In Conversation with Professor David Greenwood

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Abstract *Professor David Greenwood offers insights into the challenges and current and future development trends in the automotive industry. Based on his broad experience in this sector, Professor Greenwood discusses a wide range of topics, such as global and UK automotive industry markets, emerging technologies in energy storage and its impacts on the environment and vehicle performance, and autonomous and future vehicles.*

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Introduction

Professor David Greenwood leads the Advanced Propulsion System team at Warwick Manufacturing Group (WMG) - the University of Warwick which covers a wide remit of related areas within Energy Storage (Battery Systems); Energy Conversion (Electric Machines; Power Electronics); and Energy Management. He leads WMG's activities as the Advanced Propulsion Centre's Electrical Energy Storage Spoke, and also provides academic leadership for the development of R&D activities within the National Automotive Innovation Centre.

Professor Greenwood is a Board Member at the Low Carbon Vehicle Partnership (LowCVP) and a member of the Automotive Council Technology Group. He is also a member of the EPSRC's Energy Scientific Advisory Committee and the Advanced Propulsion Centre (APC) Advisory Board.

Professor Greenwood joined WMG in 2014 from Ricardo UK Ltd where he was Head of Hybrid and Electric Systems, leading advanced technology projects in passenger cars, defence, motorsport and the clean energy markets. Strategic projects at Ricardo included the preparation of automotive industry technology roadmaps and research priorities for the

NAIGT (New Automotive Innovation and Growth Team), TSB and Automotive Council.

The interview

Sina Shojaei (SS): How do you see the status of the UK automotive industry and its outlook compared to the global competitors? I would also like to know your opinion about the current level of investment in research in the UK and how this investment contributes to the development of the automotive industry.

David Greenwood (DG): Let's talk about the industry structure first. If you look at the way that the global auto industry is structured, it is global industry, but there are relatively few products that are genuinely sold across the globe. So what you tend to see is that there are European focused products, US focused products, and you find products that are focused on Asia for instance. They have different drivers because the governments and the economies in those areas have different situations. So for instance the US automotive industry has been focused a lot on air quality since the 1980s, and much less on fuel consumption. Even historically, fuel consumption and CO_2 were something that the US came to relatively late. So this, combined with the driving patterns of the US customers and the ability of the US customers to afford more expensive vehicles has driven relatively large vehicles which are not particularly good on fuel consumption, but are actually very clean on emissions. And so you see petrol vehicles with three-way catalyst for most of the US. If you look at Europe, the challenge has been different. Here, we've been focused on a mix of air quality and energy/ CO_2/ climate change. And so in Europe, up until relatively recently, you saw a trend where the regulators seek to balance those things. So we saw regulations that allowed for Diesel engines to come into cars, because they had a benefit in terms of CO_2 and fuel consumption, even though they were not as good as petrol engines in terms of air quality and emissions. And that was a conscious decision by the regulators to do that, in order to balance air quality against fuel consumption and CO_2. So where the UK fits into that is that the mass market products that we produce are primarily made for Europe and sold in the UK and Europe. The UK has a thriving auto industry. We make around 2,000,000 cars every year, and about 80% of that is exported. We also make about 2,000,000 engines every year, and a lot of that is exported to go into cars across the world. So it's a very large part of the UK economy, and it is one of the few parts of the UK economy which is making good money from manufacturing. The sort of companies that we have in the UK are those that are in thriving sectors. We have very good luxury car industry - if you look at JLR, Bentley, Rolls

Royce, Aston Martin, those are global brands that don't sell huge volumes but they do sell at higher margins. So, they form a very profitable part of the industry. In addition to that, we have engine manufacturing, not just for those brands, but also for companies like Ford, who are making diesel engines here that get shipped all over the world. Besides, we have assembly plants here for companies like Nissan, Honda, and BMW. So, an enormous amount of economic activity is associated with the automotive industry in the UK. That is where we are at the moment.

