Real-world to Lab – Robust measurement requirements for future vehicle powertrains

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Agenda and Content

- Introduction
- Motivation and background
- Experimental set-up and testing
- Analysis and Results
- Future direction
- Summary

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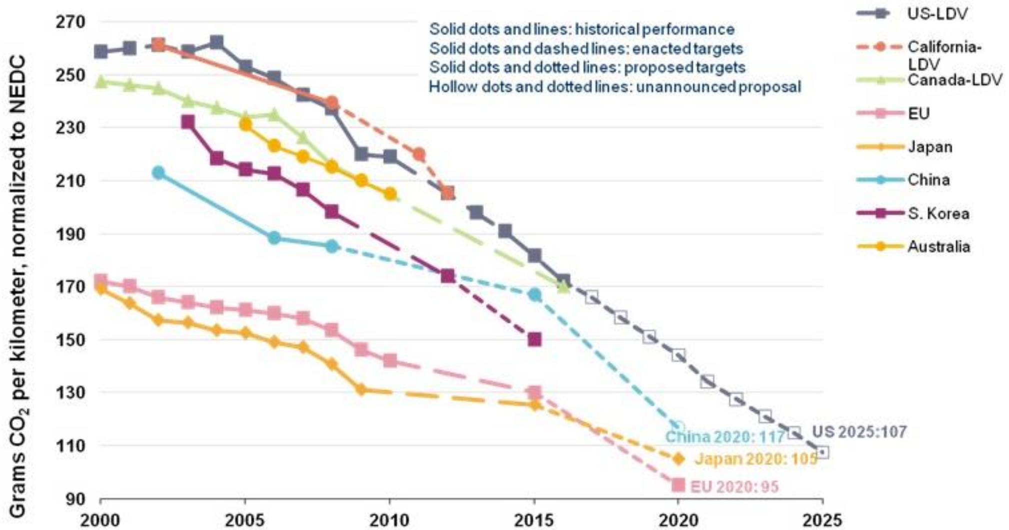
Introduction

- Evolution of the powertrain is underway
- Legislation, Consumers and Manufacturers are continually seeking the following vehicle improvements:
  - Better fuel economy
  - Lower Emissions
  - Higher Performance
  - Lower Cost
- These demands are only going to intensify



[1] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.
[2] US and Canada light-duty vehicles include light-commercial vehicles.

Source: ICCT

Remark: Recalculation in ICCT July 2012 report indicates level of 93g for passenger cars only for the US in 2025. EU's targets are comparitively more stringent. Vehicle definitions are different in the US and EU, and not directly comparable.

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Challenge of Real Driving Emissions

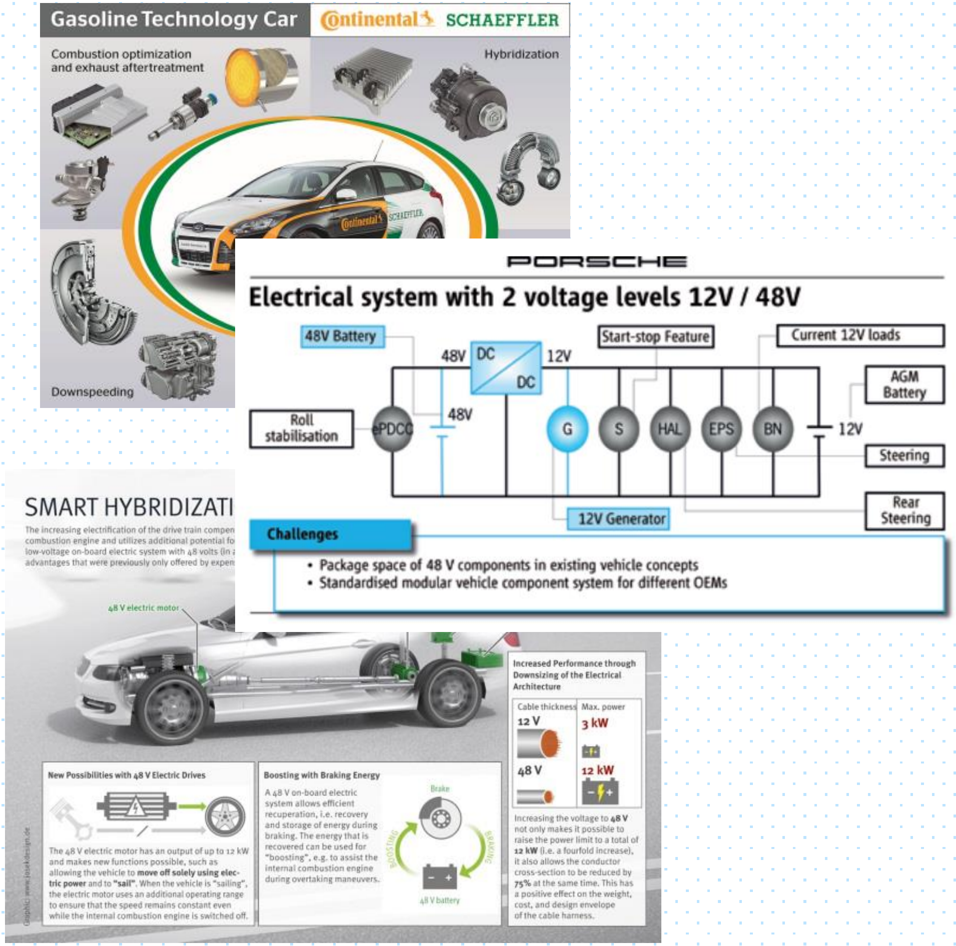
- Implementation of WLTP and RDE in September 2017 to reduce the gap between ‘Lab’ and ‘Reality’
  - More rigorous test procedures

- Main target for RDE controls is NOx and PN emissions.

- Creates new development challenges considering the targets and boundary conditions

- Clear comparison between powertrain architectures is difficult to quantify

Market drive towards electrification



- UK Government proposing minimum 50 mile EV range by 2040 for all new vehicle sales
- Increased complexity leads to increased difficulty for optimisation
- Knowledge of the energy flows is essential in order to optimise the:
  - Hybrid operating strategy
  - Efficiency of the components and control strategy
  - Driveability

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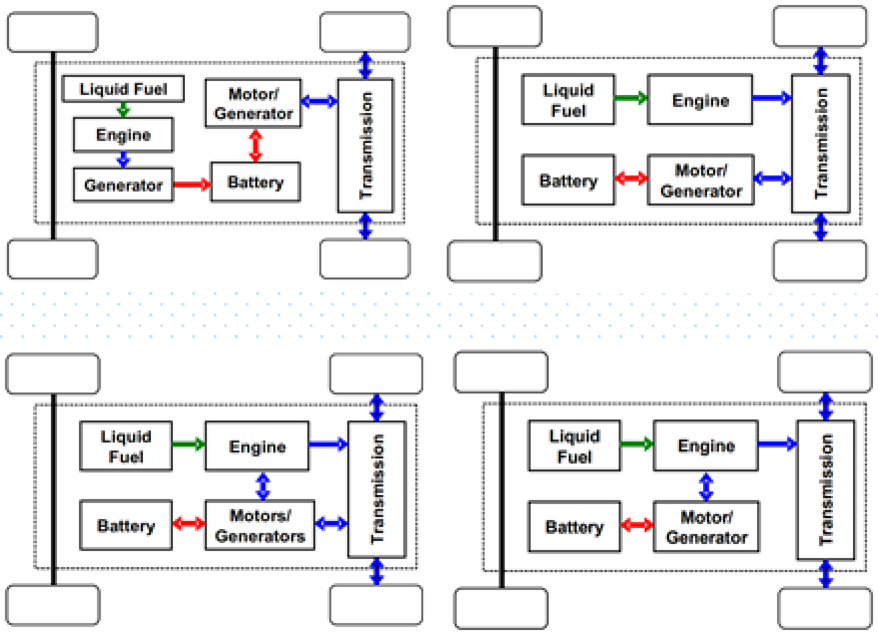
Background

- Propulsion systems for hybrid vehicles can take different forms:
  - Series – de-coupled ICE from output drive
  - Parallel – ICE and EM can provide output drive
  - Series/parallel combinations
- Combinations can become extremely complex combining the benefits of both series and parallel designs
- For each of these hybrid concepts the battery capacity defines the electrical energy availability and therefore re-charging from the grid determines the tailpipe CO_2.
- The propulsion system requires integration into the overall vehicle design at the initial concept phase.



