Exhaust Analysis Using 4 and 5 Gas Analyzers

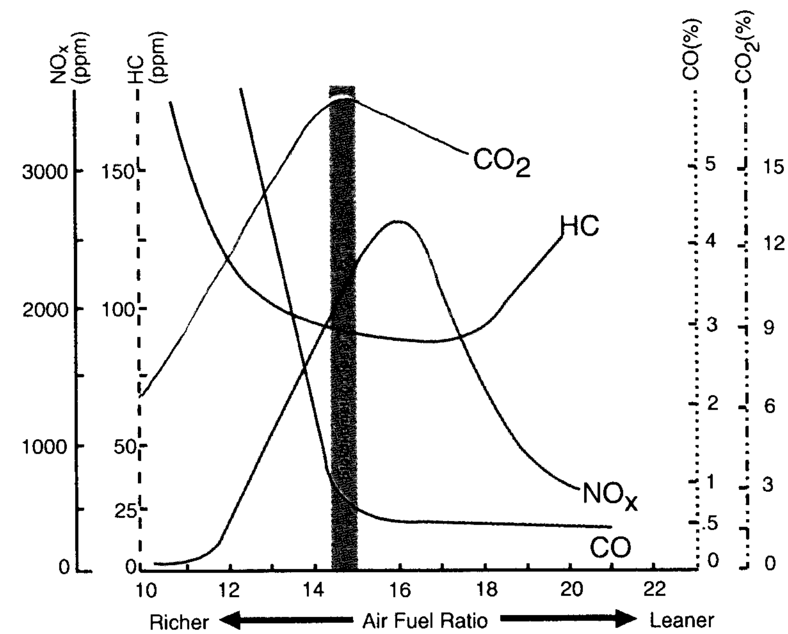
So far we've discussed how harmful exhaust emissions are produced during combustion. However, in addition to these harmful emissions, both carbon dioxide (CO2) and oxygen (O2) readings can provide additional information on what's going on inside the combustion chamber.

Carbon Dioxide (CO2)

Carbon dioxide, or CO2, 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 CO2 to decrease. Remember, "ideal" combustion produces large amounts Of CO2 and H2O (water vapor).

Effects of A/F Ratio on Exhaust CO_2

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.

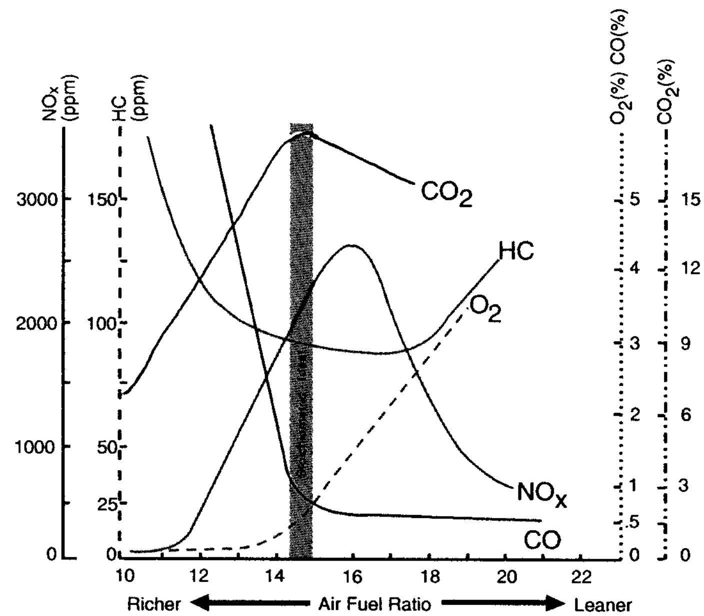


Oxygen (O2)

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 O_2

Exhaust O_2 is lowest when A/F ratio is richer than "ideal"; however, O_2 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 (HO
- 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.

