Interview: Volkswagen
Powertrain chief predicts bright future for combustion engines

Auxiliary power units
Low-carbon vehicle project shows Ricardo expertise in range extenders

Hitting new heights
Ricardo project for Caterpillar delivers highest-ever diesel horsepower

Delivering the FUTURE
Ricardo helps Intelligent Energy’s range-extended electric van return low emissions, big space and high mileage
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Contents

Ricardo Quarterly Review • Q2 • 2012

NEWS

Industry news .................04
Wind power to undercut solar photovoltaic; VW engineers eye 30 percent fuel savings; horsepower race accelerates; fuel cell locomotives for mines

RQ viewpoint ...............07
Where next after China? Ricardo Asia MD Gary Tan looks ahead to the next wave of Asia-Pacific expansion

Ricardo news ...............24
Mechanical energy storage improves diesel train efficiency; new collaborations in China; Hong Kong environment minister visits Ricardo Cambridge; monorail co-operation in Malaysia

Q&A

Heinz-Jakob Neusser, head of powertrain development, Volkswagen......................08
How much more potential do internal combustion engines still have? VW’s ex-Porsche engine chief gives Tony Lewin all the answers

FEATURES

Clean energy

Auxiliary energy ...............10
Range extender engines allow electric vehicles to increase range and reduce battery size and cost. Tony Lewin documents the latest in APU technology, as developed by Ricardo for the Low Carbon Vehicle demonstrator programme

Clean energy

Delivering the goods ....16
Ricardo has assisted Intelligent Energy with its ambitious programme for a range-extended electric delivery van in the Transit class. Farah Alkhalisi drives the prototype and talks to the engineers behind it

Defence

Hitting new heights ....20
When world-leading construction equipment maker Caterpillar was awarded a programme by the US Department of Defense to develop a high-speed, high performance diesel engine, it invited Ricardo as a subcontractor. The outcome was a mighty engine that produces sensational power, as Jesse Crosse reports

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The task of RQ is to highlight the latest thinking in global engineering and technology in the transportation and clean energy sectors and related industries. We aim to achieve this by presenting an up-to-date mix of news, profiles and interviews with top business leaders, as well as in-depth features on programmes – both from within Ricardo and other leading companies.

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Mixed Sources

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Wind will remain cheaper than photovoltaic solar energy until at least 2020 according to a study published in Nature Climate Change in April this year. The study of renewable energy costs in developing markets, carried out by the Swiss Federal Institute of Technology in Zurich, examined the cost of switching to solar or wind technologies in six nations – Brazil, India, Egypt, Nicaragua, Kenya and Thailand – and concluded that solar PV would cost between 2.2 and 4.5 times as much as wind energy in these countries. High baseline energy costs in Kenya and Nicaragua meant that a switch to wind would immediately save money, concluded the researchers.

The study’s findings come as wind power accounts for over 10 percent of energy generated in five US states, though the overall national share is still under 3 percent. Underlining Germany’s need to invest in renewables to meet the government’s 2020 target for a 35 percent share, leading civil engineering operator Strabag is developing a system which will speed up the building of offshore windfarms. Current wind turbine designs require complex and time-consuming seabed preparation prior to deployment: Strabag’s innovation employs simpler gravity-secured bases and sees a dedicated carrier vessel, equipped with five near-complete turbines that can be readily mated with the bases.

Speaking to The Engineer magazine, Strabag director Gerald Zangl said that the market was looking for some kind of series production process. “Our concept is to do as much as possible onshore – not only foundations but the tower and converter and most probably the blades – and do it in a day.”

A new generation of ultra high pressure common rail systems will allow heavy duty diesel engines to exceed the requirements of Euro VI. Running initially at 2700 bar but capable of rising to 3000 bar, Delphi’s new system is available in either distributed pump or remote pump forms and has demonstrated a 50 percent smoke reduction in tests, along with engine-out NOx levels below 2 g/kWh. An innovative digitally controlled latching outlet metering valve on each of the pumping elements allows what Delphi claims is “exceptional” transient response, with a 2000 bar pressure increase typically taking 0.2 sec. “The key challenge for the Euro VI injectors is ensuring exceptional fuelling accuracy at very high pressures, with no significant change over the lifetime of the system,” explained Delphi engineering director David Draper. “Our new system has been proven to comfortably meet our service life target of 1.6 million km.”

Announced alongside the heavy duty system at April’s Vienna Motor Symposium was Delphi’s new Unit Pump Common Rail system for small low-cost diesel engines with one to four cylinders. Under development is a 2000 bar version capable of meeting the expected requirements of a future Euro 7 standard for light vehicles.
VW engineers eye 30% fuel savings

The new generation of Volkswagen engines will achieve significantly improved performance and much lower emissions at the same time as more compact packaging, say the company’s engineers. In papers presented at the 2012 Vienna Motor Symposium, VW outlined plans for new gasoline TSI engines using 30 percent less fuel, saving 20 g/km CO₂ in a typical application. Some 8 g/km of this improvement comes from the use of active cylinder shut-off, said the engineers.

Diesel engines, meanwhile, could look forward to 45 percent lower emissions at the same time as 16 percent greater power and 26 percent more torque. Details were also given of the forthcoming pure EV Golf Blue e-motion: its 85 kW peak power synchronous motor and 26.5 kWh lithium ion battery would give a regulated top speed of 135 km/h and a potential range of 150 km, said the announcement.

In a separate statement in Wirtschaftswoche magazine, VW’s head of electric vehicles Rudolf Krebs revealed that the company expects battery costs to sink rapidly, reaching €100 per kWh soon after 2015. At this cost level an electric car could be cheaper than a conventional vehicle: current prices were around €500 per kWh, noted the article.

Presenting its third-generation engine management system at the same event, Continental AG claimed up to 10 percent energy savings thanks to the unit’s ability to predict upcoming energy demands facing the batteries in hybrid and electric vehicles. The idea behind predictive-based energy management (pEM), say Continental engineers, is that a small battery that permanently performs at full capacity is just as effective in reducing fuel consumption as a larger one that only recharges during the usual window of opportunity. The system is able to use GPS topographical data to forecast how much energy will be needed for the planned trip, and then divides the trip into segments in order to plan the best times to recharge the battery.

F1-derived Ferrari hybrid powertrain

Ferrari claims experience in F1 racing has helped development of its latest HY-KERS hybrid drivetrain, revealed at April’s Beijing motor show. Destined to appear in “a certain new model”, the drivetrain consists of a V12 engine linked to a seven-speed dual clutch transaxle: hybrid components include a traction motor mounted behind the gearbox and a control unit above the transmission. A second generator fitted alongside the front of the engine serves to maximize energy recuperation and, says Ferrari, controls drag torque based on the batteries’ state of charge.

Ferrari claims a lower centre of gravity with the system, along with no increase in powertrain size; graphs show torque increasing strongly from low rpm and power significantly boosted all the way to maximum engine speed. Overall, says Ferrari, the new HY-KERS system allows a 40 percent reduction in CO₂ compared with a conventional engine of similar power.

Ocean methane emissions puzzle

Raised levels of methane emissions over the Arctic, detected by low-flying aircraft on several flights in 2009 and 2010, have been puzzling researchers, according to a report in Nature Geoscience. The methane is coming up through expanding cracks in the Arctic ocean ice: one theory is that it originates from biological activity in surface waters. Methane is 25 times more potent than CO₂ as a greenhouse gas.

Young Americans lose interest in driving

Fewer young Americans are bothering to learn to drive, says a study reported in the Financial Times. Figures from the Federal Highway Administration show that in 2010 some 26 percent of 16 to 19 year olds did not have a driver’s licence; this compares with just 21 percent a decade earlier.

Honda is first to recycle rare-earth metals

Working in conjunction with Japan Metals & Chemicals, Honda has developed the world’s first process to extract and recycle rare earth metals on a large scale. The programme will begin with the recovery of selected metals from nickel metal hydride batteries collected from hybrid vehicles at dealers in Japan, the US and Europe. Later, other used parts will be added.

Horsepower: 600 is the new 500

Five years ago there were just six car models on sale in the US offering more than 600 hp; today, according to Automotive News, the figure is 13. This, says the paper, means that 500 hp has come to be seen as the entry level for performance models – 18 brands are now in the 500 hp club, offering more than 70 separate models.

Samsung invests in UK carbon capture

Korean giant Samsung has taken its first step into the European power market with a stake in a UK carbon capture and storage project. CO₂ captured at the coal-fired Don Valley power station in Yorkshire will be piped to depleted oil wells in the North Sea, where it is expected to help recover trickier reserves held below the sea bed.

Euro Parliament rejects fuel tax proposal

Proposals by the European Commission to reform Europe’s energy taxation system have been rejected by MEPs in the European Parliament. The proposals would have seen fuels taxed according to their energy content and CO₂ emissions, and would mean an end to diesel being favoured over gasoline. The MEPs’ vote is advisory and the Council of Ministers may decide differently.

PSA and Ford diverge on diesels

Following its tie-up with General Motors earlier this year, PSA Peugeot Citroën is scaling back its co-operation with Ford on diesel engines. The decision will initially only affect larger engines (of two litres or more) destined for commercial vehicles.
Clean Energy and Power Generation

Mitsubishi and Honda get smart

Smart grid and home energy management demonstration projects have been unveiled by two Japanese automakers, Honda and Mitsubishi.

