White Paper

Title: Using a Model 9003 2-Gas (CO/HC) Gas Analyzer for Motorcycle Tuning
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Using a Model 9003 2-Gas (CO/HC) Gas Analyzer for Motorcycle Tuning: CO as an indicator of Air/Fuel Ratio, and HC as an indicator of Combustion Efficiency-
Comparison to the Model 9004/5 with Lambda & Combustion Efficiency calculations

The Model 900303 is a hand-held 2-gas (CO/HC) analyzer which can be used for basic small engine tuning using the CO gas reading to set fuel volume, and the HC level to confirm running efficiency. The purpose of this white paper is to provide technical background on this method.

CO variation with Air/Fuel mix:

For some time, it has been recognized that the Carbon Monoxide content in engine-out exhaust gas for a well running engine is closely related to the air/fuel ratio. The following curve has been found in the public domain for many years

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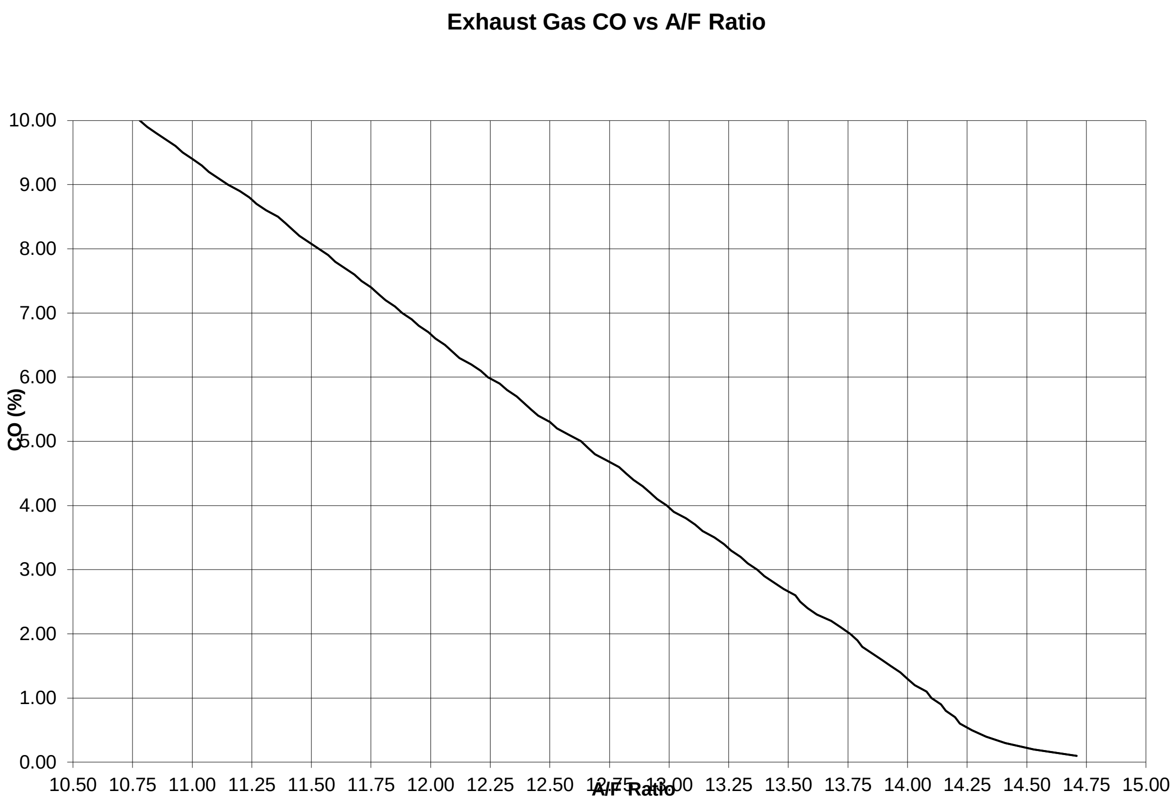

The almost perfectly linear relationship between CO and A/F ratio yields a very simple way to setup a carburetor or fuel injection – but it is wise to understand just where this comes from first.

Carbon Monoxide Production as Part of the Combustion Process:

When fuel is burned, power is produced as the H's in the fuel are oxidized to H2O (Water) and the C's are oxidized to CO2 (Carbon Dioxide). However, the Carbon oxidation path goes to CO (Carbon Monoxide) first, and then the CO is finally oxidized to CO2 as the final process.

If there is not enough air to completely oxidize the fuel, there will be free Hydrogen and CO in the exhaust gas. While free hydrogen is difficult to measure, free CO is relatively easy – and the curve above shows what happens as air (containing oxygen) is gradually reduced.

The curve above shows that there just enough oxygen to fully complete the oxidation of CO to CO2 at 14.7 lbs of air to 1 lb of fuel – a ratio of 14.7 to 1.0 – the stoichiometric

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point. At this point, all of the CO is being burned to CO2, so the CO level in the exhaust is Zero.

As oxygen is gradually reduced (or in this case, fuel is increased), there is simply not enough oxygen to completely burn the CO in the exhaust, and you can see a pretty much linear relationship. As the AFR decreases, the CO remaining in the exhaust gas increases.

Tuning for performance usually occurs on the rich side of stoichiometric to prevent the engine from running lean under transient conditions, so the curve above is very meaningful for performance tuners – who generally tune for between 2.50% and 5.50% CO – an A/F ratio of 12.5 to 13.5. Doing so ensures that under transient conditions, where there may be momentary fuel delivery problems, the mixture still remains rich enough to ignite. The downside is that the engine is running rich under steady-state conditions – so fuel economy is mitigated and high CO emissions and the propensity for spark plug loading occur as well.

