Automotive **Engineer**

Technical Update

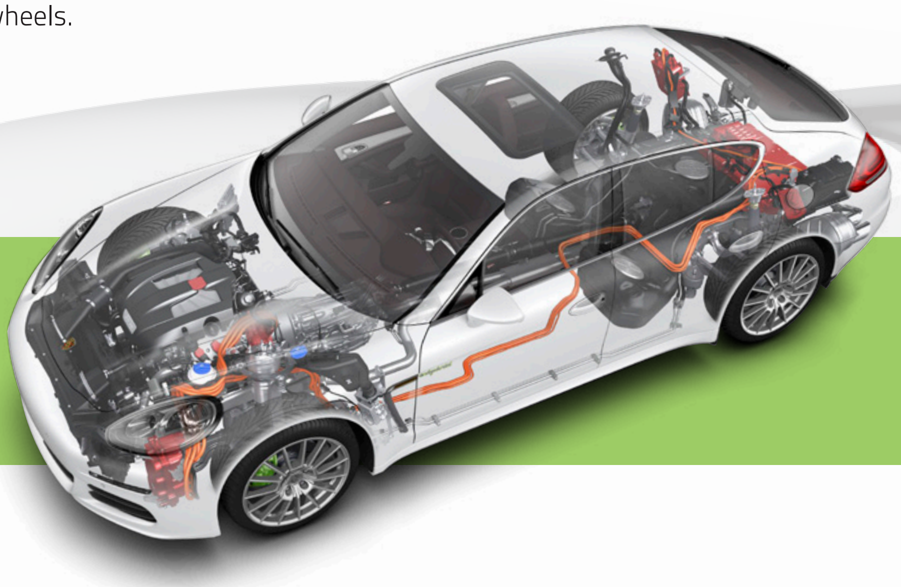
MARCH 2014

Welcome to the March 2014 issue of the Automotive Engineer Technical update for IMI Certificated Automotive Engineers (CAE) and Advanced Automotive Engineers (AAE). In this issue, we discuss the significance of the powertrain revolution and the future of vehicle propulsion.

Powertrain evolution – or revolution?

It is difficult to assess the significance of any era whilst living through it. What seems to be utterly new or ground breaking could, with the passage of time, turn out to be far less significant. However the automotive world is emphatically in the midst of the unthinkable. After a century of steady progress, everything from where vehicles are built to how they are built and even operated, is up for grabs. We have, in the past decade, seen more development than in the previous century, and that pace is picking up. Are all ideas good? In the context that all ideas have aspects which are positive, yes. But trying to tell what the technology trends are going to be in 20 years' time is far tougher than the same exercise viewed from 1980.

Take powertrain. Firstly, what is a 'powertrain'? It is the system and all the supporting systems required to take stored energy and translate that to power, in order to drive the road wheels. For more than a century that has meant an internal combustion engine and a mechanical transmission via a gearing system. Now that is openly challenged. Not just a choice of energy source – petrol or diesel – but even the way power reaches the road wheels.



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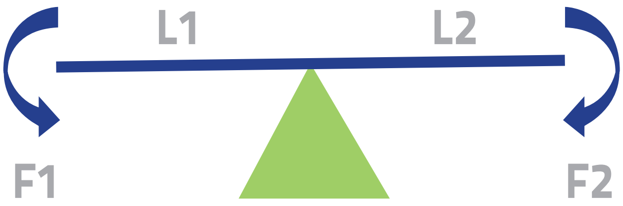
Do different types of vehicles require **different types of power?**

A key factor of powertrain engineering is matching the system to the intended use of the vehicle. For example, a race car will have a powertrain optimised to stay together for the time required to complete just one race, whereas a typical mass-market family car will require the powertrain to work with nominal maintenance for more than 10 years regardless of weather or type of use. A large 44 tonne truck will require huge torque output to move the vehicle from rest, and yet need the absolute minimum fuel consumption once on the move.