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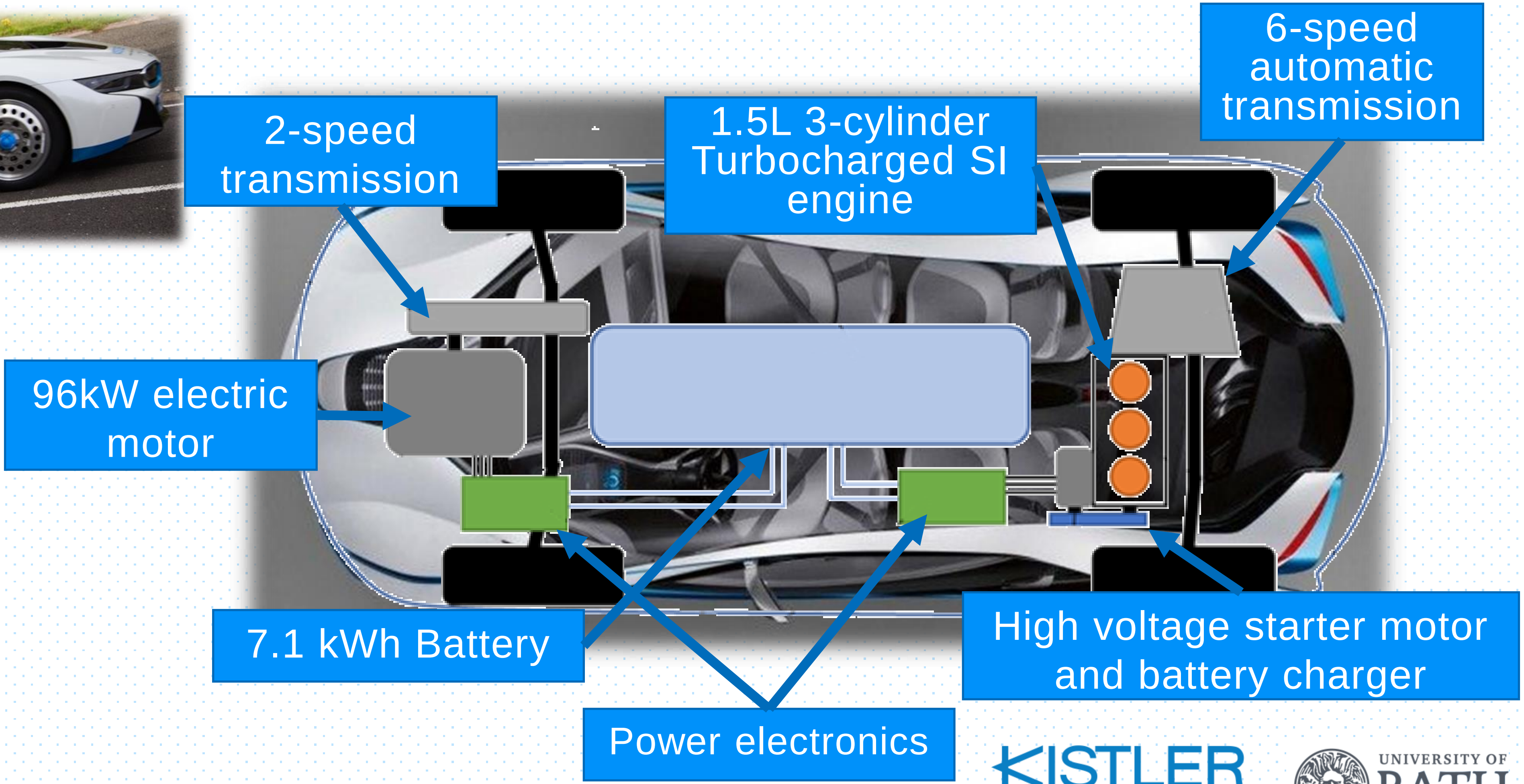
The Test Vehicle

- BMW i8 plug in hybrid vehicle (model year 2016)



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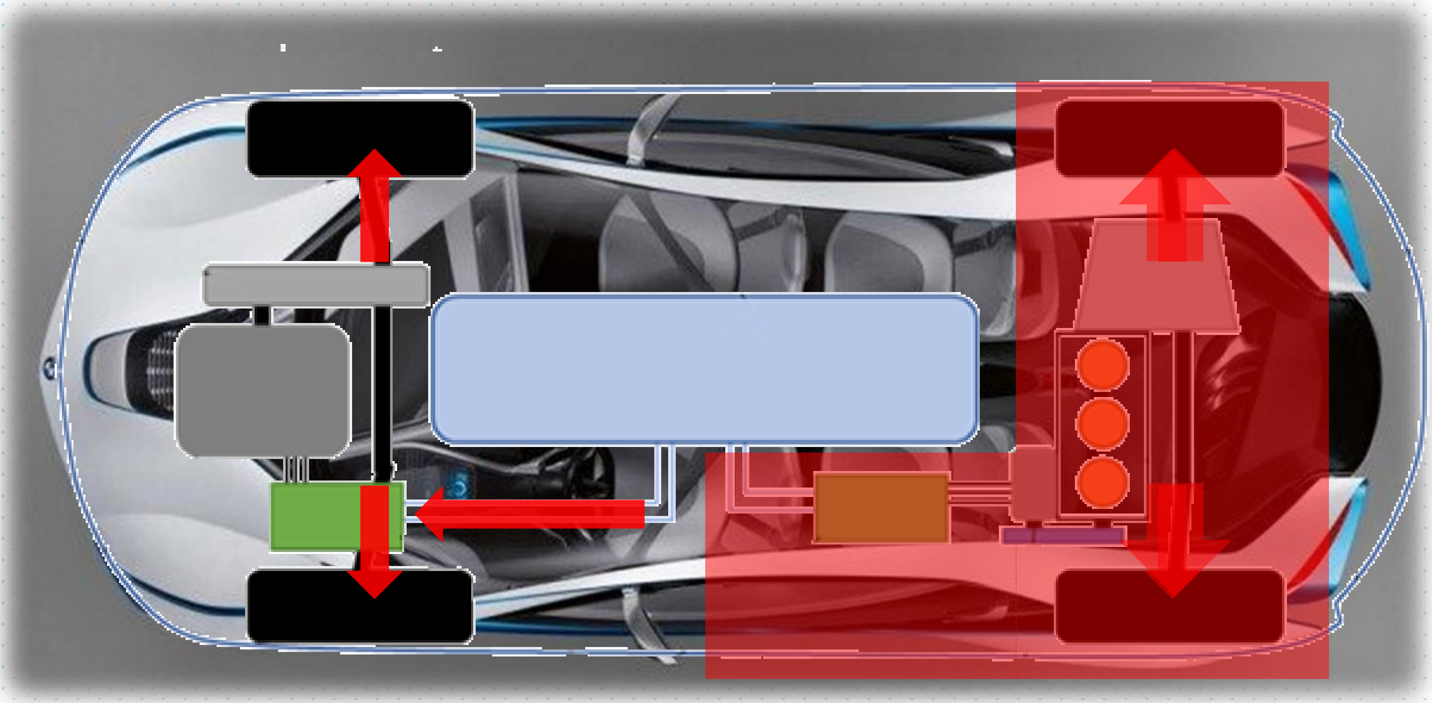
The Test Vehicle

- Vehicle is equipped with three driver-controlled modes:

- Electric only mode
- Standard “comfort” mode
- Sport mode



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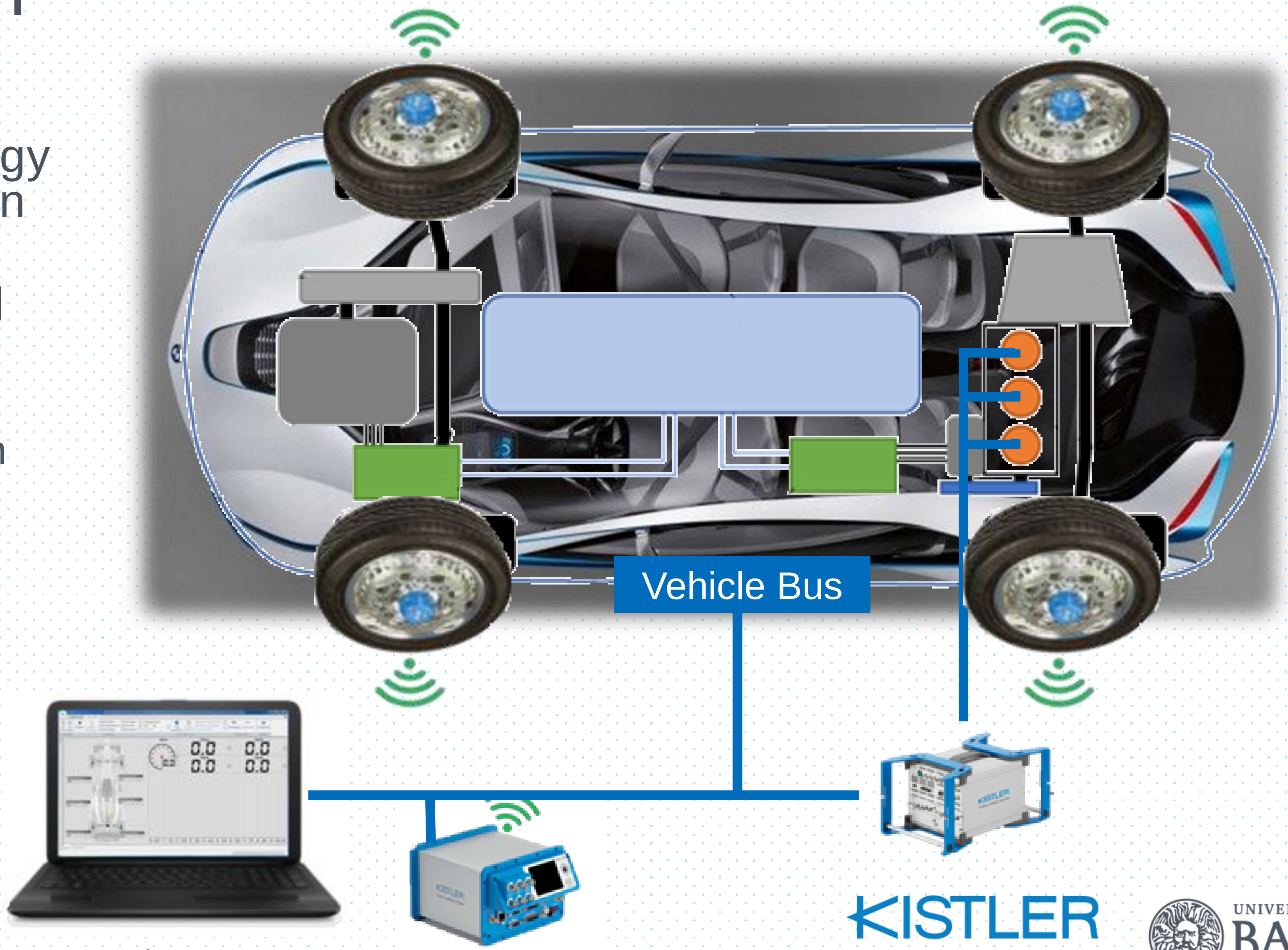
Instrumentation

- Instrumentation designed to capture the major energy flows within the powertrain
- Vehicle was instrumented as follows:
  - Kistler Roadyn system with **torque measurement wheels**
  - **Real time combustion pressure analysis** with a Kistler KiBox system
  - CAN data from the EMS (Engine Management System)



