Engine Babble by Random

The power that an engine produces can be predicted (not surprisingly) somewhat accurately by measuring how much air is sucked in through the inlet ports. It is rare to find an engine with significantly less internal friction than its contemporaries; thus, most engines in a class should follow roughly the same air/power ratio.

According to one source a 4-cycle engine breathes in 0.027899 cubic feet per second for every horsepower (hp). An engine that makes about 90 hp needs to flow about 2.51 cubic feet every second. That's quite a lot of moving air/gas. It also explains why the intake noise at full throttle can be louder than the exhaust when a CAI or short intake is used.

It's time for some info. For this article, atmospheric pressure is 14.7 pounds per square inch. e.g. 10 times atmospheric pressure = 147 psi.. It can vary with altitude and atmospheric conditions, but we'll just all it 14.7psi.

Beginning at the moment of ignition, both the inlet and exhaust valves are closed, or nearly closed. The air/fuel mixture as been compressed into the small combustion chamber and with luck is still rapidly thrashing around in all directions due to being squeezed inwards by the squish band. The spark from the spark plug initiates the burning of most but not 100% of the mixture. A little remains unburned, even in the case of a perfectly tuned engine and contributes to the noxious emissions that send the environmentalist types into frenzy. The air/fuel mix changes from a small volume of relatively low temperature gases at about 10 times atmospheric pressure to a small volume of high temperature gases and a even higher pressure of about 50 times atmospheric pressure. This pressure then causes the piston to move downwards quicker than it would if the connecting rod alone was pulling it down (say when you are coasting). The force of this high pressure pushing down on the piston, transfers its force to the connecting rod, and the crankshaft turns a bit faster.

When did the spark occur? Surprisingly, at about 30 degrees Before Top Dead Center (BTDC). It was BTDC because the air/fuel mixture takes a certain amount of time to burn and there is a particular time delay until when the burning gasses give their maximum pressure and consequently maximum push on the crankshaft. You can control when the burning gases give their most push on the piston by choosing an ignition setting. Too advanced and the push comes too early for maximum hp and the engine is in danger of sustaining over-heating related damage. Too late and the motor is not making as much hp as it safely and reliably can. Setting the ignition timing is a bit of an art, and a science.

Now, the piston is heading down, and Before Bottom Dead Center (BBDC) the exhaust valve or valves are about to open and the gas (has hopefully) completed burning well before now. After combustion is complete the pressure rapidly drops as the piston moves away from the high-pressure gases and the combustion chamber volume increases. It would seem best to allow the piston to go all the way to BDC pushed by the high pressure gases and generating all the power possible and then opening the exhaust valve. However, engines open the exhaust valves BBDC. WHY? If you have the exhaust opening BBDC you get more power from....

1. Less work needed to empty the cylinder of exhaust gases. If you let the high pressure still present in the cylinder force most of the gases out the exhaust port instead of making the piston squeeze the gases out during the next cycle, the piston doesn't have to work as hard FORCING the gases out of the cylinder. It also allows the gases to escape with “force and speed”. The high pressure still in the cylinder, and the (hopefully) low pressure in the exhaust system, means that the cylinder will be evacuated quickly, creating a low pressure area in it's wake.(leading to #2)
2. Use the exhaust system to help suck out further exhaust gases and suck in some inlet gases on the next inlet cycle. i.e. employ effective extractors and a good exhaust system design.

The exhaust valve opens at about 50 or so degrees BBDC and the exhaust gases are about 3-4 X atmospheric pressure and squirt out the exhaust port. Because of the high-pressure difference and the gases now travels down the exhaust pipe where strange dynamics occur. As the piston nears TDC again (for the upcoming intake stroke) the exhaust valve is still open and now the inlet valve opens.

What the HECK is the inlet valve doing? It is allowing the (hopefully) low pressure at the exhaust ports (and in the cylinder) to suck the inlet gas (air/fuel mixture) into the engine. Where does this low pressure come from? The high-pressure pulse that travels down the exhaust pipe is reflected back as a low-pressure pulse (i.e. momentary suction when the high-pressure pulse finally exits the header pipe). The speed at which these pulses travel can in some cases make for a low pressure pulse at 6000 rpm but a high pressure (say 1.2 atmosphere) at 4000 rpm and when a high pressure pulse is felt at the exhaust port when both valves are open ("overlap") we get less inlet gases drawn in during the inlet cycle and less hp. You can see this on a dyno graph, or feel it when driving. It's what is technically termed a "flat spot".

