ROLE OF RPM

RPM makes its contribution to horsepower by the simple fact that rpm tells us how often the engine can perform its power-producing cycle. If every cycle releases the same amount of energy, then maximum power should come at maximum rpm.

We know this is not true. Horsepower rises as a nearly straight, sloping line, then flattens out to a peak. Then it heads back down. The reason for this is that every engine has an rpm of best breathing – that is, of maximum torque. Above that best-torque/best-breathing speed, there is not enough time to complete the cylinder filling process, so torque falls. At first, the fall of torque is moderate, so horsepower continues to rise because the engine gains more from rising rpm than it loses from falling torque.

Finally, a point is reached where gains equal losses. This is peak power. After that, power falls because the continuing drop in torque has gained the upper hand.

Experienced tuners are forever saying that they prefer to make power at the lowest possible rpm. When I was inexperienced, I saw nothing wrong with pushing 250 twins to 13,000-rpm. Racing is extreme, right? So I deliberately sought extremes. And of course I bought a lot of crankshafts.

The reason for this is that mechanical stress on reciprocating parts increases in proportion to <u>the square of rpm</u>. Raise the revs by 10% and you raise the stress by 1.10 X 1.10 = 1.21 or 21%.

If you can find ways to raise torque without raising rpm, this increases parts stress by only simple proportion – raise the torque 10%, get a 10% increase in parts stress.

Another aspect of higher revs is increased vibration. This isn't so bad in auto engines, which have enough cylinders to be able to average out recip forces within the engine. But smaller engines have typically only two, three, or four cylinders. All of these arrangements vibrate, and revving them up asks for the collateral damage that vibration brings – cracked exhaust pipes and brackets, disturbed fuel mixture from carburetor bowl frothing, &c.

There are limits to raising torque. An engine's stroke-averaged combustion pressure, or <u>BMEP</u> (Brake Mean Effective Pressure) gives a good indication of how much more torque can realistically be found in the design. The highest peak-torque BMEP I have ever seen for an unsupercharged four-stroke engine is 230-psi, with a peak-power figure (naturally lower, as explained above) of maybe 210-psi. For two-strokes, 185-psi is good going – although there are reports of somewhat higher pressures being achieved in exceptional cases. As a four-stroke engine closes in on 200-psi BMEP at peak power, you are running out of things to improve and have to think about revving the engine up to get more (or blowing more air into it with some kind of supercharging). As a two-stroke gets up above 165-psi BMEP, it's also time to start thinking about more revs.

Why does an engine have an rpm of best breathing? Why can't it just pump its way to glory, rpm-wise? As the piston moves faster, air moves through intake ports or transfers faster too. But as the process reaches higher air speeds, the density of the air has to fall to reach those speeds. This is what Harry Ricardo called "wire-drawing" – the penalty for very high airspeed in a flow is density loss. Eventually, as the speed of sound is approached, at various higher-speed regions within the flow sonic velocity is reached. Shocks are formed there which obstruct further flow.

Once the end-to-end pressure difference across the duct reaches a ratio of 1.52, the flow becomes sonic. Now, no matter how fast the piston moves, information from the piston side cannot propagate upstream, through the sonic shock, to the entering air. This is a state called "sonic choking". The flow remains the same no matter what the piston does.

On the other hand, engine torque is not constant even <u>below</u> peak, but tends to decrease somewhat as rpm decreases. In a four-stroke there are two reasons for this. One is that intake velocity helps flow to continue entering the cylinder after BDC on the intake stroke – and the higher the intake velocity at BDC, the longer flow will continue to stream into the cylinder – even against a rising piston. The lower the rpm, the lower this intake velocity at BDC becomes, and the less flow will enter after BDC – to the point of actually having flow reverse and be pumped back out by the rising piston. This causes torque loss at lower rpm.

It's clear that small ports will generate high air velocity (and peak torque) at lower rpm, and vice versa. It is the ratio of intake port area to displacement that determines whether an engine gives peak torque at lower revs (Harley) or at high revs (Suzuki). This is <u>not</u> determined by stroke length. At a constant displacement, as the stroke is made longer, the piston's area and therefore the total pressure of combustion gas on its decreases in exact proportion. Therefore as you make the stroke longer, crank leverage increases, but the force acting on that leverage decreases in exact proportion. Nothing is gained. The reason for the old "long strokes make high torque" idea is that long-stroke engines tend to be older designs with small valves and ports that put peak torque at lower revs. Short stroke engines can be built with small valves and ports that move their torque peaks down to low revs so they "pull like a tractor" too.

Valve timing is another issue. To fill an engine's cylinders at higher rpm, it is helpful to leave the intake valves open for many degrees after BDC – but this in turn kills that engine's low-speed torque by allowing the piston to pump mixture back out at an rpm level where intake velocity is low. Therefore "tractor" engines tend to have short valve timings, to avoid this low rpm torque loss from back-pumping of fresh charge.

The use of four valves allows this compromise to be bridged – at least somewhat. Four valves have the area to supply airflow at high speed even <u>without</u> the long valve timings that tend to kill low-rpm torque. Racing engines designed to deliver wide-range torque are therefore given four-valve heads and limited cam timing.

In two-strokes, port areas likewise must be increased as rpm rises – and such bigger ports tend to kill lower-speed torque because of back-pumping. Getting the best compromise here is a matter either of finding a pipe design that doesn't concentrate all its pumping ability in a narrow rpm range, or of using variable-height exhaust port gate devices.