Mitsubishi has marshalled the resources of several companies within its orbit to produce the M-tech Labo, a smart grid demonstration installation that makes use of batteries in electric vehicles to shift the overall electrical load by recharging at night when demand is low. The power is returned to the grid when the factory and offices approach peak demand. The project will also explore the effectiveness of used EV batteries as a storage medium, with the expectation that this solution will be cheaper than dedicated storage batteries.

The system also includes a 20 kW photovoltaic array and can handle five EVs and five sets of used EV batteries to produce a maximum power supply of 50 kW.

Honda, for its part, has built two houses embodying its new Smart Home System (HSHS) – a comprehensive array of energy management measures designed to reduce CO2 emissions through the independent production of energy for both domestic use and transportation.

As well as intelligent controls to manage the generation and consumption of energy, the HSHS is also able to recharge electric vehicles and power products; it can also provide an independent supply of energy and mobility should a power outage or an external disaster occur. Among the technologies featured are Honda’s gas-engine co-generation system, with a claimed efficiency of 92 percent, and its new CIGS thin-film solar cell panels using copper, indium, gallium and selenium.

In a parallel move, Honda has also announced the extension of its alternative energy programmes and has opened a solar hydrogen station at its offices in Saitama prefecture. The high-pressure water electrolysis system makes use of the CIGS solar panels to produce hydrogen with zero CO2 emissions.

Motorcycles & Personal Transportation

Ducati becomes VW Group’s 11th brand

In a widely trailed move timed to coincide with Audi’s AGM and VW supervisory board chairman Ferdinand Piech’s 75th birthday, Audi has bought Italian superbike maker Ducati. Audi is part of the Volkswagen group and Ducati thus becomes the group’s eleventh brand. The group is also currently working on the integration of Porsche into its financial structure.

Ducati, founded in 1922 but subject to several financial crises in its long history, has been run by investment company Investindustrial since 2008 and has seen its glamorous high-performance superbikes succeed on the racetrack as well as in a growing number of international markets.

Though Audi CEO Rupert Stadler declared that Ducati was an excellent fit for Audi, industry commentators were less enthusiastic, citing the absence of commonalities between automobile and motorcycle technologies and manufacturing techniques. Daimler, which has operated a marketing agreement between its high-performance AMG division and Ducati for the past two years, has severed its ties with the Italian brand.

Rail

Fuel cell locomotives for mining duty

Colorado-based fuel cell specialist Vehicle Projects Inc is collaborating with Anglo American Platinum Ltd to produce five fuel cell powered locomotives to operate in the company’s mine in Limpopo province, South Africa.

The locomotives, which will operate underground, will not require any electricity from the grid, nor will they emit any noxious gases. “The purpose of the innovative vehicles is to mine platinum in a more economical, energy-secure, and environmentally-benign manner,” said Dr Arnold Miller, president of Vehicle Projects Inc (VP).

The hybrid fuel cell power plant employs a Ballard proton exchange membrane fuel cell, FCvelocity 9SSL V4 stacks and K2 Energy lithium-ion batteries, says VP. Continuous fuel cell net power is 17 kW and, together with the traction battery, maximum net power is 45 kW for approximately 10 minutes.

Hydrogen storage in metal hydride units is energy dense and ultra safe in the underground environment, says VP, with the 3.5 kg of stored hydrogen sufficient to provide 50 kWh of electrical output from the fuel cell. Recharging from a 20 bar hydrogen supply underground takes between 10 and 20 minutes.
Climate control that saves CO₂

Japan-based supplier Denso has already begun shipping an innovative heating, ventilation and air conditioning system (HVAC) that is able to reduce energy drain by only heating or cooling one part of the interior when the driver is alone in the vehicle. The system is able to separately control the climate in three different cabin zones – driver, front-seat passenger and rear seat.

“With the driver side A/C is being used only, the A/C system can save up to approximately 20 percent energy consumption on an annual basis compared with conventional models, which helps improve the vehicle’s fuel efficiency,” says Akio Shikamura, director of Denso’s Thermal Systems business group.

To achieve individual control of the three different areas, Denso engineers had to divide the internal structure of the HVAC unit into five compartments, each connected to specific air vents, while maintaining the same overall package space. Denso competitor Delphi is developing a new type of air conditioning that it claims will “dramatically increase efficiency” to help increase the range of electric vehicles and reduce the CO₂ emissions of conventional vehicles. The Unitary Heat Pump Air Conditioner (HPAC) integrates a refrigerant heat pump and coolant distribution system and is able to draw heat from the ambient air as well as from the main electric components.

Fitting Delphi’s Unitary HPAC to an electric vehicle or a hybrid that does not generate much combustion heat could significantly reduce the energy needed for cabin heating in very cold conditions, says James Bertrand, president of Delphi Thermal Systems. “Testing has shown that the reduced energy draw from the battery pack could increase the electric drive range by up to 10 percent.”

Easy cruiser

As a first step towards the long-awaited self-driving car, GM premium division Cadillac has begun road testing new technologies enabling a vehicle to travel semi-autonomously in highway driving. The suite of applications goes under the heading of Super Cruise and can provide fully automatic heading of Super Cruise and can provide fully automatic in highway driving. The suite of applications goes under the heading of Super Cruise and can provide fully automatic steering, lane-centring and braking under what are described as “certain optimal conditions”.

Super Cruise, which fuses data from radar, ultrasonic sensors, cameras and GPS mapping, “has the potential to improve driver performance and enjoyment,” claims Don Butler, vice president of Cadillac marketing. The system could be ready for production vehicles by mid decade, according to Cadillac.

The automakers of Asia have had a profound impact on the global industry over recent decades, marked by successive waves of national development whose impacts have been felt on all continents. The 1960s and 1970s saw the dramatic rise of the Japanese car makers: indeed, from today’s perspective it is hard to believe that familiar global brands such as Toyota, Honda, Nissan and Mazda were once considered very new market entrants in Europe and North America. From the 1980s onwards we saw the rise of Korean industrial groups such as Hyundai, offering products of increasing sophistication and quality – products which also succeeded well beyond their own domestic market. And today, of course, all eyes are on China as potentially the largest of them all. It boasts many new automakers, some arising from international JVs and others developing independently their own right; many of them are focused on the unparalleled opportunity presented by potentially the world’s largest domestic market, but others setting clear strategy for export-led growth.

I am often asked whether China represents the end game for the growth of the Asia-Pacific auto industries: in my view this could not be further from the truth. Whilst the Chinese auto industry will continue to grow and very probably lead the world in production terms, it would be foolish to ignore the market potential of surrounding nations.

With its economy on a healthy path and investment flowing in, the equation for energising Indonesia’s automotive industry is being completed as the aspirational middle class expands and the buying power of the population increases. And while no one is taking their eyes off China, industry watchers would do well to look ahead to the next wave of Asia-Pacific expansion – a development which could be no less interesting and no less profitable.
How far can you take downsizing?
Volkswagen has presented concepts of two-seaters, especially aimed at urban mobility. The Nils was presented at the Frankfurt Motor Show and the XL1, presented in Qatar in January 2011, will go into small-scale production in 2013.

Are you working with thermal energy recovery?
If so, what kind of system?
Our TDI and TSI engines already use exhaust-gas energy through turbocharging. Turbocharging is a key technology of the Volkswagen downsizing strategy. Further exploitation of the remaining exhaust turbo charger energy is still under investigation.

What is happening with your engine project that combines both diesel and gasoline principles?
Findings from the Volkswagen CCS (combined combustion system) research project have partially been integrated into today's engines. A complete CCS engine is not considered to be realistic in the near future.

Does the transmission have further potential to improve economy?
The latest DSG (dual clutch Direct Shift Gearbox) enables coasting or "sailing": as soon as the driver releases the accelerator pedal, the engine is disengaged from the transmission. This is even possible at higher speeds (up to 160 km/h), in other words on the motorway as well. The vehicle "rolls" significantly longer, since engine drag torque...
losses are eliminated. When drivers adopt an anticipatory style of driving, this has a direct positive effect on fuel economy.

**Will the DSG become cheaper so more customers can afford it?**

The demand for the DSG transmission at the current price is higher than can be met by present production capacity. It would be normal to assume that as production capacity rises, then prices will fall. Volkswagen has improved the accessibility of the DSG to more customers a number of years ago with the introduction of a smaller, lower torque capacity dry clutch version that is proving highly successful with smaller engines in smaller cars and vans.

**Is the DSG on the Cross Coupé still the dry clutch unit? How does it handle so much torque?**

The DSG in the Cross Coupé is a six-speed wet clutch, high torque capacity transmission.

**Do small diesel engines have a future under Euro 6 standards, or will they be too expensive?**

Even after the introduction of Euro 6 emission standard, small diesel engines will still have a future. Achieving Euro 6 is technically challenging and requires a model-specific solution.

**Overall, will we be seeing fewer diesel engines and more gasoline in Europe?**

This will depend on various factors, amongst these being legislation and fiscal measures and fuel and energy prices.