What are the challenges? Well the reason we are looking at electrification technology comes back to air quality and CO_2. Those are still the two drivers for electrified vehicles. The UK is up there with the best in delivering against that. Right now, the UK has the only operational automotive battery manufacturing plant in Europe, which is Nissan's plant in Sunderland where they make batteries for electrified Nissan Leaf. They also make the car which is then exported around Europe. So actually you can say that we are a leader in electric vehicles at the moment. Certainly, this is a market that is just starting to build. The sales of electric vehicles have gone from typically 1%- 1.5% of the auto market last year, to 4% of total sales last January. And that's quite significant because when you are selling to one percent or so you are typically selling to what is referred to as 'Early Adopter' customers. These are the people who are ready to go through a bit of pain in order to have the benefits and kudos of being able to drive something which is a new technology. By the time you get to 4% you are selling to 'Early Majority' buyers - real people who need real cars that work for them practically and economically. So, this is an indication that we are reaching a Tipping Point. I think that the January figure was a bit of a blip due to sales intensive and so on. Nonetheless, the fact that we are in a situation when we can regularly see a monthly figure of over 2% is really quite significant.

All of the major brands are bringing forward electric vehicles now, including the UK brands. Obviously Nissan was there already with the Leaf. Now you see Jaguar launching the iPace, and if you look at other companies that are building here, at the moment Ford's electrification strategy isn't centred on the UK, and neither is Honda's. But we do have the ability in the UK to be building and supplying parts to their vehicles, as and when those companies are ready to move forward with them.

SS: Any other challenges?

DG: Well the main challenge is the cost of the vehicle. If you consider what goes into an electrified vehicle, clearly it's great in terms of its ability to remove CO_2 from the tailpipe, and reduce NOx emissions inside cities. The challenge we have is that the components that you need to fit into the vehicle are much more expensive than the components of conventional vehicle. As a bit of a comparison, to make the engine with its control system and its after-treatment system for the exhaust, it typically in the region of 1000 to 1500 pounds for a traditional car today, the battery alone, for an electric vehicle, is something between 6000 to 10000 pounds. So you can see there is a massive difference in the cost of the hardware that's needed. Considering that, the battery makes up 50% or 60% of the materials cost of an electric vehicle. Many consumers are just not in the position to be able to afford that technology yet. So the biggest challenge we have is making the technology more accessible, by making it cheaper.

Second to that is then making vehicles that have enough electric range to suit most people's journeys. And also building the infrastructure needed to charge those vehicles. So there are several things that all need to keep pace with each other for this to work. But the good news is that there are a lot of activity to make sure that happens. And that's happening between government and the industry, it's not just reliant on one of those two to make it happen.

SS: It sounds like you see the battery as the main challenge.

DG: Yes, at the moment definitely. It's still the biggest cost, the biggest technical hurdle. Second to that I would say it's the power electronics. And, that's about making them cheaper, lighter and easier to cool. Then next to that I say it's electric motors, understanding how to make electric motors at high volume in the quantity that we need. Here at WMG we have active research teams working on all those major technologies.

For batteries, we have a large team. Different people are leading different parts of it. We have Emma Kendrick who is leading our electro-chemicals materials group, which is looking at new electro-chemistries for batteries, Rohit Baghat's team who are looking at electro-chemical engineering, including how to build battery cells and how cells perform in different circumstances. We have Mark Ellis's team who are looking at battery systems, including how to use battery cells in a manufacture-able battery pack which can work in high volume production. In power electronics, we have Richard McMahon, who joined us from Cambridge, his team is looking at wide-band-gap semi-conductors, which includes

how we can make power electronics faster, smaller, lighter and cheaper. And a group working on electric machines, led by Juliet Soullard and John Wale, who are looking at the design of an electric motor, the materials you use and the manufacturing process – and in particular, how they all conspire to give you a machine with a particular quality, durability and cost.

