ALTERNATIVE POWERTRAIN NEWS

A Ricardo Knowledge product
RICARDO INFORMATION SERVICES

ALTERNATIVE POWERTRAIN NEWS

NOVEMBER 2016

A monthly bulletin
dedicated to
fuel cell, hybrid electric
and other alternative powerplants,
common issues, components,
marketing
and industry news
Notes

Alternative Powertrain News is a monthly newsletter, published by the Ricardo Information Services Department. It summarises the published literature on hybrid, fuel cell and other alternative powerplants, mainly for automotive applications.

Items included in this publication are based on literature received by the Ricardo Library in October. Entries may contain additional information on products covered in earlier editions. Copies of the source documents may be obtained by quoting the Library reference, which appears in bold at the bottom of each article. An additional charge is made for this service.

Other products offered by Ricardo Information Services include:

**Powerlink** - An online database containing over 250,000 abstracts of engine and vehicle literature

**EMLEG** - Worldwide exhaust emissions legislation summaries online

---

**New Engine News**
Contents - summaries of main technical features of new engines of all types and applications

**Fuels & Lubricants News**
Contents - Developments in fuel and lubricants technology as applied in engines and vehicles

**Control & Electronics News**
Contents - control, electrical and electronic engineering. Practical applications and research & technology

**Transmissions News**
Contents - New and modified transmissions, and driveline technology

**Components News**
Contents - Internal combustion engine components, materials, research and design.

**Vehicle Engineering News**
Contents - All aspects of vehicle engineering including chassis, brakes, electrical, Powertrain and transmissions, including a review of new vehicles.

**Fuel Economy News**
Contents - Fuel economy improvement, weight reduction, practical examples of vehicle applications

**Gas Engine News**
Contents - Natural gas, LPG and biogas technologies and applications. Published quarterly.

Contact details - Roland Christopher, Information Manager, Ricardo UK Ltd
Tel. +44 (0) 1273 794230, email: Roland.Christopher@ricardo.com.

Ricardo has used reasonable endeavours to ensure that the information supplied in this service is correct. However, no responsibility or liability can be accepted for any errors or omissions. Entries in this publication do not imply endorsement of any product or service by Ricardo.
Contents

FUEL CELL POWERTRAINS ........................................................................................................ 5
   TYPES ................................................................................................................................. 5
   Polymer electrolyte membrane ......................................................................................... 5
   AUTOMOTIVE APPLICATIONS ....................................................................................... 6
   Race cars .......................................................................................................................... 6
   Buses ................................................................................................................................. 6
FUEL CELLS AS COMPONENTS OF OTHER POWERTRAINS ............................................ 7
   COMMON ISSUES .............................................................................................................. 8
   Energy management ......................................................................................................... 8
   COMPONENTS .................................................................................................................. 9
   Catalysts ............................................................................................................................ 9
   Control systems ............................................................................................................... 9
   Stacks ............................................................................................................................... 9
   Thermal systems ............................................................................................................. 10
HYBRID ELECTRIC POWERTRAINS .................................................................................. 11
   AUTOMOTIVE APPLICATIONS ....................................................................................... 11
   Cars ................................................................................................................................. 11
   NON-AUTOMOTIVE APPLICATIONS ............................................................................. 12
   Rail ................................................................................................................................. 12
   FORMAT AND OPERATION MODE ................................................................................ 13
   Plug-in hybrid .................................................................................................................. 13
   COMMON ISSUES ............................................................................................................ 15
   CAE ................................................................................................................................. 15
   Calibration ...................................................................................................................... 15
   CO2 ................................................................................................................................. 15
   Control ............................................................................................................................. 16
   Energy management ........................................................................................................ 18
   Fuel consumption ........................................................................................................... 19
   NVH ................................................................................................................................. 19
   Power management .......................................................................................................... 20
   Research and development ............................................................................................. 20
   Thermal issues ................................................................................................................ 21
   TRANSMISSIONS AND DRIVELINES .......................................................................... 22
MILD OR MICRO HYBRID POWERTRAINS ...................................................................... 27
   COMMON ISSUES ............................................................................................................ 30
   Fuel economy .................................................................................................................. 30
   Starting ............................................................................................................................. 31
ELECTRIC POWERTRAINS .................................................................................................. 32
   AUTOMOTIVE APPLICATIONS ....................................................................................... 32
   Light electric vehicles (LEVs) ......................................................................................... 32
Race cars ............................................................................................................................................... 32
Trucks .................................................................................................................................................. 32
Buses ................................................................................................................................................... 33
VEHICLE ENGINEERING ..................................................................................................................... 34
TRANSMISSIONS AND DRIVELINES ................................................................................................. 35
COMMON ISSUES ............................................................................................................................... 37
Charging ............................................................................................................................................... 37
Control ............................................................................................................................................... 38
Emissions ........................................................................................................................................... 39
Energy efficiency/consumption ........................................................................................................... 40
Infrastructures .................................................................................................................................... 41
Legislation, politics, economics and society ....................................................................................... 42
NVH ................................................................................................................................................... 43
Safety .................................................................................................................................................. 44
COMPONENTS ................................................................................................................................. 47
Battery chargers ................................................................................................................................. 47
Batteries ............................................................................................................................................ 48
Energy storage devices ....................................................................................................................... 49
Wheel motors ....................................................................................................................................... 49
RANGE EXTENDER POWERTRAINS .................................................................................................... 50
OTHER ALTERNATIVE POWERTRAINS ............................................................................................ 51
PNEUMATIC ....................................................................................................................................... 51
UNCONVENTIONAL INTERNAL AND EXTERNAL COMBUSTION ENGINES ........................................ 52
Free piston engines ............................................................................................................................. 52
Miller cycle engines ............................................................................................................................ 52
Opposed piston engines ...................................................................................................................... 52
Rankine cycle engines ........................................................................................................................ 53
COMMON ISSUES IN ALTERNATIVE POWERTRAINS ..................................................................... 56
COMPONENTS AND SYSTEMS ......................................................................................................... 56
Motors ................................................................................................................................................ 56
CAE ................................................................................................................................................... 57
ELECTRIC POWER ............................................................................................................................. 58
Charging ............................................................................................................................................ 58
LIFE CYCLE ANALYSIS ....................................................................................................................... 59
MARKETING ....................................................................................................................................... 60
OPERATING RANGE ............................................................................................................................ 61
RESEARCH AND DEVELOPMENT ....................................................................................................... 62
TRANSMISSIONS AND DRIVELINES ................................................................................................. 63
WASTE HEAT/ENERGY RECOVERY ................................................................................................... 64
NATIONAL NEWS .............................................................................................................................. 65
FUEL CELL POWERTRAINS

TYPES

Polymer electrolyte membrane

A MODULAR AND DYNAMIC QUASI-2D MODEL APPROACH TO POLYMER ELECTROLYTE MEMBRANE FUEL CELLS

Vienna University of Technology

Polymer Electrolyte Membrane Fuel Cells (PEMFC) are a promising addition to the portfolio of electric drivetrains and so there is a demand for both black and white box models of PEMFC. Computationally efficient white box models that maintain a fairly high resolution, however, are nearly non-existent up to now. This paper presents a modular and dynamic model of PEMFC that attempts to fill this gap. What makes the model unique is: 1) It describes the dynamics of species transport and electrochemical reactions in PEMFC in a modular way. 2) Numerical instabilities at the borders between those modules are prevented by the use of standard PI-controller concepts. The complete PEMFC model is separated into submodels according to the dominant transport phenomena: The Channels (CL) with convection driven transport, the Gas Diffusion Layers (GDL) with multicomponent diffusion and the Polymer Electrolyte Membrane (PEM) with electro-osmotic drag and diffusion driven water transport. An additional electrochemical submodel (EL) covers the electrochemical processes. Simulation results of a single cell are presented and compared to literature and well established CFD-software results.

See vCD 403 N24.pdf (Powertrain Modelling and Control, Testing, Mapping and Calibration (PMC2016), Loughborough University, Sep 2016, 11pp.)
AUTOMOTIVE APPLICATIONS

Race cars

FORZE DELFT FUEL CELL PROJECT: A FORZE TO BE RECKONED WITH

What are the chances that we'll see a hydrogen fuel cell race car from a major manufacturer in the next years? There have been persistent rumours that BMW or Audi could enter a car in the experimental Garage 56 class at Le Mans, possibly as soon as 2018, you can also imagine somewhere like pikes peak being a prime candidate for a demonstration drive. But whenever and wherever one of the large carmakers does decide to pitch its hat into the ring, it is highly likely that a group of students from The Netherlands will have beaten them to it.

Around the time that this issue goes to press the Forze Delft team should begin track testing with a new fuel cell-powered car that it plans to enter into the Dutch Supercar Challenge. Like most fuel cell vehicles, the Forze VII is effectively a hybrid. The fuel cell stack runs at a fixed output, supplying a capacitor-based energy storage system known as the accumulator. This handles all the transient power demands - reacting almost instantaneously to the driver's throttle inputs while the fuel cell keeps topping it up at a fixed rate in the background.

See Doc.148304 (Race Tech, Nov 2016, pp22-24 & 26-27.)

Buses

A HYBRID ELECTRIC FUEL CELL MINIBUS: DRIVE TEST

National Research Council of Italy

Meeting the worldwide energy demand for the present and future transportation systems with the least impact on the environment is a big challenge. In the i-NEXT (Innovation for green Energy and eXchange in Transportation) project a Fuel Cell Hybrid Electric Vehicle (FCHEV) minibus for people transportation has been implemented. This paper reports some preliminary test drive. The vehicle architecture has been developed considering that, both recharge time and autonomy of a purely electric vehicle are operational limits, and the fuel cell technology is able to enhance these parameters. An electric engine with lithium ion batteries and a 20 kW Fuel Cell System characterize the vehicle. The test drive has been carried out in Capo d'Orlando municipality (Sicily) allowing the acquisition of key data.

See vCD 395 EVS29-5220276.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 8pp.)

EUROPEAN ROLL-OUT STRATEGY FOR HYDROGEN FUEL CELL BUSES

Element Energy

Contents:
- Context: key developments to date - Why choose fuel cell buses?
- Future plans for FC bus deployment
- JIVE project: Joint Initiative for Hydrogen Vehicles across Europe
- Conclusions:
  The technology has been demonstrated in a range of real-world environments – millions of km and thousands of refuelling events to date
  Key challenges to further adoption:
  – Improved availability of vehicles
  – Cost reductions
  A commercialisation process is underway that could lead to competitive fuel cell buses in the 2020s.
Covers - CHIC project.

FUEL CELLS AS COMPONENTS OF OTHER POWERTRAINS

BREEZE! - FUEL CELL RANGE EXTENDER FOR BATTERY ELECTRIC VEHICLES

RWTH Aachen University

This paper describes the development of a fuel cell range extender (REX) for an existing battery electric vehicle and its integration into the vehicle. To this end, the scenario-based design concept is presented first, through which we measured the power necessary for the range extender. Following that, the operation parameters and the components required for operation are explained. With the help of modularization in functional groups, the installation spaces are used efficiently and a compact REX module was developed. The volume of the cell stacks is approximately 15.5 l, leading to a volumetric gross power density of 2.2 kW/l. With a volume of 67 l, the entire REX module achieves a volumetric gross power density of 0.45 kW/l and a gravimetric gross power density of 0.25 kW/kg, including operating materials. The fuel cell range extender thus lies in the same range as combustion engine range extenders. The example of the cooling system shows the particular challenges regarding the vehicle integration of fuel cells, given that cell stack, system, and HV development strongly interact here. The REX module was successfully commissioned on the test bench; operation with system components using nominal power of approximately 30 kW and with a system efficiency level of 42% produced results similar to those obtained in the previous laboratory test. The initial operating experience with the overall system for the vehicle has already occurred.

Covers - Air supply, hydrogen supply, thermal management.

See vCD 413 Session 03, 08_A2.3_Walters_VKA.pdf (25th Aachen Colloquium, 10-12 Oct 2016, Session 03_Hybrid and Electric Vehicles, 20pp.)

INTEGRATION OF A FUEL CELL RANGE EXTENDER

RWTH Aachen University and FEV

Electric mobility with passenger cars can be realised also by fuel cell drives and hydrogen. RWTH Aachen University and FEV present results of the Breeze project which aim was to develop a PEM fuel cell range extender (REX) drive for the subcompact category. Therefore, the FEV Liliona was used as an existing battery electric vehicle which is based on a Fiat 500.

See Doc.148284 (ATZ Worldwide, Oct 2016, pp26-32.)
COMMON ISSUES

Energy management

A SPECIFICATION INDEPENDENT CONTROL STRATEGY FOR SIMULTANEOUS OPTIMIZATION OF FUEL CELL HYBRID VEHICLES DESIGN AND ENERGY MANAGEMENT

University of Salerno

The present work proposes an in-depth analysis of a heuristic control strategy, developed in such a way as to enhance model-based design of fuel cell hybrid electric vehicles (FCHEVs). Particularly, suited normalization and denormalization techniques are proposed, so as to adapt optimized control rules to a number of FCHEV powertrains, ranging from low to high degree of hybridization. A scenario analysis was conducted to verify the effectiveness of proposed powertrain-adaptable control strategies, thus revealing their high potential, both to reduce the off-line development phase, as well as to enable simultaneous preliminary optimization of FCHEV powertrain sizing and real-time energy management.

See vCD 393 1-s2.0-957-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp369-376.)
COMPONENTS

Catalysts

IN-SITU LIQUID TEM STUDY ON THE DEGRADATION MECHANISM OF FUEL CELL CATALYSTS

Toyota

Electrode catalyst (platinum) degradation represents a major challenge to the performance and durability of polymer electrolyte membrane fuel cells (PEMFCs) in fuel cell vehicles (FCVs). While various mechanisms have been proposed and investigated previously, there is still a need to develop in situ imaging techniques that can characterise and provide direct evidence to confirm the degradation process. In the present study, we report an in situ transmission electron microscopy (TEM) method that enables real time, high-resolution observation of carbon-supported platinum nanoparticles in liquid electrolyte under working conditions. By improving the design of the Micro Electro Mechanical Systems (MEMS) sample holder, the migration and aggregation of neighbouring platinum nanoparticles could be visualised consistently and correlated to applied electrode potentials during ageing process (i.e. cyclic voltammetry cycles). It can be expected that information acquired through this novel approach would provide valuable insight that may lead to the optimal design of new electrode catalysts to resolve the catalyst degradation issue.

See SAE 2016-01-1192 (2016, 6pp.)

Control systems

DEVELOPMENT OF FUEL CELL SYSTEM CONTROL UNDER SUB-ZERO AMBIENT CONDITION

Toyota and Nippon Soken

Recently, due to environmental issues such as global warming and air pollution, vehicle which is capable to harmonize with environment is required. In 2014, we developed the new fuel cell vehicle (FCV) to meet these demands. The New FCV is able to achieve start-up from -30°C. It has improved fuel cell performance and usability under sub-zero ambient condition by new water management technology. In this paper, we will report about the concept of the start-up control method of new FCV under sub-zero ambient condition.

See vCD 371 378ms.pdf (Japanese Paper) (JSAE Annual Congress (Spring), May 2016, Paper JSAE 20165378, 6pp.)

Stacks

DEVELOPMENT OF FUEL CELL STACK SECURING HIGH DURABILITY FOR FCVS

Toyota

Enhancing performance and further reductions in size and cost are required to facilitate the commercial widespread adoption of fuel cell vehicles (FCVs). Toyota Motor Corporation met these challenges by developing the world's first FC stack without a humidifying system. This was achieved by the development of an innovative cell flow field structure and membrane electrode assembly, enabling a power density of 3.1 kW/L and durability equivalent to 15 years more than approximately threefold that of the conventional stack and allowing the stack to be installed under the floor in a sedan-type FCV. Measures taken about each degradation mode of FC stack will be described in this section.

See vCD 371 374ms.pdf (Japanese Paper) (JSAE Annual Congress (Spring), May 2016, Paper JSAE 20165374, 4pp.)
PERFORMANCE EVALUATION OF 70 MPA DIFFERENTIAL-PRESSURE WATER ELECTROLYSIS STACK

Honda
In high differential-pressure water electrolysis stack, failure mechanism of solid polymer electrolyte membrane was clarified, and determined the specification of sustaining 70 MPa differential-pressure. Sealing structure of centre channel stack for long time use was certified. As a result, new 70 MPa stack reduced approximately 30% of power consumption to generate 70 MPa compressed hydrogen, as compared with the conventional hydrogen station.

See vCD 371 379ms.pdf (Japanese Paper) (JSAE Annual Congress (Spring), May 2016, Paper JSAE 20165379, 5pp.)

Thermal systems

ELECTRO-THERMAL MAPPING OF AIR-COOLED OPEN-CATHODE FUEL CELLS: SMART REDUCTION OF THE NUMBER OF EXPERIMENTS

University College London and AVL
The influence of the cooling flow rate and current density on the temperature, voltage and power density is a challenging issue for air-cooled, open cathode fuel cells. Electro-thermal maps have been generated using large datasets (530 experimental points) to characterise these correlations. This large dataset enables an accurate empirical model to be built. This work uses the design of experiment (DoE) approach to reduce the number of experiments, yet reach identical results (i.e. determination of the maximum power). Since fuel cell polarisations are highly non-linear, an S-optimal design plan is used to reduce the number of experiments required from 530 to 55. The modelled data based on this reduced dataset provides the same maximum power as the large-scale dataset.

Covers - Polymer electrolyte fuel cells (PEFCs).
See vCD 403 N28.pdf (Powertrain Modelling and Control, Testing, Mapping and Calibration (PMC2016), Loughborough University, Sep 2016, 21pp, 35 refs.)
HYBRID ELECTRIC POWERTRAINS

AUTOMOTIVE APPLICATIONS

Cars

THE DRIVETRAIN OF THE NEW BMW 225XE iPERFORMANCE ACTIVE TOURER

BMW

The BMW 225xe plug-in hybrid with electric all-wheel drive is the third vehicle of the manufacturer to share this drive concept. While a 1.5-litre three-cylinder gasoline engine drives the front wheels, an electric motor powers the rear axle. Integrating the various functions of the powertrain components is key to achieving sporting characteristics and intelligent power management.

