PROTEAN

Electric Automotive Technology

Protean Electric

Transient lateral performance of a four wheel in-wheel-motor torque vectoring strategy

Director, Applications Engineering China

Contents

Section 1

Introduction to Protean & Protean Drive

We are technology pioneers of the in-wheel motor

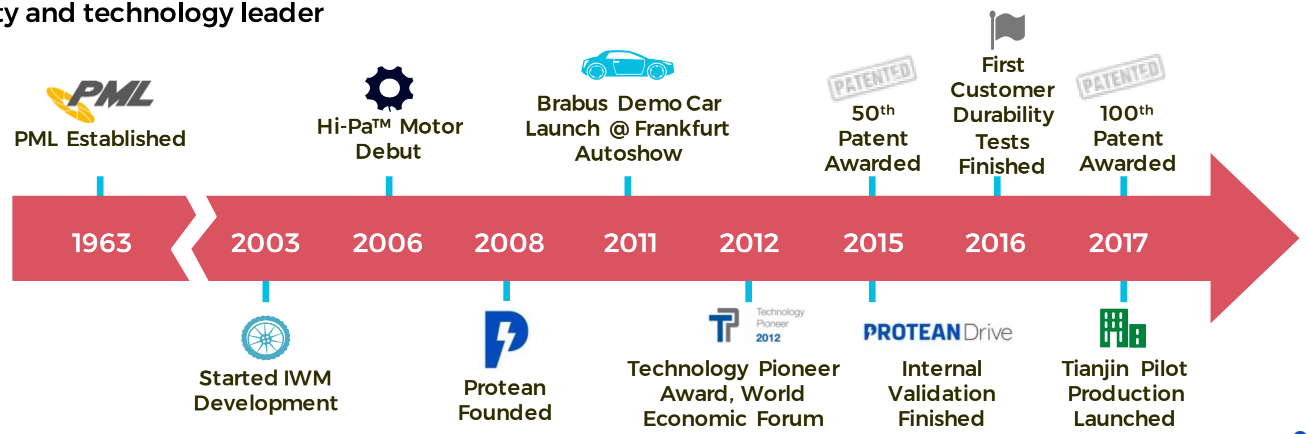
- An automotive technology company and the world leader of in-wheel motors
- Founded in 2008, we are over 100 people based in the US, UK and China
- Our mission is to drive sustainable transport through innovation
- We are at the cusp of accepting business from major OEMs, having successfully tested our motors with OEM’s in China, Europe and the US
- Our motors have driven over 420,000 miles on 31 different vehicle types in all conditions. Over 680,000 miles driven including lab testing

Protean has a strong heritage in innovation

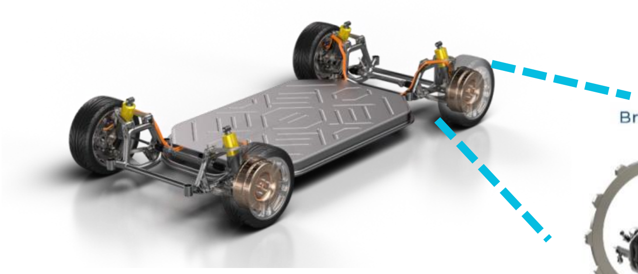
Key highlights:

- Predecessor PML was founded in England in the 1960s and specialized in low-profile motors using printed armatures:
  - PML was acquired by a group of entrepreneurs and began focusing on in-wheel motor development in 2003
  - The Hi-Pa™ in-wheel motor developed by PML debuted in 2006 and was subsequently demonstrated on the Ford F-150, Volvo C30 and BMW Mini Cooper. This was the foundation of our motor development
- In 2008, Protean was formed out of PML to focus 100% on in-wheel motor technologies:
  - Protean Holdings Corp is a U.S. company which was formed in 2009
  - Financial support provided by charter investor, Oak Investment Partners
- Protean's strategy and focus for its products have been consistent since formation:
  - In-wheel motor with integrated electronics
  - Direct-drive with permanent magnets and no gears
  - Best-in-class quality and technology leader

