TORQUE TALK

Engine tuning traditionally concentrates on raising peak power, but in truth it's torque – rotational force – that does most of the hard work, argues Chris Horton. Photos by Porsche and the author

996 Turbo – here in Cabriolet form with a factory hard-top – had an impressive enough 420bhp at 6000rpm, but what really did the business was its torque 'curve', essentially a flat, 560Nm plateau from 2700rpm to 4600rpm. Even with a supposedly 'lazy' Tiptronic transmission – and perhaps because of it – 0–62mph was easily and consistently achievable in the factory's claimed 4.3 seconds, and 0–100mph in 9.5. Power is one thing; torque – and the ability to use it – quite another

The headline benefit of raising any engine's swept volume, as we've suggested elsewhere in this analysis of Hartech's enlarged M96 and M97 units, is an increase in power. It's what magazine road-tests, tuning features and *Top Gear* presenters have banged on about for years. (With arguably one notable exception; see below.) But to Barry Hart – and, in truth, to the rest of us, if we did but know it, and had not become fixated on mere bhp – the most important gain is a comparable increase in torque. And, if you and/or your engine builder have done your sums, a modest but no less useful reduction in the engine speed at which both curves subsequently peak.

'Porsche sports cars have gearing that most owners will never exploit to peak revs – and certainly not in the higher gear ratios,' says Barry. 'Tuning a given engine to raise the revs for maximum power looks impressive on paper, but often fails to provide the real-world performance increase that the graph implies. But even a modest increase in capacity will usually result in much better torque, and so the easier, faster acceleration that will also suit both typical road users and occasional trackday drivers far more than the results of purely external modifications alone. And a modest increase in capacity will often result in the engine being less stressed than it is by conventional tuning.'

It's all about what Barry calls the rev-drop area. 'Your engine's maximum brake horsepower is effectively the same in any gear – and simply determines its potential to do different things, depending on the way in which it transmits the output. But torque is not quite the same thing. You have the most torque at the wheels in the lowest gears – which is why when driving on mud or ice you need to stay in as high a gear as possible, in order to reduce the chances of wheelspin – and as you shift upwards the torque reduces in inverse proportion to the ratio. Torque in sixth gear – again at the driven wheels, of course – is typically between four and five times less than it is in first.

'When you change up through the gears, you inevitably exchange that torque for rotational speed. To put it another way: increase wheel speed, so that the car can travel faster, and you reduce the available torque by the same proportion. This is why your car naturally accelerates faster in the lower gears, and less quickly in the higher ratios. And why, when you come to climb a gradient, you have to change down in order to maintain your speed.

'When you change gear at the rev limit the engine speed naturally drops to the level that is effectively determined by the next higher ratio. So if you are driving to maximum revs before changing gear you create a "rev drop" – or more likely a series of rev drops – in which the vehicle has to accelerate back up to the rev limit before you shift up again. And this rev drop varies in size depending on which gear you are in. It's usually at its greatest between first and second gear, and at its lowest between fifth and sixth. Essentially, the fastest overall acceleration will be achieved by having the greatest average torque in that rev-drop area.

'Typically, tuning an engine to rev more quickly will usually produce more power at or close to maximum revs – and in so doing place more stress upon it, of course. But it will also tend to produce lower torque at lower revs, and lower average torque within that crucial rev-drop area. So its acceleration will necessarily be compromised. You can, of course, exploit beneficially higher bhp at higher revs – even though it reduces average torque – if you can also change all the gear ratios and the final-drive ratio to suit. But if, as is almost inevitable, you are stuck with the ratios you already have, then increasing average torque in the rev-drop area that you are also stuck with will usually increase performance by a greater margin.

'The reason it is difficult to create extra torque at higher revs is purely because as the revs go up the period during which the inlet and exhaust valves are open – to allow fuel and/or air in, and exhaust gases out – reduces by the inverse proportion of the engine speed, until there is simply insufficient time for the engine to breathe effectively. It's like a world-class athlete who, however powerful his muscles might be, just cannot get sufficient air into or out of his lungs quickly enough. Trying to improve breathing at the very highest revs at which the engine is already struggling is not easy, and brings few rewards. By way of contrast, at lower revs – when there is more breathing time available – the valves are open for longer, and as a result they can handle more air flow and create more torque.