Covers - three-cylinder TwinPower turbo engine, high-voltage starter generator (HVSGR), six-speed automatic transmission, E-Transmission, electric machine, electric machine electronics, high-voltage battery, operating strategy of the BMW 225xe iPerformance.

See Doc.148195 (MTZ Worldwide, Sep 2016, pp16-20.)

THE GM RWD PHEV PROPULSION SYSTEM FOR THE CADILLAC CT6 LUXURY SEDAN

General Motors

This paper describes the capabilities of a new two-motor plug-in hybrid-electric propulsion system developed for rear wheel drive. The PHEV system comprises a 2.0-litre turbocharged 4-cylinder direct-injected gasoline engine with the new hybrid transmission, a new traction power inverter module, a liquid-cooled lithium-ion battery pack, and on-board battery charger and 12V power converter module. The capability and features of the system components are described, and component performance and vehicle data are reported. The resulting propulsion system provides an excellent combination of electric-only driving, acceleration, and fuel economy.

Covers - Electric Variable Transmission (EVT), continuously variable transmission (CVT) action, cross section of the EVT for the CT6.

See SAE 2016-01-1159 (2016, 6pp.)

ROAD TEST: HONDA NSX

Honda

Road test of the Honda NSX hybrid supercar covering acceleration, brakes, dimensions, emissions, engine, fuel consumption, handling, interior, performance, power, ride, rivals, safety, steering, suspension, torque, transmission, turning circle, tyres, visibility, wheels.

Behind the cabin is a low-slung 3.5-litre V6 petrol engine, with turbochargers sitting outside the vee in order to keep the centre of gravity lower. The engine revs to 7500 rpm and produces peaks of 500 bhp and 406 lb-ft. Fixed to the V6 is a 47 bhp electric motor, and behind that a nine-speed dual-clutch automatic gearbox, all of which drive the rear wheels.

At the front, meanwhile, sit two 36 bhp electric motors, one driving each front wheel and giving the NSX a vast array of torque-vectoring properties (and also meaning that, along with a few of the NSX’s 10 radiators, there’s no luggage space under the bonnet).

The NSX is a hybrid, then, but you can’t plug it in, and don’t expect to go very far on electric power alone; the motors are there to boost performance and offer a marginal fuel economy increase.

See Doc.148293 (Autocar, 5 Oct 2016, pp38-45.)
NON-AUTOMOTIVE APPLICATIONS

Rail

MODEL-BASED COMPARISON OF HYBRID PROPULSION SYSTEMS FOR DIESEL MULTIPLE UNITS

Voith Turbo, Loughborough University and University of Applied Sciences Ulm

In order to reduce operating costs, rail vehicle operators need to find technical solutions to improve the efficiency of diesel multiple units on non-electrified railway routes. This can be achieved by hybridisation of diesel multiple unit propulsion systems with electrical energy storage systems to allow for brake energy recuperation. A simulation model of a generic diesel multiple unit in a 3-car formation is developed and equipped with three types of power transmissions. Simulations on realistic service profiles with different driving strategies show the potential for fuel consumption reduction for the different transmission types. On a suburban service profile a 3-car diesel multiple unit is able to achieve simulated fuel savings of up to 0.3% and 14.8% on a regional service profile. Life cycle cost analyses for a number of cases with battery storage systems show payback periods between 5 and 6 years and a return on investments of 600-800 k€ for vehicle operators on the basis of a 20 year service life.

Covers - energy management, energy storage systems, double-layer capacitors (DLC), flywheel technology, lithium-ion batteries, hydromechanics transmissions, four-speed automatic transmission, six-speed automatic transmission, six-speed automatic transmission.

See vCD 403 N34.pdf (Powertrain Modelling and Control, Testing, Mapping and Calibration (PMC2016), Loughborough University, Sep 2016, 17pp, 46 refs)
FORMAT AND OPERATION MODE

Plug-in hybrid

DEVELOPMENT OF LOAD DATA APPLICABLE TO AN EMERGING MARKET – USING SIMULATION TO CREATE THE LOAD DATA REQUIRED FOR VEHICLE POWERTRAIN DEVELOPMENT IN A PREVIOUSLY UNCHARTERED ENVIRONMENT

AVL and Great Wall Motor Company

GWM and AVL have been collaborating to develop a plug-in hybrid electric vehicle (PHEV), based on 5-door SUV vehicle, which will be unveiled in 2017. The intended powertrain configuration for the vehicle is a so-called P1-4 Topology, i.e. a belt-starter-generator on the combustion engine at the front wheel drive combined with an electrified rear axle module. This full hybrid vehicle is from today's perspective one of the most promising approaches in view of short-term vehicle electrification providing substantial benefits such as environmental friendliness, low fuel consumption, high longitudinal performances and driving comfort.

In the hybridisation of the GWM PHEV vehicle, the powertrain can be described as follow:

The P1-4 hybrid powertrain architecture consists of two sub-group of components.

The first sub-powertrain on the front axle is composed of:
- 2-litre TGI engine including the modified control unit (EMS), modified front end accessory drive (FEAD), aftertreatment system and fuel tank system. This engine can develop a maximum power 165 kW and a maximum torque of 350 Nm.
- High voltage belt starter generator including power electronics, control module (BSGCU). This BSG can perform engine start with a peak torque of 50 Nm and ensure boost and power derivation with a peak power of 15 kW.
- Front axle transmission: 6-speed DCT including modified control unit (TCU), hydraulics circuit and electric oil pump (EOP)

The second sub-powertrain on the rear axle is composed of:
- eAD System: Electric traction motor including power electronics (AC/DC and DC/DC), control module (MCU). The rear e-motor is mainly used for pure electric driving and regenerative braking. The e-motor can reach a maximum peak torque of 195 Nm and a peak power of 85 kW.
- Rear axle transmission: 2-speed gearbox with neutral position including shift motor, shift controller. The automated actuated 2 speeds gearbox in the rear axle powertrain is used to operate the rear axle e-motor at its best operating points. There is no mechanical connection between the front axle and rear axle powertrains beside the indirect connection through the road surface.
- The rear e-motor, BSG, DCDC and HVAC are powered by a 96 cells li-ion HV battery. The battery pack has a total energy of 12.4 kWh and can ensure an electric driving range of 50 km on NEDC cycle.


GET TOGETHER AT THE CHARGING STATION – THE ALL NEW PLUG-IN HYBRID FAMILY OF BMW

BMW

The first member of BMW’s third generation of hybrid vehicles was launched in 2015 with the BMW X5 xDrive40e plug-in hybrid. Since the initial series launch of hybrid vehicles at BMW in 2009, their topologies and operating strategies have undergone further development and refinement. The hybridization strategy has been systematically pursued, with the result that all vehicle segments and architectures are now “hybridized”. With the BMW i3 electric vehicle and the BMW i8 plug-in hybrid sports car came the development of an electric drive system that established a baseline for the electrification of future BMW vehicles. Whilst the first two generations of hybrid vehicles used eight- and six-cylinder engines, the third generation of hybrids sees the introduction of efficient three- and four-cylinder engines in combination with new batteries and powerful electric motors.
This paper presents the latest vehicle in the BMW plug-in family - the 740e iPerformance. It will focus specifically on the intelligent drive system and operating strategy functions. Covers – Hybrid transmission with integrated electric machine, fuel consumption, energy management, State of Charge (SOC) control, navigation based predictive operating strategy. See vCD 413 Session 03, 06_A2.1_Schmitz_BMW.pdf (25th Aachen Colloquium, 10-12 Oct 2016, Session 03_Hybrid and Electric Vehicles, 18pp.)
COMMON ISSUES

CAE

MODEL VALIDATION OF THE HONDA ACCORD PLUG-IN
Argonne National Laboratory

This paper presents the validation of an entire vehicle model of the Honda Accord Plug-in Hybrid Electric Vehicle (PHEV), which has a new powertrain system that can be driven in both series and parallel hybrid drive using a clutch, including thermal aspects. The Accord PHEV is a series-parallel PHEV with about 21 km of all-electric range and no multi-speed gearbox. Vehicle testing was performed at Argonne’s Advanced Powertrain Research Facility on a chassis dynamometer set in a thermal chamber. First, components (engine, battery, motors and wheels) were modelled using the test data and publicly available assumptions. This includes calibration of the thermal aspects, such as engine efficiency as a function of coolant temperature. In the second phase, the vehicle-level control strategy, especially the energy management, was analysed in normal conditions in both charge-depleting and charge-sustaining modes. The third part examined how different thermal conditions such as environmental conditions (−7°C or 35°C with solar load) or vehicle state (soaked or warmed-up vehicle) affect the control strategy. Finally, the validation of the model implemented in Autonomie, a high-fidelity, forward-looking vehicle simulation tool, is presented. The fuel consumption figures are within the test-to-test variability, while many of the operation and control signals are also matched. Now that it has been validated, this model can be used for a wide range of simulations studies that include temperature as a parameter for the comparison and optimization of components, vehicle powertrain system, or control algorithm.

See SAE 2016-01-1151 (2016, 7pp.)

Calibration

VIRTUAL CALIBRATION OF CONVENTIONAL & HYBRID DRIVETRAIN STRATEGY
AVL

This publication shall show new approaches and results in AVL for development of an objective method in the very subjective field of "driveability in respect to drive strategy calibration". Methods and tools to allow target setting, objective comparison, analysis and optimisation, as well as the frontloading approach in the virtual calibration of vehicles with automated transmissions will be presented.


CO2

CO2 SAVING POTENTIAL BY 48V ECO DRIVE SYSTEM
Continental

Fuel economy, cleaner emissions, higher power density, and propellant infrastructures are the global megatrends that shape the future of powertrain electrification. Particularly in Europe, the hurdle that needs to be taken by 2021 is the 95 gCO2 per kilometre average. This target cannot be achieved just by improving combustion engines for many vehicle segments. A full hybrid or a mild hybrid system has been used to gain substantial fuel efficiency by using motor as power source, yet HVs are not gaining popularity in Europe due to complex and costly system configuration. A 48V hybrid can achieve considerable efficiency level with simpler system configuration than conventional HV.

See vCD 371 434ms.pdf (Japanese Paper) (JSAE Annual Congress (Spring), May 2016, Paper JSAE 20165434, 4pp.)
ON-LINE CONTROLLER FOR FUEL CONSUMPTION ON SPILT-TYPE HYBRID ELECTRIC VEHICLE

NIDEC ELESYS and Tokyo Denki University

This paper proposes a controller used by an extremum seeking (ES) algorithm with semi-optimal controller gains for a hybrid electric vehicle system. The semi-optimization gains connect at each output of sample controllers that are given by benchmark problem in advance. These gains are decided according to the approximate convex on fuel economy function via each gains. The target engine speed of EMI controller is perturbed with the ES algorithm based on fuel economy and State of Charge (SOC). Furthermore, the proposed algorithm switches controller depending on SOC for restraining of the decline of SOC. The sample controllers have four units, and each unit controller controls the driving of HEV. For showing the validity of our proposed controller, fuel economies of the proposed controller and sample controller are compared by simulator for this benchmark. While the fuel economy achieved by the sample controller is 41.44 mpg, the final fuel economy on the proposed method is almost 59.29 mpg, and the final SOC is 64.45%. The performance of fuel economy can be improved by almost 43% compared to the sample controller.

See vCD 393 1-s2.0-581-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp245-250.)

TESTING AND ANALYSIS OF THE CONTROL STRATEGY OF HONDA ACCORD PLUG-IN HEV

Tsinghua University

PHEVs have shown their potential to further reduce fuel consumption and emissions, and many OEMs have put forward their mass-produced PHEV models. However, the series-parallel configuration PHEVs are seldom seen in the market. This paper discusses the testing and analysis of a Honda Accord PHEV, whose powertrain configuration is series-parallel. The NEDC cycle test, dynamic acceleration test, and static cruise test are finished in a four-wheel drive chassis dynamometer at the China Automotive Engineering Research Institute. Powertrain configuration design, control strategy, and fuel economy of the vehicle are analysed. The test results show that the series-parallel configuration has the potential to reduce transmission mechanical losses, and the series operating mode tends to be more efficient in most working conditions.

See vCD 393 1-s2.0-453-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp153-159.)

ENERGY EFFICIENT CONTROL OF THE AIR COMPRESSOR IN A SERIAL HYBRID BUS BASED ON SMART DATA

Dresden Institute of Automotive Engineering

The development of new concepts for a public transport is motivated by reducing environmental pollution and traffic jams in city areas. Another essential reason for energy efficient vehicle concepts is to reduce transportation costs. Accordingly, a design and production of environmental friendly and emission free vehicles for urban public transportation is an important research and technological task. The architecture of a serial hybrid bus has the big capability to achieve above-mentioned aims because such vehicles have two energy sources (more degree of freedom) and more than one energy storage unit (battery, air tanks of vehicle pneumatic system). Thus, there is a big potential for the development of predictive control algorithms for various systems to enhance the overall energy efficiency and driving performance of such type of public transport. Today the control algorithms of different systems in hybrid electric vehicles are implemented often as the kind of open-loop control. A typical example is the control strategy of vehicle air compressor. Currently, this unit of vehicle pneumatic system is operated by the principle of two-point controller regardless of the vehicle driving status and location on a route, the traffic situation and battery state, the number of passengers, etc. Taking into account modern networking technologies it is possible to achieve a higher level of vehicle systems control with the aim to enhance the overall
energy efficiency of vehicle operation. The goal is to develop vehicles on various types of closed-loop control systems (e.g. battery state of charge depending on system and route parameters) towards smart vehicles (interconnection with the environment, additional history data, prediction, etc).

Authors focus on the development of closed-loop control strategy for the air compressor in a serial hybrid bus, as a first step, to improve the energy efficiency of compressor operation. Furthermore, the paper discusses how to increase the overall efficiency of vehicles including already implemented networking technologies.

See vCD 393 1-s2.0-970-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp385-392.)

ENGINE SPEED CONTROL DURING GEAR SHIFTING OF AMT HEVS WITH IDENTIFIED INTAKE-TO-POWER DELAY

Jilin University

For hybrid electric vehicles with traction motors installed behind the transmission, motor torque can be used to compensate for traction loss during gear shift. Thus, engine speed control can be used to achieve speed synchronisation without disengaging the clutch. To improve the speed tracking performance during gear shift, an engine speed control system is designed based on gain-scheduling PID and PD controllers and Smith predictor. Gain-scheduling PID and PD controllers are used to address the system nonlinearities and Smith predictor is used to compensate the intake-to-power delay. An accurate engine model is built, and the delay time of intake-to-power is identified. By intensive off-line calibration, the control settling time is less than 1 s, and the range of tracking error is 0 to +20 rpm, which satisfy the performance requirements of the synchroniser engagement during gear shift of AMT (Automated Manual Transmission).

See vCD 393 1-s2.0-4665-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp793-799.)

POWER MANAGEMENT OF A HYBRID ELECTRIC VEHICLE DURING WARM-UP PERIOD CONSIDERING ENERGY CONSUMPTION OF CABIN HEAT COMPONENTS

Osaka Sangyo University

This paper proposes a predictive control for hybrid electric vehicles (HEVs) under conditions that exhaust heat power from an internal combustion engine (ICE) is needed. Owing to motor-generators (MGs) and a battery, the ICE in an HEV can be selectively operated under high efficiency conditions. This aims to reduce the amount of fuel converted into exhaust heat power as low as possible. However, this may cause a lack of heat power when an ICE is warming up or when the cabin heating system is operating in cold weather. Under such conditions, the ICE and MGs should be controlled to balance heat power, fuel consumption and electricity usage. In this paper, a predictive control is used with models for ICE, MG, battery, cabin heat components and ICE coolant. This control determines ICE power by minimising a cost function that includes predicted warm-up time and fuel consumption. Finally, the effectiveness of the control is demonstrated by simulation.

See vCD 393 1-s2.0-982-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp393-398.)

TRANSMISSION-MOUNTED POWER CONTROL UNIT WITH HIGH POWER DENSITY FOR TWO-MOTOR HYBRID SYSTEM

Honda and Keihin Corporation

A second-generation power control unit (PCU) for a two-motor hybrid system is proposed. An optimally designed power module, which is a key component of the PCU, is applied to increase heat-resistant temperature, while the basic structure of the first generation is retained and the power semiconductor chip is directly cooled from the single side. In addition to the optimum design, by decreasing the power loss as well as increasing the heat-resistant temperature of the power semiconductors (IGBT: Insulated Gate Bipolar Transistor and FWD: Free Wheeling Diode), the proposed PCU has attained 25% higher power density and 23% smaller size compared to first-
generation units, maintaining PCU efficiency (fuel economy). To achieve a high yield rate in the power module assembly process, a new screening technology is adopted at the initial stage of power module manufacturing. In the proposed technology, the maximum current required by hybrid systems can be applied to the component power semiconductor chips at high temperatures before power module assembly. The proposed PCU is directly mounted on the transmission case in the engine compartment of the vehicle and connected to the motor using three-phase connectors. Since conventional three-phase AC cables are eliminated in the layout, space saving and flexibility in the engine compartment layout are provided, simplifying the process of vehicle assembly. See SAE 2016-01-1223 (2016, 7pp.)

Energy management

CONVEX OPTIMIZATION FOR ENERGY MANAGEMENT OF PARALLEL HYBRID ELECTRIC VEHICLES

Renault and University of Orleans

This paper presents a comparison between two optimization methods for the energy management of a parallel hybrid electric powertrain: convex programming and Pontryagin's Minimum Principle (PMP). The objective of this comparison is to validate the analytical solution by comparing the results with the ones obtained on the original model with Dynamic Programming (DP). Therefore, before its application, some necessary approximations and convexification were made on the original nonlinear and non-convex model. The validation of the simplified model was also carried out. In this paper, two cases are studied. In the first case, the supervisory control considers only the torque split between the Internal Combustion Engine (ICE) and the electric machine. In the second case, a binary decision ICE On/Off is included in the optimization problem. In order to solve the problem of the binary decision, which makes the problem non-convex, a analytical solution based on PMP is then proposed. The results show that the analytical solution is close to the optimal solution given by DP. See vCD 393 1-s2.0-623-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp271-276.)

