iGAS
Intelligent Gas Analyzer

Training

Advanced Diagnostics Using The Five Gas Analyzer

by Bernie Thompson

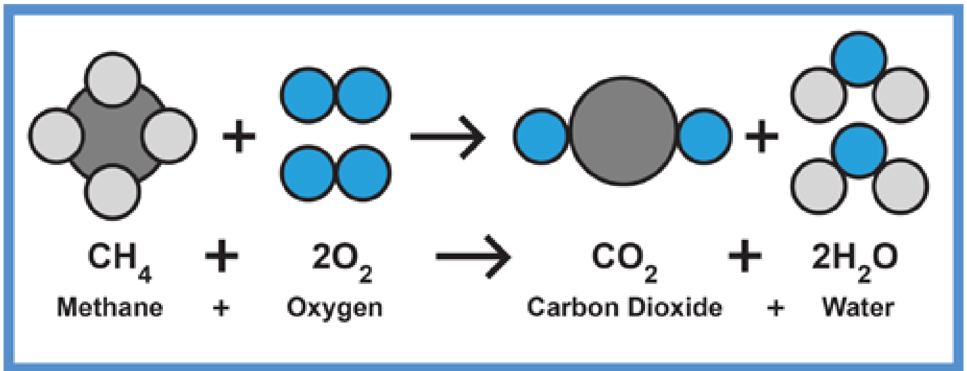
The internal combustion engine has been around for over two hundred years. In this time there have been many changes to the engine, the fuel, and the automobile. We attribute the modern engine to Nikolaus Otto. Nikolaus was a German engineer who developed the compression charge internal combustion engine that ran on liquid petroleum gas. Nikolaus' engineering marvel is still used to power the modern vehicle.

The fuel stock and the internal combustion engine have undergone some changes in the past years, but the basics are still the same. The fuel stock that we will cover is a liquid petroleum product that we refer to as gasoline. Modern gasoline is a mixture of different chemical components with varying vapor points and varying auto-ignition temperatures. Basically when these components are mixed together and form gasoline, they have an approximate flash point of -45°F and an approximate auto-ignition point of 536°F.

It will be necessary to understand that liquid gasoline cannot burn in this state (liquids do not burn). In order to burn gasoline it must be heated so that it takes a phase transition and turns into a vapor (vapors can be burned). The compression within the cylinder accomplishes the heating of the fuel. When air is compressed rapidly the molecules are accelerated off of the moving piston where they hit one another. The kinetic energy from the piston is turned into thermal energy in the air charge. This occurs from the atoms hitting one another which in turn starts the atoms vibrating, causing a heating effect. This process is called Adiabatic Compression. The Adiabatic processes are characterized by zero heat transfer with the surroundings, such as the piston, cylinder and cylinder head. In the case of rapid compression, the process occurs too quickly for any heat transfer to occur to these components. Heat transfer is a slow process. This rapid compression of the air creates a rapid heat increase within the air charge. Thus this heat increase is put into the fuel that is suspended within the air. When this air/fuel charge is heated it turns the fuel into a vapor that can be burned.

Now that the fuel is in a vapor format and is ready to burn, a spark takes place across the sparkplug electrode. The spark ionizes the spark plug electrodes producing a state of plasma which takes the fuel well past the auto-ignition temperature of the fuel; setting up the ignition phase of the fuel. This is where the temperature in a localized area around the sparkplug starts to burn. The next stage is the combustion phase. This is where the charge changes from chemical energy to thermal energy. The heat released is then driven into the next layer of the charge thus igniting it. This is referred to as deflagration. Deflagration is the combustion that propagates at subsonic speeds through the gas that is driven by the transfer of heat. This heat transfer heats the working fluid (nitrogen) which in turn puts pressure on the piston, thus pushing the piston down the cylinder.