If we consider applying a tightening torque to a nut, bolt or screw to achieve the correct clamping force, it is a function of the force applied multiplied by the length of the spanner / wrench / bar. Looking at a beam sitting on a pivot we can see that:



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Force 1 (F1) x L1 = Force 2 (F2) x L2

No matter where the pivot is on the beam, this equation will hold. But, as L1 becomes shorter, so F1 will need to increase. If L1 becomes longer, so F1 will decrease. That is the core mechanism between the crankshaft pin offset and the associated stroke of the piston assembly inside the cylinder bore. An engine also produces mechanical effort which is expressed as 'power' and 'torque':

- Torque (applied force x moment) – Nm
- Power (torque per second) – Nm/s, or 'Watt'

We have said that powertrain engineering is about matching the system performance to the intended use of the vehicle. Unless the vehicle is very light and/or slow, the internal combustion engine is not capable of generating enough torque at low engine speeds and enough power at higher engine speeds to drive the vehicle through its desired speed range all by itself. The transmission has a specific task – to amplify the output of the engine so the power/torque demand of the vehicle is available for the entire speed range. Hence the transmission and final drive are as much a part of the system as the engine.

What type of output would a **motor bike** need?

The layout has a relatively small aerodynamic frontal area and not much structure – the occupants sit on top of the engine and gearbox whilst the frame ties the whole lot together. The result is a relatively light vehicle for one or possibly two people, so the engine does not need to produce a huge amount of torque to alter the vehicle speed. However, outright power is more interesting, so the engine is optimised to have a relatively short stroke as well as large piston surface area to produce power at relatively high engine speeds. The transmission is optimised to boost the powertrain output torque in the lower gears and has relatively small overlap between ratios to flatter the relatively small power band.

What type of output would a **car** need?

Compared to a motor bike, a car has a far larger structure. It can carry passengers alongside the driver as well as behind the driver, whilst all occupants are fully protected from the weather - even for a convertible. Inevitably the aerodynamic frontal area is much larger and the weight of the vehicle structure is greater, so the engine needs to produce much more torque lower in the engine speed range than a motor bike. In addition, the type of user will require far less frequent service intervals so the powertrain engineering will be inherently more conservative. Generating that additional low speed torque creates a bigger crankshaft offset (bigger moment) and a heavier crank case too. Essentially this is why car engines for a given swept volume are heavier than a motor bike engine, and why the maximum power output will be lower too.

What type of output would a **truck** need?

The frontal area is defined by the maximum width (2.5m) and height (4m in most EU state, almost unlimited in the UK at the moment), which relates directly to payload volume within the maximum permissible vehicle length as well as overall vehicle weight. Complex? Oh yes. Each truck operator will know if they have a volume or weight dominant payload type, and select the layout of axles as well as configuration (rigid, rigid plus trailer or semi-articulated). Given most heavy trucks weigh upwards of 7,500kg through to 44,000kg, the effort required to get the vehicle moving is rather greater than of a passenger car at around 1,300kg. Once again, the required torque is far greater, leading to immense crankshaft offset and simply huge crank case assemblies. However, once on the move the engine needs to consume minimal fuel, so the power band is optimised to deliver torque and maximum power in a relatively small engine speed range. The transmission has many more gear ratios to provide the range of required torque multiplication to cope with moving the vehicle from rest through to high speed cruise.

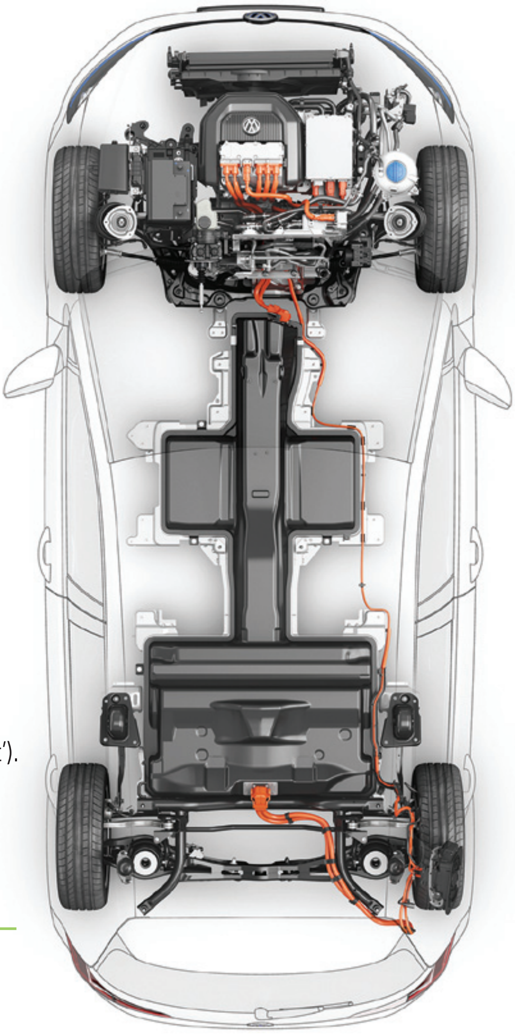
What is all the fuss about '**powertrain**'?

