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

Andrew Lewis, Edward Chappell, Richard Burke, Sam Akehurst, Simon Pickering
University of Bath
Simon Regitz, David R Rogers
Kistler Instrumente AG
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
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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
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)
The Test Vehicle

- Vehicle is equipped with three driver-controlled modes:
  - Electric only mode
  - Standard “comfort” mode
  - Sport mode
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).

Dr. Andrew Lewis – 13th International AVL Symposium on Propulsion Diagnostics

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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
Test cycles

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<table>
<thead>
<tr>
<th>Test number</th>
<th>Start temperature</th>
<th>Vehicle Driving Mode</th>
<th>Battery state of charge</th>
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<td></td>
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<td></td>
<td>Start (%)</td>
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</tbody>
</table>
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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.
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
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
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
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
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
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
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 $\eta$ and auxiliary offset → simplification, as $\eta$ and auxiliary power are not constant
- Using an iterative approach, auxiliary power and $\eta$ may be evaluated throughout the drive-cycle
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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