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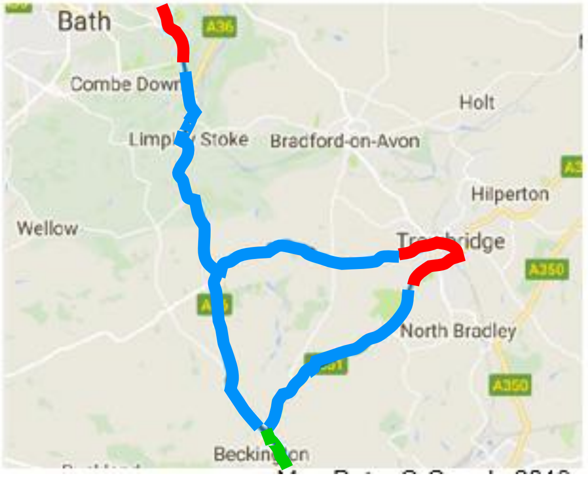
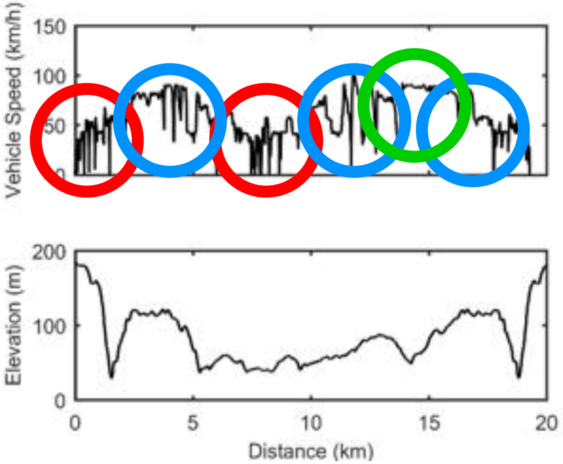
Test cycles

Road

- Features of RDE
  - Urban
  - Rural
  - Highway
- Repeated in different driving modes and battery SOC





Chassis Dyno

- 4-wheel drive chassis dynamometer facility at the University of Bath
- WLTC test cycles
- Repeated in different driving modes and battery SOC

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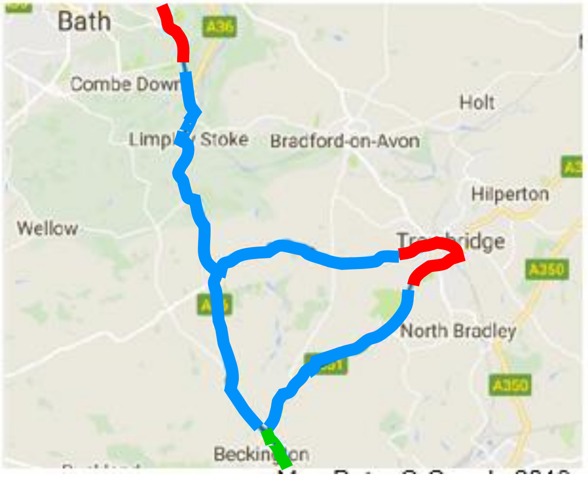

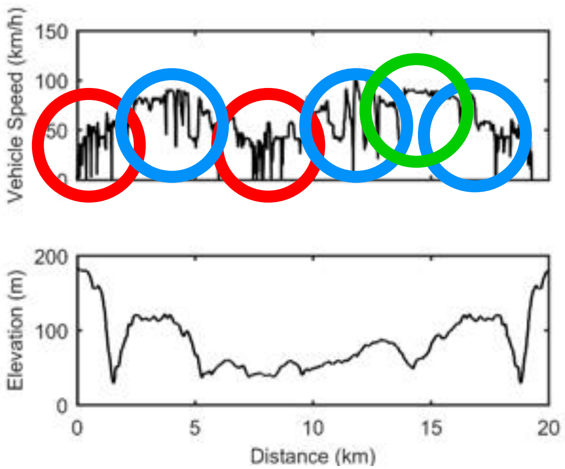

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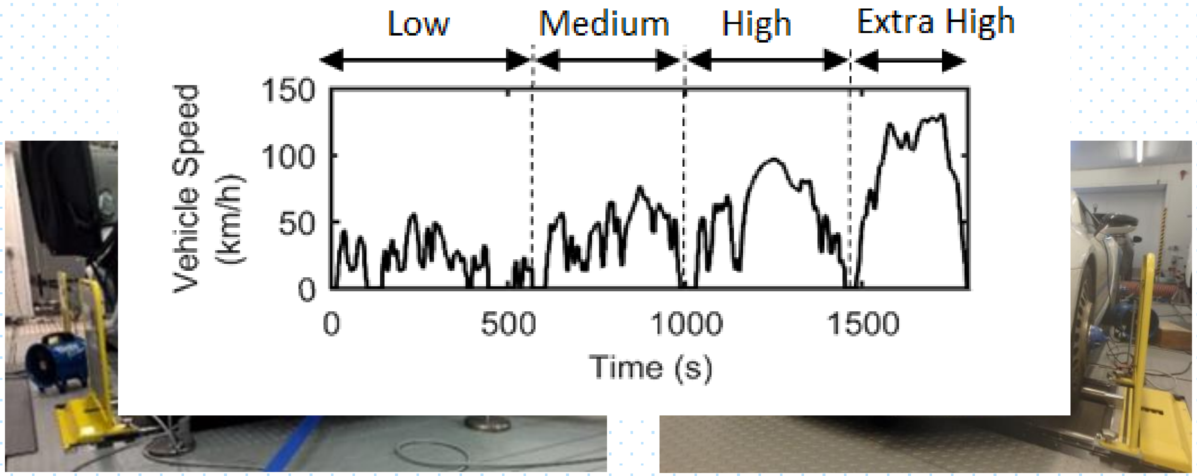

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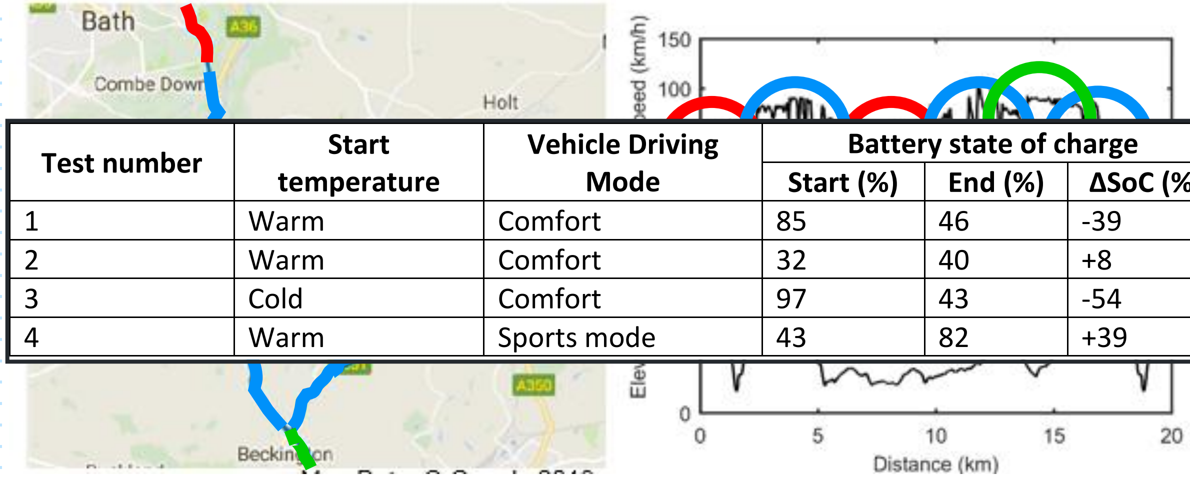

Test number	Start temperature	Vehicle Driving Mode	Battery state of charge		
			Start (%)	End (%)	ΔSoC (%)
1	Warm	Comfort	85	46	-39
2	Warm	Comfort	32	40	+8
3	Cold	Comfort	97	43	-54
4	Warm	Sports mode	43	82	+39

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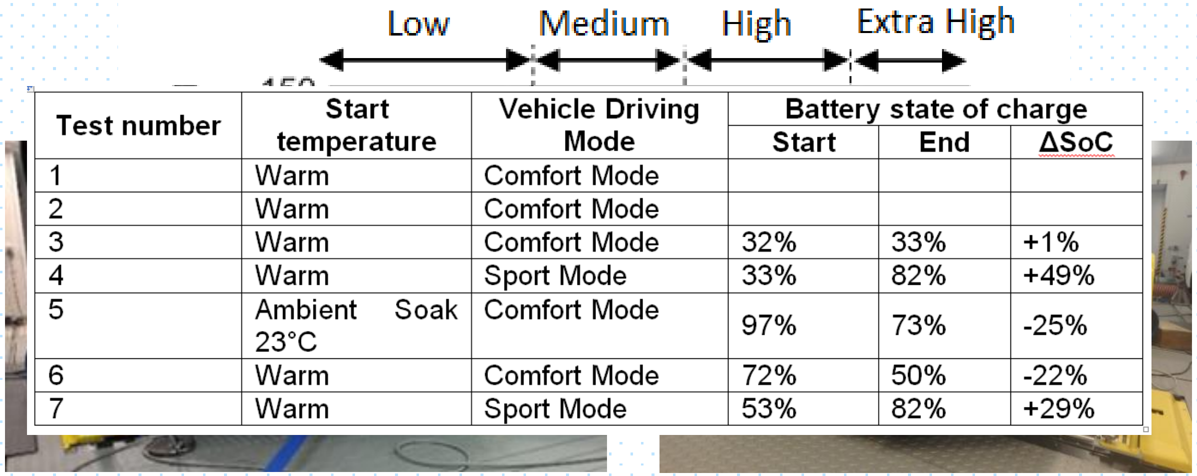

Test number	Start temperature	Vehicle Driving Mode	Battery state of charge		
			Start	End	ΔSoC
1	Warm	Comfort Mode			
2	Warm	Comfort Mode			
3	Warm	Comfort Mode	32%	33%	+1%
4	Warm	Sport Mode	33%	82%	+49%
5	Ambient Soak 23°C	Comfort Mode	97%	73%	-25%
6	Warm	Comfort Mode	72%	50%	-22%
7	Warm	Sport Mode	53%	82%	+29%