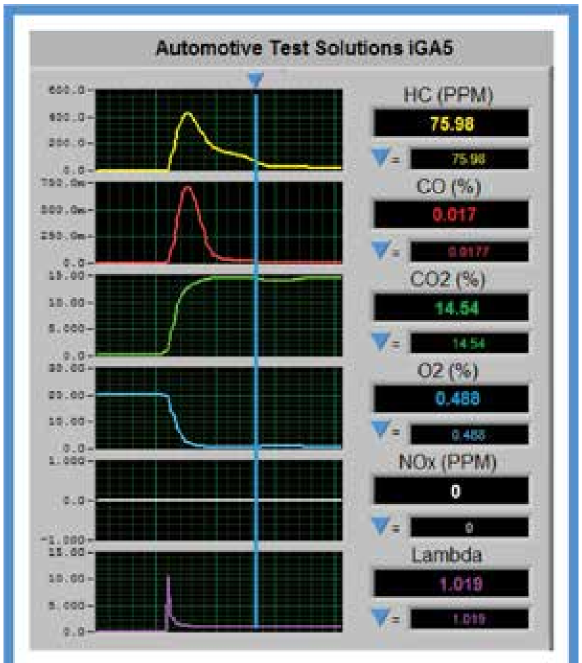
In the spark ignition method the charge prior to ignition is that of a homogenous charge. This means that the air/fuel charge is evenly mixed throughout the cylinder volume. In order to completely burn an evenly distributed mixture within the cylinder, the air/fuel ratio must be very close to that of stoichiometry. Stoichiometry refers to the weights of the chemicals that will react. In an internal combustion engine the fuel is thereactant and the air is the oxidant. Air is comprised of approximately 78.09% nitrogen, which is used as the working fluid, and 20.95% oxygen which is used as the oxidant. The reaction will occur between the fuel, which is hydrocarbon based, and the oxidant, which is the oxygen. The stoichiometric ratio between the fuel and air is one where the hydrocarbons and oxygen are at a weight ratio that, once they react with one another, will no longer be present. This means that the hydrocarbons break apart becoming hydrogen and carbon. In the presence of oxygen, the hydrogen combines with the oxygen forming a new chemical; dihydrogen monoxide (H2O water). The carbon attaches to the oxygen forming a new chemical; carbon dioxide (CO2). If the hydrocarbons and oxygen are at a stoichiometric ratio and react with one another then neither of these chemicals will remain present within the combustion gases, see Figure 1. The chemical weight will be the same but the new chemicals formed during a complete reaction will be water and carbon dioxide. Although the mixture is at a stoichiometric ratio, in the real world a complete reaction between all of the chemicals does not occur so there will always be some Hydrocarbons and oxygen left after the combustion process. This is due to the flame front being unable to get into the crevasses around the spark plug, valve pockets, and piston rings.



A stoichiometric diagram of the combustion reaction of methane

Fig. 1

If the cylinder compression is present then; the fuel was vaporized, the air/fuel ratio was that of stoichiometric, the cylinder is homogeneous and the spark occurred correctly, the vast majority of fuel and air will react with one another. When this occurs the tailpipe gas charge will have high CO2 > 14%, low O2 < 1%, low CO < 1%, and low HC < 100 Parts Per Million (PPM), as seen in Figure 2.



HC (PPM) 75.98
▼= 75.98
CO (%) 0.017
▼= 0.0177
CO2 (%) 14.54
▼= 14.54
O2 (%) 0.488
▼= 0.488
NOx (PPM) 0
▼= 0
Lambda 1.019
▼= 1.019

Start and Run

Fig. 2

Figure 2 shows an engine with no problems on start and run. Since the hydrocarbons react with the oxygen then; the hydrocarbon level will drop, the oxygen level will start at atmospheric condition at about 21% and drop sharply, the carbon dioxide will rise sharply and the carbon monoxide will drop as well. At this point the catalyst (catalytic converter) is not hot enough to further the reaction of the fuel. There will be more on this later.

Carbon monoxide forms when the air/fuel mixture does not have enough oxygen to fully oxidize the carbon. The chemical reaction will always drive to that of carbon dioxide. Note the difference is that carbon dioxide has one carbon atom and two oxygen atoms, where carbon monoxide has one carbon atom and one oxygen atom. If there is oxygen present around the carbon during the combustion process then two oxygen atoms will always stay together and will bond to a single carbon atom. Thus, when CO levels rise this is usually created by a rich condition as seen in Figure 3. CO and CO2 are very good combustion indicators; CO is produced by incomplete combustion where CO2 is produced by complete combustion. Therefore the presence of high CO2 gases of 14% to 16% represents good combustion has occurred within the cylinders.

A rich mixture condition is one that has more hydrocarbons than oxygen. When this occurs there is not enough oxygen to oxidize the carbon and hydrocarbons. Thus, there are extra hydrocarbons left after the reaction and each carbon only has one oxygen atom bound to it making carbon monoxide, as seen in Figure 3.