Development Timeline:



It has taken us 10 years to develop ProteanDrive



ProteanDrive:

- All our in-wheel motors have integrated electronics, braking and digital control
- Design achieves both “In-Wheel” and “Direct Drive”
- We have partnered with automotive brake system suppliers to provide fully functional friction brake solutions which can be customized for specific vehicle applications
- Provides customers with the closest solution to a “Plug and Play” option available today

The conceptual advantages of in-wheel motors are clear

Range & Efficiency: Drive Longer

- In-wheel motors remove efficiency losses associated with gear, differential and CV joints situated around the vehicle

Meaning
- Greater range
- Reduced running costs
- Lower charging frequency

Driving Experience: Better Handling

- Individual wheel motors allow torque distribution to different wheels (torque vectoring)

Meaning
- Improved driver experience
- Enhanced stability and control
- Improved ABS/ESP function

Design Flexibility: Creative Freedom

- In-wheel motors revolutionize car design
- No requirement for existing driveline components means car design is no longer compromised

Meaning
- Flexible vehicle design
- Flexible manufacturing process
- Simpler development of hybrids

Cost Benefits: Production Efficiency

- In-wheel motors with integrated inverters do not require a gear, differential, drive-shafts or external drive electronics

Meaning
- Comparable system cost
- Reduced development cost
- More opportunity for modularity

Today the advantages of ProteanDrive technology are real

Range and Efficiency:

- 3% consumption advantage on EPA regulatory test in a direct power-train comparison (BMW i3) increasing range by 4 miles
- Further 21% increased range on i3 by increasing battery size with space saved by IWM
- 30% lighter than equivalent electric drive-trains (BMW i3)
- Up to 8% efficiency gain when a vehicle is designed with IWM

Driving Experience:

- 5% faster acceleration than BMWi3 by replacing power-train with 2 Pd18 motors
- Torque vectoring allows higher cornering speed, greater stability and smaller turning radius
- 5ms command to delivered torque (over CAN) improves active safety via augmented ABS/ESP

Cost Benefits:

- Competitive vehicle system BOM cost via reduction in part count and battery size optimisation
- The ultimate option in powertrain modularisation -> 2 or 3 part numbers can provide A segment through SUV eDrive, saving Engineering, Supplier Management and Tooling costs
- Low CAPEX manufacturing process to reduce upfront investment

Design Flexibility:

- 100% design freedom. No driveline components = any design is possible to propel
- Easy hybrid conversion. Ability to provide both electric and ICE power to the same wheel
- Ability to provide e-AWD function where central mounted solutions cannot be packaged
- Modularisation of drivetrain to allow a range of vehicles built from one chassis / frame