Unless the exhaust pipe is sucking the exhaust out and bringing in some inlet mixture, some exhaust will remain in the combustion chamber when the engine next tries to breathe in some air/fuel mix. This residual gas stays in the compression volume of the combustion chamber and dilutes the fresh inlet gases to a varying degree (and also warms it, expanding it, meaning even LESS air/fuel mixture can enter). When the throttle is closed this effect is at its maximum and when the throttle is wide open it's at it's minimum. The diluted air/fuel mixture unfortunately burns slower and so requires a more advanced ignition timing to ensure it's completely burning by the time the exhaust valve opens. It is the reason why most engines have ignition systems that advance the spark timing when a high inlet manifold pressure exists i.e. when the engine is idling.

At about 20 degrees BTDC the inlet valve is open an appreciable amount and gases will be either sucked in during the next 20 degrees, blown out or a combination of the two (due to the action of the exhaust system). The piston travels a relatively small distance during 20 deg. Before TDC to Top Dead Centre so the piston movement contributes little to the first part of the inlet flow. This period when both valves are open is called "overlap" and can be as short as 10 degrees or as long as 100 or more in the case of racing cams.

The exhaust valve closes finally some time after TDC. You may be wondering the exact times when valves open and close and these I can tell you vary considerably from engine to engine and tune to tune. With the exhaust closed and the inlet valve opening further and further the piston is heading down the cylinder, reducing the pressure inside and so allowing the inlet port to flow air and fuel. There is only about 14.7 pounds per square inch of negative pressure that can be achieved anywhere on this planet Earth and even in the most expensive scientific lab equipment the maximum vacuum is still only ever going to be about minus 14.7 psi. This simple fact is what limits how much pressure will push air in through the throttle body, down the inlet port, past the inlet valve and into the engine cylinder. If you want more air in you must push it instead of sucking it and that is what supercharging & turbocharging does. This limit to how hard anything can suck is the reason why it is possible to predict the power output of any given engine when only the amount of air the engine drawn in through the inlet port is known. Maybe re-read the first paragraph to refresh your memory.

The piston by now is at about 90 degrees after TDC and is halfway down the inlet stroke. The speed the piston has reached is at a maximum and is creating the best suction it will ever achieve, pulling air (and fuel if you remembered to put some in the tank) into the engine. At Bottom Dead Centre the piston stops and changes direction again but the inlet valve is still open. Is this wise because the piston will now start squirting the inlet gases back out the inlet port. The valve is still open and will be closing at about 40 degrees after BDC. Why not close it at exactly BDC?

Now, did you know that air is also a fluid? It has a weight (or more precisely a mass) of about 1.3 gram per liter and as a result when air begins to move it wants to keep moving, just like anything else that has a mass. The inertia of the air traveling down the inlet port - which includes the intake manifold, throttle body, and intake system - can be used to push a little more mixture into the engine before the inlet valve closes. There is also a problem with this inlet gas inertia. It works well for some speeds but not so well for others. It takes energy and a certain amount of time to get the gases moving and if this time taken is a large proportion of the time the inlet valve is open then it is better to have shorter inlet manifolds for those and higher revs. Another explanation I've read uses theory and formulae derived from organ pipe resonance. I find it difficult to understand.

So the summary is – short intake manifold runners for high revs but long manifold runners for low revs. It is not possible to have a perfect length, only compromises are possible. Some cars have enjoyed variable length inlet manifolds, or attempts at them. (Daewoo's “DTEC” system is an example of an attempt)

Finally the inlet valve is closed and the piston can now begin the easy bit. Simply squeezing the gases doesn't need sophisticated camshafts, titanium con rods or any other exotic engine components. You just need a cylinder, piston and rings that don't leak much gas, weigh too much and can handle being throwing up and down 220 times a second (at the 13,000+ rev limit for contemporary motorcycles). The gases started at atmospheric pressure and about 65-100 degrees F prior to being sucked down the inlet tract. The evaporating fuel cooled the inlet air flow to some extent and the inlet port and cylinder head, piston and barrel have heated it again by radiation of heat from these much hotter parts. Now the air/fuel mix is being squeezed to about 5 times atmospheric pressure and will approach 10 times atmospheric pressure. If the ignition is working with the throttle well open, the spark occurs at about 30 or so degrees before TDC during engine running, or 10 deg. Before TDC if you are trying to start it. This gives you an idea of how long it can take for the mixture to burn.