The simple truth is, regardless of the actual environmental impact of the motor vehicle, there are more than 33 million vehicles in the UK and around 65 million people. So every day all of us are but metres away from a vehicle either parked or moving. Quite simply, vehicle emissions are very, very high profile.

Right from the start of the self-propelled vehicle, use of the on-board energy to provide the maximum speed and range has preoccupied engineers. The beauty of oil-derived fuel is the available energy in each and every litre is almost unparalleled and it can be recharged in a matter of minutes. A point not wasted on early motorists, even if they had to organise supplies to be delivered along the desired route in advance and usually via a horse drawn cart.

That follows two simple ideas:

- Poor combustion leads to poor performance (junk 'in' = junk 'out').
- The power and torque curve need to be matched with the transmission to the overall vehicle performance.



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What **conditions** are required for combustion?

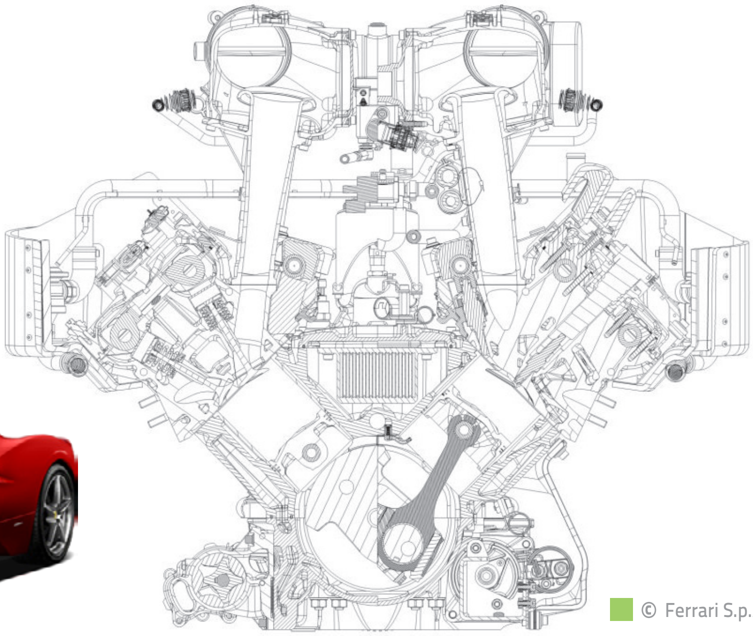
The classic air fuel ratio required for complete combustion where no hydrocarbons are left occurs when 14.7 times the volume of air is combined with a single unit of hydrocarbon vapour. For petrol engines this is the 'stoimetric' reference point, often called by the symbol for this ratio Lambda (λ).

'Rich' (less air, more hydrocarbon fuel)	<14.7:1 >	**'Lean'** (more air, less hydrocarbon fuel)
$\lambda > 1$	$\lambda = 1$	$\lambda < 1$

An engine will be calibrated to seamlessly move between these limits depending on the load demand from the user. Typically 'rich' fuelling will be used to assist with acceleration, whereas 'lean' fuelling will be found in use during steady state light load conditions. As load increases, so the fuel quantity/ timing will alter accordingly.

So what are the **real limits** of an internal combustion engine?

Just take a look at the section of the engine from a Ferrari 458 Italia shown - the equipment required to fill the combustion chamber with combustible mixture, the equipment to allow the resultant hot gasses to leave the combustion chamber, the structure around the combustion chamber and the linkage to the mechanical energy output shaft – the crankshaft.

