The gasoline-powered internal combustion engine takes air from the atmosphere and gasoline, a hydrocarbon fuel, and through the process of combustion releases the chemical energy stored in the fuel. Of the total energy released by the combustion process, about 20% is used to propel the vehicle, the remaining 80% is lost to friction, aerodynamic drag, accessory operation, or simply wasted as heat transferred to the cooling system.

Modern gasoline engines are very efficient compared to predecessors of the late '60s and early '70s when emissions control and fuel economy were first becoming a major concern of automotive engineers. Generally speaking, the more efficient an engine becomes, the lower the exhaust emissions from the tailpipe. However, as clean as engines operate today, exhaust emission standards continually tighten. The technology to achieve these ever-tightening emissions targets has led to the advanced closed loop engine control systems used on today’s Toyota vehicles. With these advances in technology comes the increased emphasis on maintenance, and when the engine and emission control systems fail to operate as designed, diagnosis and repair.

To understand how to diagnose and repair the emissions control system, one must first have a working knowledge of the basic combustion chemistry which takes place within the engine. That is the purpose of this section of the program.

The gasoline burned in an engine contains many chemicals, however, it is primarily made up of hydrocarbons (also referred to as HC). Hydrocarbons are chemical compounds made up of hydrogen atoms which chemically bond with carbon atoms. There are many different types of hydrocarbon compounds found in gasoline, depending on the number of hydrogen and carbon atoms present, and the way that these atoms are bonded.

Inside an engine, the hydrocarbons in gasoline will not burn unless they are mixed with air. This is where the chemistry of combustion begins. Air is composed of approximately 21% oxygen (O₂), 78% nitrogen (N₂), and minute amounts of other inert gases.

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**Atmospheric Make-Up**

Approximately 99% of “air” is made up of Nitrogen (N₂) and Oxygen (O₂). The “other gasses” include Argon (Ar), CO₂, HC, NOₓ, SO₂, and trace amounts of other gases.
The hydrocarbons in fuel normally react only with the oxygen during the combustion process to form water vapor (H2O) and carbon dioxide (CO2), creating the desirable effect of heat and pressure within the cylinder. Unfortunately, under certain engine operating conditions, the nitrogen also reacts with the oxygen to form nitrogen oxides (NOx), a criteria air pollutant.

Components of Basic Combustion

These components, along with other very specific conditions, are needed in order for basic combustion to occur.

The ratio of air to fuel plays an important role in the efficiency of the combustion process. The ideal air/fuel ratio for optimum emissions, fuel economy, and good engine performance is around 14.7 pounds of air for every one pound of fuel. This "ideal air/fuel ratio" is referred to as stoichiometry, and is the target that the feedback fuel control system constantly shoots for. At air/fuel ratios richer than stoichiometry, fuel economy and emissions will suffer. At air/fuel ratios leaner than stoichiometry, power, driveability and emissions will suffer.
"Ideal" Combustion

If "perfect" combustion were to occur, hydrocarbons (HC) would be oxidized into water (H₂O) and carbon dioxide (CO₂). Also, nitrogen (N₂) would pass through unaffected.

Under "Ideal" Combustion Conditions

In a perfectly operating engine with ideal combustion conditions, the following chemical reaction would take place:

- Hydrocarbons would react with oxygen to produce water vapor (H₂O) and carbon dioxide (CO₂).
- Nitrogen (N₂) would pass through the engine without being affected by the combustion process.

In essence, only harmless elements would remain and enter the atmosphere. Although modern engines are producing much lower emission levels than their predecessors, they still inherently produce some level of harmful emission output.

The Four Stroke Combustion Cycle

During the Intake Stroke, air and fuel moves into the low pressure area created by the piston moving down inside the cylinder. The fuel injection system has calculated and delivered the precise amount of fuel to the cylinder to achieve a 14.7 to 1 ratio with the air entering the cylinder.

