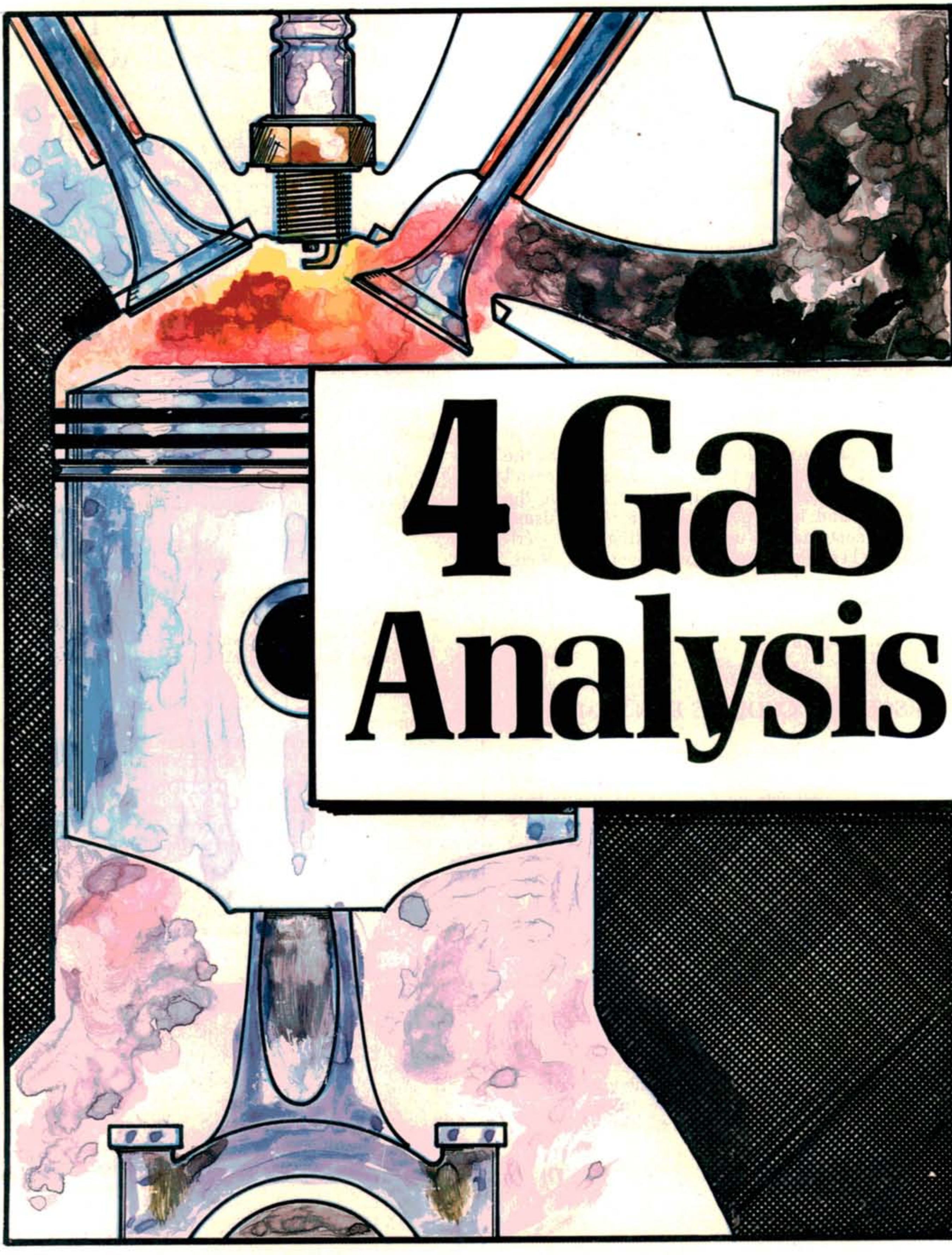


4 Gas Analysis

As mandatory emissions testing gets to be a hotter and hotter topic, the 4 gas emission analyzer will soon be finding its way into more and more shops. But rather than spend a lot of time discussing the legal aspects of emissions testing, we thought it might be interesting to look at ways to use a 4 gas as a diagnostic tool.