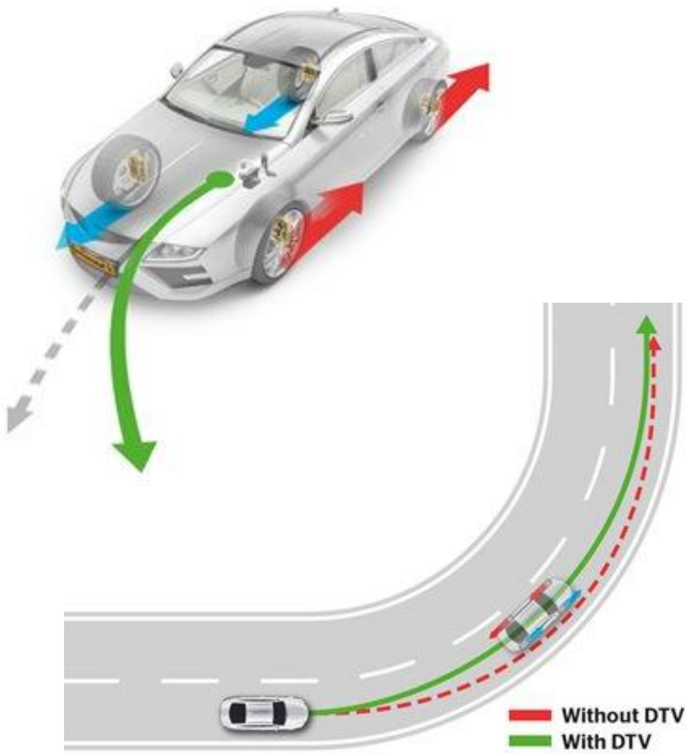
Section 2

Existing Torque Vectoring Applications

Existing Torque Vectoring Applications

- **Dynamic Torque Vectoring (DTV)**
  - DTV is a control function to improve agility and the individual characteristic steering behavior of the vehicle.
  - DTV distributes the drive torque individually to the wheel side – generating a yaw rate around the vertical axis – with the gain of active steering of the vehicle

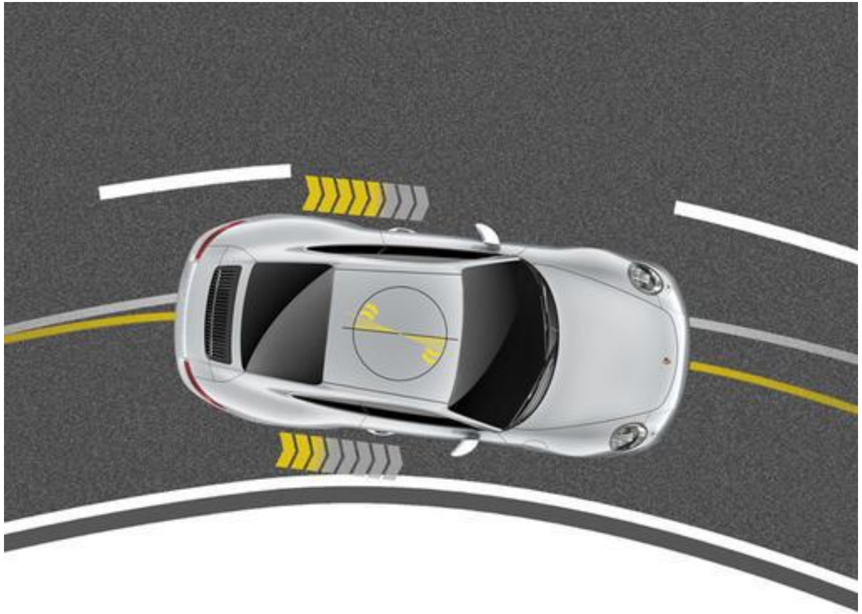
- **Features & Benefits**
  - Changes the self-steering behavior of the vehicle to behave more neutral
  - Reduces driver's steering effort and reaches higher steering precision
  - Increases the agility of the vehicle and supports the vehicle reaction to be more sporty
  - The vehicle follows the driver's intention faster on low and high μ surfaces



Source: https://www.continental-automotive.com/en-gl/Passenger-Cars/Chassis-Safety/Software-Functions/Dynamics/Dynamic-Torque-Vectoring