As the piston moves upward during the Compression Stroke, a rapid pressure increase occurs inside the cylinder, causing the air/fuel mixture to superheat. During this time, the antiknock property or octane rating of the fuel is critical in preventing the fuel from igniting spontaneously (exploding). This precise superheated mixture is now prime for ignition as the piston approaches Top Dead Center.

Intake and Compression Stroke

During intake, air and fuel is drawn into the cylinder by the downward motion of the piston. During compression, cylinder pressure is increased making the air/fuel charge prime for ignition.
Just before the piston reaches top dead center to start the **Power Stroke**, the spark plug ignites the air/fuel mixture in the combustion chamber, causing a flame-front to begin to spread through the mixture. During combustion, hydrocarbons and oxygen react, creating heat and pressure. Ideally, the maximum pressure is created as the piston is about 8 to 12 degrees past top dead center to produce the most force on the top of the piston and transmit the most power through the crankshaft. Combustion by-products will consist primarily of water vapor and carbon dioxide if the mixture and spark timing are precise.

After the mixture has burned and the piston reaches bottom dead center, the **Exhaust Stroke** begins as the exhaust valve opens and the piston begins its return to top dead center. The water vapor, carbon dioxide, nitrogen, and a certain amount of unwanted pollutants are pushed out of the cylinder into the exhaust system.

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**Power and Exhaust Stroke**

During power stroke, the air/fuel charge is ignited and the combustion pressure is exerted on the piston. During exhaust stroke, combustion gases are expelled into the exhaust system.
Harmful Exhaust Emissions

As previously mentioned, even the most modern, technologically advanced automobile engines are not "perfect”; they still inherently produce some level of harmful emission output. There are several conditions in the combustion chamber which prevent perfect combustion and cause unwanted chemical reactions to occur. The following are examples of harmful exhaust emissions and their causes.

Exhaust Emissions

Automobile engines inherently produce some level of harmful emission output.

Hydrocarbon (HC) Emission

Hydrocarbons are, quite simply, raw unburned fuel. When combustion does not take place at all, as with a misfire, large amounts of hydrocarbons are emitted from the combustion chamber.

A small amount of hydrocarbon is created by a gasoline engine due to its design. A normal process called wall quenching occurs as the combustion flame front burns to the relatively cool walls of the combustion chamber. This cooling extinguishes the flame before all of the fuel is fully burned, leaving a small amount of hydrocarbon to be pushed out the exhaust valve.

"Quenching"

Quenching occurs when the front combustion flame-front is extinguished before all the fuel is burned.
Another cause of excessive hydrocarbon emissions is related to combustion chamber deposits. Because these carbon deposits are porous, hydrocarbon is forced into these pores as the air/fuel mixture is compressed. When combustion takes place, this fuel does not burn, however, as the piston begins its exhaust stroke, these hydrocarbons are released into the exhaust stream.

The most common cause of excessive hydrocarbon emissions is misfire which occurs due to ignition, fuel delivery, or air induction problems. Depending on how severe the misfire, inadequate spark or a noncombustible mixture (either too rich or too lean) will cause hydrocarbons to increase to varying degrees. For example, a total misfire due to a shorted spark plug wire will cause hydrocarbons to increase dramatically. Conversely, a slight lean misfire due to a false air entering the engine, may cause hydrocarbons to increase only slightly.

Excess hydrocarbon can also be influenced by the temperature of the air/fuel mixture as it enters the combustion chamber. Excessively low intake air temperatures can cause poor mixing of fuel and air, resulting in partial misfire.

*Effects of A/F Ratio on Exhaust HC*

As shown, exhaust HC production is lowest when A/F ratio is slightly leaner than "ideal"; however, HC’s increases dramatically when the mixture becomes too rich or too lean to the point of misfire.
Carbon Monoxide (CO) Emission

Carbon monoxide (CO) is a byproduct of incomplete combustion and is essentially partially burned fuel. If the air/fuel mixture does not have enough oxygen present during combustion, it will not burn completely. When combustion takes place in an oxygen starved environment, there is insufficient oxygen present to fully oxidize the carbon atoms into carbon dioxide (CO2). When carbon atoms bond with only one oxygen atom carbon monoxide (CO) forms.

