LOTUS ENGINEERING

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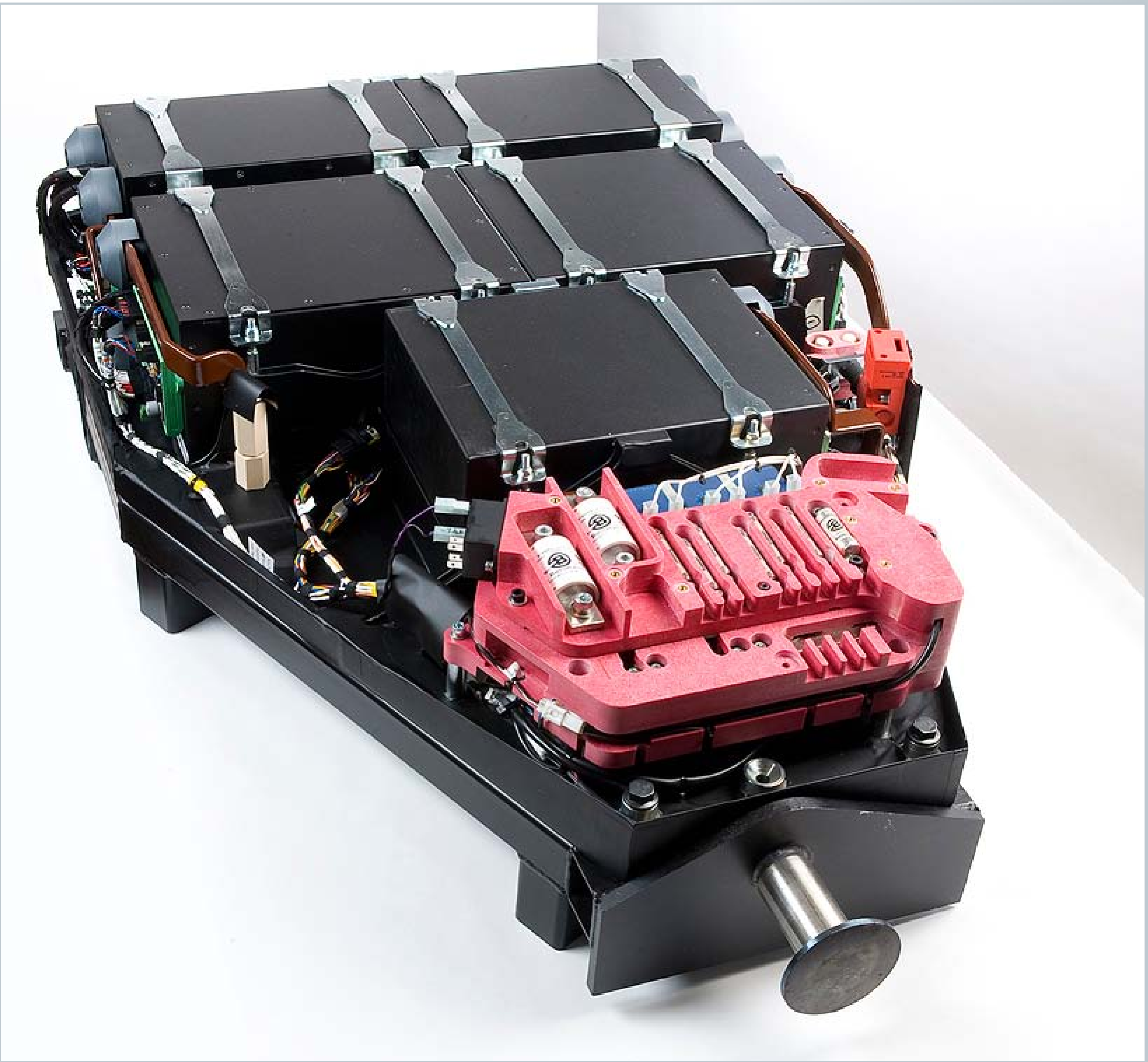
The official e-magazine of Lotus Engineering



Battery Pack Integration in a Vehicular Environment

Electric Motors and Drives for Propulsion

Feeding the Omnivore Engine on Gasoline, Ethanol and Diesel

The Effect of Hub Motors on Vehicle Dynamics

Autumn 2010

ISSUE 38

Contents

Welcome

Hard work is leading to success all across Lotus and for our engineering division the dedication and vision of our teams continues to reap rewards.

Our recently completed study into viable medium volume lightweight engineering approaches has generated much interest from the industry. More pleasing, however, the Air Resources Board in California has recognized the importance of the study and Lotus Engineering has now been commissioned to carry out a detailed design and analysis of the vehicle architecture. Gregg Peterson concludes his technical report on the first study inside.

Turning to engines, we have now reached an important agreement with Fagor Ederlan to take the Lotus Range Extender to production and elsewhere the testing of our Omnivore concept has arguably exceeded our own expectations. The research team was always confident that the paradigm shift to our novel yet simple, affordable, 2-stroke variable compression design could be cleaner and far more efficient on gasoline and alcohol fuels than four-stroke technology. However it even runs on diesel, and with the ability to start from cold on gasoline and alcohol in HCCI mode, without the need for spark, it raises the possibility of a future multi-fuel engine without the need for an ignition system. More on the results in this issue.

Finally, I was at the Goodwood Festival of Speed recently, a fantastic event with all manner of classic, sports and racing cars thrilling huge crowds. As well as Lotus's extensive display of its own cars, the festival was also the first public drive of the hybrid fuel cell taxi. I'm incredibly impressed by both the performance of this zero emission vehicle and, perhaps more so, the integrity of the integration and packaging of all the different systems that has been achieved by the team. I'm grateful that Henri Winand of Intelligent Energy, the providers of the hydrogen fuel cell technology for this taxi, has kindly been the subject of this issue's industry interview.

Enjoy the read.

Robert Hentschel

Director of Lotus Engineering

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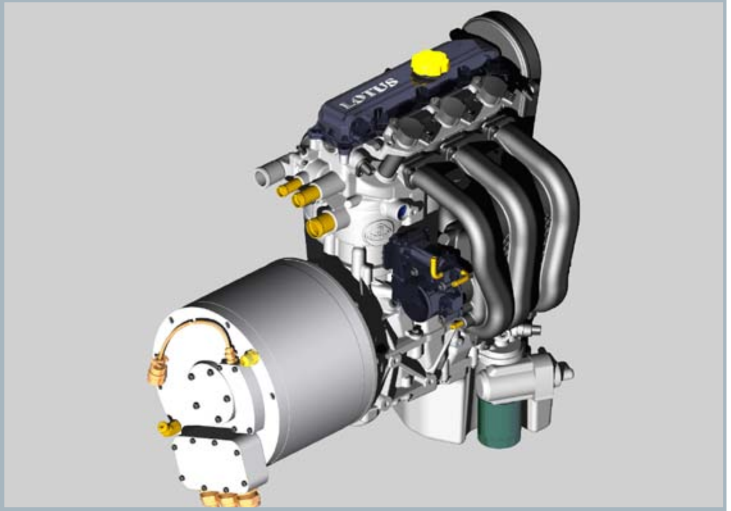

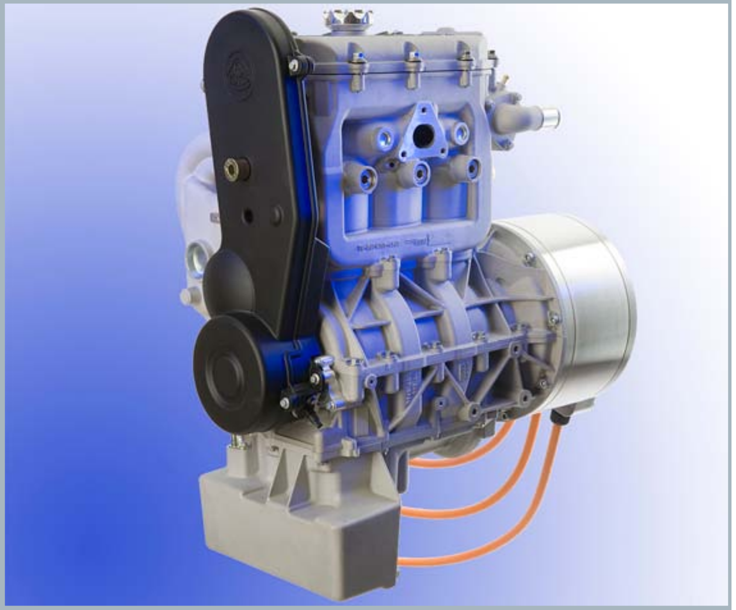

Lotus Range Extender Engine set for production

A collaboration between Lotus Engineering and Fagor Ederlan will develop the Lotus Range Extender Engine for series production.

Lotus Engineering and Fagor Ederlan, part of the Mondragon Corporation Cooperativa, the biggest co-operative group in the world, have completed a joint technical and market study analysing the best route to production for the Lotus Range Extender Engine. The study has culminated with an agreement for Lotus Engineering to develop the engine for series production and sale by Fagor Ederlan for the global automotive market.

The three-cylinder, 1.2 litre Range Extender engine from Lotus Engineering has been designed specifically for series hybrid vehicles and the production engine will offer a fast route to market for manufacturers wanting to source a dedicated range extender. The high efficiency, low mass design will enable low emissions vehicles to be produced cost effectively across a wide range of hybrid vehicle applications, as already demonstrated in both the Lotus Evora 414E Hybrid and the PROTON Emas concepts, which were shown at the 80th International Geneva Motor Show this year.

Source: Lotus Engineering

The people have spoken: Let the cars do the talking

Readers of prestigious German car magazine "Sport Auto" have voted the New Lotus Elise (MY2011) and the Exige S as the "Most Sportiest Car" in their respective categories in the magazine's 2010 awards. Stable-mates the Elise SC MY2011 and the Evora also managed podium finishes.

The awards come just weeks after the brand new Lotus Elise MY2011 was launched to a strong reception from the media, many of whom chose to focus on the low emissions of just 149g CO2/km and the class leading fuel consumption. The Elise received an incredible 29.8% of the reader vote in the category of open sports cars up to €40,000, resulting in the sought after 'Most Sportiest Car' title.

And it's not only the Elise models that were recognised in the awards, the high performance, lightweight Exige S was also victorious in the category of Coupes up to €50,000. The Exige stole an even better percentage of the vote with 34% of all readers pushing it, placing it nearly 20% ahead of its nearest rival in the class.

Lotus cars were nominated in two further classes: Coupes up to €100,000 and Cabriolets up to €60,000. The Evora finished second in the Coupes up to €100,000 just missing out on the top spot by a fraction with the Elise SC coming in third in the Cabriolets category just 0.8% behind the second car.

Source: Lotus Cars

LOTUS ENGINEERING

The New Lotus 125 and the "Exos Experience by Lotus" – an Elite Club

The Lotus 125 is an exclusive ultra high performance F1™ inspired race-car complete with Cosworth 3.5 litre GP V8 engine producing 640bhp linked to a six-speed semi automatic gearbox with paddle shift.

A bespoke carbon composite with nomex and aluminium core chassis with carbon composite panels contribute to a super light weight of just 560kg resulting in a phenomenal power to weight ratio of nearly 1000 hp per tonne.

Unlike a Formula One car however, an army of technicians and mechanics is not required to start the engine and keep the car running. The start button is all the driver needs to press to get going.

Purchasers of the Lotus 125 will be able to chose from a stylization of a classic Lotus livery, the Exos (explained below) concept design, or as an option, request their own, bespoke livery.

The 'Exos Experience by Lotus' is a new concept for these most exclusive owners and members to improve their race craft and engineering prowess, learn how to set-up a car working with a race engineer, focus on mental and physical fitness and enjoy a driving experience quite literally out-of-this-world. A team of engineers, aerodynamicists, tyre specialists and experts from every field have the specific aim of delivering the optimum performance vehicle. But it is not just the performance of the vehicle which will be optimised, the driver will be brought up to a high level through an F1 level fitness programme including nutrition, strength and fitness training and through driver training from former Lotus F1 drivers to raise the customers' skill levels to F1 standard.

The 'Exos Experience by Lotus' will be held at European circuits with first class facilities, like the famous Paul Ricard Circuit in the south of France, and the Autódromo do Algarve, Portimao in Portugal.

Each event will be structured to enable the driver to hone their skills allowing them to develop as a more complete driver and experience a near facsimile of a Grand Prix weekend. They will be advised on all aspects of car and driver performance to ensure that they benefit fully from the ownership of a Lotus 125. Lotus' team of driver coaches, technicians and physiotherapists will be at their service throughout the event: helping to improve race-craft, technical understanding and preparation for the physical strains of driving. The 'Exos Experience by Lotus', will provide a unique opportunity to extend driving skills in a safe but challenging atmosphere.

Source: Lotus Cars

*Exos = Exosphere - a reference to the earth's outer atmosphere - the exosphere - where space begins and G-forces lessen where atoms are on ballistic trajectories and the lightest gases including atomic oxygen reside.