SS: Will the Lithium ion technology continue to be the backbone of EV batteries, or will that change?

DG: In the automotive industry, I think li-ion is going to be with us for at least the next 8 to 10 years, and the reason I say that is to take a chemistry from laboratory scale through to something which you could buy in a car takes about that period of time. If you look at the development path, first you have to make the chemistry works in the laboratory at the gram scale of material, looking at half cells. To reach the point that the chemistry works can take a year or ten years or may never happen, so predicting that bit of the process is virtually impossible. But once you've got to that point, to go from there to the point where the material works at large scale takes around 3 to 6 years. At the end of that you have a cell with a new chemistry, which takes 2 - 3 years for the car companies to make battery pack with, and prove it is safe and durable. Overall that means is that it is very unlikely that there will be a car sold in the market, within the next 8-10 years, that uses a battery technology that we don't have visibility of in laboratory today. At the moment, we don't see anything which has reached that point. So right now, I can say with some confidence that Li-ion is going to be with us for that period.

What I can see is that there are some very promising technologies coming along which can surpass that in the future. The ones that we are particularly interested in here in at WMG are the Sodium Ion chemistry, which works a lot like Li-ion, but using a Sodium-ion rather than a Li-ion as the charge transport device, and the advantage of that is that the sodium material is much cheaper than lithium. You don't end up with a battery that is quite as high in performance as li-ion, but it's much lower in cost. And as we start to move from a position where electric vehicles are a few percent of the market to a position where they are 50% or 80% of the market, we will need those low cost moderate performance batteries. Today, we can make 600 horsepower supercharged v8 engines – and they are great, but if you look at the cars in the carpark outside, not every car has that. Because 99% of the people don't need it and aren’t prepared to pay for it. Most people are driving around in cars with a 1.0 Litre or 1.2 Litre engine, because actually that suits our needs better

and it's cheap. I think that sodium ion battery has a very interesting future in a similar manner.

SS: I read somewhere that Li-ion resources are limited as well. Is that true?

DG: Not really. If you look at the materials that go into a lithium ion battery, an awful lot of it is copper, aluminium and graphite, which are all industrial products today. Yes, we need a lot of it, but they're not resources that are currently scarce. Regards the lithium material itself, only about 4% of the mass of a battery pack is lithium. As a material, lithium is relatively abundant, particularly, in the northern parts of South America, in places like Bolivia, Chile, and Argentina, there are quite big reserves. And in terms of abundance, there is easily enough to be able to provide 20 to 30 years' worth of automotive manufacture. But the challenges are going to be how fast that industry can develop. There will be times at which we get out of pace, when the automotive demand moves faster than the Lithium manufacturing can build up, and vice versa, there'll be times when there will be more lithium in the market that the automotive industry needs and vice versa - so, you'll see some price volatility on lithium in the future. It might become a commodity market. The key point is that at the moment we don't have any good processes to recover material from used batteries, so the challenge that we have is that whilst we are OK for now, if we don't develop a process by which we can recover that material and re-use it, we're going to run into a problem in 20 years' time - that we've taken what was an abundant material, and lost it. At the moment, if you look at the route by which those batteries are disposed of, the lithium ends up getting incinerated and we can't afford to do that forever. So, we need to develop processes to recover those materials on an industrial scale.

SS: I'll come back to your point about recycling batteries, but before that, is any of the material used in motors and power electronics scarce?

DG: Yes, the magnets. The main materials that we use are copper and steel. But for many of the electric machines that we build we use rare-earth magnets, typically using neodymium or samarium. The issue interestingly is not with the scarcity of the material, it's with the economy of producing it. So at the moment, the rare-earth industry is dominated by China, and in various points in its history they have introduced trade barriers in order to maximise their revenue. So we have seen a lot of price volatility in rare-earth magnets, and by volatility I mean multiplying the price by a factor of 20 in the space of less than a year in some cases. That is very difficult for the industry to deal with so,

there is a big effort at the moment, looking at whether we can move away from rare-earth material in designing switch reluctance and induction machines - or if we can move to cheaper, and more readily available material like ferrite and still get similar levels of performance.