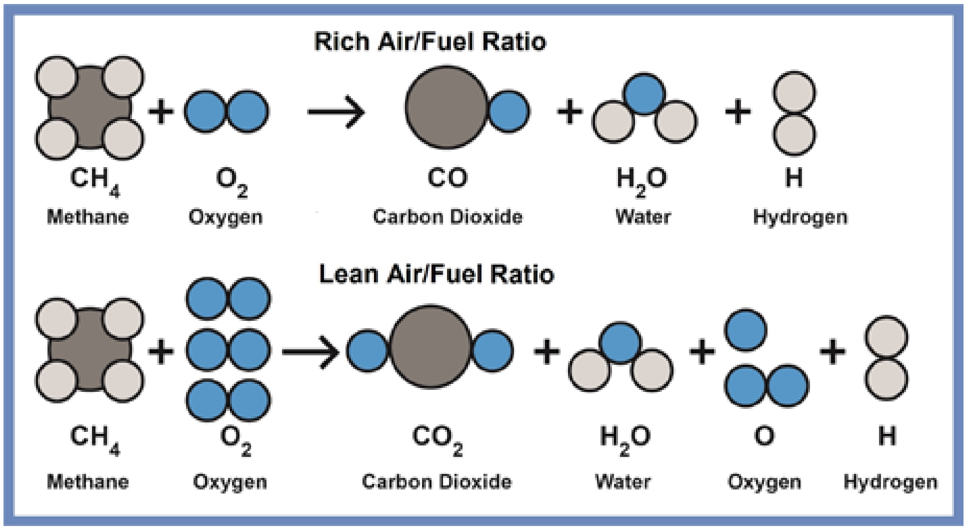


Fig. 3

A lean mixture condition is one that has more oxygen than hydrocarbons. When this occurs there is not enough hydrocarbons for the amount of oxygen atoms, so the reaction leaves additional oxygen atoms as well as extra hydrogen, as seen in Figure 3. One may ask; why did the additional oxygen not oxidize the hydrogen during the reaction? This is due to the air/fuel charge not being that of a stoichiometric ratio. In this condition the air/fuel charge has too much space between the hydrocarbons. Therefore as the flame front starts to propagate across the combustion chamber these large areas between the hydrocarbons create impedance to the flame front movement. This in turn slows the flame front allowing only a partial burn of the gasoline. This will leave oxygen, hydrocarbons and hydrogen.

In order to have complete combustion in a spark ignition gasoline based engine the air/fuel charge must be that of a homogeneous charge. A substance is homogeneous if its composition is identical wherever you sample it. This means that the charge mixture (air and fuel) has a uniform composition throughout the cylinder. Additionally the air/fuel charge must be that of a stoichiometric ratio.

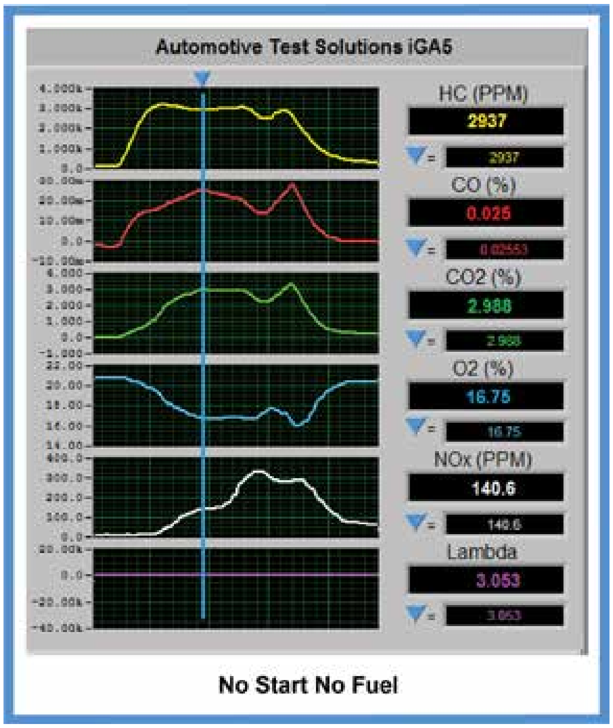
A stoichiometric ratio, as discussed above, is where the two reactants that started the reaction are no longer present at the end of the reaction. Different chemicals will have different chemical weights, so these chemical weights will change the stoichiometric ratio. For example methanol has a stoichiometric ratio of 6.45:1. Ethanol has a stoichiometric ratio of 9:1. Where gasoline, being comprised of various chemical components, has a stoichiometric ratio of 14.5:1 to 14.7:1. If ethanol is blended with the gasoline the stoichiometric ratio will drop depending on how much ethanol is used in the blend.

