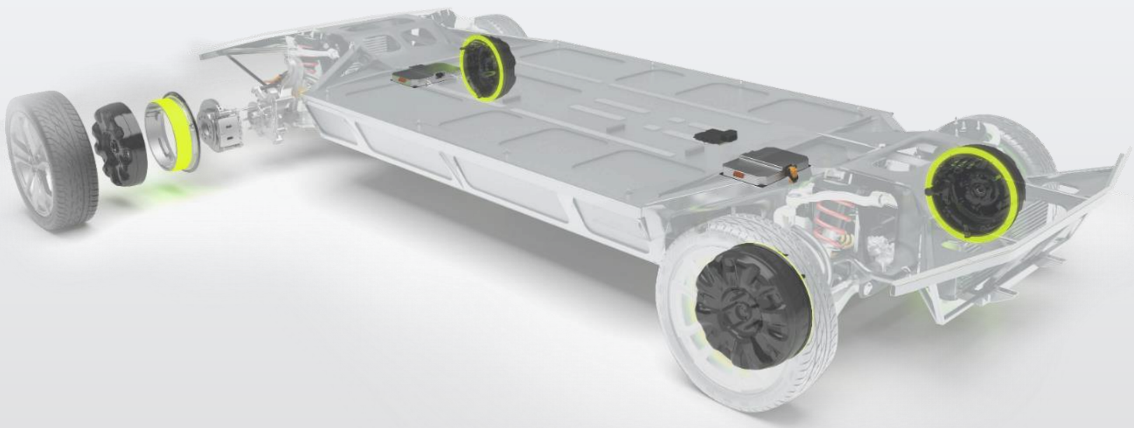
elaphe

Propulsion Technologies

Role of electric powertrain in ultimate comfort and safety…



…for the next-generation EV

Advanced e-motor technology, Munich, February 2023

In a nutshell

Elaphe propulsion technologies

History since 2006

Full system including multiple wheel control

Validated on benches and in 100+ vehicles

First customer vehicles launched

180 dedicated employees

Global presence

Innovative patented solutions

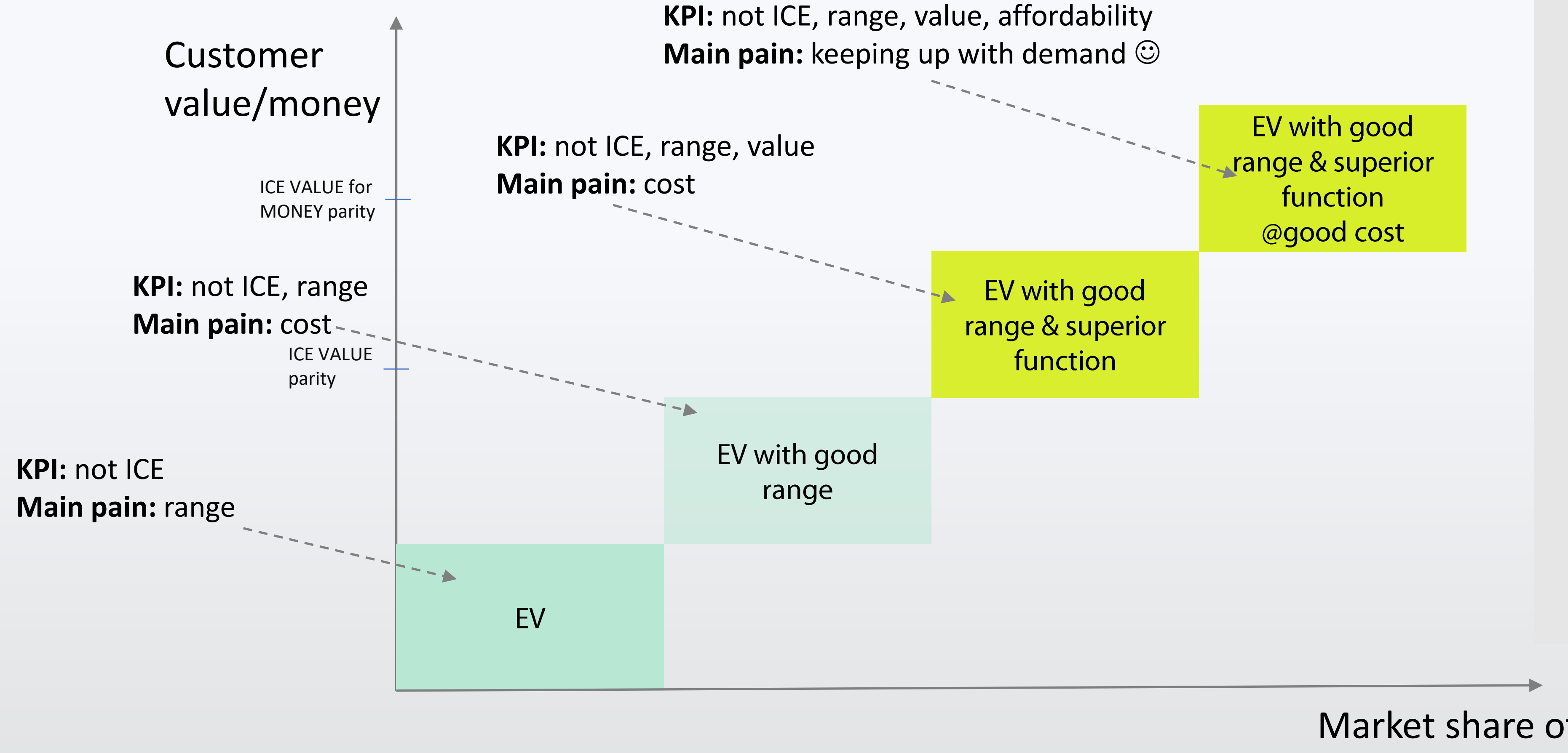
Results

- **Powering a vehicle with >30% improvement of range over state-of-the-art** - Lightyear 0
- **Enabler of new architectures that allow disruptive advantages** - public example: Aptera “Never charge”
- **Extensive in the field robustness and durability tests in extreme conditions** - public example: Lordstown motors
- **Ongoing legacy OEM projects with roadmap to SOP** – several global OEMs



Why comfort and safety?

