Technical Support Note

Title: Air Dilution Correction using O2 and CO2
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Overview – Qualify the exhaust by using the O2 and CO2 readings:

The purpose of this document is to provide insight into air dilution – the major cause of gas measurement errors in tailpipe testing of vehicle exhaust – and a methodology to qualify the integrity of the exhaust gas sample being measured.

The Problem - Getting good exhaust gas delivery with pulsating exhaust:

Internal combustion engines produce exhaust gas pulses – which can easily be mixed with air – as ambient air gets drawn into the tailpipe. Sometimes it is difficult to obtain good exhaust gas – due to low exhaust gas volume and pulsations at low rpm's, insufficient or difficult probe insertion, or an extraneous air leak. Fortunately, the levels of O2 and CO2 in the delivered gas can be used to 'qualify' the integrity of the gas sample and determine the relative amounts of exhaust gas to ambient air in the gas sample. The oxidation of the hydrocarbon fuel produces H2O (water) and CO2 and CO – and use up the oxygen in the air to do so. While water vapor is not measured, the carbon products are, as is oxygen – allowing a quick and easy way to tell if the gas being measured is air-diluted.

Exhaust Gases – Principle of Combustion:

The purpose of the engine is to use the oxygen in ambient air (about 21%) to oxidize the hydrogen and carbon atoms in the fuel – producing heat as a result, and then to use this heat to create mechanical power. To do this, the engine intakes ambient air, mixes it with the correct ratio of fuel, intakes it into the cylinder, ignites it, and uses the heated expanding gas to create power. The air/fuel mix is balanced so that there should be just enough oxygen in the incoming air to burn all of the fuel in the intake charge. This is called Stoichiometric combustion – and spark-ignited engines seek to maintain air fuel mixtures close to stoichiometric throughout the range of rpm and power settings. This means that the exhaust gases produced should have very low levels of unused oxygen and high levels of CO2 in them – as opposed to ambient air which has high levels of oxygen and low levels of CO2. This can be used to determine if there is ambient air in the measured gas.

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How to use the O2 and CO2 Readings to estimate air dilution:

Because we know that there is 21% oxygen in ambient air, every extra 1.0% O2 in the exhaust is an indication of 5% air dilution. So, for example, if the analyzer is indicating 4.5% O2, and you are expecting to see 0.5% O2, then you have 4.0% excess Oxygen – meaning about 20% air dilution. So – always look first at the O2 reading to see if it is low enough. If it is not – you have a high probability of air dilution.

This air dilution means that all of the other gases will be reading lower than they would be on true exhaust gas too, and you can use this fact to confirm that you are seeing air diluted exhaust – and the next thing to do is to add up all the 'carbons' in the exhaust gas.

The combined addition of CO and CO2 on gasoline is about 15% for gasoline, and 12% for LPG. Look at the CO and CO2 readings, add them together, and evaluate the sum.

For the case above you would see only 80% of the expected 15.0% CO+CO2 in gasoline exhaust – or about 12%. For LPG, where the expected carbon sum is 12%, you would be seeing about 10%. The combination of high O2 and low carbon sums are proof of air dilution, and can easily be used to qualify exhaust gas sampling and find air leaks.

This method allows you to evaluate and reduce the amount of air dilution in the gas sample by changing the probe insertion length, position, or partially blocking the exhaust - or by increasing the throttle setting to increase the gas flow to fill the exhaust system better.

Once you have achieved the best sampling you can, you can compensate for it in the other gas readings. In the case above, for example, dividing CO, HC, CO2 and NOx by 0.8 will correct the readings for the 20% air dilution.

Correcting the Sources of Air Dilution – what to look for:

When the probe is first inserted in the exhaust pipe (engine running), you should expect to see the indicated O2 reading go down from 20.6% to 1.0% or less within about 10 seconds. If the O2 level does not go down low enough – but stabilizes at a higher than expected reading, this is an indication that air dilution exists, and the level of air dilution can be determined by multiplying the excess O2 reading (subtract the normal O2 reading from the indicated O2 reading first) by 5% air dilution. A good number to obtain is less than 10% air dilution, or less than 2.0% excess O2 in the gas being measured. If you see more than this, you should troubleshoot the system and correct it if possible.