**What is the outlook for diesel in the US?**

Volkswagen has just begun an initiative to revive its success in the US with models specifically for that market. This has resulted in a dramatic increase in sales during 2011 and 2012 with both diesel and gasoline models. Volkswagen already offers the Touareg Hybrid for the US market and will soon offer a hybrid version of the Jetta. The current objective is to ramp up production of Beetle, Jetta and Passat models to meet sales demand of these US models that are specifically matched to US market requirements. Diesel engines in the US passenger car market have a small, but growing, fan base. Due to our long-term activities and product range off er, diesel vehicles are mainly associated with Volkswagen.

**Will VW Group achieve the planned 2020 European fleet average limit of 95 grams CO₂ per km on time?**

The Volkswagen Group has committed to achieve emissions below 120 g CO₂ per km in 2015. Every new model generation will on average be 10 to 15 percent more efficient than its predecessor. But Volkswagen is not only working on developing the most environmentally-friendly vehicles, but also on building them with the greatest possible sustainability. Geneva 2012 marked the start of a fundamental ecological restructuring of the Volkswagen Group, as our CEO Prof Dr Winterkorn announced at the show. He set the target of making production in the Volkswagen Group 25 percent more environmentally compatible by 2018.

**Approximately what percentages of output will be hybrid and pure electric?**

The Group is taking E-mobility to volume production and wants to be the market leader in E-mobility in 2018. Apart from pure electric vehicles Volkswagen will also set a focus on plug-in hybrid technology. Volkswagen currently forecasts that 3 per cent of its production will be hybrid or pure electric by 2020.

**Dr Heinz-Jakob Neusser**

2011 Volkswagen AG, head of Volkswagen brand drivetrain development
2001 Porsche AG, head of drivetrain development
1996 Porsche AG, head of project management, engine development
1990 FEV GmbH, senior executive
1986 FEV GmbH, research engineer
1986 RWTH, Aachen, doctorate in mechanical engineering

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**Volkswagen’s engine technology showcase**

The name and the silhouette may have been familiar, but the Cross Coupé presented by Volkswagen at the 2012 Geneva model represented a significant step forward over the similarly shaped concept shown at Tokyo just four months earlier.

With its gasoline-electric plug-in hybrid drivetrain the Tokyo concept had already garnered a host of headlines for its 62 g/km CO₂ emissions and 195 kW total system power. The Geneva version, finished in red instead of silver, goes one better, swapping the gasoline combustion engine for the latest EA 288 TDI diesel engine rated at 190 hp. This engine, along with a 40 kW electric motor, powers the front wheels through a six-speed dual clutch transmission, while a more powerful motor – 85 kW – is integrated into the rear axle to provide all wheel drive as well as traction for zero emissions running. The lithium ion battery stores 8.8 kWh of energy, sufficient for a range of 45 km at speeds of up to 120 km/h.

Despite an all-up weight of over 1850 kg the Cross Coupé can reach a top speed of 220 km/h and achieves CO₂ emissions of 46 g/km.

Volkswagen stresses that the Cross Coupé is just a concept and that there are no current plans to put it into production. However, as it is built on the new MQB modular platform and its powertrain elements are designed to fit into the platform system, it clearly has an important role as a template for future ultra low emission vehicles from the VW group.
Interest is building rapidly in range-extended electric vehicles that use an auxiliary power unit to reduce the requirement for a large on-board battery and also to eliminate range anxiety. As part of the UK Low Carbon Vehicle Technology Project, Ricardo has integrated an APU into the programme’s battery-powered Freelander, breaking new ground in the process. Tony Lewin has the inside story.

For more than four decades California has provided the world with a template for ever-tightening regulations on automobile emissions, especially when it comes to the mandating of zero- or near-zero emission vehicles. The latest rules set standards for battery electric vehicles with a small top-up auxiliary power unit (APU); although there has been some interest worldwide in these compact add-on power units that provide a ‘limp home’ capability, most activity has been centred on larger APUs, typically giving 30 to 50 kW, that allow the vehicle to be driven as normal even when the battery is depleted.

The majority of journeys are less than 60km, so can be completed in EV mode, but in the near to medium term customers will expect the same vehicles to also complete longer journeys when required. For pure electric vehicles to provide a range comparable with conventional vehicles will require large, heavy and, perhaps critically, expensive batteries. With current battery pack technology costing $800 to $1000 per kWh, and even the most optimistic forecasts suggesting costs will only fall to $250-$300 per kWh, replacing some of the battery capacity with an APU makes economic sense. An auxiliary power unit can provide the functionality to complete longer journeys, at lower total vehicle cost than a pure EV with a large battery. Furthermore, the APU can also be rapidly refuelled using existing infrastructure.

Ricardo, too, has focused closely on the whole area of range-extended EVs [an example of a commercial project is described on pages 16-19 following this article] and has been one of the lead partners in the recently completed UK government Low Carbon Vehicle Technology Project (LCVTP). Among the technologies explored by Ricardo in the programme was that of an auxiliary power unit to help turn the demonstrator vehicle – in this case the relatively large Land Rover Freelander SUV – into a highly efficient RE-EV.

Dedicated solutions

Clearly, says Ricardo technology innovation and strategy manager
Nick Powell, in charge of the overall APU design in the Low Carbon Vehicle Technology Project, the priorities will be different for different types of vehicle. “An APU can be anything from an emergency get-you-home device, giving quite small amounts of power, to something that provides the full functionality of the vehicle once the battery has been depleted.”

It is not surprising that the majority of current APUs are in the latter class, notes Powell. “Right now, customer expectations are that the vehicle will continue to do what a normal vehicle does, so most APUs are now falling into the 30 kW to 50 kW power range. So while light weight and compact size are a major priority on a get-you-home APU as it is hardly ever used and thus represents dead weight, different considerations can apply to larger units.”

For the 30 to 50 kW size of APU, because they will be used much more of the time, efficiency becomes more important, explains Powell. “In this condition the RE-EV is in effect a series hybrid and you have inefficiencies of energy conversion from mechanical to electrical in the generator and back to mechanical in the motor. The inefficiencies in these conversions need to be offset by efficiency in the APU itself – otherwise, on a long journey you will end up with a rather inefficient vehicle.”

**Exotic technologies**

While the popular media has seized onto exotic range extender technologies such as gas turbines, Stirling engines and fuel cells (see panel p14), the reality according to Ricardo is that issues such as fuel consumption, air handling and start-up mean such solutions will not become reality for some while. “In the short to medium term these will be rather less likely than conventional technologies, probably leaning towards gasoline because of its lower cost and weight and lower emissions,” reveals Powell.

Furthermore, forecasts suggest that in the near to medium term the market for APUs is relatively small, and unlikely to justify the investment in the production of dedicated engines.

Adaptation of existing volume-production engines is a more realistic option. There is much that can be done to adapt a good existing engine to an APU duty cycle, notes Powell, and the substantial extra cost of a dedicated engine is unlikely to be reflected in a significant gain in efficiency.

It was precisely this practical approach that guided the LCVTP team in its choice of APU for the Freelander technology demonstrator vehicle. The team was not looking to make a statement of what Ricardo considers the theoretically ideal APU: instead, the project sought to explore the challenge of integrating and optimizing a readily available off-the-shelf unit already in volume production. This realistic and economically sound strategy would have the greatest relevance to present-day industry and consumer needs, reasoned the team.

**Freelander APU: which size?**

The first step in deciding on the most suitable APU for the Freelander was to establish the power required. “Our Low-carbon demonstrator based on Land Rover Freelander uses two-cylinder Fiat engine as its auxiliary power unit. Predicted CO2 emissions are 61 g/km, compared with 158 g/km of the 2.2 litre diesel original.”

Low-carbon demonstrator based on Land Rover Freelander uses two-cylinder Fiat engine as its auxiliary power unit. Predicted CO2 emissions are 61 g/km, compared with 158 g/km of the 2.2 litre diesel original.
Taking the conventional APU further

The Fiat TwinAir-based APU in the LCV technology project vehicle represents what can be done by optimizing an existing production engine for APU duty without making costly changes to its hardware or construction. With more freedom to make larger design changes, further potential efficiency improvements could be unlocked as APUs become more specialised and diverge from engines in standard vehicles. These are some of the measures that could cut consumption still further:

- **Atkinson and Miller cycles**: the Atkinson cycle, or Miller cycle for boosted engines, uses a high geometric expansion ratio for improved fuel consumption, with the effective compression ratio reduced typically by late inlet valve closing to control knock.

- **Downspeeding**: the frictional losses within an engine increase dramatically as engine speeds rise, so lowering the operating range so that the engine’s residency was at lower rpm could provide some efficiency gains, especially when used in conjunction with a smaller, up-speeded electric generator.

- **Breathing**: with no need to rev beyond around 4000 rpm and no need to sustain a stable idle speed, the valve train and induction systems of future APUs could be simplified and optimized for a much narrower speed range.

- **Overspeeding**: with no risk of over-revving due to, say, driver abuse or a missed gear change, an engine reconfigured for APU use would not have to be over-dimensioned to withstand the stresses of high rpm. It could be lighter and simpler as a result.