SS: Going back to the issue of recycling, how do you see the recycling technology progressing, in terms of batteries specifically?

DG: We have projects at the moments on how we should recycle batteries in particular. If you imagine, every electric vehicle is going to have a battery that weighs around half a ton, and inside that there are valuable materials - although we have spent the last five years to take out as many of the valuable material batteries as possible, in order to make batteries cheaper. What that means is that if you are a recycling company, there is less valuable stuff in a battery. And actually at the moment the cost of getting to the material is significantly higher than the value of the materials themselves. So the net value of a battery at the end of its life is currently negative. It will cost about 500 pounds in landfill taxes, to dispose of a battery. Even though it has these materials inside that you might think of as being valuable.

SS: There might be some environmental incentives that encourage that recycling

DG: Absolutely. If you look at what's happened to the car industry, there's regulation in place now called the 'end of life directive', that says about 95% of the vehicle needs to be recyclable. At the moment, that doesn't apply to batteries in exactly the same way, and we have no way of doing it. I think what we will see is a combination of economics and regulations starting to drive towards that. If you look at the battery packs are designed today, they are really not friendly to the recycling process. A lot of car manufacturers are welding the packs together, and they are gluing things in place. The physical structure of the battery has many tiny layers, only tens or hundreds of microns thick, with the materials distributed through those layers - so, actually getting to those materials to recover them is really hard. And at the moment we just don't have the processes to do that. The only batteries that re economically recycled are lead acid, because it is easy to get to the materials, and typically things like mobile phone and laptop batteries are recycled, because there are a lot of cobalt in them - and cobalt is expensive, so there are processes for extracting the Cobalt, but the rest of it is pretty much incinerated.

SS: The other question I had, and I was keen to know the answer to this myself is about fuel cells. Do you think there is a future for fuel cells in the automotive industry?

DG: I will say this one is relatively controversial. There are organizations who are still putting a lot of resources into understanding fuel cells for automotive. My personal opinion on this is that I don't have a problem with fuel cells themselves. I can see some good ways in which we could engineer fuel cells to be cost competitive with diesel engines, for instance, in the medium term. My biggest problem is not the fuel cell, it's the hydrogen that we need to run it – and I think that's the inhibitor to fuel cells for the automotive industry. To me it appears that as batteries have got better and better, they've been eating into the market that fuel cells were originally intended to target, which is the longer-range vehicles. You know it's expensive but you could buy a Tesla today with two or three hundred miles of real world range. And the infrastructure that you need to charge electric vehicles, whilst it does need a lot of money, the basic infrastructure is there, and it can grow with the fleet as the fleet grows, whereas there is no infrastructure for hydrogen. And most of the hydrogen we get today comes from cracking of natural gas, so it's not zero CO_2. We could generate hydrogen from renewables, but if you look at the energy efficiency of the process of taking renewable energy from a wind turbine, electrolysing to make hydrogen, compressing it, transporting it, compressing it again to go into a vehicle's fuel tank, then expanding it, then running it through a fuel cell, then running thorough a set of power electronics, all the way to the motor and the wheels and onto the road, unless you are quite careful about how you do that you can lose 80% of the energy between extracting it from the wind and using it in the car. And renewable though it may be, I just don't think that as a society we'll be in a position where we can afford to see that level of energy waste. So, my personal view is that I don't think hydrogen fuel cells are the right answer for the car industry. I think there are some really good applications for fuel cells, but they are linked to network reinforcements and grids, as well as energy storage at relatively large scale. I don't think that we should stop work on fuel cells, but I think we should focus it on static applications. Perhaps the one area I would consider as potentially disruptive is that of the solid oxide fuel cell – whereby gas can be reformed on board the vehicle, and the fuel cell is tolerant to impurities – that way you use an existing refuelling infrastructure and eliminate some of the energy conversion steps.

