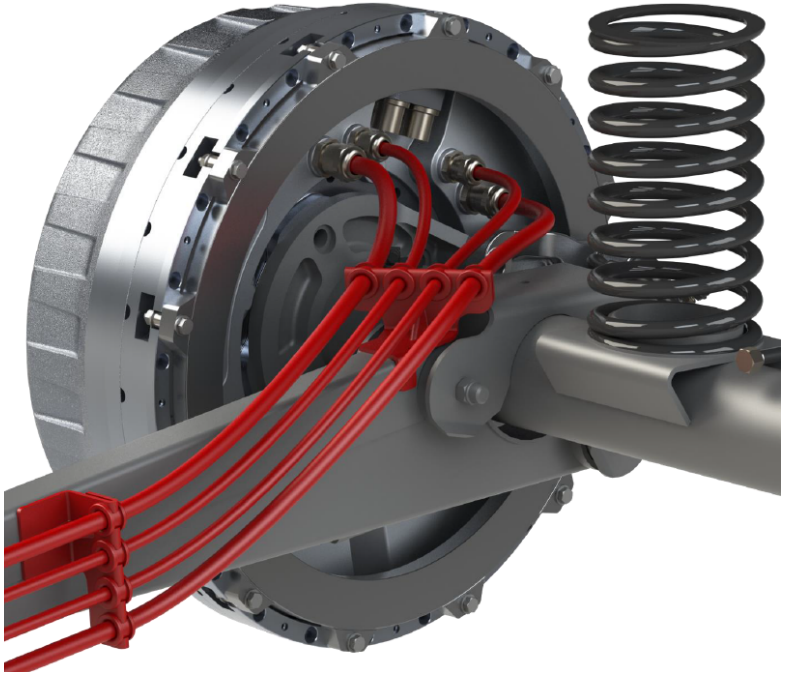




Suspension and Brake Design and Packaging

3. Packaging

- Custom adaptor would convert **Protean Drive™** motor bolt pattern to standard wheel rim bolt pattern to allow the same wheel to be used on all four corners.
- Axle design would feature guide brackets to route the power and control cables safely along the suspension trailing arms. This would allow the cables to transfer to the chassis at the point where the suspension travel is minimised, reducing the amount of flex in the cables.



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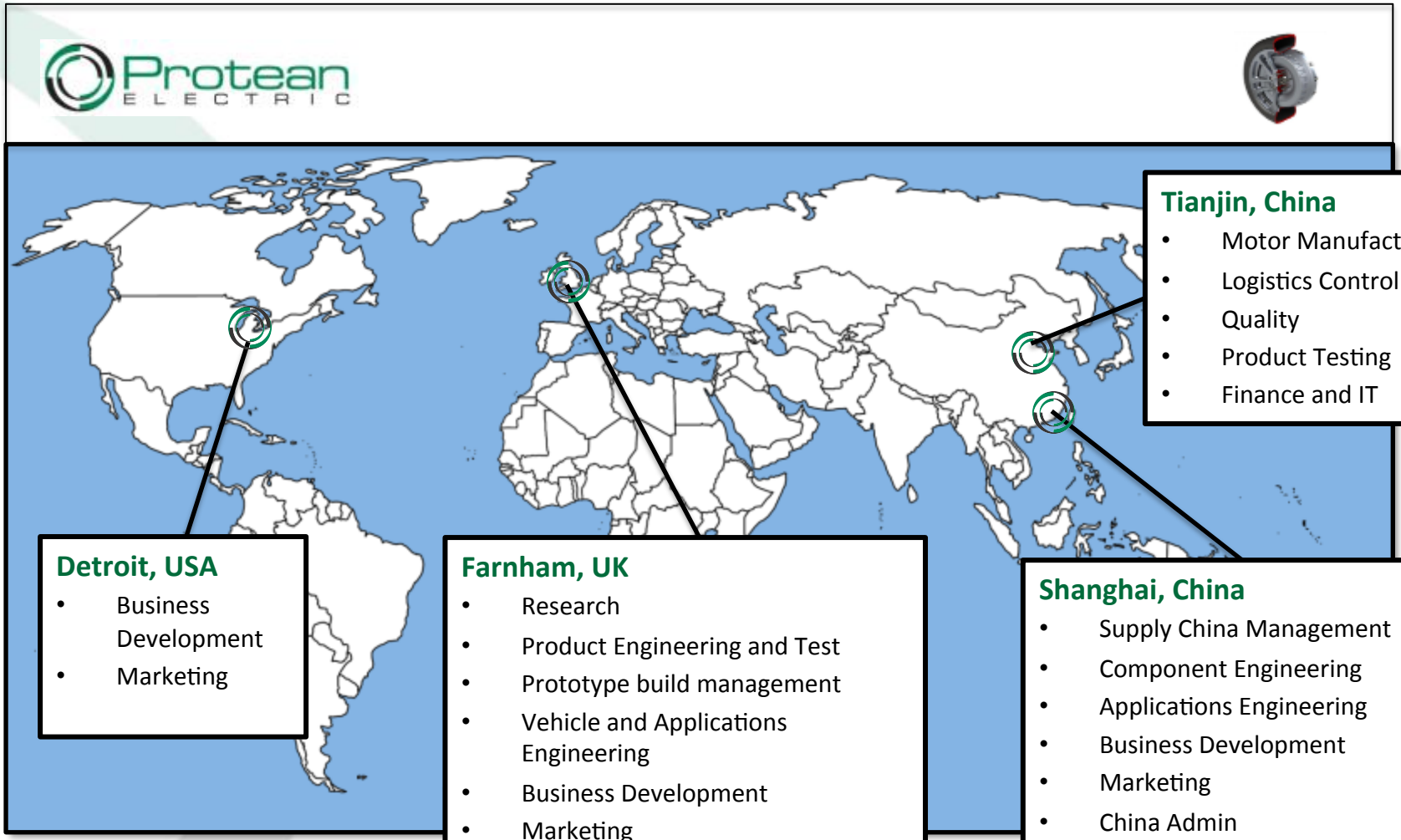
Company Overview