- **Electric machine**: for its compactness, efficiency and volume production availability. Optimization for APU use avoided costly changes to hardware or structure. For example, the generator has no bearings of its own, instead relying on the crankshaft bearing for support, which brings benefits but also challenges. Likewise the relatively low maximum speed made an outer rotor design possible, increasing torque density and helping to keep the machine axially short to assist packaging.

- **Vee engines in standard vehicles**: these are some of the measures that could be unlocked as APUs become more specialised and diverge from its hardware or construction. With more freedom to make larger design changes, further potential efficiency improvements could be unlocked as APUs become more specialised and diverge from engines in standard vehicles. These are some of the measures that could cut consumption still further.

- **Starting point**: the LCVTP was to find an APU that gave a reasonable cruise speed and good functionality. It is that sustained cruising that largely defines the power requirement,” says Powell.

With the field narrowed down to units of around 50-60 kW, the team looked at several potential two- and three- and four-cylinder gasoline engines, finally settling on the two-cylinder Fiat TwinAir. "The Fiat is a good example of a modern compact engine,” he observes, “and another reason for the choice was to explore the challenges of fitting a generator to a two-cylinder engine. In terms of package it has advantages, too – and that’s why it is interesting to explore from a research point of view: most APUs in the future are expected to be two- or three-cylinder.”

After the team had acquired two brand-new Fiat 500 models and removed their TwinAir engines, work could begin to move from software and simulation into the nuts and bolts of actual hardware. Already, after the study of a number of alternatives, the decision had been made to package the all-important electric generator into the space normally occupied by the Fiat’s flywheel. One of the implications of that decision was that the electric machine, designed by Ricardo’s electric drives chief engineer John Reeve, would have a triple role: not only would it generate current, but it would also have to act just like a standard flywheel in smoothing out the engine’s operation – and it would have to act as a motor for starting the engine.

**Electric machine: key know-how**

"From a design point of view we had to consider that the electric machine was connected to a crankshaft, which is a dynamic system,” explains Powell. “All the air gaps, for instance, had to be carefully considered through analysis. It’s on the end of the crankshaft with a longer overhang than a conventional flywheel, so things like inertia and whirl characteristics have to be taken into account, as do the additional loads placed on the crankshaft.”

"An electric machine targeted as an APU generator looks very different from a traction machine,” adds Reeve. “For example, the generator has no bearings of its own, instead relying on the crankshaft bearing for support, which brings benefits but also challenges. Likewise the relatively low maximum speed made an outer rotor design possible, increasing torque density and helping to keep the machine axially short to assist packaging.”

"Also, particularly being two-cylinder, it has high torsional velocity fluctuations,” notes Powell. “Those need to be considered carefully in the integration of the design.”

Likewise, the low-level control software for an APU generator needs to be different in several subtle but important ways from standard motor control software if one is to get the best from the APU. The outer rotor permanent magnet (PM) architecture allows for exceptionally high torque density: the generator is rated at 55 kW at 4000 rev/ min and is able to take the full load of the engine. The outer rotor PM machine
was just one of many machine types that could have been selected and, like the whole APU, does not represent Ricardo’s view of an optimum choice for all APUs. Other machine types, including AC induction and reluctance machines, could equally well have been selected, each offering a different balance of attributes.

The final design was built to print by project partner Zytek.

Thermal management of the generator is a key consideration and a number of concepts were explored as part of LCVTP. The machine was designed to use engine coolant, although in the current implementation of the technology demonstrator vehicle it uses a separate low-temperature cooling system that also takes in the battery and the power electronics. Engine temperature control is through a separate liquid cooling circuit.

Integration into the vehicle

Appearances can be deceptive: the smart and professionally finished underhood layout of LCVTP’s RE-EV Freelander gives every indication that this is a production vehicle rather than a rolling testbed for new and experimental technologies. “The fact that it looks very finished is a credit to the team that built it,” says Nick Powell. “But it’s important to remember that this is a technology demonstration and validation vehicle, not a production solution.”

Hidden beneath the neat Fiat TwinAir engine cover and the grey shield on the right hand side is a maze of wiring, piping, trunking and all the other experimental engineering necessary to validate the concept in its various iterations. “There are a lot of systems to package,” observes Powell, with a hint of understatement. “The electrical system and power electronics, the two different cooling systems, the APU and the motor and gearbox. That’s in addition to all the normal engine fittings such as exhaust and intake systems and other ancillaries.”

Ricardo engineers were able to “assemble” the project car’s componentry in a virtual environment prior to the hardware stage, learning vital lessons on the way. They stress that while the equipment on this research vehicle manages to fill even the Freelander’s generous underhood space, any production applications of this type of technology would be much more efficiently packaged. Nick Powell again: “For this project we just looked at this particular vehicle, but clearly the approach and the understanding of the boundary conditions and the trade-offs is applicable to any other type of vehicle.”

“Something that also came out of the project was a very good understanding of the constraints on the high-voltage distribution system,” he adds. “For example, the sizing and routing of high-voltage cables needs very careful consideration of many factors including power loss, EMC, weight and cost, minimum bend radii, and safe mounting – these things need to be considered as early on as possible in the design process as well.”

The cooling system, or systems, also proved quite a challenge. With a high- and a low-temperature circuit already decided upon, the team explored the trade-offs involved in which circuit the

Exotic options

Many glamorous and innovative power sources have been suggested as possible candidates for APU packs. Here are the pros and cons of some of them:

Gas turbine: compact and with multifuel capability, but current technology is less efficient than conventional gasoline and the high speed of turbines demands either high-speed generator technology or gearing

Stirling: relatively unsuited to APU use due to low power density, though possible application for waste heat recovery

Diesel: heavier and more expensive than gasoline due to emissions control requirements, and with inferior NVH

Fuel cell: a neat longer-term solution but needs development of hydrogen infrastructure and on-board storage. No moving parts

Wankel rotary: smooth and with some potential in the under 10 kW class where efficiency is less important

Motorcycle engine: powerful, light in weight. Wide variety, but more adaptation required than car engines

How APU technologies compare

<table>
<thead>
<tr>
<th>Technology</th>
<th>&lt;10kW</th>
<th>~35kW</th>
<th>35kW &amp; 90kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased in gasoline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atkinson / Miller ICE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel ICE - with or without HCCI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low cost conventional ICE - gasoline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air engine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free piston with linear generator</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary - Wankel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Split cycle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel cell</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External combustion [e.g. Stirling cycle]</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Steam turbine</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Gas turbine with heat recovery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas turbine</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Weighted assessment*

* - Source: Results of an analysis of the collective views of the LCVTP partners regarding the suitability of various candidate APU technology options based on power requirements.
Generator should be connected to. “We tested both on the testbed,” says Powell, “and in the current application we decided on the low-temperature loop.”

Providing adequate cabin heat is a challenge with any electric vehicle; to this end, the project RE-EV is fitted with a PTC heater for when it runs in electric mode. One option, says Powell, is to integrate this into the engine circuit so that the engine can be pre-heated for a more efficient cold start.

Control strategy

Many engineers argue that this is where the real expertise in electric and hybrid vehicles lies – designing and implementing a strategy which enables the most effective power delivery for the lowest emissions and energy outlay. The Ricardo team’s strategy for the RE-EV is in general to run the engine as close as possible to the optimum efficiency line of fuel consumption versus power. Yet nothing is ever quite that simple, and account must also be taken of both NVH and over all emissions.

NVH is a particularly sensitive issue, as Powell observes: “We did some work on the subjective expectations of the driver to changes in APU speed and load: our findings suggested that some relationship between engine speed and vehicle speed is desirable, so the control strategy we developed will typically have the engine operating between 1500 and 4000 rev/min.”

With the engine frequently stopping and restarting, emissions are the other challenge, he explains. Starting off, the engine is unlikely to go immediately to, say, 2500 rev/min: the gas flow would be too high prior to catalyst light-off. Instead, the engine restarts at lower rpm, though not at idle, and selects an optimum speed and load point to achieve catalyst light-off.

The frequency with which the engine stops and restarts depends on the duty cycle – Powell is reluctant to disclose too much detail here – but in an urban situation where there is less masking noise from the road and air flow, the engine is more likely to remain switched off. Overall, the fact that there are fewer transients to deal with makes some aspects of the calibration more straightforward – idle stability is never an issue, for instance – though because of the high gas flow rates from the hard-working engine, the catalyst still has to be quite large.

Yet the aspect of the vehicle integration process that is most likely to be noticed by the eventual customer is likely to be that of noise and vibration. Here, says Powell, three systems are key: intake and exhaust design, and structure-borne noise transmitted through the powertrain mountings. The exhaust system was modelled in WAVE to refine its NVH performance, while the engine mounts, never simple on a two-cylinder engine, were optimized using ADAMS. At one point, says Powell, encapsulation was tried for some elements.