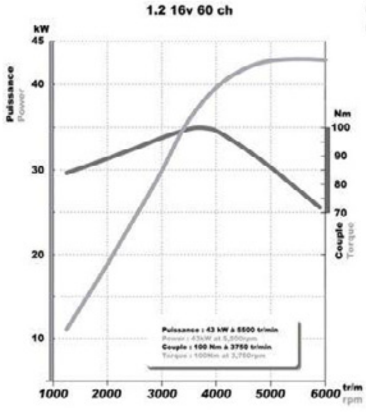


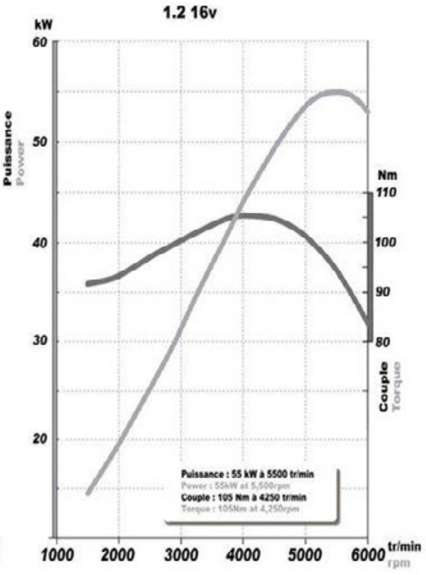
🟩 © Ferrari S.p.A.

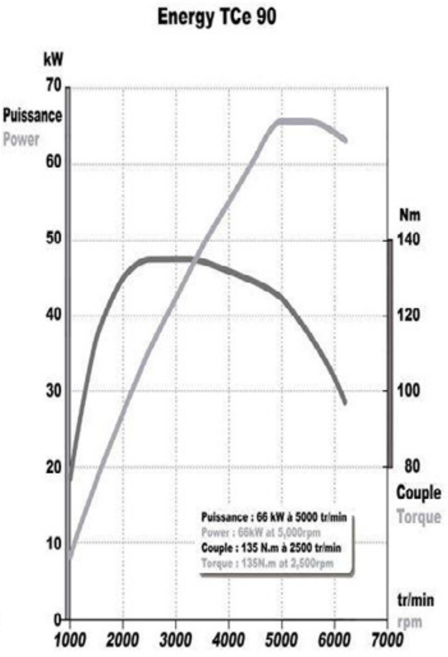
The **limitations** include:

- Maximum combustion temperature is limited by the formation of NOx, which is a specific pollutant monitored as part of the emission certification process.
- The speed of intake and exhaust gas transfer - the point at which both systems could be open – is limited by the amount of hydrocarbons that do not get burnt. Again, this is a specific pollutant linked directly to the formation of smog which is monitored as part of the emission certification process as well as the MOT inspection.
- Carbon monoxide is a highly poisonous combustion gas by-product, which is monitored as part of the emission certification process as well as the MOT inspection.
- Carbon dioxide is the main combustion gas and we can breathe it if required. However this is now considered to be a greenhouse gas contributing to global warming, it is not monitored as part of the emission certification process but does form a means of taxing vehicles.
- The thermal limit of the lubrication oil, which in turn governs the size of the crankshaft bearings as well as the speed of the engine.
- The cylinder head gasket, which limits the ultimate in-cylinder peak pressure possible. This in turn limits the power produced per litre to around 150 bhp for engines without forced induction (turbo or super chargers), and to 250 bhp for forced induction engines This limits how small an internal combustion engine can be for a given peak output.
- The engine will produce a peak torque and peak power figure. The torque curve can be artificially capped to extend the available peak value over a bigger engine speed, but the only real choice is where those peaks occur.
- Efficiency is best optimised around a relatively narrow engine speed range, which is at odds with the required performance of a vehicle (typically anywhere from 0 mph to around 70 mph).
- Every time the engine increases speed or meets an increased load, the fuel system, along with the ignition timing, is altered, so leading to 'transient' conditions. It is this which is responsible for most of the tailpipe emissions either in the emission lab or the real world.

But – and it is a huge but – the internal combustion engine is produced on every continent of the earth and is easily the least costly to build let alone use. As the demands for increased fuel economy, increased power and reduced tailpipe emission increase, so the allowable build cost per engine has also increased in the past three decades. This is to the point where twin camshafts, four valves per cylinder, camshaft phasing relative to the crankshaft, cylinder deactivation, forced induction and direct fuel injection (especially for petrol engines) are now available on a very wide array of engines. Just look at the effect of adding technology to the same four cylinder 1.2l engine:







Single camshaft

2 valves per cylinder
Naturally aspirated

Power – 43 kW

Twin camshafts

4 valves per cylinder
Naturally aspirated

Power – 55 kW (+ 28%)

Twin camshafts

4 valves per cylinder
Turbocharged and intercooled

Power – 66 kW (+ 53%)

Yet the very best internal combustion engines extract 50% of the available energy from each litre of fossil fuel, whereas most extract not much more than 30% of the available energy. Effectively, the internal combustion engine has reached a technology plateau where most of the techniques one could apply have been applied. Reducing the mass of the vehicle and improving aerodynamic performance helps, but more help is needed to further reduce tailpipe emissions.