Existing Torque Vectoring Applications

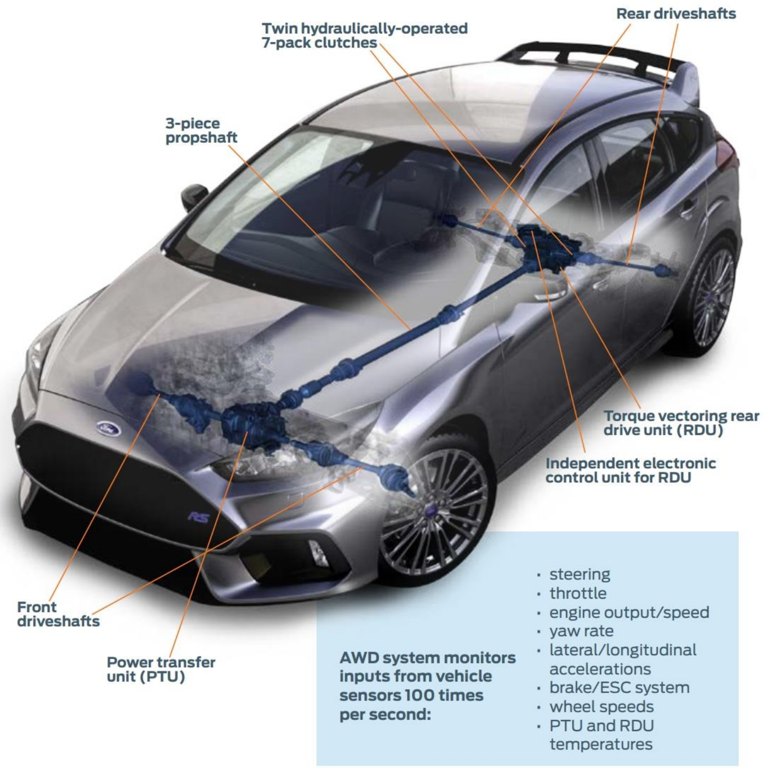
- **Porsche Torque Vectoring (PTV) and PTV Plus**
  - When the car is driven assertively into a corner, moderate brake pressure is applied to the inside rear wheel.
  - Consequently, a greater amount of drive force is distributed to the outside rear wheel, including an additional rotational pulse (yaw movement) around the vehicle's vertical axis.
  - This results in a direct and sporty steering action from the turn-in point.
  - With PTV, the rear differential lock is regulated mechanically, while PTV Plus is equipped with electronic control offering fully variable torque distribution.
  - In interaction with PSM, the system improves driving stability not least on road surfaces with varying grip as well as in the wet and snow.
  - For the driver, this means strong resistance to destabilizing side forces, outstanding traction and great agility at every speed – with precise turn-in and well-balanced load transfer characteristics.
  - What else? Tremendous fun in the corners.



Source: https://www.porsche.com/usa/models/911/911-carrera-models/

Existing Torque Vectoring Applications

- The ground-breaking Ford Performance AWD system features innovative technology to deliver outstanding driving dynamics:
  - twin electronically-controlled clutch packs on each side of the rear drive unit (RDU) manage the front/rear torque split – and the side-to-side torque distribution on the rear axle
  - independent RDU control unit continuously varies the front/rear and side-to-side torque distribution to suit the current driving situation
  - intelligent system monitors multiple vehicle sensors 100 times per second
  - a maximum of 70 per cent of the drive torque can be diverted to the rear axle; up to 100 per cent of the available torque at the rear axle can be sent to each rear wheel
  - during cornering, the RDU pre-emptively diverts torque to the outer rear wheel immediately based on inputs such as steering wheel angle, lateral acceleration, yaw and speed
  - to optimise handling and stability, the car's brake-based Torque Vectoring Control is tuned to work in parallel with the torque vectoring AWD system
  - AWD hardware is compact and weight-efficient to maximise vehicle performance



Source: http://drivingspirit.com/ford-focus-rs-dynamic-torque-vectoring-explained/

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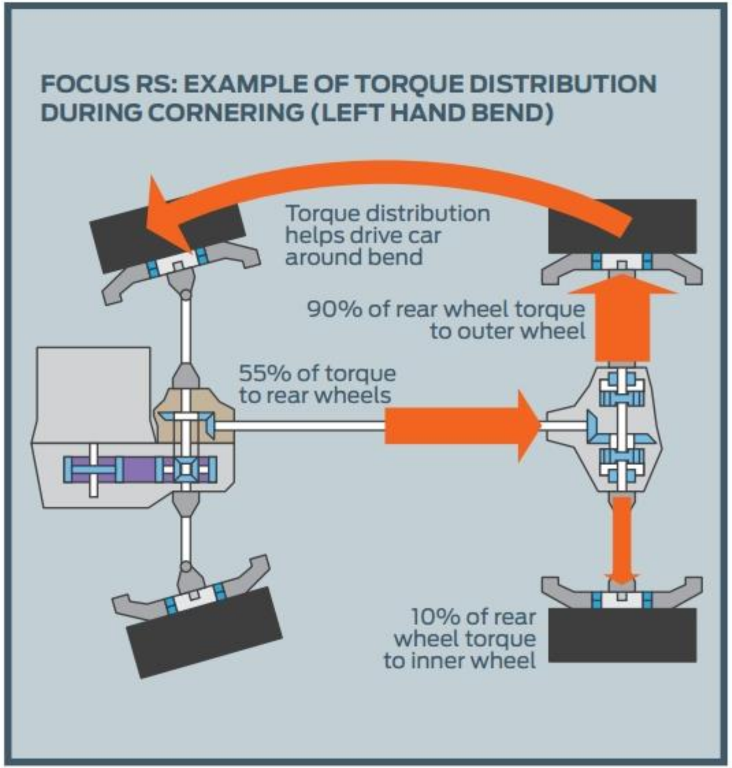