“For Ricardo’s engineers it is second nature to look one step ahead – to evaluate the effectiveness of a whole host of additional measures that could be applied to the project vehicle”

The Low Carbon Vehicle Technology Project (LCVTP) was a two-year research initiative launched in early 2010 as part of a UK government initiative to declare the West Midlands region a Low Carbon Economic area for advanced automotive engineering. It comprised a combined financial investment worth £19 million by regional development agency Advantage West Midlands, the European Regional Development Fund and contributions from the project’s industrial research partners. In addition to Ricardo, the partners in the project included Jaguar Land Rover, MIRA, Tata Motors European Technical Centre, Zytek Automotive, Coventry University and the Warwick Manufacturing Group (WMG).
Performance and emissions
With an ongoing research project dedicated to exploring new and innovative ideas rather than detailed optimization, any quoted performance and emissions results will of necessity be no more than a freeze-frame of the project at any particular moment. Yet with so much of the original Freelander’s hardware having been changed or modified it is not so much a question of comparing the original vehicle with the project vehicle, more a question of exploring how much improvement individual candidate technologies are capable of delivering.

For the record, however, the project vehicle in its current form is predicted to deliver CO2 emissions in the NEDC cycle of some 61 g/km – an impressive advance over the standard Freelander’s 158 g/km.

Yet for Ricardo’s engineers it is second nature to look one step ahead – to evaluate the effectiveness of a whole host of additional measures that could be applied to the project vehicle. What will be the effect of systematic friction reduction in the APU and elsewhere? With the engine’s maximum speed reduced to 4000 rev/min, how much benefit will be gained by optimizing the breathing system for this lowered speed range? Intelligent cooling and lubrication strategies will also be fed into the mix, as will an exploration of engine operation on the Atkinson cycle.

More exotically, Ricardo engineers will also investigate the possibility of further savings through the recovery of waste energy via turbo generators in the exhaust system. Every step of the way, experience is being gained and vital know-how built up, enabling this state-of-the-art knowledge to be fed directly into client programmes. The design of APUs and generators and, especially, the integration of APU systems into the vehicle are set to become the key areas of automotive expertise in the very near future – and through its continuing research and development efforts, Ricardo is ensuring that it remains well ahead of the curve.

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**Specification sheet**

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original vehicle</td>
<td>Land Rover Freelander 2.2 eD4 2WD</td>
</tr>
<tr>
<td>Manufacturer’s quoted kerb weight</td>
<td>1710 kg</td>
</tr>
<tr>
<td>Manufacturer’s quoted emissions</td>
<td>158 g/km CO2</td>
</tr>
<tr>
<td>APU base engine</td>
<td>Fiat TwinAir gasoline, two cylinder, 875 cm³</td>
</tr>
<tr>
<td>Manufacturer’s quoted outputs</td>
<td>85 hp @ 5500 rev/min, 145 Nm @ 1900 rev/min</td>
</tr>
<tr>
<td>APU operating range</td>
<td>1500 – 4000 rev/min</td>
</tr>
<tr>
<td>Electric starter-generator</td>
<td>Crankshaft-mounted outer rotor permanent magnet type; 55 kW peak output @ 4000 rev/min</td>
</tr>
<tr>
<td>Battery</td>
<td>Lithium ion, capacity 22.8 kWh</td>
</tr>
<tr>
<td>Predicted emissions on NEDC UNECE 101 cycle</td>
<td>61 g/km CO2</td>
</tr>
</tbody>
</table>

Range-extended architecture allows the engine to operate at maximum efficiency as there is no mechanical link between the prime power source and the wheels.
Intelligent Energy, as the leader of a consortium to design a range-extended electric delivery van, called upon Ricardo’s expertise in simulation, powertrain control and telematics. Farah Alkhalisi looks at the t-001 RE-EV demonstrator vehicles and talks to the team involved in this project.

February 2011 we signed a contract with Ricardo, and at that stage, we had already identified the diesel engine, battery, motor and generator and inverter suppliers contributing to the project. However, we did not have the exact specifications. Ricardo’s technical activities and strengths and their knowledge of electric vehicles and EV drivelines, made us confident in their ability to do the simulation work.

Ricardo was subcontracted for the simulation and also to develop and supply the vehicle control system, which has now been fitted into two prototype demonstrator vehicles built by Revolve.

**Driveline details**
The t-001 features a 25 kWh lithium-ion battery with a 75 kW traction motor and a Ford four-cylinder, 1.4 litre diesel engine coupled to a 54 kW generator. The t-001’s rear wheels are driven by the motor, which is directly coupled to the differential; the engine acts only as a ‘range-extender’ to run the generator. This gives an all-electric range of up to 106 km before the engine kicks in, and fuel consumption over a 200 km route of 2.0 l/100 km; in simulations, a carbon dioxide output of 22 g/km was achieved.

The van’s total possible range between refuelling or recharging stops is over 645 km, and its battery can be recharged in 3-4 hours from a three-phase power supply; different recharging solutions could be adopted in a production vehicle, but this current arrangement would be adequate for a fleet van returning to a fixed base. Performance remains acceptable for a vehicle of this type – a top speed of 130 km/h, acceleration to
“Ricardo’s technical activities and strengths and their knowledge of electric vehicles and EV drivelines made us confident in their ability to do the simulation work”
Chris Hiett, IE LEV programme director

100 km/h in 8.5 seconds – and crucially, it maintains a kerb weight of just 1650 kg and a payload of 1400 kg, thanks to its lightweight structural components and body panels.

“This was designed to be all about low carbon, reduced total cost of ownership and fleet volume adoption, a real-world application”, says Nick Tebbutt, project director at Ricardo. “The powertrain was picked to support these requirements. IE came to Ricardo saying they wanted to do an RE-EV; they had already carefully calculated the business model for the application and were looking for a practical execution of the idea. The inclusion of the APU gets around range anxiety and is a way of addressing the variability of fleet use, not necessarily doing a fixed route like a bus.

“We used relatively mature technology parts, broadly speaking those available within the timescale of the project – 18 months to build a fully-functioning vehicle from scratch. It’s not an experimental powertrain,” adds Tebbutt. However, many of the components were sufficiently new that there was little data from their suppliers. “We had to use our own expert assumptions from previous projects to build a model which best represented the components,” says Scott Porteous, a graduate engineer on Ricardo’s Development and Simulation team. “Then it evolved as more data became available.”

“We did a lot of work looking at the electric motor, looking at the battery, the electric currents you could expect. There were concerns over how hot the battery could get, so we looked in-depth at the current and voltages. The idea was to get as much information from the simulation as possible before the vehicle was built for testing.

“The main focus was the fuel economy. We would get out of the engine. As a range-extender, you have the freedom to operate the engine independently of vehicle speed or driver demand to optimize efficiency, but we also looked at its emissions. IE wanted to use as little after-treatment as possible to keep the costs down, but you have a trade-off with efficiency. So we looked at the drive cycles and optimized it to get the best operating strategy which would also meet the emissions requirements, keeping things as simple as possible.”

Careful control
Developing the vehicle’s control systems was key to the optimization. “Ricardo supplied the vehicle controller, which manages components on the vehicle – talking to the battery, the motor controllers, the engine management system and all the base vehicle systems,” says the chief engineer on the programme, Andrew Preece.

“Thermal systems, custom control, electrical architectures, vehicle networks, a CAN interface bespoke for this application – our core expertise is in building this sort of solution,” adds Nick Tebbutt, who explains that this can then all be taken a stage further by integrating the ideas from Ricardo’s Sentience technology (originally reported in RQ Q2/2009 – see box-out). Sentience combines telematics and telecommunication, navigation and intelligent mapping, for forward planning of the route.

“You can schedule the powertrain, for example, if it knows that there is a zero-emissions zone coming up,” says Tebbutt. “The system looks at the journey profile and rearranges the strategy to deploy the engine earlier to ensure it has sufficient charge to go through the EV zone. When in range-extended operation mode, it will also use knowledge of the remaining journey distance to ensure that the engine...”

Driving the demonstrator
Engineers from Ricardo have been carrying out the final validation and calibration work on the demonstrators at a test track facility, and this phase of the programme is now effectively over. Though some elements of the t-001 prototype may yet be changed for production, and its cabin, its interior TFT-screen displays and driver interface will all be further developed, its powertrain is functioning smoothly. A simple drive/neutral/reverse selector takes the place of a conventional gearbox, and the motor pulls away strongly from a standstill. Fine-tuning of the suspension and power-assisted steering is still on-going, but this is a very complete concept ready to move into its next phase of development.

“The transmission is single-speed, with the motor directly mounted onto the differential,” says Andrew Preece. “In addition to providing tractive force, the motor provides the t-001 demonstrator with regenerative braking.” During the next phase the braking will be optimized, implementation of an ‘eco’ mode that allows the user to trade off vehicle performance with economy would also be possible.
Intelligent energy

Sentience – conscious control

Ricardo’s Sentience research vehicle, the result of a 15-month project during 2008 and 2009, was based on a Ford Escape full-hybrid SUV, and explored the application of intelligent mapping, navigation and telecommunications to achieve a reduction in fuel consumption of up to 24 percent. Using topographical data about the road ahead and real-time information on traffic conditions, the technology analysed the best points in the route to engage electrical power, to modulate the engine load to best effect on different gradients and in different conditions, to control acceleration and deceleration to smooth out progress, to maximize the energy recuperation from the regenerative braking system, and to control the air conditioning.

Sentience (defined as “consciousness”) was integrated in the research vehicle with its existing cruise control system, and showed the potential for further implementation in conjunction with vision-based control systems such as autonomous braking or crash-sensing technologies, identification of road signs and pedestrian sensing, as well as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) devices. Yet despite Sentience’s extensive capabilities, Ricardo calculated at the time that, in a vehicle already equipped with a phone and satellite navigation, the technology could be incorporated for as little as 50 euros per vehicle.