DESIGN AND CONTROL CO-OPTIMIZATION FOR HYBRID POWERTRAINS: DEVELOPMENT OF DEDICATED OPTIMAL ENERGY MANAGEMENT STRATEGY

IFP Energies Nouvelles (IFPEN)

Computationally-efficient optimal energy-management strategies are required for the optimal design of hybrid electric vehicles with respect to fuel economy and other criteria. In this paper, the novel Selective Hamiltonian Minimization (SHM) technique is introduced. Based on Pontryagin's Minimum Principle, the SHM is developed by explicitly calculating possible optimal control modes, and then selecting the one that minimizes the Hamiltonian function. Parametric analytical models of powertrain components are developed to compute Hamiltonians in closed form. Engine and battery models are further expressed in terms of their main design parameters and technologies thanks to a statistical analysis over several sample components. An example of design optimization is presented to illustrate the effectiveness of the proposed approach. See vCD 393 1-s2.0-635-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp277-284.)

TOWARDS A GENERIC CONTROL-ORIENTED MODEL FOR HEV PREDICTIVE ENERGY MANAGEMENT

Renault; Orleans University, CentraleSupelec-CNRS-University and University Paris-Saclay

The increased interest in model-based control techniques for the energy management of hybrid electric vehicles has led to a focus on generic modelling in order to allow an effective integration in model-based design procedures. An architecture-free model ensures modularity with a view to control design. Under mild assumptions, a generic model for the torque and the rotational speed of a hybrid electric vehicle is proposed in this article. In addition, the mathematical formulation of the fuel consumption minimization and the intrinsic problem of torque split are addressed. In order to
illustrate its ability to handle the constraints, a model predictive control formulation is presented and applied to a dual-clutch transmission hybrid architecture.  

See vCD 393 1-s2.0-60X-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp259-264.)

Fuel consumption

ENERGY BASED METHOD TO ANALYSE FUEL SAVING POTENTIAL OF HYBRID VEHICLES FOR DIFFERENT DRIVING CYCLES  

Chalmers University of Technology  

Fuel saving potential of hybrid electric vehicles (HEVs) depends mainly on driving cycle and on sizing of powertrain components. Since a complete driving cycle, representing the whole life usage of a vehicle, is very long it is time consuming to predict the fuel saving potential, especially if many different types of HEVs should be analysed. This paper presents an energy based method to quickly screen different types of HEVs for many and long driving cycles, in order to find interesting candidates for deeper and more accurate analysis. The technique used also allows to derive the fuel consumption analytically, and thus it is a very effective tool to explain the main fuel savings mechanisms of different types of HEVs and how they are influenced by the driving cycle. Some of the simplifications will lead to errors, but since the sign of the main errors are known it is still easy to draw several clear conclusions using the method.  

See vCD 393 1-s2.0-4434-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp641-648.)

NVH

MPC FOR ACTIVE TORSIONAL VIBRATION REDUCTION OF HYBRID ELECTRIC POWERTRAINS  

Technische Universität Darmstadt  

Trends such as downsizing and downspeeding of internal combustion engines (ICE) shift the excitation spectrum of automotive powertrains by the ICE torque leading to demanding requirements for passive vibration reduction measures. Hybrid electric vehicles (HEV) offer a possibility to implement active vibration reduction using the electric traction machine (ETM). This paper proposes a model predictive controller (MPC) for active vibration reduction of a plug-in parallel HEV powertrain with a downsized 2-cylinder combustion engine. Both time and frequency domain variants have been implemented. The frequency domain MPC-variant uses a spectral cost based formulation. Low bandwidth of the tracking controller of the energy management (EM) has been extended by the regulation based MPC vibration controller. Further, a 2 degree of freedom (DoF) controller structure has been adopted for the integration of the MPC-based vibration controller with the EM controller of the HEV. Simulation analysis of the proposed approach under stationary and dynamic ICE operating conditions shall be discussed focusing on the stationary/dynamic performance and time-variant constraint handling.  

See vCD 393 1-s2.0-4604-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp756-761.)

TORSIONAL VIBRATION REDUCTION WITH MAGSPLIT DEDICATED HYBRID TRANSMISSION

Magnomatics  

This paper will describe and demonstrate the ability of Magnomatics' proprietary magnetic power split or MAGSPLIT to filter torsional vibration (TV) from the engine into the powertrain as an alternative to conventional engine damper systems. The principal of MAGSPLIT operation will be discussed, with comparisons made to a conventional 3 rotor power split eCVT, highlighting the inherent torsional vibration transmission path due to the nature of the variator components. This will be compared and contrasted with the MAGSPLIT system, describing the unique "virtual variator", which is a massless magnetic field that controls the
gear ratio between the input and output shafts. It will be shown that the virtual variator is capable of reacting and repositioning itself to the engine’s rotational oscillations and resulting torsional vibrations, performing its ratio control function with high resolution and precision, thereby substantially reducing reflected inertia into the powertrain. The initial mechanical testing results will be presented that demonstrated our initial findings, which are then validated by engine tests. The result is the ability to offer substantial powertrain torsional vibration improvement, simplifying or eliminating damper systems, whilst requiring no additional control effort or consuming additional power.


Power management

A STUDY ON POWER MANAGEMENT STRATEGY OF HEV USING DYNAMIC PROGRAMMING

Seoul National University

For hybrid electric vehicle, it is necessary to control power distribution among multiple power sources to improve fuel economy performance of vehicle. In this paper, power management strategy of hybrid electric vehicle using Dynamic programming is studied. Deterministic dynamic programming could present outstanding fuel economy, while its application as real time control of vehicle is limited. Thus, different kinds of power management strategy using dynamic programming are studied. Stochastic dynamic programming, artificial neural networks and rule-based power management strategy using results from dynamic programming are studied. Simulations using parallel type hybrid electric vehicle model are conducted. Simulation results including fuel economy performance on diverse driving cycles are compared and analysed.

See vCD 395 EVS29-4940242.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 7pp.)

DEVELOPMENT OF POWER CONTROL UNIT FOR COMPACT-CLASS VEHICLE

Toyota and Denso

Toyota Motor Corporation has developed the new compact-class hybrid vehicle (HV). This vehicle incorporates a new hybrid system for the improvement of fuel efficiency. For this system, a new Power Control Unit (PCU) is developed. The feature of the PCU is downsizing, lightweight, and high efficiency. In expectation of rapid popularization of HV, the aptitude for mass production is also improved. The PCU, which plays an important role in the new system, is our main focus in this paper. Its development is described.

See SAE 2016-01-1227 (2016, 8pp.)

Research and development

RESEARCH PROJECT ECOCHAMPS

RWTH Aachen University

The significant additional costs of hybrid powertrains are still the greatest barrier to their wide market penetration. An international consortium, made up of twenty-five manufacturers, suppliers and research facilities now aims to tackle this challenge from two sides within the EU-funded research project Ecochamps. Standardisation and modularisation of hybrid components across vehicle classes should decrease costs. Simultaneously, the new hybrid vehicles’ amortisation period should be further reduced through increased fuel savings. Covers - modular system and standardisation, Class B demonstrator – Fiat 500X plug-in hybrid, Class C demonstrator – 48V hybrid based on a Renault Megane, medium-duty commercial demonstrator – Iveco Daily delivery cab vehicle with a parallel hybrid powertrain, City bus demonstrator – MAN, heavy tractor demonstrator – DAF electric Waste-Heat-Recovery system.

See Doc.146278 (MTZ Worldwide, Oct 2016, pp18-23.)
Thermal issues

EFFICIENCY IMPROVEMENT IN EXHAUST HEAT RECIRCULATION SYSTEM

Toyota and Sango Co.

In order to speed up engine coolant warm-up, the exhaust heat recirculation system collects and reuses the heat from exhaust gases by utilising the heat exchanger. The conventional system improves actual fuel economy at the scene of the engine restart in winter season only. The heat recirculation system becomes more effective at the low outside temperature because it takes longer time to warm up engine coolant. However, the heat recirculation system becomes less effective at the high outside temperature because it takes shorter time to warm up engine coolant. Therefore, the new exhaust heat recirculation system is developed, which adopted as follows: 1) a fin-type heat exchanger in order to enhance exhaust recirculation efficiency 2) a thinner heat exchanger component and smaller amount of engine coolant capacity in the heat exchanger in order to reduce the heat mass. As a result, the actual fuel economy is more improved in winter season. In addition, even at the high outside temperature seasons, the actual fuel economy is improved. Due to the change mentioned above, the weight of the heat exchanger is reduced by 20% compared to the heat exchanger in the conventional system. The new exhaust heat recirculation system has been adopted to the 4th generation Prius.

See SAE 2016-01-0184 (2016, 7pp.)

IMPROVEMENT OF ADHESION PROPERTIES BETWEEN EPOXY RESIN AND PRIMER AND BETWEEN PRIMER AND NI PLATING IN HYBRID VEHICLE POWER SEMICONDUCTOR MODULE UNDER HIGH TEMPERATURE CONDITIONS

Toyota

In this report, adhesion mechanism between epoxy resin and primer and between primer and Ni plating in Hybrid vehicle (HV) was investigated. Adhesion forces are thought to be a combination of mechanical bond forces (such as anchor effect), chemical bond forces and physical bond forces (such as hydrogen bonding and Van der Waals force). Currently there is insufficient understanding of the adhesion mechanism. In particular, the extent to which the three bond forces contribute to adhesion strength. So the adhesion mechanism of polyimide primers was analysed using a number of different methods, including transmission electron microscope (TEM) and atomic force microscope (AFM) observation, to determine the contributions of the three bonding forces. Molecular simulation was also used to investigate the relationship between adhesion strength and the molecular structure of the primer.

See SAE 2016-01-0500 (2016, 6pp.)
TRANSMISSIONS AND DRIVELINES

AVL 7- AND 8-MODE DEDICATED HYBRID TRANSMISSIONS

AVL

Existing hybrid powertrains are focusing on utilising conventional transmissions with add-on hybrid solutions due to low hybrid production volumes. This approach some benefits like reuse of the existing components, flexibility of production, reducing the development efforts and risks. But how far these add-on hybrid solutions can bring powertrains to the future targets of fuel economy? Will add-on approach stay as the mainstream solution for hybridisation or can we achieve more with new transmissions structures?

The first dedicated hybrid transmission from Toyota actually provides answers to these questions. The success of the dedicated hybrid transmission can also be seen from the production volumes, as it proves that the dedicated hybrid transmission solution has the highest acceptance from the customers.

AVL evaluated several different powertrain configurations to assess the future technologies for transmission hybridisation. The results of these studies have proven that the DHTs were superior compared to add-on solutions with respect to several different requirements on cost, efficiency, weight, etc.

According to these evaluations AVL developed its first Dedicated Hybrid Transmission (DHT) – Future Hybrid 7 Mode Transmission to imply improvements on costs and increase fuel efficiency. As the Future Hybrid 7 Mode Transmission was the first DHT of AVL, it provided many results and answers to the question of what is possible with a DHT. In addition, there are extensive lessons learned on DHTs like; how to evaluate a DHT, what kind of methodologies are needed for synthesis of a DHT, how a DHT powertrain system can be optimised, what new control functionalities are required, etc. With this experience and lessons learned, AVL has developed its second DHT transmission, called AVL Future Hybrid 8 Mode Transmission.

This paper focuses on the complete development process of the new DHT, starting from synthesis techniques, system functionalities of a DHT and evaluation methodology for different DHT’s with a wide system scope. Furthermore, AVL Future Hybrid 8 Mode Transmission is presented in detail.

Covers - eCVT mode, cost analysis.


DEDICATED HYBRID TRANSMISSIONS (DHT) - A NEW CATEGORY OF TRANSMISSIONS

AVL

MT, AT, AMT, CVT, DCT and now DHT – what is the reason for introducing this new category of transmissions? A DHT (Dedicated Hybrid Transmission) is a transmission, which has the power source for electrical propulsion fully integrated and its functionality depends on the integrated electrical components. Without an E-motor the transmission cannot fulfill the requirements. In contrast to DHTs, Add-on hybrid transmissions are introduced that build on an existing conventional transmission. Typically, by adding a module or replacing the launch device by a module the electrification is accomplished. Such transmissions are already available in the market, e.g. from Honda, Daimler, BMW, VW, etc. There are many different variants of the Add-on hybrid transmissions already in production, yet each is produced in relatively small volumes.

This actually is the main motivation for the modular approach of building on existing conventional transmissions, because the volumes would not justify the development and industrialization of a fully integrated transmission according to the newly defined transmission category DHT.

The only DHT for several years – Toyota Hybrid System (THS), labelled “Hybrid Synergy Drive” on these vehicles – was developed already 20 years ago and launched in the Toyota Prius in 1997. It sells quite well and reaches attractive production volumes already for quite some time. So far no other hybrid transmission was able to reach similar production volumes.

The ever increasing pressure by legislation, society and consumers to reduce fuel consumption in the next decade will boost the market share of hybrid vehicles significantly. Probably the volumes...
of hybrid propulsion systems will exceed the current predictions. Based on that, the business cases for DHTs will improve significantly, the expected volumes will justify development and industrialization efforts for DHTs and enable the utilisation of further benefits of this transmission category, e. g. reduced weight, package, complexity, etc. A couple of years ago DHTs moved into focus and investigations in this area have started. Meanwhile many OEMs and key suppliers launched development programs for DHTs. This was the reason for the Advisory Board of the "CTI Symposium Automotive Transmissions, HEV and EV Drives" to define this new transmission category "DHT" and position it during the 10th anniversary CTI Symposium USA with a plenary speech and an own section as a special focus. Covers – fuel economy statues and legislation targets. See vCD 406 P3_Brunner_AVL_Paper_EN.pdf and P3_Brunner_AVL_Slides_EN.pdf (5th International CTI Symposium China Automotive Transmissions, HEV and EV Drives, Shanghai, China, 21-23 Sep 2016, Plenary Speeches, Paper - 16pp, Slides - 44pp.)

DEDICATED TO E-MOBILITY: PHEV PRODUCT MODULARITY FROM ZF

ZF Friedrichshafen

ZF continues to pursue the development of the modular kit for hybrid transmissions and thus can offer technologies which, on the one hand, can help to fulfill short- and medium-term CO2 targets and, on the other hand, can offer economic powertrain solutions in an environment of slowly increasing volumes of hybrid vehicles. With the new plug-in hybrid transmission 8P75PH as part of this modular kit, ZF has succeeded in fulfilling the further increased requirements compared to full hybrid transmissions:
- increased electric power for pure electric driving over complete driving cycles
- improved efficiency in electric drive mode for higher range and lower battery costs
- minimum additional installation space compared to conventional transmissions has been realized by a high level of component integration
- modular kit approach for cost optimisation on system and component level
- comfort features to meet expectations in terms of decoupling of vibrations and of start-up functionalities also in conjunction with new three and four-cylinder engines

This article reveals that despite conflicting requirements within one transmission system an optimum overall solution can be reached if all key qualifications (mechanics, hydraulics, functionality, system development) are brought together into one development responsibility. With this approach ZF is able to offer a plug-in hybrid transmission system to the vehicle manufacturers with few interfaces towards the higher-level system "plug-in hybrid vehicle". The new plug-in hybrid transmission 8P75PH is now ready for series production and offers the comfort and agility customers know from the 8HP base transmission. As an outlook, this article shows ZF’s approaches to the next generation PHEV solutions. Covers - torsional damping system, separating clutch, integrated launch element (IAE), integrated electric pump (IEP).


GKN INNOVATIVE 2ND GENERATION eAXLE FOR THE NEW PLUG-IN-HYBRID BMW 225XE

GKN Driveline

GKN Driveline has successfully launched the second generation version of its single speed eAxle, which debuts on the new BMW 2 Series Active Tourer 225xe. The technology was developed at GKN Driveline Tech Centre in Lohmar, Germany, and is being manufactured at GKN Driveline Bruneck, Italy. The eAxle is an evolution of current mass-produced eTransmission technology for hybrid and electric vehicles. It has been optimized for compact car applications and can be easily integrated into global vehicle platforms, enabling eAWD and eBoost functionality with significant fuel and emission reduction.
This paper describes the general layout of the eAxle, as well as specific details about the optimization of the gear train in terms of efficiency and NVH and the functional principle of the unique electronic disconnect differential.

Covers - Electronic Disconnect Differential (EDD).

See vCD 406 F6_Mair_GKNDriveline_Paper_EN.pdf and F6_Mair_GKN_Driveline_Slides_EN.pdf (5th International CTI Symposium China Automotive Transmissions, HEV and EV Drives, Shanghai, China, Sep 2016, Session F, Paper - 12pp, Slides - 17pp.)

GKN'S INNOVATIVE 2ND GENERATION EAXLE FOR THE NEW PLUG-IN-HYBRID BMW 225XE

GKN Driveline

GKN Driveline has successfully launched the second generation version of its single speed eAxle, which debuts on the new BMW 2 Series Active Tourer 225xe. The technology was developed at GKN Driveline Tech Centre in Lohmar, Germany, and is being manufactured at GKN Driveline Bruneck, Italy.

The eAxle is an evolution of current mass-produced eTransmission technology for hybrid and electric vehicles. It has been optimized for compact car applications and can be easily integrated into global vehicle platforms, enabling eAWD and eBoost functionality with significant fuel and emission reduction.

This paper describes the general layout of the eAxle, as well as specific details about the optimization of the gear train in terms of efficiency and NVH and the functional principle of the unique electronic disconnect differential.

See vCD 413 Session 03, 09_A2.4_Haniche_GKN.pdf (25th Aachen Colloquium, 10-12 Oct 2016, Session 03_Hybrid and Electric Vehicles, 14pp.)

GKNs NEW HIGH PERFORMANCE eAXLE FOR THE VOLVO XC90 T8

GKN Driveline

Contents:
- The Hybrid Concept of the Volvo XC90 Plug-In-Hybrid
- Gearbox Specification and its Resulting Integrated Design
- Electronic-Disconnect-Differential (EDD)
- Development Challenges
- Package
- Efficiency and Lubrication
- NVH and Gear Layout
- GKN-eAxle - Animation

Summary:
- GKN's new high performance eAxle for the Volvo XC90 T8
- GKN has successfully developed and launched the co-axial eAxle for the Volvo XC90 T8 Twin Engine into series production. The co-axial eAxle is an evolution of GKN's market-proven family of eAxles, which have featured on the Peugeot 3008 Hybrid, BMW i8 and Porsche 918 Spyder.
- The co-axial eAxle is GKN's first semi-integrated design and delivers benefits in terms of packaging, weight, efficiency and NVH. It is the most compact variant of GKN's transmission designs and is designed to fit in the same package space as the rear drive module on the conventional XC90 AWD driveline, thus enabling easy integration into the global vehicle platform.