Causes of Excessive Oxides of Nitrogen

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 02 sensor voltage

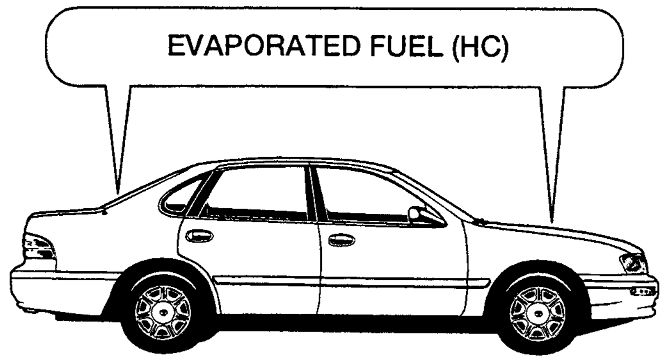
- Improper or inefficient operation of EGR system
  - restricted EGR passage
  - EGR valve inoperative
  - EGR modulator inoperative
  - plugged E or R port in throttle body
  - faulty EGR VSV operation
  - leaky/misrouted EGR hoses

- 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.



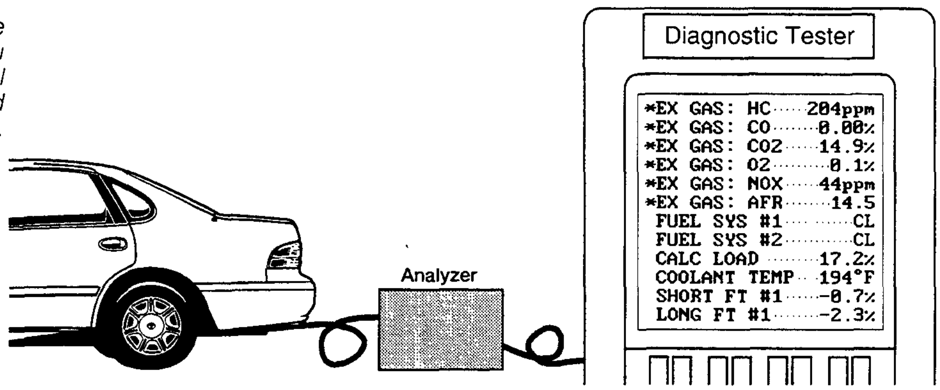
Evaporative Emissions
Up to now, we've only discussed the creation and causes of tailpipe or exhaust emission output. However, it should be noted that hydrocarbon (HC) emissions come from the tailpipe, as well as other evaporative sources, like the crankcase, fuel tank and evaporative emissions recovery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

Exhaust Gas Analyzers

5-Gas Exhaust Analyzers are now available that allow you to "zero-in" on potential causes of emission and driveability concerns.



Diagnosis Using an Exhaust Gas Analyzer

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, CO2, O2 and NOx. Remember, HC, CO, CO2, 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:

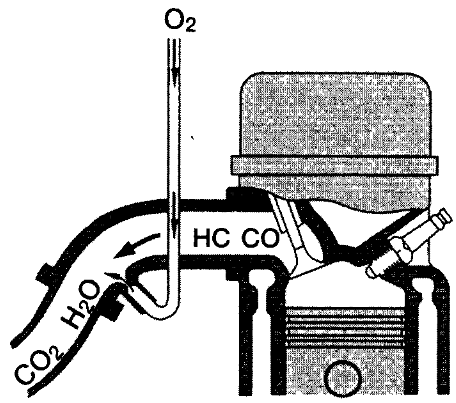
- What is the symptom?
- What are the "baseline" exhaust readings? At idle, 2500 rpm, acceleration, deceleration, light load cruise, etc.
- Which sub-system(s) or component(s) could cause the combination of exhaust gas readings measured?

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 introduces 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.



Analyzing Exhaust 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 goes 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.