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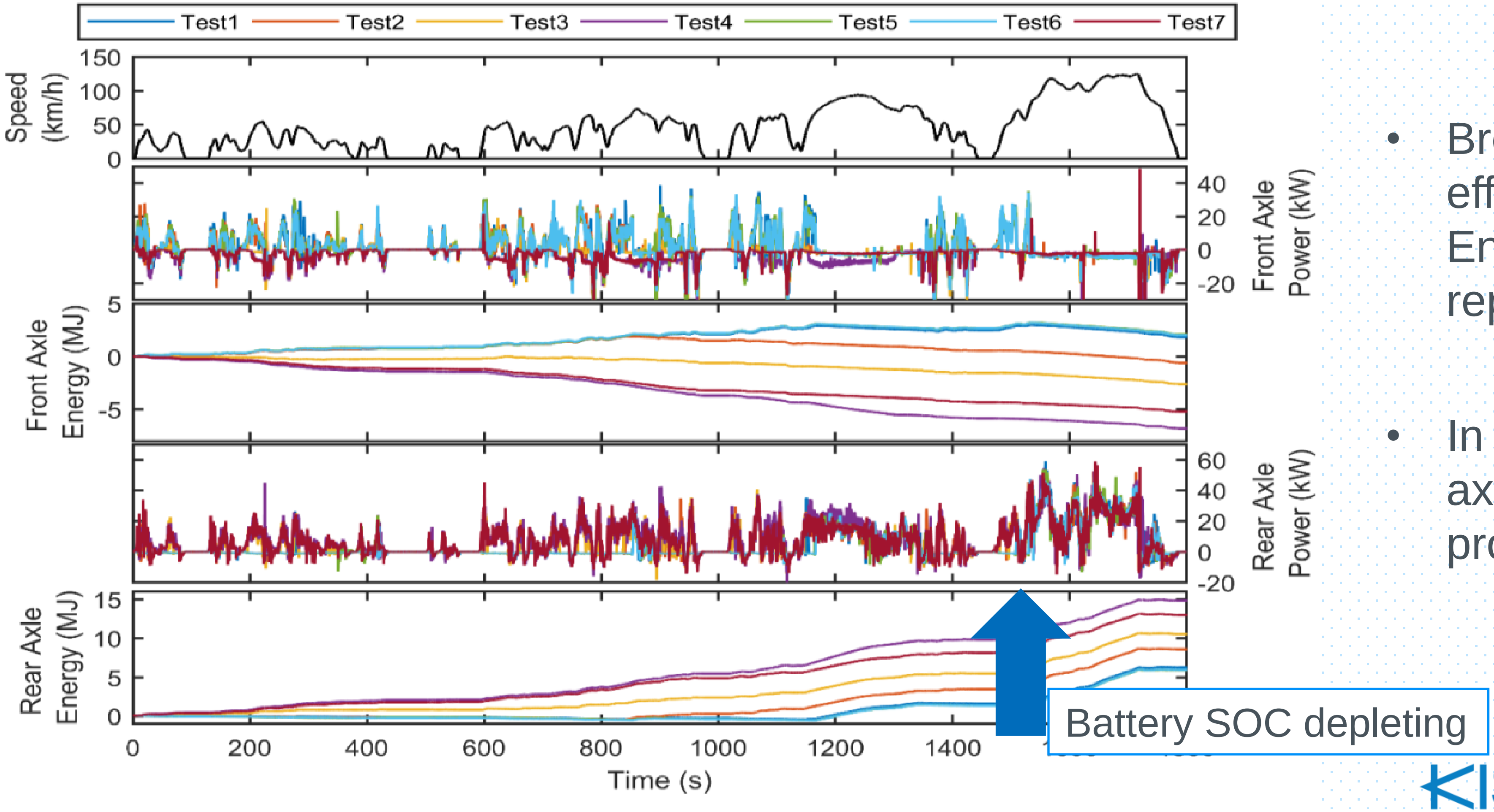
Results and discussion

- Results section was classified into two parts:
  - High level hybrid strategy over the different WLTC drive cycles,
    - Highlighting the key differences depending on the battery state of charge and the driving modes.
  - Detailed energy balance from both the chassis dynamometer and on-road driving
    - Highlighting some of the analysis that can be conducted with the proposed level of instrumentation.

Results and discussion

Wheel Torques – Hybrid strategy analysis

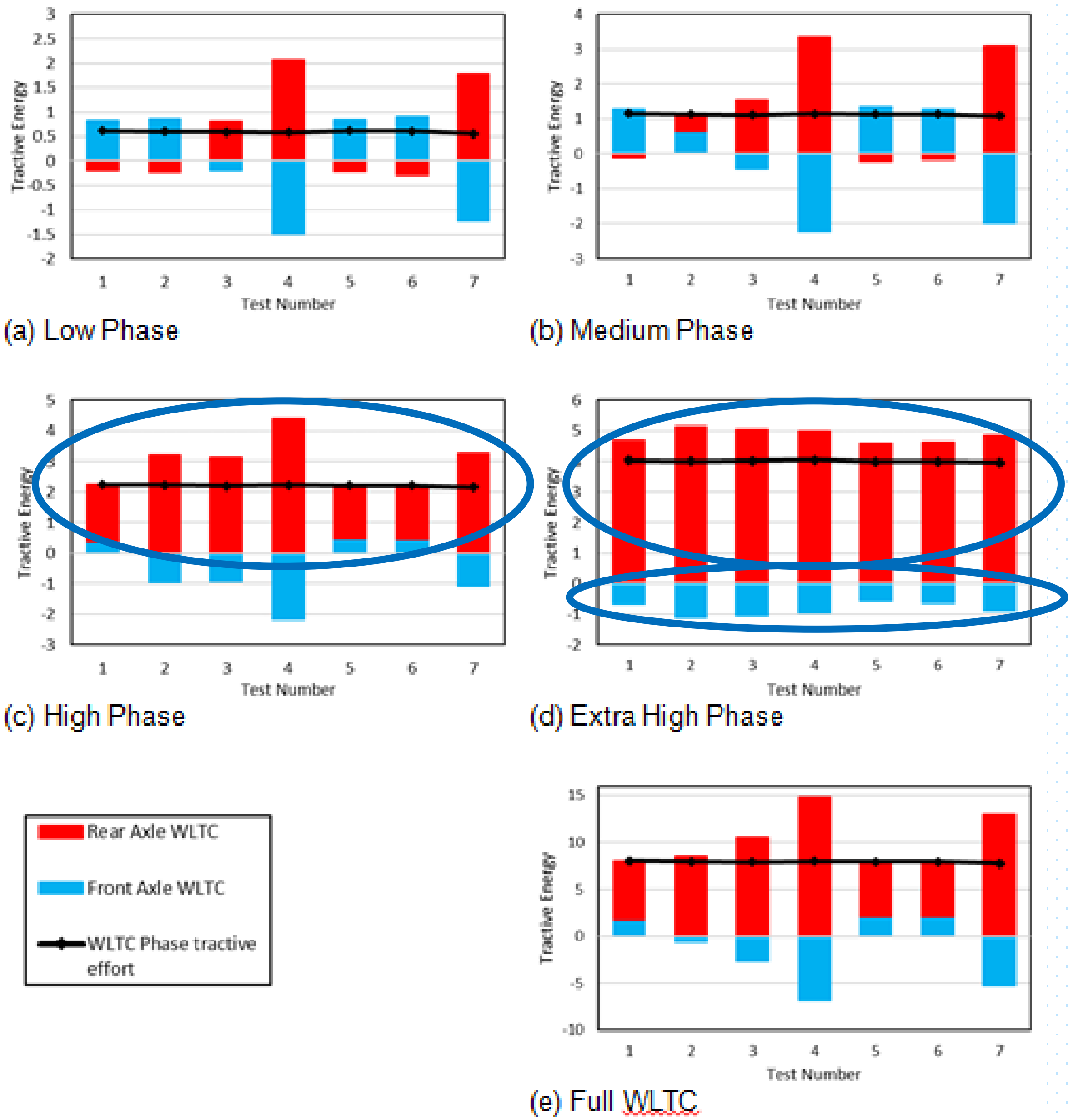


- Breakdown of tractive effort (Power and Energy) by axle for all repeated WLTC cycles
- In “comfort” mode rear axle energy usage proportional to SOC.

Results and discussion

Wheel Torques – Hybrid strategy analysis

- Analysis of the breakdown of axle power over each of the four phases of the WLTC cycle.
- The results show in all tests, the vehicle uses **the rear axle considerably** during high and extra high phases
- Little test-to-test variation in recuperation through the front axle in the extra high phase
- SOC and driving mode significantly effect the front/rear axle split.