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Section 3

Standard Test Procedures and Initial Result

Protean TV Testing Vehicle

- Benz E-class
- 4WD – EV
- 4 in-wheel motors
- Torque vectoring inside

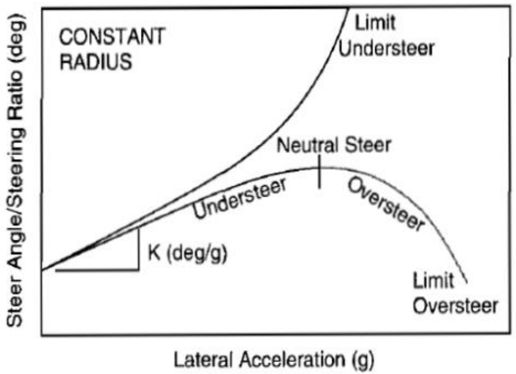
Standard Test Procedures

- Steady State Circular Driving Behaviour (BS ISO 4138:2012)

  - Three main test methods:
    - Constant radius
    - Constant steering wheel angle
    - Constant speed

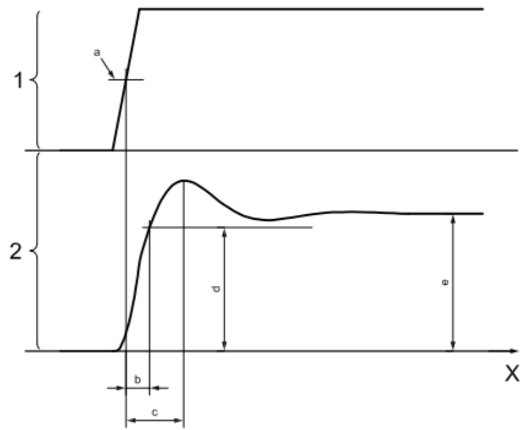
  - Constant Radius Test Measurements:
    - Longitudinal velocity
    - Lateral acceleration
    - Steering wheel angle

  - Understeer gradient (K) estimation:
    - Steer Angle (deg)/ Lateral Acceleration (g)
      - K > 0 – Understeer
      - K = 0 – Neutral steer
      - K < 0 - Oversteer



Standard Test Procedures

- Lateral Transient Response Behaviour (BS ISO 7401:2011)
  - Two main test methods:
    - Time domain:
      - Step input
      - Sinusoidal input
    - Frequency domain:
      - Random input
      - Pulse input
      - Continuous sinusoidal Input
  - Test Measurements:
    - Longitudinal velocity
    - Lateral acceleration
    - Steering wheel angle
    - Yaw velocity