A reading given for stoichiometry on a gas analyzer is that of Lambda. Lambda is a calculation that is based on all of the gas traces that are read by the exhaust gas analyzer. This equation takes the gases that are coming out the tailpipe and calculates the amount of oxygen and fuel that went in. Make no mistake, what goes in must come out. The weight of the atoms do not change. The molecules are structured differently after the combustion process, however the weight is the same. By taking the exhaust gas weights one can calculate what gases went in. It is extremely important that there are no exhaust leaks in the exhaust system. This allows oxygen to enter into the exhaust system, however this oxygen was not part of the combustion gases. This false oxygen will move the Lambda equation to the lean side when it is not really lean. If there is an exhaust leak Lambda cannot be used.

A Lambda reading of 1.0 is that of a stoichiometric ratio. A Lambda greater than 1 indicates a lean condition. So a Lambda of 1.2 indicates the air/fuel ratio is 20% lean of a stoichiometric ratio. A lambda less than one indicates a rich condition. So a Lambda of .8 indicates the air/fuel ratio is 20% rich of a stoichiometric ratio.

Nitrogen Oxide (NOx) is a gas that is produced during the combustion process. This is where oxygen bonds to nitrogen. These chemicals do not want to bond with one another so they will stay separated until they are force together. This force will be provided by temperatures greater than 2500°F during the combustion event or extreme pressure conditions during the combustion event.

Now that we have set the parameters to combust a gasoline based fuel stock in the cylinder, let's analysis some data from different engine problems. The first engine problem is a no start condition as seen in Figure 4. The blue cursor at the top of the graph marks the position that all of the gases are measured at. The gases are then read as a digital number on the right hand side of the graph next to the specific gas trace such as; HC, CO, CO2, O2, NOx, and the calculation of Lambda. We will discuss what the gas traces indicate and what is happening within the engine. First we will take note that; the HC is reading 2937 PPM, the CO is reading .025, the CO2 is reading 2.98%, the oxygen is reading 16.75%, the NOx is reading 140.6 PPM, and the Lambda is at 3.05%.

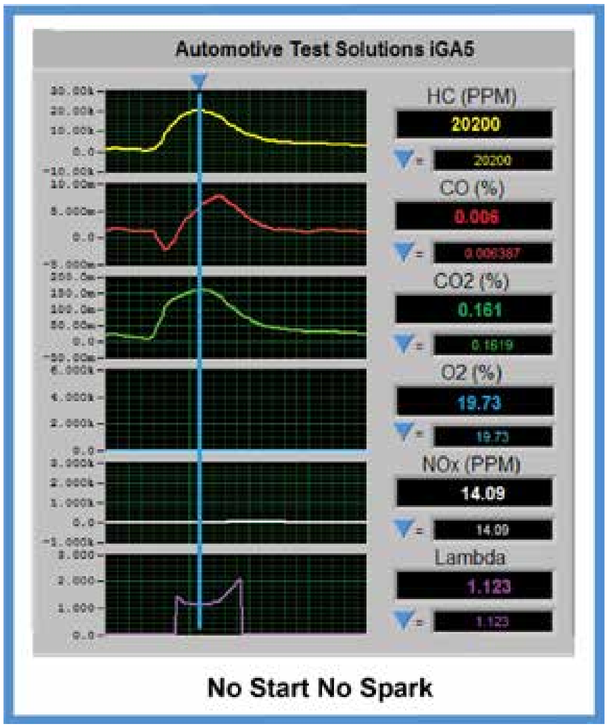


No Start No Fuel

Fig. 4

The HC at 2937 PPM seems like a lot but, when taken with the other gas data, really is not. Since there is CO2 present at 2.98% and the oxygen fell from 21% to 16.75% we know that some of the hydrocarbons reacted with oxygen. This would indicate that fuel and oxygen are in the cylinder and a spark has occurred. Since the engine is cold the spark is present due to the CO2 reading of 2.98%. If there was no spark present then the reaction could not occur, therefore there would not be any production of CO2 gas. The CO is also very low at .025%. This indicates that there is more than enough oxygen in the cylinder for the combustion process. The NOx gas at 140.6 PPM also indicates that there was some combustion within the cylinder. The key here is the Lambda reading of 3.05%. This indicates that the air/fuel ratio is 3 times too lean. With a lean air/fuel ratio the flame front is impeded and cannot propagate through the cylinder. So the spark starts the ignition event and creates enough heat for the point of ignition. This then starts the combustion event, however, the combustion event starts but is stopped due to the lean air/fuel ratio. This engine has a lack of gasoline causing the no start problem. This vehicle's problem was a bad fuel pump.