Vehicle-Related Air Dilution:

Pulsating Exhaust Gas:

Increase the engine rpm to create more exhaust gas volume and smooth the flow, and watch the exhaust gas analyzers. If the O2 reading goes down to acceptable levels after

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about 10 seconds or so – you are getting air dilution at the probe tip. This can be corrected by either increasing the insertion depth of the exhaust probe, or restricting the area between the probe and the tailpipe to prevent outside air from entering the exhaust pipe. Additionally, the engine speed can be increased to create a better fill of the exhaust pipe.

Air Leaks in the Exhaust, or Intentional Air Injection:

Examine the exhaust system for air leaks, and make sure Air Injection Control is disabled during the test. Even small air leaks close to the sampling site can cause serious air dilution problems.

Analyzer-Related Air Dilution:

Correct Ambient Air Leaks in the Probe or Sampling Line:

Examine the probe fittings to make sure that they are tightly sealed – especially the filter interfaces – as sometimes when filters are changed, they either are not tightly installed, or have thread impaction that allows air leaks to occur. The entire gas transport system operates under a vacuum from the probe tip into the analyzer, so any leak in the path can cause unwanted air dilution. Makes sure the gas transport system is leak-free.

Water Trap Valve:

Examine the water trap valve at the base of the clear water trap. If this valve has particles in it, it cannot seal well – and will leak air. This is indicated by bubbles appearing in the water in the water trap, or can be easily tested by temporarily placing your thumb over the water trap valve housing when the probe is installed to ensure a tight seal, and observing its effect on the O2 reading on the analyzer.

Backup Test of the Analyzer– Check a Modern Car or Truck:

Overall System Verification – a Functional Test using Standard Automotive Exhaust:

Modern (after 1996) gasoline fueled vehicles have advanced engine control systems with electronic closed-loop fuel injection systems and catalytic converters. These vehicles produce excellent examples of complete combustion exhaust gas leaving the tailpipe. They can be used to verify that the exhaust gas analyzer is operating properly, as they produce very low levels of O2, CO, and HC, while keeping CO2 at quite high levels – around 15%. The exhaust gas analyzer can be used to measure the exhaust from a gasoline fueled road vehicle as well as LPG-fueled equipment – and by knowing that the road vehicle produces very consistent gas levels, both the operation of the gas analyzer and the amount of air dilution in the gas sampling system can be readily assessed. This process can be used as a back-up method to determine whether a problem is due to the gas analyzer or gas sampling method.

Mathematical correction for air dilution:

There is a strict mathematical method that uses the O_2 reading to determine air dilution, and then the CO_2 reading can be used to check the calculated value. This is handy for those cases where there is no easy remedy to correct the source of air dilution. The mathematical process is given below:

1. Record the O_2 reading.
2. Subtract the normally expected exhaust gas O_2 reading from it (0.5% to 1.0% for non-catalytic converter equipped vehicles.)
3. Divide the remainder by 20.6 – the oxygen in ambient air. The result is the air dilution factor – the fraction of gas being measured that is ambient air. (This number should be less than 1.00 – and as low as possible (0.10 or less) is what you are aiming for.)
4. Subtract the air dilution value obtained above from 1.00. This is the exhaust gas dilution factor, the fraction of gas being measured that is true exhaust gas. (This number will always be less than 1.00, but make it as high as possible.)
5. Divide the reported CO and CO_2 readings by the exhaust gas dilution factor obtained above. The result in a dilution corrected sum value, which should agree with the typical values of that exist in the true exhaust. (15.0% for Gasoline and 12.0% for LPG.)
6. If the results of the test calculation confirm the air dilution calculation, you may use the exhaust gas dilution factor obtained in '4.' to correct the CO, HC, and NO readings. Divide the CO, HC, and NO readings by the exhaust gas dilution factor to obtain dilution corrected readings.
7. If the results of the test calculation in '5.' do not confirm the dilution correction because the corrected $CO+CO_2$ is still too low, you may have estimated too much normal O_2 in the exhaust – and there may be more dilution than you calculated. Some refinement may be necessary.

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The Exhaust Gas Dilution Correction equations look like

$$AirDilution = \frac{[O_2 \mathrm{Re}ading] - [ExpectedO_2]}{20.60}$$

$$ExhaustGasDil = 1.00 - AirDilution$$

$$\left\{ExhaustGasDil = 1.00 - \frac{[O_2 \mathrm{Re}ading] - [ExpectedO_2]}{20.60}\right\}$$

$$CorrectedGas\mathrm{Re}adings = \frac{Gas\mathrm{Re}ading}{ExhaustGasDil}$$

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