Key

1 steering-wheel input
2 vehicle response time
X time

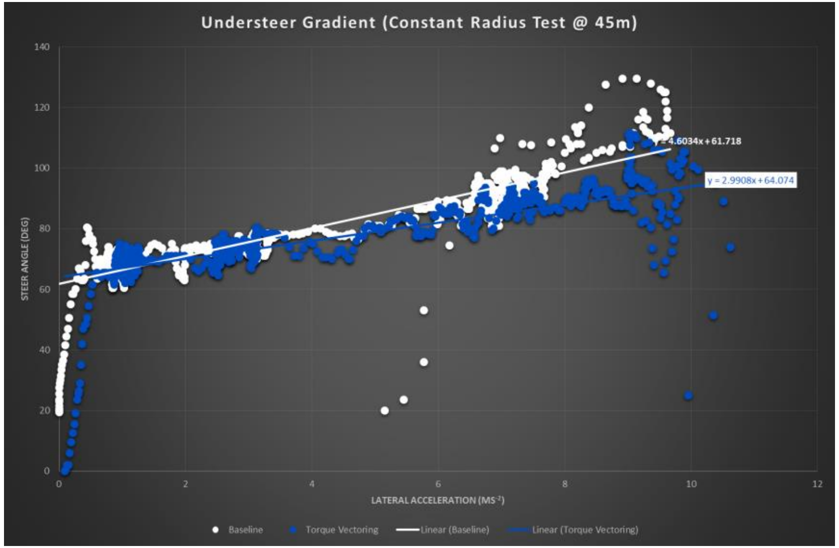
a 50 % level.
b Response time; T.
c Peak response time; Tmax.

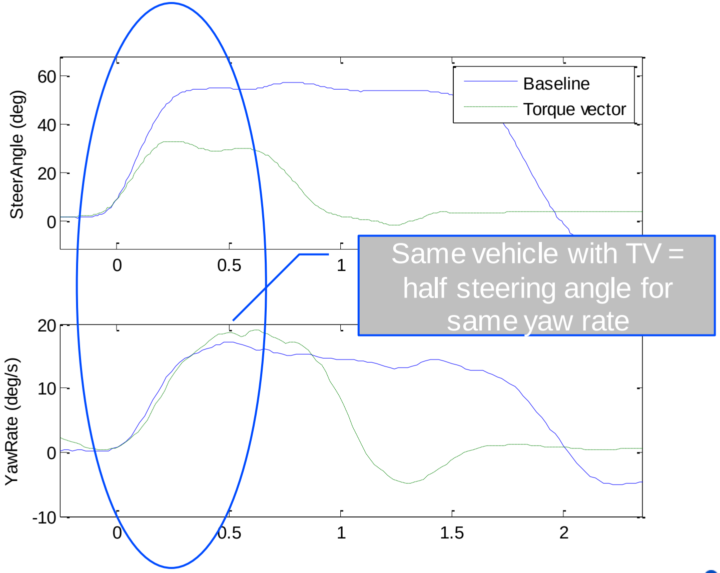
d 90 % steady state.
e Steady state.

