Five Gas Exhaust Analysis Theory
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When we do exhaust analysis, we are being a ***detective***. We look at what came out of the exhaust and figure out what could have happened before to create those emissions. What happened in the combustion chamber, or before the combustion chamber, to create these results?

We can use clues and patterns of exhaust readings to figure out if we have a problem in one of the following areas:

* Air/Fuel Ratio
* Combustion
* Ignition
* Emission Control Device

Then we know where to start our diagnosis with visual and functional tests.

Let's start by reviewing ***good combustion.*** The idea is to properly burn up all the gasoline and not have any "leftovers". Into the combustion chamber we put gasoline, symbolized by 'HC' for hydrocarbons. These are combinations of hydrogen and carbon atoms, organic matter from old dinosaurs maybe? We also add lots of air, which contains oxygen, symbolized by 'O2'. (Oxygen atoms feel more comfortable going around in pairs.) Normal air is about 20.7% oxygen, and if your shop smog machine doesn't show about this when reading the air inside your shop, you could have a bad oxygen sensor in your smog machine, or a serious problem with the air in your shop, or the planet has a problem... Back to combustion. The air we add to the combustion chamber is mainly nitrogen, about 78%. (No, that's not nitrous, but related.) This doesn't burn, it just goes along for the ride and expands with the heat, helping to push down the piston.

Coming out of the combustion chamber we have carbon dioxide, water and nitrogen. The carbon dioxide is symbolized CO2. (One carbon atom combined with two oxygen atoms) It's good, in that plants like it and it doesn't hurt us, but too much is blamed for global warming. The water is symbolized by H2O, two hydrogen atoms combined with one oxygen atom. Did you realize that for every gallon of gas we burn, the tailpipe puts out about about a gallon of water? And then good combustion also puts out all the nitrogen that came in.

Good combustion is simply put this way:
HC + O2 + N2 = H2O + CO2 + N2.

I leave out the numbers which show proportions. Most of you know we want an ideal mixture of 14.7 pounds of air to one pound of gasoline for the cleanest burning. (Stoichiometric ratio, a term used in chemistry where the right amount of ingredients are present so everybody has a dance partner and nobody is left out.)

Now for ***Bad Combustion***. This is where the wrong things happen, and the byproducts of combustion produce gases which contribute to air pollution or other problems. One example is raw gasoline (HC) which goes in, then comes out, and isn't burnt up in the process. Another example is carbon monoxide (CO). It doesn't create smog, but it's deadly, so you don't want it around. A third example is NOx. It helps create out brown smog. These are all a problem, and we are soon going to talk about them in more detail. But first, look at what it takes to create photochemical smog:

HC + NOx **+ Still air + Sunlight = Smog.** Get the idea? The HC and NOx are what it takes to create smog, so if we prevent them from coming out of the tailpipe, we cut down on the smog.

Next we need to know ***what the Smog Machine measures***. These are the gases that the 4 or 5-gas smog machine sees:

- HC: Unburned Gasoline
- CO: Partially Burned Gasoline
- CO2: Completely Burned Gasoline
- O2: Oxygen, the Good Stuff
- NOx: Oxides of Nitrogen (This is only seen by a 5-gas smog machine)

When the tailpipe emissions are bad, what kind of problem do we look for? Here is a **summary** of what we are going to talk about:

- **HC: misfire or bad burn**
- **CO: too rich**
- **CO2: engine efficiency**
- **O2: too lean or just air**
- **NOx: too hot or too lean**

Now, let's talk about these gases in more detail, and see what causes each of them to be out of normal range.

HC, Hydrocarbons: HC is measured in parts per million (ppm), and a normal good vehicle may put out about 50 or less. When we have HC coming out the tailpipe, it is gasoline that didn't burn in the combustion chamber or somehow escaped the flame of the combustion chamber. So when we see excess HC, think ***Misfire or Bad Burn***.

Many conditions can cause this:

- Ignition problems
- Air/Fuel ratio too rich or too lean
- Mechanical engine problems
- Emission control device not working properly

An **Ignition** example: if a spark plug is fouled, gas in that chamber doesn't burn, and lots of raw HC is pumped right out the tail pipe. You will often see close to 2000 ppm in this case. (2000 is the highest many machines will read.) Or, if the catalytic converter is working pretty well, you may see a lot less. Many high levels of HC come from a variety of ignition problems: open or grounded spark plug wires, switched plug wires, weak coils, etc.... Don't forget that higher HC's can come from ignition timing that is too far advanced. Why? The spark occurs before the air/fuel mixture was compressed enough for best vaporization, so it doesn't burn as completely. And some HC are left over. Or if the spark plug gap is too small, not enough gas molecules are ignited to start the flame, and the flame may not eat up all the HC.

If the **Air/Fuel** ratio is wrong, the conditions are not right to burn up all the fuel, and some HC will end up coming out. If the cylinder is too rich, there is not enough air too burn all the fuel, and some is left over. If the mixture is too lean, there is too much air which makes the fuel too far apart to burn all of it effectively, so some escapes the flame.