(a) Low Phase
(b) Medium Phase
(c) High Phase
(d) Extra High Phase
(e) Full WLTC

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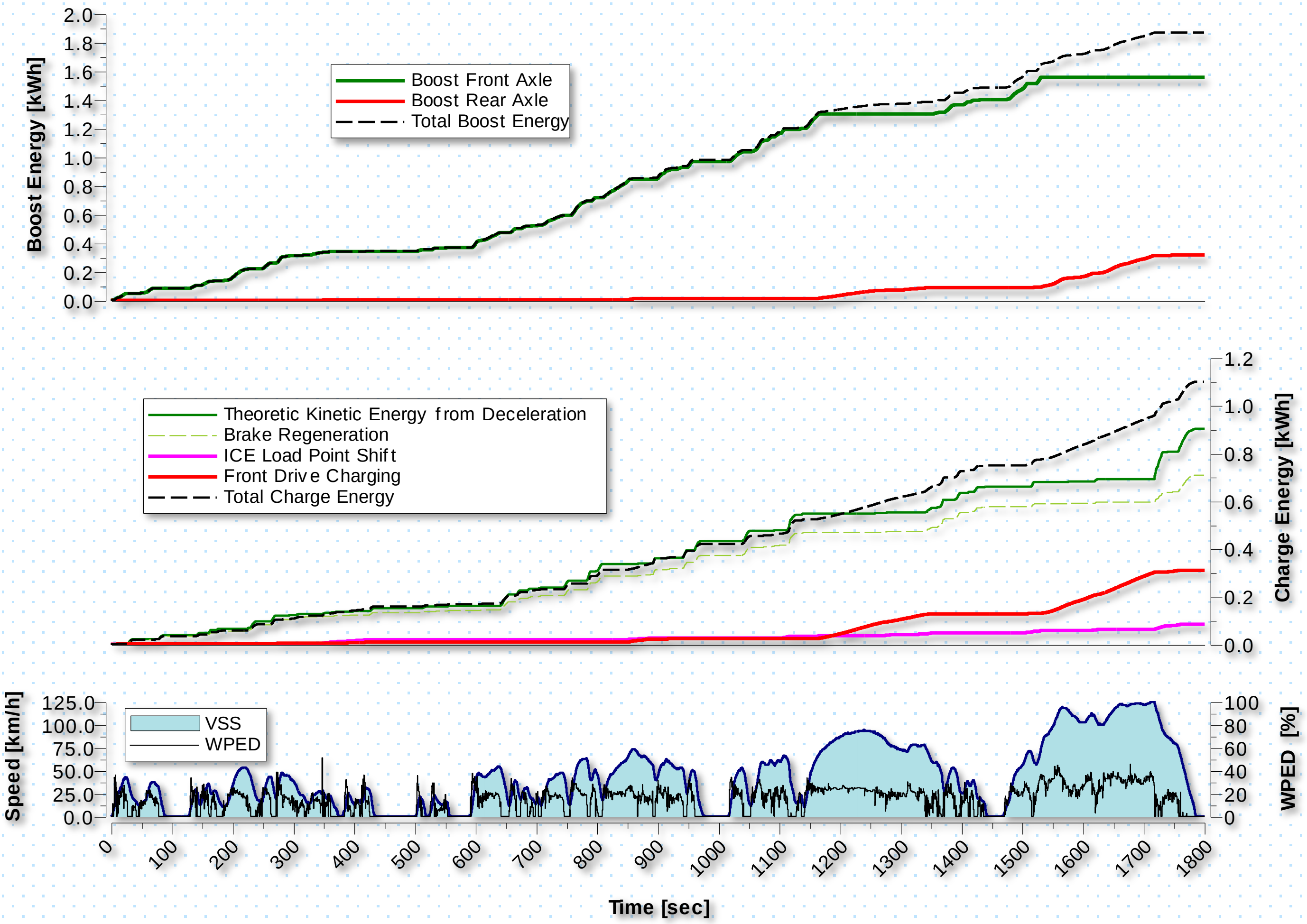
Results and discussion

Powertrain – Energy flows – WLTC



- Estimated **Boost** and **Charge Energies** over a complete WLTC determined from driving condition, wheel and ICE power.
- 1.85kWh total electrical energy used to drive the vehicle
  - 1.55kWh front axle
  - 0.3kWh rear axle
- 1.1kWh of energy provided to the battery
  - 0.7kWh KE recovery from decelerations
  - 0.3kWh front axle charging
  - 0.08kWh engine mounted e-machine

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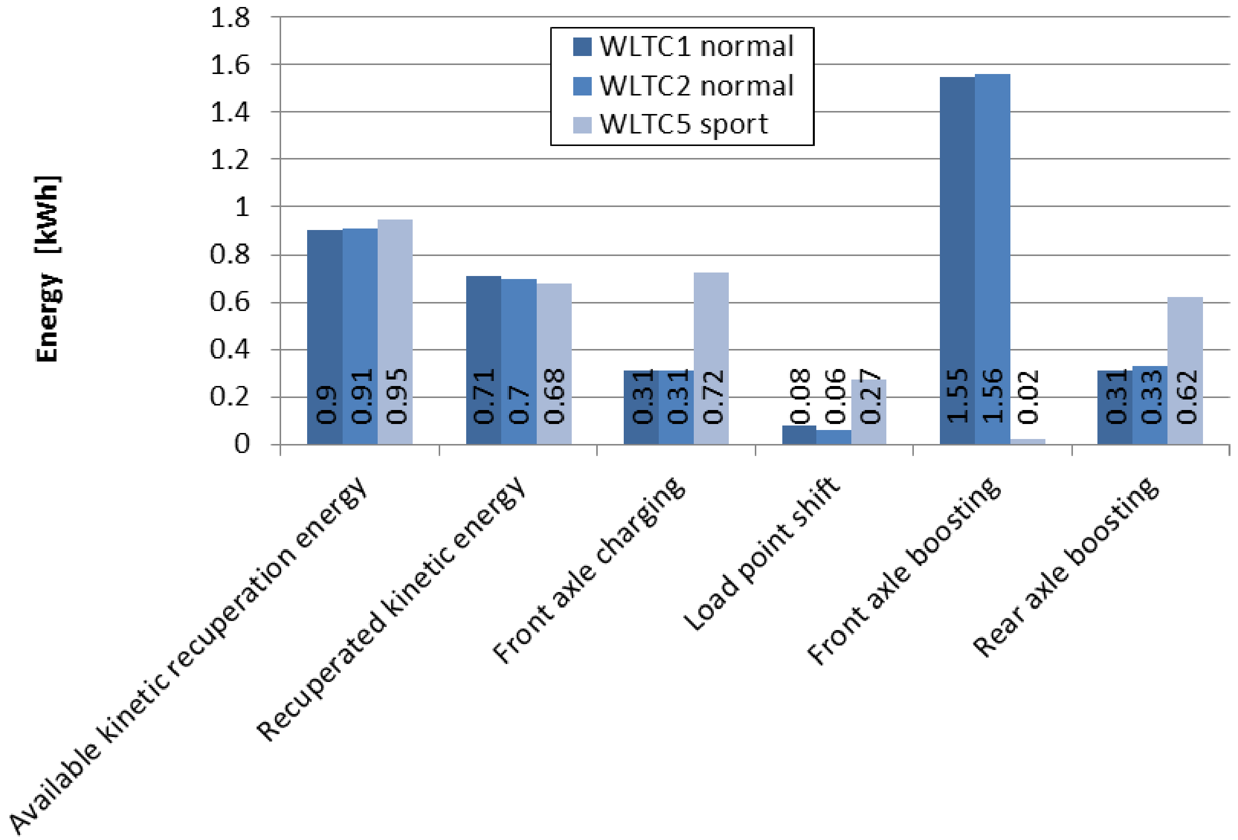
Results and discussion

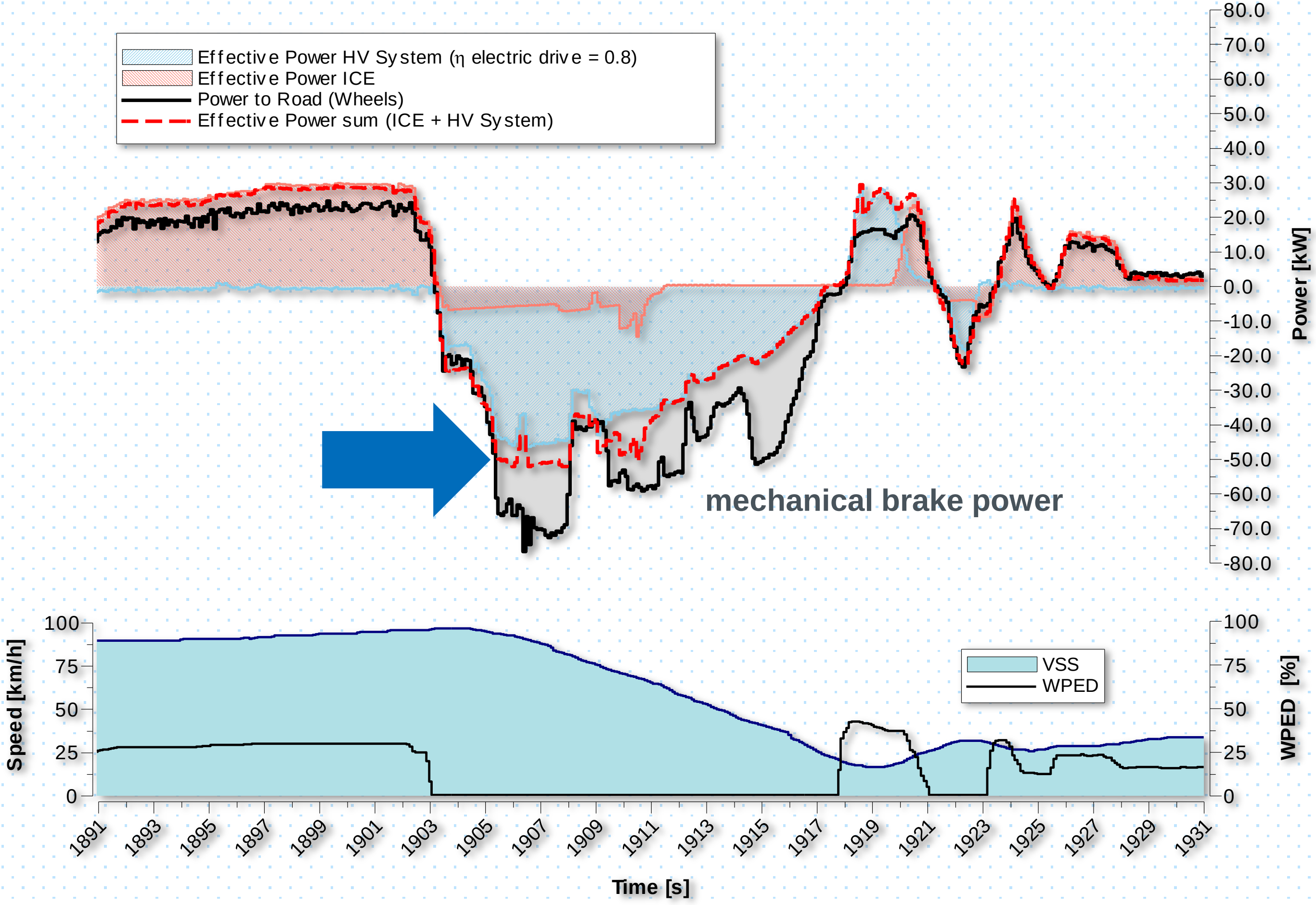
Powertrain – Energy flows – WLTC



- Overall energy values of three different WLTC cycles
- The theoretical maximum kinetic **energy recovery is similar for all cycles** as this is defined by the vehicle speed trace of the WLTC
  - Recuperation efficiency estimated to be in the region of 79%.
- Significant differences can be seen in the **hybrid charging and boosting** strategy