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Industry News

just-auto editor Dave Leggett reviews some of the past quarter's news highlights:

FIRST DRIVE: Nissan's voltswagen makes good impression

The buzz over electric vehicles has been gaining more traction lately as important model launches get nearer. Renault-Nissan's CEO Carlos Ghosn has made no secret of his belief that electric vehicles have a major role to play in the near future and the company has been a leading investor in new product. The Nissan Leaf is a fully electric vehicle that hits European markets at the back end of this year. just-auto deputy editor Graeme Roberts has driven the vehicle and talked to Nissan staff about the initial marketing strategy.

http://www.just-auto.com/news/nissans-voltswagen-makes-good-impression_id105275.aspx

GERMANY: BMW 'Megacity' makes extensive use of CFRP

It's still a few years away from production, but BMW revealed that its upcoming Megacity electric car will employ carbon fibre-reinforced plastic (CFRP) for the body shell. It's a move that is sure to be watched with interest by the whole industry, especially in terms of the manufacturing process and the resultant cost curve.

http://www.just-auto.com/news/bmw-megacity-makes-extensive-use-of-cfrp_id104967.aspx

US: Tesla and Toyota to develop electric RAV4

Tesla Motors has signed a deal with Toyota Motor Corp to start developing an electric version of the RAV4. With an aim to market the EV in the US in 2012, prototypes will be made combining the RAV4 compact SUV model with a Tesla electric powertrain. Tesla plans to produce and deliver a fleet of prototypes to Toyota for evaluation within this year. The first prototype has already been built and is now undergoing testing. Toyota announced in May that it would invest US$50m in California-based Tesla and jointly develop electric models.

http://www.just-auto.com/news/tesla-and-toyota-to-develop-electric-rav4_id105145.aspx

Industry News

US: Fisker completes purchase of former GM plant

Another West Coast start-up EV company, Fisker Automotive, announced that it has finalised its purchase of a former GM factory where it will build plug-in hybrid electric vehicles. The southern California-based company is now in full possession of the 3.2m square foot Wilmington Assembly plant in Wilmington, Delaware, for which it paid Motors Liquidation Company (MLC) US$20m.

http://www.just-auto.com/news/fisker-completes-purchase-of-former-gm-plant_id105163.aspx

GERMANY: VW to build electric Golf by 2013

Meanwhile, Volkswagen Group revealed plans for a number of electric models including an all-electric version of its Golf model by 2013.

http://www.just-auto.com/news/vw-to-build-electric-golf-by-2013_id105154.aspx

RESEARCH ANALYSIS: Toyota leads in full hybrids, but others are following

Is that it for hybrids then? Not exactly. There are plenty of full hybrids in the pipeline and they will continue to play a role in providing low-CO2 solutions.

http://www.just-auto.com/analysis/toyota-leads-in-full-hybrids-but-others-are-following_id105218.aspx

JAPAN: Nissan unveils its own hybrid system

Nissan said its first hybrid model will nearly double the mileage of its petrol-engined equivalent, while keeping costs down with a simple, single motor system. The company is launching a petrol-electric Infiniti M sedan, called Fuga in Japan, late this year. Nissan claimed said its one motor, two clutch system would achieve far better fuel economy, at a much lower technical cost compared with hybrid leader Toyota's two motor system.

http://www.just-auto.com/news/nissan-unveils-its-own-hybrid-system_id105002.aspx

Industry News

US: GM to use new a/c refrigerant from 2013

Still on the broad global warming theme, GM said it will introduce a new “greenhouse gas-friendly” air conditioning refrigerant in 2013 models in the US, claiming it would keep vehicle interiors as cool as today while reducing heat-trapping gases in the atmosphere by almost 100%. Yes folks, it’s a 99.7% improvement on the measure of ‘global warming potential’ (GWP) with the new refrigerant.

http://www.just-auto.com/news/gm-to-use-new-ac-refrigerant-from-2013_id105200.aspx

JAPAN/GERMANY: Fuso claims twin clutch transmission first

Fuso claimed to be the first truck manufacturer to introduce a double clutch automatic transmission for commercial vehicles. Called Duonic, the transmission combines automated driving with the advantages of a manual transmission, Fuso said.

http://www.just-auto.com/news/fuso-claims-twin-clutch-transmission-first_id105252.aspx

US: Wayne plant to be Ford’s manufacturing benchmark

On the manufacturing front, Ford said that its Wayne assembly plant in Michigan, home of the 2012 Ford Focus, will become the company’s ‘most flexible high-volume manufacturing facility in the world’. Wayne is one of three truck plants in North America that Ford is revamping to make fuel-efficient passenger cars. The plant will build the new Focus and an electric variant beginning next year with more models coming in the future. One up for Michigan.

http://www.just-auto.com/news/wayne-plant-to-be-fords-manufacturing-benchmark_id105300.aspx

US: GM crash dummy ‘retires’ to Smithsonian

And finally, a story a little off the beaten track. A General Motors crash test dummy whose 15 years of service included scores of full-vehicle crash tests and a host of special assignments will spend a peaceful retirement in the Smithsonian’s National Museum of American History. The donation of 50H-1, an Anthropomorphic Test Device, or ATD, is part of a museum initiative to collect materials related to technological advancements in the auto industry to improve safety features.

http://www.just-auto.com/news/gm-crash-dummy-retires-to-smithsonian_id105106.aspx

Source: just–auto.com editorial team

Battery Pack Integration in a Vehicular Environment

Modern vehicles have many systems and a simplistic view would be to consider each of these systems as separate and independent. However, as we strive for more and more energy efficiencies, particularly when it comes to hybrid and electric vehicles, it becomes more important to manage power and energy storage by making sure the systems are integrated with each other and work together in the best possible way.

At the heart of the hybrid or electric vehicle is the battery system and this has many characteristics and it is necessary to have a full understanding of these in order to design and integrate a battery pack in a vehicle. Key characteristics are, firstly, the specific energy (usually expressed in Watt-hours per kilogramme) which has an impact on the physical weight and size of the battery pack and, secondly, specific power (expressed in Watts per kilogramme) which relates to the power level the battery can deliver. Ideally, selecting a battery with the highest figure on both merits presents the best solution. In practice, this is not always possible. There is often a need to balance the ratio between energy and power to arrive at a practical solution.

At a battery cell construction level, optimising for power can be achieved using thinner active layers on the electrodes and stacking more of them – less internal resistance and therefore more power. This is important for hybrid vehicles where power is more important than capacity.

Optimising for energy is where a thicker active layer on the electrode does increase internal resistance but increases the capacity for discharge, therefore storing more energy – so here, capacity takes the priority and is the important factor for electric vehicles.

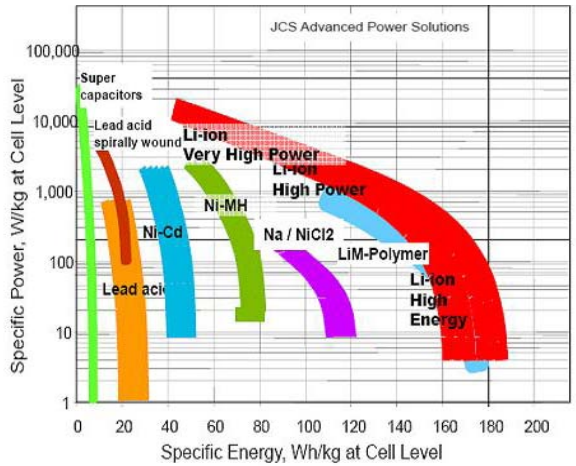


Figure 1 Specific Power versus Specific Energy of Various battery chemistries

The temperature range and impact resistance have a bearing on safety and reliability and this is where we start to have to manage 'trade-offs' between different characteristics. For example, some cell chemistries are inherently more stable than others but for a given level of energy or capacity, the battery may be larger and heavier.

The life expectancy of a pack can be improved by operating the cells within a narrow band of State Of Charge but this will decrease the usable capacity therefore impacting the vehicle range. By understanding these characteristics we can now start to specify and source the cells from cell manufacturers.

At a practical level there are three main types of cell – prismatic, cylindrical and pouch (sometimes referred to as coffee-bag cells). It is more straightforward to package cylindrical and prismatic cells in a battery system, however the trade-off will be volume and the number of cells to integrate and manage. For example the Electrical Storage System fitted in the Tesla Roadster is made up of 6831 cylindrical cells – the type that can be found in laptops and other consumer goods. Clearly design, integration and management of this number of cells is a significant task.

Whatever type of cell is chosen, consideration must be given on the mechanical design and layout of the pack. The cells must be mounted in a way that withstands the vehicle dynamic forces such as lateral acceleration or braking deceleration, shock loading coming from the suspension system and of course a vehicle crash event. It is not a simple case of just packing the cells into a metal box.

To a large extent, safety issues can be mitigated by developing an intelligent thermal management system and a good battery management system (BMS).

The thermal management system can be complex, but it is necessary to keep the cells within their normal operating temperature range. Generally, cells will not accept charging at temperatures below freezing so a heating system may be included for vehicles that are operating in cold climates. The chemicals and components within a cell start to degrade at high temperatures so the thermal management system should be developed to cool the battery system.

There are many different kinds of battery management system but the basic principle is to always make sure the cells operate within their specifications.

Figure 2 Cell options for vehicle battery packs

The BMS must be integrated into the battery pack and will take on multiple roles to ensure the pack always works efficiently within its design parameters. Generally, a number of cells will make up a module. This could be 8 cells or more, with a local BMS monitoring board. A number of modules will be connected together and will form the battery pack with a main or master BMS unit communicating with each of the local units.

Though manufactured to tight tolerances, cells connected in a series configuration tend to drift out of balance over time. Some cells will experience capacity fade and manifest an increase in impedance. This renders a battery pack only as good as the lowest quality cell in the circuit. What is required is a BMS that balances the cells to maintain a near equilibrium voltage across the entire series battery string. For hybrid electric vehicles, this cell equalisation process is much more critical compared to pure electric vehicles.

To use a case study as an example of integration, the fuel cell series hybrid London Taxi co-developed by Lotus Engineering demonstrates the practical application of a high voltage battery system integration process. There are a number of steps that are fundamental to the design. Firstly, the design requirements were defined. This is where vehicle performance targets such as acceleration, maximum speed and driving range were analysed to calculate the energy throughput, power delivery and torque requirement. Through design iterations, the appropriate drive system and energy storage was specified. This then set the voltage, power and energy content of the battery system.

The practical constraints now come into the equation. For this vehicle, there was a requirement that there were no changes to the interior passenger space. This meant that we were limited to the space under the floor to package the battery system. In addition, only minimum changes to the steel chassis were permitted. With the specification and constraints defined, the battery pack could then be designed.

Analysis showed we needed a 14kWh battery capacity having a 70kW nominal power with a peak power requirement circa 100kW. In total, 7 modules comprising of 14 cells per module made up the battery pack. To meet the multi objective design criteria, a Lithium Ion Nickel-Cobalt-Manganese chemistry was selected. Cell management and protection was achieved via localised BMS units in conjunction with a top level vehicle control system. In total, the 98 cells connected in series form a battery pack having a voltage of 363V with a BMS channel monitoring each individual cell.

In conclusion, there are many different cell chemistries and characteristics and a full understanding of these is required to design a battery pack and manage the interaction of the battery system with the other vehicle systems – both electrically and mechanically. Managing the many trade-offs will create an optimum solution but it's more than likely this will be application specific. There is little or no chance there will be a standard solution that applies to more than one vehicle or platform.

Figure 3 London Fuel Cell Taxi battery pack assembly

For the auto industry there are a number of real world challenges that are new and potentially life-threatening. On the mechanical side of things there will be battery system solutions that weigh hundreds of kilogrammes that need to be assembled safely into a vehicle. On the electrical side we are assembling battery packs that store a lethal amount of energy. Training programmes for the auto industry are being developed with this in mind.

The integration of the battery system with all the other vehicle systems is really important to create a vehicle that is not only fit for purpose but works in the most efficient manner. An important aspect of this in a hybrid vehicle will be managing the power delivery from a number of sources and to do this effectively will require maximum use of the on-board energy storage.

Source: Phil Barker, Lotus Engineering

Intelligent Energy is a leading clean power systems company specialising in the application of fuel cell technologies in a number of industrial sectors, including automotive. just-auto editor Dave Leggett caught up with CEO and Executive Director Dr Henri Winand.

Dave Leggett: Can you summarise the nature of your company's operations?

Henri Winand: We describe ourselves as a clean power systems company. We are focused on engine technology, specifically fuel cell technology, that enables our customers in different market segments to have a more efficient and cost-effective way to bring the next generation of engines to the market. Fuel cell technology is very versatile, so the application of our fuel cell engine goes from consumer electronics – such as small portable devices – to combined heat and power to applications on two and four wheels. It is very versatile.

The unique selling point of our technology builds on this versatility to yield more efficient manufacturing, that is highly recyclable and cost-effective – if done well. We're dealing in electricity with fuel cells so you can motorise it and it's very versatile as a result.

DL: So the same principles are involved, with some common elements, whatever the application?

HW: Yes, that's right, so the fuel cell engine that is in the taxi we have developed also shares core building blocks with what's in the combined heat and power systems we have developed, and the aircaft systems. And the consumer electronics technology we have

developed, scaled up, that's what we use in the scooter.

DL: Where are the main commercial applications for fuel cell technology right now?