Mechanical problems cause excess HC. Worn piston rings which don't allow good sealing of the combustion chamber can stop the high pressure and temperature from developing, so good vaporization of the fuel doesn't take place. Then it doesn't all burn and the HC's are higher, just like in advanced timing. A burnt exhaust valve will just let out raw gas into the exhaust. A burnt intake valve may mess up the flow going into other chambers. If a connecting rod is bent, like from an intake gasket leaking coolant into the chamber that couldn't be compressed, you will have lower compression pressures and poor vaporization. So HC's get out. Lot's of carbon deposits in the chamber can absorb gasoline so it escapes the flame, then gets released on the exhaust stroke of the piston so, again, more HC gets out.

An **Emission Control Device** that doesn't work right may be an EGR valve where the spring has lost it's tension and the valve opens too much under light load. So with too much exhaust in the chamber, the flame front is cooled off as it tries to spread out because the exhaust can't burn again. Again, too much HC gets out. Or if air injection isn't working, there may not be enough extra O_2 to complete the burning of the leftover HC's. If the catalytic converter isn't efficient, not all the leftover HC will be burned up the way it should be.

***CO, Carbon Monoxide*:** We measure CO as a percentage (%) of the exhaust sample. And less is better, usually 0.5 % or less. Too much CO is always from a rich condition. There wasn't enough oxygen to let the burn process finish to get to CO_2. The richer the condition, the more CO you will have. At the ideal 14.7:1 air/fuel ratio we get less than 1% CO. At 14:1 air/fuel ratio we get about 1.4% CO, at 13:1 we get about 3.5% CO, at 12:1 we get 6% CO, at 11:1 we get a whopping 8% CO. You get the idea. And don't forget, CO is very hungry to attach to another oxygen, (remember that Oxygen atoms like to pair up) especially in a warm environment like your lungs. It only takes 0.3% CO for about 30 minutes and you are history and won't ever have to renew your smog license again.

CO2, Carbon Dioxide: CO_2 also gets measured as a percentage (%) of the exhaust sample. Remember CO_2 is one of the end products of the burning of gasoline. And it is only created in the combustion chamber or the catalytic converter. (Well, maybe a little in the exhaust passages if it is really hot.) So the more CO_2 we create, the better our engine and cat were working. So we use CO_2 as an indicator of engine efficiency. The more, the better. Usually we see 13 - 15 %, sometimes even more. Any problem with the engine will bring CO_2 down. Too rich, too lean, misfire, these will all lower the engine efficiency and CO_2 comes down. Beware: proper air injection into the exhaust will also dilute the CO_2 and bring it down, but this is not a problem. But exhaust leaks can be a problem for catalytic converter efficiency and they will bring down CO_2. (And the O_2 will come up, but we'll get to that next.)

O2, Oxygen: O_2 is also measured as a percentage. Remember normal air has about 20.7% oxygen, and air that has been burned has very little oxygen left in it. (Maybe 1 - 3% depending on how leak free the exhaust and muffler are.) So O_2 is normally low, unless there is a lot of air injection in the exhaust. This can bring the O_2 up to as much as about 8% O_2 with an air pump, much less with pulse air injection. So use O_2 to tell you if the air pump is turned on or if there are exhaust leaks. When there is a misfire, this will also bring up the O_2. Air got pumped in, it didn't burn, so you will see it when it gets pumped out. O_2 can also indicate a lean condition. The leaner the engine runs, the more excess oxygen you see coming out the exhaust.

NOx, Oxides of Nitrogen: We measure NOx as parts per million (ppm). It is created under high heat (over 2500 F) and pressure. Think ***stress***. What happens is that as everything is coming apart and recombining in the restructuring of the combustion process, the high heat and pressure of combustion just get to be too much. Nitrogen is forced to combine with different amounts of Oxygen. And we get NOx. This happens only under a load, when the engine is working hard. A lean air/fuel ratio can cause more heat than normal so this will happen. Or if the engine is overheating. Maybe the EGR valve isn't flowing enough, so the combustion isn't cooled down the way it should be. Maybe carbon in the combustion chamber is causing a higher compression ratio, this causes more pressure and heat, and more NOx. Perhaps the ignition timing is too advanced. This causes more pressure and heat because the spark is sooner, and the piston does more upward travel, compressing more as the flame front is already expanding. Last, but not least, the catalytic converter may not be cleaning up all the NOx it should. (It should do a lot, that's what we pay it for.)

To review: when these gases are abnormal, look for this kind of problem:

* **HC: misfire or bad burn**
* **CO: too rich**
* **CO2: engine efficiency**
* **O2: too lean or just air**
* **NOx: too hot or too lean**

Now I have a confession to make, I've been holding out on you. You need to see this in chart form. We call it the ***Five Gas Chart.*** It helps you think about ***relationships. (***Not with your girlfriend, but among the gases--how they relate to each other.) The chart shows how much each of the gases we normally see coming out the tailpipe, depending on how rich or lean the air fuel ratio is. The colored curved lines represent the gases. And rich or lean is represented by how far left or right you are on the chart. So, as you go to the left, you get richer and the CO line goes up. And as you go to the right you get leaner, the oxygen increases and the O2 line gets higher. And you notice the lowest emissions are in the center at stoichiometry, where we have the highest efficiency. And HC's get worse as you go too much to the left or right, either too rich or too lean.