Results and discussion

Powertrain – Energy flows – On-road



- **Torque blending situation** – wheel torque exceeds estimated powertrain torque
- Electromechanical torque is estimated (no shaft measurement available)
- Difference between estimated effective power and wheel power is mechanical braking

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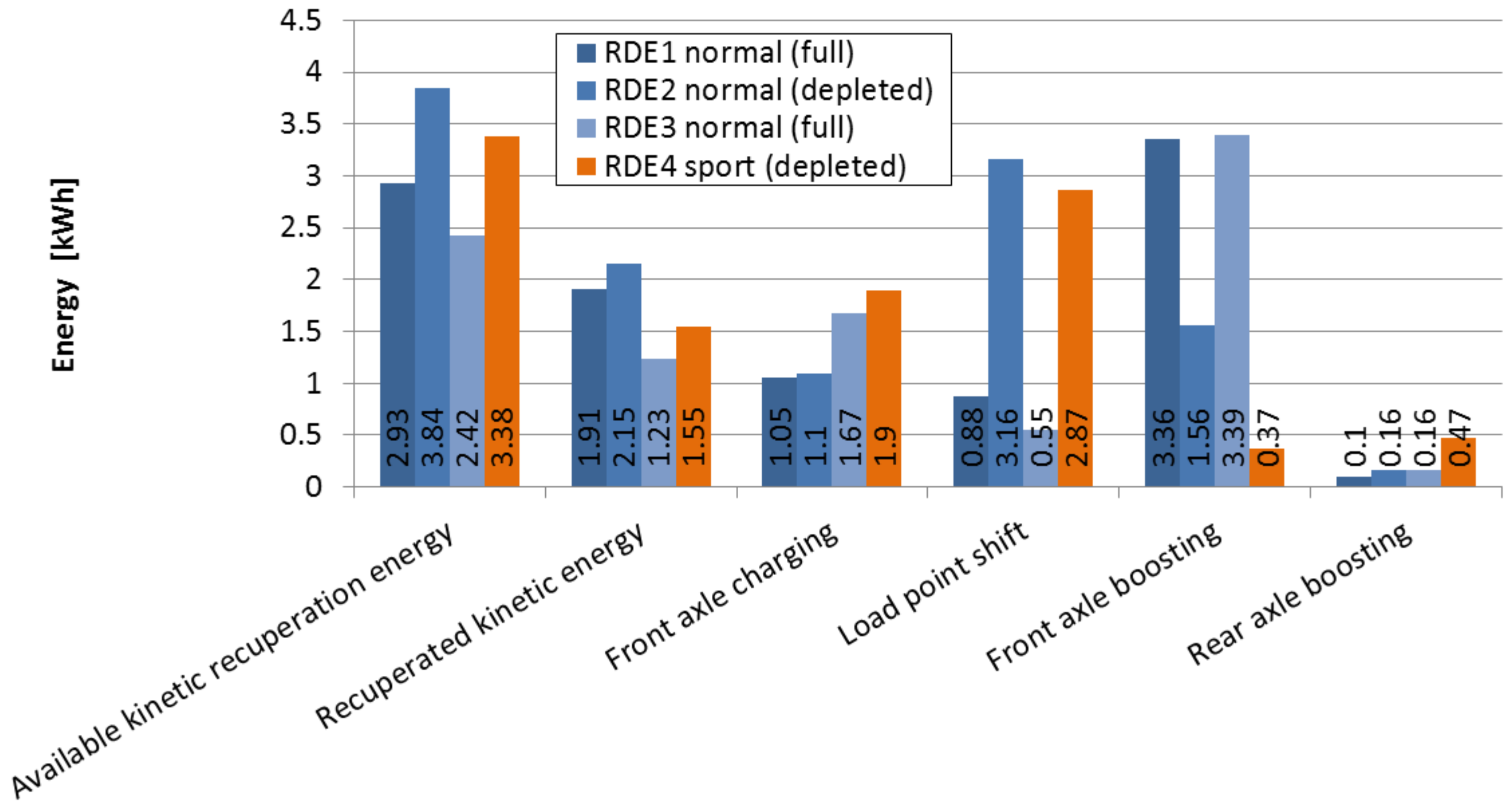
Results and discussion

Powertrain – Energy flows – On-road measurements



- Energy fractions of the different operating states for RDE cycles
- On-road-data shows a bigger variation in comparison to the WLTC data
  - Reduction in recuperation efficiency

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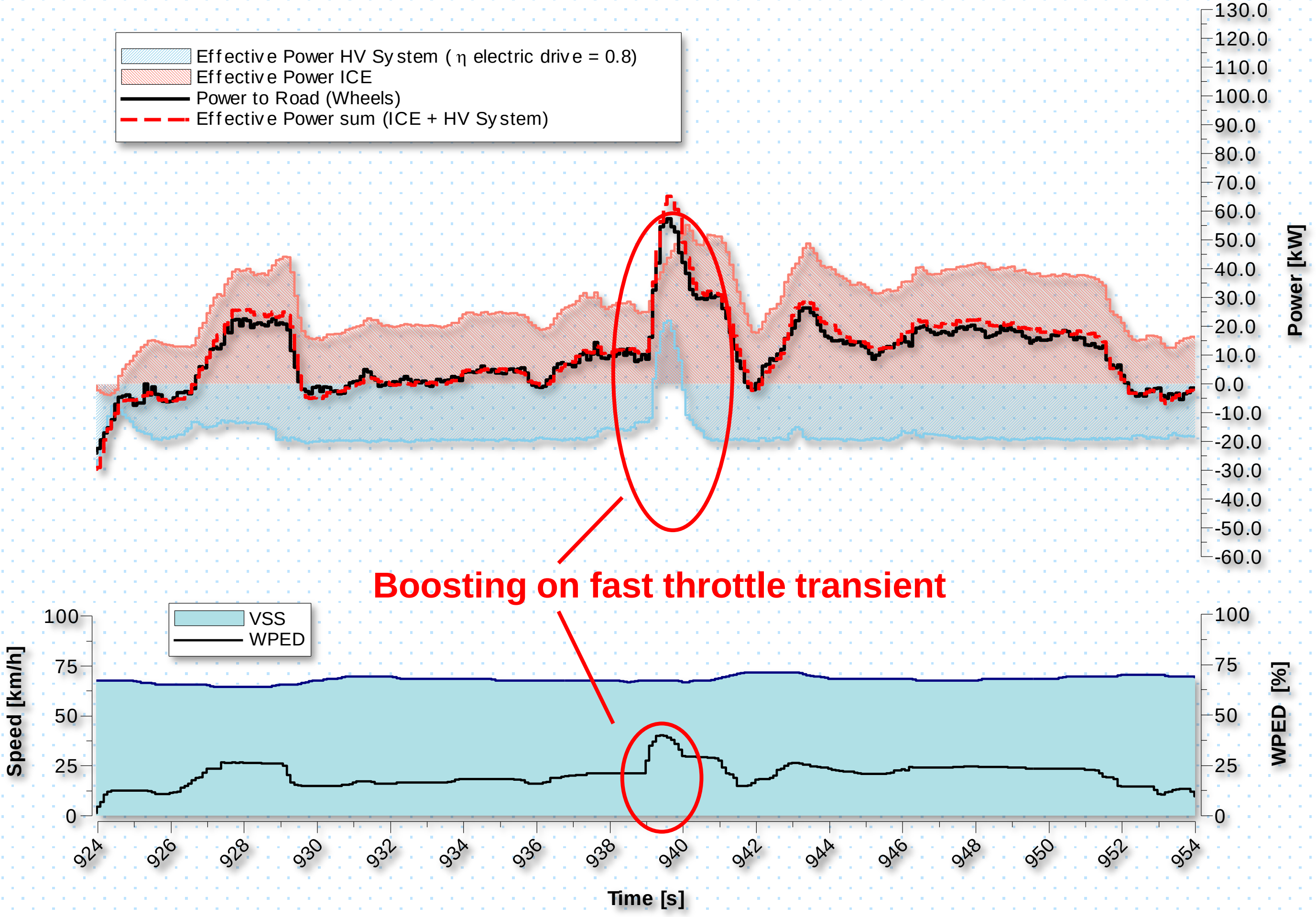
Results and discussion

Powertrain – Energy flows – On-road measurements



- **Boost Situation** – in sport mode, the powertrain is trimmed for maximum torque response
- During steady state driving in sport mode, the front axle is generating negative torque to pre-tension the powertrain
- The result is a rapid response on fast pedal transients as the pre-loaded ICE torque is released instantly