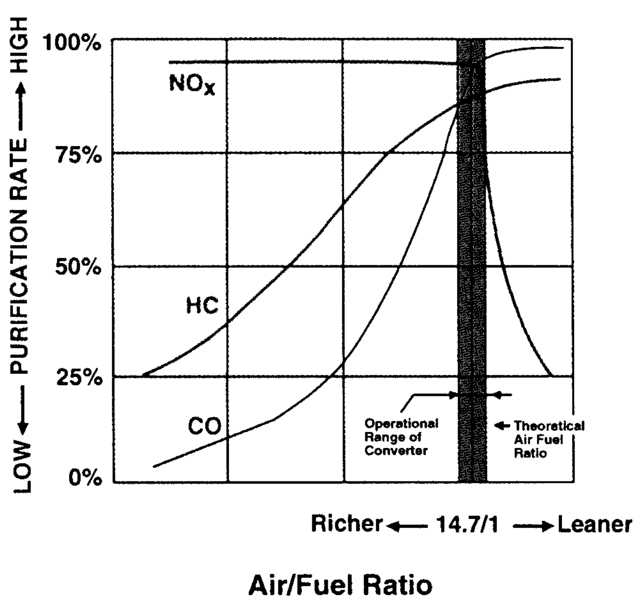
- Carbon Dioxide measured by an exhaust analyzer in percent (%) or parts per hundred. Carbon dioxide is a by-product of efficient and complete combustion. Near perfect combustion will result in carbon dioxide levels which approach the theoretical maximum of 15.5%. Carbon dioxide levels are effected by 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.

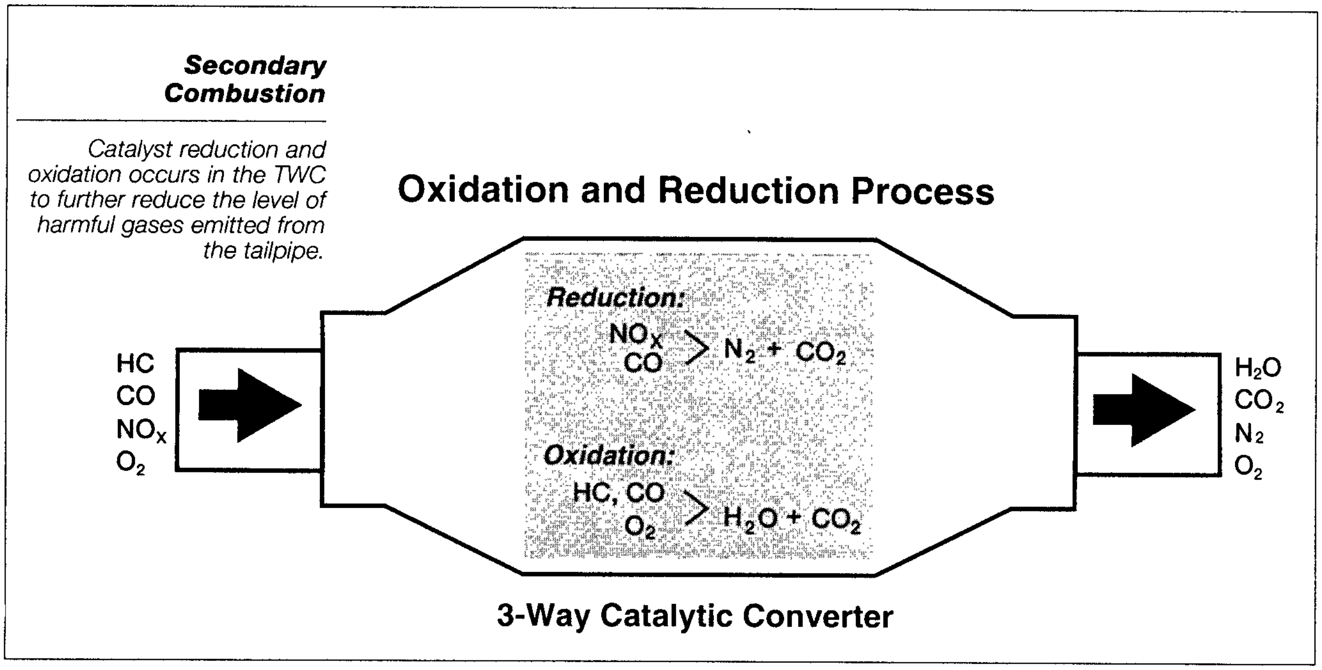
Another factor in analyzing NOx emissions are the two primary emissions sub-systems designed to control NOx levels, the EGR and reduction catalyst systems. NOx emissions will increase when the EGR system malfunctions or when the reduction catalyst efficiency falls. Efficiency of the reduction catalyst 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