HW: Okay, our business model is that our customers scale-up their manufacturing operations themselves to take the technology to market – so some are in the public domain, some not. The earliest applications are back-up power – grid support in places where economic growth is very high and there is a requirement for more distributive power for electricity. Secondly, for consumer devices where people have demand for energy on the move but do not necessarily have the opportunity to recharge as much as they would like. And also on systems on wheels like scooters where you don't need a lot of hydrogen fuel and you are largely utilising existing infrastructure – gas deployment essentially.

DL: You are clearly involved in a variety of different types of application, but are there any that seem more suitable than others to the technology in an innate way – perhaps due to size of device, energy density or something like that?

HW: Like any engine technology, you always need to do your analysis on a well-to-wheel basis looking at the whole value chain to see what is the most appropriate technology. Our technology is called the Proton Exchange Membrane (PEM) and it's particularly versatile due to high power densities, modular construction and low temperature of operation – below 100 degrees Celsius. It has very specific advantages – it's a high efficiency system that it is particularly good where you are need to cycle it a lot. So if you think about the car it's good for that because you can switch it on and off very quickly. There are quick transient responses. And you don't have all the materials issues you have with high temperature operations of say a few hundred degrees. And it's particularly good where the consumer is going to be close to it, you could put your hand on it and not burn yourself.

Another thing is that space can be an issue and our proprietary technology has been designed to be compact. So, in the case of motor vehicles, it can retro-fit into existing chassis, as we have shown with case studies – which also deliver a range and rapid refuelling that consumers will recognise. And we are talking slight modifications without having to go into the body-in-white and change things which is, of course, very expensive.

DL: So what are the main advantages of your technology from an automotive application point of view?

HW: Very simply, it is very compact on a weight and volume basis, so it can fit into places where competing fuel cell vehicle systems would not fit. And it has been designed from the outset for mass markets. It takes about twenty years to make a good engine, from the time you think you're going to go to market to the time it does. The four founders who are still with the business had the idea of how to make a cheap fuel cell design in 1988. So if you roll the clock forward 22 years, that's why we are growing quite rapidly now, with commercial activity rather than R&D.

It is mass manufacturable and we are talking about processes that manufacturers understand and recognise. It is compact and highly efficient.

If you think of an internal combustion engine, you have to have a piston cylinder which is your chemical reactor, so to speak, and around it you need timing belts, pumps, alternators, heaters and so forth. The fuel cell engine is, in a sense, no different – you can think of the fuel cell stack as the chemical reaction – the piston in the cylinder. The parts around that, the water pumps and things are important for reliability. Our system has 20%-40% fewer bits than any competing system, which means far higher reliability and more compact again.

DL: Is the technology very expensive?

HW: Scale and volume are obviously important to answering that. Our technology is designed so that when you make it at volume it is no more expensive than standard technology. How do we grow the motive market from a standing start? Our focus is on back-to-base fleet vehicles where you can grow on total cost of ownership as opposed to the standard retail model for ordinary customers. With the total cost of ownership approach we can focus on cities where the drivers have a requirement for range and quick refuelling time, which conventional electric battery vehicles can't deliver, and where vehicles with zero-emissions in use are also sought.

DL: Taxis might be a good example?

HW: Yes, taxis and other types of urban delivery vehicle or indeed any type of logistics business that comes with critical targets on emissions. The upside is that they can have a vehicle they recognise as being a fully functional vehicle with very short refuelling time and a full operating range.

DL: And refuelling is in a closed loop?

HW: Yes, back-to-base refuelling. For vehicles operating on two-wheels with 300g of hydrogen you can do more than 200 miles. And the infrastructure is largely the existing infrastructure of gas, that gas companies already do. Cars, however, need more fuel and that usually calls for a larger refuelling station – and of course if you went for consumer markets immediately, you would have a very large infrastructure deployment on your hands.

DL: Infrastructure is an issue then?

HW: It is a much bigger issue if you go straight for the consumer with cars. If you start with scooters and target fleets with larger vehicles it can be gradually rolled out. If a fleet vehicle does 200 or more miles a day and is typically never more than 50 miles from a refuelling pump back at base, then the infrastructure is perhaps one station that serves a whole fleet.

And it is important to remember that all fuels come with an infrastructure cost.

DL: And you think we're just looking at fuel cell powered scooters rather than cars for consumers for the foreseeable future?

HW: Yes, for the early days, but what is very interesting is that the dynamics of the market are changing quite a bit, since Germany made its announcement in September 2009 for increased hydrogen transport by 2015.

Interest in fuel cell powertrains for vehicles is ramping up quite rapidly because of that.

It's a significant move. If you just concentrate on small vehicles in cities not driving many miles that fails to address the national picture of vehicle usage that includes larger vehicles driving long distances. So, to step up, you really need to have something that consumers will recognise in terms of operating performance and range, refuelling time. And that requires careful thinking in terms of how you roll out the infrastructure and how you manage that. But it's early days.

DL: What sort of pace of growth do you see ahead for fuel cell powered vehicles? What kind of timescale are we looking at?

HW: Let's look at what the German government said last September. They want hydrogen fuel cell vehicles for consumers to be launched by 2015. That seems to be a timescale that the OEMs and infrastructure players have taken note of.

As I have said, our speciality is to take an existing chassis and modify things slightly. But with a different powertrain and to get the qualification for that, including certification, for users to start to scale-up on manufacturing, we're looking at a cycle of about four years. I would say that between now and then you start to scale up with the fleets – between 2011 and 2013/14, and then go consumer later on.

DL: And you see the mass-market for cars eventually going over to fuel cells within the next thirty years?

HW: Yes and most likely sooner than that. When you look at different energy vectors – biofuel, hydrogen, electricity and so on – it strikes me that the world of energy is actually fairly simple.

There are three things, in particular, to look at:

1. Where are the energy buffers – in the tank, car, petrol station or somewhere else?

2. You look at the regulatory framework;

3. The capital and operating expenditures in the context of well-to-wheel lifecycle costs.

When you analyse the key drivers there, if you do more renewable on the power grid – which more countries are trying to do - that comes with problems of matching supply to demand according to how fast the wind is blowing. When surplus energy is generated, hydrogen is actually a very good way to store energy and quite a cost-effective one (certainly more cost-effective than flow batteries). So you can generate hydrogen from that.

And then there's the carbon capture and storage debate. Countries will use the coal they have – because unlike renewables they can switch it on and off easily, but it's not very clean. Pre-combustion carbon capture and storage can use Victorian technology to gasify the coal to form a hydrogen-enriched gas which can be cleaned using a refinery type of cleaning kit which leaves pure hydrogen on one side and CO2 on the other which you pump back into the ground. That could yield a lot of hydrogen.

I believe there are long-run trends that are working in favour of the production of clean energy through hydrogen. And an industry has to come together – top to bottom – to develop and produce the products that people want to buy, at an appropriate price – hydrogen fuel cell powered cars for example – alongside a viable supporting infrastructure.

History tells us that at various times there can be some rapid technology switches that have big implications for the way we live. Usually there are multiple factors that bring about the change, say three of four key drivers that can push a market in one direction so that things happen very quickly. Mobile phone telephony is an example. You needed cell masts and phones to kick it off. To begin it was expensive. When the infrastructure was deployed, it needed a catchment area and then cell phone operators moved in with propositions that made commercial sense by getting many users on board at point of sale cheaply. Ultimately it was a business model innovation more than a technology innovation.

Look at the regulatory framework applying to vehicles and the direction it is moving in, the growing pressures internationally to reduce CO2 emissions, governments and cities interested in cleaner technologies in all areas, including transport – where we believe we have a unique contribution to make with commercially viable technology. I think we are on the cusp of one of those technology switches.

Dr Henri Winand

Intelligent Energy, Chief Executive Officer and Executive Director

Dr Winand joined the Board as Chief Executive on 1 September 2006.

He was most recently Vice President of Corporate Venturing at Rolls-Royce plc, the power systems provider for land, sea and air.

During his time with Rolls-Royce, Dr Winand managed a power systems business, introduced new manufacturing technologies into the group and was responsible for defining and supervising the implementation of strategies for deriving additional value from the group's technology assets (involving serving on the boards of directors of some of the joint ventures in which Rolls-Royce invested).

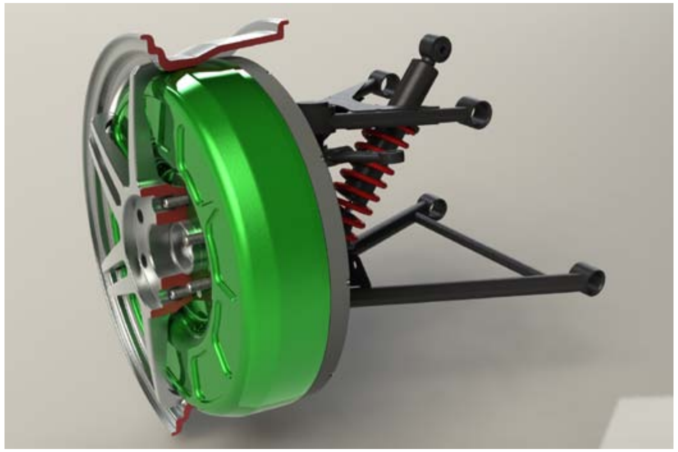
Dr Winand has a PhD from the University of Cambridge, a Masters of Business Administration from Warwick University and a BEng from Imperial College, London.

The Effect of Hub Motors on Vehicle Dynamics

The current interest in the development of EV and HEV vehicles has led to considerable discussion about the relative merits of chassis or hub mounted motors. Much of the debate has been concerned with issues of vehicle package, cost and driveline efficiency, however, the effect on vehicle dynamics has also emerged as a key factor, with apparently conflicting attributes making the advantage of one layout over the other difficult to define.

On the face of it, hub motors appear to offer real benefits over chassis mounted motors. However, the transfer of the vehicle's powertrain from the chassis to the hubs represents a significant shift in the ratio of sprung to unsprung mass and as every vehicle dynamics engineer knows, high unsprung mass is not desirable.

In the hub motor's favour, we have the advantage of independent control of drive torque to two or even all four wheels, without the cost, complexity and packaging implications of controlled differentials and driveshafts. This makes hub motors the obvious choice for torque vectoring control of the vehicle's response and stability, as well as four wheel drive traction. In addition, an EV's body package is freed from all requirements to accommodate the vehicle's powertrain, whilst a hybrid may retain the conventional IC powertrain package, with both EVs and HEVs needing extra space for batteries only.



The wheel and knuckle 'massed up' to replicate a hub motor

With such a powerful argument for the use of hub motors, Lotus undertook to conduct a unique study to evaluate the real world impact of the increase to unsprung mass.

Working with Protean Electric, Lotus took a mid segment sedan with class leading vehicle dynamics and replicated the unsprung mass and inertia characteristics of a range Protean's hub motor design by adding ballast to the wheels and knuckles.

Lotus then commenced a vigorous programme of benchmarking the vehicle dynamic performance of the 'massed up' vehicle. Lotus ride and handling engineers recorded subjective evaluations of the vehicle's steering, handling, stability, ride comfort and NVH, before collecting objective measurements of the same vehicle attributes. Finally, Lotus generated a comprehensive vehicle dynamics CAE model using their RAVEN software, and shadowed the physical benchmarking with a parallel virtual study.

A total of seven conditions were investigated, representing different levels of mass increase.

Initial subjective assessments identified four that were considered to offer sufficient separation in perceived performance to merit objective measurement.

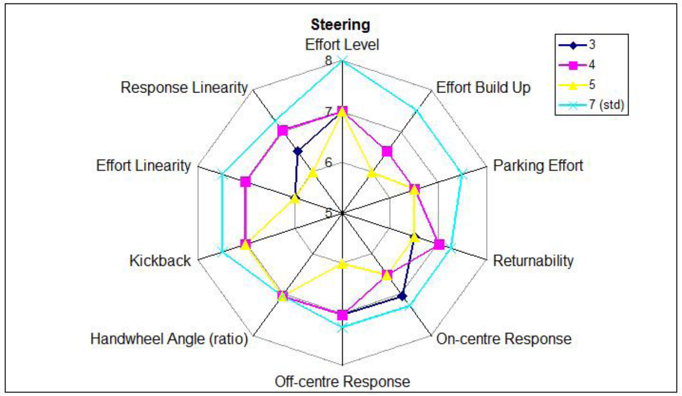
Assessment Number	Front Hub	Front Wheel	Rear Hub	Rear Wheel
3	23kg	7.5kg	23kg	7.5kg
4	15kg	5kg	15kg	5kg
5	10kg	5kg	10kg	5kg
7	Std	Std	Std	Std

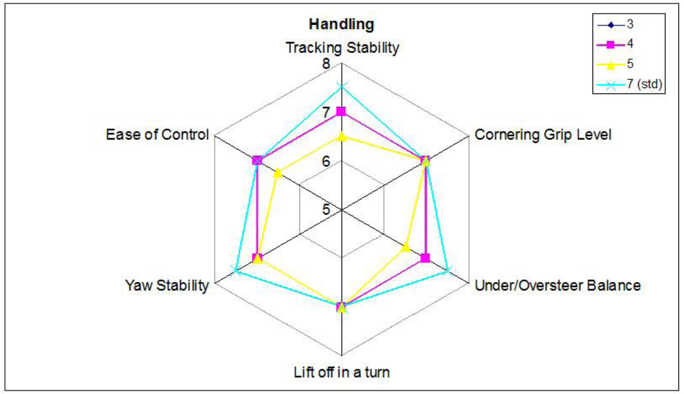
The vehicle was subjectively assessed for steering, handling and ride comfort, with detailed Vehicle Evaluation Rating scores given to different aspects of each category.