We selected three different vehicles, each with a different fuel injection system: a Motronic system on a BMW, an LH system on a Volvo, and a K-Lambda system on a Volkswagen. These systems have different design characteristics, so we created several problems and recorded real readings. Sometimes, the systems responded very rapidly and attempted to compensate for our tampering. Each system responded a little differently to each different problem. But the differences aren't as important as the similarities when we use the 4 gas to troubleshoot.

The key to successful 4 gas analysis, like the key to using other diagnostic tools, is to look for general patterns and trends. You know the old joke about "Your mileage may vary"? Well it's not as much of a joke as you might think. As we said, the specific readings shown in this article are real ones from real cars. The readings you get from similar problems will vary depending on the type of system being tested, the general condition of the vehicle, and the severity of the problems you encounter. But the overall trends should help you isolate a few common problems by general type.

All of our tests were done at idle although it's important to note that the use of a dyno, or a portable 4 gas like the MPSI PGA 9000, can help you record emission-under-load readings which can be used to isolate and repair driveability problems.

But that's another story.

Why 4 Gas?

One of the reasons your old HC/CO machine has fallen from favor, is that catalytic converters have gotten very, very good at controlling our old 2 gas friends HC and CO. So much so, that a good catalyst can almost eliminate tailpipe emissions of HC and CO, even if the catalyst needs to work a little overtime cleaning the exhaust coming from an engine running slightly below par. We'll look at real example of this later.

The other two gases, oxygen and carbon dioxide, can fill in the diagnostic gaps left by 2 gas analysis, even when we test at the tailpipe. Some cars have an upstream test point which allows you to sample exhaust before the catalyst can scrub it.

On cars without these test points, you can test at the tailpipe using a procedure described by MPSI as "preconditioning." This procedure puts the catalyst to sleep long enough for you to take exhaust readings which haven't been scrubbed.

Preconditioning includes the following steps:

- Disconnect the air supply to the catalyst.
- Warm the engine completely (thermostat open).
- Shut the engine off and let the catalyst cool.
- Start the engine and complete your tests before the catalyst relights.

We should note here, that none of our test vehicles had an air pump or pulse air injection system. But don't forget to disconnect the air injection if the car being tested is so equipped.

Ground Rules

Before we start, let's give a very brief description of our 4 gases. Understanding what each of the 4 gases represents is **Step One** of 4 gas analysis:

- **CO tells us about the ratio of fuel to air**, basically richness or leanness. It does not necessarily tell us about how efficiently the mixture is being burned.
- **HC tells us how much of the available fuel was NOT burned.** (Think of high HC as the sooty smoke you get when you burn wet wood in your fire place.) Low HC (no soot) is good. High HC is the result of incomplete burning of the fuel mixture. High HC can result from anything causing incomplete combustion.
- **O_2 tells us how much oxygen is left over**, normally 1 to 2 percent. O_2 emissions should be fairly stable until the air/fuel ratio goes above 14.7/1, then they rise quickly. That makes O_2 a good indicator of a lean condition. (Our atmosphere contains about 21 percent oxygen.)
- **CO_2 measured before the catalyst is a measure of combustion efficiency.** High CO_2 is a good indication of combustion efficiency, and CO_2 readings will peak when the air fuel ratio is at its highest efficiency. Careful here. CO_2 is also produced by the catalyst as it combines CO and O_2. Comparative readings before and after the catalyst can also tell us whether or not the catalyst is working. Once again, we'll show you a real example.

Quick Look at a Good Mixture

Now let's take **Step Two** in understanding 4 gas analysis. Using what we just learned, we can paint a pretty accurate picture of how a 4 gas sample from a mechanically sound, well tuned engine running at stoichiometric efficiency would look:

- **HC will be low.** Very little fuel is left unburned after combustion.
- **CO and O_2 will be about the same.** Think of it as a healthy balance. The available fuel is combining evenly with the available oxygen.
- **CO_2 will rise as an indication of combustion efficiency and also of catalyst action.** Readings above 13 percent are now common tailpipe readings on catalyst equipped cars.