Oxygen Starved Combustion

During combustion with rich A/F mixtures, the carbon from HC only partially oxidizes, resulting in carbon monoxide (CO) rather than carbon dioxide (CO2).

An oxygen starved combustion environment occurs as a result of air/fuel ratios which are richer than stoichiometry (14.7 to 1). There are several engine operating conditions when this occurs normally. For example, during cold operation, warm-up, and power enrichment. It is, therefore, normal for higher concentrations of carbon monoxide to be produced under these operating conditions. Causes of excessive carbon monoxide includes leaky injectors, high fuel pressure, improper closed loop control, etc.

Effects of A/F Ratio on Exhaust CO

Exhaust CO is lowest when A/F ratio is leaner than "ideal"; however, CO increases dramatically with richer mixtures.
When the engine is at warm idle or cruise, very little carbon monoxide is produced because there is sufficient oxygen available during combustion to fully oxidize the carbon atoms. This results in higher levels of carbon dioxide (CO₂) the principal by-product of efficient combustion.

**Oxides of Nitrogen (NOₓ) Emission**

High cylinder temperature and pressure which occur during the combustion process can cause nitrogen to react with oxygen to form Oxides of Nitrogen (NOₓ). Although there are various forms of nitrogen-based emissions that comprise Oxides of Nitrogen (NOₓ), nitric oxide (NO) makes up the majority, about 98% of all NOₓ emissions produced by the engine.

Generally speaking, the largest amount of NOₓ is produced during moderate to heavy load conditions when combustion pressures and temperatures are their highest. However, small amounts of NOₓ can also be produced during cruise and light load, light throttle operation. Common causes of excessive NOₓ include faulty EGR system operation, lean air/fuel mixture, high temperature intake air, overheated engine, excessive spark advance, etc.
Effects of A/F Ratio on Exhaust NOₓ

Exhaust NOₓ production is highest when A/F ratio is slightly leaner than "ideal". This inverse relationship with HC and CO production poses a problem when attempting to lower all three emission levels at once.

Air/Fuel Mixture Impact on Exhaust Emissions

As you can see in the graph above, HC and CO levels are relatively low near the theoretically ideal 14.7 to 1 air/fuel ratio. This reinforces the need to maintain strict air/fuel mixture control. However, NOₓ production is very high just slightly leaner than this ideal mixture range. This inverse relationship between HC/CO production and NOₓ production poses a problem when controlling total emission output. Because of this relationship, you can understand the complexity in reducing all three emissions at the same time.
So far we’ve discussed how harmful exhaust emissions are produced during combustion. However, in addition to these harmful emissions, both carbon dioxide ($CO_2$) and oxygen ($O_2$) readings can provide additional information on what’s going on inside the combustion chamber.

Carbon dioxide, or $CO_2$, is a desirable byproduct that is produced when the carbon from the fuel is fully oxidized during the combustion process. As a general rule, the higher the carbon dioxide reading, the more efficient the engine is operating. Therefore, air/fuel imbalances, misfires, or engine mechanical problems will cause $CO_2$ to decrease. Remember, “ideal” combustion produces large amounts of $CO_2$ and $H_2O$ (water vapor).

**Effects of A/F Ratio on Exhaust CO2**

Exhaust $CO_2$ production is highest when A/F mixture is at the “ideal” 14.7/1 ratio. $CO_2$ is an excellent indicator of efficient combustion.
Oxygen (O2) readings provide a good indication of a lean running engine, since O2 increases with leaner air/fuel mixtures. Generally speaking, O2 is the opposite of CO, that is, O2 indicates leaner air/fuel mixtures while CO indicates richer air/fuel mixtures. Lean air/fuel mixtures and misfires typically cause high O2 output from the engine.