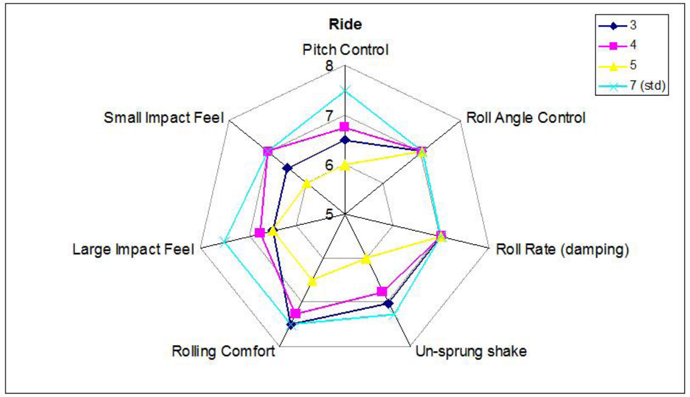
The standard vehicle was characterised by its overall very good steering attributes which lead the market sector and its good overall handling capabilities, which were considered to be responsive and well pitched within its target market. Ride comfort, whilst firm, was felt to be well controlled.

The increased unsprung mass brought about a small reduction in agility and a reasonable increase in overall steering efforts. Ride comfort with the highest unsprung mass was actually found to be as good as the standard vehicle for rolling comfort, but as expected unsprung mass shake was more apparent, which reduced the subjective rating for impact feel even though initial impacts were softer.

Contrary to expectations, the vehicle behaviour was found to exhibit the greatest degradation not when the unsprung mass was at its greatest, but at the intermediate conditions. Subsequent objective measurements would reveal the reason for this apparent anomaly.

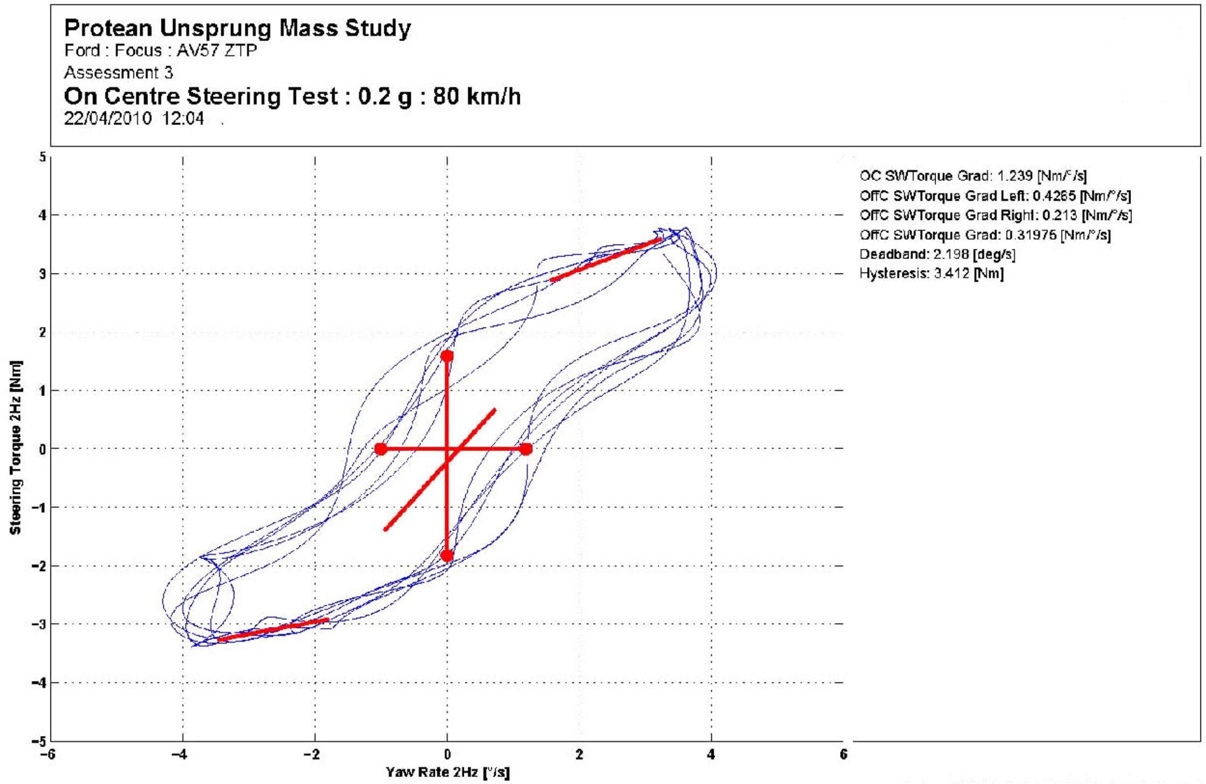






Following on from the findings of the subjective assessment, objective steering and handling measurements were conducted using an "on-centre" steering manoeuvre. This test highlights the dynamic response of the vehicle to a continuous sinusoidal steering input, the test being run at different steering input magnitudes in order to highlight non-linearitys in the vehicle behaviour.

Small differences in lateral acceleration and yaw velocity response were identified, with a slight increase in yaw response phase lag. The changes were considered to be consistent with the increase in vehicle yaw inertia associated with the mass added at each wheel. The steering torque build up was found to be less linear with the increased unsprung mass. The initial rate of torque increase relative to yaw rate was increased, but then reduced off centre. The characteristic was considered to be consistent with the combined effects of the yaw response lag, increased steering friction and increased wheel and hub inertia about the steering axis.



The Effect of Hub Motors on Vehicle Dynamics

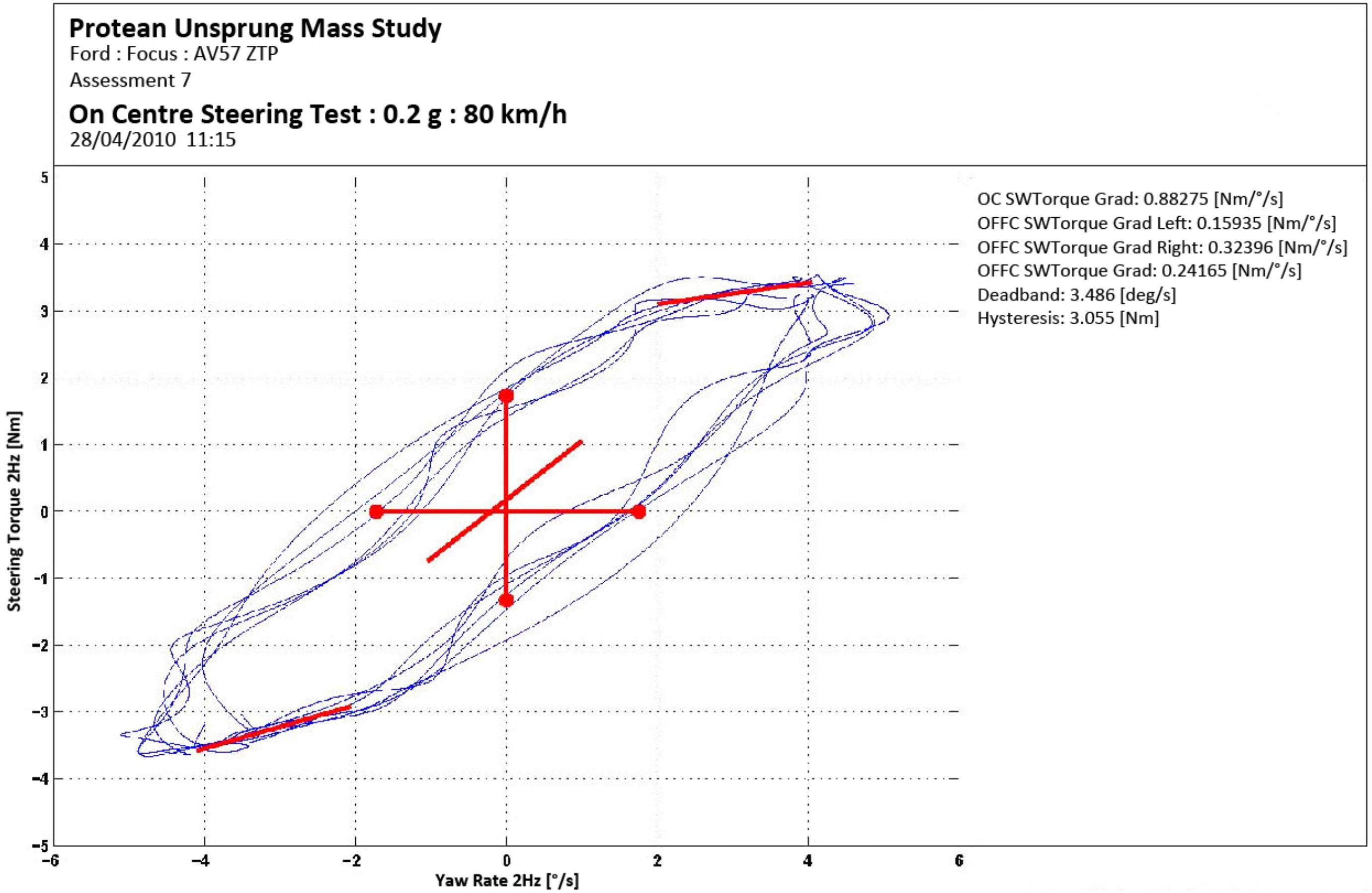
CAE models were used to better understand the dynamic mechanisms responsible for the observed differences in the vehicle responses.

Steady state cornering analysis revealed a small reduction in the vehicle's lateral acceleration limit, whilst body roll and side slip were also found to increase as one might expect to result from a 132 kg increase in total vehicle mass, whether sprung or unsprung.

Steering input swept since analysis highlighted the differences in the vehicle's transient response as a function of input frequency. Here the CAE confirmed the slight yaw response delay observed in the objective vehicle measurements. The CAE models also allowed the effects of the increased unsprung inertia and gyroscopic torques to be quantified. It had been expected that these may have a significant effect upon transient steering efforts.

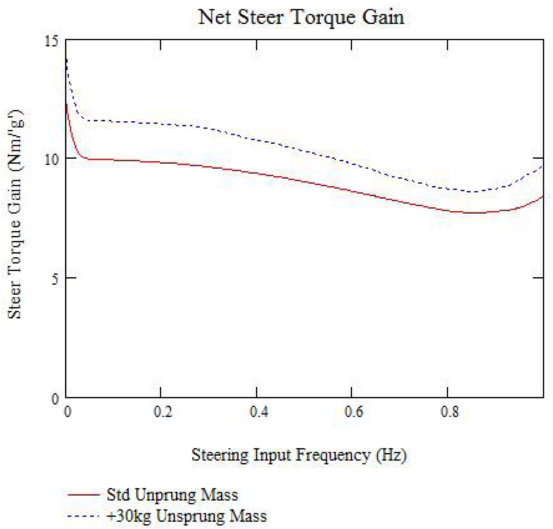
The steering torques generated by unsprung inertia are dependent upon steer velocity (the rate of change of steer angle) and wheel rotational velocity. Typical vehicle response to transient steering inputs has a bandwidth of around 1 Hz; beyond this frequency, vehicle response is completely out of phase with steering and is not within the operating range normally experienced by the vehicle user.

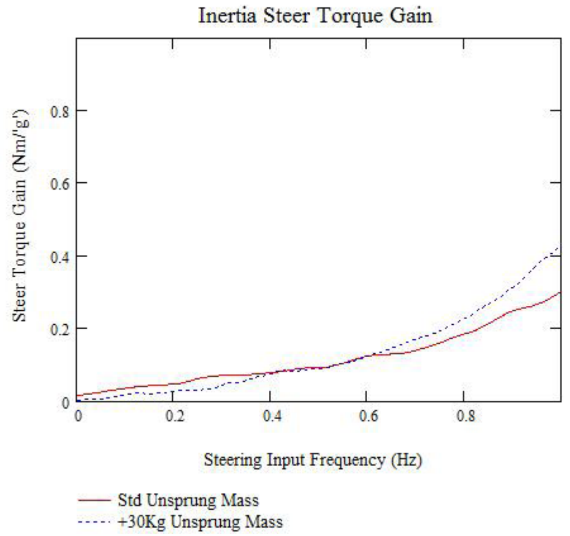
Steering wheel input rates may reach 750 deg/s in exceptional circumstances. With a typical steering ratio of 16:1, this relates to a peak roadwheel angular acceleration of 2.6 radians/s2 for a 0.5 Hz excitation. Even at this extreme steer acceleration, the transient resisting torque due to the unsprung mass inertia of a typical car is about 1.56 Nm. Reduced by the

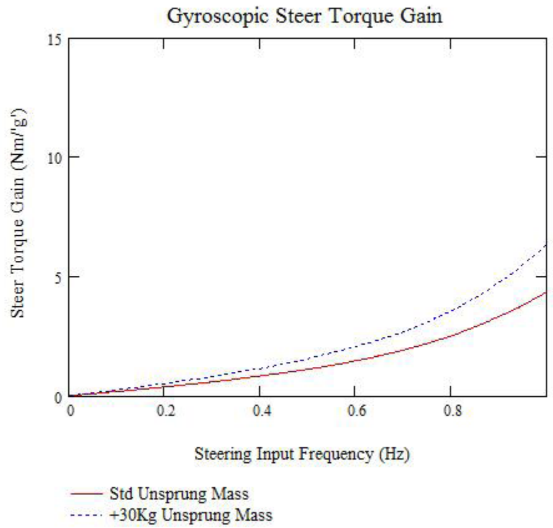


mechanical advantage of the steering gear, this results in just 0.1 Nm felt by the driver. With the added inertia of the heaviest hub motor, the contribution to steering effort from a transient steering input increases to 0.17 Nm, a figure which is still negligible compared to the total steering effort.