Now let's analyze Figure 5. This is also a no start condition. We will discuss what the gas traces indicate and what is happening within the engine. First we will take note that; the HC is reading 20200 PPM, the CO is reading .006%, the CO2 is reading .1619%, the oxygen is reading 19.73%, the NOx is reading 14.09 PPM, and the Lambda is at 1.14%.



No Start No Spark

Fig. 5

The HC reading of 20200 PPM is the correct amount of gasoline to combust within the cylinder. The CO at .006% also shows there is not a lack of oxygen within the cylinder. The CO2 at .1619 indicates that there is no, or very little, reaction between the hydrocarbons and the oxygen. The oxygen at 19.73 confirms no, or very little, reaction took place. The lambda at 1.14% indicates that the air fuel ratio is 14% lean of stoichiometric. However this is a combustible air/fuel mixture. The lack of a reaction is not based on the air/fuel ratio, but on the spark. If there is no spark event to bring the temperature above the auto-ignition point of the gasoline, there will be no reaction between the hydrocarbons (fuel) and the oxidant (oxygen). It is important to understand that if the engine is hot and compression took place then some of the hydrocarbons can react with some of the oxygen without a spark present. However, this will still represent a small amount of CO2. If combustion is established the CO2 will rise sharply. This vehicle's problem was a bad ignition coil, causing a no spark condition.

Now let's analyze Figure 6; this is a long hard start condition. We will discuss what the gas traces indicate and what is happening within the engine. First we will take note that; the HC is reading 26710 PPM, the CO is reading 3.24%, the CO2 is reading 1.164%, the oxygen is reading 14.54%, the NOx is reading 29.67 PPM, and the Lambda is at .63%.

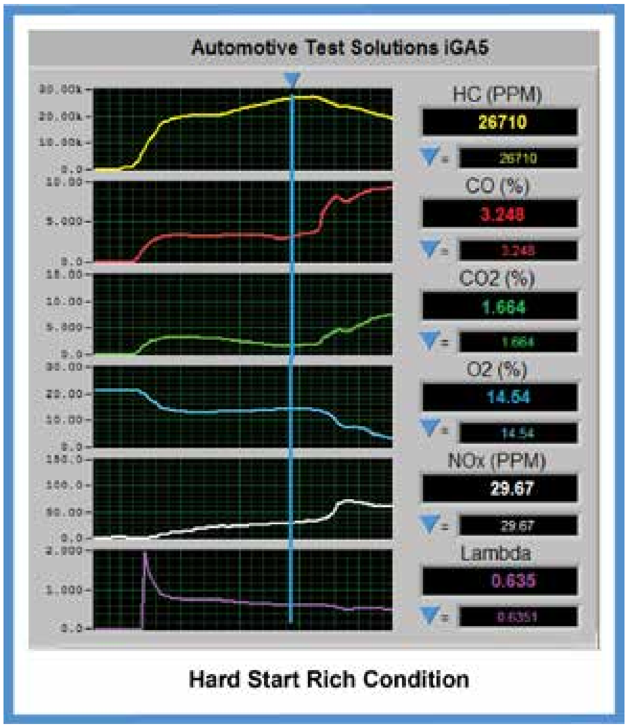
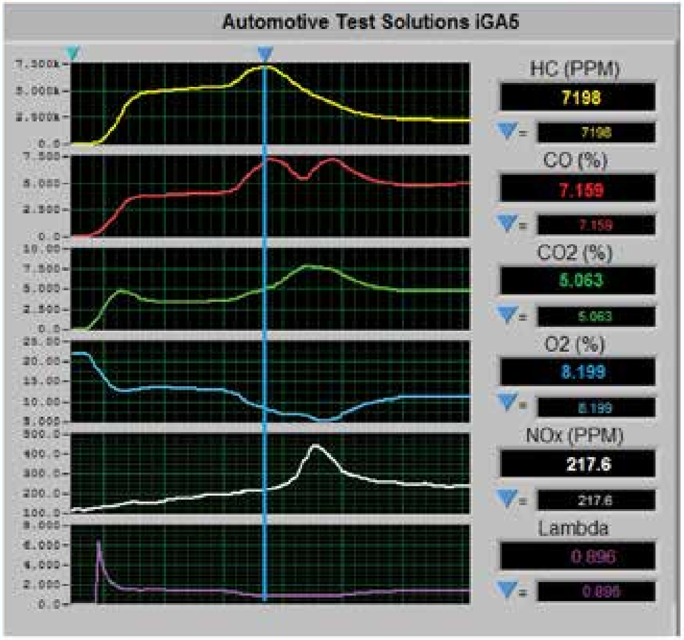