- **Protean Electric Vision**
  - Leading global supplier of in-Wheel and compact electric motor technology
- **"Best in Class" and Proven Technology**
  - Best performing and only validated IWM on market
  - Excellent for Electric, Plug-In Hybrid, and Range Extender Hybrid New Energy Vehicles
  - Technology architecture adaptable to other applications where technology gives advantages
- **Company Goals**
  - Lead the Industry with Technology
  - Low volume production in-house
  - License Technology to the industry for high volume production

Global Capabilities



Production Motor Specifications

- In-wheel, direct drive
- Permanent magnet synchronous motor
- Outer rotor
- Integrated inverter and control
- Water/glycol cooling
- 1600 rpm top speed
- Fits into 18” conventional wheel rim
- Integrated friction brake
- 35 kg mass per motor
- Torque control over CAN
- 200 - 400 Vdc Operating Range
- 300,000km and 15 year life*
- Fully compliant to all Automotive Environmental Requirements
- Developed according to ISO26262

	Torque	Power
Peak	1250 Nm*	75 kW
Continuous	650 Nm	54 kW

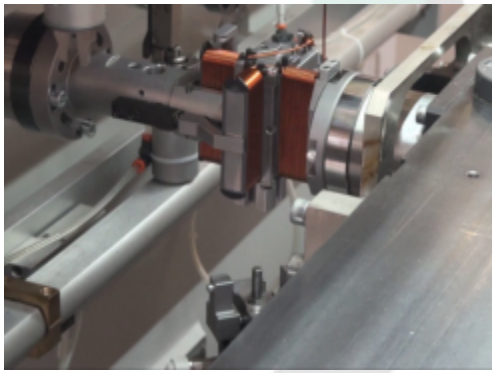
* Available Q1 2016

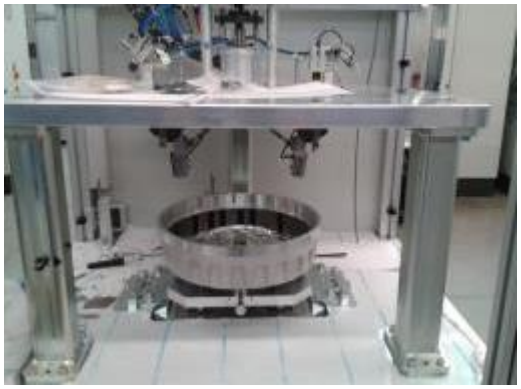
Key Partners Summary

- **Key partners supporting our Protean Technology**
  - **SKF** - bearing systems, sealing and sensor integration
  - **Mahle Powertrain** - vehicle integration
  - **Alcon Components** - brake
  - **Trelleborg Sealing Solutions** - seal
  - **AB Mikroelektronik** - power and control electronics
  - **FEV** - testing and automotive engineering services
  - **MIRA** - ISO26262 support
  - **Prodrive** - hazard analysis on-track verification
  - **Millbrook Proving Ground** - vehicle testing
  - **UK Universities** - vehicle modeling and motor design support

Production Motor Manufacturing

- Motor is designed for manufacture from outset
- Tools for small series line developed with European partners
- All critical assembly processes have tooling in place with 2 years of manufacturing trials completed
- Rotor production in China since 2014
- Tianjin WOFE registered and building leased
- Full motor production at Tianjin site by Q2 2016





MARSILLI

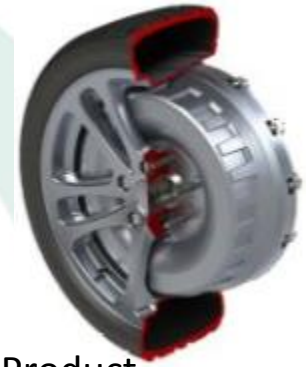
ATS

HÜBERS

Protean Drive – a Scaleable Technology

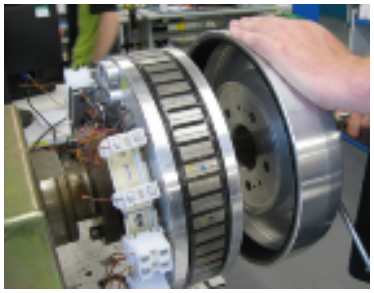
- **Protean Drive Technology can become bedrock of clean transport and energy**

PD18



- Launch Product
- Mainstream Passenger Cars and LCV
- 1250Nm/75kW peak per motor

PD16



- Bench prototype
- Mainstream Passenger Cars and LCV
- Up to 700Nm/50kW Peak per motor

PD14

- Product concept complete
- Micro EV Market
- Up to 400Nm/20kW peak per motor

Automotive

- PDXX for Medium/Heavy duty commercial vehicles
  - Concept studies carried out
- P2 and P4 Hybrid motors
  - Concept studies carried out

Non - Automotive

- Protean technology applicable to clean energy generation
  - Wind Energy Project underway
  - Concepts for other generation projects carried out

Visionary Design . Practical Solution
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