'So although increasing capacity might or might not increase maximum bhp at maximum revs – or, at least, by not as much as some expect – it always creates exactly what makes a car accelerate faster. That is to say, more mid-range torque in that crucial rev-drop area, and that allows the driver to go faster while revving the engine more modestly. This brings improved longevity, of course, and the better mid-range response – as a result of increased torque – makes it less important to be constantly changing gear in order to drive quickly.

'You could be surprised to learn that whereas an increase in capacity of, say, eight per cent, from 3.6 litres to 3.9, might increase bhp by around the same percentage – and at peak revs when the breathing limit is reached it could be even less – in the rev-drop area, where there is more time when the valves are open, the extra capacity can allow in more air and expel more exhaust, and increase torque by up to 15 per cent. With that kind of improvement comes the sort of increase in acceleration that you might have previously expected from a car with the same engine tuned for a 15 per cent increase in bhp at higher revs – which is actually extremely difficult to achieve. And certainly not for anything like the same cost.'

All well and good. But just what is this mysterious and so frequently misunderstood torque? And why is it so often confused with power? To explain that is going to require some GCSE-level Physics, but try to stick with us here, because once you have grasped the basics of this fascinating subject you will never feel quite the same again about the simple brake horsepower – or more correctly, perhaps, the mundane kilowatt.

In its very simplest terms, it's all about force. In physics, a force is said to do work if, when acting, there is a displacement of the point of application of the force in the same direction as that force. If you push your car with a force of, say, 50 newtons*, but the handbrake is on, you will have expended energy, certainly, but perhaps surprisingly you will have done no work. Release the handbrake, however, and push the car a distance of 50 metres (on level ground; we need to keep this as simple as possible, without gravity clouding the issue) then the work done – that is to say, the force multiplied by the distance – will be 2500 joules. Well done; have a well-earned rest. From this, it follows fairly logically that power can be defined as the rate of doing work. Let's say that you now ask a friend to help you push the car, and thereby double the force to 100 newtons. This will enable you to halve the force with which each of you has to push – or else both to push with the same force as before, and to halve the time the process takes. (So-called 'wind resistance' is not really relevant at this low speed, although unfortunately it remarkably soon becomes so.)

So far, so straightforward. But car enthusiasts (and car journalists and even car manufacturers, all of whom ought to know far better) don't talk about newtons or joules, but about horsepower (or, more confusingly still, brake horsepower) and torque. Or torques, as Jeremy Clarkson ironically but actually quite perceptively and helpfully puts it. The accepted wisdom being that the more you have of both the better. (And the 'torques' thing an obvious jibe at the fact that few people really understand the concept in any case.) But horsepower is, in truth, an archaic term, dating from as far back as the 18th century, when Scottish engineer James Watt needed a way of comparing the output of early steam engines with the capabilities of the draft horses they were gradually but inexorably replacing. In fact, the correct SI measurement of power is today the watt, named after that same engineer.

Either way, this particular problem is further compounded by all the different 'types' of horsepower there are: mechanical (also known as imperial); metric; electrical; hydraulic; boiler; shaft; drawbar. See what we mean? For the purposes of this exercise, however, we shall stick to watts or, since in automotive terms those are rather small (one metric horsepower is equivalent to around 735.5 watts), the now increasingly widely used kilowatts. (One kilowatt is equal to 1000 watts.) The arguably equally archaic brake horsepower is also an imperial unit: a measure of the force that needs to be applied to the engine's crankshaft in order literally to brake it, or in other words to stop it rotating. In this context it is of genuine value only when measuring and comparing power outputs on an engine dynamometer connected directly to the crankshaft.