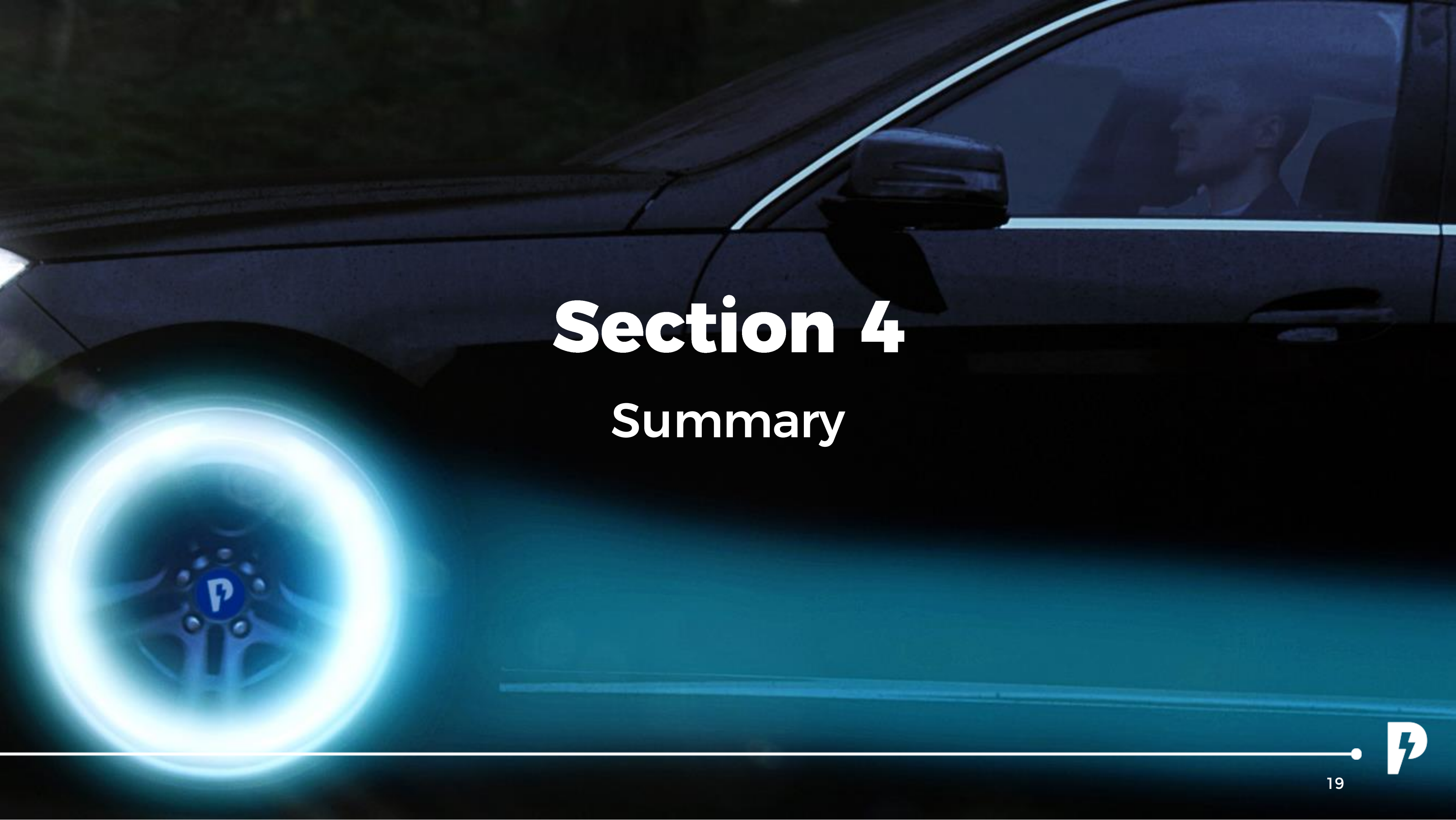
Summary of Results

- Steady State Circular Driving Behaviour
  - Ability to alter understeer gradient by varying torque applied to each wheel

- Lateral Transient Response Behaviour
  - Ability to rapid response (90% of torque demand in 2ms) means that ABS/TC/ESP systems can all be improved