EV roadmap



+ Value by powertrain:

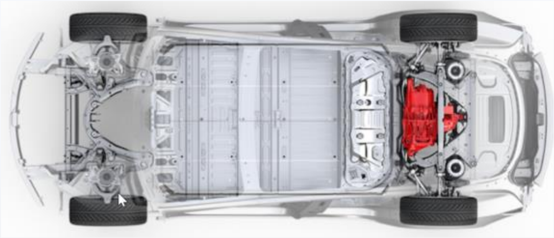
- Performance
- Range
- Agility
- Safety
- Comfort
- Vehicle complexity
- Road data

Drive towards increased EV market share demands improvement in value for money

Adding value

Evolution of the EV architecture

One driven axle

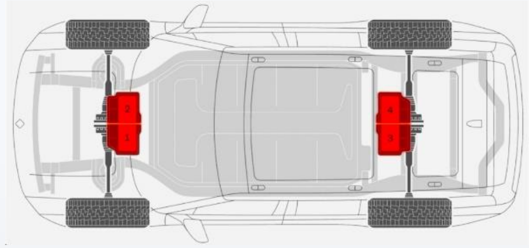


- Range ++
- Vehicle complexity +

RWD + FWD

- Range -
- Performance ++
- Safety +
- Agility +
- Vehicle complexity -

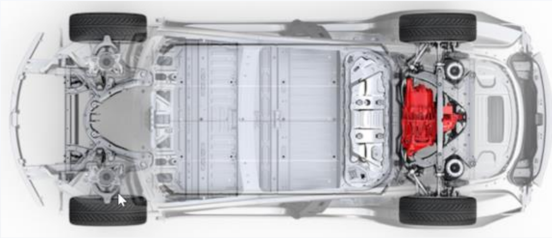
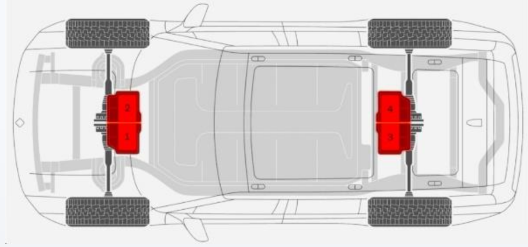
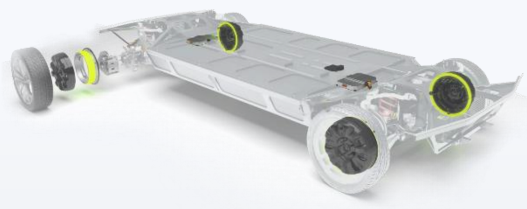
True AWD



- Range -
- Performance ++
- Safety ++
- Agility ++
- Vehicle complexity --

EV architecture is evolving in pursuit of value increase, adding complexity and cost…

Evolution of the EV architecture

One driven axle	RWD + FWD	True AWD	Gearless True AWD
			
• Range ++ • Vehicle complexity +	• Range - • Performance ++ • Safety + • Agility + • Vehicle complexity -	• Range - • Performance +++ • Safety ++ • Agility ++ • Vehicle complexity --	• Range +++ • Performance ++ • Agility +++ • **Safety +++** • **Comfort ++** • Vehicle complexity ++ • Road data ++

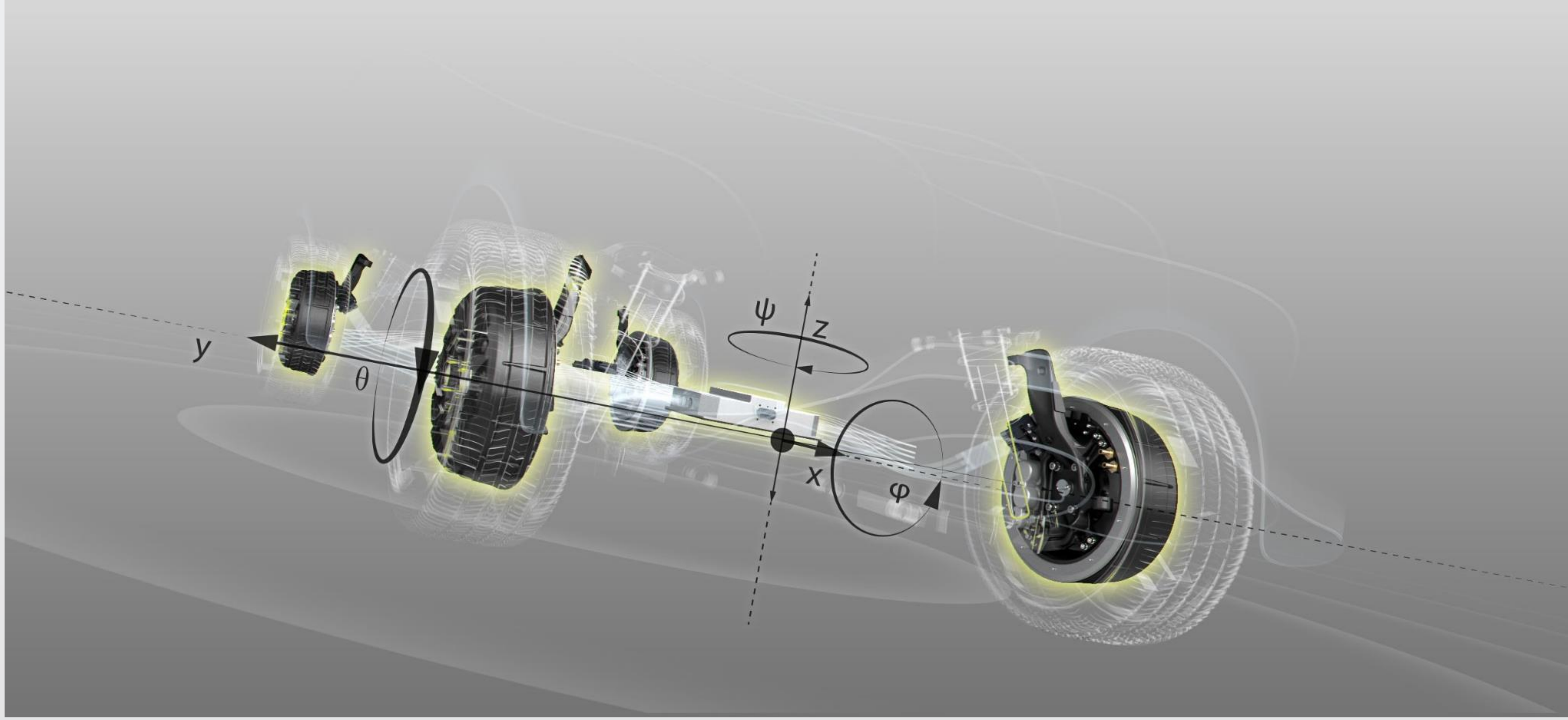
…so novel architectures should provide more value & reverse the complexity trend