SS: I know WMG has become involved with research on autonomous cars. I was hoping you can tell us a bit more about what that research entails and how in general you think the technology will develop in the medium term.

DG: Professor Paul Jennings is WMG's lead person for autonomous and connected vehicle. I very purposefully call it autonomous and connected vehicles, rather than just autonomous vehicles because very often when you read about vehicle automation, it jumps straight to autonomous vehicles, as though you can miss out all the middle steps and go from where we are today to a situation where all vehicles magically communicate with each other and drive without any intervention at all. The reality is that we have a transition to go through. Whether that transition is going to take ten years or twenty years is open for debate at the moment. What Paul's group is looking at is what the technology is going to look like at each of these steps - and understanding it not just from a technical perspective but also from a human's perspective. There are lots of factors that need to be considered around how people are going to interact with these vehicles – and that will be just as important to how quickly they are adopted as the sensors or algorithms that they use. You may have seen that Paul's group have a huge simulator here at WMG. It's referred to as a vehicle simulator but it's actually the entire world around the vehicle that is simulated, including the electronic environment. The simulator is in a Faraday cage, so we can hi-jack the GPS, the 3G or other electronic signals that the vehicle sees. In that environment, we can project a 360° photo-realistic view of a landscape that both the driver and the cameras on-board the vehicle can interpret. Obviously, we can't simulate the 3D environment as far as the Lidar sensor is concerned, because the sensor will recognise it's sitting in a glass fibre cylinder, but what we can do is compute the signal that the Lidar sensor would generate, and then inject that signal behind the sensor so the rest of the vehicle believes that it is in the real world.

SS: I understand there is an effort to introduce the UK as the global hub of developing autonomous vehicles.

DG: The UK is actually a very good environment to be developing autonomous vehicle technologies. The legislation that we have already is very helpful to allowing people to test autonomous vehicles in the public domain. Clearly, there are safety implications that need to be considered seriously, but the legislation and the regulation is open to it. The UK has also realised that it can have quite a big role in this. So there are discussions between the government and the industry on investing in the development environment that is needed for autonomous vehicles. That

environment covers a broad range of activities. At one end of the development spectrum you have completely virtual development where everything is on a computer, models working against models, testing control systems, and so on - with the benefit that you can achieve hundreds of tests per day, and you can test the same difficult scenario, say a crash, every couple of seconds. The downside is that you are not testing the real vehicle or the real system, so any mismatch between what is in the model and what is in the real vehicle can influence the result. At the other end of the spectrum, you can have real vehicles running on real roads, in which case you need to drive millions of miles because 99.9% of that driving is really boring, nothing interesting happens, the vehicle keeps control, and there are no issues. The fraction of a percent that you are interested in, what we call the 'corner cases', are where some particular set of circumstances comes along that really forces the autonomous system to work hard. So what Paul Jennings and his group are looking at is how we should fill that gap between completely virtual and completely real - and that is where their simulator comes in because you can use it to re-create real situations very quickly and you can then test them against the real vehicle. The vehicle believes it is in a real world and if we want to generate a difficult scenario, like a crash or a pedestrian stepping out in front of the car, we can do that many times per day without any risk to the person or the vehicle, in an environment that allows you to get reliable data as well.

SS: How do you rate the investment in UK on autonomous vehicles, compared to other European countries?

DG: I would say perhaps we've been a little behind up until now, but that said we still have some very high quality stuff happening in the UK. If you look at the work that WMG does, or the work that Paul Newman is doing at Oxford University, there really is some tremendous quality activity in the UK. There is a dialogue going on between the government and the industry about a significant increase in the amount of investment in the autonomous vehicles research in the UK. So it has been recognised that we have a role to play and that we need to increase the current scale of activity.