We are back where we started, at the moment the spark initiates the burning of the mixture. Now, I want to talk a little of the combustion process. It is of vital importance to the viability of the engine and the power that can be generated from it.

When a compressed volume of inflammable gas starts to burn the pressure may rise so high and quickly that other parts of the unburned mixture may be compressed so much that it spontaneously ignites. All of it at once. Bang. Boom. This is called detonation. If the mixture detonates instead of burns the pressure rises incredibly fast and creates shock waves which transmit large amounts of energy to the various bits in the combustion chamber. Soon a hole will get punched in the middle of the piston, or a ring land will break, and it's time to start sourcing a junkyard motor. Detonation is easy to cause, simply raise the compression ratio to about 20:1 or so and stand well back. The sound the owner makes when he discovers the damage to the piston, cylinder, head, small and big end bearings will turn most bystanders off their beer for a week, some even longer. Sometimes the carbon that gradually accumulates from normal use can start glowing red hot and set off the burning of the mixture before the spark ignition. This is called pre-igniting or "pinging". It also can destroy engines but nowhere nearly as fast as detonation.

Normally, the mixture starts burning from the spark that starts at the gap between the spark plug electrodes and spreads to nearly all parts of the combustion chamber in an orderly fashion. The rate at which the flame travels can be altered more than somewhat. Faster flame fronts mean more hp, slower mean less hp. Why? It has a lot to do with the combination of piston position, gas pressure change rates, piston ring performance, con rod length, the crankshaft stroke, air/fuel burn rates. It is exceedingly complex and I don't dream of hoping to understand this but with a dyno and a few hp tests at different ignition settings you can find a good setting. To get faster flame fronts, the best way is to raise compression, because a higher pressure mixture burns faster, just like the detonation effect only this time it's much milder with only one part burning and the rest waiting for the flame front to arrive. The higher CR means that a little more air/fuel mix is drawn into the engine because there is a smaller combustion chamber volume, which does absolutely nothing good for getting air into the engine. You also get more heat from your fuel of choice when you burn it at higher pressures so the piston gets a bigger shove. The flame front has a smaller distance to travel too, in some cases and this means combustion will be completed a bit more quickly. And finally some very difficult engineering formulas show the engine becomes more "thermally efficient" with higher CRs.

The higher CR probably will require better fuel, which is less prone to detonating/pinging and this, means a higher octane rating.

Also for more flame front speed make sure the gases in the combustion chamber are tumbling around vigorously during combustion. To make the gases move rapidly a narrow area around the outside of the piston comes close to the cylinder head at TDC. This squashes the gases into the centre of the combustion chamber very quickly and gives the gas a very turbulent motion. Ideal to allow the flame front easy access to all the flammable mixture. All the Hyundai engines I've seen have a squish band. Squish bands vary in size and the wonderful thing is that to get a high compression ratio you also tend to get lots of good squish, at least in the case of modern engines. The next thing you can do is make the inlet port flow more air into the engine and this extra air will become compressed to a higher pressure because more air is inside the engine when the inlet valve closes. Better port design, bigger valves, longer manifolds (good only for low revs of course) or super/turbo charging all have this effect.

Closing the inlet valve earlier than normal keeps more air/fuel inside the combustion chamber at low revs. So more torque at low revs. Advancing the cam timing some 12 degrees on some engines and you'll notice the engine will start to ping under certain conditions. Earlier closing of the inlet valve (i.e advancing the cams) meant less mixture changed direction and went back out the inlet port when the piston started to rise so more was kept inside the engine. More gasses to compress, burn, push the piston down and push the dyno roller. The compression tests for standard cam timing were 140psi and with advanced cams it was about 175psi. Note this will reduce torque/HP at higher RPM. This is because the inlet valve is closing too early and is closing when the air/fuel contained in the inlet tract is still moving downwards towards the inlet valve under the influence of inertia. Bad for top end power but good for low down grunt.

It is difficult to burn the tiny bit contained between the piston and the first piston ring because it is very narrow - at about 0.1mm. This contributes to some of the worst exhaust emission chemicals. The wonderful world of Chemistry can help things too with fuels that burn faster than ordinary gas. ELF, the French petrochemical company have specialized lately in developing fuels that burn faster and heat the burnt gases to a higher temperature than the gas we have to use. F1 cars attribute about 100 hp of their 700+ hp to special fuels. I would rather they use what we call “unleaded” because it would ensure the race teams would develop better combustion chambers, etc that will be of direct benefit to us. Not much use knowing all about an engine that uses $50 a gallon fuel. Currently some race cars have to use "unleaded" fuel and this means $5-$25 per gallon stuff that can deal with 12:1 compression ratios and 16,500 rpm. Not to be confused with the unleaded we buy at the corner station.