The solution

1. Unprecedented torque response time

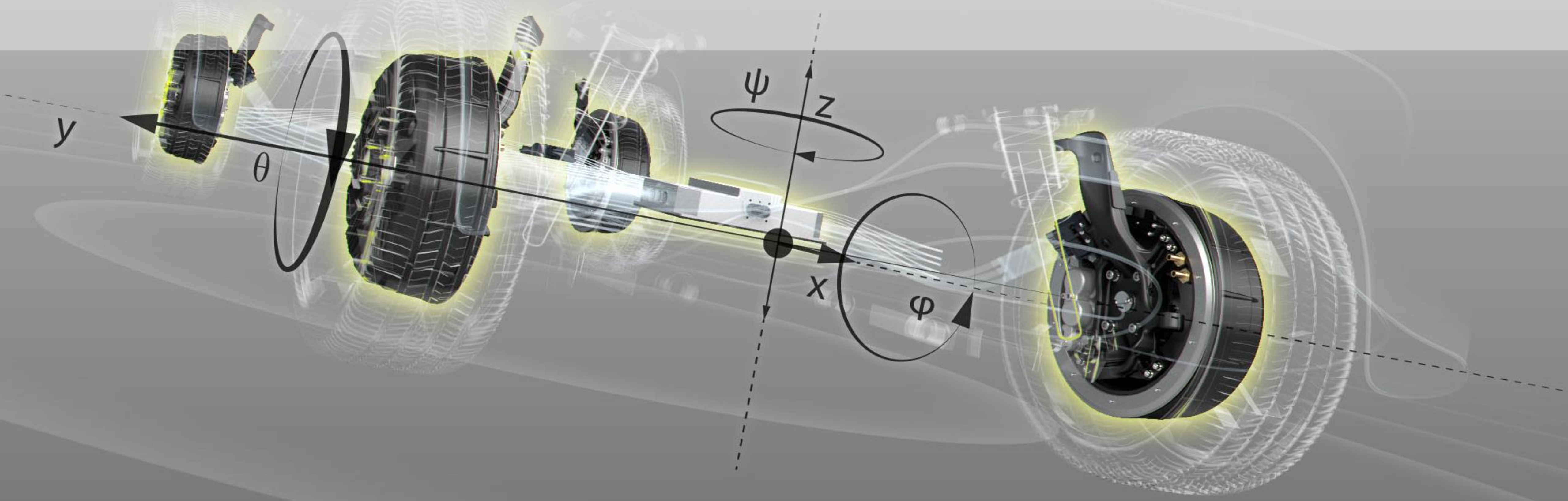
2. Immediate bidirectional torque delivery

3. Accurate and high bandwidth sensing



The solution

Unprecedented torque response time



Motor response time

Electrical time constant

$$\tau_e = \frac{L}{R}$$

Torque response

Mechanical time constant

$$\tau_m = \frac{R\,J}{k_T k_e}$$

Speed response

Torque response is key, but speed response is also a benefit

Electromagnetic torque increase rate

Example for an Elaphe in-wheel motor:

$$\tau = \frac{L}{R} \approx 5\,ms$$

- τe is the electrical time constant (in seconds)
- L is the winding inductance (in henries)
- R is the winding resistance (in ohms)

$$T(t) = \mathrm{T}(0) + \frac{k_T \tau U}{L} * e^{-2t/\tau}(e^{t/\tau} - 1)$$

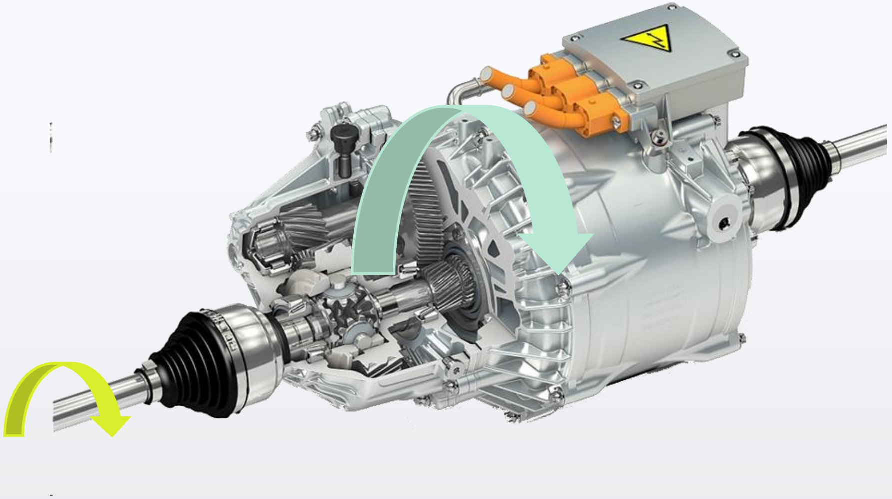
- k_T is the torque constant
- U is the phase voltage