Fig. 6

The HC reading of 26710 PPM indicates there is sufficient gasoline within the cylinder. The CO at 3.24% indicates that there is a lack of oxygen in the cylinder for the amount of hydrocarbons, additionally a spark has started a reaction to occur. The CO2 at 1.64% indicates that a reaction occurred but was incomplete. The oxygen starting at 21% and dropping to 14.54% indicates a reaction took place with the carbon producing high CO gas traces and low CO2 gas traces. The NOx at 29.67 indicates that combustion occurred. The Lambda at .63 indicates the air/fuel mixture is 37% rich of stoichiometric. The air/fuel mixture at the beginning of the starting process is too rich for the starting conditions of the engine. Thus a long hard start condition is present. This vehicles problem was a misreading Engine Coolant Temperature (ECT) sensor which allowed the cold start enrichment to be active, thus creating a rich start condition.

Now let’s analyze Figure 7; this is a hard start condition with poor engine running. We will discuss what the gas traces indicate and what is happening within the engine. First we will take note that; the HC is reading 7198 PPM, the CO is reading 7.159%, the CO2 is reading 5.063%, the oxygen is reading 8.199%, the NOx is reading 217.6 PPM, and the Lambda is at .89%.

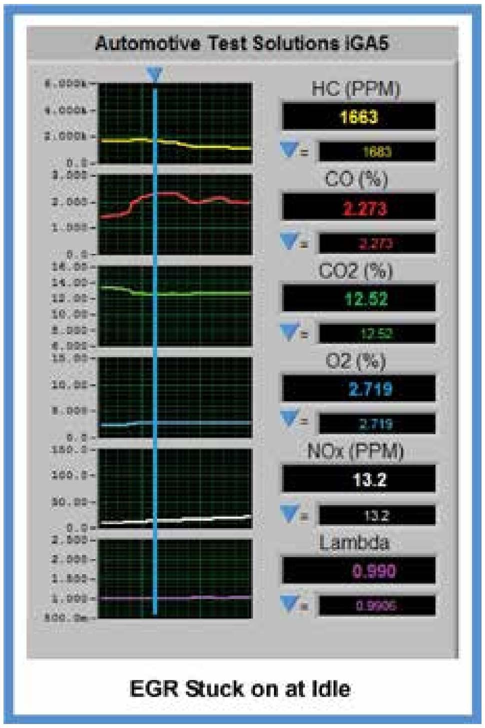


Poor Start and Run, Timing off

Fig. 7

The HC reading of 7163 PPM indicates that the hydrocarbons are not burning completely. The CO at 7.159% indicates a poor combustion process, but indicates that a spark event occurred. The CO2 at 5.063% confirms poor combustion of the gasoline. The oxygen starting at 21% and falling to only 8.199% shows that the combustion event happened but is incomplete. There are leftover hydrocarbons and leftover oxygen that should have been combusted in the reaction. The NOx is at 217.6 showing a reaction occurred. The Lambda at .89% is 11% rich of stoichiometric. However this should be a combustible mixture that is just slightly rich. This is caused by either a weak spark or the ignition timing is off. This vehicle’s problem is a late ignition timing event.

Now let’s analyze Figure 8; this is a rough running idle condition. We will discuss what the gas traces indicate and what is happening within the engine. First we will take note that; the HC is reading 1663 PPM, the CO is reading 2.27%, the CO2 is reading 12.52%, the oxygen is reading 2.71%, the NOx is reading 13.2 PPM, and the Lambda is at .99%.