The analog in four-strokes is variable cam timing. Closing intake valves soon after BDC maximizes torque at low rpm, while closing them later as rpm rises maintains peak torque across the range. To maintain good combustion (high in-cylinder turbulence = high flame speed) at lower speeds, some engines leave one intake valve closed to double the airspeed through the other one. High-end auto engines have such systems now, and they will spread.

The biggest determinant of power is how often an engine fires, and it's here that the two-stroke has its big advantage. Even if it peak BMEP is somewhat lower than that of a good four-stroke (165 vs 190-psi, say), the fact that each cylinder fires once per revolution rather than once in two revolutions gives it a big advantage.

To attempt to make up for this, four-stroke engines are designed to rev very high. For a long time we have heard of a "limiting piston speed" of something like 4000 or 4500 feet per minute, as a "barrier to higher revs". There is a barrier, but it is not piston speed, and it is not permanent. What makes engines unreliable at higher revs is <u>piston acceleration</u>, which can make rings stop sealing, break rods, and streak and fail con-rod bearings. To avoid it, the stroke is made shorter, the bore bigger. This works out well because a four-stroke's valves are in its head. The higher we rev it, the more valve area it needs, and the happier we are to have a larger bore in which to put those valves.

A two-stroke works entirely differently, because its ports are in its cylinder wall. Work through the math and you will see that port area increases <u>as stroke is increased</u> – the very opposite of a four-stroke. A decent compromise between wanting a short stroke to limit piston acceleration, and wanting a long stroke to maximize port area seems to come at the point where bore and stroke are equal. Most modern two-strokes therefore have bores approximately equal to their strokes. For this reason two-strokes have excellent torque (firing twice as often) but cannot for reasons of port area take full advantage of shorter strokes to reach high revolutions.

Not so with four-strokes. While car engines must, for emissions reasons, have bore = stroke, motorcycle engines tend to have bore/stroke ratios of 1.5 – 1.6. Even more extreme are F1 engines. To let their 300-cc cylinders survive and pump air at 19,000-rpm their bore/stroke ratios are near 2.25.

Why not just go overboard in this direction, with pie-plate pistons vibrating up and down through 5-mm strokes? As bore/stroke ratio increases, the combustion chamber becomes wide and very thin – a terrible situation for high-speed flame propagation because turbulence has no way to exist in such a space. F1 engines today lose a lot of heat by having to fire their cylinders at over 60-deg BTDC. Compare that with some bore=stroke race engines of the past, which have needed as little as 23-deg BTDC spark lead. And so it's a compromise – to get good combustion we want bore = stroke (which is why the EPA likes it), but to get high rpm and so high horsepower we need a short, short stroke that takes us into The Land of Slow Combustion.

Living in that strange land means searching for strange fuels that smell peculiar, give us instant headaches, and come in pale turquoise-colored drums. To speed combustion we try making the intake ports smaller – this stirs the charge as it fills the cylinder with its fast-moving jets. But it's hard to get high intake velocity AND high intake flow – hence the long hours and lost minds at the airflow bench, trying to combine the two desired but incompatible qualities. Technicians in lab coats cover experimental cylinder heads with ionization gages to map the flame's spread, hoping to find some shape, some demon tweak that will shorten combustion time by 10% - or even 5%. They aim laser Doppler anemometers into cylinders through quartz windows, hoping to learn more about exactly how in-cylinder turbulence can best be preserved as the rising piston crams all that motion into too little space. You can't square-dance in a closet.

Everyone knows that peak combustion pressure rises with compression ratio. What isn't so popular is that combustion speed and efficiency fall as compression rises – because the tighter the combustion space is made, the less room there is for the turbulence that boosts flame speed. So again a compromise is struck – high compression on racetracks where acceleration is essential, low compression on courses where top speed is the key to laptimes. F1 engines – whose combustion chambers are horrible to begin with – have to make do with lower-than optimum compression ratio in order to have acceptable flame speed.

RPM also affects performance through the limits it places on valve motion. With a spring of reasonable size, and therefore with a limited peak valve acceleration, it takes a definite amount of time to lift a valve a given distance, stop it, and then close it again gently enough to ensure its survival. At peak rpm this may mean that you have to use longer cam timing than you would like, in order to get the lift you want. This, in turn, means that the valves are open longer during overlap – that period near TDC at the end of the exhaust stroke when both intakes and exhausts are open together. The more open the valves must be during overlap, the deeper their clearance cutaways in the piston must be fly-cut – and the lower compression ratio must fall.

Even a desmodromic (springless) system has limits – because the levers that move the valves are loaded in bending and cannot be made infinitely stiff. One "answer" has been the use of titanium springs, which fail in fatigue much more slowly that steel and are 40% lighter. Another is pneumatic springs.

Now let's think about mechanical losses. Engine designers aim for a figure of 85% mechanical efficiency, and even F1 designers claim to have achieved this. The problem they fight is that bearing losses increase faster than rpm, so at some high speed the losses will eat up any possible gains. The path around this is to lighten the parts and thereby reduce bearing friction. Pistons become flat disks with mini-skirts to "stabilize" them in the bore, and with only two rings. Con-rods become mere sticks with rings on their ends. Wristpins are shortened even at the cost of locating their bosses on the underside of the very hot piston crown (wristpin galling remains a serious problem). Onward to dreamland, and the (perhaps) soon-to-come ultra-light carbon-carbon pistons with zero thermal expansion, hooked to metal composite con-rods priced to sell only to Bernie Ecclestone or the USAF. With such light parts of such tremendous strength and endurance, revs can rise even higher, higher, until the engine's sweet song (and my voice as I think of it) becomes a barely audible squeak. But you get the idea.

Speed effects are everywhere – personifications of the demons in Dante's Hell, jabbing us with their sharp compromises.