Achievable torque rate ≈ **3500 Nm/ms**

Electrical time constant is not a bottleneck

eDrive torque increase rate

Direct drive
Rotor stiffness determines torque response



eDrive with driveshaft
Many parts contribute, but driveshaft is most influential for torque response

Direct drive torque transfer is much stiffer

eDrive torque increase rate - eAxle

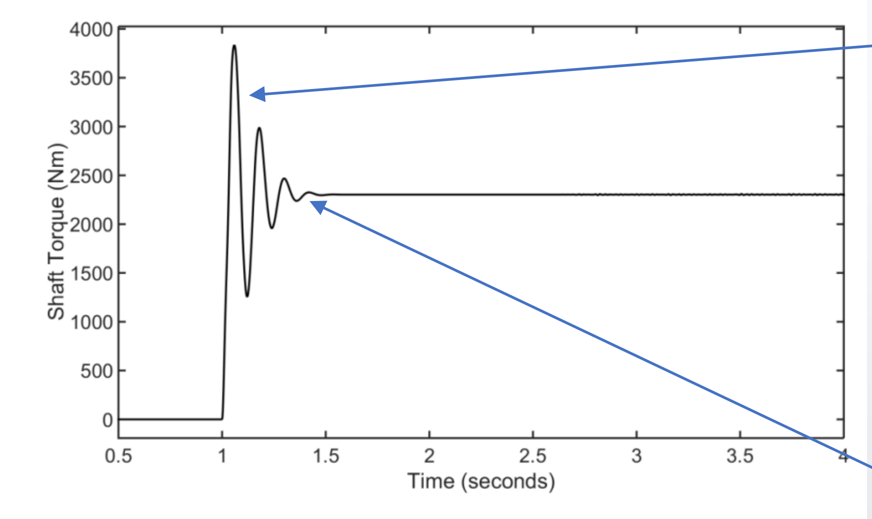


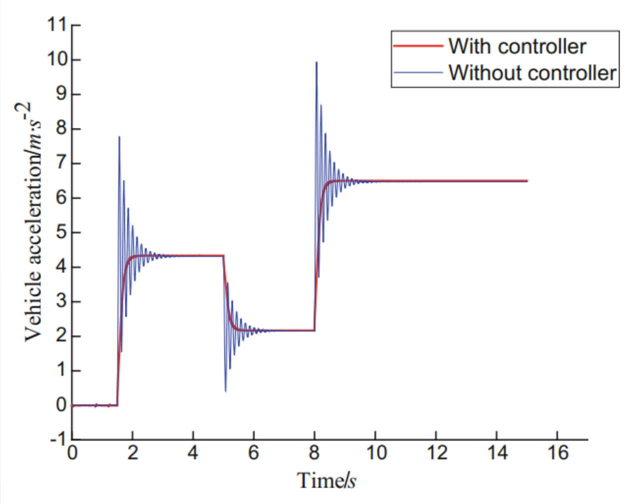
Figure 19. Shaft torque for a step input of 287 Nm for the powertrain model.

~10 Hz shuffle eigenfrequency

400 ms to match input and output torque

Source: VICTOR HERMANSSON & KEDARNATH MOPARTHI, Control of an Electric Vehicle Powertrain to Mitigate Shunt and Shuffle

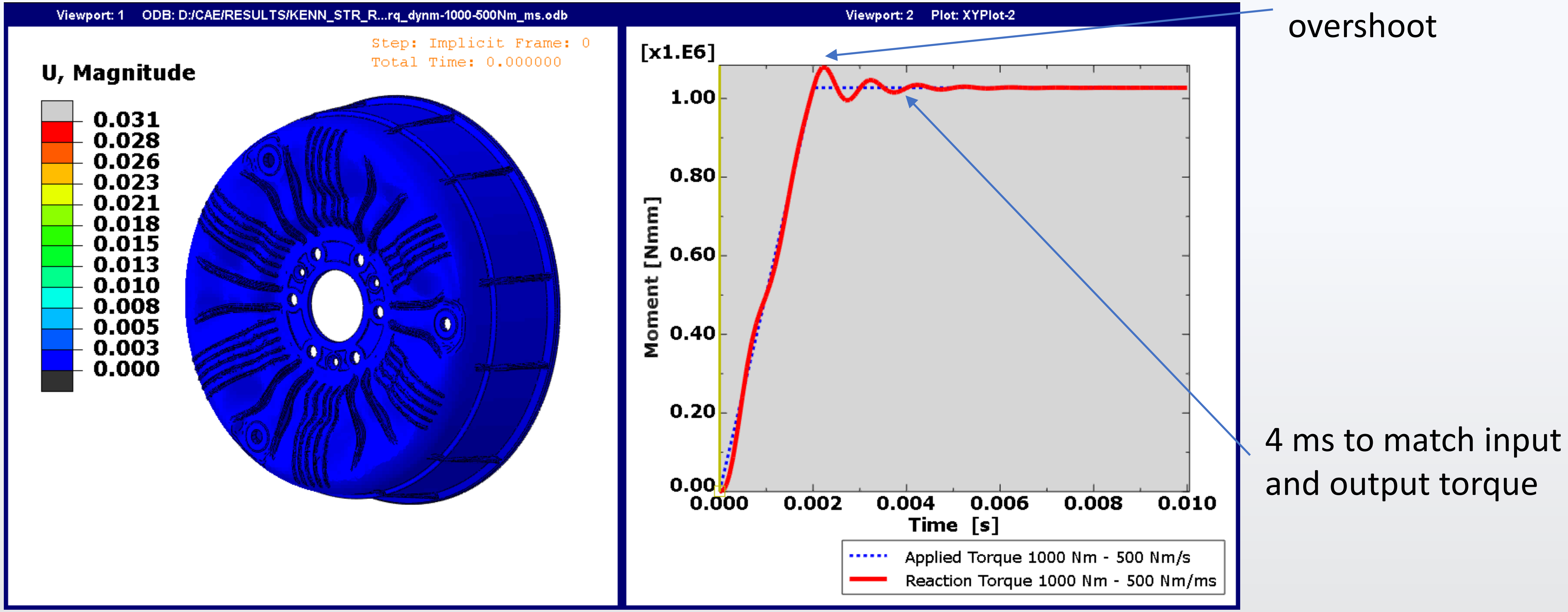
Active control is required to prevent jerk.