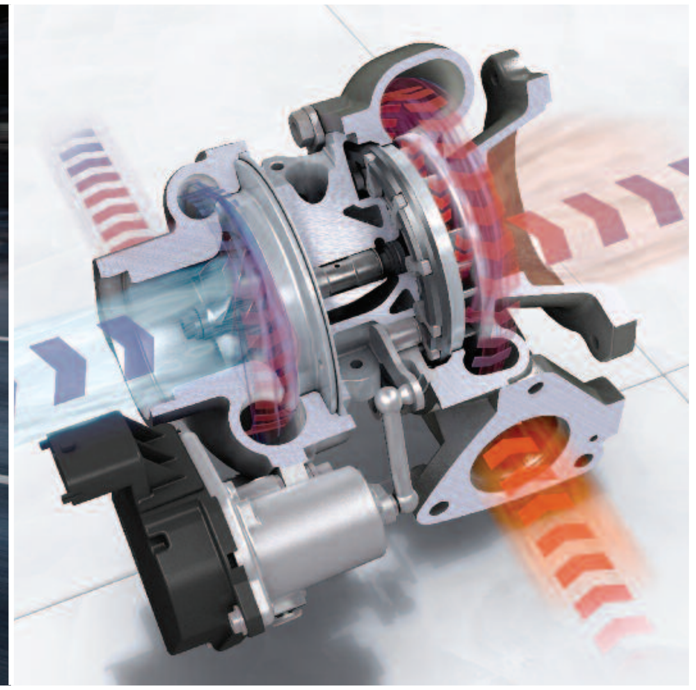
The concept of torque is on the face of it only marginally less perplexing for the many of us without a long background in mechanical engineering – and that includes this writer. Think of it as rotational force, however, and it begins to make rather more sense. Plainly your engine does not propel the car in the same simplistic way as you and your mate straining against the rear bumper, your thigh muscles burning with the unaccustomed effort. Instead it applies, via the gearbox, the differential and not least the wheels and tyres, a surprisingly widely variable rotational force to the road surface. ('Horsepower' – or perhaps just power, ie kilowatts – is torque applied over time.) As we have seen, the more of that force you have, the faster you can cover a given distance. And, crucially, the faster you will be able to accelerate the car, to overcome its inertia and get it rolling, even if only to walking pace. Once you grasp that basic concept, everything else starts falling into position.

> "The concept of torque is on the face of it only marginally less perplexing"

As with power, there are many ways of expressing torque – most of them thoroughly confusing. Here in the UK we have determinedly hung on to all manner of absurdly old-fashioned terms, but the SI unit is the newton metre (all lower case), usually abbreviated to N m or Nm, or in other words a force of one newton applied at a distance of one metre from the point of rotation. (And from this it follows that torque at the road surface is also determined by the car's gearing, or the mechanical advantage that confers. Even the diameter of the wheels and thus the size of the tyres has an effect, as Barry Hart discovered to his cost when he realised that two tyres of nominally the same

The Carrera GT's V10 offered 612bhp at 8000rpm, and a hefty 590Nm at 5750rpm, but 'clean' standing starts were not easy to achieve – and its 205mph top speed is by today's standards hardly remarkable

** The 'units' used throughout science can be baffling, not least because there have evolved so many ways of expressing the same thing. Pounds or kilograms? Miles or kilometres? Gallons or litres? The newton (lower-case 'n') is the International System of Units- (or SI-) derived unit of force. It is named after the English polymath Sir Isaac Newton (1642–1726) for his work on classical mechanics, including his famous laws of motion. One newton is the force needed to accelerate a mass of one kilogram at the rate of one metre per second squared. Other units of force are the dyne, the kilogram-force, the pound-force and the poundal. The joule, named after another English physicist, James Prescott Joule (1818–1889), is an SI unit of energy, defined as that transferred to an object when a force of one newton acts upon it in the direction of its motion through a distance of one metre. If you want to know more about all of this, then pour yourself a strong drink and settle down with Wikipedia on your laptop...*



size can vary in diameter by up to 10 per cent – or in other words by roughly the same amount as the percentage gain in torque that can result from increased engine capacity.)

What it all boils down to is that, to some extent regardless of its apparent 'power' output, your engine's ability to get the car moving – and then to keep it moving against inertia, gravity and inevitably that wind resistance we talked about – is governed more than anything else by the torque it generates. That's what really does the business, pushing (and/or pulling) you down the road; past that on-the-limit truck on a challenging two-lane highway. The more torque you have, the more flexible and responsive the car will feel, and – generally speaking – the easier and the more relaxing it will be to drive for a given throttle position.