Gyroscopic torque is a function of both steer velocity and wheel rolling velocity. However, as wheel rolling velocity increases (with vehicle speed), steering angles and hence steer velocities reduce. Thus the typical contribution to steering effort due to gyroscopic effects rarely exceeds 0.75 Nm, whilst with the heaviest hub motor this value increases by just 0.25 Nm. So although the gyroscopic effect is greater than that of the increased inertia about the







steer axis, neither can be said to have a significantly detrimental effect on steering effort build up.

Ride comfort is the aspect of vehicle dynamics traditionally considered to be most affected by unsprung mass. Lotus conducted road measurements on surfaces deliberately chosen to excite the natural frequencies of the unsprung mass in order to emphasis any differences due to the unsprung mass increase. Accelerations were measured at the strut tops, damper rod and wheel hubs, to give a clear picture of vehicle body disturbance, as well as insight into the suspension behaviour.

The results showed a shift in the frequency at which peak hub acceleration occurred; this wheel hop frequency is primarily a function of unsprung mass and tyre radial stiffness. Although the difference in hub acceleration is clearly apparent, the resulting change in body accelerations is small and was subjectively assessed as being unlikely to be noticeable unless a direct back to back comparison of the standard and high unsprung mass vehicles were conducted.

Further testing was conducted on a concrete highway surface at higher vehicle speeds. This test highlights the vehicle's response to higher frequency excitation. From this testing it can clearly be seen that the higher unsprung mass reduces the acceleration response of the vehicle body at frequencies above the wheel hop frequency, giving improved higher frequency noise and vibration attenuation.

The final road testing used a purpose built double bump to measure the vehicle response to an impact event. The test clearly shows that the increased unsprung mass allows the suspension to absorb the bump impact better, resulting in reduced accelerations on the vehicle body.

Lab testing of the vehicle using two post rigs produced good correlation of the road measurement results, and clearly highlighted the shift in wheel hop mode frequency, from around 14Hz down to 10.5Hz. The measurements also showed the vehicle to have a powertrain vertical mode of 12.75 Hz. This provides the explanation for the subjective performance being worse for the intermediate unsprung masses rather than the highest unsprung mass. For the intermediate unsprung mass conditions, the wheel hop mode was close to the powertrain vertical mode, giving a coupling of the two modes. Normal powertrain mounting design practice would avoid coupling of powertrain modes with wheel hop frequencies.

CAE modelling was again used to correlate the findings of the physical testing, as well as providing Lotus with valuable insight into how tuning of suspension components could be use to mitigate the effects of

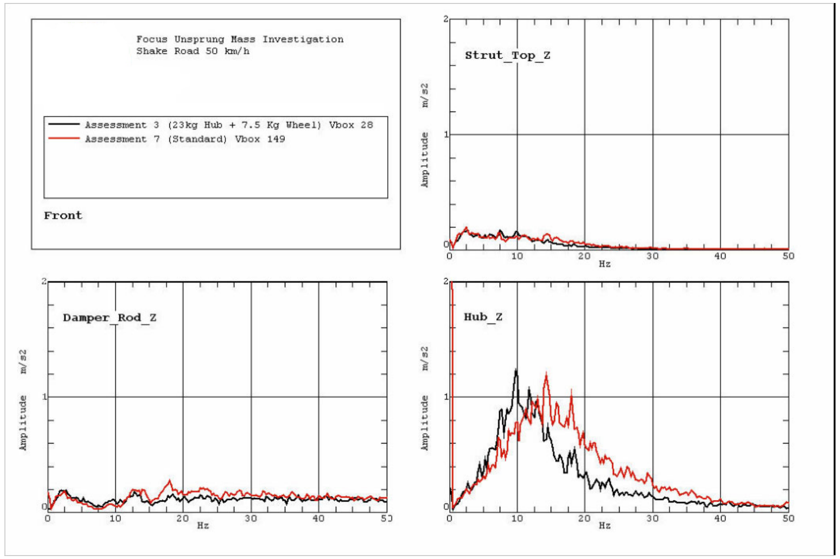
The Effect of Hub Motors on Vehicle Dynamics

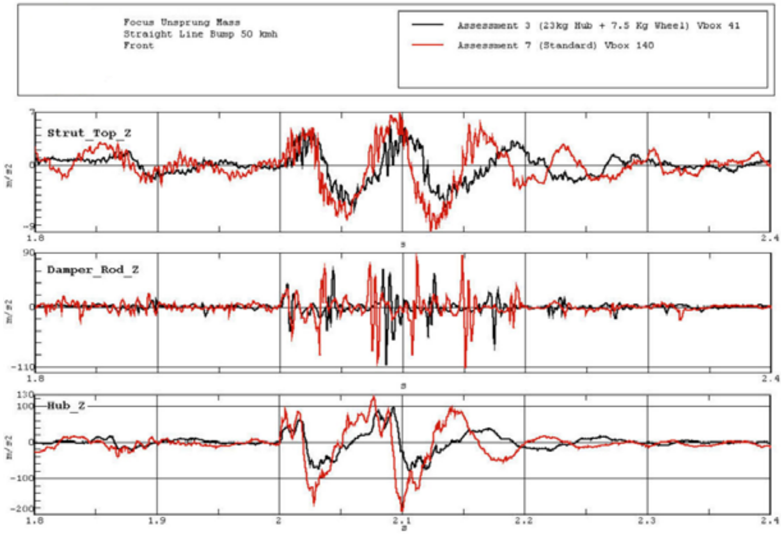
the increased unsprung mass and recover the vehicle's performance.

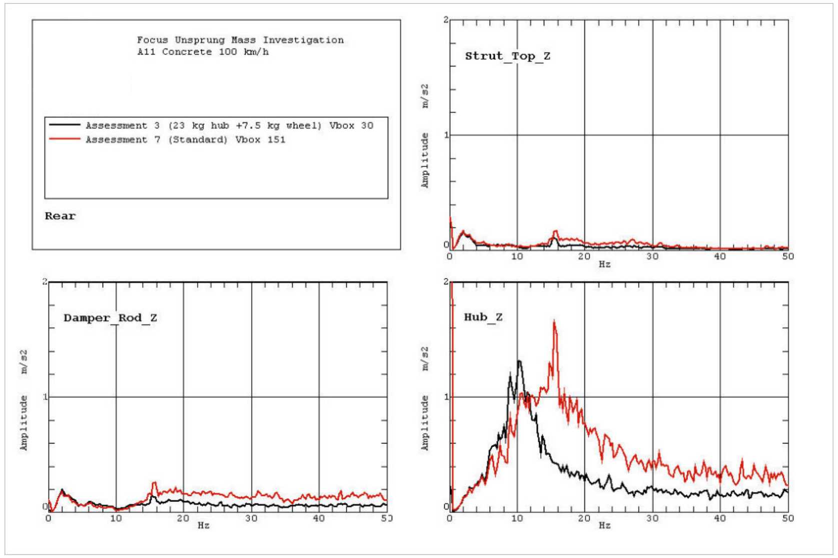
Whilst it is true to say that the vehicle dynamic performance was degraded by the increase in unsprung mass, the degree to which this was noticeable was small and could be said to have moved the overall dynamic performance of the test vehicle from class leading to mid class. Further more, the understanding gained from this study has led Lotus to believe that the small performance deficit could be largely recovered through design changes to suspension compliance bushings, top mounts, PAS characteristics and damping, all part of a typical new vehicle tuning program.

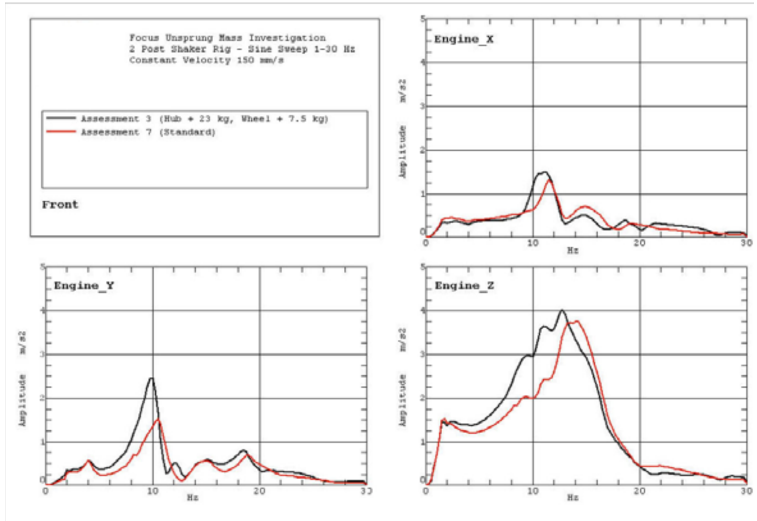
Add the powerful benefits of active torque control and Lotus's findings make a strong argument for the vehicle dynamic benefits of hub motors as an EV drivetrain.

Source: Steve Williams, Lotus Engineering









Feeding the Omnivore Engine on Gasoline, Ethanol and Diesel

'Omnivore' is Lotus's new engine concept which combines variable compression ratio (VCR), variable charge trapping, direct injection (DI) and the 2-stroke operating cycle to produce an engine theoretically free of throttling loss and with the attributes to operate in wide-range homogenous charge compression ignition (HCCI) at very high efficiency with minimal emissions.

Throttling loss reduction is currently the major area of research for the spark-ignition engine industry and is at the root of nearly all engine-based efficiency improvement (and with it CO_2 emission reduction). In 4-stroke engines downsizing, variable valve trains, stratified DI and cylinder deactivation are all operating strategies which derive their benefits primarily through reducing the amount of throttling an SI engine has to employ to operate at the low loads; even HCCI and hybridisation derive a significant portion of their fuel efficiency improvement from throttling loss reduction. Against this background and as a previous article in proActive pointed out [1], it is perhaps ironic that there is another engine operating cycle – the 2-stroke cycle – which does not suffer from throttling loss but which is to a large extent overlooked by the automotive industry while being near-universal elsewhere.

Adopting the loop-scavenged 2-stroke cycle (as invented by Joseph Day) frees the cylinder head architecture so that a simple wide-range VCR mechanism can be incorporated. A combination of VCR, the suitability of the operating cycle to the combustion mode and the use of Lotus's variable charge trapping valve system (CTVS) to control residual rate can all be used to realise wide-range HCCI, controllable across its full operating range and on a variety of fuels with dissimilar characteristics. This is the basis of the Omnivore concept and the manner in which the different technologies interact is shown in Figure 1.

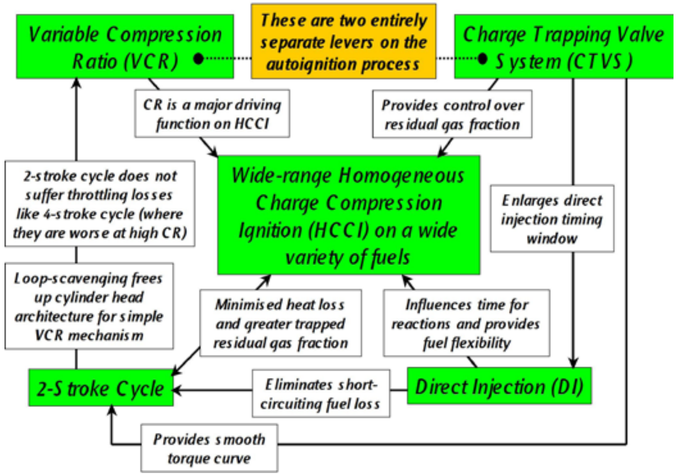


Fig. 1: Omnivore engine technology interactions. The box in the centre represents the desired outcome

To this end Omnivore was designed and built with financial support from the UK Government as part of a consortium comprising Lotus, Jaguar Cars Limited, Queen's University Belfast, Bioethanol Limited and Orbital Corporation Limited. The initial testing phase of this government-supported phase has now finished and this article will report some of the results before assessing whether the original hypothesis – that a full-range HCCI engine can be created by following a different technology path and which is capable of operating on fuels of varying characteristics – has been verified, while more-complete details can be discerned in two recent SAE papers [2,3].

