White Paper

Title: Using Lambda and CE to Diagnose Fuel Control and Cat Converter Efficiency
TSN Number: 27A
File:\\MII-SRV1\Metron\Bridge_Analyzers\Customer_Service_Documentation\White_Papers\27A Lambda and CE for Diagnostics.docx
Created by: R. Schrader
Last Revision Date: 02-May-08

The Bridge Model 9004 (4-Gas) and Model 9005 (5-Gas) analyzers calculate the Oxygen/Combustibles balance (λ - Lambda) from the values of O2, CO, CO2, HC (unburned furl) , and NOx (for the Model 9005) in the tailpipe gas using the 'Brettschneider Formula' specified in international exhaust gas analyzer standards. This provides an independent verification of fuel control – which is particularly important for modern (OBD-II) vehicles as well as standard carbureted or fuel injected vehicles.

While lambda is a common tuning parameter – equivalent to AFR, but generic in nature, it is often overlooked regarding its important in vehicles with closed loop fuel control and having a catalytic converter. The reason that it is important for these vehicles is that they all use 3-way catalytic converters to ensure that the tailpipe gases meet EPA standards for cleanliness. The catalytic converter has to not only complete the oxidation of CO (carbon monoxide) and HC (unburned fuel), but also reduce NOx to appropriate levels. To do both these jobs, the input exhaust stream to the cat converter must be within a very narrow range – about 2% of perfect stoichiometric balance. Too rich, and the NOx reduction is enhanced, but there will be excess CO and HC in the exhaust. Too lean and the opposite will occur – the oxidation of CO and HC is enhanced, but the reduction of NOx is limited. Being able to determine the true Lambda (AFR) of the exhaust gases is critical to validating that the vehicle is truly in fuel control.

If lambda is 0.980 to 1.020 – then the cat converter should be about 90% efficient in completing oxidation of CO and HC, and still better than 75% in reducing NOx. While it is not possible to determine the cat converter oxidation and reductions efficiency without having access to pre and post cat converter gases, the tailpipe gases can be readily analyzed for lambda and combustion efficiency – which are a very good indicator of cat converter efficiency.

First, the exhaust gases are analyzed to determine their stoichiometric balance – Lambda. Then, they are analyzed to determine their combustion efficiency.

Bridge Analyzers, Inc.
PO Box 39325
Solon, Ohio 44139 USA
(510) 337-1605 office
(216) 274-9262 fax
support@bridgeanalyzers.com

Normal Lambda and CE Values in Various Normal Engine Operating Mode.:

Lambda	Combustion Efficiency	Cause / Result
0.920><1.000	90.00><95.00	Cold Start: Open Loop / Cold Start: Normal engine-out / cold cat converter values– assumed slightly rich running.
0.980><1.020	95.00><98.00	Warming Up: Closed Loop / Cat Converter still cold.
0.980><1.020	98.00><99.50	Warmed Up: Closed Loop / Cat Converter at operating temp.

Comparing the Lambda and the CE values allows the technician to make considerable decisions about the fuel control in the vehicle as well as the efficiency of the cat converter.

First – look at Lambda to assess fuel control:

Lambda	**Cause / Result**
< 0.900	Rich tuning. Usually used for performance applications, where raw power is more important than emissions or fuel economy. Combustion Efficiency will be low due to insufficient oxygen to complete oxidation. CO and HC will be high – NOx will be low.
0.900><0.980	Slightly Rich Tuning. Getting away from raw power and into the range where performance does not suffer much except in transient conditions whre the mixture is likely to go lean. Combustion efficiency remains low – but as the mixture gets closer to 1.000, the cat converter should begin to complete oxidation. 95.00% CE is equivalent to engine gases at stoichiometric tuning so can be used as a reference point.
0.980><1.020	Normal: Typical ranges for closed loop fuel control using a lambda sensor (commonly referred to as an 'Oxygen Sensor'.) This is the operating range that must be maintained for a 3-Way cat converter to work correctly.
1.020><1.100	Slightly lean. NOx will increase in concentration due to the combined effects of increased generation in the combustion chamber and lowered reduction in the 3-Way cat converter.