With theoretically optimal control 90% of max torque can be reached in 160 ms.

Torque transfer through compliant driveshafts leads to slow torque response

eDrive torque increase rate - IWM



Step response with 500 Nm/ms electromagnetic torque increase rate

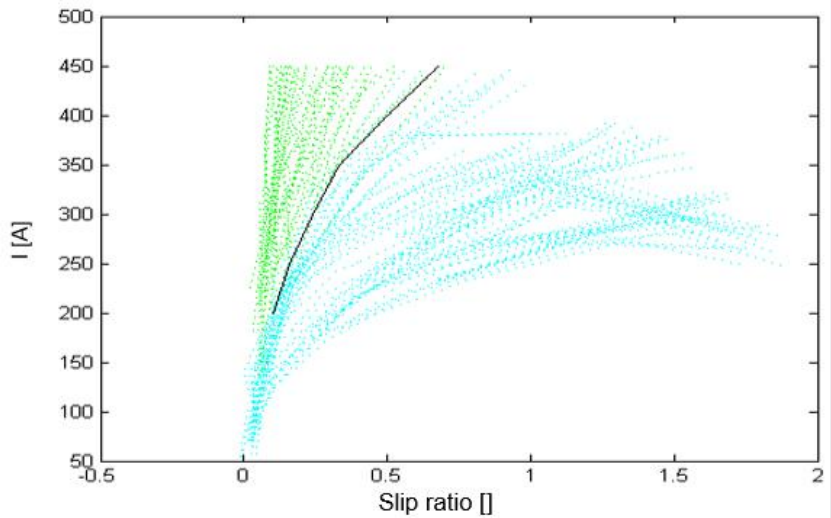
Stiff and direct torque transfer - does not need to be actively controlled

Importance of response time

SAFETY

µ estimation:

- New possibilities for more accurate passive and proactive road grip estimation
- Classification of surfaces
- Recognition of tire condition
- Individual vehicle of fleet use of data



Road grip mapping with high frequency probing (wet vs. dry).
Source: ELAPHE

Road perception

The solution

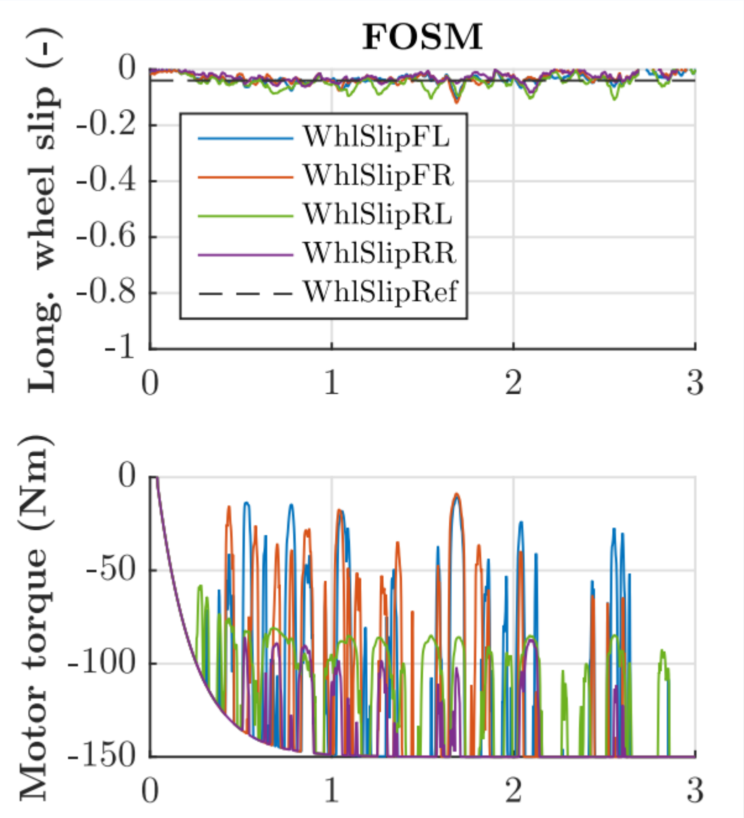
Importance of response time

SAFETY

Braking & traction control:

- Use of new algorithms designed for high bandwidth actuators
- Incorporating superior μ estimation