See vCD 406 E2_Gasch_GKNDriveline_Slides_EN.pdf (5th International CTI Symposium China Automotive Transmissions, HEV and EV Drives, Shanghai, China, 21-23 Sep 2016, Session E, 19pp.)

HIGH-PERFORMANCE HYBRID TRANSMISSION FOR FUTURE PLUG-IN HYBRID DRIVES

IAV

The growing demand for electrified vehicles with differing requirements in terms of efficiency, costs and performance is creating a huge variety of possible drive topologies. IAV has introduced in MTZ Sep 2016 an end-to-end development process for all-encompassing assessment of this variety. It
is used now to define the IAV PowerHybrid concept – a high-performance hybrid transmission for passenger cars which is drafted as a dedicated hybrid transmission (DHT) for a P2 parallel drive. Also see Doc.148198 for article on development process.

See Doc.148283 (ATZ Worldwide, Oct 2016, pp16-21.)

MULTIMODE TRANSMISSION - A UNIQUE TRANSMISSION CONCEPT FOR HYBRID VEHICLES

GKN Driveline

The Mitsubishi Outlander Plug-in Hybrid Electric Vehicle (PHEV), launched in 2013, has been first on the market with a unique Multimode transmission concept. This transmission, developed by GKN, drives the front wheels and combines an internal combustion engine (ICE), generator and electric motor to provide either fully electric, parallel or serial hybrid mode with smooth, comfortable transition, fully transparent to the driver.

The Multimode transmission allows switching modes to operate in:

- Pure EV
- Serial Hybrid, supported by the ICE via generator in situations with high-power-demand or low battery SOC
- Parallel Hybrid with direct ICE support for best efficiency and maximum performance

This flexibility in operation modes provides unmatched performance in terms of fuel consumption and CO2 reduction.

The paper describes the basic requirements and provides an overview of Multi-Mode Transmission layouts. Finally, the paper addresses the technical challenges and the technological trend for this unique, dedicated hybrid transmission (DHT) concept.


OPTIMAL CONTROL OF ENGINE CONTROLLED GEARSHIFT FOR A DIESEL-ELECTRIC POWERTRAIN WITH BACKLASH

Linkoping University

Gearshift optimal control of a hybrid powertrain with a lumped/decoupled transmission model and backlash dynamics in the driveline is studied. A model is used for a heavy duty powertrain including a validated mean value diesel engine model with electric generator, transmission dynamics representing the dynamics of the automated manual transmission system and driveshaft flexibilities. Backlash dynamics are also included in the driveline model by introducing a switching function. By applying numerical optimal control methods and dividing the gearshift process into separate phases, optimization problems are solved to investigate the minimum time and low jerk gearshift transients. The controls are also calculated with fuel penalties added to the minimum jerk optimization and the transients are analysed.

See vCD 393 1-s2.0-4616-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp762-768.)

P2-HYBRID VERSUS DHT-HYBRID DRIVETRAINS – EVALUATION AND OPTIMIZATION

Technical University of Braunschweig

Electrification opens up completely new design possibilities for the vehicle drivetrain. By actively using of at least one electric machine, transmission concepts can be realised with fully new drive modes (ICE-solo, EM-solo, eCVT, parallel hybrid and serial hybrid) without conventional starting elements. These so-called Dedicated Hybrid Transmissions (DHT) open up the potential of being able to simultaneously reduce consumption and costs. New DHT concepts can be identified by drivetrain synthesis. However, the concept variety is extremely high and therefore requires a systematic analysis and comparison of variants.

The evaluation tool must be able to model and evaluate with modular design any drivetrain concepts. This includes not only various gear sets but also any number of in drivetrain integrated electrical machines. In this presentation, a new evaluation tool will be presented, with which every
A hybrid drivetrain concept can be parameterised and calculated. In addition, the underlying methodology is explained. In addition to the full calculation of all possible combinations of operating points, an operating strategy has also been integrated, which utilises the Equivalent Consumption Minimisation Strategy (ECMS) to select the optimal drive mode under all driving situations. The strategy has been supplemented by various criteria in order to achieve a realistic control of drivetrains. The extension of ECMS with the criteria leads to very good fuel economy and realistic driveability.

In addition to the topology of a hybrid drive, the dimensioning of electric machines and transmission plays an essential role. For this reason, the evaluation tool is combined with an optimisation tool. In this presentation, a P2- and a DHT-hybrid drivetrain are analysed with the criteria mentioned above and optimised afterwards. The optimisations are carried out in legally stipulated driving cycles as well as in customer driving cycle. This enables the optimised design of the drivetrains regarding the efficiency and vehicle performance.

MILD OR MICRO HYBRID POWERTRAINS

12+12V AND 12+48V ARCHITECTURES & FUNCTIONS: A MODULAR APPROACH

Valeo

The powertrain industry is now driven by regulations on emissions and CO2 with more and more challenging targets. Despite huge progresses still expected on internal combustion engines, there is no chance to reach the global targets without several levels of hybridization. Chinese market has specific requirements due to dedicated regulation and customer demand. Regulation aims to reduce city air pollution via dedicated subsidies. The cost of the vehicle, and so the added cost of any hybridization system, is very acute for the customers. As the market trend is still based on comfortable cars with quite high performances powertrains, affordable solutions have to be proposed to lower this powertrain consumption with low compromises and performances. Among the various hybridization levels, the 12+12 volts affordable architecture represents the basic architecture allowing the benefits of hybridization, thanks to the energy recovery during braking. The 12+12 volts electrical architecture is based on 2 batteries which are supplied or could supply electric power in 12V voltage.

The 12+48V electrical architecture is an easy way to enhance 12+12V functionalities and enter deeper in the hybrid application field. With the extended power field offer by 48V components, more vehicle segments and applications can have more benefits at a still limited over cost. As basic hybrid functionalities and electrical architecture topology are quite similar between 12+12V and 12+48V systems, a modular approach can be done. This approach can also help to lower the cost of the systems integration in vehicle which can be a significant part of the total system application cost. This can thus contribute to a large application field for mild hybrid systems and by the way contribute to a greater vehicle fleet CO2 reduction.

This dual battery architecture is the gateway to complementary functions requiring safety constraints, as coasting, higher stop and start activation speed or high current devices such as electric supercharger. We will examine how 48V system can address more efficient hybridization architectures (from P1 to P4) allowing more CO2 emission reduction and even open the gateway for low cost pure electrical vehicle.

We will illustrate how the electrical board net can be defined for 12+12V applications and how complementary functions can be added in a modular way. The similar topology of the 12+48V architecture will then be showed. We then show how the different hybridization architectures can be addressed in a modular building bloc structure for components. This last level of modularity is an additional lever to lower the hybridization cost. Combining the electrical board net modular predisposition and the field of 48V hybridization would open ways to access further CO2 emission reduction with the best cost ratio.

See vCD 406 E7_Zhang_Valeo_Paper_EN.pdf (5th International CTI Symposium China Automotive Transmissions, HEV and EV Drives, Shanghai, China, Sep 2016, Session E, 14pp.)

48 VOLT TECHNOLOGY – MORE THAN A MILD HYBRID

Continental

The clear motivation for using 48-volt technology in vehicles is the increasing importance of electricity as a flexible form of energy in vehicles. It can be implemented for both the powertrain and any components in the on-board power supply as a whole. Electrical power also offers other benefits, including an increase in the efficiency of available functionalities and the introduction of brand new functions. The biggest single advantage offered by the 48-volt on-board power supply is when this second voltage level is used to hybridize the drive unit. In this case, the low-voltage electrification can make significant contributions to ensuring that vehicles comply with future CO2 limits. With regard to safety, the new 48-volt voltage level is as unproblematic as the 12-volt on-board power supply as both voltages do not exceed the valid international limit of 60-volt for protection against electric shock from direct current components. The higher voltage level of 48-volt is also more electrically
efficient. The increasing number of high-current consumers can also be more efficiently operated if there are applied to 48-volt as well as designed to be lighter and more compact.

Covers - CO2 reduction via 48-volt mild hybridisation, load point shifting, electrically heated catalysts (EHC), electric compressor (eCompressor), Broadnet optimisation, energy management. See vCD 406 E6_Koch_Continental_Paper_EN.pdf E6_Koch_Continental_Slides_EN.pdf (5th International CTI Symposium China Automotive Transmissions, HEV and EV Drives, Shanghai, China, Sep 2016, Session E, Paper - 10pp, Slides - 20pp.)

CAN MILD HYBRIDS SAVE THE CAR INDUSTRY?

Ricardo

With the EU CO2 targets very close (at least in terms of automotive timescales) and diesel looking set to become a more premium-priced powertrain, where does this leave the European car industry?

Not without hope, because mild hybrid technology – a less expensive form of drivetrain electrification than that seen in classic hybrids such as the Toyota Prius – is maturing just in time. And much of this technology is being pioneered by UK-based engineering consultancies. Shoreham-based Ricardo's Advanced Diesel Electric Powertrain (ADEPT) project is just one example. It takes one of Ford's most frugal models – the 1.5-litre diesel Focus – and adds a 48V electrical system, a turbocharger, a super-fast stop-start generator and a low-cost but high-tech battery pack.

Ricardo's mild hybrid adaptation of the Focus is extensive. Out goes the 12V alternator, the mechanical air-con compressor and mechanical water pump. In their place comes a 48V integrated starter generator (ISG), which acts as a super-fast starter motor and charger and can also assist the engine at low speeds.

ISG also provides the power for a 48V air-con compressor and a 48V water pump. A DC/DC converter is used to power the rest of the Focus's 12V electrical systems.

The 48V battery pack is a lead-carbon unit rather than the more conventional (and expensive) lithium ion unit. This battery tech is still in development but is said to be more much more tolerant of extremes of temperatures than lithium ion.

The most remarkable idea on Ricardo's prototype is probably the Turbogenerator Integrated Gas Energy Recovery System (TIGERS) 'e-turbine', which sits in the exhaust stream and uses exhaust gas to drive a generator. Ricardo calculates that at motorway speeds, TIGERS could recover around 1.4 kW of energy to the battery.

See Doc.148301 (Autocar, 14 Sep 2016, pp52-55.)

GLOBAL STANDARDIZATION OF 48 VOLT AUTOMOTIVE TECHNOLOGY

IQPC

The introduction of 48 volt technology promises a variety of benefits for the automotive industry, including reduced emissions and the ability to power the growing range of electrical systems in today's vehicles. This move towards additional power supplies also presents a number of challenges, and although many issues have been addressed and preliminary solutions identified, the need for globalized standards for 48 volt systems remains apparent.

We have already seen the introduction of 48V technology in the Audi SQ7 and the Bentley Bentayga, and these first examples are indicative of the changes expected over the next decade. Bentley presented an electrically actuated suspension system powered by 48V architecture, while Audi opted to showcase the performance benefits with a 48V sub-system driving an electric powered compressor.

These first steps demonstrate some of the new capabilities of new electrical architectures, but the developers of such technology are also facing up to the need for an internationally agreed 48V electrical standard. This is something that will almost certainly be required by the global automotive industry to achieve the economies of scale demanded by OEMs.

Earlier this year it was announced that Controlled Power Technologies, a developer of vehicle driveline electrification based on state-of-the-art switched-reluctance machines (SRMs) has partnered with Ricardo, Tata Motors European Technical Centre (TMETC) and Provector to apply
its low voltage electric motor technology to the rear driveline of a B-segment city car. Innovate UK has awarded £1.8 million of funding towards the total project investment of £3.4 million. Project FEVER (Forty-Eight Volt Electrified Rear-Axle) will help to further introduce advanced mild hybrid functionality to mainstream vehicles at significantly reduced cost compared with high-voltage plug in hybrid and pure electric vehicles. The innovative electrified rear-axle technology aims to provide an important step towards enabling OEMs to improve both regulated and real world fuel economy in modern urban city driving conditions.


See Electronic Document 7987 *(IPQC, Oct 2016, 5pp.)*
COMMON ISSUES

Fuel economy

48V ADEPT PROJECT: FULL-ON MILD

Ricardo

The Ricardo-led 48-Volt ADEPT project shows how intelligent electrification can deliver fuel and CO2 savings equivalent to full-hybrid capability. What is more, the concept's low-cost mild hybrid architecture is adaptable for diesel, gasoline or alternative-fuelled powertrains. Covers - 48V cost advantage, intelligent electrification, ADEPT powertrain architecture, CPT's water-cooled SpeedStart switched reluctance belt-driven integrated starter generator (B-ISG), energy recovery, CPT's exhaust-mounted 48V turbine-integrated exhaust gas energy recovery system known as TIGERS, Applicability to gasoline and alternative fuelled powertrains, intelligent electrification.


DOWNSIZED, BOOSTED GASOLINE ENGINES

International Council on Clean Transportation (ICCT) and Ricardo

In 2012, the US Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) finalised a joint rule establishing new greenhouse gas and fuel economy standards for vehicles. The standards apply to new passenger cars and light-duty trucks covering model years 2012 through 2025. A mid-term review of the standards will be conducted in 2017.

Assuming the fleet mix remains unchanged, the standards require these vehicles to meet an estimated combined average fuel economy of 34.1 miles per gallon (mpg) in model year 2016, and 49.1 mpg in model year 2025, which equates to 54.5 mpg as measured in terms of carbon dioxide emissions with air conditioning refrigerant credits factored in. The standards require an average improvement in fuel economy of about 4.1 percent per year.

The technology assessments performed by the agencies to inform the 2017–2025 rule were conducted four to five years ago. The ICCT is collaborating with automotive suppliers on a series of working papers evaluating technology progress and new developments in engines, transmissions, vehicle body design and lightweighting, and other measures that have occurred since then. Each paper will evaluate:

- How the current rate of progress (cost, benefits, market penetration) compares to projections in the rule;
- Recent technology developments that were not considered in the rule and how they impact cost and benefits;
- Customer-acceptance issues, such as real-world fuel economy, performance, driveability, reliability, and safety.

This paper provides an analysis of turbocharged, downsized gasoline engine technology developments and trends. It is a joint collaboration between ICCT, Eaton, Ricardo, JCI, BorgWarner, Honeywell, and the ITB Group. The paper relies on data from publicly available sources and data and information from the participating automotive suppliers.

Covers - turbocharger technology and efficiency impacts, two-stage boosting systems, historical estimates of costs and benefits, EPA/NHTSA 2017-2025 projections: market penetration, costs, and benefits, current turbocharger market penetration and latest projections, current production costs and benefits, Miller cycle, VW's EA211 TSI evo engine family, Mazda 2.5-litre turbocharged I4 (SKYACTIV-G 2.5T), Ricardo "deep" Miller cycle concept - downsized boosted engine (termed Magma), E-Boosting and 48 volt hybrid systems, Ricardo's prototype "HyBoost" engine (a modified 1.0-litre EcoBoost), Continental and Schaeffler 48V system, Valeo micro- and mild-hybrid systems, Volvo engine that uses an electrically powered compressor to spool up two twin turbos, Speedstart, electrically assisted variable speed (EAVS) supercharger from Eaton, BorgWarner's eBOOSTER, Delphi 48V mild hybrid system with an electrical supercharger, variable compression ratio (VCR),

Starting

POWERTRAIN MODELLING AND ENGINE START CONTROL OF CONSTRUCTION MACHINES
University of Warwick and JCB
This paper aims to develop an engine start control approach for a micro/mild hybrid machine for a capable of cranking the engine without injection. First, the powertrain is physically modelled using a co-simulation platform. Second, experiment data of the traditional machine is acquired to optimise the model. Third, a model-based adaptive controller is designed for the starter to crank the engine quickly and smoothly to minimise the operator discomfort. The effectiveness of the proposed approach is validated through numerical simulations with the established model. See vCD 403 N46.pdf (Powertrain Modelling and Control, Testing, Mapping and Calibration (PMC2016), Loughborough University, Sep 2016, 13pp.)
ELECTRIC POWERTRAINS

AUTOMOTIVE APPLICATIONS

Light electric vehicles (LEVs)

RESOLVE – NEW VEHICLE ARCHITECTURE FOR URBAN MOBILITY

Ricardo Motorcycle Group

Contents:
Consortium
Objectives and Strategies
- Develop an integrated, scalable, modular range of fully electric LV drivetrains
- Showcase advances in two tilting 4-wheeler demonstrators belonging L2e and L6e category
- Improve driver experience of ELVs
- Make ELVs more attractive to car drivers for their urban travel needs

Project Status
Demonstrators
ELV improvements - driver experience, efficiency, cost reduction
Perspective.

Covers - RESOLVE (Range of Electric SOlutions for L category VEhicles).

See Electronic Document 7998 (1st World Light Electric Vehicle Summit, Barcelona, Spain, 20-21 Sep 2016, 19pp.)

Race cars

G-G DIAGRAM GENERATION BASED ON PHASE PLANE METHOD AND EXPERIMENTAL VALIDATION FOR FSAE RACE CAR

Beijing Institute of Technology

In order to discuss the limit handling performance of a FSAE race car, a method to generate the G-G diagram was proposed based on phase plane concept. The simulated G-G diagram was validated by experiments with an electric FSAE race car. In section 1, a nonlinear 7 DOFs dynamic model of a certain electric FSAE race car was built. The tyre mechanical properties were described by Magic Formula, and the tire test data was provided by FSAE TTC. In section 2, firstly the steady-state yaw rate response was discussed in different vehicle speed and lateral acceleration based on the simulations. Then the method to generate the G-G diagram based on phase plane concept was proposed, and the simulated G-G diagram of a certain FSAE race car was obtained. In section 3, the testbed FSAE race car was described, including the important apparatuses used in the experiments. Based on the race track experiment, the G-G diagram of the race car was obtained. The comparison between simulated and actual G-G diagram shows that, the phase plane method provides an efficient way to generate the G-G diagram.

See SAE 2016-01-0174 (2016, 7pp.)