Enter the **electric motor**

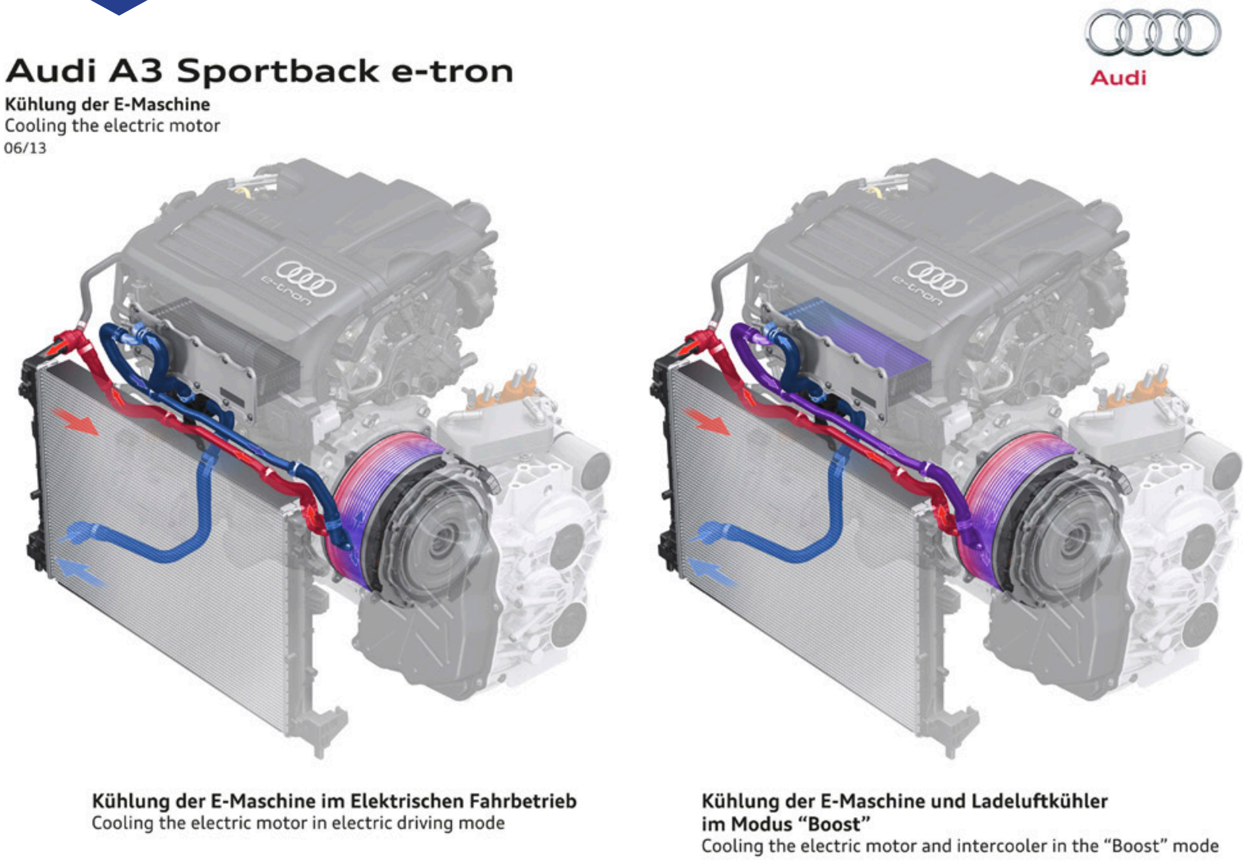
The electric motor is slightly older than the petrol or diesel fuelled internal combustion engine, and was around at the time of the earliest self-propelled vehicles. The irony is that it was not used in mass market motor vehicles for nearly a century.

The advantage is that an electric motor output torque from rest is almost the same as at speed. That flat and rather big torque allows drive torque to reach the wheel without a single molecule of CO2 coming out of the tailpipe, depending on how the electric energy is created/stored. Better than that, for internal combustion engines, an electric motor can fill in the missing parts of the torque curve demanded by the vehicle without getting into the emissions caused by transient fuelling from an internal combustion engine. Further, the electric motor has pure rotary motion so has a far greater tolerance to big speed ranges than an internal combustion engine, so permitting direct drive without the use of additional transmission ratios.