RESULT =
Up to 15% improvement of stopping distance (low μ, split μ)*



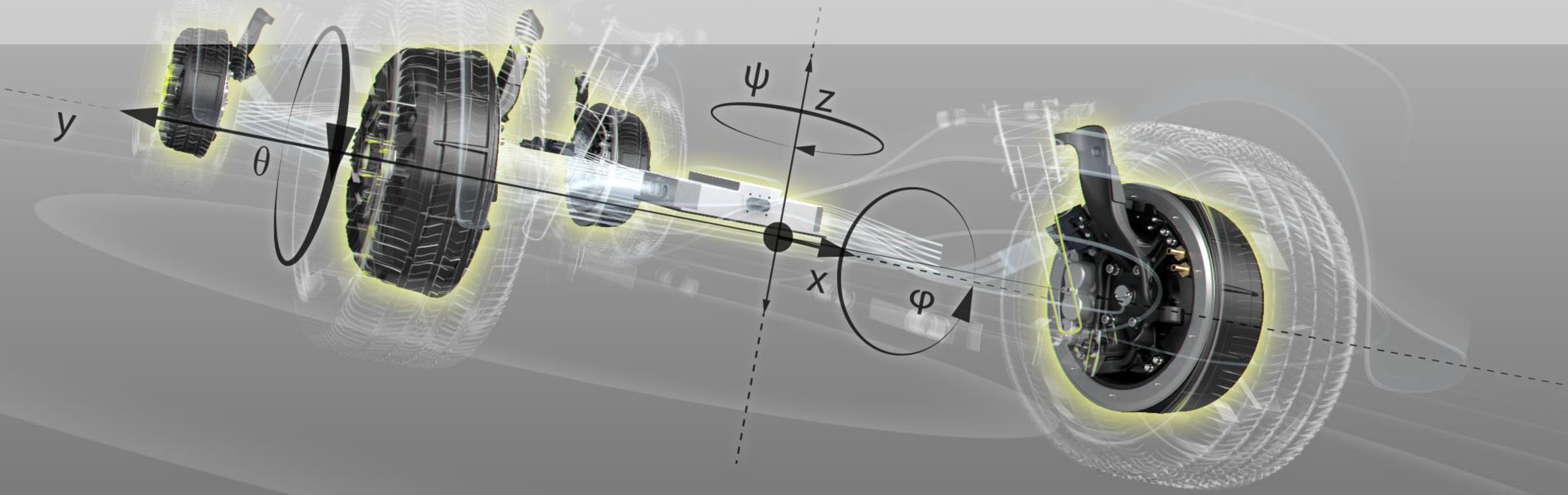
Source: 10.1109/TIE.2019.2942537

Reduced stopping distance and improved stability in braking and acceleration

*DOI:10.1177/0954407019867491

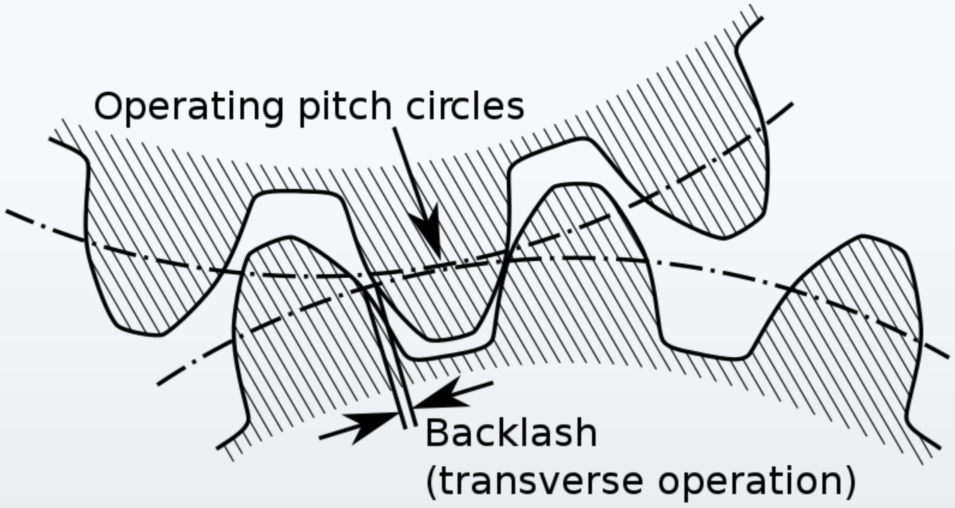
The solution

Immediate bidirectional torque delivery



Transition from positive to negative torque

Direct drive
Change of torque direction is seamless



eDrive with gears
Damage accumulation due to gear knock limits the bidirectionality (bandwidth, cycles)

Bidirectionality is intrinsic for direct drive IWM, but a great challenge geared drives

Importance of bidirectional torque

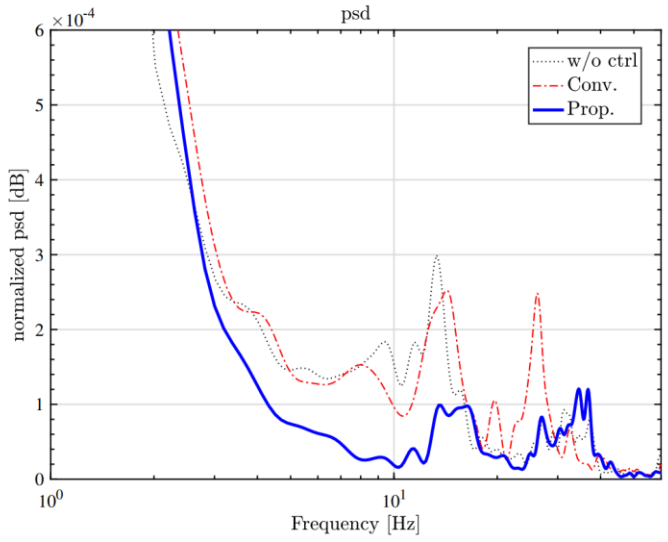


Fig. 13. Experimental comparison of the PSD of the step responses between the conventional method and the proposed method.

Source: 10.1109/AIM.2017.8014069

Secondary mode damping:

- Traction force can be used to generate vertical force
- Vertical force can be use to dampen vibrations but requires fast transitions between positive and negative torque

RESULT =
substantial improvement in comfort during acceleration/deceleration and on uneven road