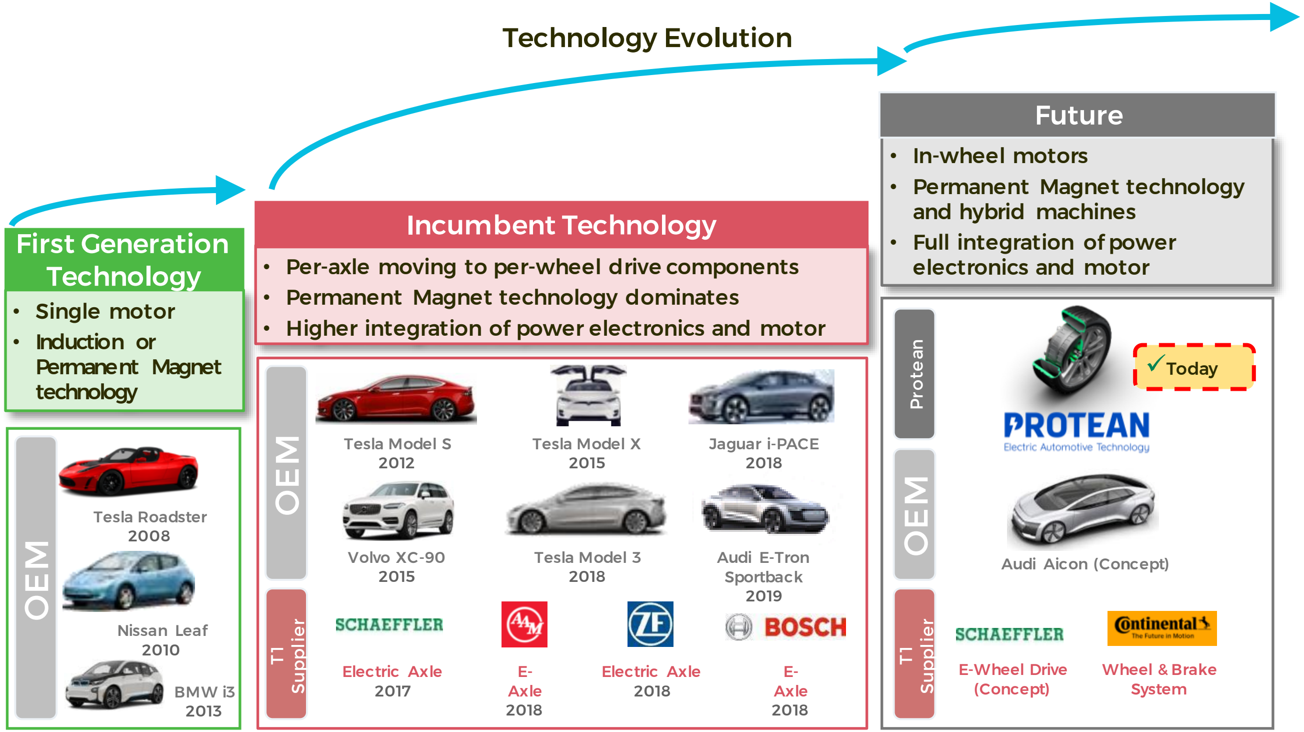


Section 4

Summary

The industry is now moving power closer to the wheel

- OEMs are increasingly placing power closer to the individual wheel
- Tier 1 suppliers are now developing technology to combine motor, transmission and power electronics to support OEM direction



Source: Company materials, press.
Note: Cars presented on this slide are not an exhaustive representation of models in each technology category.

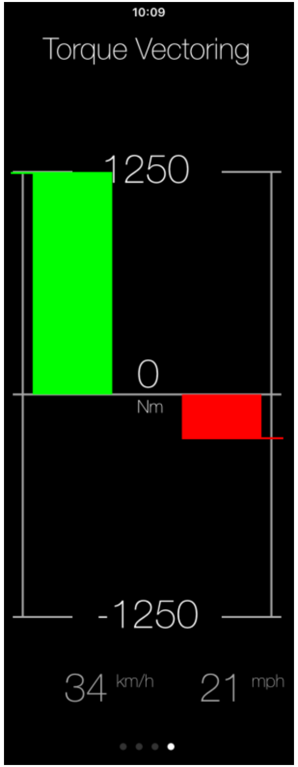
Drivetrain – Individual wheel torque control

- Torque vectoring – means many things and can be implemented in many ways. E.g. active diff, brake control, inboard individual wheel motors etc.

- Can achieve:
  - Improved initial steering response. Good for lane change manoeuvres where building the slip on the tyres can take significant time.
    - Rapid response is harder if sideshafts are involved.
    - Can be achieved by active braking but negative brake torque needs to be offset by increase in power unit torque. Rate of change of this is limited again by sideshafts.
  - Steady state cornering balance (i.e. understeer/oversteer gradient of car)
    - Car dynamic characteristics can be changed by software. E.g. sports mode, town mode etc.
    - Can be achieved with most systems but anything involving friction plates (diff, or brakes) will be energy inefficient.
  - Low speed manoeuvrability
    - Torque vectoring at high steer angles can reduce turning circle by around 10%.
      - Not possible with active diff.
  - Reduced steering effort (system downsizing)

Vehicle Controls

- Control features development focus
  - Regenerative Braking
  - Torque Vectoring
  - Functional Safety
  - ABS/ESP



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Thank you

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