Bridge Analyzers, Inc.
PO Box 39325
Solon, Ohio 44139 USA

(510) 337-1605 office
(216) 274-9262 fax
support@bridgeanalyzers.com

>1.100	Lean Tuning. Risk of misfire due to inability of spark ignition to occur – causing spike in HC and unused oxygen readings.

Then look at CE combined with Lambda to assess cat converter efficiency:

Combustion Efficiency	Lambda	Cause / Result
<80.00	<0.850	Normal, low CE due to very rich tuning – insufficient oxygen exists to complete the oxidation reactions.
<80.00	0.950><1.050	Misfire or other combustion efficiency issue. The fuel control is functioning correctly, but the gases are not being oxidized
90.00><95.00	0.950><1.050	Cat Converter not there or not working. Normal engine-out exhaust CE. If a cat converter is present, it is not oxidizing the gases adequately due to poor cat converter oxidation efficiency.
97.00><99.00	0.980><1.020	Normal closed-loop fuel control and cat converter combustion efficiency.
<95.00	>1.020	Cat converter is not working, even though the gases are lean. This may be also be due to a partial misfire condition – causing the engine-out gases to be considerably unoxidized The cat converter should be quite hot in this case, indicating that it is trying to complete the oxidation of poorly combusted gases.
<95.00	>1.100	Almost certainly a misfire. HC and O2 readings should be commensurately high. The cat converter should be quite hot – as there will be a good deal of oxidation to complete.

What is Lambda?

'Lambda' (λ) is a dimensionless term that relates to the stoichiometric value of air to fuel. At the stoichiometric point, Lambda = 1.000. A Lambda value of 1.050 is 5.0% lean, and a Lambda value of 0.950 is 5.0% rich. Once Lambda is calculated, A/F ratio can be easily determined by simply multiplying Lambda times the stoichiometric A/F ratio for the fuel used - e.g. 14.71 for gasoline, 15.87 for LPG, and 17.45 for CNG.

Details of the Lambda Calculation:

Lambda is calculated by determining the degree to which the oxygen atoms and the carbon atoms are balanced in the exhaust gas. Two oxygen atoms are required for every carbon atom to complete the oxidation of Carbon to Carbon Dioxide – CO_2. Hydrogen is accommodated by knowing the ratio of carbon to hydrogen in the fuel. In essence, all the oxygen is counted, whether it is free oxygen (O_2), or tied up in CO or CO_2 – and an estimation of the oxygen tied up in water vapor (H_2O) is estimated from the ratio of CO to CO_2. Then all the carbon atoms are counted by looking at CO, CO_2, and HC, and hydrogen is added based on its known ratio to carbon in the fuel being used.

Knowing both the oxygen present and the oxygen demand required by the combustibles allow the ratio to be calculated. A result of 1.000 means that there is exactly enough oxygen for all the combustibles present – whether or not it is being used for that purpose. This is an important point – the calculated Lambda value is independent of combustion efficiency – and therefore independent of the gas mix. A misfire does not effect lambda, nor does looking at lambda pre and post cat converter. Lambda is a ratiometric value – and is invariant of the degree to which the oxygen is used.

The Relationship between Lambda and A/F ratio:

Because Lambda = 1.000 when the oxygen and combustibles are in perfect stoichiometric balance, Lambda can easily be used to calculate A/F ratio for particular fuels.

The A/F ratio is simply the calculated Lambda times the stoichiometric A/F ratio for the specific fuel used (14.71 for gasoline, but other fuels have different values)

The effect of various 'octane' fuel mixes on Lambda:

Various mixes of gasoline contain differing ratios of short and long hydrocarbon chains, resulting in a variation of octane rated fuels. This has a small effect on the ratio of hydrogen to carbon in the fuel, but these variations have a trivial effect on the lambda calculation. Essentially, the lambda calculation is not 'octane' dependant.