Trucks

2015 E-TRUCK TASK FORCE: KEY BARRIERS AFFECTING E-TRUCK ADOPTION, INDUSTRY AND POLICY IMPLICATIONS, AND RECOMMENDATIONS TO MOVE THE MARKET FORWARD

CALSTART

CALSTART’s E-Truck Task Force (ETTF) produced a report outlining the markets for electric drive trucks (E-Trucks), the prime barriers facing their success and provided key findings and recommendations to support expanding E-Truck adoption. Four key findings have been identified by the E-Truck Task Force as barriers currently affecting the growth and viability of E-Truck sales; 1) high incremental cost, 2) poor vehicle quality and support from supplier(s), 3) unexpected costs
and energy planning with infrastructure, and 4) reduced operation in extreme climates. The E-Truck Task Force developed a set of action-oriented recommendations for overcoming each barrier. Covers - Cold Weather Performance.

**See vCD 395 EVS29-6120414.pdf** (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 2 - Dialogue with the experts, 9pp.)

### Buses

**ENERGY SAVING POTENTIAL OF A BATTERY-ASSISTED FLEET OF TROLLEY BUSES**

**Swiss Federal Institute of Technology (ETH)**

This article investigates the opportunities of integrating battery-assisted trolley buses into a given trolley bus network in public transportation. In this new generation of vehicles, the diesel-powered auxiliary unit is replaced with a high-performance traction battery. On the one hand, the new vehicles can be operated without the overhead wire, while on the other hand the battery capacity improves the overall system efficiency. The energy saving potential is identified via simulation of a realistic trolley bus line including the optimization of the energy management strategy. The problem is formulated as a convex optimal control problem. The results show that up to 20% of energy can be saved, compared to the case with conventional trolley buses only. **See vCD 393 1-s2.0-969-main.pdf** (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp377-384.)
VEHICLE ENGINEERING

CHASSIS DESIGN FOR AWD ELECTRIFIED PICK UP TRUCK

Metalsa, Applus IDIADA and Tecnologico de Monterrey

Developments of new electric and hybrid propulsion systems demands chassis adaptations. The purpose of the XeV project was to develop and integrate a full suite of active chassis systems to deliver a fully electrified all-wheel-drive pick-up truck. To achieve so, a new chassis frame, engine cradles and battery box were designed to bring direct drive from electric motor to wheel. On the other hand, for a four-wheel-independent-drive, a new rear suspension design was implemented, and a complex torque vectoring and traction control strategy was developed to provide optimum on and off road performance.

All systems were tuned to meet the new drivetrain configuration, weight distribution and vehicle loading conditions making it possible to achieve comparable results with respect to the original combustion engine vehicle.

Covers - iTORQ+, iTORQ-, Active Chassis Control Systems (ACCS).

See SAE 2016-01-1675 (2016, 8pp.)
TRANSMISSIONS AND DRIVELINES

A HYBRID PULLEY-CVT AS A CARRIER FOR WIDE RANGE ELECTRIFICATION LEVELS

Punch Powertrain

Contents:
- Global and Chinese CAFC/CO2 regulations
- Market projects electrification
- Collective solutions in achieving better fuel economy
- Punch Powertrain's choice for P3 Hybrid/PHEV CVT
- HS2 Structure and functions
- Fuel Consumption Results
- Roadmapping
- Conclusions.

See vCD 406 SF_E_Yang_Punch Powertrain_Slides_EN.pdf (5th International CTI Symposium China Automotive Transmissions, HEV and EV Drives, Shanghai, China, Sep 2016, Session E, 22pp.)

EV TRANSMISSION: LESSONS LEARNT

Drive System Design

Main Lessons:
- Why a transmission?
- How many speeds/ratios?
- Shift method for multi-speed
- Efficiency and durability
- Low noise optimisation
- Mounting strategy.

See vCD 406 G8_Tylee-Birdsall_DriveSystemDesign_Slides_EN.pdf (5th International CTI Symposium China Automotive Transmissions, HEV and EV Drives, Shanghai, China, Sep 2016, Session G, 27pp.)

HIGH SPEED ROTATING TRANSMISSIONS FOR E-DRIVES IN COMMERCIAL DRIVELINES

AVL

Along with the introduction of electric motors in commercial drivelines a significantly increased speed capability of the transmission is requested. Missing the dominant noise source "combustion engine" the requirement for low noise emission and high efficiency in the drive train has increased dramatically. Therefore, new approaches for noise mitigation, lubrication and cooling are required. The high speed turning input shaft as well is asking for new approaches in sealing and bearing technology. The focus in this presentation is
- To identify areas which are critical due to the increased speeds
- To show potential approaches to handle the new challenges
Covers - EV Transmissions for different applications, transmission components including bearings, seals, gear design/NVH, lubrication.


MODULAR MULTI-SPEED TRANSMISSION FOR MD-EV

Eaton

The systematic development approaches of a drive system for a medium-duty electric vehicle (MD-EV) are introduced in this paper. The paper starts with a brief introduction of market trends of EV worldwide with special attention to China EV market. The major customer wants and needs are
summarized for different EV platforms and applications. The various drive system concepts are compared against the critical design criteria and winning drive is selected accordingly. Model-based simulations have been carried out to investigate the influence of major design parameters of the drive system on vehicle performances, namely vehicle energy efficiency, gradeability, max vehicle speed, and acceleration time. The paper will introduce a robust, modular, multi-speed (MS) transmission concept based on Eaton’s proven technology. This Eaton EV drive system will provide the efficiency, reliability, and ready to market benefits to medium-duty vehicle platforms and applications.


TWO-MOTOR, TWO-AXLE TRACTION SYSTEM FOR FULL ELECTRIC VEHICLE
University of Bologna

The paper deals with the description of a low voltage, two-battery pack, two-motor, two-axle powertrain configuration for a full performance compact electric car. It gives an analytical method for selecting the two different drives for front and rear axle, a performance and economical evaluation criteria for choosing the low voltage active components and gives details about the power stage layout of the traction inverter.

See vCD 395 EVS29-5900342.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 15pp.)
COMMON ISSUES

Charging

AN INTEGRATED GLOBAL PHILOSOPHY OF EV CHARGING

AeroVironment

Electric Vehicle (EV) charging methods have evolved over the past two decades to reflect the radical evolution of EVs. In some cases these methods have been of varying usefulness to the EV driver. DC fast charging, which made a brief appearance in the late 90s, is now a valuable EV market enabler, but suffers from the political and technical disagreements of multiple protocols. Globally, EV charging will evolve further to meet the demands of the new consumer EVs and the demands of the EV driver. This paper proposes an integrated global philosophy to meet these demands.

See vCD 395 EVS29-760117.pdf (EVS 29, Montreal, Canada, Jun 2016, Session 1C – Electric Drive Infrastructure Strategies, 6pp.)

DYNAMIC OPTIMIZATION OF THE E-VEHICLE ROUTE PROFILE

Czech Technical University

Current vehicles, especially the electric ones, are complex mechatronic devices. The pickup vehicles of small sizes are currently used in transport considerably. They often operate within a repeating scheme of a limited variety of tracks and larger fleets. Thanks to mechatronic design of vehicles and their components and availability of high capacity data connection with computational centres (clouds), there are many means to optimize their performance, both by planning prior the trip and recalculations during the route.

Although many aspects of this opportunity were already addressed, the paper shows an approach developed to further increase the range of e-vehicle operation. It is based on prior information about the route profile, traffic density, road conditions, past behaviour, mathematical models of the route, vehicle and dynamic optimization. The most important part of the procedure is performed in the cloud, using both computational power and rich information resources. Suitable route discretization into sections is most important part of the algorithm. The various information resources are used. Accumulated experience coming from fleet operation is very important as well. Methods for automation of this procedure are presented. Subsequently, feasible initial values of section parameters are found using heuristic rules devised from good driver’s practice and backward calculation based on dynamic programming principals. Designed velocity profile is further optimized based on simplified, but very fast energy consumption models, verified and fine-tuned on detailed simulation model of the vehicle. The velocity profile is updated when requested and finally loaded into on-board control unit. Model based predictive controller is used to keep the vehicle with its driver efficiently on defined track. The proposed strategy is verified in simulation environment and prepared to be implemented on test vehicle and cloud system.

See SAE 2016-01-0156 (2016, 10pp.)

EXPERIMENTAL DEMONSTRATION OF SMART CHARGING AND VEHICLE-TO-HOME TECHNOLOGIES FOR PLUG-IN ELECTRIC VEHICLES COORDINATED WITH HOME ENERGY MANAGEMENT SYSTEMS FOR AUTOMATED DEMAND RESPONSE

Toyota and Waseda University

In this paper, we consider smart charging and vehicle-to-home (V2H) technologies for plug-in electric vehicles coordinated with home energy management systems (HEMS) for automated demand response. In this system, plug-in electric vehicles automatically react to demand response events with or without HEMS's coordination, while vehicles are charged and discharged (i.e. V2H) in appropriate time slots by taking into account demand response events, time-of-use rate information, and users’ vehicle usage plan. We introduce three approaches on home energy management: centralized energy control, distributed energy control, and coordinated energy control. We implemented smart charging and V2H systems by employing two sets of standardized
communication protocols: one using OpenADR 2.0b, SEP 2.0, and SAE standards and the other using OpenADR 2.0b, ECHONET Lite, and ISO/IEC 15118. We show that the both communication protocol sets enable the same energy management by adding some properties and class into ECHONET Lite that are equivalent to existing function sets in SEP 2.0 such as demand response, pricing, energy flow reservation. We evaluated developed systems in a demonstration platform, called the Energy Management System (EMS) Shinjuku Demonstration Center established by Waseda University upon the initiative by the Ministry of Economy, Trade and Industry (METI) in Japan. We show that developed systems enable automated demand response and peak shift by automatically reacting to demand response events without users’ inconvenience. We also show that smart charging and V2H system with HEMS’s coordination provides more peak demand reduction than one without HEMS’s coordination and one without V2H capability.

See SAE 2016-01-0160 (2016, 8pp.)

THE AVTE INTEROPERABILITY PROJECT: PHASE 1, AC CONDUCTIVE CHARGING

Intertek
This discussion will review the goals and progress of the Dept of Energy AVTE (Advanced Vehicle Testing and Evaluation) program, the current status of ongoing programs and potential upcoming projects. This will include focus on EV charging issues, such as the recent completion of the SAE J2953 EVSE Level 2 interoperability study, and challenges related to DC Fast Charging.

See vCD 395 EVS29-6200439.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 2 - Dialogue with the experts, 7pp.)

Control

LATERAL STABILITY CONTROL OF DYNAMIC STEERING FOR DUAL MOTOR DRIVE HIGH SPEED TRACKED VEHICLE

Beijing Institute of Technology, Technical University of Berlin and Foton Motor
In this paper, the torque and power required by dual motors for electric tracked vehicle during dynamic steering manoeuvres with different steering radiuses are analysed. A steering coupling drive system composed of a new type of centre steering motor, two Electromagnetic (EM) clutches, two planetary gear couplers, and two propulsion motors is proposed for the dual motors drive high speed electric tracked vehicle (2MHETV), which aims to improve its lateral stability. An average torque direct distribution control strategy based on steering coupling and an optimization-distribution-based close-loop control strategy are designed separately to control the driving torque or regenerative braking torque of two propulsion motors for vehicle stability enhancement. Then models of the 2MHETV and the proposed control strategy are established in Recudyn and Matlab/Simulink respectively to evaluate the lateral stability of dynamic steering for the 2MHETV with different steering radiuses on hard pavement. The simulation results show that the lateral stability of the 2MHETV can be significantly improved by the proposed optimization-distribution-based close-loop control strategy based on steering coupling system.


MODEL-INDEPENDENT SELF-TUNING FAULT-TOLERANT CONTROL METHOD FOR 4WID EV

Tsinghua University
To solve the problem of the existing fault-tolerant control system of four-wheel independent drive (4WID) electric vehicles (EV), which relies on fault diagnosis information and has limited response to failure modes, a model-independent self-tuning fault-tolerant control method is proposed. The method applies model-independent adaptive control theory for the self-tuning active fault-tolerant control of a vehicle system. With the nonlinear properties of the adaptive control, the complex and nonlinear issues of a vehicle system model can be solved. Besides, using the online parameter identification properties, the requirement of accurate diagnosis information is relaxed. No detailed model is required for the controller, thereby simplifying the development of the controller. The system robustness is improved by the error based method, and the error convergence and input-
output bounds are proved via stability analysis. The simulation and experimental results demonstrate that the proposed fault-tolerant control method can improve the vehicle safety and enhance the longitudinal and lateral tracking ability under different failure conditions.


MPC BASED FAN CONTROL FOR AUTOMOTIVE APPLICATIONS

AVL and Graz University of Technology

A major drawback of pure electrical vehicles is their low range compared to conventional cars. The present work focuses on increasing cruising range of electric vehicles by reducing the power consumption for e-motor and power electronics cooling.

Standard implementations for cooling circuit control which are taken over from conventional cars with internal combustion engine usually involve a temperature based bang-bang control. These implementations are simple to implement but lead to oscillating temperatures. To meet hard temperature constraints usually safety offsets have to be introduced leading to increased cooling ventilation which results in significantly higher power consumption mainly caused by the cooling package fan.

The proposed approach aims to enhance control performance in order to significantly reduce temperature safety margins in reference values resulting in a more efficient cooling and a lower power consumption. The approach involves a separation of the plant model into a linear and a nonlinear part, which is then advantageously used for control. The proposed control approach consists of a standard linear observer plus a linear model predictive control. Nonlinearities caused by the radiator are addressed separately.

A possible real-time execution on standard automotive hardware is also addressed. Results are shown on simulation examples, as well as on first testbed experiments.

See vCD 393 1-s2.0-994-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp399-405.)

REGULARIZED MPC FOR POWER MANAGEMENT OF HYBRID ENERGY STORAGE SYSTEMS WITH APPLICATIONS IN ELECTRIC VEHICLES

Cranfield University and Imperial College, London

This paper examines the application of Regularized Model Predictive Control (RMPC) for Power Management (PM) of Hybrid Energy Storage Systems (HESS). To illustrate, we apply the idea to the PM problem of a battery-supercapacitors (SCs) powertrain to reduce battery degradation in Electric Vehicles. While the application of Quadratic MPC (QMPC) in PM of HESS is not new, the idea to examine RMPC here is motivated by its capabilities to prioritize actuator actions and efficiently allocate control effort, as advocated by recent works in the control and MPC literature. Thorough simulations have been run over standard urban test drive cycles. It is found out that QMPC and RMPC, compared to rule-based PM strategies, could reduce the battery degradation over 70%. It is also shown that RMPC can slightly outperform QMPC in reducing battery degradation. Moreover, RMPC, compared to QMPC, could potentially extend the range of that SCs can be used, thus exploiting the degree of freedom of the powertrain to a larger extent. We also make some discussions on the feasibility issues and tuning challenges that RMPC faces, among others.

See vCD 393 1-s2.0-611-main.pdf (8th IFAC Symposium on Advances in Automotive Control, Norrkoping, Sweden, Jun 2016, pp265-270.)

Emissions

VIRTUAL MODELLING OF UNINTENTIONAL AND INTENTIONAL ELECTROMAGNETIC EMISSIONS FROM ELECTRIC VEHICLES

CSA Group

This paper describes virtual testing of plug-in electric vehicles (PEVs) according electromagnetic compatibility (EMC) requirements for the unintentional emissions and according the radio
frequency spectrum allocation for the intended emissions of communications systems. It includes numerical model creation and related validation with real-life measurements. As a consequence, performing simulation approaches can save significant development cost and accelerate notably PEVs time-to-market.

See vCD 395 EVS29-5040306.pdf (EVS 29, Montreal, Canada, Jun 2016, Session 2A - Predicting Real World EV Performance, 8pp.)

Energy efficiency/consumption

A NEW APPROACH TO CALORIMETRIC EFFICIENCY MEASUREMENTS AND ANALYSIS OF ELECTRIC VEHICLE DRIVE LOSSES

University of Kassel

The development of battery electric vehicle drives comes along with comprehensive and time-consuming finite element methods and extensive measurement campaigns. The drive efficiency has drawn great attention from engineers and customers, because it influences the size of the drive, the cooling measures and the vehicle range. Indirect efficiency acquisition accomplished by comparing inward and outward power, has a low accuracy which arises from a relatively small difference between inward and outward power of highly efficient drives. Therefore, the indirect efficiency acquisition is insufficient to evaluate advanced development measures. This paper presents measurement and analysis methods developed within a collaborative research project, which aims at accelerating the development cycles of electrical drives by implementing and combining accuracy-improved Finite Element Simulations (FEM), extremely rapid Lumped Parameter Thermal Networks (LPTN) and a new efficiency measurement method with high accuracy. Findings of this project provide possibilities to optimize drive construction, material selection and control strategy. The new approach of efficiency measurements is based on a direct loss measurement. Moreover, this approach adopts an innovative calorimetric measurement principle with the support of conventional dynamic measurement procedures: The calorimetric measurement principle yields to a high steady-state-accuracy; the conventional measurement identifies dynamic transitions. This paper not only introduces highly precise measurement methods for evaluating heat dissipation of electric drives, but also new evaluation methods for the determination of internal power losses. An evaluation of test bench measurements is shown, in order to demonstrate the process of distinguishing different losses.

See SAE 2016-01-1168 (2016, 7pp.)

ASSESSMENT OF NEXT-GENERATION ELECTRIC VEHICLE TECHNOLOGIES

International Council on Clean Transportation (ICCT)

Automakers and governments are actively investigating what it will take to shift to a fleet of electric vehicles in various markets around the world. Among the critical questions about such a transition are the pace of battery technology development and how quickly its costs are reduced. Manufacturers are continually making technology improvements, including increasing range and reducing costs, to increase the viability of electric vehicles. A key question is how quickly next-generation electric vehicle production might allow greater economies of scale and greatly increased electric vehicle range at reduced electric vehicle prices.

This study analyses emerging light-duty electric vehicle technologies in terms of their performance characteristics and costs. We assess the key technology trends in electric vehicle attributes, such as electric range and battery cost, which are widely expected to impact the broader consumer attractiveness of electric vehicles. The scope of the work includes an analysis of the specifications of major electric vehicle models in China, Europe, Japan, and the United States through 2015. An analysis of evolving battery costs beyond 2020 is presented. This analysis is based on a synthesis of public data from energy laboratories, academic research literature, and supplier and automobile company announcements.