The first phase of testing concerned 2000 rpm operation on 98 RON gasoline. The basic principle behind Omnivore is that all ignitable mixtures can be forced to ignition by increasing compression; indeed, this is the reason why devices such as rapid compression machines and shock tubes are used for combustion research. With Omnivore, although it has been initially configured with a spark plug, it is envisaged that in fully-developed form it will run in HCCI throughout its operating range. A sweep in load was considered important to gauge emissions and economy because, while most engines are compared at a speed and load condition of 2000 rpm, 2 bar brake mean effective pressure (BMEP), there is a frequent argument as to whether when comparing with a 4-stroke engine at 2 bar BMEP the condition of 1 bar BMEP should be used for a 2-stroke in order to account for the two-times-higher firing frequency. Providing load sweep data gives more transparency.

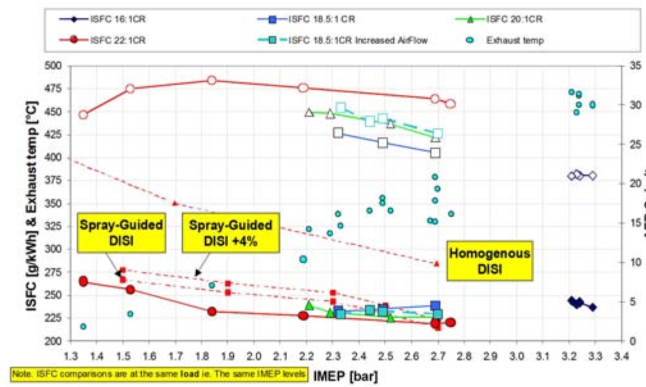


Fig. 2: ISFC, AFR and bulk exhaust temperature versus IMEP for Omnivore research engine when operating on 98 RON gasoline. Open symbols relate to AFR and closed symbols to ISFC and exhaust temperature

Having said this, all results presented here will use indicated MEP (IMEP) since the single-cylinder test engine does not drive its own pumps and scavenge blower, etc. The results of this first sweep on 98 RON gasoline are shown in Figure 2, in which, for the purposes of comparison, data from a homogeneous DI 4-stroke engine is included as well as a state-of-the-art stratified DI 4-stroke from Daimler-Benz [4].

In Figure 2 there are two lines for the spray-guided results. One represents data from reference [4] adjusted using representative levels of friction and the other is the same data with 4% added on to allow for the typical increase necessary to run the NOx exhaust gas after-treatment necessary with a lean SI combustion system. It can be seen that the results for Omnivore comfortably undercut either set of results, in places by 25%, promising the potential of significantly-improved levels of fuel consumption, especially considering that the potential improvement due to optimized levels of residual trapping has not actually been investigated yet; all of the results presented here are with fixed CTVS timing. The sensitivity of the results to CR is clear: higher CR yields better results, exactly as is dictated by Otto efficiency considerations; furthermore, increasing air flow to increase the air-fuel ratio AFR of the mixture improves ISFC (shown by the two sets of results at a CR of 18.5:1), exactly as expected.

One of the promises of HCCI combustion systems in general is a reduced requirement for exhaust gas after-treatment, because in theory the only requirement is for a simple oxidation catalyst and no NOx catalysis (itself an expensive subsystem). The emissions results associated with Figure 2 show

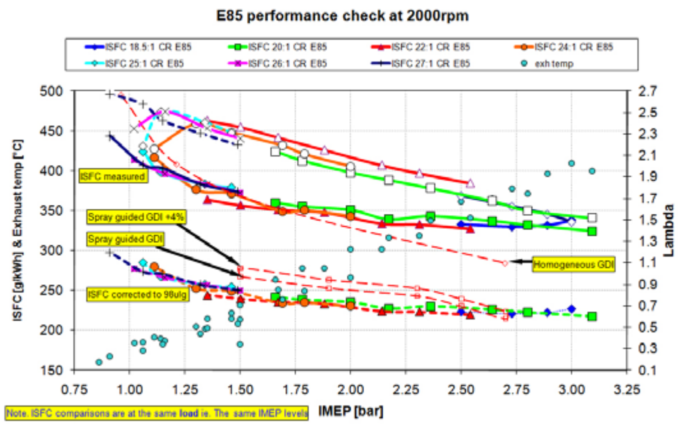


Fig. 3: ISFC, relative AFR (Lambda) and bulk exhaust temperature versus IMEP for Omnivore research engine when operating on E85 gasoline. Note lower set of ISFC results adjusts the upper set to the lower heating value of gasoline. Open symbols relate to Lambda and closed symbols to ISFC and exhaust temperature

levels comfortably below 25 ppm NOx at less than 2.2 bar IMEP (equivalent to 4.4 bar IMEP in a 4-stroke engine), with the same observations regarding potential improvements in emissions performance due to further optimization of the CTVS timing.

In addition to 98 RON gasoline, Omnivore has been operated on other fuels. Results when operating on E85 (85% ethanol in admixture with gasoline) are shown in Figure 3. Here the same general trends can be seen as for gasoline in Figure 1 except that, when corrected to the lower heating value of 98 RON gasoline, in general the E85 results are 3-6% better. Again this is a function of Otto efficiency, and is indicative of a less-autoignitive fuel requiring a higher CR for ignition, hence yielding a higher indicated thermal efficiency (ITE).

Generally NOx emissions are about 30% less than those when operating on 98 RON gasoline, and therefore in line with the emissions performance of the two fuels in conventional SI combustion systems.

The engine has also been operated on diesel fuel, with no hardware changes. This has been possible because the use of an Orbital 'air blast' injection system (initially chosen because it is a production solution for outboard 2-stroke engines) permits satisfactory atomisation of fuels with low volatility such as diesel. On this fuel NOx is generally higher than when operated on gasoline and efficiency is lower, as would be expected from the fact that diesel fuel is designed to be very autoignitive and hence has to be used at a low CR, with obvious implications on efficiency. Nevertheless, practically speaking the only other internal combustion engines capable of operation on such a broad range of fuels with such widely varying physicochemical characteristics and no hardware modifications are gas turbines. Consequently, Omnivore more than lives up to its name.

The aim of wide-range HCCI operation on different fuels would, however, only be truly realised if it was possible to start and idle the engine in HCCI; this is a primary requirement of the term 'full-range HCCI'. This has been done. The engine has been successfully idled at 450 rpm with the ignition system turned off. As the engine speed was reduced the compression ratio was increased commensurately, thus providing more compression pressure and temperature and driving the reactions to completion, despite the increased time in the compression stroke at those low speeds for heat to be lost from the combustion

Feeding the Omnivore Engine on Gasoline, Ethanol and Diesel

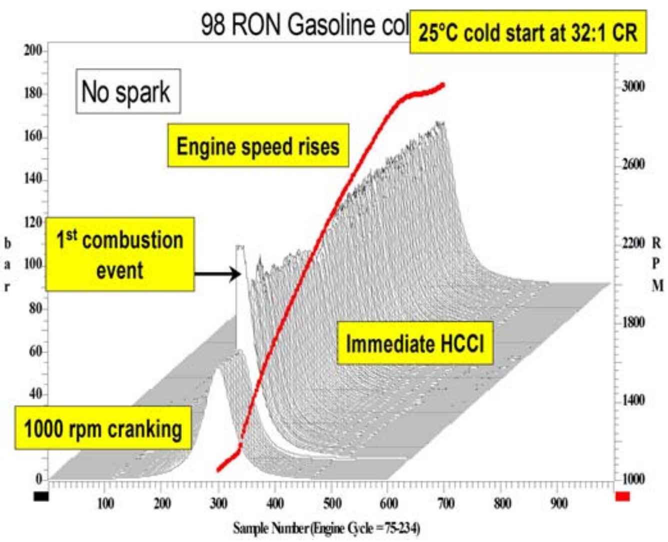


Fig. 4: 'Straight-to-HCCI' cold start in 25°C ambient conditions with the spark-ignition system disconnected for Omnivore research engine when operating on E85 gasoline

chamber. Again, CTVS timing was not adjusted, and its optimization can be expected to impact the results favourably. Assuming idle conditions of 0.9-1.0 bar IMEP, ITEs of 28-30% have been recorded, again primarily due to the increase in CR (at 450 rpm a CR of 36:1 was being used). Speeds lower than 450 rpm have been achieved but stability of air supply was becoming an issue in the test cell.

The cold start results are perhaps even more impressive. With the ignition system completely disconnected, the engine has been started from cold in a 25°C ambient by cranking and then injecting fuel at high CR. In this 'straight-to-HCCI' cold start the first cycle ignites the fuel and then, because a 2-stroke operating cycle is used, the next cycle is immediately in full HCCI. The results in Figure 4 show a starting event with 98 RON ULG in which the engine is cold cranked at 1000 rpm with a CR of 32:1, the fuel is switched on, the engine fires and then the speed rises until the engine is caught by the pre-set dynamometer speed of 2000 rpm. Consideration of the end-of-compression conditions in this test suggests that a CR of 50:1 would enable a cold start at -30°C without the use of a spark plug. From the observations made above concerning idle speed and CR, starting at lower speeds is not expected to provide insurmountable problems. Furthermore, the same straight-to-HCCI cold start has been demonstrated using diesel fuel, albeit with a lower CR of 23:1.

Thus the results for Omnivore bear out the original promise of a practical, full-range HCCI engine using a novel combination of technologies which is capable of operating on fuels with widely-differing characteristics in one hardware specification. It has already yielded better than state-of-the-gasoline-art fuel consumption together with emissions which will probably not require NOx catalysis in fully-developed form. Primarily, these engine technologies are VCR, variable charge trapping, DI and the 2-stroke cycle. Furthermore, it should be possible to delete the ignition system, representing a significant system saving in cost. The full range of CR adjustment provided in the initial Omnivore research engine (10 to 40:1, with the potential to go significantly higher) has been used in initial testing with no problems and the concept is straightforward to engineer. To all intents and purposes, the same range of CR adjustment would be impossible to achieve in a conventional poppet-valve 4-stroke engine. Furthermore, the engine is manufactured using common automotive materials and processes and therefore is not dependent on any breakthrough technologies to be productionized.

It is a genuine Omnivore, capable of being fed nearly anything combustible, and the original hypothesis has been verified.

Source: Jamie Turner

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The Lotus Interview: Darren Somerset, head of Lotus Engineering's North American operations

In the latest interview with people at Lotus Engineering, Dave Leggett speaks with Darren Somerset, head of North American operations.

DL: Can you describe the Lotus Engineering set-up in the US and how it fits in to the international organisation?

DS: From an organisational standpoint Lotus Engineering Inc (LEI) reports into Robert Hentschel at Hethel who oversees all of Lotus' engineering operations around the world.

The global engineering group's directive including LEI's is to develop a core set of services and technologies – leveraging the Lotus brand – aligning with industry demand and the major technology paradigms.

Clearly there is a big push right now for green technologies and a major part of that is driven by vehicle mass and greenhouse gas emission reductions.

To meet this industry demand, Lotus Engineering is focussing heavily on Lightweight Architectures and Efficient Performance. Two core competencies which leverage Lotus' substantial experience in the design and development of low mass innovative structures and clean, efficient powertrains.

The third core competency area is driving dynamics, which showcases not just Lotus' traditional expertise in ride and handling and chassis dynamics' technical excellence, but also how we can engineer a wider range of dynamic attributes such as aerodynamics, NVH, and ergonomics.

The fourth and newest core competency area is Electrical/Electronic Integration, which includes hybridisation, electrification and the design and development of the Human Machine Interface. This has a high growth potential in the US.

These four cores form a conglomerate of attributes which provide the skill sets necessary to deliver whole vehicles programmes.

DL: How does Lotus maintain its key engineering and brand values across an international footprint of operations?

DS: The way this has been achieved is by having a number of ex-pat Lotus Engineers supporting the technical delivery for the core competencies previously mentioned. These engineers work at all levels within LEI all of whom have had substantial experience in delivering Lotus product and third-party client powertrain and vehicle programmes back at Hethel. These engineers have been responsible for migrating traditional Lotus Engineering best practices and methodologies to LEI. Our strategy then has been to recruit local talent, bringing US expertise together with the Lotus approach. This hybrid delivery team has given LEI a unique local delivery mechanism – client focussed, commercially aware engineers capable of developing system level vehicle solutions from first principles.

With this local delivery mechanism, the ability to tap into group engineering resources and the Lotus Cars brand, LEI is in a strong position relative to its

competition. Lotus is both an engineering consultancy and an OEM in its own right so we are very aware of what it means to go from a blank piece of paper or subjective wish list. What does best-in-class for ride and handling mean? How do you quantify that? What are the objective metrics around that? How do you develop a Vehicle Technical Specification from first principles? How do you cascade that down to sub-system and the component level? Lotus can demonstrate its expertise by pointing towards over 60 years of iconic product as well as numerous third-party engineering programmes. Lotus provides tactile proof of its engineering excellence – you can subjectively feel that excellence every time you take a Lotus for a drive.

This is an extremely compelling message to deliver to our US clients. We can support OEMs with OEM best practices and methodologies; LEI engineers have a very deep understanding of system level engineering and are very multi-skilled.

The Lotus Interview: Darren Somerset, head of Lotus Engineering's North American operations

DL: What's the physical set-up of operations in the US?