The best part? Not one country so far looks at the carbon dioxide impact of the electricity generated to store inside a vehicle, unless that is provided by the on-board internal combustion engine or the carbon dioxide impact of creating the electric drive system. It is for the moment carbon dioxide 'free'.

How are electric motors applied inside the drive system with an internal combustion engine? **Examples include:**

Inside the transmission case. Some systems (such as Toyota and GM) allow both the engine as well as the electric motor to drive the wheels, either separately or together.

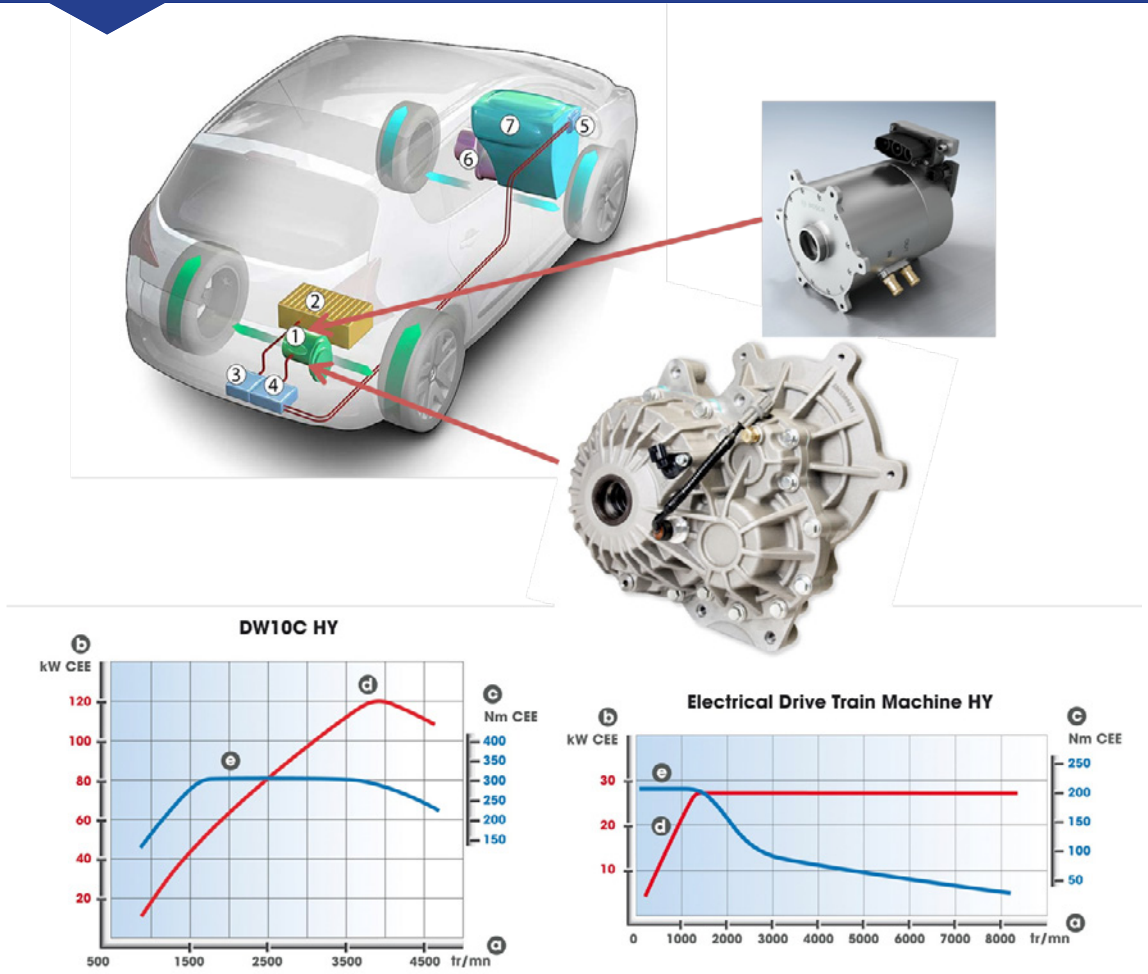


Kühlung der E-Maschine im Elektrischen Fahrbetrieb
Cooling the electric motor in electric driving mode

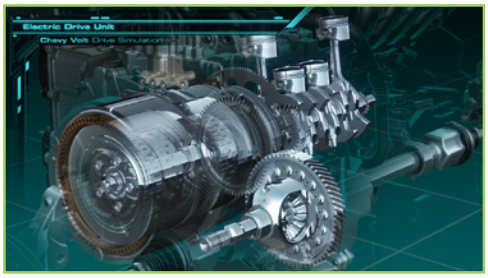
Kühlung der E-Maschine und Ladeluftkühler im Modus "Boost"
Cooling the electric motor and intercooler in the "Boost" mode

© Audi AG

Direct drive to the wheels, working in parallel with an internal combustion powertrain driving other wheels. This system has been used by Peugeot Citroën (Hybrid4) as well as Lexus. It allows the electric drive system to provide the all important assistance from rest as well as during acceleration.