Based on our analysis, we draw the following three conclusions:

- Increased diversity of electric vehicle models is creating more alternatives across all market segments:
  - Manufacturers are increasingly offering all-electric or plug-in hybrid models in most vehicle


classes. Over 25 different plug-in electric models were offered in 2015 in the three largest national markets of China, Europe, and the US. An assortment of plug-in options for smaller cars, sedans, crossover sport-utility vehicles, low cost brands, luxury brands, and models with all-wheel drive, are more broadly meeting consumer demands.

Electric vehicles with increased electric range are entering the market from 2016-2018:
- Battery technology advancements and greater production volume are allowing companies to offer electric vehicles with improved performance and range. More vehicles with greater battery capacity, electric efficiency, and range have been sold in steadily larger numbers through 2015. Announced next-generation Chevrolet, Nissan, and Tesla models indicate mass-market cars with at least 200 miles of electric range will accelerate this trend.

Companies are making the move to higher production and lower cost:
- Vehicle and battery manufacturers, with government support, are developing early electric vehicle markets. By 2015, 15 automakers produced over 10000 plug-in electric vehicles per year, and five battery suppliers produced over 50000 battery packs for plug-in electric vehicles per year. Many companies could increase their production volume to hundreds of thousands of electric vehicles per year in the 2020-2023 timeframe. As a result, leading companies' battery pack costs would decrease to $150- $175 per kilowatt-hour in the 2020-2023 timeframe.

The evolving market with next-generation electric vehicle technology will spur policy changes. The increased economies of scale with new battery packs are expected to dramatically reduce vehicle costs, up to $8000 for a 120-mile battery electric vehicle, with the savings dependent on vehicle range and manufacturer volume. The decreased cost allows for a combination of longer electric range and more affordable electric vehicles, thereby addressing key adoption barriers and greatly broadening the electric vehicle market. These changes indicate that gradual tapering of government financial incentives targeted at reducing initial cost differences between conventional vehicles and electric vehicles over that time period could be warranted.


ONLINE PREDICTION OF BATTERY ELECTRIC VEHICLE ENERGY CONSUMPTION
Eindhoven University of Technology

The energy consumption of battery electric vehicles (BEVs) depends on a number of factors, such as vehicle characteristics, driving behaviour, route information, traffic states and weather conditions. The variance of these factors and the correlation among each other make the energy consumption prediction of BEVs difficult. This paper presents an online algorithm to adjust the energy consumption prediction during driving. It includes a vehicle parameter estimation algorithm and a driving behaviour correction algorithm. The vehicle parameter estimation algorithm can assess the vehicle mass and rolling resistance during driving. The driving behaviour correction algorithm can adjust the energy consumption prediction based on the current driving behaviour, and considers the influence of wind and road slope. The online energy consumption prediction algorithm is verified by 21 driving tests, including highway, city, rural and hilly area tests. The comparison shows that the mean absolute percentage error between the actual energy consumption value and online prediction result is within 5% for every test.

See vCD 395 EVS29-800099.pdf (EVS 29, Montreal, Canada, Jun 2016, Session 2A - Predicting Real World EV Performance, 12pp.)

Infrastructures

A MODEL FOR PUBLIC FAST CHARGING INFRASTRUCTURE NEEDS
Fraunhofer Institute for Systems and Innovation Research (ISI), Chalmers University of Technology and Exigal Technologies

Plug-in electric vehicles can reduce GHG emissions although the low availability of public charging infrastructure combined with short driving ranges prevents potential users from adoption. The rollout and operation, especially of public fast charging infrastructure, is very costly. Therefore, policy makers, car manufacturers and charging infrastructure providers are interested in determining a number of charging stations that is sufficient. Since most studies focus on the placement and not on the determination of the number of charging stations, this paper proposes a
model for the quantification of public fast charging points. We first analyse a large database of German driving profiles to obtain the viable share of plug-in electric vehicles in 2030 and determine the corresponding demand for fast charging events. Special focus lies on a general formalism of a queuing system for charging points. This approach allows us to quantify the capacity provided per charging point and the required quantity. Furthermore, we take a closer look on the stochastic occupancy rate of charging points for a certain service level and the distribution of the time users have to wait in the queue. When applying this model to Germany, we find about 15000 fast charging points with 50 kW necessary in 2030 or ten fast charging point per 1000 BEVs. When compared with existing charging data from Sweden, this is lower than the currently existing 36 fast charging points per 1000 BEVs. Furthermore, we compare the models output of charging event distribution over the day with that of the real data and find a qualitatively similar load of the charging network, though with a small shift towards later in the day for the model. See vCD 395 EVS29-5020270.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 2 - Dialogue with the experts, 12pp.)

CHARGING INFRASTRUCTURE TO SUPPORT EV MARKET AND SMART GRID: LEARNINGS AND TRENDS

Renault

Agenda:
Charge is a must
Infrastructure is there
Infrastructure: a loose-loose situation
New grid services are needed.
Covers - H2020 project NEMO.
See vCD 404 sebastien-albertus.pdf (CENEX LCV2016 Low Carbon Vehicle Event, Millbrook, UK, Sep 2016, 14pp.)

Legislation, politics, economics and society

A SOCIOECONOMIC STUDY INTO THE DEMAND FOR ELECTRIC VEHICLES

The importance of electric vehicles (EV), from an economic perspective, is rooted in their superior operational efficiency in mobilizing labour and capital when compared to current available alternatives. The use of EVs ensures that the most efficient means of mobilization, from both the consumption of resources and externality generated, is adopted. The challenges facing the mass adoption of EVs will be critically assessed from a socioeconomic standpoint to gain a better understanding of the demand determinants of consumers. Understanding the mind of the vehicle consumer, the autoist, is paramount to accelerating the mass adoption of EVs globally. The consumer’s perception and willingness to purchase the vehicle is the fundamental change that is required to advance the new technology to a level of economic normalization. It is evident that a consumer’s propensity to adopt the new technology will only increase sufficiently if the following criteria are met:
1 - It is equivalent, or superior, in performance and functionality;
2 - It is equivalent, or superior, in safety and comfort;
3 - It is equivalent, or superior, in initial acquisition cost;
4 - It is superior, in the cost of operating the vehicle.
See vCD 395 EVS29-310009.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 2 - Dialogue with the experts, 12pp.)

ECONOMIC EVALUATION OF ELECTRIC TAXIS IN MEGACITIES - EXAMPLE OF SINGAPORE

TUM CREATE

This research makes a contribution to the question of the cost effectiveness of battery electric taxis (e-taxis) compared to conventional taxis with internal combustion engine. The assessment is based on the total cost of ownership, and it combines technical, economic, regulatory as well as
behavioural data from taxi drivers and passengers. The results indicate that e-taxis can be advantageous compared to conventional taxis, as they allow the drivers to earn higher profits, which is considered a key element for the success of e-taxis. However, some key parameters such as the vehicle battery life time need to be further investigated. In addition, the high purchase price of e-taxis may impact the fare structure and leasing rates of e-taxis which can be an obstacle for their acceptance by both drivers and passengers.

See vCD 395 EVS29-2130156.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 – Dialogue with the experts, 11pp.)

MODELING THE DEMAND FOR RENTING ELECTRIC VEHICLES IN CANADA: A STATED PREFERENCE CHOICE APPROACH

University of Windsor

The introduction of electric vehicles (EV) is considered by many as an effective solution to alleviate petroleum dependency; however, the number of EVs in the current market remains scarce despite of its potential benefits. Many studies have been conducted to identify and assess various factors that significantly affect EV ownership. In contrary, little has been done regarding the potential EV adoption for commercial fleets. This paper addresses this limitation by focusing on rental vehicles. It is found that rental cost, vehicle attributes (e.g. maximum range and recharging time), and attitudinal statements have significant effect on EV rental choice.

See vCD 395 EVS29-1760112.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 12pp.)

THE IMPACT OF CONNECTIVITY/AUTONOMOUS DRIVING ON ELECTRIC VEHICLES

IHS Markit

Summary:
5 Levels of autonomy – L3 is the interim for testing and refining, L4/L5 is when the car can drive itself without the need for human input.
Forecasts:
- 2025 is when we will start to see L4/L5 vehicles on the road.
- In 2035, IHS Markit estimates that there will be ~20 million L4/L5 cars sold which is ~32% of new vehicle sales.
- In Western Europe, it will take until 2040 before >50% of vehicles are L4/L5.
Car-based urban mobility is reshaping transportation. Moving towards an autonomous on-demand mobility network (car as a service) and away from traditional car ownership.
Autonomous driving will cause disruption in the market. L5 autonomous driving presents the strongest operational efficiency for battery electric vehicles (and wireless charging). Disruption opens up the market to new players, new start-ups. Big opportunities – possible Apple scenarios.

See vCD 404 ben-scott.pdf (CENEX LCV2016 Low Carbon Vehicle Event, Millbrook, UK, Sep 2016, 14pp.)

NVH

DEVELOPMENT OF ACTIVE INTERIOR SOUND USING THE NVH DRIVING SIMULATOR

Hyundai

Contents:
- NVH Simulator
- Active Sound System Integration
- Development Process
- Case Study - Electric Vehicle Interior Sound Concept Development complying with the Hyundai & Kia brand identities Kia Soul EV and Hyundai ix35 fuel cell
- Outlook.

NVH AND ACOUSTICS ANALYSIS SOLUTIONS FOR ELECTRIC DRIVES

AVL

Recently, hybrid and fully electric drives have been developing widely in variety, power and range. The new reliable simulation approaches are needed, in order to meet the defined NVH targets of these systems and implementing CAE methods for front loading, Design Validation Process (DVP). This paper introduces the application of a novel NVH analysis workflow on an electric vehicle driveline including both electromagnetic and mechanical excitations for an absolute evaluation of the NVH performance. At first, the electromagnetic field is simulated using FEM method to extract the excitations on the stator, rotor bearings as well as the drive torque. Then, the multibody dynamic model of the driveline is built-up, driven by this torque. The effect of eccentricity and skew angle of rotor in electromagnetic excitations are shown. The total NVH response of the system, e.g. the structure normal surface velocity levels are generated by means of a coupled model using Multi-body dynamics and electromagnetic excitations.

See SAE 2016-01-1802 (2016, 6pp.)

A PERSPECTIVE ON NVH FUNDAMENTALS FOR NEW ENERGY VEHICLES

Nextev

Contents:
- How About the New Electrical Vehicles Differentiation
- Brief Review on Latest NEV NVH Publication
- Structural Performance
- A Step Further on NVH Refinement
- NVH Cross-Attribute Balance

Perspective on Technical Challenges and Opportunities
- Lightweight and bigger batteries are key enabler to NEVs Drive range.
- Still few vehicles in the market as reference for structural integration.
- Importance on integration to support deeper lightweight and excellent user driving experience (quietness, comfort, smoothness...)
- Efficient design and integration are big contributors to electrical vehicle NVH.
- NEVs are less forgiving to execution flaws on NVH fundamentals.
- Looking forward to see next EVs generation and what’s coming next.


Safety

PYROTECHNIC SAFETY SWITCHES FOR SAFE AND QUICK HV CIRCUIT DISCONNECTION AT HIGH FAULT-CURRENTS

Autoliv Development

Safe and instantaneous disconnection of a High Voltage Battery Circuit at high fault-currents can be achieved with Pyrotechnic Safety Switches (PSS).

Traditional alternatives are melting fuses and relays. In contrast to those traditional circuit breakers, a PSS offers an instantaneous disconnection within a time range of fractions of milliseconds to a few milliseconds. The speed and high level of safety due to clean disconnection and no bouncing effect is attributed the pyrotechnics that provide a forceful thrust to an insulated guillotine cutting a conductor. Additionally, a PSS consumes no power during ordinary vehicle operations.

See vCD 395 EVS29-2140139.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 9pp.)

SAFETY ANALYSIS APPLIED TO ELECTRIC VEHICLES

SECTOR

Technological developments including those issued from electric propulsion require the application of appropriate risk assessments to ensure the safety of the driver, passengers and external people.
The current safety standards (e.g. ISO 26262) are not always appropriate and do not systematically cover all causes of risk or any type of technology. SECTOR specializes in risk analyses adapted to the vehicle as a whole and the context in which it is marketed, whatever the technological innovations it presents.

See vCD 395 EVS29-2110129.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 12pp.)

SAFETY AND EFFICIENCY OF THE WIRELESS CHARGING OF ELECTRIC VEHICLES

University of Georgia, Southern Company Services and Sonnenbatterie

Wireless power transfer is a promising method to address the concerns over charging an electric vehicle. Since wireless charging stations operate without large cables or above-ground stations, they can be conveniently installed in public locations without the risk of vandalism or weather-inflicted damage, improving the lifespan of the electric vehicle charging station. In order for wireless charging stations to become widespread, possible health effects regarding exposure to the strong electromagnetic fields present during wireless power transfer must be investigated. This work examines, first, the potential human safety hazards, second, the electronic device interference, and, third, the thermal heating effects of wireless charging systems. A 3.3 kW wireless power transfer prototype was built in order to examine these effects. Changes in the wireless power transfer efficiency due to the coil misalignment were also investigated using an automated three-axis platform. Design considerations for electric vehicle wireless charging systems and safety recommendations are presented.


SIMULATION RESEARCH ON ELECTROMAGNETIC RADIATION EFFECTS OF ELECTRIC VEHICLE ON THE OCCUPANT HEALTH

Tongji University and Tongji Automotive Engineering Center

Nowadays researches of automotive electromagnetic field mainly focus on the component level and electromagnetic compatibility, while there is a lack of relevant studies on internal electromagnetic environment of the vehicles. With the increasingly complex internal electromagnetic environment of the vehicle, people are increasingly concerned about its potential impact of human health. This article researches on a type of electric vehicle and the occupants and analyses its electromagnetic radiation effects on human health. Firstly, considering the characters of Pro/E, Hypermesh and FEKO, the “Characteristics grouping subdivision” method is used to establish the entire vehicle body FE model. According to the requirement of MOM/FEM method, the entire vehicle model is optimised to be a high quality body model with simple construction and moderate grid size. Secondly, Using transfer vehicle electromagnetic radiation function of the simulation method, simulation study was made on the electromagnetic radiation characteristics of the subsystems. Then simulation results and vehicle electromagnetic radiation limit in GB 18387-2011 standard are compared and analysed. At last, a human body electromagnetic model is established based on the biological electromagnetism. The electromagnetic radiation absorbed dose of occupants in vehicles are studied. At the same time, the specific absorption ratio (SAR) of occupants on different location in vehicles is compared and analysed.

See SAE 2016-01-0135 (2016, 8pp.)

WHAT IS ACCEPTABLE SAFETY? PERSPECTIVES ON EV BATTERY TECHNOLOGY

Scania

Factors that can potentially trigger hazardous conditions, especially exothermic degeneration of the Li ion cell and initiate a thermal event:

Environmental (application) factors
Overcharge
Overcurrents
Overtemperature
Overtemperature caused by external heat source
Internal short circuit by deformation
Spontaneous internal short circuit.

Summary:
Perception of safety is plays a major role in technology acceptance
There is currently a lack of confidence in real safety characteristics of high energy density battery technologies, e.g. Li ion batteries
Failure to address perceived safety concerns may lead to technology restrictive/prohibitive requirements and tests
Thermal propagation (field failure) caused by thermal runaway of a single cell internal short circuit is the most challenging issue for assessment
- No reliable test methods
- System design and vehicle design must be considered when evaluating risk
- Safety requirements must allow technology development of EV battery as well as EV vehicle technology.
Covers - UN ECE Vehicle regulation – R100.02, UN ECE vehicle regulation – EVS-GTR – the next step. Chemical risks with electrolyte exposure, Thermal runaway and propagation.
See vCD 404 annika-ahlberg-tidblad.pdf (CENEX LCV2016 Low Carbon Vehicle Event, Millbrook, UK, Sep 2016, 10pp.)
COMPONENTS

Battery chargers

IMPROVING ENERGY YIELD FOR EV-MOUNTED SOLAR

Rutgers University

Solar arrays on vehicle roofs provide only rather modest amounts of cumulative energy output; thus vehicle designers cannot depend on them for major traction power. However, the trickle charging can provide a useful amount of energy and offset the use of grid-supplied electricity and improve the carbon footprint of EV transit. This paper examines the energy congestion effect when the roof-top solar is used to supply the main traction battery. Regular commuters who have access to workplace charging may experience substantial reduction in energy capture because of the speed of grid charging. Strategies for improving energy yield are presented.

See vCD 395 EVS29-6180428.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 6pp.)

MODULAR FAST CHARGER STATION FOR ELECTRIC VEHICLES WITH ENERGY STORAGE ELEMENT

Federal University of Santa Maria

This paper describes one off-board fast charge station for electric vehicles. The proposed station is modular and expandable with an integrated energy storage unit. The expansible feature allows a reduced up-front investment and permits the site owner to add more charge points when the demand for fast charge increases. In addition, the proposed off-board has an energy storage system which allows shaping the power demanded from the grid, reducing power peaks and possibly the total energy cost, since battery bank is used to store energy when few vehicles are connected. The proposed off-board fast charge station is comprised of the following blocks:

i) transformer operating from a medium voltage grid followed by a twelve pulse non-controlled rectifier with a small active filter;
ii) energy storage system;
iii) a 600V DC distribution bus;
iv) charging end-points composed of buck interleaved converters.

Each end-point, which has potentially low cost, complexity and footprint, gives up to 60 kW charge to an electric vehicle. Simulations results are given to demonstrate the feasibility of the proposed off-board fast charging. Also, results from current harmonics at the grid side and analysis of converters responses are presented. Moreover, a viability study shows how the battery bank can help the fast charge system to reduce the use of energy from grid during peak hours, making it profitable.

See vCD 395 EVS29-2490337.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 2 - Dialogue with the experts, 9pp.)

NEXT GENERATION “VOLTEC” CHARGING SYSTEM

General Motors and Delta Products

The electric vehicle on-board charger (OBC) is responsible for converting AC grid energy to DC energy to charge the battery pack. This paper describes the development of GM’s second generation OBC used in the 2016 Chevrolet Volt. The second generation OBC provides significant improvements in efficiency, size, and mass compared to the first generation. Reduced component count supports goals of improved reliability and lower cost. Complexity reduction of the hardware and diagnostic software was undertaken to eliminate potential failures.