The effect of Oxygenated fuels on Lambda:

Oxygenated fuels contain a very small amount of oxygen in the fuel, which is released as the fuel is burned. The total O_2 equivalence in typical oxygenated fuel is on the order of 0.1% O_2, so this effect is very small and has little effect on the lambda calculation.

The effect of NOx on Lambda:

NO has a relatively immaterial effect on the lambda calculation, as 1,000 ppm NO is only equivalent to 0.05% Oxygen utilization.

Bridge Analyzers, Inc. (510) 337-1605 office
PO Box 39325 (216) 274-9262 fax
Solon, Ohio 44139 USA support@bridgeanalyzers.com

Sample Dilution and Air Injection Effects on Lambda:

As a side note, it is important to understand the effect that sampling air leaks or outright air injection may have on lambda calculation. **The percentage of extra air in the exhaust gases will result in the same percentage error in the Lambda calculation.**

I.E, a 5% air leak will not only dilute (lower) the CO, HC, CO2 and NOx gas readings by 5%, but will increase the Oxygen reading by about 1.00% (5% of 20.9%) and will result in the calculated Lambda being 5% leaner than it should. That means that a perfect Lambda of 1.000 will be reported as 1.050 if there is 5% air leak (1.00% excess O2) or injection.

This is a significant error, and can occur relatively easily. It should be noted that air leaks or injection will always bias the lambda calculation toward the lean side – so they should be dealt with and corrected before lambda can be used as a diagnostic tool.

Engine Misfire – the effect of Combustion Efficiency on Lambda:

Because the Lambda calculation determines the balance between Oxygen and combustible gases by comparing all the oxygen available to the combustibles bearing gases – it is relatively insensitive to the degree to which the combustibles have been oxidized. Thus, an engine misfire has absolutely no effect on the balance calculation.

Pre and Post Catalytic Converter gases:

Because the Lambda calculation determines the balance between Oxygen and combustible gases by comparing all the oxygen available to the combustibles bearing gases – it is relatively insensitive to the degree to which the combustibles have been oxidized. Thus, the gas stream before a catalytic converter should calculate the same Lambda value as the gases after a catalytic converter.

Combustion (Carbon Oxidation) Efficiency:

One of the ways to look at the efficiency of an oxidation process is to evaluate how much of the carbon in the fuel is oxidized by looking at the relative concentrations of CO, CO2 and HC in tailpipe gas. For example, a gasoline engine oxidizes a blend of hydrocarbons containing almost purely hydrogen and carbon atoms to produce water vapor (H2O) and Carbon Dioxide (CO2). By looking at the degree to which the carbon atoms in the fuel have been converted to CO2, combustion efficiency can be assessed. This is done by measuring CO2, CO, and HC. CO2 is the desired result, and is weighted at 100% CE, CO, being an intermediate oxidation form, is weighted 50% CE, and HC is weighted at 0%.

Note that it is actually the ratio of CO2/CO/HC that is important here – which means that CE is totally independent of exhaust gas dilution – which effects all the gases above the same. Even if there is air dilution of the exhaust gas sample due to an air pump or exhaust system leak, the CE will be unaffected.

Bridge Analyzers, Inc.
PO Box 39325
Solon, Ohio 44139 USA

(510) 337-1605 office
(216) 274-9262 fax
support@bridgeanalyzers.com

Some benchmarks for CE is that the engine-out exhaust should be about 95.0% for a properly running engine at close to stoichiometric Lambda, and the post-CAT CE should be 99.0% or above under the same condition – which also implies that the CAT converter oxidation efficiency should be 80.0% or greater. (The incomplete oxidation in the engine-out gas is 5.0%, and gets knocked down to 1.0% or less by the cat converter.)

When λ gets below about 0.980 or so, though, the CAT can no longer oxidize carbon very efficiently, so you have to be a little careful of this. With λ above 1.050 or so, lean misfire can occur, and the Pre-CAT CE gets pretty bad – and the CAT has to work very hard to clean up the exhaust gases.

Bridge Analyzers, Inc.
PO Box 39325
Solon, Ohio 44139 USA

(510) 337-1605 office
(216) 274-9262 fax
support@bridgeanalyzers.com