EGR Stuck on at Idle

Fig. 8

The HC reading of 1663 PPM indicates that the hydrocarbons are not burning correctly. The CO at 2.27% indicates that there is poor combustion within the cylinders, but a spark event did occur. The CO2 at 12.53 is a little low indicating that the combustion is poor. The oxygen at 2.71% is a little high indicating that the combustion event is incomplete. The NOx is quite low at 13.2 PPM. The Lambda is .99% indicating that the engine is running at a stoichiometric ratio. Since the air/fuel ratio is correct at a Lambda of 1 the air/fuel charge is definitely combustible. However the combustion event is incomplete. Additionally, just off idle the combustion gases are good. So the problem occurs just at idle. This vehicle’s problem is the Exhaust Gas Recirculation (EGR) valve is intermediately sticking open at cruise and when it returns to idle dilutes the air/fuel charge. This puts too much space between the hydrocarbons creating an impediment to the flame front and, thus, incomplete combustion.

Now let's analyze Figure 9; this is a vehicle with a DTC P0420 catalytic converter efficiency. We will discuss what the gas traces indicate and what is happening within the engine. First we will take note that the HC is reading 166 PPM, the CO is reading 1.26%, the CO2 is reading 13.81%, the oxygen is reading .426%, the NOx is reading 1183 PPM, and the Lambda is at .979%.

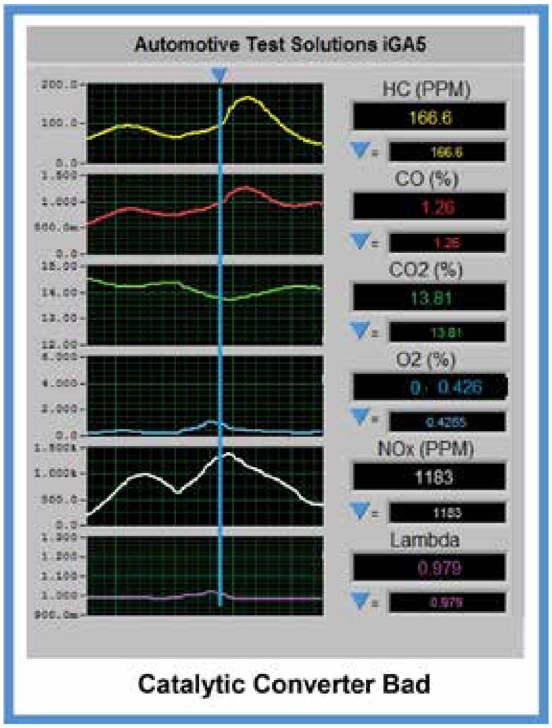


Fig. 9

The HC reading of 166 PPM indicates that the hydrocarbons are slightly high. The CO at 2.27% indicates that there is poor combustion within the cylinders, but a spark event did occur. The CO2 at 13.81 is a little low indicating that the combustion is incomplete. The oxygen at 2.71% is slightly high indicating that the combustion event is not complete. The NOx is quite high at 1183 PPM. The Lambda is .979% indicating that the engine is running 2% rich of a stoichiometric. Since the air/fuel ratio is correct at a Lambda of close to 1 the air/fuel charge is definitely combustible, however, the combustion event seems incomplete. This exhaust gas data was taken while driving under load. These exhaust gas traces are correct for the condition that they were under. The problem is that the catalytic converter is not functioning properly and can no longer react the exhaust gases, further combusting these gases.

The catalytic converter is a device that further combusts the exhaust gases through catalysis. This is where heated metals drive a chemical reaction to a different chemical species. All metals will drive catalysis, but the chemical species at the end will vary depending on which metal was used. Automotive three-way catalytic converters use platinum, palladium, and rhodium. These rare earth metals are used because they drive the catalysis to a desired chemical species. These metals will need to be hotter than 700°F in order to function correctly. This means on cold start the catalytic converter is not working for the first 20 seconds to one minute. Once the catalytic converter has obtained operational temperature it will further combust the exhaust gas through catalysis. So any exhaust gas analysis must take this into account. For example, if the engine is misfiring one would expect to see incomplete combustion gases at the tailpipe such as high HC readings with high oxygen readings. However the modern catalytic converter, when at operating temperature, can continue to combust the gases where there are no signs of incomplete combustion.

It is clear that the exhaust gases can be used for advanced engine diagnostics. We have seen just a few examples presented in this text. Be aware that you can use these gases to do far more than what has been presented in this article. With a little knowledge and a little practice you will be diagnosing engine problems that use to take hours, in just minutes.