See SAE 2016-01-1229 (2016, 6pp.)
Batteries

LITHIUM-ION BATTERIES – ANALYSIS OF NON-UNIFORMITY OF SURFACE TEMPERATURE OF COMMERCIAL CELLS UNDER REALISTIC DRIVING CYCLES

Vrije Universiteit Brussel

In this work, large format commercial li-ion pouch cells of two different chemistries and capacities were studied under realistic EV driving profiles in order to determine the non-uniformity of the cell surface temperature by using high resolution infrared thermography.

A comparison of the surface temperature behaviour was made under continuous constant current charge-discharge current profile. A 1-dimensional electro-thermal model was developed based on an equivalent circuit with RC elements. The simulation results were validated by obtained experimental result to predict the behaviour of the cells.

See vCD 395 EVS29-810054.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 13pp.)

LOW TEMPERATURE PERFORMANCE OF LITHIUM-ION BATTERIES FOR DIFFERENT DRIVE CYCLES

University of Warwick

Lithium-ion batteries, suitable for Battery-electric vehicles (BEVs) due to their high energy and power densities, and lifetime demonstrate deterioration in energy and power available at lower temperatures. It is attributed to reduction in capacity and increase in internal resistance. Investigations are carried out to determine energy, and power decline for four drive-cycles: FTP, NEDC, UDDS and US06. The minimum temperatures where the battery meets the drive-cycles’ energy and power requirements are determined. The impact of regenerative braking and self-heating on battery performance is discussed. The minimum temperature where any drive-cycle is met by the battery is directly proportional to its aggressiveness.

See vCD 395 EVS29-1010206.pdf (EVS 29, Montreal, Canada, Jun 2016, Session 1B - Batteries and Electrochemical Storage for Transportation, 12pp.)

REVIEW OF TRACTION BATTERY INDUSTRIALIZATION FOR PLUG IN ELECTRIC VEHICLES IN CHINESE MARKET

Tsinghua University

Developing plug-in electric vehicles (PEVs) has been taken as state strategy by Chinese government and series supporting policies have been introduced, leading to the rapid growth of PEVs industry of China. China ranks the first in PEVs output and ownership, and becomes the biggest traction battery production country with capacity exceeding 20 GWh in 2015. The traction battery technologies roadmap is diversity for different kind of new energy vehicles in China. To review the characteristics of the revolution of traction battery technologies and industry is very necessary for Chinese government to re-evaluation the reasonability of the state research and development plan in next 10 years.

In this research, a lot of survey of traction battery technology and industry is done. Based the detailed statistics, the rules the traction battery revolution has been found. The technology roadmap of various traction battery is clarified and the progress of traction battery industrialization is reviewed by models of new energy vehicles. Based on the analysis of traction battery technology and industry progress, the prospective of traction battery roadmap can be presented reasonable.

See vCD 395 EVS29-4760315.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 7pp.)
Energy storage devices

REDUCING THE PEAK-TO-AVERAGE POWER RATIO FOR ELECTRIC VEHICLES USING HYBRID ENERGY STORAGE SYSTEMS (HESS)

Sydney University of Technology

In this paper, a simple but innovative algorithm is developed to effectively reduce peak-to-average power ratio for electric vehicles powered by battery pack (BP) alone under real-life load fluctuation. A converter-supercapacitor pack (SP) coupled Hybrid Energy Storage topology upon which such algorithm is deployed is proposed to divert excess power that would otherwise damage BP into SP via power converter (PC) in a regulated fashion. Along with the algorithm itself, a simplified HESS model is also developed in Matlab to validate such algorithm and simulation results prove its effectiveness across various real-life drive cycles with significantly extended battery lifecycle.

See vCD 395 EVS29-280026.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 5pp.)

Wheel motors

AN EXPLANATION OF THE IN-WHEEL MOTOR DRIVE SYSTEM’S VIBRATION AT LOW VELOCITY USING MOTOR-WHEEL FREQUENCY CHARACTERISTICS

Tsinghua University

The in-wheel-motor (IWM) drive system has some interesting features, such as the vibration of this structure at low velocity. An explanation of this phenomenon is given in this paper by considering the dynamics performance of the in-wheel motor drive system under small slip ratio conditions. Firstly, a frequency response function (FRF) is deduced for the drive system that is composed of a dynamic tyre model and a simplified motor model. Furthermore, an equation between the resonance velocity with the parameters of the drive system is obtained by combining the resonance frequency of this drive system with the fundamental frequency of the motor. The correctness of the equation is demonstrated through simulations and experimental tests on different road surfaces. The impact of different parameters on the vibration can be explained by this equation, which can give the engineer some instructions to design a control method to avoid this feature.

See SAE 2016-01-1673 (2016, 6pp.)
RANGE EXTENDER POWER TRAINS

DYNAMIC PARAMETERS MATCHING AND POWERTRAIN OPTIMIZATION OF AN EXTENDED RANGE CITY BUS

China Automotive Technology and Research Center (CATARC)

This paper focuses on the dynamic parameters matching and powertrain ratio optimisation of an ERCB (Extended Range City Bus) for improving fuel economy. Firstly, according to the bus data and design targets of an ERCB, dynamic parameters are matched. Simulation models of each component that makes up the whole powertrain are established depending on the platform of AVL-CRUISE, including battery, motor, main reducer, wheels, etc. Dynamic performance, such as full load acceleration, climbing performance, maximum speed performance and endurance mileage, is simulated successively using AVL-CRUISE. Also the fuel economy performance under Chinese Urban Driving Cycle (CUDC) is worked out. The simulation results of each performance are analysed. To improve the fuel economy, the transmission ratio and final ratio are optimised with Isight software. Results before and after optimisation are compared, which indicate that the bus’s design of driving system is relatively rational and it has a good dynamic and fuel economy performance.

See SAE 2016-01-1178 (2016, 9pp.)
OTHER ALTERNATIVE POWERTRAINS

PNEUMATIC

OPTIMISATION OF EXPANSION RATIO OF AN ADVANCED COMPRRESSED AIR ENGINE KIT

Delhi Technological University

Worldwide, research is going on numerous types of engines that practice green and alternative energy such as natural gas engines, hydrogen engines, and electric engines. One of the possible alternatives is the air powered car. Air is abundantly available and can be effortlessly compressed to higher pressure at a very low cost. After the successful development of compressed air engines, engineers shifted their focus in making this technology cost effective and feasible. This led to advancement in the field of pneumatics that is advanced compressed air engine kit (used for conversion of a small two-stroke SI engine to compressed air engine) where its frugality and compatibility is kept at high priority. This research is in continuation with our previous project of development of an advanced compressed air engine kit and optimisation of injection angle and injector nozzle area for maximum performance. Compressed air engine kit demonstrated significant imperative results in performance testing which fuelled the need for optimising various parameters such as injection angle, injection pressure and injector nozzle area. Most of the optimisation was piloted on injection parameters which provided substantial merits such as low cost and easy modifications with same amount of input energy required hence increasing efficiency. This paper explains another injection parameter optimisation, which is expansion ratio (final volume/initial volume). A number important and performance analysis were performed in order to pinpoint maximum torque and power generated which eventually leads to optimised expansion ratio. Valuable data from previous studies and testing on above mentioned intake and injection parameters are considered in account, and testing and performance analysis is conducted after rectifying changes on injection angle and injector area. This study leads to optimisation injection parameters simultaneously, which aids in eliminating power and energy losses building it more productive and efficient.

See SAE 2016-01-1283 (2016, 11pp, 32 refs.)

DESIGN AND OPTIMISATION OF THE PROPULSION CONTROL STRATEGY FOR A PNEUMATIC HYBRID CITY BUS

Loughborough University

A control strategy has been designed for a city bus equipped with a pneumatic hybrid propulsion system. The control system design is based on the precise management of energy flows during both energy storage and regeneration. Energy recovered from the braking process is stored in the form of compressed air that is redeployed for engine start and to supplement the engine air supply during vehicle acceleration. Operation modes are changed dynamically and the energy distribution is controlled to realise three principal functions: Stop-Start, Boost and Regenerative Braking. A forward facing simulation model facilitates an analysis of the vehicle dynamic performance, engine transient response, fuel economy and energy usage. To identify respectively (1) the maximum overall fuel economy, (2) the maximum amount of air and energy recovered during the braking and (3) the minimum loss of available energy during acceleration, a number of variables in the control strategy are selected in an optimisation process. Three optimisation algorithms are compared in different aspects of the control strategy: (1) using the Pattern Search to optimise the initial air tank pressure for every stop-start event in order to maximise the pressure increment in the air tanks; (2) conducting the Genetic Algorithm optimisation to find out the best gear change strategy during braking in order to maximise the energy recovery to the air tanks; and (3) implementing the multi objective optimisation to simultaneously minimise the fuel consumption and the loss of available energy in the air flow during acceleration. The rationale for the choice of optimisation methods is explained and recommendations made for the development of energy management strategies in which a variety of different vehicle functions contribute to an overall fuel economy benefit.

See SAE 2016-01-1175 (2016, 17pp.)
UNCONVENTIONAL INTERNAL AND EXTERNAL COMBUSTION ENGINES

Free piston engines

A TWO STROKE FREE PISTON ENGINE'S PERFORMANCE AND EXHAUST EMISSION USING ARTIFICIAL NEURAL NETWORKS

University of Ulsan

The performance and exhaust emissions of a Free Piston Linear Engine (FPLE) were ascertained for various equivalence ratios (0.7, 0.8, 0.9, 1.0, 1.1 and 1.2). After that, the usability of Artificial Neural Networks (ANNs) in case of FPLE has been tested. Actually, the aim was to examine the best suited operational condition of, and show the possibility of using ANN, for this kind of engine technology. We first interrogated the thermal efficiency, generated power, total heat release rate, indicated mean effective pressure, exhaust gas temperature, and exhaust emissions such as CO, CO2, NOx and O2 for the chosen range of equivalence ratios and then gathered experimental data in order to train and test an artificial neural network model for prediction. The experimental results showed that, running the engine on the slightly lean side stoichiometrically, can fulfil the goals of higher engine performance and lower emissions. We used the back propagation learning algorithm for ANN and observed that the correlation coefficients (R) vary between 0.990-0.999, Mean absolute percentage error (MAPE) vary between 0.885-5.9%, and coefficient of determination (R2) vary between 0.937-0.999; which showed a well-defined relationship between the predicted and experimental values.


Miller cycle engines

MAGMA ENGINE: EFFICIENCY UPLIFT FOR EVERYONE

Ricardo

Ricardo’s Magma concept represents the latest thinking on super-efficient gasoline power, employing production-ready components in an extreme application of the Miller Cycle principle. By employing an extreme version of the Miller Cycle as opposed to the baseline Otto Cycle, the Magma engine is able to achieve higher thermodynamic efficiency through increased knock resistance and an extended power stroke. This helps it draw out every last ounce of energy from the expanding gases. Pumping losses on the induction stroke are reduced, too, particularly at unboosted conditions. All of which adds up to a significant improvement in fuel economy over a broad range of operating conditions. Covers - high-pressure boosting.

See Electronic Document 7988 pp22-23 (Ricardo Quarterly Review, Q3 2016, Oct 2016.)

Opposed piston engines

THE INVESTIGATION OF SELF-BALANCED PROPERTY AND VIBRATION ON THE PARTICULAR CRANKSHAFT SYSTEM FOR AN OPPOSED PISTON ENGINE

Tongji University

For an in-line diesel engine with four cylinders operating in four-stroke mode, the second-order reciprocating inertia forces generally cannot be well balanced with direct approach. The unbalanced second-order inertia forces are the main reason to cause vibration and noise in a diesel engine within low frequency range. The more superior tone quality for modern diesel engine has been expected even for bus application all the time, and there are tougher requirements for truck noise in developed countries, i.e. in Europe and USA. In present research a unique crankshaft system configuration was proposed, which including opposed piston, inner and outer connecting rod, and crankshaft but running in two-stroke mode, to eliminate the second-order
inertia force considerably rather than by adding an extra balance shaft mechanism. The theoretical equations describing self-balancing property of crankshaft system were obtained based on relevant reasonable assumptions, and then the CAD model was constructed on the basis of optimized results. The multi-body dynamic simulation was also carried out with rigid-flex coupling model. The vibration acceleration was measured at several critical positions in a prototype engine. The comparisons were implemented between conventional diesel engine and opposed piston engine eventually. The results were shown that the special crankshaft system owns tremendous potential to reduce the engine vibration noise clearly as well as owning higher power density, equivalent fuel economy and emission level, compared with a conventional diesel engine. See SAE 2016-01-1768 (2016, 9pp.)

**Rankine cycle engines**

**IMPROVING SAFE OPERATION OF ORGANIC RANKINE CYCLE UNITS IN AUTOMOTIVE APPLICATIONS USING MODEL PREDICTIVE CONTROL**

**Ghent University, University of Liege and Flanders Make**

Outline:
- Motivation
- System description
- Model Predictive Control
- Control architecture
- System identification
- Simulation results

Conclusions and perspectives:
A linear MPC using a low-order model has been successfully designed and implemented, thus allowing to:
- Satisfy actuator constraints (i.e. maximum, minimum and slew-rate)
- Maintain system in safe conditions (i.e. vapour quality and pressure at expander inlet)
- Maximize output power by operating as close as possible to the maximum allowed evaporating pressure
- Include feed-forward actions in a systematic way to enhance control performance.
See vCD 405 Andres-Hernandez.pdf (3rd Annual Engine ORC Consortium 2016 Workshop, Belfast, Northern Ireland, Sep 2016, 18pp.)

**OPTIMIZATION OF INVERTIBLE HTHP/ORC SYSTEM FOR COOLING WATER WASTE HEAT RECOVERY FROM INTERNAL COMBUSTION ENGINES**

**University JaumeI of Castellon**

Outline:
Background
- Low GWP working fluids for VCC and ORC.
- Trigeneration from renewable energy.
- ORC for LGWHR in industrial processes.
- HTHP and reversible systems for ICES WHR.

Theoretical Model
Optimization
Results
Prototype.
Conclusions:
Reversible HTHP/ORC systems can be used as a flexible technology to improve the electrical and thermal energy of ICE, profiting from the jacket cooling water waste heat. A net electrical efficiency upper than 5% and a COP close to 3 can be reached with an optimized system. A prototype of an electric power of 1 kW is going to be constructed to study the actual possibilities. See vCD 405 Bernardo-Peris-Perez.pdf (3rd Annual Engine ORC Consortium 2016 Workshop, Belfast, Northern Ireland, Sep 2016, 48pp.)

SMALL-SCALE ORC FOR WASTE ENERGY RECOVERY FROM A HIGH EFFICIENCY 1 KW ICE-SACI GENERATOR SYSTEM

Ghent University, Purdue University and Air Squared

Outline:
Project Insights
Bottoming ORC
Cycle Modelling
Fluid Selection and Cycle Architectures
Single-Stage Scroll Expander
Two-Stage Scroll Expander
Conclusions and Future Work:
A high-temperature ORC has been investigated as bottoming cycle for waste energy recovery from a novel ICE.
The project aims to achieve a total conversion efficiency of 40%
After carrying out a working fluid screening, R1233zd(E) has been identified as best candidate to meet both design constraints and performance.
A two-stage semi-hermetic scroll expander with integrated working fluid pump mechanism has been designed. The internal volume ratio of each stages are 3.25 and 1.0.
Work in progress:
- Sizing of heat exchangers
- Design of dedicated ORC test bench
- Finalise the novel expander concept design and prototype.
See vCD 405 Davide-Ziviani.pdf (3rd Annual Engine ORC Consortium 2016 Workshop, Belfast, Northern Ireland, Sep 2016, 20pp.)

TESTING OF A FLEXIBLE ORC THERMAL ARCHITECTURE

University of Brighton

Background:
The cost-effective deployment of ORCs for the mid-to-large scale ICE is partially suggested by:
- Employing new practice for high-grade applications,
- Addressing challenges of integrating multiple heat sources,
- Experimental demonstration of new concepts, etc.
To investigate some of these challenges, a programme of ‘concept-to-demonstration’ of an ORC test facility is in progress at the University of Brighton.
The key features of the facility are related to:
- Heat source setup,
- Utilisation of exhaust gases,
- Working fluids,
- Thermal architecture,
- Pressure-temperature operating capability.
Conclusions:
The key features of the ORC facility in progress at the University of Brighton, which may contribute towards reduced system costs and increased overall conversion efficiency can be summarised as:
- A variable heat source setup,
- Direct utilisation of exhaust gases,
- Deployment of pure alcohols and their water blends,
- Flexible thermal architecture offering charge air and internal heat recuperation, and
- Advanced pressure-temperature operating capability. Demonstrating the operational capability of the thermal architecture concludes phase 1 of 4. The thermal architecture can be tailored for dual source heat recovery for effective heat utilisation and/or internal heat recuperation for increased thermal efficiency. Covers - flexible heat source setup, direct utilisation of exhaust gases, blends/alcohols for high source/sink temperature applications, flexible thermal architecture, pressure-temperature operating capability.

See vCD 405 Angad-Panesar.pdf (3rd Annual Engine ORC Consortium 2016 Workshop, Belfast, Northern Ireland, Sep 2016, 17pp.)

THERMO-ECONOMIC OPTIMIZATION OF ORGANIC RANKINE CYCLE SYSTEMS FOR WASTE HEAT RECOVERY FROM EXHAUST AND RECIRCULATED GASES OF HEAVY DUTY TRUCKS

University of Liege

Introduction:
ORC waste heat recovery
- Fuel consumption and CO2 emissions

Design:
- Essential part of the process
Library of steady-state models
- Numerous steady-state models of different candidate ORCs
Design in three steps
- Selection of the design conditions
- Design (Optimization)
- Evaluation of the off design performance.