Pure electric drive with range extender.
The system developed by GM has an electric motor which provides drive for most conditions, and since there is no transmission, the internal combustion engine is primarily there to generate power for the electric drive system once the battery energy has been used up.
In addition, the internal combustion engine can assist the electric motor to drive the wheels but only once the road speed is above 65 mph.
Again, because there is no transmission apart from a final drive ratio.



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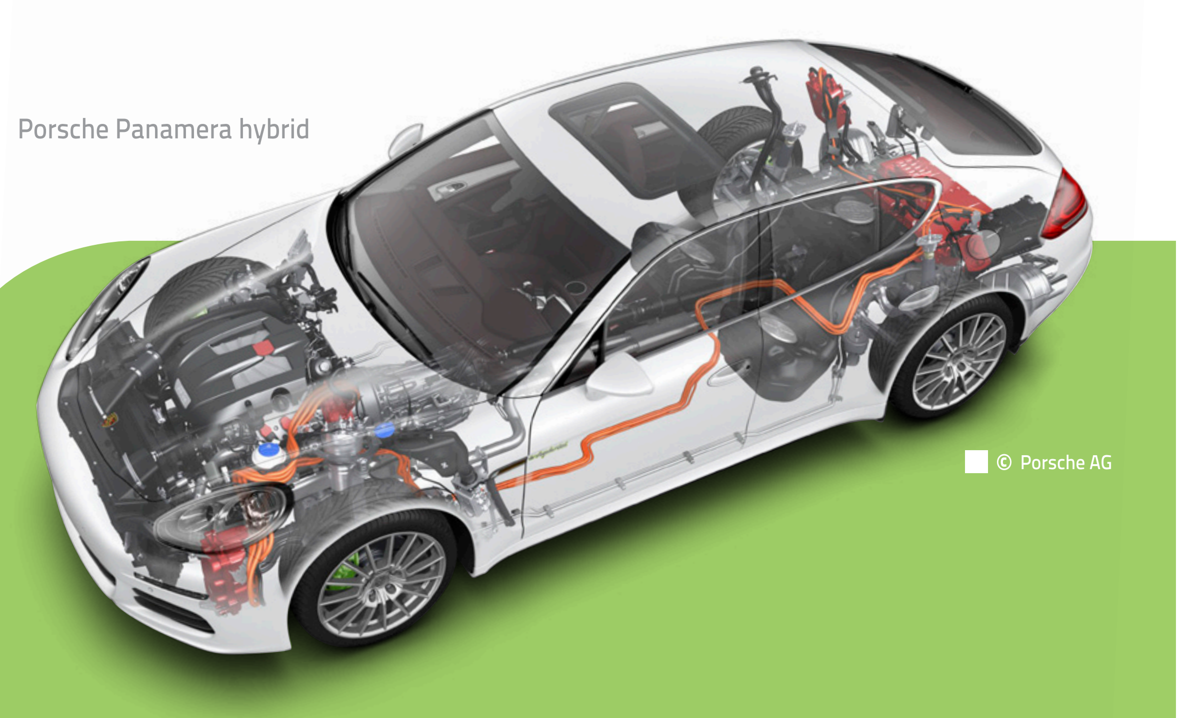
Why use both an internal combustion engine and an electric motor?

The question revolves around the main limitation of an electric motor – mobile electric energy storage. Systems already in use have around 10% of the energy storage density compared to either petrol or diesel, so to provide like-for-like range would require a 'tank' 10 times the size of a petrol or diesel fuel tank volume. There are losses in translating petrol or diesel into mechanical energy, as there are losses when converting stored electrical energy into mechanical drive. In the latter case, there is significant build-up of heat which requires cooling – hence everything from the power controller to the motor and the energy source. Added to this, a typical large battery will perform better at normal room temperature than when at less than 10°C, and we can see that the electric drive system needs to be cooled as well as heated depending on what is going on at the time.