**Effects of A/F Ratio on Exhaust O2**

Exhaust O2 is lowest when A/F ratio is richer than “ideal”; however, O2 increases dramatically with leaner mixtures.

Other Exhaust Emissions

There are a few other exhaust components which impact driveability and/or emissions diagnosis, that are not measured by shop analyzers. They are:

- Water vapor (H2O)
- Sulfur Dioxide (SO2)
- Hydrogen (H2)
- Particulate carbon soot (C)

Sulfur dioxide (SO2) is sometimes created during the combustion process from the small amount of sulfur present in gasoline. During certain conditions the catalyst oxidizes sulfur dioxide to make SO3, which then reacts with water to make H2SO4 or sulfuric acid. Finally, when sulfur and hydrogen react, it forms hydrogen sulfide gas. This process creates the rotten egg odor you sometimes smell when following vehicles on the highway. Particulate carbon soot is the visible black "smoke" you see from the tailpipe of a vehicle that’s running very rich.
Causes of Excessive Exhaust Emissions

As a general rule, excessive HC, CO, and NOX levels are most often caused by the following conditions:

- Excessive HC results from ignition misfire or misfire due to excessively lean or rich air/fuel mixtures
- Excessive CO results from rich air/fuel mixtures
- Excessive NOX results from excessive combustion temperatures

There are lesser known causes to each of these emissions that will be discussed later. When troubleshooting these types of emissions failures, you will be focusing on identifying the cause of the conditions described above. For example, to troubleshoot the cause of excessive CO emissions, you need to check all possible causes of too much fuel or too little air (rich air fuel/ratio). The following lists of causes will help familiarize you with the sub-systems most often related to excessive CO, HC and NOx production.

Causes of Excessive Hydrocarbons

As mentioned, high hydrocarbons is most commonly caused by engine misfires. The following list of problems could cause high HC levels on fuel injected vehicles. As with any quick reference, there are other less likely causes that may not be included in the list. Here are some of the more common causes:

- Ignition system failures
  - faulty ignition secondary component
  - faulty individual primary circuit on distributorless ignition system
  - weak coil output due to coil or primary circuit problem
- Excessively lean air/fuel mixture
  - leaky intake manifold gasket
  - worn throttle shaft
- Excessive EGR dilution
  - EGR valve stuck open or excessive EGR flow rate
  - EGR modulator bleed plugged
- Restricted or plugged fuel injector(s)
- Closed loop control system incorrectly shifted lean
- False input signal to ECM
  - incorrect indication of load, coolant temp., O2 content, or throttle position
- Exhaust leakage past exhaust valve(s)
  - tight valve clearances
  - burned valve or seat
- Incorrect spark timing
  - incorrect initial timing
  - false input signal to ECM
• Excessive combustion blowby
  - worn piston rings or cylinder walls
• Insufficient cylinder compression
• Carbon deposits on intake valves

Causes of Excessive Carbon Monoxide

High carbon monoxide levels are caused by anything that can make the air/mixture richer than "ideal". The following examples are typical causes of rich mixtures on fuel injected vehicles:

• Excessive fuel pressure at the injector(s)
• Leaking fuel injector(s)
• Ruptured fuel pressure regulator diaphragm
• Loaded/malfunctioning EVAP system *(two speed idle test)*
• Crankcase fuel contamination *(two speed idle test)*
• Plugged PCV valve or hose *(two speed idle test)*
• Closed loop control system incorrectly shifted rich
• False input signal to ECM
  - incorrect indication of load, coolant temp., O2 content, or throttle position

NOTE

It should be pointed out that due to the reduction ability of the catalytic converter, *increases in CO emissions tend to reduce NOx emissions*. It is not uncommon to repair a CO emissions failure and, as a result of another sub-system deficiency, have NOx increase sufficiently to fail a loaded-mode transient test.
Excessive oxides of nitrogen can be caused by anything that makes combustion temperatures rise. Typical causes of high combustion temperature on fuel injected vehicles include:

- Cooling system problems
  - insufficient radiator airflow
  - low coolant level
  - poor cooling fan operation
  - thermostat stuck closed or restricted
  - internal radiator restriction
- Excessively lean air/fuel mixture
  - leaky intake manifold gasket
  - worn throttle shaft
- Closed loop control system incorrectly shifted lean
- Improper oxygen sensor operation
  - slow rich to lean switch time
  - rich biased O2 sensor voltage
- Improper or inefficient operation of EGR system
  - restricted EGR passage
  - EGR valve inoperative
  - EGR modulator inoperative
  - plugged E or R port in throttle body
  - faulty EGR VSV operation
  - leaky/misrouted EGR hoses
- Improper spark advance system operation
  - incorrect base timing
  - false signal input to ECM
  - improper operation of knock retard system
- Carbon deposits on intake valves
HC From Evaporative Sources

HC emissions can also originate from evaporative sources, such as the crankcase, fuel tank, and EVAP system components.

Evaporative Emissions

Up to now, we've only discussed the creation and causes of tailpipe or exhaust emission output. However, it should be noted that hydrocarbon (HC) emissions come from the tailpipe, as well as other evaporative sources, like the crankcase, fuel tank and evaporative emissions recovery system.

In fact, studies indicate that as much as 20% of all HC emissions from automobiles comes from the fuel tank and carburetor (on carbureted vehicle, of course). Because hydrocarbon emissions are Volatile Organic Compounds (VOCs) which contribute to smog production, it is just as important that evaporative emission controls are in as good a working order as combustion emission controls.

Fuel injected vehicles use an evaporative emissions system to store fuel vapors from the fuel tank and burn them in the engine when it is running. When this system is in good operating order, fuel vapor cannot escape from the vehicle unless the fuel cap is removed. The subject of Evaporative Emissions Systems is addressed in the next section of this program.
Use of a four or five gas exhaust analyzer can be helpful in troubleshooting both emissions and driveability concerns. Presently, shop grade analyzers are capable of measuring from as few as two exhaust gasses, HC and CO, to as many as five. The five gasses measured by the latest technology exhaust analyzers are: HC, CO, C02, O2 and NOx- Remember, HC, CO, C02, and NOx are measured in Enhanced I/M programs.

All five of these gasses, especially O2 and CO2, are excellent troubleshooting tools. Use of an exhaust gas analyzer will allow you to narrow down the potential cause of driveability and emissions concerns, focus your troubleshooting tests in the area(s) most likely to be causing the concern, and save diagnostic time. In addition to helping you focus your troubleshooting, an exhaust gas analyzer also gives you the ability to measure the effectiveness of repairs by comparing before and after exhaust readings.

In troubleshooting, always remember the combustion chemistry equation: Fuel (hydrogen, carbon, sulfur) + Air (nitrogen, oxygen) = Carbon dioxide + water vapor + oxygen + carbon monoxide + hydrocarbon + oxides of nitrogen + sulfur oxides

In any diagnosis of emission or driveability related concern, ask yourself the following questions:

- What is the symptom?
- What are the "baseline" exhaust readings? At idle, 2500 rpm, acceleration, deceleration, light load cruise, etc.
- Which sub-system(s) or component(s) could cause the combination of exhaust gas readings measured?
The Effects of Secondary Air

Some Toyota engines use a secondary air system to supplement the oxygen supply for the oxidation catalyst. This supplementary air is introduced into the exhaust stream upstream of the catalytic converter. Secondary air increases the oxygen content of the exhaust stream and reduces the carbon dioxide by diluting it.

Secondary Air Systems

Secondary air systems introduce oxygen into the exhaust stream to further oxidize engine out-gases. It is important to keep in mind the effect these systems have on tailpipe emission readings.