Both power and torque are – in automotive terms, anyway – generally expressed at specific crankshaft speeds. Maximum power (the maximum rate of doing work, remember; and power is torque over – or divided by – time) tends naturally to occur toward the top of the rev range. Which is all very well for racing or perhaps trackday work, but since few people – out on the public road, anyway – routinely explore even half of their engine's full potential, raising power has relatively little effect in terms of everyday performance. Quite the opposite, in fact, if as a result the engine becomes less tractable; more peaky, as another old term puts it. Even modestly increased torque, however – a natural by-product of increased cylinder capacity; think of it as 10 of you pushing against the bumper rather than just you, or even you and your mate, rather than you alone trying to push 10 times harder – makes a huge difference to the way the vehicle behaves in everyday circumstances. Potentially to its efficiency and thus fuel consumption, as well. The more torque you have, the less difference it makes what gear you are in when you wish to accelerate – and the more naturally responsive the car will be in the higher gears.

A good example in Porsche terms is surely a direct comparison between the eight-valve 944 and the 16-valve 944S, both with 2.5-litre, four-cylinder engines. Peak power and torque for the former is generally quoted as 163bhp at 5800rpm, and 205Nm at 3000rpm, respectively. In the 'S', peak power rose to an impressive-sounding 190bhp at 6000rpm, and maximum torque to 230Nm at 4300rpm. On the face of it that should have made the 'S' a bit of a rocketship, but the reality tells a very different story. The plain fact of the matter is that the 'S' has far less mid-range flexibility than the eight-valve car, and as a result (or so believe most of us who have experienced them) can be incredibly frustrating to drive. You have to keep the engine on the boil by changing gear all the time; rowing it along on the gear lever, to quote yet another old car-magazine cliché. Even the later 944 Turbo, with 250bhp and no less than 350Nm, suffers from a relative lack of torque until the blower is actually boosting, and it is really only the naturally aspirated 3.0-litre S2 (211bhp at 5800rpm, and 280Nm at 4000rpm) that puts a smile on your face the moment you floor the throttle.

Perhaps having learned a lesson from this, Porsche itself made much of the favourable torque characteristics of the 996-model 911 Turbo when it was launched in 1999, for the 2000 model year. (And turbocharging has famously become an 'easy' route, in all manner of engines, to not just improved power but crucially also to substantially improved torque.) Maximum power – a not exactly unimpressive 414bhp – was developed at 6000rpm, but the engine's *tour de force* was in practice a plateau of muscular torque the size of South Africa's Table Mountain, from as low as 2700rpm all the way to 4600rpm. This concept of a broad and easily accessible torque spread was further honed over the following years, thanks to techniques such as variable turbine geometry, or VTG, with the result that the 580bhp 991 Turbo 'S' has no less than 750Nm from just 2250rpm, and this barely tails off at the 7200rpm red-line.

What it meant – and still does, of course – was that you could leave the transmission in almost any gear, with the crankshaft rotating at perhaps a leisurely 1500–2000rpm, and still take off like a guided missile whenever you nailed the throttle. Which is a very neat trick if you can pull it off. And one so utterly addictive that you will surely repeat it at every available opportunity. **PW**

Apogee of the water-cooled flat-six engine is surely – for the time being, anyway – the 991 Turbo 'S', which thanks to its ingenious variable turbine geometry (above), first seen in a Porsche some 15 years ago, cranks out a frankly astonishing 750Nm from as little as 2250rpm

Published figures – and established logic – suggested that the 16-valve 944S (far left) should have been a much stronger performer than the original eight-valve car, but you had to rev it hard to access the extra torque, and on the road it was all rather disappointing. Likewise the 944 Turbo (below), and it's the 16-valve, naturally aspirated S2, with its nearly 3.0-litre engine, that many enthusiasts – us included – consider to be the best of the breed

POWER UNDER PRESSURE

Steam engines have huge power and torque from effectively zero revs, but how does that translate into reality? Who better to explain than Cayman owner Peter Maynard, who has experience of many different types, from diminutive 0-6-0s to massive 2-10-0 freight engines. Photos by Peter Robain and Chris Horton

Most road vehicles have internal combustion engines of one form or another, but the steam locomotive has at least two *external* combustion engines, fed with steam from a boiler. Instead of generating energy within each cylinder, the steam locomotive creates the energy required to move it by heating water by fire, most often using coal, but sometimes oil.