As shown, catalyst purification efficiency is highest (100%) when A/F mixture is maintained at the "ideal" 14.7/1 ratio.



Pre-Catalyst Versus Post-Catalyst Testing
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.

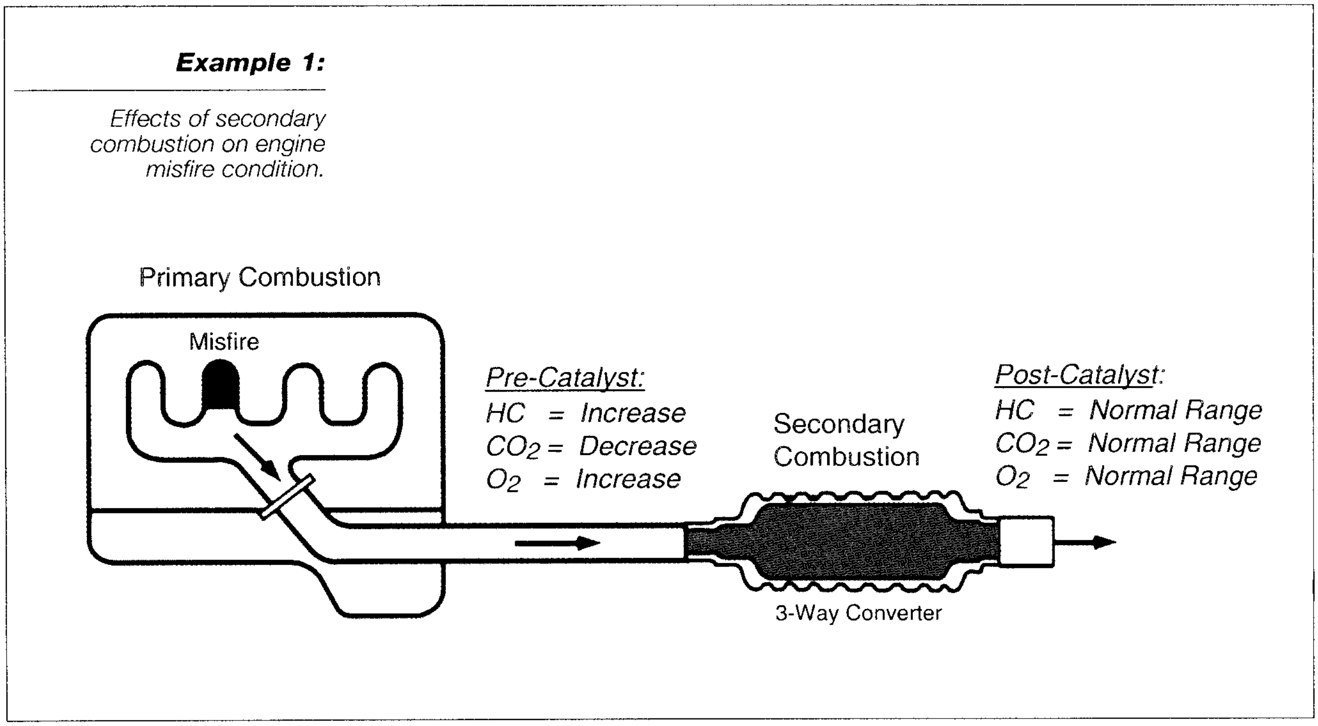


Catalyst Reduction
First, nitrogen oxide gives up its oxygen. This only occurs when a sufficient amount of carbon monoxide is available for the oxygen to bond with. This chemical reaction results in reduction of nitrogen oxide to pure nitrogen and oxidation of the carbon monoxide to form carbon dioxide.