Still, it is relatively common for tuners to set the mixture on a bike to produce 4.00% CO or so at steady-state running in order to get the desired transient performance.

Using HC as an indicator of Combustion Efficiency:

HC is unburned fuel vapor. When an engine has high combustion efficiency, it is burning each and every intake charge as well as it can. There may be some CO produced if the A/F mixture is rich, but the amount of HC in the exhaust is still quite low. Thus, the HC content in the exhaust gas is more a function of combustion efficiency than it is a function of A/F ratio.

For example, a lean misfire (A/F ratio much to high) can cause the intake charge to not ignite. If this happens, unburned fuel vapor will appear in the exhaust gas – and you will see lots of HC.

The difference in HC content in the exhaust of a well running engine (Combustion Efficiency of 95% or so) and a poor running engine (Combustion efficiency less than 90%) is quite extreme – going from 100's of ppm to 1000's of ppm. So, the HC level in the exhaust can be a reasonably good measure of combustion efficiency.

Errors in the CO and HC Only Method:

CO to A/F Ratio:

CO production is also a function of combustion efficiency. If the intake charge does not burn completely, then there will be CO in the exhaust gas. For example, while the published curve shows that CO goes to about 0.00% at 14.71 to 1.0 A/F ratio, this rarely happens. The combustion efficiency of an internal combustion engine is generally less than 95%, and at this level, there will still be 1.00% CO produced – even if the air and fuel are in perfect balance.

In addition, if there is a small misfire, then the unburned charge gas dilutes the exhaust from the properly firing cylinders. We have seen small misfiring dilute the CO from correctly firing cylinders to cause artificially low CO readings in the total exhaust gas. So – the true relationship between CO in the exhaust gas and Air/Fuel ratio is not quite what the curve above suggests. The effect of combustion efficiency has to be taken into account here as well – and this can get somewhat complex. Suffice it to say that this method of relating CO to A/F ratio is a good first approximation. It is not quite accurate, but it is close – A/F within about 0.75 (Lambda = 0.025).

HC to Combustion Efficiency:

HC is an indication of pretty gross combustion inefficiency. It does not take into account at all of partial combustion effects – but only focuses on unburned fuel – which is not only due to misfire, but incomplete combustion due to combustion chamber design or air/fuel ratio. As such, it is a general misfire indicator or an indicator of seriously incomplete combustion, but that is about it.

A Better Way – 4-Gas Analysis:

When CO2 and O2 are measured along with CO and HC, then the problems above are resolved. Lambda, A/F Ratio, and Combustion Efficiency can be directly calculated from the exhaust gases and compensated to correct the above deficiencies. These parameters are calculated every ¼ second automatically using the true exhaust gas readings on the Model 900403 and 900503:

The Lambda (A/F Ratio) Calculation:

Lambda is the ratio of oxygen available to complete the combustion process vs oxygen required by the fuel present. If there is just enough oxygen for the demand, then Lambda= 1.000. If there is 5% less than needed, (5% rich) then Lambda=0.950. If there is 5% too much (5% lean), then Lambda = 1.050. This balance calculation uses at least 4 gases (CO, HC, CO2, and O2) to make – as an exact accounting of all of the Oxygen and Carbon atoms must be made to determine the Air/Fuel balance. (Hydrogen is burned too, of course, but we know the ratio of Hydrogen atoms to Carbon atoms in the fuel – so knowing the Carbons we can account for the Hydrogen demand.)

Lambda exactly relates to A/F ratio. If at Lambda=1.000 (the stoichiometric point) A/F ratio is 14.7, then A/F ratio = Lambda x 14.7. This is a strictly linear relationship, so, for example, at Lambda=0.950, the equivalent A/F ratio would be 13.97. (We display them both, of course.)

The equivalent Lambda for tuning at an A/F ratio of 13.0 is 0.884 – 11.6% rich. So, something in the order of 10% rich is typically required for performance tuning.

Lambda calculation (which is done by calculating the oxygen and combustibles content in the exhaust gases) is exact – and is NOT a function of combustion efficiency. If the Lambda value (or A/F ratio – both are reported by the Model 9004) is stoichiometric – then it really IS stoichiometric, regardless of how well the engine is running at the time. This is because all of the Oxygen, Carbon and Hydrogen atoms are measured or accounted for in the exhaust gas, whether or not they are oxidized.

The Combustion Efficiency (CE) Calculation:

Combustion Efficiency is a measure of the degree to which the fuel is completely burned.

The Model 9004/5 measures unburned fuel (HC), partially burned Carbon (CO) and fully burned Carbon (CO2) and calculates how complete the carbon oxidation process is. This value is a function only of how fully the carbon in the fuel is being fully converted to CO2 (Hydrogen follows along with carbon, so it is similar) – and gives a very good indication of the running performance of the engine – largely independent of AFR.

Having both Lambda (AFR) and Combustion Efficiency (CE) directly calculated from exhaust gas levels provides the engine tuner with better and more repeatable measures of engine performance than the 2-Gas (CO/HC) method described above.

We still feel that the tuner himself should make the decision of the value of each of these methods based on his needs and experience. The gas analyzer should be considered only to be a tool – albeit a sophisticated one – to aid the technician in his work. It is his judgment that matters the most at the end of the day – and he should expect to learn to relate good results to gas readings, Lambda, AFR and CE based on tuning experience.

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