The integration of Sentience into the t-001 project was intended from the start, says Intelligent Energy’s Chris Hiett. “Our desire was to use a clever way of controlling and optimizing the vehicle. We see it as an area where you can put a lot of options into the system, there’s a whole raft of opportunities including how you manage charging and optimizing the route – all benefits for the fleet manager.”

Emerald Automotive t-001

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>75 kW (nominal), 167 kW (peak); torque 600 km (launch)</td>
</tr>
<tr>
<td>Generator</td>
<td>50kW (nominal)</td>
</tr>
<tr>
<td>Range-extender engine</td>
<td>1.4 litre Hi diesel</td>
</tr>
<tr>
<td>Battery</td>
<td>25 kW total, lithium-ion</td>
</tr>
<tr>
<td>EV range</td>
<td>106 km*</td>
</tr>
<tr>
<td>Total range</td>
<td>747 km*</td>
</tr>
<tr>
<td>Top speed</td>
<td>130 km/h (limited)</td>
</tr>
<tr>
<td>Acceleration 0-100 km/h</td>
<td>8.5 seconds</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>2.0 l/100 km over first 200 km*</td>
</tr>
<tr>
<td>Carbon dioxide emissions</td>
<td>50 g/km over first 200 km*; 20 g/km average**</td>
</tr>
<tr>
<td>Kerb weight</td>
<td>1650 kg</td>
</tr>
<tr>
<td>Payload</td>
<td>1400 kg</td>
</tr>
<tr>
<td>Gross vehicle weight</td>
<td>2950 kg</td>
</tr>
<tr>
<td>Rear cargo space</td>
<td>5.2 cubic metres, will accommodate 3 Euro standard pallets</td>
</tr>
</tbody>
</table>

*Figures based on NEDC cycle in Ricardo simulations. **Calculated using the official UNECE 101 methodology. This is effectively a weighted average of the vehicle’s CO2 emissions in both battery-depleting (pure EV) and battery-recharging (hybrid) modes and does not account for grid electricity CO2 emissions.

Light, but affordable

“This is a different proposition to a converted vehicle with a steel body, and batteries adding yet more weight,” says Chris Hiett. “We’re managing to maintain a good payload by starting with our own ground-up design. A riveted and bonded aluminium spaceframe structure, with composite exterior panels and lightweight seats and interior components, means that the t-001 prototype weighs in at 1650 kg and its payload is 1400 kg – comparable to that of the similarly-sized short-wheelbase Ford Transit, with which it shares its braking and suspension systems, along with its stock wheels and tyres.

The use of carry-over parts is integral to keeping the overall cost of the vehicle down, though for final production other sources and suppliers could be used, depending on the global location and local market requirements. Design of the exterior has been done in-house at Intelligent Energy by chief stylist Jonathan Gould, using off-the-shelf details such as headlights where possible to further keep cost down, and including the use of easy-to-replace front and rear bumper corners and lower body mouldings.

Affordability has thus been an important aspect to the project, and whilst the range-extended powertrain and bespoke structure will add to the van’s purchase price, the selling proposition is the total cost of ownership, says Hiett.

“The total cost to a fleet user is reduced, when you take into account the whole life of the vehicle, it is more expensive to buy initially, but over a typical four-year...
cycle there are net savings, especially with fuel costs in the UK and Europe.”
Exemption from levies such as the London congestion charge, and incentives such as CO2-based taxation, all speed up the payback period.
Large fleet operators including the UK Royal Mail Group and DHL have contributed to the project, providing data on duty cycles and talking to Intelligent Energy about their needs. The aim is to build the van in batches of 10,000, manufacturing at different locations around a central hub; to this end, Intelligent Energy has formed a subsidiary division, Emerald Automotive, to further develop and market the vehicle for production. In the next 24-month phase of the programme, more prototypes will be built, and a small number will go out to fleets – initially in the UK and Europe – for field testing.
Emerald Automotive intends for the van to meet a five-star standard in the Euro NCAP crash tests, and for it to meet emissions legislation in both Europe and in North America. Further into the future, different powertrains are possible on the same flexible and scalable platform: an RE-EV with a gasoline engine for selected markets, as well as fuel cell, an intention from the start of the programme.

“In addition to providing tractive force, the motor provides the t-001 demonstrator with regenerative braking system. During the next phase of development the braking will be optimized” Andrew Preece, Ricardo chief programme engineer
How things have changed. Time was, when the diesel was a lowly technology serving a utility function in both light duty and heavy duty applications. Now, the light duty diesel is on a par with the gasoline engine and is not only frugal, but quiet, responsive and high revving. One day, the same could be true of heavy duty diesels. It is not beyond the realms of possibility that a super-race of powerful, high-revving giants may evolve in just the same way as their light duty counterparts did. And it is equally possible that a recent project undertaken by Caterpillar and Ricardo may provide the trigger. The project, entitled High Speed Diesel Engine Combustion, certainly lives up to its name.

The programme was fully funded by the US Department of Defense under the umbrella of the US Army RDECOM-TARDEC (Research, Development and Engineering Command, Tank Automotive Research, Development and Engineering Center). The demanding $6 million programme aimed, in simple terms, to establish the maximum possible performance that could be extracted from a diesel engine while meeting aggressive targets for heat rejection [transfer of heat into the exhaust and cooling system]. To ensure minimum conspicuity on the battlefield, a further challenging requirement was that the engine should emit no visible smoke.

Towards 200 hp per litre – on jet fuel too
The final specification called for a stupendous specific power output of 200 horsepower per litre, an engine speed of greater than 5500 rev/min, and heat rejection of no more than 0.59 kW for every kW of power delivered. Although at any one time in battlefield conditions the engine would use a single fuel type, it would also need to be multi-fuel compliant, capable of running on regular low sulphur diesel, high sulphur diesel and JP-8 heavy jet fuel. The Caterpillar team worked with fuel suppliers providing several different flavours of JP-8, since its thermophysical properties vary quite widely depending on location and source. With regards to diesel fuel, the team used both Ultra Low Sulphur Diesel (ULSD) containing less than 10 ppm sulphur, as well as diesel containing up to 10,000 ppm.

The power density had to be demonstrated for all three fuels - the JP8 providing its own special challenges. From a specific heat standpoint it is similar to diesel but at the same time more volatile. Despite that, it has a longer ignition delay, once in the gas phase, than regular diesel. The engine would have to run on the same calibration for each fuel, although for optimal performance the injection timing and pressure would need to be changed, something Ricardo provided help with.

Fuel injection processes were investigated in Caterpillar’s high temperature pressure vessel, a world-class facility in which it is possible to control the temperature up to 1,000 K and the pressure up to 150 bar, before injecting fuel with any mix of air and nitrogen to simulate EGR. Using this resource, it is possible to observe the evolution of a spray being injected into an environment representative of typical top dead centre engine...
conditions. Individual spray plumes can be characterized in terms of liquid- and vapour penetration, flame lift-off, and can also be compared across different fuel types and conditions (e.g. injection pressures, EGR-rates, pressures and temperatures).

**Base engine – reduced to 4.7 litres**

The chosen base engine was a 9.3 litre, Caterpillar C9 six-cylinder inline, pushrod, diesel engine, its capacity reduced to 4.7 litres by redesigning the crankshaft with a shorter stroke. At the requested power density the engine would produce close to 1000 hp. It was a big task. “The rated engine speed of a C9 would typically be less than half the programme goal of 5,500 rev/min,” say Caterpillar programme managers, Carl Hergart and Scott Fiveland, “going to a significantly shorter stroke was necessary in order to keep mean piston speeds and friction within limits at the higher crankshaft speeds.”

The work began with analysis to find out what was needed to meet the requirements. “We looked at air-fuel ratios, boost pressures, displacement and bore/stroke ratio,” they continue.

For the engineering teams involved, the sheer physics involved in handling this much power and heat was a daunting prospect. The diesel engine with the highest power density previously tested by Ricardo was the JCB444SLR, two of which powered JCB Dieselmax to a world land speed record for diesel engines in 2006. Each engine produced 750 hp at 4500 rev/min from 5.0 litres, representing a hefty specific power output of 150 hp per litre, but the Caterpillar project would clearly need to exceed that by a considerable margin.

Ricardo was given a number of tasks, including analysis of the crankshaft, con-rods, cylinder head (which would be equipped with exhaust valve seat cooling) and valvetrain dynamics, including valve springs, rocker arms and camshafts. A team at Caterpillar was responsible for developing the combustion and air systems recipe. This involved advanced simulation to define the geometry of the combustion chamber, injector configuration, and fuel system requirements. To achieve such a high output also required a high degree of ingenuity in designing a turbocharger system and it would be necessary to run the engine at extremely high cylinder pressures. Even equipping a test cell to evaluate such an engine would pose a major challenge.

“Our engineers had to adopt a completely different mindset for this project,” says Hergart. “We are usually designing an engine to last upwards of 10,000 hours but for the purpose of this project, we were talking about 50 hours for the prototype. The project had to be based around an off-the-shelf engine and another major consideration was the sheer amount of air that it would have to ingest to make the figures.” The intake manifold of the C9 is inside the cylinder head and it had been designed for around a third of the airflow we needed to push through it,” says Ricardo lead project engineer, Richard King.