The formula is (BORE x BORE x 3.14159 x STROKE x No. of cylinders)/4 and so....

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I want to explain some of the ideas pertinent to the burning inflammable liquids and gases inside a internal combustion engine. After reading this you will then be able to cope with the following articles on Carburetors and EFI.

In the ideal world an engine requires and receives exactly the right amount of fuel to burn in the supplied air. Chemistry shows that approximately 14.7 units of air will burn up 1 (one) unit of fuel by weight. eg. 14.7 kg of air for every 1 kg of fuel. Now, that is looking at burning of the fuel from the point of view of a chemist who is interested in atoms and molecules. He (lots of women choose Chemistry as their field too) is usually not interested in tire shredding horsepower. That's for goons (Don't worry, I'm a goon too).

Goons like us asked the automotive engineers to take a look at exactly how richer or leaner an engine would like its fuel/air mixture to maximize various criteria. Best fuel economy demands a leaner mix, maximum power a richer mix and for least exhaust emissions just about stoichiometric is best. Stoicio-HUH? – Metric-what? We call this 14.7:1 ratio derived theoretically by the chemists the 'Stoichiometric Ratio' of fuel and air. I'll abbreviate it to 'stoic' from now on and whenever you see it, think of the chemically exact, theoretically perfect fuel/air ratio.

Why not always set the carbs or program the EFI to deliver the perfect stoic ratio? Usually there are other factors to consider. The fuel/air ratio that maximizes power has been shown to be about 12:1 or 12.5:1 and is about 20% richer than stoic. This extra fuel is required because not all the fuel is delivered in vapor form, some proportion is still made up by small droplets of liquid. This doesn't burn completely because in the tiny volume surrounding the droplet there just isn't enough Oxygen to combine with the fuel. So some fuel remains unburned and usually can be seen exiting the exhaust pipe in the form of tiny black sooty particles or a gray/blackish smoke.

Other effects come into play, for example the cooling effect of evaporating fuel in the inlet gases as it is drawn into the engine. This increases the total mass of air (and fuel) that is sucked into the engine and so adds a little more hp. A bit like inter-cooling on a turbo, the cooler inlet gases will produce more hp because the gases are more dense than usual. But there is a problem with this good for hp but over rich fuel/air mixture,

Some of the fuel simply passes straight through the engine without completely burning. Instead of only water vapor and Carbon Dioxide making up the exhaust gases some rather nasty compounds are formed during combustion. Air is mainly Nitrogen, which is as useful as a bicycle to a fish when it comes to generating power. It mostly passes through the engine unchanged but a small proportion combines with some Oxygen to form various oxides of Nitrogen (NOx). Nitrogen Dioxide (NO2) is particularly noxious, it attacks lung tissue if you breathe it. It helps produce smog and acid rain. Nitrous Oxide (N2O) is commonly termed 'laughing gas' and also is produced, but it then simply ends up adding to the smog/acid rain problem. Unburned hydrocarbons exit the exhaust pipe in various forms. Carbon Monoxide (CO) is extremely poisonous and in it's pure form is odorless, colorless and difficult to detect without proper equipment. This Carbon Monoxide poisons human blood by preventing the red blood cells from transporting Oxygen around the body. Some of the original fuel compounds also pass through unburned and is simply a waste of resources and poisons us as well. A rich fuel/air mix tends to produce black soot type particles that are almost completely Carbon and it's these we see as a darkish exhaust gas. Bad for lungs because these particles are tiny and are implicated in lung cancer. Typically cars are set to give maximum power and so deliver about 20% more juice than the Chemist would recommend. Bugger him, he's wrong, we're right.

But Chemists have their uses, one being maintaining the exhaust gas analysis equipment in the dyno room and this is where it gets a bit iffy. Emissions compliance (for cars at least) demands certain limits on exhaust gas emissions. This can only be achieved by altering what was optimal for power to something that allows the engine to produce small enough amounts of Carbon Monoxide, Nitrous/Nitric Oxides and Unburned Hydrocarbons in the exhaust pipe. Usually these changes only effect idle, pickup from idle and cruise type throttle openings (that's the only place emissions tests “test”). I like to think (even if I'm in error) that big throttle opening situations are not compromised by these environmental concerns. With motorcycles and cars in particular I doubt if 10% of all “modified” vehicles still produce the original exhaust emission characteristics. We all like to fiddle with them. We also make up such a tiny proportion of the total traffic that the EPA seem to want to leave us and our exhaust gases alone. So, compromises are made to the engine and it's fuel delivery. These usually cost hp, and throttle response.