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).

Examples of Deceiving Post-Catalytic Analysis

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.



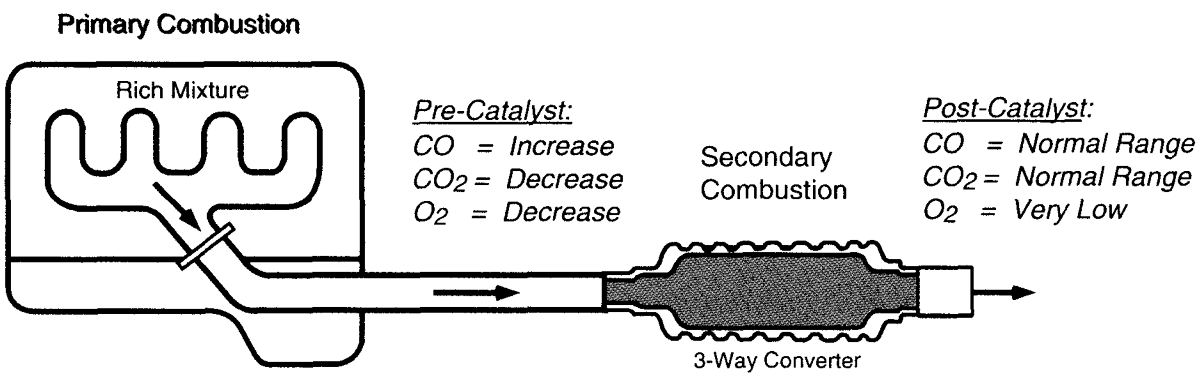
- **Example 1**: A minor misfire under load is causing a vehicle to surge. The exhaust gas from the engine would show an increase in HC and O2, and a reduction in CO2. However, once this exhaust gas reaches the catalytic converter, especially a relatively new and efficient catalyst, the oxidation process 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.

Example 3:

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

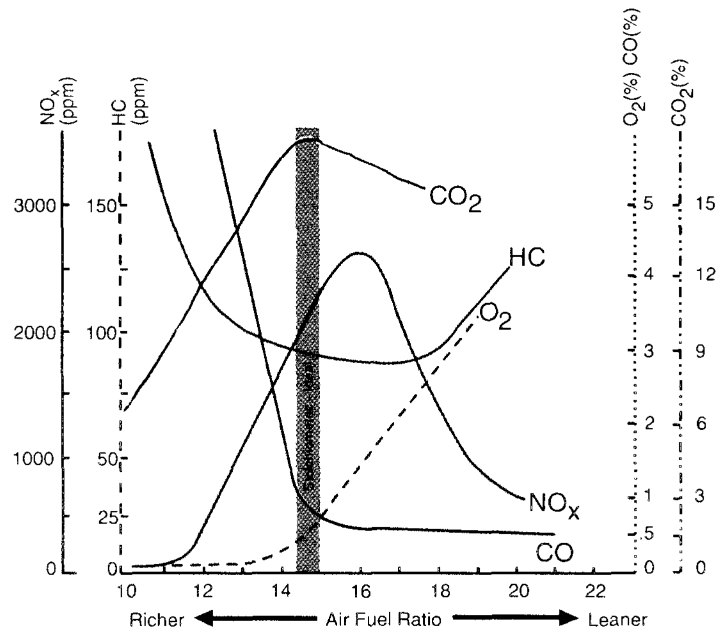


- **Example 3:** A restriction in the fuel return line elevates pressure causing an excessively rich air/fuel ratio and a 20% decrease in fuel economy. Although carbon monoxide emissions from the engine are elevated as a result of this rich air/fuel ratio, the catalytic converter is able to oxidize most 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.

Factors That Degrade Emissions & Driveability

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