SS: How do you think Brexit and possible change in US policies affect the future of the UK and global automotive industry?

DG: The UK has benefited from the ability to access markets in Europe. Cars made in the UK are sold in Europe with no trade tariffs. There is free trade of components going forwards and backwards. And if you think

about the process of building a car, it's not the case that everything gets built in one country and gets transferred to its point of sale. If you tracked all of the components that went into a vehicle, they come from all over the world, come together in the assembly plant, and then the vehicle will travel from there to somewhere else. In some cases as you go from nuts and washers to sub-components and components and systems, these bits will have travelled around Europe and crossed borders many times in the process. So one of the things that would potentially impact the car industry negatively is if we saw trade tariffs that added friction to that process at every step. Because those tariffs will then potentially end up getting applied several times before you get to the final product. So, I guess one of the concerns that the UK automotive industry will be tracking is that given that we export a lot of our cars at the moment, how Brexit could impact on that. My personal view is that we'll find a way through that. I don't know what the answer is, but given that the UK is quite a large car market for the European manufacturers as well, I think there is probably a mutual benefit to get some sensible arrangements. The worry is that the car industry is a very important one for the UK and may be used as a negotiating chip. So I'm more concerned about the uncertainty leading up to the any form of agreement, than I am about what the agreement is at the end of it. The good news is that the UK government recognises the concern. And if you look at the policies that are being rolled out at the moment, things like the Industry Strategy, the government is actively looking to step up and overcome some of those potential barriers and support the industry in the right way.

In terms of the research activities, we have benefited tremendously from the mobility of labour, not just in Europe, but around the world. If you look around the Warwick University you realise that we are a very diverse community. A large number of people come from the overseas. In the short-term, I am worried about the impact of Brexit on the ability to recruit good European staff and students. We'll see what comes about at the end. We already successfully recruit people from countries outside of Europe. And once we have the arrangement in place I am confident that we'll be in a position that we can recruit people from inside Europe too, but it's the uncertainty of what the arrangements might look like that can make life difficult in the short term.

SS: What about possible changes in US policies?

DG: I am concerned about the direction that the US politics could go to and the impact it might have on the automotive industry. There seems to be a difference of opinion between the political and scientific communities which is concerning. What is very interesting to me looking

at the rhetoric at the moment, is that up until now, things like air pollution and fuel consumption standards for the US have had to be driven by the governments, because consumers didn't care enough about them to make those choices themselves. So consumers elected politicians who set up measures for cleaning up the air and for improving CO_2 emissions and preventing climate change, but the consumers were not actively involved in setting up those measures. So up to now it was a politically driven process. What you see at the moment seems like a polarisation of opinion. There is a group of the public who say all of the concern about CO_2 is politically generated, is not real, so let's carry on burning oil and have low cost products for the economic benefit that it brings compared to the countries that follow the CO_2 reduction agenda. Equally though, there is public voice which has not really been there before, which is saying that we do believe the climate science, we do believe that we should maintain the quality of clean air that we developed since 1980s. The shift in the political discourse may result in a shift in the public discourse that makes this consumer driven, rather than politically driven. I am watching it with great interest. In some ways I am worried about where it could end up, and in some ways optimistic about the fact that it has generated a public debate that has not been seen before. If we got to a situation where the US government was to adopt radically different standards to the rest of the world, the US is already a big-enough market that there are vehicles that are designed to US standards. It would affect those vehicles and it would affect the CO_2 and air quality standards of those vehicles - but I think the knock-on impact on Europe and Asia may be surprisingly small because at the moment I don't see Europe or Asia stepping away from the fact that air quality is a concern, and that CO_2 and climate change remains important. So, I'm not too worried yet about seeing that as a global knock on.

SS: Thank you very much Dave for your time. It was a very interesting discussion and I think we touched on a wide range of topics.

DG: Sure, I hope the readers will find it useful.

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