**Triple turbochargers**

Pressure ratios were five to six times atmospheric pressure and these would be impossible to achieve with a single stage system for this size engine while at...
“That level of BMEP is not something you would normally expect to see outside of a Top Fuel dragster”

Richard King, Ricardo

The same time maintaining acceptable range. One of the challenges was to get the relatively large turbos, required to provide sufficient air flow to the engine, to spool up. After looking at a range of options, the Caterpillar air-systems team established that a three stage turbocharger system would be essential. The extreme boosting system was equipped with massive pipe diameters of up to 16 inches (400 mm) and the first stage was effectively a pilot turbo to get stages two and three onto boost. Once these stages were spooled up, the first stage was bypassed. The system was designed to provide the necessary air-fuel ratios without focusing too much on transient response.

The first stage of testing was carried out by Caterpillar in its own facilities using a single-cylinder engine. For this purpose, a multi-cylinder engine with five of its six cylinders deactivated (holes machined in pistons, preventing compression pressure to build and dummy injectors) was used. Such an arrangement has the added benefit of offering a stable platform with adequate balancing, as well as providing good insight into oil flow and bearing management and how much air would be needed by the full size engine.

“This drove the development of the air system,” explains Hergart. Using a single cylinder enabled the design team to fine-tune the air system requirements and also reduced the amount of air demanded by the engine inside the test cell.

Multi-cylinder testing was carried out at Ricardo’s Detroit facility where a test cell had to be specially prepared (above). One of Caterpillar’s many products that use engines similar to the production C9 (below) performance results achieved on the research engine (top right) and Caterpillar’s high temperature pressure vessel (right) used for combustion system development.

The full size engine was quite a different matter. At this stage, Ricardo took responsibility for much of the design work on the valvetrain system. It also worked on the design of the coolant rail (for the cooled valve seats) and undertook a complete redesign of the crankshaft, in addition to working on the design of and performing analysis on the coolant jacket. The Caterpillar team took on the combustion development work and performance analysis simulation, with additional input from Ricardo. This work included friction estimates at the higher engine speeds and evaluation of cylinders pressures drawing heavily on Ricardo’s database of existing engines.

Substantial modifications

The challenges were many. The Caterpillar-Ricardo team identified several key limiting factors which would need to be overcome. The turbine bypass valve actuators would not allow modulation of boost during three-stage operation. There would be a limit to the amount of fuel and its pressure that could be delivered at the fuel rail, placing an upper limit on power and fuel efficiency. All cylinders would need to perform equally to achieve optimum results. This in turn would require an even spread of peak cylinder pressures while the integral inlet manifold would also limit the engine’s ability to breathe, despite the forced induction.

Although the starting point was a production engine, there were substantial modifications needed to withstand the massive performance increase. Sodium-cooled exhaust valves replaced the standard components, the valve heads on both intake and exhaust valves were made from Ni 80 nickel-chrome steel, valve seats were cooled and the crankshaft was given an isotropic (super polished) finish. Other components received special surface finishing too, such as the con-rods and rocker shafts which were shot peened, and the valve bridges which were phosphate coated. The steel pistons were given their own cooling system by means of oil jets, injection pressures were dramatically raised and K-factor injector nozzles fitted.

Because of the extreme nature of the modified engine, ancillaries such as the water pump, fuel pumps and oil pump were handled externally. Standard pumps were not designed to operate at anywhere near such high speeds, nor could they deliver the volumes demanded. The oil flow required, for example, was much higher than for the standard engine, partly because of the increased revs but also because of additional features like oil cooling jets for the pistons. There were also two fuel pumps, each with its own ECU, so a separate unit was designed by Caterpillar to house them, powered by a 40 kW electric motor.

Multi-cylinder testing was carried out at Ricardo’s Detroit facility where a test cell had to be specially prepared. “The combination of 6000 rev/min

HD diesel
and 1000 hp is something that went beyond our current test cell capability,” says Hergart. Not only would the cell have to handle the physical size of the installation with its substantial pipework, but the dynamometer was upgraded to handle 1000 hp and a fuel system installed capable of delivering up to one gallon (4.5 litres) per minute. Heat rejection would be higher than the target at times, so cooling systems had to be capable of removing the equivalent of 1000 hp of waste heat.

**Epic performance figures**

Once up and running, some of the figures recorded were of epic proportions. With the engine stretched to the limit, peak cylinder pressures reached were over 274 bar (some 60 percent higher than a C9 engine would normally be expected to operate at) and the highest BMEP (brake mean effective pressure) was 46 bar. “That level of BMEP,” says King, “is not something you would normally expect to see outside of a Top Fuel dragster;” it was achieved with the engine developing a stupendous 1709 Nm at 3600 rev/min.

The combination of the two, believes King, is a world record. The highest power achieved was 944.6 hp at 5000 rev/min, or 201.8 hp per litre, exceeding the original brief. Even allowing for the removal of parasitic losses (due to the external electric pump system) the engine still returned a remarkable 193.2 hp per litre at 5000 rev/min. The amount of energy in play to deliver this kind of performance was equally impressive, the high-pressure turbo compressor inlet temperature reaching 330°C and the turbine inlet reaching 860°C.

With the project completed, the engineering teams had time to reflect on the valuable lessons learned, lessons that will be useful in developing real-world off-highway or military powerplants of the future. To achieve the required levels of performance, fuel systems, injection, boosting, charge air cooling and mechanical efficiency all came under the closest scrutiny. The main objective of the programme was driven by gaining a fundamental understanding of combustion at elevated engine speeds and power density levels. Clearly meeting this objective, the success of the project means the outer limits of high performance diesel engine design are perhaps better defined now than they have ever been before.

**Comparison of normalized intake mass flow and rated power**

Caterpillar C4.7, multi-cylinder engine demo (MCTE)

Programme sponsor: US Department of Defense
TARDEC [Contact: Dr. Peter Schihl]
Engine Displacement: 4.7 litres
Configuration: Inline 6 cylinders
Power density: 200 bhp/litre (149 kW/litre) demonstrated for ULSD fuel (the highest 4-stroke engine cycle power density tested at Ricardo)
Fuel consumption: 231 g/kWhr BSFC at several points below 3600 rev/min
Power density adjusted for parasitics: 193 hp/litre (144 kW/litre) @ 5000 rev/min, 1288 Nm.
Heat Rejection: best point achieved was 0.85 kW/kW at 3600 rev/min and 604.7 kW adjusted (810.9 hp).
Emissions: No visible smoke
Engine speed (demonstrated): 5400 rev/min (limited by auxiliary pump motor; design capable of 6000 rev/min)
Kinergy rail energy storage

A ground-breaking collaborative research and development project on rail brake energy recovery is scheduled to begin in the second half of this year; the project will see Ricardo join forces with fluid power expert Artemis Intelligent Power and world-leading rail technology expert Bombardier Transportation. The system to be researched is based on the use of Ricardo’s high speed flywheel energy storage technology, Kinergy, coupled with the Artemis Digital Displacement® transmission system. It is conceived as a cost-effective solution that could be retrofitted to existing rolling stock as well as incorporated into new rail vehicles.

To demonstrate a complete rail driveline incorporating this energy storage technology, the system will be coupled to a wheel-set supplied by Bombardier and will be tested on a dynamometer rig at Artemis’s facility in Midlothian, Scotland. It is anticipated that a follow-up project will progress to installing and testing the system on an operating train.

If successful, the project will enable this ground-breaking technology to be integrated into diesel trains for the first time. Furthermore, it can be tailored to suit various operating philosophies, including alteration of the engine demand to enable it to operate closer to its optimum brake specific fuel consumption, thus saving fuel and reducing carbon dioxide emissions. The system may also be configured to use stored energy to augment the peak acceleration of the vehicle and thus increase the operational flexibility of older rolling stock.

“While we are already evaluating the Kinergy in a commercial bus application, this project will be the first to deploy this very promising, cost-effective and efficient mechanical energy storage technology in a rail application,” said Ricardo head of rail vehicle technology, Jim Buchanan. “I believe that with its combination of the Artemis high-efficiency hydraulic transmission technology and Bombardier’s established position as a leader in rail vehicle design and construction, this project has the potential to demonstrate a highly compelling fuel saving and performance enhancing solution, equally applicable to retrofit installation or incorporation in new rolling stock.”

“As a global rail technology leader, Bombardier is continuously looking to challenge and improve the energy efficiency of its products,” said Paul Roberts, Bombardier chief country representative, UK & Ireland. “We are proud to announce the collaborative project with Artemis Intelligent Power and Ricardo that aims to deliver a cost-effective solution to recover and re-use energy normally lost through braking on diesel trains – an industry first. The project will enable us at Bombardier to further support our customers in their continuing drive to reduce energy use and CO2 emissions and help towards supporting improvements in the long term operational viability of legacy diesel fleets.”

Passenger Car

Chery CVT

Ricardo has built upon its long-standing collaboration with Chinese automaker Chery – a collaboration which saw the two companies work together to develop a 50 strong fleet of hybrid vehicles that were used for transportation during the 2008 Beijing Olympics – and has provided support in the development of the CVT system launched in the new Chery E5 vehicle.

