White Paper

Title: Tuning an LPG Engine using 2-gas and 4-gas analyzers – CO for Air/Fuel Ratio, and HC for Combustion Efficiency- Comparison to Lambda & Combustion Efficiency
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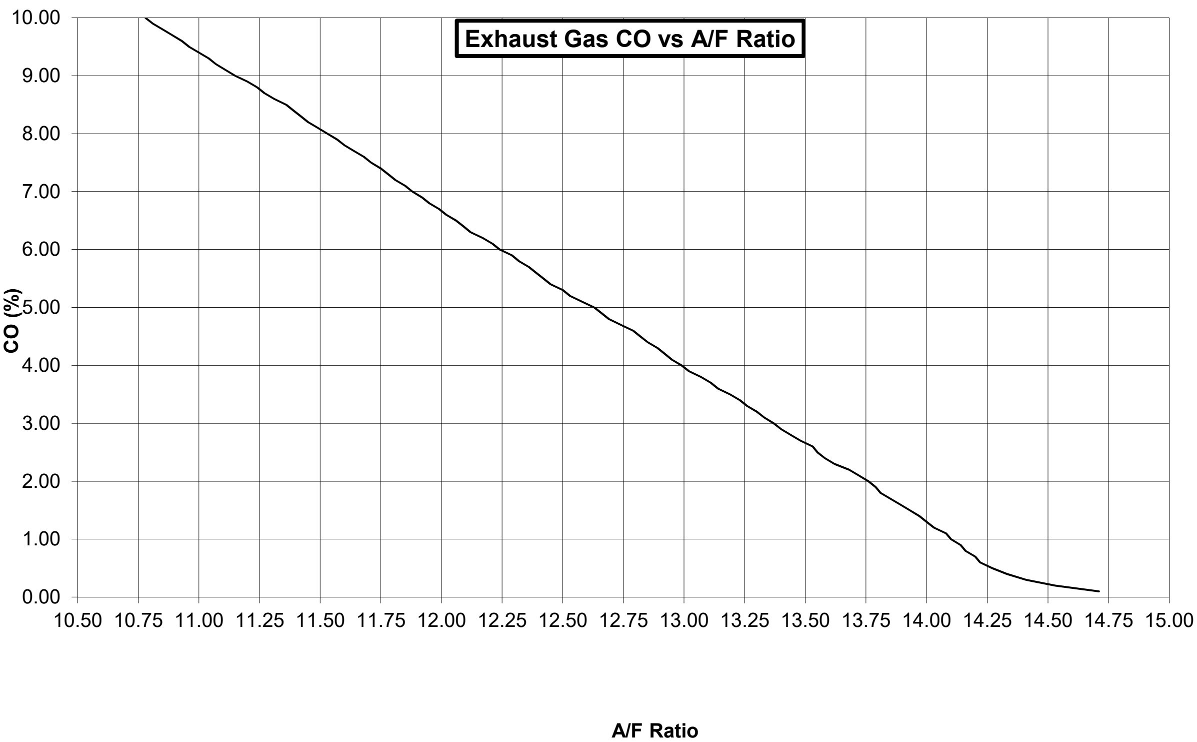
A 2-gas (CO/HC) analyzer which can be used for basic small engine tuning using the CO gas reading to set fuel mixture, and the HC level to confirm running efficiency. The purpose of this white paper is to provide technical background on the use of the analyzer in this method.

CO variation with Air/Fuel Ratio:

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, used to performance tune gasoline fueled equipment has been 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 gasoline – a ratio of 14.7 to 1.0 – the stoichiometric point for gasoline-fueled equipment. (Each fuel has its own unique A/F ratio, but the principles remain the same.) At this point, all of the CO is being burned to CO2, so the CO level in the exhaust is Zero if there is 100% combustion.

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 Oxygen ratio to fuel decreases from the stoichiometric point, the CO remaining in the exhaust gas linearly increases. This is due to the linear (straight line) reduction in Oxygen as the AFR decreases. The same principle applies for any fuel. Although the AFR at the stoichiometric point is different than 14.71, as it is for gasoline, as the AFR is decreased, the combustion process linearly runs out of oxygen, and CO (partially oxidized carbon) is created instead of CO2. This is an important fact to realize. Carbon is oxidized to CO first by the combustion process, then into CO2. Carbon that is not fully oxidized o CO2 by the combustion process remains as CO. So – as CO increases in exhaust gas, CO2 decreases. CO2 comes from CO – and high CO means that this second oxidation process is not running to completion.

Performance Tuning:

Getting back to performance, tuning for performance usually occurs on the rich side of stoichiometric to prevent the engine from running lean and misfiring under transient

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conditions, so the curve above is very meaningful for performance tuners – who generally tune very heavily for CO - between 2.50% and 5.50% CO – a gasoline A/F ratio of 12.5 to 13.5. Doing so ensures that under transient conditions, where there may be momentary fuel delivery or mixing problems, the mixture still remains rich enough to ignite. The downside is that the engine runs rich under steady-state conditions – so fuel economy is mitigated and high CO emissions occur.

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

CO Emissions Tuning:

The case is just the opposite for those concerned with CO emissions. They tune at stoichiometric or a little lean in order to keep CO emissions low. In doing so, they are walking the tightrope of performance vs CO emissions, as the intake charge may not ignite or combust fully – resulting in deteriorated performance.

In general, tuners of LPG equipment will tune lean enough to reduce CO emissions, but not so lean as to sacrifice performance. And – it is easy to see why the other elements (spark plugs, wiring, spark coil, timing, etc) that may effect charge combustion all come into play. In addition, any element that effects general performance (air filters, compression, oil contamination, etc) have to be considered as well.

It can be difficult to obtain the requisite balance between CO emissions and vehicle performance – as the equipment must have a close-to-stoichiometric air/fuel mixture to get the CO emissions low, but not exhibit significantly lowered performance due to lean tuning for lowered emissions.

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 by comparison to an outright misfire. 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, the unburned fuel vapor will appear in the exhaust gas – and you will see very high values 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 Methods Above:

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 can easily be less than 95%, and at this level, there will still be 0.50% to 1.00% CO produced – even if the air and fuel are in perfect balance.

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 and you can generally get A/F within about 0.75 (Lambda = 0.025) with this method.

HC to Combustion Efficiency:

High HC is an indication of pretty gross combustion inefficiency, as it does not take into account partial combustion effects – but only focuses on truly unburned fuel. As such, it is a good misfire indicator or an indicator of seriously incomplete combustion, but that is about it, and does not really give a measurement in a way that can be correlated to true combustion efficiency.

A Better Way – 4-Gas Analysis – Lambda and CE:

When CO2 and O2 are measured along with CO and HC, then the problems above are resolved, and Lambda, A/F Ratio, and Combustion Efficiency can be directly calculated from the exhaust gases – and are calculated automatically 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 to do so. If there is just enough oxygen, 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.

Lambda relates exactly to A/F ratio. If at Lambda=1.000 (the stoichiometric point) and the stoichiometric A/F ratio for gasoline is 14.7 to 1.0, then A/F ratio = Lambda x 14.7. So, for example, at Lambda=0.950, the gasoline A/F ratio would be 13.97. (Other fuels have their own mass ratio at the stoichiometric point, but the Model 900403 and 900503 automatically use the right values if the fuel is selected correctly – so the AFR shown is correct for the fuel being used.)

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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 and Carbon and Hydrogen atoms are measured and 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 by direct output gas measurement. Point is that 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 A/F ratio.

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

However, the tuner himself should make the decision of the value of each of these methods based on his needs and experience.

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