- **Hydrocarbons** are measured by an exhaust analyzer in parts per million (ppm). As you know, HC is unburned fuel that remains as a result of a misfire. When combustion doesn’t take place or when only part of the air/fuel charge burns, hydrocarbon levels go up.

- **Carbon Monoxide** is measured by an exhaust analyzer in percent (%) or parts per hundred. CO is a byproduct of combustion, therefore, if combustion does not take place, carbon monoxide will not be created. Based on this premise, when a misfire occurs, the carbon monoxide that would have normally been produced during the production process is not produced. Generally speaking, on fuel injected vehicles, high CO means too much fuel is being delivered to the engine for the amount of air entering the intake manifold.

- **Nitrogen Oxides** measured by an exhaust analyzer in parts per million (ppm). Nitrogen oxides are a by-product of combustion. NOx is formed in large quantities when combustion temperatures exceed about 2500°F. Anything which causes combustion temperatures to rise will also cause NOx emissions to rise. Misfire can also cause NOx to rise because of the increase in oxygen that it causes in the catalytic converter feed gas.

- **Carbon Dioxide** measured by an exhaust analyzer in percent (%) or parts per hundred. Carbon dioxide is a by-product of efficient and complete combustion. Near perfect combustion will result in carbon dioxide levels which approach the theoretical maximum of 15.5%. Carbon dioxide levels are effected by air/fuel ratio, spark timing, and any other factors which effect combustion efficiency.
• **Oxygen** is measured by an exhaust analyzer in percent (%) or parts per hundred. The amount of oxygen produced by an engine is effected by how close the air/fuel ratio is to stoichiometry. As the mixture goes lean of stoichiometry, oxygen increases. As mixture goes rich of stoichiometry, oxygen falls close to zero. Because oxygen is used up in the combustion process, concentrations at the tailpipe will be very low. If misfire occurs, however, oxygen will increase dramatically as it passes unused through the combustion chamber.

Another factor in analyzing NOX emissions are the two primary emissions sub-systems designed to control NOX levels, the EGR and reduction catalyst systems. NOX emissions will increase when the EGR system malfunctions or when the reduction catalyst efficiency falls. Efficiency of the reduction catalyst is closely tied to normal operation of the closed loop fuel control system. Reduction efficiency falls dramatically when catalyst feed gas carbon monoxide content is too low (oxygen content too high.)

![Catalyst Efficiency](image_url)

*As shown, catalyst purification efficiency is highest (100%) when A/F mixture is maintained at the “ideal” 14.7/1 ratio.*
When using an exhaust analyzer as a diagnostic tool, it is important to remember that combustion takes place twice before reaching the tailpipe. First, primary combustion takes place in the engine. This determines the composition of catalyst feed gas, which dramatically effects catalyst efficiency. When the exhaust gases reach the three-way catalytic converter, two chemical processes occur.

**Secondary Combustion**

Catalyst reduction and oxidation occurs in the TWC to further reduce the level of harmful gases emitted from the tailpipe.

**Oxidation and Reduction Process**

- **Catalyst Reduction**: First, nitrogen oxide gives up its oxygen. This only occurs when a sufficient amount of carbon monoxide is available for the oxygen to bond with. This chemical reaction results in reduction of nitrogen oxide to pure nitrogen and oxidation of the carbon monoxide to form carbon dioxide.

- **Catalyst Oxidation**: Second, hydrocarbon and carbon monoxide continue to burn. This occurs only if there a sufficient amount of oxygen available for the hydrogen and carbon to bond with. This chemical reaction results in oxidation of hydrogen and carbon to form water vapor (H2O) and carbon dioxide (CO2).
When troubleshooting an emissions failure, your primary concern will be what comes out of the tailpipe. In other words, it doesn't matter whether the efficient burn occurred in the engine or the catalyst. However, when troubleshooting a driveability concern, the catalytic converter may mask important diagnostic clues which can be gathered with your exhaust analyzer. The following are examples of situations where post-catalyst reading may be deceiving.