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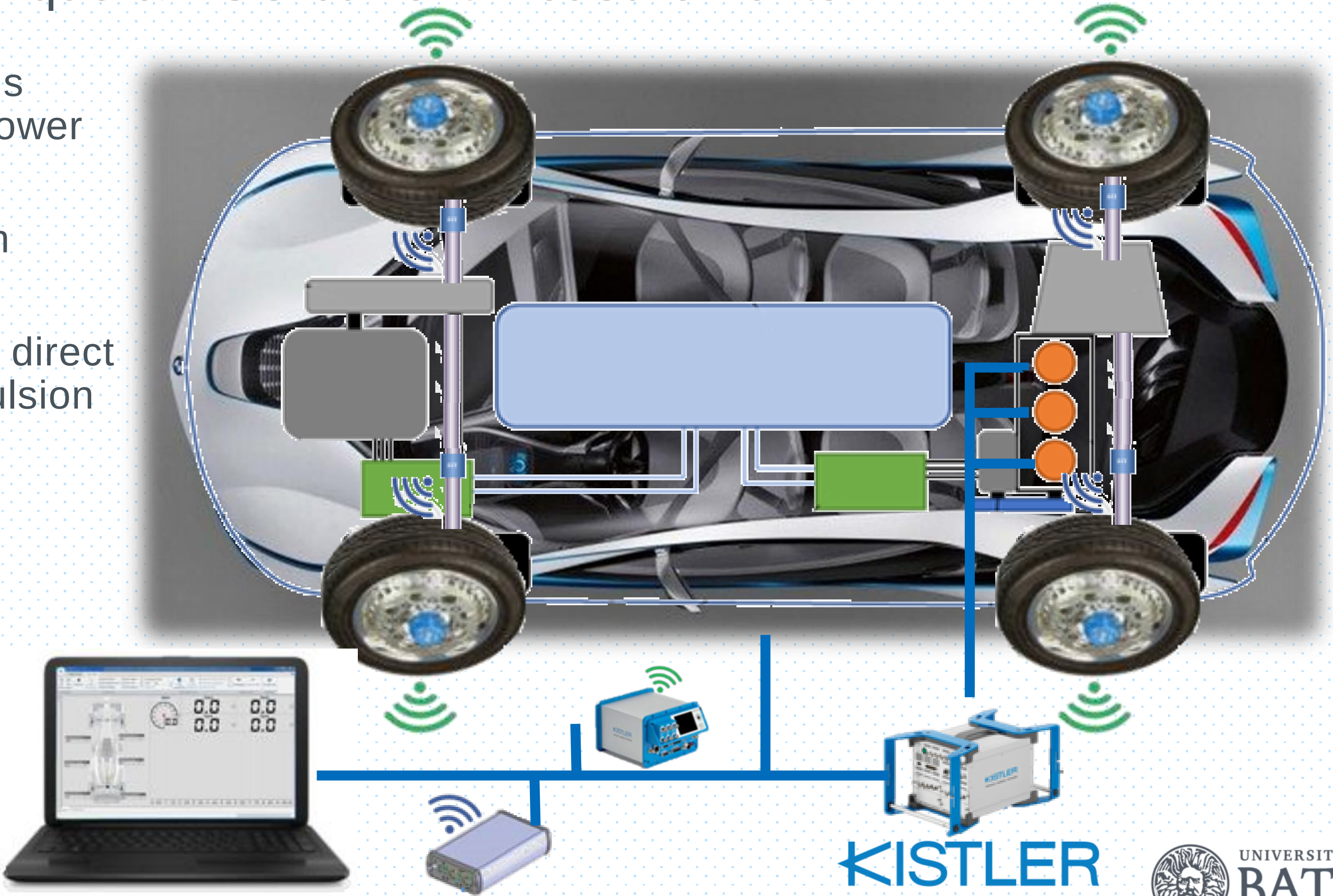
Further work

Addition of drive-shaft torque & BSG current measurements

- Addition of drive-shaft torque is beneficial to understand the power flux to the wheels
- All four drive-shafts have been instrumented
- BSG current measurement for direct determination of electric propulsion fraction on the rear axle



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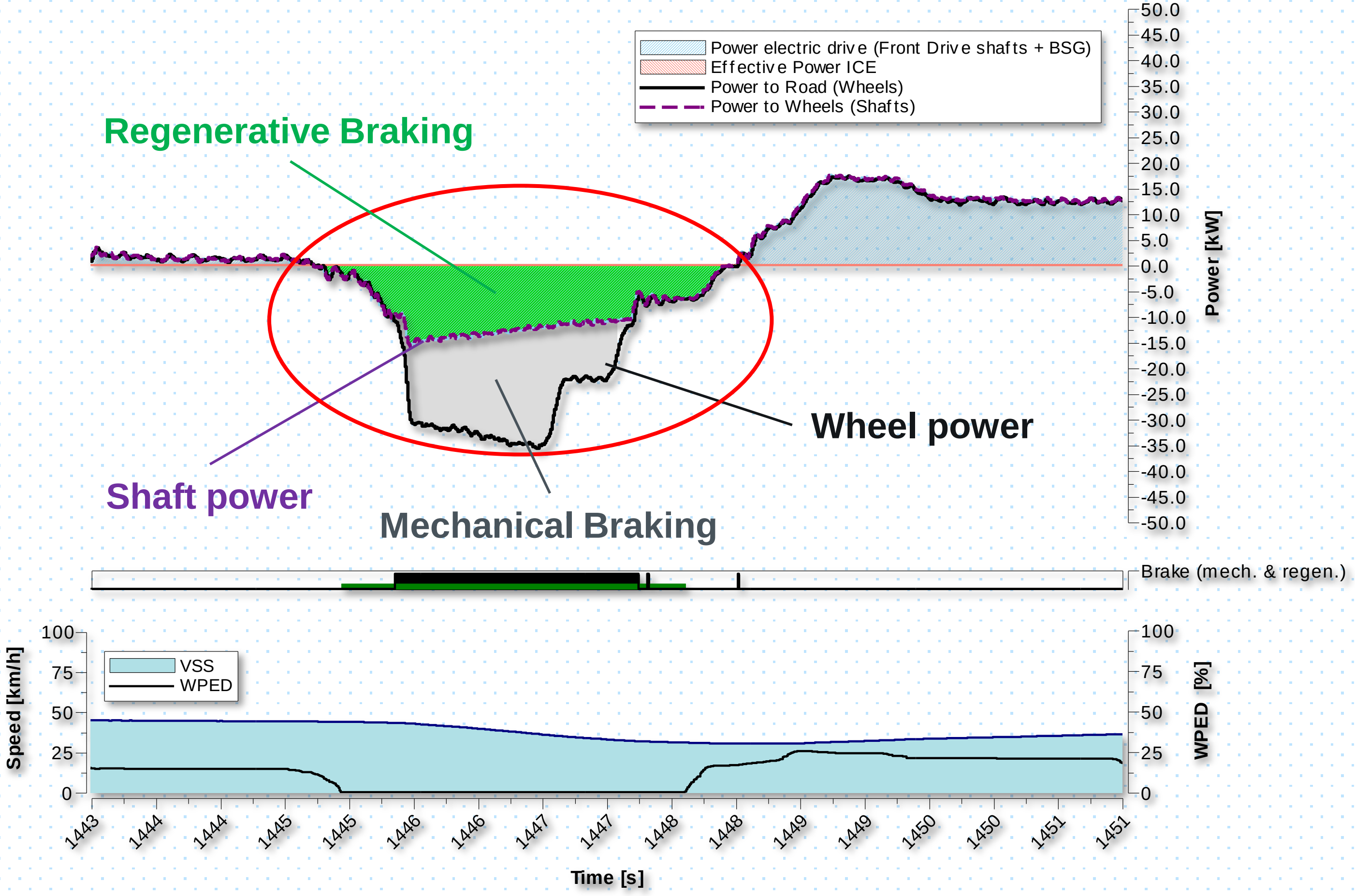
Further work

Powertrain energy flow – the benefit of drive-shaft torque

- **Torque Blending** situation
- Harvested and lost energy can be precisely determined
- Excellent correlation between shaft & wheel power in normal driving conditions
- Addition of drive-shaft torque greatly improves analytic possibilities in regard to **torque blending** & **torque vectoring**



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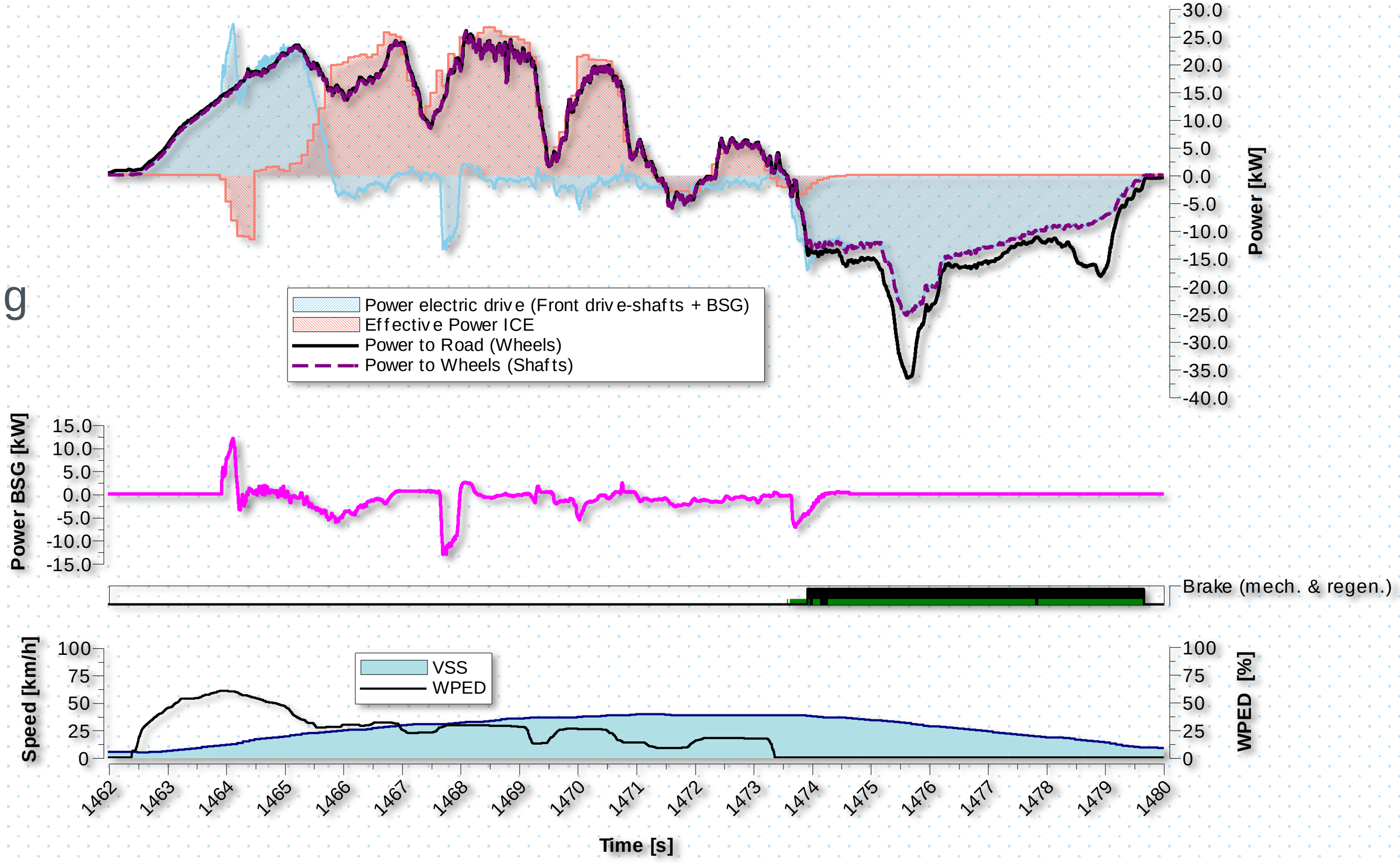
Further work