The stoichiometric fuel/air ratio for gasoline is 14.7 parts of air to 1 part fuel. If you want to use Methanol (such as the Shell racing fuel that contains 95% Methanol 5% Acetone) you will find the ratio is about 6:1 now. This means double or more in fuel flow.

Using alcohol has some distinct advantages when the engine's power output is the most important criteria. Firstly, the engine runs a bit cooler even though it's making more hp. Next, about 20% extra power can be found, due to the strong cooling effect the evaporating Methanol has on the surrounding air as it's drawn down the inlet port. If gasoline has 10 units of cooling per unit mass when evaporating, then Methanol has more than 70 units of cooling. The cooler air is more dense so more Oxygen is drawn into the engine to burn with the fuel. More power.

An engine can have a much higher compression ratio when running on alcohol because it is less prone to detonation compared to gasoline. More power from the higher compression ratio. Some race tuned engines can run very well on (alcohol) fuel/air mixtures way richer than the approximately 6:1 correct mixture. This extra fuel which doesn't get burnt simply cools the inlet air. This makes the inlet mixture more dense and so more air (as measured by weight) is present inside the engine when the inlet valve closes. More hp again. Early Alfa Romeo GP cars (pre WW2) did as little as 1 or 2 miles per gallon. They enjoyed 2 stage supercharging with a very much over rich fuel mixture to maximize the amount of air introduced into the combustion chamber. What Oxygen was present was completely used up burning some of the fuel. The rest of the fuel exited via the exhaust in vapor form, probably helping the exhaust system in subtle ways as well. This laughably over-rich mixture allowed the engine to run very cool and some people termed this car "Alcohol Cooled" because of the relatively small radiators fitted to the car. This sort of engine is a source of wonder to me but sends environmentalists into psychotic rants/raves.

Simply introducing some fuel and some air into an engine is not even half the story. How well the fuel is distributed within the air is very important. A typical 4-stroke engine receives fuel in 3 forms. Firstly fuel is evaporated and this gas is carried inside the inlet tract by the flowing air and so will be very well mixed with the air when the inlet valve closes. Some fuel doesn't get a chance to evaporate and is carried into the engine in the form of tiny droplets of liquid. Again the flowing air can easily keep most of this mist airborne as it flies into the engine. Finally some fuel doesn't even get airborne for very long and collects on the inside of the intake manifold walls, and all the way along the inside of the inlet port. This fuel can make up a very significant proportion of the fuel the engine receives and can't be ignored. It flows into the engine at a speed much less than the speed of the intake air.

For the mixture to ignite, some air and fuel (in vapor form) must be present in the spark plug gap. The air/fuel proportion could be anywhere from 12:1 to 16:1 but the important thing is that enough fuel vapor (not droplets) is present in this region. Droplets of liquid fuel are not burnable, rather it's the fuel vapor mixed with the air is what burns.

To start a cold engine, a much richer mixture is required because a smaller proportion of fuel is evaporated during the inlet stroke because evaporation rates are effected by temperature. The rest of the un-evaporated fuel we simply waste and it exits the exhaust pipe in various incompletely burnt forms, one of which is Carbon Monoxide. A good reason to warm your car/motorcycle up outside the garage. This "liquid" fuel also coats the cylinder, piston crown, cylinder head and inlet valve(s). Gasoline is not a very good friction/wear resisting liquid, unlike oil, and is one of the factors that contributes to high engine wear rates when starting and warming up.

As the engine warms up, more and more fuel is evaporated in the inlet air flowing into the engine and so we can progressively reduce this extra enrichment demanded for the cold start.

When the engine is fully warm most but not all fuel is burnt inside the engine. Still some fuel is wasted and some of this fuel contributes to a cooler and more dense inlet mixture which is good for power. (Remember the 12:1 fuel/air ratio which was best for power?) Other liquid fuel is flowing down the inlet manifold and some of this is evaporated and burnt as it is flung past the valve seats.

So when trying to tune for maximum power, don't use an exhaust gas analyzer or any other guide but the dyno, and A/F ratios. It's far too complicated.