The work was carried out through a collaborative engineering programme that involved engineers from both companies working together in both China and the UK. The scope of the programme included the software development process definition, control strategy implementation, and validation. Ricardo worked with Chery to enhance development process maturity, in particular in the area of testing, including tools and techniques. Support was also provided by Ricardo for hot and cold climate vehicle calibration development testing, which was led by Chery. The product calibration was specifically targeted at delivering the unique feel and quality of response that is demanded by customers within the Chinese domestic market, and thus distinguishes the product from other imported systems.

“We are extremely pleased to be able to reveal our role in supporting Chery with the development of its new CVT product,” said Ricardo Asia president Gary Tan. “This highly successful engineering programme demonstrates very clearly the manner in which Ricardo is able to provide the very latest in automotive technology to Chinese customers, while also providing the crucial technology transfer benefits.”
Low carbon vehicles

Hong Kong environment minister visits Ricardo

Mr Edward Yau, Secretary of State for the Environment in Hong Kong, visited the Ricardo Cambridge Technical Centre with a major trade delegation as part of a European fact-finding mission in April.

The visit was arranged by Cambridge Cleantech, the members’ organization supporting the growth of environmental goods and services or “cleantech” companies in the Greater Cambridge area. The Hong Kong delegation visited Cambridge to both explore the range of environmental solutions being developed in the city and to discuss the opportunities for partnerships and joint ventures involving cleantech companies in the region.

“There is an increasing demand for innovative low-carbon vehicles from countries around the globe and we were therefore delighted to host Mr Yau and his delegation,” said Dr Roger Thornton, Ricardo director for hybrid & electric vehicles. “We were pleased to be able to show the delegation our innovative powertrain technologies including a demonstration of several hybrid and electric vehicles outside the Ricardo Cambridge Technical Centre.”

Ricardo has announced the signing of a co-operation agreement with China’s Wuxi Fuel Injection Equipment Research Institute (WFIERI) covering a range of engine technologies and market development opportunities in China. Originally formed in 1980 and now part of the First Auto Works group, WFIERI has a long-standing reputation in the research and development of internal combustion engine fuel injection systems and associated technologies. Under the terms of the co-operation agreement announced in May this year, WFIERI will provide support to Ricardo in its efforts to develop its rapidly growing presence within the Chinese engine manufacturing industries.

At the same time Ricardo will assist WFIERI by providing technology-focused consultancy services and support based on Ricardo’s extensive experience of engine development for international markets.

As the international consultant partner of WFIERI, Ricardo engineers will visit WFIERI frequently in order to exchange views on advanced technology and development strategies being adopted throughout the global automotive industry. In doing so Ricardo will in particular provide its views on the facilities, methods and technologies that are most appropriate to the Chinese market and to WFIERI’s business requirements. Both Ricardo and WFIERI envisage that their co-operation will lead to wide ranging collaboration on advanced technology programmes over the coming years.

“We are very pleased to be able to sign this agreement with Ricardo, marking the start of a new phase in the collaboration between our two companies,” said Zhu Jianming, director of WFIERI. “WFIERI shares Ricardo’s focus on technology development and we look forward to a highly successful, enduring and mutually beneficial business relationship.”

Helping Shengrui establish UK technical centre

Elsewhere, Ricardo has also signed a Memorandum of Understanding (MoU) with Shengrui covering assistance in the establishment of a UK technical centre for the leading Chinese tier 1 automotive supplier. Weifang Shengrui Power Machinery Technology Co Ltd is a successful independently held supplier of engine components to the automakers and engine builders in the domestic Chinese market as well as to the leading international manufacturers.

The company’s strategy of developing advanced technology transmissions and driveline systems was assisted significantly in mid-2009 when it commenced its collaboration with Ricardo on the development of the advanced 8AT 8-speed automatic transmission.

The new MoU announced today will see the collaboration between Ricardo and Shengrui enter a new phase, as the two companies seek commercial opportunities for future product development projects. It is intended that these will cover further engineering developments of the Shengrui 8AT transmission – including, for example, hybrid applications as well as possible lower torque and stop-start variants. More generally it is also envisaged that Ricardo will provide broad-ranging support to Shengrui in the establishment of a virtual Shengrui-UK Engineering Centre.

WFIERI and Ricardo executives at the signing ceremony in May. The co-operation agreement covers a range of engine technologies and market development opportunities in China.
Scomi Rail to collaborate with Ricardo

Scomi Rail Bhd of Malaysia, a subsidiary of Scomi Engineering Bhd, has announced an agreement with Ricardo plc to collaborate in the development of a new driveline system. Ricardo’s world-class driveline design and development expertise will complement Scomi’s capabilities in the design and manufacturing of monorails, light rail vehicles and metro systems.

Scomi is a leading international provider of public transportation solutions through the design and manufacture of coaches, rail wagons, monorail systems and special purpose vehicles. Its GUTRA (Scomi Urban Transit Rail Application) straddle type monorail system is particularly attractive to fast-growing cities where transit corridors are limited in space and dense in nature.

“We are extremely pleased to be working with Ricardo on this project, which integrates Scomi’s acknowledged international leadership in rail systems innovation with Ricardo’s expertise in world-class transmission and driveline technology,” commented Suhaimi Yaacob, president of Scomi Rail. “Scomi and Ricardo share a common vision to deliver high-level quality products to rail operators – products that help improve the consumer’s travelling experience. Our partnership with Ricardo will allow us to further enhance our products to cater to the growing and changing needs of rail systems across the world.”

“This engineering partnership is a further demonstration of the breadth of the Ricardo rail engineering capability,” added Ricardo head of rail vehicle technology, Jim Buchanan. “We now have a proven capability spanning all types of vehicles from high-speed fleets to mass transit, and from conventional steel wheel/steel rail to alternative systems, and we can deliver this on a truly global basis.”

New US business development VP

David McShane has joined Ricardo Inc as vice president of business development, bringing more than 20 years of broad-based executive leadership and business development experience in a variety of commercial and technical roles. Most recently, McShane served as executive vice president at International Battery, where he was responsible for all aspects of the company’s engineering and business development activities for its lithium ion energy storage systems. Previously, he was president and CEO of Wellington Drive Technologies, where he was responsible for all aspects of corporate development including raising capital, profit and loss, and sales and marketing. McShane has also worked for Capstone Turbine Corporation, Wavepower Ltd and The Technology Partnership.

“David is a strategic addition to the team, whose experience will provide a significant boost to Ricardo’s sales growth and commercial success here in North America,” said Kent Niederhofer, president of the company’s US subsidiary Ricardo Inc. “His expertise will support our goal of establishing Ricardo as the leader in engineering and technology consulting services to many industries, including automotive, and to be seen as a strategic partner to companies at a worldwide level.”
Gain a thorough understanding of the subject from the experts

Ricardo is a leading global multi-industry engineering provider of technology, product innovation and strategic consulting.

With almost a century of innovation and automotive heritage to its name, Ricardo has been responsible for many breakthrough technologies and products that have transformed the way we live today.

Our courses are developed by our experts for anyone looking to enhance their own understanding. They are designed to transfer professional and detailed knowledge gained from years of experience. Past attendees range from entry-level to director level, who are from OEMs, fuels and lubricants companies or suppliers to the automotive or related industries.

For more information about our current seminar programme or to discuss individual company-specific training requirement, please contact: seminarinfo@ricardo.com

Seminar programme:

Automotive Transmissions Fundamentals
11-12 July 2012; 14-15 November 2012
A two-day seminar covering the fundamentals of automotive transmission technology. The seminar will cover the main types of automotive transmission and is aimed at engineers who wish to gain a broad understanding of transmission technology, applications and future trends.

Internal Combustion Engine Fundamentals
17-18 July 2012; 16-17 October 2012
Two one-day seminars covering the fundamentals of gasoline and diesel engine combustion and technology. The seminars are aimed at engineers and scientists who wish to gain a broad based knowledge of engine technology, and who wish to broaden their understanding of engine combustion, emissions and related issues.

Introduction to Life Cycle Assessment
07 November 2012
This one day course is ideal for anyone who wants to understand what Life Cycle Assessment (LCA) is and learn the process for conducting a LCA study. It will help you understand how to interpret the results from a LCA study and begin to apply a life cycle philosophy when you return to your organization. The course includes a mixture of case studies, lectures and practical workshops all developed from the Low Carbon Vehicle Technology Project (LCVTP).

Problem Solving Workshop
08 November 2012
This one day course is ideal for anyone who wants to adapt a structured approach to solving problems. It will present Ricardo’s seven step process, which will help you see through the symptoms to tackle the root cause, thus making sure you implement the correct solution. The course includes detailed notes, tools and examples that you can apply when you return back to the workplace.

Introduction to Hybrids & Batteries for Hybrids
21-22 November 2012
A two-day seminar discussing recent developments in battery technology for hybrid, plug-ins and electric vehicles. Covers the latest in electric motive technology and an overview of recent trends and advances in battery pack technology, the key enabler of the electrification of the vehicle network.

“Excellent set of notes. Nice number of staff presenting.”
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