COMFORT

Control of vibration

Importance of bidirectional torque

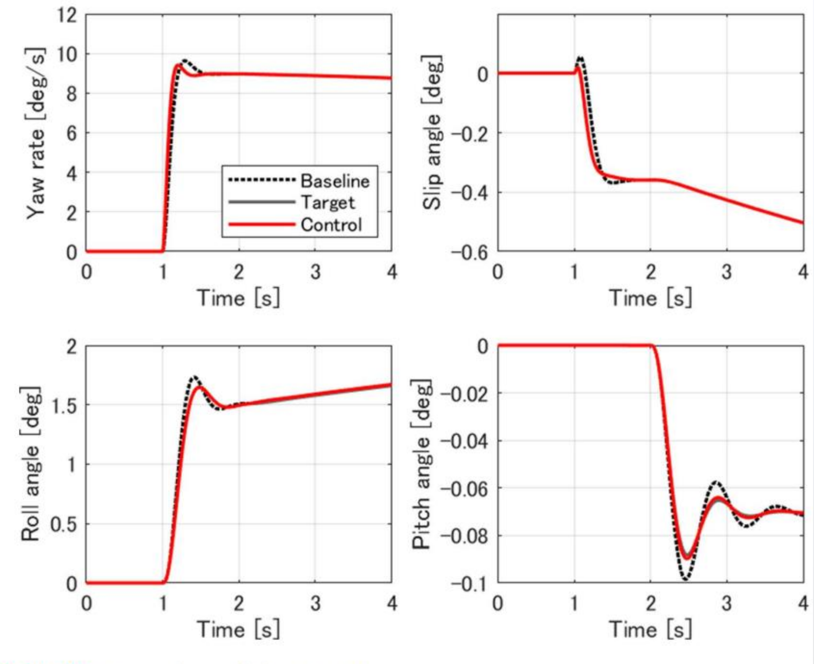


Figure 25. Target and controlled motion (4 DoF).

Source: 10.1080/00423114.2021.1916048;

Vehicle posture control:

- Using same principle with 4 independent IWMs allows control of vehicle posture
- Control of all 6 DoFs including pitch, roll and heave
- Use of wide bandwidth to address different phenomenon

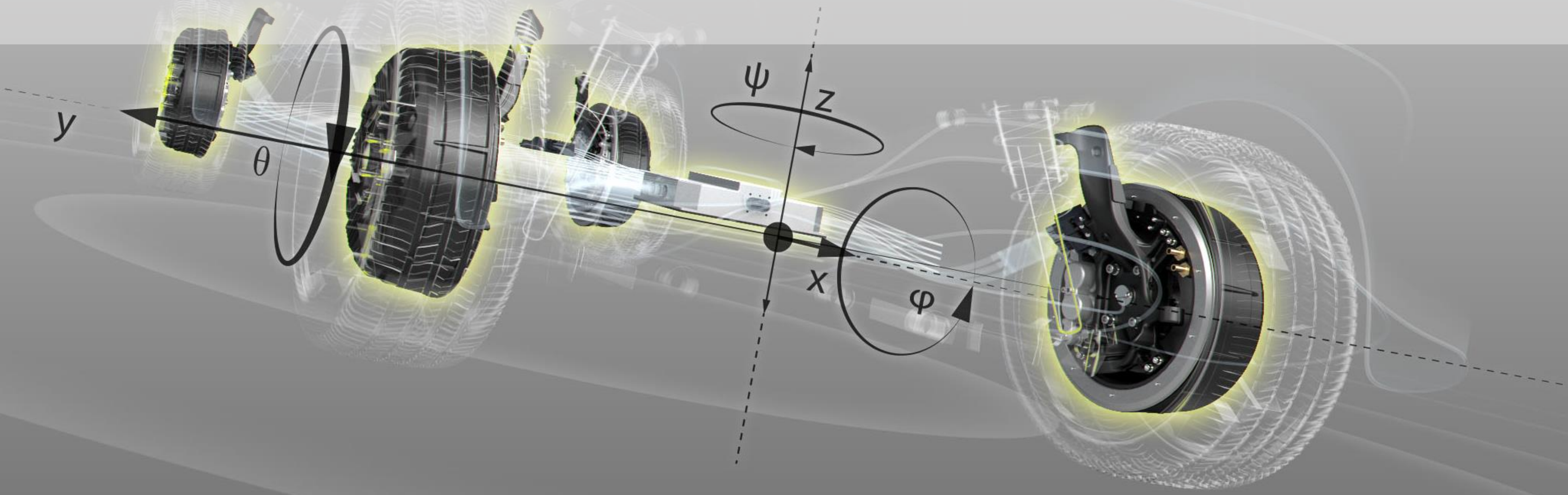
RESULT =
Confirmed 20% improvement in planar motion and 50% improvement in roll and pitch damping coefficients = same as using active suspension!

COMFORT

Removed mechanical constrains unlocks 6 Degrees of Freedom control

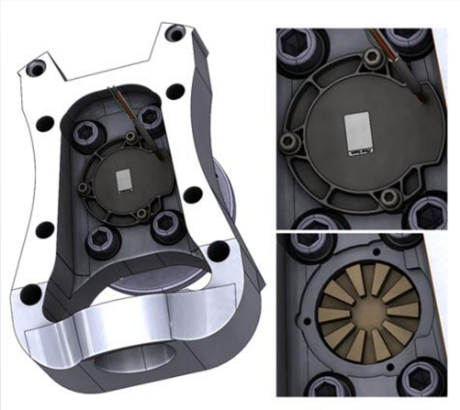
The solution

Accurate and high bandwidth sensing



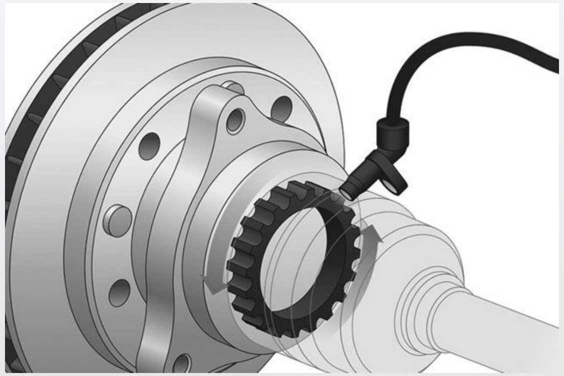
Sensing comparison

- Accurate wheel speed sensing – 0.1° mechanical position resolution
- High bandwidth sampling at all speeds – 10 kHz
- Accurate phase current measurement with high correlation to corner events



In-wheel motor

- SotA wheel speed sensing – 5° mechanical resolution
- Slow sampling bandwidth (@low speeds down to 10 Hz)
- Accurate phase current measurement with low correlation to corner events