**Example 1:**

Effects of secondary combustion on engine misfire condition.

- **Example 1:** A minor misfire under load is causing a vehicle to surge. The exhaust gas from the engine would show an increase in HC and 02, and a reduction in CO2. However, once this exhaust gas reaches the catalytic converter, especially a relatively new and efficient catalyst, the oxidation process will continue. The excess HC will be oxidized, causing HC and O2 to fall, and CO2 to increase. At the tailpipe, the exhaust readings may look perfectly normal.

In this example, it is interesting to note that NOx readings will increase because of the reduced carbon monoxide and increased oxygen levels in the catalyst feed gas. This could be detected with a five gas analyzer.
• **Example 2:** A small exhaust leak upstream of the exhaust oxygen sensor is causing a false lean indication to the ECM. This resulted in excessively rich fuel delivery to bring oxygen sensor voltage back to normal operating range. The customer concern is a sudden decrease of 20% in fuel economy.

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**Example 3:**

Effects of secondary combustion on rich A/F mixture condition.

![Diagram showing effects of secondary combustion](image)

- **Pre-Catalyst:**
  - CO = Increase
  - CO₂ = Decrease
  - O₂ = Decrease

- **Secondary Combustion**

- **Post-Catalyst:**
  - CO = Normal Range
  - CO₂ = Normal Range
  - O₂ = Very Low

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• **Example 3:** A restriction in the fuel return line elevates pressure causing an excessively rich air/fuel ratio and a 20% decrease in fuel economy. Although carbon monoxide emissions from the engine are elevated as a result of this rich air/fuel ratio, the catalytic converter is able to oxidize most of it into carbon dioxide. The resulting tailpipe readings appear to be normal, except for oxygen, which is extremely low for two reasons. First, the increase in CO caused a proportionate decrease in O₂ in the converter feed gas. Second, the little oxygen left over was totally consumed oxidizing the CO into CO₂.

Based on this example, you can see that oxygen is a better indicator of lean or rich air/fuel ratios than carbon monoxide when testing post catalytic converter.
Effects of A/F Ratio on Engine-Out Gases

Use the following graph to study the relationship A/F mixture has on exhaust gas output levels.

General Rules of Emission Analysis

- If CO goes up, O₂ goes down, and conversely if O₂ goes up, CO goes down. Remember, CO readings are an indicator of a rich running engine and O₂ readings are an indicator of a lean running engine.
- If HC increases as a result of a lean misfire, O₂ will also increase.
- CO₂ will decrease in any of the above cases because of an air/fuel imbalance or misfire.
- An increase in CO does not necessarily mean there will be an increase in HC. Additional HC will only be created at the point where rich misfire begins (3% to 4% CO).
- High HC, low CO, and high O₂ at same time indicates a misfire due to lean or EGR diluted mixture.
- High HC, high CO, and high O₂ at same time indicates a misfire due to excessively rich mixture.
- High HC, Normal to marginally low CO, high O₂, indicates a misfire due to a mechanical engine problem or ignition misfire.
- Normal to marginally high HC, Normal to marginally low CO, and high O₂ indicates a misfire due to false air or marginally lean mixture.
To verify that the exhaust readings are not being diluted in the exhaust system or analyzer sampling point, combine the CO reading with the CO2 reading. An undiluted sample should always have a sum of greater than 6%. Remember, the secondary air system may be diluting the sample if it is not disabled during analysis. In fact, engines with secondary air injection systems will have relatively high oxygen concentrations in the exhaust because of the extra air pumped into the exhaust, post combustion.

The following major factors contribute to the overall increase in exhaust emissions levels and degraded vehicle driveability:

- Lack of scheduled maintenance
  - Sub-system failures
  - Combination of multiple marginal sub-systems
- Tampering
  - Removal of emissions sub-system equipment
  - Modification of engine/emissions sub-systems
- Use of leaded fuels or incompatible additives in closed loop control systems