DS: There are two locations. There is a facility in Ann Arbor, Michigan, which is primarily LEI's powertrain test and validation facility. That was acquired about ten years ago. That was pretty much when Lotus started to get serious about the US; by acquiring that facility we inherited the incumbent client base and a natural footprint in Detroit.

DL: Who was that acquired from?

DS: A company called MARCO – Michigan Automotive Research Company. This facility and its engineering personnel form the foundation and the linchpin to LEI's Efficient Performance and Electrical/ Electronic Integration strategy going forward and its powertrain test and validation expertise effectively provide a fifth core competence for LEI here in the US. The Ann Arbor facility has 27 dyno cells and has the capacity and fidelity to test small weed wacker engines right up to 16 cylinder diesel marine engines. For a broad range of testing applications, the Ann Arbor team have the ingenuity to get the job done. The team is working hard right now to generate a mix of high-end powertrain development services as well as highly competitive durability testing. There are about 50 personnel at Ann Arbor.

DL: And the other facility?

DS: That is in Southfield, Michigan and was set up because it was right in the middle of a triangle between Chrysler, GM and Ford. Powertrain engineering and vehicle engineering are located there. The engineering staff, in particular the powertrain team, migrate backwards and forwards between the two locations depending on programme demands. We have about 40 engineers based at Southfield, including contract staff.

DL: What's the mix of ex-Hethel engineers and local ones?

DS: I guess the ex-Hethel engineers constitute 10%-15%. But it's very much a global operation. Where possible we look to maximize Engineering's global utilisation where commercial and technical constraints permit. Some of the jobs we are bidding on right now mean that we are looking to leverage our team in Malaysia – clearly there is a big drive by OEMs to keep costs down and we have the luxury of being able to tap in to our group in Malaysia. The Lotus Malaysia team has been supporting Lotus parent company (Proton) programmes and third-party client programmes in that region for over ten years; immersed in all the Lotus best practices and methodologies. It's a great resource to be able to call on and amounts to very cost-effective off-shoring without the risk of the costly rework that can sometimes result from off-shoring.

DL: And you are seeing good signs of recovery in the US auto industry?

DS: Things are really waking up now and we are seeing some very good signs with the US Big Three. The Big Three's plight over the last few years has strongly influenced the strategic decisions of LEI. With the recession and downsizing of the auto industry around here two or three years ago there was hardly any work for us in the traditional areas, so LEI looked to migrate its engineering expertise to other industries. We have, as a result, moved heavily into the military sector.

In the last three years I would estimate that 80% of our workload has been for military prime contractors – working on programmes such as the HMMVV replacement – Joint Light Tactical Vehicle (JLTV); and the Mine Resistant Ambush Protected (MRAP) for the Prime Contractor OEMs.

DL: What sort of work would you be doing for a Humvee replacement?

DS: We have transferred all of our core engineering capabilities especially in Lightweight Architectures, Driving Dynamics, Efficient Performance and Powertrain Test and Validation over to the military business and we were fortunate enough to get on right at the start of the programmes. We have been able to provide our systems integration expertise to help ensure that subjective and objective targets – in the product profile and VTS given to prime contractors – for attributes like durability, ride and handling, manoeuvrability, mass, commonality, cost have been achieved. In all cases our multi-skilled engineers have taken the roles of technical and programme leads integrated amongst the client's resources – our personnel are treated with the highest levels of respect and have been welcomed as an extension of the Prime Contractor's key personnel.

The Lotus Interview: Darren Somerset, head of Lotus Engineering's North American operations

We have delivered numerous lightweight architecture programmes. There are highly stringent targets for mass on these vehicles. Lotus has been able to develop highly efficient total vehicle system level architectures by developing well integrated sub-systems and components, innovative use of materials and process and the application of advanced analytical techniques.

On the powertrain side of the business we have been working with a prime contractor looking at the powertain integration, design, development, validation and test of the diesel powertrain going into the JLTV.

So while the auto industry has been consolidating and planning its strategic comeback, the military sector has allowed LEI to continue its growth strategy through the downturn.

DL: Is the military work growing?

DS: No, we expect it to taper off over the next few years – for one thing there is pressure on federal budgets. Also within three years the JLTV programme would have gone into production. These vehicles have a long production run; the HMMVV has been in production for over 25 years. However, I am confident that we have built up relationships that will maintain a steady flow of military work coming in for the future. Indeed we have strong business development initiatives underway with the Special Opps division to look at an exciting niche vehicle concept.

Over the course of the next few years we'll probably see the traditional automotive business moving up to an 80% share of our work, a reversal of the current position, 15-20% we expect to be maintained as military.

DL: You are confident about the US automotive work?

DS: Well, not only is the industry in recovery from a very serious recession, but there is a structural shift to market segmentation taking place – away from relatively heavy trucks and SUVs towards lighter passenger vehicles and innovatively packaged CUVs running on alternative fuels and alternative propulsion systems. That's where we are extremely well positioned with lightweight architecture technologies, efficient performance and Electrical/Electronic Integration. Furthermore, the scale of redundancies in the industry mean that OEMs are having difficulty delivering on programmes – which has given us the opportunity to supply support directly into the OEM. Where a lot of key experienced guys retired or were laid off – in the OEMs and Tier 1s – we can now fill in the gaps or provide turn-key solutions with expertise that the OEM trusts to deliver from concept through to production.

The companies that are left, who have weathered the storm, who have a strong USP, are in a strong position. We see a bright future.

DL: And you are working with 'non-traditional OEMs' – non-Big Three for example?

DS: Yes, we are. There are a number of start-up companies – Carbon Motors for example – we have been working with; we're able to provide the engineering skills and support to start-up companies who lack the initial infrastructures – their internal resources having to ramp up in line with the investment schedule of the programme.

We are heavily involved in government-funded research opportunities and projects – particularly with energy efficiency and reduction of green house gas emissions. Most notably in April this year, LEI concluded the first part of a study, released by the International Council on Clean Transportation in California, which recognised that a reduction in vehicle mass of 38% can be achieved for medium volume vehicles (around 50,000 units a year) with just an increase in 3% in vehicle cost and a 23% reduction in fuel consumption. LEI has now begun the second phase of this programme where we will be proving out analytically the recommendations we made in the first phase.

DL: Is there a difference in culture in dealing with military customers as opposed to automotive ones?

DS: Yes, there is. One of the distinct differences we noticed was the timing on the programmes. They are highly compressed in the military. And that's understandable – there's a need in theatre for a new product to protect the servicemen and servicewomen out there and there are extreme pressures to compress the timings to get that product out there as quickly as possible. That can mean things are done in half the time on a military programme compared with a traditional automotive programme.

It does create pressure, but it has also created opportunities for us where we can expedite the timing on a programme very competitively because of our competitive strength as a systems integrator and our ability through the systems level approach for 'right first time' solutions.

DL: How do you see the challenges and opportunities in the US going forward?

DS: The short-term challenges are around the strength of financial rebound. We are seeing a proliferation of new product programmes and that's extremely exciting for us because we are strongly positioned to be involved in these programmes.

But how robust is consumer confidence out there? The industry wants and needs to get back to 14m units a year and we are still some way off that. Is the automotive industry out of this global economic crisis? Time will tell.

DL: How do you see the health of the US supplier industry?

DS: We have seen a lot of consolidation over the past decade. But we have also seen companies look for other opportunities and be astute about it – a number of key Tier 1 suppliers have also gone for military business, other industry sectors and start ups, for example, and been very successful. I think the Tier 1 suppliers are seeking out new business, diversifying where they can. There is obviously a lot of pressure on cost in the auto business still. However, the ones who are still standing are in a stronger position having restructured and right-sized. The key being in all cases if you have a strong portfolio of USPs that are in alignment with what the market wants you are in a good position.

Electric propulsion of vehicles includes two key components: drive electronics to convert battery DC power to variable frequency AC power and a motor to convert this AC power to mechanical output.

UQM Technologies is a U.S. developer and manufacturer that focuses on these components and has done so for over 25 years, ever hopeful that the energy storage problem would be conquered with some new electrochemical solution. Not that propulsion motors and drives were entirely ready for automotive primetime a quarter of a century ago, it's just that the technology was not the showstopper. They worked, but had their deficiencies. Twenty-five years ago, power electronics consisted of MosFET switches that were large for a given output and had a tendency to relieve themselves of active duty prematurely due to switch flaws. Semiconductors have vastly improved since this time and consist mainly of IGBTs for the higher voltages used within electrified vehicles. These switches are smaller, lighter and more efficient, continuing to improve today due to technology and manufacturing maturation. Also 25 years ago, permanent magnets for motors were either limited to low operating temperatures and expensive, or capable of acceptably high operating temperature and extremely expensive. This led to the selection of non-PM motors, primarily induction machines in the 1980s for vehicles such as the GM Impact, which later became the EV1. In the 1990s, however, neodymium-based magnets improved in both areas, becoming capable of operating at over 200 degrees Celsius and affordable enough to compete with induction machines. Now, IGBT-based

UQM Facility

drives and PM-based motors are the most commonly selected technologies for electric and hybrid-electric vehicles, from Toyota's hybrid lineup to GM's plug-in hybrid to Nissan's electric car. The challenges, or opportunities, confronting motors and drives now include vehicle integration, controls optimization, and production investment.

Vehicle integration relates to mounting, coupling to the gearbox, electrical interconnections, and component cooling. Mounting is vehicle dependent, but chassis mounting is adopted much more frequently than in-wheel or hub mounting of motors. Wheel motors are appealing from a conceptual point of view, but introduce cost, torque, and unsprung weight challenges. Proponents are out there, but UQM is not among them (at least not yet). Regarding cooling, water-ethylene-glycol is most commonly adopted, although some companies like Tesla are using air-cooled components. Since heat is ultimately rejected to ambient air, direct air cooling appears to eliminate a set of components, but radiators and fans are effective and inexpensive means of heat dissipation. These components can be quite small due to the efficiency of the technologies (the combined motor and drive efficiency is around 90%). Wrapping radiator-like heatsinks around the motor and onto the drive electronics package is not so easy, requires higher pressure blowers in place of fans, and can create

UQM Propulsion System (PowerPhase® 100)

component hotspots if dirt and debris accumulate on the heatsink.

Controls optimization is an active area in drives development, as the interaction between the electronics and the motor may be managed in many different ways to accomplish wheel torque. The overall objective is to sculpt the electric current into waveforms that make the motor turn, while considering the needs of both the motor and the drive. Most motors appreciate smooth, sinusoidal current waveforms. Drives appreciate minimized chopping of the DC voltage and would rather supply square waves to minimize switching. It is out of this conflict that creative solutions have emerged. UQM utilizes a method of phase timing advancement, refined and now dubbed "full wave commutation" that creates smooth, quasi-sinusoidal currents with a minimized amount of switching. The key is to design a motor with parameters (voltage, frequency, impedance) that are compatible with the method of control. The strategy allows UQM to increase the current due to lower switching losses and create higher motor power due to low current harmonic content. It is the key technology that has roughly doubled the output power for a given size system across the company's product line (75 to 125 kW and 100 to 200 kW). Other companies are designing their own strategies to balance the needs of both the motor and the drive, knowing that their separate optimized states do not overlap naturally and tradeoffs are inevitable.

Finally, the last ingredient to create markets for plug-in electrification is to make the vehicles affordable (range anxiety and large-scale infrastructure notwithstanding). Energy storage is the dominant hurdle to affordability, but other systems also have their cost challenges. Prototype components are inherently expensive (e.g. machined housings) and investments in a given design, combined with production volumes, brings these costs down dramatically (e.g. castings). The industry has been in a bit of a buyer-supplier standoff, with high costs preventing volume orders from manufacturers and no volume to bring down costs for suppliers. As industry leaders begin to see a price path into niche markets, catalyzed by decreases in energy storage costs, government incentives, and the anticipated rising cost of petrol, production investments are now being made. Public and private funds are in the kitty to help this industry move forward. UQM was a recipient of a US Department of Energy $45 million grant to invest in manufacturing infrastructure and the company raised additional private funds through a stock offering to increase this amount by $30 million. Battery makers have received higher levels of funding to invest in manufacturing. In the end, a combination of manufacturing investment, production volumes, and government incentives will establish markets for electric and plug-in hybrid electric vehicles.

UQM Technologies' most pressing role in this emerging market is to take its R&D and prototyping experience and make adjustments to bring the technology to market. Design changes and additions based on automotive needs were the first step to this transition (addressing Standards, DFMEA, PFMEA, DFM and DFA). Purchasing and outfitting a manufacturing plant was the second step, occurring in parallel with supplier tooling investments. This is where UQM finds itself now, in the middle of running off tooling and equipment in anticipation of late 2010 production launch of its 100 kW (134 hp) propulsion system. Other products will follow, as the company now provides propulsion systems rated from 50 kW (67 hp) up to 200 kW (268 hp) to propel a wide range of electric and hybrid electric vehicles.

In the foreseeable future, market penetration of electrified vehicles is very much a function of progress related to energy storage. Lithium-ion batteries dominate right now for high energy storage vehicles, and if they prove reliable and durable, large markets are anticipated if the cost of the technology drops to $500 per kilowatt-hour or lower. Most battery industry leaders believe this goal is only a few years away, and if they are right, electrification is about to move beyond the "hands off" hybrids of the present and toward "plug in" electrics of the future.