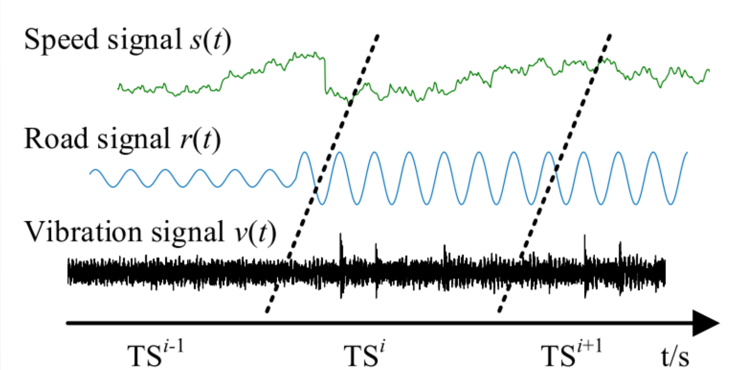
On-board motor

Generating data that can feed into fast and accurate virtual sensors

The solution

Importance of accurate high bandwidth sensing

COMFORT



Example training data for vibration and road profile detection
Source: 10.1109/ACCESS.2019.2935770 ;

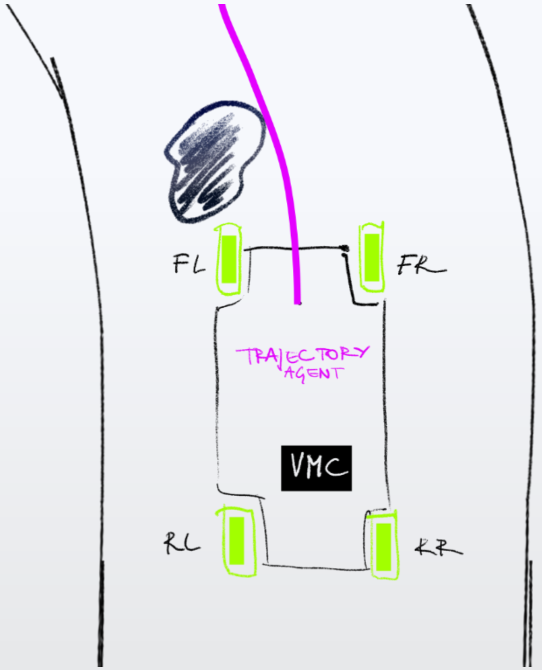
Vehicle and road condition monitoring:

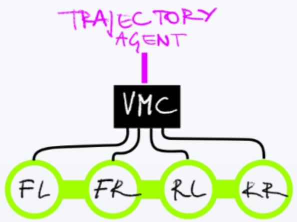
- Support of fast and accurate slip control
- Support of vibration damping functionality
- Fast fault detection (motor, bearing, tire)
- Virtual sensing of other vehicle and road condition parameters (road unevenness, tire wear,…)
- Sensor fusion with other sensors on the vehicle

SAFETY

Virtual sensing is a basis for a dynamic vehicle and environment interaction model

Scenario

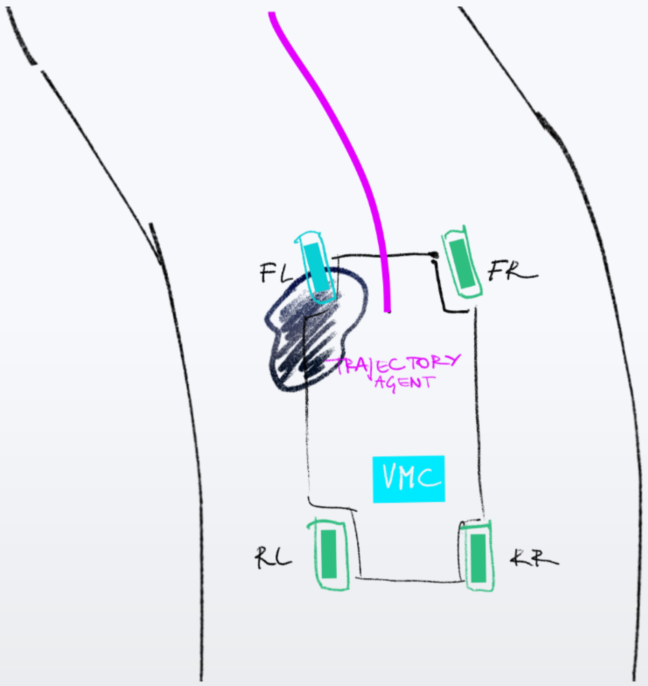


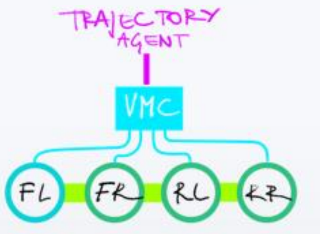


	IWM & CAS	Conventional
Detection-to-command latency	<1 ms	>20 ms
Execution latency	<10 ms	>100 ms
Travelled distance @108 kph	<0,3 m	>3.6 m
Trajectory correction needed	No	Yes
Trajectory correction latency	N/A	100-200 ms in ADAS, >200 ms in humans
Passenger discomfort	No	Yes

Complex edge scenarios reveal importance of bandwidth and agent based system design

Scenario





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Complex edge scenarios reveal importance of bandwidth and agent based system design

Conclusion

Powertrain role in Safety and Comfort

- IWM architecture transcends low bandwidth longitudinal traction functions – it allows 6 DoF vehicle control
- IWM full torque response happens on a millisecond scale as opposed to 100 ms scale
- The result is:
  - Much better sensing of the road conditions
  - Up to 15% improvement in stopping distance
  - More than 50% increase in vehicle secondary mode damping
  - 20% improvement in planar motion and 50% improvement in roll and pitch damping coefficients

Safety and Comfort character of the vehicle becomes SW driven!

SW defined vehicle

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Propulsion Technologies

Pitch control during corner entry for optimal weight distribution

Roll control for a balanced traction

Yaw control for optimal steering

Secondary mode control with traction force

Pitch control during corner exit for optimal acceleration

1 ms slip control in any condition

Most comfortable

Most fun