Getting electrical energy into and out of storage devices is improving, but recharging still takes many times longer than a visit to a fuel pump. Yes, improvements have been made with battery chemistry along with three phase rapid chargers, and imminent super capacitor developments could lead in time to recharging in about the same time as filling a tank with petrol or diesel fuel.

Porsche Panamera hybrid



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The best compromise for at least the next decade is to use both systems. This allows flexibility by using the immense infrastructure built for dispensing petrol/diesel, whilst also accessing mains electricity when possible. The applications? Most likely (and already on the market with a 2.2l turbo diesel hybrid drive S-class, hybrid drive BMW 7 series, and the second generation of Porsche Panamera hybrid shown above, for example) are larger, heavier cars. Here the combined drive system can deliver yet more performance whilst reducing fuel consumption and tailpipe emissions. Smaller cars (sub Ford Focus or Volkswagen Golf size) are less likely to require this technology to meet emission standards due in the next decade.

Is there **another** solution?

An alternative to using an internal combustion engine as a means of working alongside an electric motor is to have a mobile electricity power generation system - the fuel cell. These devices are under development and can use pure hydrogen (tailpipe emissions are pure steam) or can use fossil fuels with much less environmental impact than an internal combustion engine. In the latter case, the first applications will be for refrigerated semi-trailers where the air conditioning plant is typically run by a small and rather inefficient diesel engine until either it is hooked up to mains electricity or the load is delivered.

There is a race between Daimler AG, Toyota and Hyundai to see who will build the first commercially viable fuel cell vehicle. Already Hyundai has built fuel cell powered ix35 prototypes on the same assembly line as regular ix35s, and will complete 1000 prototype builds by 2015. The system cost is falling from around $250,000 per vehicle in 2010 to $25,000 per vehicle by 2015. The source energy for the fuel cell 'stack' would preferably by hydrogen which are stored in tanks (like the ix35 unit shown above) at 700 bar or cooled to minus 290°C and a pressure of just 4 bar. Significantly, a fuel cell system still needs to store electric energy, as it is best suited to generating a stable output rather than matching the output to transient demands from the vehicle driver.

There can be no escape from the issue of mobile electric energy storage.

There remain significant logistic issues in establishing a national hydrogen distribution system, so the first applications have been for fleet vehicles operating from a single location, like buses. This situation will change over the next decade, but only then will there be an effective national network of hydrogen refuelling stations.

Conclusion:

The future of vehicle propulsion will still feature the internal combustion engine. Right now there is a revolution under way, one that will be difficult to assess for at least another five years. Initial thoughts had been to replace the internal combustion engine, but the path taken by many vehicle manufacturers is to address the shortcomings of the engine with rapidly advancing electric powertrain technology. The drivers are a mix of taxation incentives, emission taxation taken directly from vehicle manufacturers, and the over-arching concern for our environment.

Pure electric vehicle power is about 10 years away from having the same refuelling time as well as range of current petrol/diesel powered cars. Fuel cell technology could provide an answer, but is nearly two decades away from a comparable system cost to a current petrol /diesel powered car. Yet the demands for reduced tailpipe emissions and improved fuel economy will not stand still. So how can these apparently conflicting demands be met?

Apart from a raft of improvements to the rest of the vehicle, powertrain engineering will selectively deploy electrically-assisted drive systems, very much depending on the size/weight of the vehicle. That in turn means an ever more complex range of possible powertrains arriving in the aftermarket. Porsche, for example, is on its second hybrid drive system in less than three years, whilst outwardly the vehicles appear to be unchanged. Lack of standardisation of key components means there will be more than a decade of vehicles built with 'unique' systems, which will be common enough for almost everyone everywhere to come across.

Now there's a challenge.

Reflect **questions**

1. What is 'torque'?
2. What is 'power'?
3. What are the measurement units for torque or power?
4. What are the three main internal combustion engine exhaust gas pollutants?
5. Why is carbon dioxide considered to be a pollutant gas?
6. How can an electric motor assist and internal combustion engine?
7. Can an electric motor drive the vehicle without using a set of transmission ratios?
8. Does the Chevrolet Volt/Vauxhall Ampera internal combustion engine ever drive the wheels?
9. What are the limitations of electric energy storage on board a vehicle?
10. What does a fuel cell do?
11. Can a fuel cell run on anything apart from hydrogen?