Source: Jon Lutz, Vice President of Technology, UQM Technologies, Inc. www.uqm.com

Lotus Low Mass Study for the 2020 Production Timeframe

In the last issue of proActive, we looked at the first part of a study Lotus Engineering was commissioned to undertake, investigating the opportunities for reducing mass on 2017 - 2020 production vehicles. This study was published by the International Center on Clean Transportation earlier this year.

This article reviews the second part of the study for a 2020 vehicle using advanced manufacturing and assembly methodologies feasible in 2017. The resulting vehicle architecture achieves a 38% mass reduction, less powertrain, with an estimated piece cost increase of 3%. This cost effective mass reduction is a direct result of the Lotus holistic, total vehicle methodology which utilized substantial parts integration, multi-function hardware, electronic controls and efficient load paths. Key examples of the process are provided including the BIW, interior and chassis/suspension as well as a cost analysis. The powertrain investigation was conducted separately by the U.S. Environmental Protection Agency and is included in the ICCT publication.

Methodology

A Toyota Venza was selected by the client as the baseline vehicle and was benchmarked to establish mass, dimensional and volumetric parameters as well as a Bill of Materials (BOM). These values established the component, subsystem and system level targets. The vehicle constraints included maintaining the exterior size and internal volumes as well as key occupant relationships and vision angles. The vehicle was divided into eight systems: Body in White (BIW), Closures/Fenders, Interior, Chassis/Suspension, Front and Rear Bumpers, Thermal (HVA/C), Glazing and Electrical.

Cost targets were established for all parts based on the estimated cost of the baseline components. Individual components such as lower control arms, and sub-systems such as suspension assemblies, were not cost constrained. Vehicle systems (e.g., the chassis/suspension), and the total vehicle were limited to a 50% piece cost increase relative to the baseline cost. All piece costs were relative percentages based on a baseline value of 100%.

The Lotus mass reduction methodology utilized a holistic, total vehicle approach. This was essential to meeting the mass objectives while minimizing the vehicle cost.

The design process focused on minimizing the effect of bending load inputs and maximizing section inertias to exponentially increase the component strength and stiffness. Computer aided engineering tools were utilized to verify structural characteristics. A high level of component integration was used; all parts were required to perform multiple functions. Proven structural adhesives and friction spot joining replaced traditional resistance spot welds and fasteners.

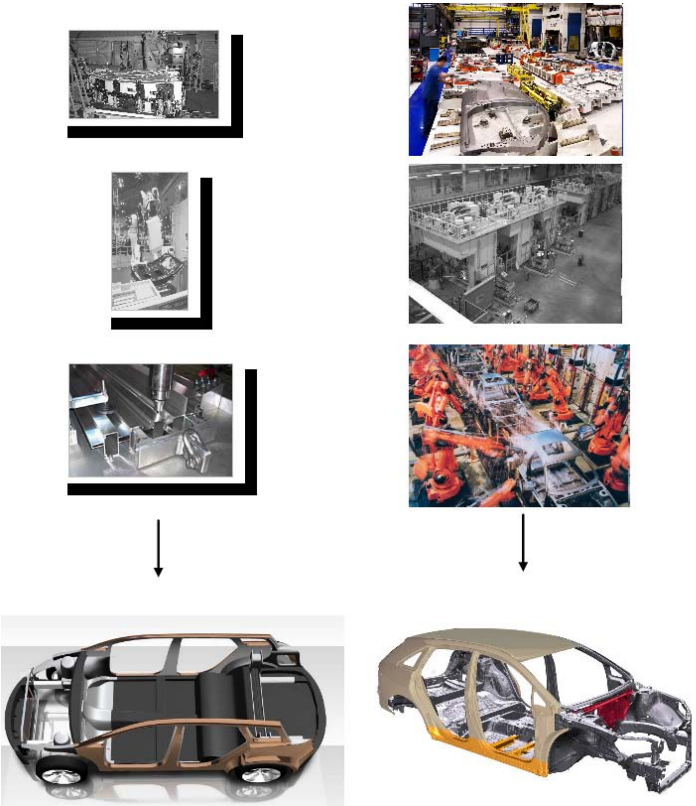
Materials from automotive and non-automotive applications were evaluated. A knit to shape digital process used for office seats was incorporated for much of the interior, including door trim and seat material. This process eliminates scrap (about 25% - 30% in traditional cut and sew operations) and offers outstanding flexibility in terms of customization for patterns, logos and color combinations. Another example of a non-automotive material was an inert gas injected plastic used to mold food containers. It reduces material density by 30%, uses less forming energy and allows nearly doubling the rib thickness without creating sink marks on the visible surface. This technology eliminates the traditional issue of needing to increase the part thickness to accommodate thicker ribbing based on analysis results. Carbon fibre, titanium, high strength steel, aluminium, magnesium and a variety of thermoplastics were also considered.

The design was driven by manufacturing, processing and energy considerations. The number of parts was reduced substantially through component integration thereby reducing the tool count. The design of the parts minimized the need for large stampings such as body side apertures which helps reduce the forming energy as well as material scrap. Programmable, robotically adjustable fixturing, computer controlled adhesive dispensers and automated low energy, low heat friction spot joining are all combined into one assembly platform that can be programmed to build body structures ranging from a sub-compact to a large SUV.

The exterior styling was carried out by Lotus at its facility in Southfield, Michigan. The design incorporated free standing bumpers to minimize low speed impact damage, reduced tumblehome (front view angle that the body side makes with the roof) to improve stiffness for roof crush as well as a substantial front crush zone for high speed impact protection.

Lotus Low Mass Study for the 2020 Production Timeframe

Figure 1: BIW Processing Comparison



2020 Low Mass BIW **Typical Steel BIW**

Mass and Cost Summary	Baseline CUV	Low Mass	Low Mass
		Mass	Cost Factor
Body	382.50	221.06	1.35
Closures/Fenders	143.02	83.98	0.76
Bumpers	17.95	15.95	1.03
Thermal	9.25	9.25	1.00
Electrical	23.60	15.01	0.96
Interior	250.60	153.00	0.96
Lighting	9.90	9.90	1.00
Suspension/Chassis	378.90	217.00	0.95
Glazing	43.71	43.71	1.00
Misc.	30.10	22.90	0.99
Totals:	1289.53	793.76	
Base CUV Powertrain Mass	410.16	Mass	Wtd. Cost
Base CUV Total Mass	1699.69	61.6%	103.0%

Table 1

System Analysis

Body in White

The BIW consisted of six modules: floor and underbody, dash panel assembly, front structure, left and right body sides and roof assembly. The BIW incorporated magnesium castings for the heat exchanger support, extruded aluminium rails, pressure molded magnesium suspension supports, a magnesium front of dash, a glass reinforced polyurethane passenger compartment floor with aluminium reinforcements and a glass filled polypropylene rear load floor. The body side apertures are magnesium with aluminium/thermoplastic inner and outer panels. The roof is an aluminium skin with cast magnesium cross bows. Many of these low mass components are either in production today or have been developed to the point where they are now installed on test vehicles to assess performance and durability.

Figure 1 to the left illustrates the basic difference in processing for the two body structures. The 2020 BIW eliminates the need for large stamping presses, replaces resistance spot welds with an adhesive secured by friction spot joints (which require a fifth of the energy of resistance spot welds and do not change the material characteristics), and eliminates steel fixtures by using robotically controlled locators. The 2020 BIW low heat bonding process does not affect the joined metal characteristics; resistance spot welding can change material properties because of the high heat.

Table 1 above summarizes the relative mass, material and cost for the 2020 low mass body vs. the baseline BIW. The 2020 low mass BIW was 161 kg lighter, a 42% mass reduction. The cost factor of 135% does not include adjustments for the 208 stamping tools that were eliminated, the simplified assembly

Figure 2

Figure 3

processing, the difference in forming/joining energy costs required to fabricate and assemble the BIW or the elimination of in-plant priming/painting processes.

Interior

The interior design, also done in-house by Lotus, eliminated many traditional features such as a stand alone instrument panel, full carpeting, seat risers, steel seat structures, steel seat springs and thick foam for the seating surface. The lower seat mounting legs served as a structural member to box the tunnel and the sill to assist in managing side impact forces. The interior design also used the HVA/C module as an integral part of the console; the module contained non-electrically heated/cooled cup holders. Figure 2 illustrates the interior and shows the seat attachment to the sill and tunnel; both are much stiffer elements than the flat floor pan. This eliminated seat risers and the need for floor pan reinforcements for the front seats. Figure 3 is an exploded interior view showing driver and passenger modules, console, carpeting and seating. The steering column module includes a driver information display, steering wheel, air bag and pedals. The passenger module includes an air bag, knee bolster and storage area. The center navigation/driver controls screen includes transmission and parking brake controls; they actuate solenoids and eliminate the need for robust mounting structures and linkages. The screen incorporates haptic feedback provisions for "eyes off" operation.

The 2020 low mass interior was 98 kg lighter than the baseline interior; this represented a 39% savings. The estimated cost factor was 96% or a cost savings of 4%. This was due to a high level of parts elimination, component integration and the utilization of non-traditional interior materials and processes.

Chassis/Suspension

The chassis/suspension mass reduction was based on the gross vehicle weight (GVW) which included the powertrain mass and the baseline vehicle payload capacity. The gross total vehicle mass reduction was 26%. This meant the load bearing components, such as wheels, tyres, springs, and control arms could be mass reduced a similar amount as a direct result of the lower vehicle mass.

The chassis/suspension system included:

- suspension support cradles
- control links
- springs
- shock absorbers
- bushings
- stabilizer bars and links
- steering knuckles
- brakes
- steering gearbox
- bearings
- hydraulic systems
- wheels
- tyres
- jack
- spare tyre (deleted)
- steering column

Front and rear gross axle weight ratings were calculated and a tyre size selected to meet the load requirements. The baseline 19" wheel diameter was used for the low mass vehicle per customer request.

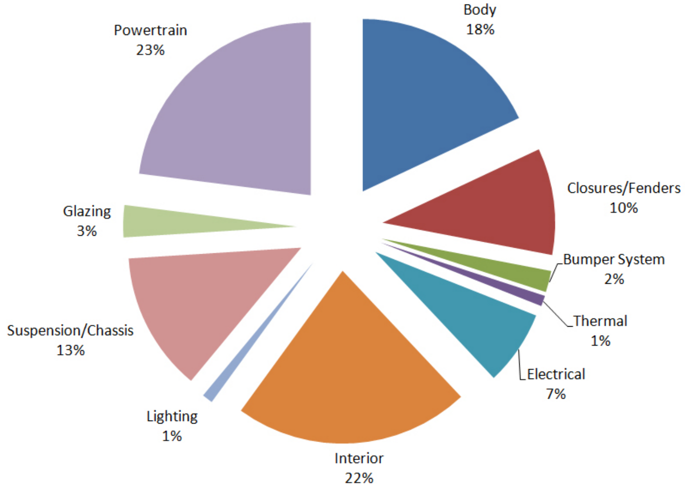
Key areas for mass reduction, in addition to the linear reduction based on the reduced vehicle GVW, included utilizing narrower tyres and wheels, eliminating the spare tyre/wheel, replacing cast iron steering knuckles with aluminium knuckles and replacing steel cradles with magnesium units. The total mass savings was 162 kg, a 43% reduction; the cost factor was 95%. This 5% savings was due to the smaller tyres and wheels, the elimination of the spare tyre and the reduced amount of material required.

Cost Analysis

The pattern of reduced costs for non-BIW systems also repeated for closures (24% cost savings) and electrical (4% savings). The bumper system cost increased by 3%. Air bags, glazing, thermal and lighting were not mass reduced for functional/safety reasons; their cost was the same as the baseline system.

A generic system cost chart (see Chart 1 below) was created based on Lotus experience and supplier feedback to provide a cost weighting mechanism. Each system cost factor was then multiplied by the estimated weighting factor, e.g., BIW = 135% x 18% = 24.3%.

Chart 1: Estimated Vehicle System Costs



Summary

The system values were summed to create a total vehicle cost as shown in Table 2 below.

	2020 Low Mass BIW	Baseline CUV BIW
Mass	221 kg	382 kg
Parts Count	211	419
Materials	% of BIW Mass	% of BIW Mass
Aluminium	39%	0%
Magnesium	32%	0%
Composite	22%	0%
Steel	7%	100%
Cost Factor	135%	100%

The Lotus holistic, total vehicle methodology utilized a high level of multi-system component integration and increased component functionality to reduce mass. The use of non-traditional components and sub-systems as load bearing elements, such as utilizing the front seat mounting structure to transfer side loads into the tunnel, also contributed to reduced mass. Robust mechanical control systems, such as the parking brake and shifter, were replaced with electronic switches and lightweight solenoids. This systematic, highly integrated methodology effectively eliminated 2 kg from every 5 kg for the systems analyzed.

The study results indicate, by using the above engineering methodology, that it is possible to offset much of the cost of an advanced low mass body structure by using a holistic, total vehicle approach to mass reduce all vehicle systems.

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