See vCD 405 Ludovic-Guillaume-1.pdf (3rd Annual Engine ORC Consortium 2016 Workshop, Belfast, Northern Ireland, Sep 2016, 20pp.)
COMMON ISSUES IN ALTERNATIVE POWERTRAINS

COMPONENTS AND SYSTEMS

Motors

DC MOTOR WITH SALIENT POLES ROTOR AND ALL COILS PLACED ON THE STATOR

University College Dublin and South Ural State University

DC motors are the most controllable electrical machines but more complicated for fabrication, in comparison with induction motors having simplified design but more complicated for control. Regular DC motor contain excitation (field) coil on the stator and armature coil on the rotor. Armature coil connected with external voltage source by a mechanical commutator with brushes. This arrangement complicates fabrication of DC machine, increases its cost, lowered reliability, and demands regular maintenance. Electromagnets inside of the stator increase dimensions of DC motor. In DC motor with salient pole rotor, there are no coils on the rotor, and mechanical commutator with brushes is eliminated, and eliminated all disadvantages connected with this arrangement. In this paper, we consider the new version of DC machine with DC stator excitation in compare with presented earlier. The difference is in using individual coil excitation for each armature coil, placed on the stator. In this case, we can design one, two, three or multiple phase machines. The reason for design two and three phase machine is for improvement of start condition and increase power of the DC motor. In the paper, we discuss theoretical bases design of motor with salient poles rotor and all coils placed on the stator. As in a regular DC motor, we consider series and parallel connection armature and field coils. In the considered motor, the power transistors commutator and the reflective optical sensor of rotor position are used instead mechanical commutator in regular DC machines. We consider design configuration of power transistor commutator and the reflective optical sensor of rotor position which depend from number of phases realised in particular version of the machine. Prototype DC motors with salient rotor poles and all coils placed on the stator where fabricated and tested. Tests results confirm theoretical bases of design brushless DC machines with DC stator excitation, and its properties.

See SAE 2016-01-0001 (2016, 6pp.)
CAE

A LARGE SCALE SIMULATION PROCESS TO EVALUATE POWERTRAIN TECHNOLOGY TARGETS WITH REAL WORLD DRIVING

Argonne National Laboratory and University of Waterloo

System Simulation is an accepted approach to evaluate the fuel economy potential of advanced (future) technology targets. Many technological advancements in vehicles result in 'real world benefits' which may not be adequately captured by the standard procedures and drive cycles. It is becoming increasingly important to evaluate the technologies on real world drive cycles. Generally, the approach for real world evaluation has been to synthesise a limited number of representative cycles from a large dataset, in order to limit the number of system simulations. This paper will present an approach based on a large scale simulation process, where simulations will be performed over thousands of real world drive cycles. An important qualification for the choice of real world drive cycles is the unbiased or representative nature of the drive cycles. The paper will detail a process to randomly down-select form the thousands of simulations to a (large) subset of simulations which represent the distribution of daily driving as per the NHTS survey of 2009. Multiple such drive cycle sets will be randomly generated to show the variance in benefits for a single distribution curve.

See vCD 395 EVS29-2290375.pdf (EVS 29, Montreal, Canada, Jun 2016, Session 2A - Predicting Real World EV Performance, 8pp.)
ELECTRIC POWER

Charging

EFFECT OF FAST CHARGING OF LITHIUM-ION CELLS: PERFORMANCE AND POST-TEST RESULTS

Argonne National Laboratory, University of Warwick and US Department of Energy

The effect of charge rate was determined using constant-current (CC) and the USABC Fast-Charge (FC) tests on commercial lithium-ion cells. Charging at high rates caused performance decline in the cells. Representing the resistance data as ΔR vs Rn-1 plots was shown to be a viable method to remove the ambiguity inherent in the time-based analyses of the data. Comparing the ΔR vs Rn-1 results, the change in resistance was proportional to charge rate in both the CC and FC cell data, with the FC cells displaying a greater rate of change. Changes, such as delamination, at the anode were seen in both CC and FC cells. The amount of delamination was proportional to charge rate in the CC cells. No analogous trend was seen in the FC cells; extensive delamination was seen in all cases. These changes may be due to the interaction of processes, such as lithium plating and i2R heating.

See SAE 2016-01-1194 (2016, 7pp.)

USING OPENADR WITH OCPP - COMBINING THESE TWO OPEN PROTOCOLS CAN TURN ELECTRIC VEHICLES FROM THREATS TO THE ELECTRICITY GRID INTO DEMAND-RESPONSE ASSETS

Eindhoven University of Technology, OpenADR Alliance, E-land Foundation, Greenlots and Alliander

If you are responsible for any part of the electricity grid, you are probably aware that a large share of renewable electricity and electric cars could lead to imbalances, blackouts, and force you to make large investments.

You are probably also aware that smart grids and demand response are a cost effective solution to this potential problem. This is made possible if electric cars with all their inherent power, storage and flexibility could become demand-response assets.

This paper shows you how to do this by combining the leading open protocol for demand response (OpenADR 2.0) and the leading open protocol for charging electric cars (OCPP).

We conclude by presenting a project using the approach outlined in this paper.

See vCD 395 EVS29-6080404.pdf (EVS 29, Montreal, Canada, Jun 2016, Session 1C – Electric Drive Infrastructure Strategies, 6pp.)
LIFE CYCLE ANALYSIS

LIFECYCLE IMPACTS OF LITHIUM IONS - A REVIEW

Norwegian University of Science and Technology

This review considers life cycle assessment studies on lithium-ion batteries, summarizes the most sensitive assumptions of the studies, and discusses how the environmental performance of LIBs can be improved. We identify the main source of discrepancy and uncertainty of battery production impact to stem from differing assumptions regarding energy requirements in cell assembly. There are few studies assessing the use and end-of-life phases and the associated impacts are found to be smaller than that of the production phase, although there is some uncertainty associated with the findings. Access to primary data will provide more useful results with higher certainty.

See vCD 395 EVS29-657088.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 – Dialogue with the experts, 9pp.)

LIFE CYCLE ASSESSMENT OF VEHICLE LIGHTWEIGHTING: A PHYSICS-BASED MODEL TO ESTIMATE USE-PHASE FUEL CONSUMPTION OF ELECTRIFIED VEHICLES

Ford

Assessing the life-cycle benefits of vehicle lightweighting requires a quantitative description of mass-induced fuel consumption (MIF) and fuel reduction values (FRVs). We have extended our physics-based model of MIF and FRVs for internal combustion engine vehicles (ICEVs) to electrified vehicles (EVs) including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). We illustrate the utility of the model by calculating MIFs and FRVs for 37 EVs and 13 ICEVs. BEVs have much smaller MIF and FRVs, both in the range 0.04–0.07 L/(100 km 100 kg), than those for ICEVs which are in the ranges 0.19–0.32 and 0.16–0.22 L/(100 km 100 kg), respectively. The MIF and FRVs for HEVs and PHEVs mostly lie between those for ICEVs and BEVs. Powertrain resizing increases the FRVs for ICEVs, HEVs and PHEVs. Lightweighting EVs is less effective in reducing greenhouse gas emissions than lightweighting ICEVs, however the benefits differ substantially for different vehicle models. The physics-based approach outlined here enables model specific assessments for ICEVs, HEVs, PHEVs, and BEVs required to determine the optimal strategy for maximizing the life-cycle benefits of lightweighting the light-duty vehicle fleet.


REDUCING GREENHOUSE GAS EMISSIONS BY ELECTRIC VEHICLES IN CHINA: THE COST-EFFECTIVENESS ANALYSIS

Tsinghua University

Compared with conventional vehicles, electric vehicles (EVs) offer the benefits of replacing petroleum consumption and reducing air pollutions. However, there have been controversies over greenhouse gas (GHG) emissions of EVs from the life-cycle perspective in China’s coal-dominated power generation context. Besides, it is in doubt whether the cost-effectiveness of EVs in China exceeds other fuel-efficient vehicles considering the high prices. In this study, we compared the life-cycle GHG emissions of existing vehicle models in the market. Afterwards, a cost model is established to compare the total costs of vehicles. Finally, the cost-effectiveness of different vehicle types are compared. It is concluded that the GHG emission intensity of EVs is lower than reference and hybrid vehicles currently and is expected to decrease with the improvement of the power grid. The total cost of EVs is relatively high compared with reference gasoline vehicles in 2014 but it is expected that EVs will possess an improved cost-competitiveness in the future. In terms of cost-effectiveness, medium-range EVs do not have an obvious advantage over other fuel-efficient vehicles currently. But the cost-effectiveness of EVs is predicted to become better in the next ten years.

See SAE 2016-01-1285 (2016, 9pp, 31 refs.)
MARKETING

HISTORY V SIMULATION: AN ANALYSIS OF THE DRIVERS OF ALTERNATIVE ENERGY VEHICLE SALES

Sandia National Laboratories

Simulations of the US light-duty vehicle stock help policy makers, investors, and auto manufacturers make informed decisions to influence the future of the stock and its associated greenhouse gas emissions. Such simulations require an underlying framework that captures the key elements of consumer purchasing decisions, which can be uncertain. This uncertainty in a simulation's logic is usually convolved with uncertainty in the underlying assumptions about the futures of energy prices and technology innovation and availability. By comparing simulated alternative energy vehicle (AEV) sales to historical sales data, one can assess the simulation's ability to capture the dynamics of consumer choice, independent of many of those underlying uncertainties, thereby determining the factors that most strongly impact sales. The market for diesel vehicles, hybrid electric vehicles, and to a lesser extent plug-in hybrid electric vehicles and all-electric vehicles, has now matured sufficiently to make such a study possible. In this work, we measure the results of the Sandia ParaChoice model under a variety of input assumptions against historical sales data. We observe that (1) the underlying simulation logic is sound, capturing key drivers of consumer choice, (2) AEV model availability has a significant impact on sales, and (3) AEV consumers are very likely aware of purchasing incentives and factoring those incentives into their purchasing decisions.

See SAE 2016-01-9142 (2016, 17pp, 75 refs.)
OPERATING RANGE

A PROBABILISTIC RANGE ESTIMATION METHOD FOR ELECTRIC VEHICLE WITH DYNAMIC TRAFFIC INFORMATION

Tsinghua University

The accessible range for the electric vehicle (EV) is related to travelling energy consumption along the trip, which is directly influenced by the changing traffic environment. A proper remaining range estimation method should reflect the changing feature of traffic system. In this paper, a probabilistic range estimation method is proposed based on the time-dependent stochastic traffic model, and stochastic simulation-based genetic algorithm is applied to evaluate the driving energy consumption, and therefore, EV accessible range can be estimated by the stochastic programming analysis model. Simulation comparison with two other range estimation methods proves that the proposed method receives an estimation result with higher accuracy and low variation in most simulation scenarios, which indicates the advantage of the proposed method.

Covers - state of charge.

See vCD 395 EVS29-860039.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 – Dialogue with the experts, 11pp.)

FUNDAMENTAL RESEARCH ON RANGE EXTENSION AUTONOMOUS DRIVING FOR ELECTRIC VEHICLE BASED ON OPTIMIZATION OF VEHICLE VELOCITY PROFILE IN CONSIDERATION OF CORNERING

University of Tokyo, National Traffic Safety and Environment Laboratory and Ono Sokki

Electric vehicles (EVs) have been intensively studied over the past decade, owing to their environmentally-friendly characteristics, however, their miles-per-charge is relatively short. To improve the miles-per-charge, the authors’ group has proposed Range Extension Autonomous Driving (READ) system which minimizes the consumption energy by optimizing the velocity profile. This paper extends READ system to be applied to not only straight driving but also curvy road by modelling the vehicle rotation motion and the cornering resistance. The effectiveness of the proposed method is verified by simulations and experiments.

See vCD 395 EVS29-980069.pdf (EVS 29, Montreal, Canada, Jun 2016, Session 1A - Advances in Electrified Transportation Autonomy, Performance and Efficiency, 12pp.)
RESEARCH AND DEVELOPMENT

E-CARRUS - A NEW CLUTCH-ON HYBRID ELECTRIC VEHICLE (CHEV) AND APPLICATION

**e-drives**

e-carrus (Latin --> wagon) is overall a new mobility concept for urban regions, using vehicles in a very new way of hybridization. A conventionally ICE-driven car with a coupling device will be pushed by an electrical driven two-wheeler. By this combination of a conventional car and an electric wagon a new type of hybrid vehicle is defined. The application is only used in urban regions, finally with fully automatic coupling and autonomous operation of e-carrus before and after coupling. Business models for shared economy have been developed. Technology and details will be presented.

*See vCD 395 EVS29-960331.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 11pp.)*

NEX GENERATION CAR – TECHNOLOGIES FOR FUTURE EVS

**German Aerospace Center (DLR)**

The German Aerospace Center has merged a wide range of technological research and development for future cars in a meta-project called "Next Generation Car". Within this large research project technologies for three vehicle concepts for different applications (urban, regional and interurban), and with different powertrains (fuel-cell, battery and hybrid) are developed. Research questions on different levels from conceptual question about vehicle modularity down to detailed technological aspects like combining hydrogen storage with cabin climatisation are covered by this project. This paper shows the holistic research approach and presents a selection of vehicle concepts and technology topics.

*See vCD 395 EVS29-5860399.pdf (EVS 29, Montreal, Canada, Jun 2016, Session Dialogue 1 - Dialogue with the experts, 12pp.)*
TRANSMISSIONS AND DRIVELINES

NEW VISION – CHINA TRANSMISSION MARKET PROSPECT

IHS Automotive

Contents:
- China Light Vehicle production market
- Transmission market overview
- Key trend of China transmission for passenger car market - manual, automatic, DCT 2010-2025
- Who are reshaping the market?
- EV/HEV market outline.

See vCD 406 G2_Wang_IHS_Slides_EN.pdf (5th International CTI Symposium China Automotive Transmissions, HEV and EV Drives, Shanghai, China, Sep 2016, Session G, 19pp.)
WASTE HEAT/ENERGY RECOVERY

A TAPE OF TWO CIRCUITS: ORCS FOR ELECTRICAL GENERATORS OR FOR FOSSIL FUELLED VEHICLES

AgriAD Power
Covers - anaerobic digestion in Northern Ireland, advantages of AD CHP electrical generation, Bio-methane for stationary or mobile applications, fossil fuelled versus electric vehicles, Biomethane for transport, end-user energy costs, CASE Waste Heat Recovery project, ORC for CHP:
Expander Technology.

Conclusions
- AD is a growing sector of renewable energy
- Bio-methane useful for CHPs and mobile applications
- There is large amounts of wasted heat from AD CHPs
- Application of ORC to CHP engines offers great potential
- AD CHP more efficient for EV charging
- ORC application to recover waste heat an added benefit.

See vCD 405 Thomas-Cromie.pdf (3rd Annual Engine ORC Consortium 2016 Workshop, Belfast, Northern Ireland, Sep 2016, 26pp.)
NATIONAL NEWS

AN ANALYSIS OF THE GERMAN ELECTRIC MOBILITY MARKET FROM AN INTERNATIONAL PERSPECTIVE

Deutsches Dialog Institut

There is growing awareness that preventing climate change can only be achieved by making societal changes. Policy makers have introduced regulations for carbon emissions in the automobile industry with the aim of promoting a new market for low-emission vehicles. The market for electric mobility holds great potential and larger industrial countries are at the fore front of establishing a market with innovative technologies. In this paper we present an analysis of the German market for electric mobility from an international perspective based on stakeholder interviews. Our goal is to review the current German market situation from an outside perspective.

See vCD 395 EVS29-1470097.pdf (EVS 29, Montreal, Canada, Jun 2016, Session 1E - Analysing Market Success Across the Globe, 11pp.)

CHINA’S POWERTRAIN CHALLENGE, A GLOBAL OPPORTUNITY

SMTC UK


See vCD 406 G3_Holdstock_SAIC_Slides_EN.pdf (5th International CTI Symposium China Automotive Transmissions, HEV and EV Drives, Shanghai, China, Sep 2016, Session G, 22pp.)

THE NEW GENERATION OF TOYOTA POWERTRAIN

Toyota

Covers – Toyota Environmental Challenge 2050, CO2 reduction challenge, HEVs, Toyota New Global Architecture (TNGA) Powertrains, laser cladded valve seats, TNGA transmissions (Direct Shift 8AT).

See vCD 413 Session 01, 2_P1.2_Sugiyama_Toyota.pdf (25th Aachen Colloquium, 10-12 Oct 2016, 01_Opening Plenary Session, 14pp.)

THE NORWEGIAN EV SUCCESS CONTINUES

Norwegian Electric Vehicle Association

Norway is leading the way for the transition to zero emission electric cars. In 2015, electric vehicles had a 22% market share in Norway. This is due to a substantial package of incentives developed to promote zero emission cars. The Norwegian EV Association conducts a yearly survey among EV owners regarding why they bought their electric car, how they use it and what they think is the most important policy and measures to promote electric vehicles. These experiences are a unique test case for decision makers in governments and the industry globally. In this paper, we will present the results from the 2015 survey and compare it to previous surveys in 2014 and 2013.

See vCD 395 EVS29-1420055.pdf (EVS 29, Montreal, Canada, Jun 2016, Session 1E - Analysing Market Success Across the Globe, 9pp.)
TECHNICAL TRAINING BY ENGINEERING EXPERTS

Frequent courses offered in a wide range of disciplines

**Internal Combustion Engines - Basic**
- 26 Apr 2016
- Location: Ricardo Shoreham Technical Centre
- Price: £750 per person

**Internal Combustion Engines - Advanced**
- 27-28 Apr 2016
- Location: Ricardo Shoreham Technical Centre
- Price: £750 per person per day

**Automated Transmissions**
- 27-28 Jan 2016
- Location: Ricardo Midlands Technical Centre
- Price: £750 per person

**Noise, Vibration & Harshness (NVH)**
- 21-22 Jun 2016
- Location: Ricardo Shoreham Technical Centre
- Price: £750 per person per day

**Diesel & Gasoline Engine Calibration**
- 18-19 Oct 2016
- Location: Ricardo Shoreham Technical Centre
- Price: £750 per person per day

**Why Hybrid? Market Drivers & Legislation Explained!**
- TBC - Contact us for details
- Location: Ricardo Shoreham Technical Centre
- Price: £750 per person

**Hybrid Electric Vehicle**
- 17-18 Feb 2016
- Location: Ricardo Cambridge Technical Centre
- Price: £750 per person per day

**Turbocharging & Boosting Systems**
- TBC - Contact us for details
- Location: Ricardo Shoreham Technical Centre
- Price: £750 per person per day

**Internal Combustion Engines - Basic**
1. Book your courses online at our new eStore.

Testimonials

“This course has provided a valuable detailed insight into engine construction and market drivers. But more than that it was a thoroughly interesting course at a world class organization”

“Excellent knowledge transfer from the enthusiastic presenters at the cutting edge of their field”

For more details, please contact: Glen Hall on +44 (0) 1273 794469 or Donna Wild on +44 (0) 1273 794632 or email traininginfo@ricardo.com
estore.ricardo.com
Delivering Excellence Through Innovation & Technology www.ricardo.com