Each 'engine' on the locomotive typically takes the form of a cast-iron cylinder block with an integral valve chest located above the cylinder. Some engines have two cylinders, some larger ones three. The valve employed may be of the slide type or, on more powerful locomotives, a piston valve sliding to and fro, admitting and exhausting steam to and from each end of the cylinder in turn. (The steam engine scores a point over its internal-combustion rivals by being double-acting. Every piston stroke counts.) Steam engineers flirted with poppet valves – as in modern internal-combustion engines – but seemed always to return to the trusty piston valve.

Steam locomotives don't have a gearbox but they do have a 'reverser', which not only controls the direction of travel (in theory the engine can travel as fast in 'back gear' as it can in forward gear) but also the amount of steam admitted to the cylinder during each piston stroke. This can be as much as 75 per cent (steam is admitted for the first three-quarters of the piston travel, and then 'cut off' for the remaining quarter) to as little as none, in which case the loco is in 'mid-gear', ie not in forward or back gear.

The work done by expanding steam in the cylinder is converted to motion along the track by a connecting-rod and a crank attached to one of the driving wheels (or driving axles in the case of a cylinder inside the locomotive's frames). Power – typically expressed in pounds of 'tractive effort' – is a function of boiler pressure, cylinder diameter and driving-wheel size. Higher boiler pressure: more force to drive the pistons. Big cylinders: able to accommodate more steam. Small driving wheels: the work carried out during one rotation moves the train a smaller distance than would be the case with a big driving wheel. Freight engines that needed to move heavy trains at low speeds had small drivers, whereas the 'racehorses' like *Flying Scotsman*, designed to work faster and lighter passenger expresses, had much larger ones – effectively a higher final drive. So-called 'mixed traffic' locomotives had a compromise somewhere in between.

Assuming full boiler pressure – on a large, modern locomotive over 200 pounds per square inch (say around 1400kPa or 14 bar) – the driver has at his disposal maximum power and torque at maximum (ie 75 per cent) cut-off. Thus when starting from rest judicious application of the regulator, which controls the flow of steam from the boiler to the cylinders, is called for in order to avoid wheelslip. 'Traction control' is the driver's hand gripping the regulator handle, deftly reducing the flow of steam through the regulator valve. Large regulator openings and long cut-offs, though, are hugely wasteful: in car terms it would be like cruising at 60mph in second gear. The correct approach, once nicely on the move, is to reduce the cut-off so that steam is admitted to the cylinders for a shorter length of the piston stroke; it takes only a relative puff of steam to keep the train moving. And at the same time the regulator can be opened more widely; the reduction in torque due to the shorter cut-off reduces the likelihood of wheelslip.

Assuming sufficient traction is available (and you are dealing with narrow steel 'tyres' on possibly wet and greasy steel rails, remember), maximum acceleration is with full regulator and 75 per cent cut-off; the car equivalent is a wide-open throttle in first gear. Once up to speed, full regulator delivers maximum power but at a short cut-off a lower amount of torque. Think of it as being akin to your foot flat on the floor in sixth or seventh gear. And, just as you change down (for more torque) to climb a hill, so the engine driver lengthens the cut-off to achieve the same effect.

With steam locomotives, then, there is no 'rev-drop effect'. They actually have a continuously variable transmission, except that the variability comes from the valves that control the admission of steam to the cylinders. And steam locomotives are certainly not 'automatics'. **PW**

The author of this piece, Peter Maynard, now owns a 2015 Cayman GTS in place of this 2013 'S' model (below left), photographed at the heritage Great Central Railway in Loughborough, Leicestershire, where he both fires and drives all kinds of classic British steam engines. That's Peter – lucky chap – at the controls of 92220 *Evening Star*, as it was badged in 2015, as a tribute to the last such locomotive built by British Railways in 1960, although it has since been returned to its 'correct' guise, 92214 (below). Key to any such engine's efficient operation is the so-called reverser (far left, bottom), which determines the percentage of each piston stroke during which steam is admitted to the cylinders – hence the numbers you can see on the drum. Think of it as a cross between a Porsche engine's variable valve timing and its gearbox