Powertrain energy flow – complex torque-split situations

- Electric drive initially
- Lost **energy** for **engine start** can be determined
- Evaluation of **torque control** during **switch-over**
- Full description of **complex deceleration** condition with four negative torque components:
  - ICE
  - BSG
  - Front electric machine
  - Mechanical brakes



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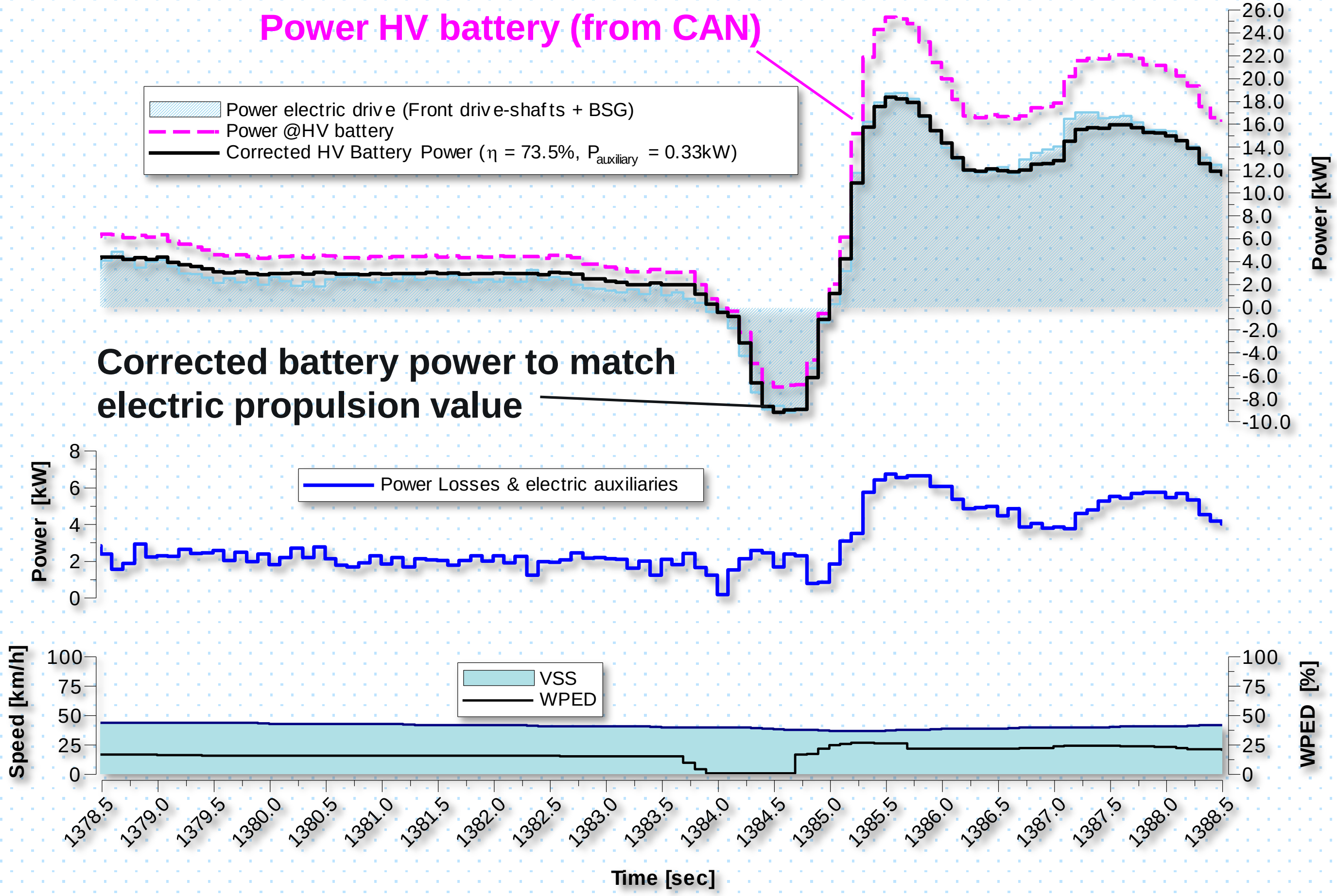
Further work

Powertrain energy flow – HV system efficiency estimation

- Efficiency of the HV system can be estimated by comparing the electro-mechanical power to the measured power at the HV battery
- Plot shows fixed η and auxiliary offset → simplification, as η and auxiliary power are not constant
- Using an iterative approach, auxiliary power and η may be evaluated throughout the drive-cycle



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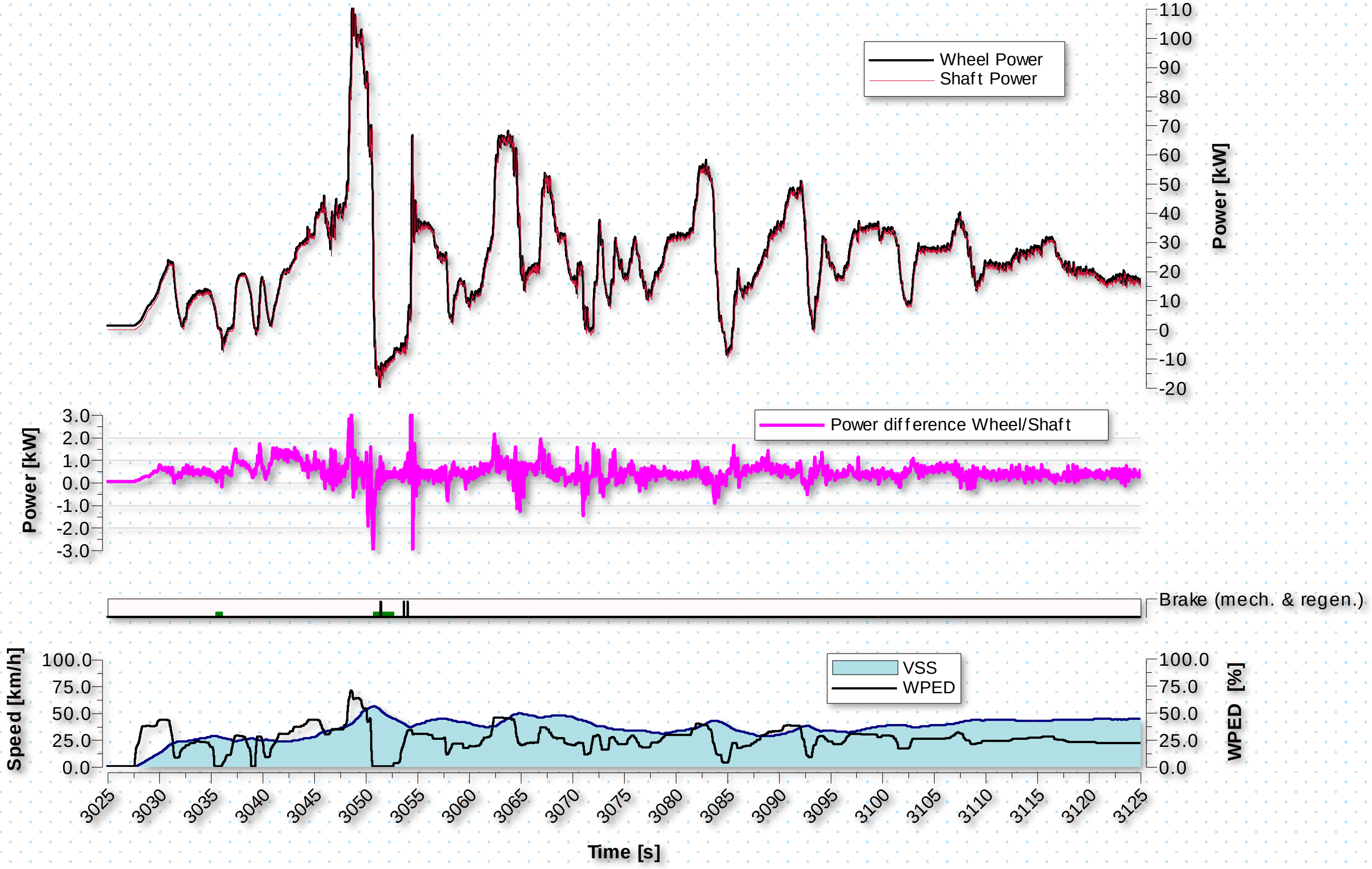
Further work

Powertrain energy flow – Correlation between wheel and shaft power

- Excellent correlation between shaft and wheel torque measurement
- Deviation is in the region of 0.2 – 0.5 kW in normal driving conditions
- As a result, the recuperation efficiency can be determined with a very high level of accuracy



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- The approach allowed a **simplified analysis of energy flows** to be established **quite easily**

- Charging and boosting **energy flows could be determined**
  - Boosting energy can further be broken down into front axle and rear axle driving.
  - Charging energy can be broken down into kinetic energy recovery, front axle charging, and ICE load point shifting

- Standardised tools and measurements for holistic powertrain analysis are essential for modern development processes

ANY QUESTIONS?

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