This is **Step Three**—Interpreting readings based on what we've just learned. But rather than drag you through any more theory, let's rig some cars to create real problems, and use our 4 gas to see what happens.

Our thanks to the following folks for their assistance in the preparation of this article:

- Cliff Baker, Sun Electric Corporation
- Tom Fudali, Bear Automotive Service Equipment Co.
- Tim Cooper, Allen Test Products
- We'd also like to thank Tom Carter at MPSI for his technical assistance and for loaning us the PGA 9000 portable 4 gas analyzer used in our tests.

—By Ralph Birnbaum

Taking the Catalyst Out of the Picture

Let's start by preconditioning one of our test vehicles. We check the exhaust for leaks, warm the engine until the thermostat opens, and look for good warm coolant flow throughout the entire cooling system. Then we shut the car off. If the car has an air injection system, we disconnect it. (You'll find that catalysts on some cars will "go out" by themselves during prolonged idling.) Then we let the catalyst cool for about 10-15 minutes. When we start the car, we allow it to idle and take our readings. Since we're testing at the tailpipe, we won't be sure at first if the catalyst is really off, but we'll check the catalyst in a moment anyhow.

HC - 82 PPM
CO - 0.6%
O_2 - 0.5%
CO_2 - 15.2% (indicating good efficiency)
Air fuel ratio 14.83/1

Checking the Catalyst

Now we want to relight the catalyst, so we can take comparative readings. Our car doesn't have air injection, but on a car with an air injection system, reconnect the air supply to the catalyst. Now start, and rev the engine to get the catalyst up to operating temperature. As the catalyst starts cleaning the exhaust, readings for HC and CO should come down. Readings for these two may even get so low they'll disappear. Readings for oxygen should go down compared to O_2 readings from the non-catalyzed exhaust. Readings for CO_2 should go up as CO and O_2 combine to make carbon dioxide (CO_2). Also note that the air fuel ratio calculated for the car didn't change.

HC - 15 PPM (lower with catalyst)
CO - 0.02% (lower with catalyst)
O_2 - 0.4% (lower with catalyst, but 02 may rise on cars with air injection)
CO_2 - 15.8% (high indicating combustion efficiency and catalyst action)
Air fuel ratio 14.83/1

High CO and HC With Regular Misfire (Warm Idle)

On this car, the mixture is so rich that it's fouling plugs, causing a misfire. We have more fuel available than the engine can burn. Leaking injectors, high pressure in the fuel rail caused by a faulty pressure regulator, or a saturated float or leaking power valve on carbureted cars, are all possible causes. We should also include a close inspection of the evaporative system and check purge valve operation when diagnosing this type of problem. A tough one to find is an accumulation of minor enrichments from several sources which all add up to a fuel air mix too rich to burn efficiently.

HC - 425 PPM
CO - 5.63%
O_2 - 2.3% (Since we have a miss, some of our oxygen is not being used. But remember, O_2 isn't a really accurate indicator of a rich mixture—CO is telling us more in this case.)
CO_2 - 10% - At the same time CO and HC rise during a misfire, CO_2 will go down.

Rich Mixture-High CO (Warm Idle)

Let's stick with high CO for a moment. Remember, high CO indicates a rich mixture. Anything which richens the mixture can cause high CO readings, including the following possibilities:

- A sticking choke
- High fuel pressure or a leaking fuel injector
- A plugged air filter
- A saturated charcoal canister or bad purge valve
- A heavy carburetor float
- The already mentioned fuel in the crankcase.

In this particular case, our high CO was caused by nothing more than an improperly adjusted base mixture. But that won't always be the case. The following 4 gas readings were taken upstream on our K-Lambda Volkswagen before we made our adjustments. It's rich, but not rich enough to cause a miss caused by plug fouling.

HC - 85 PPM
CO - 2.9% (Higher than normal-higher than O_2)
(O_2 may be normal, or even a little lower than normal depending on how rich the mixture gets—O_2 is not always a good rich mixture indicator)
O_2 - 0.8%
CO_2 - Low, below 12%—combustion efficiency is lower than normal because of high CO)

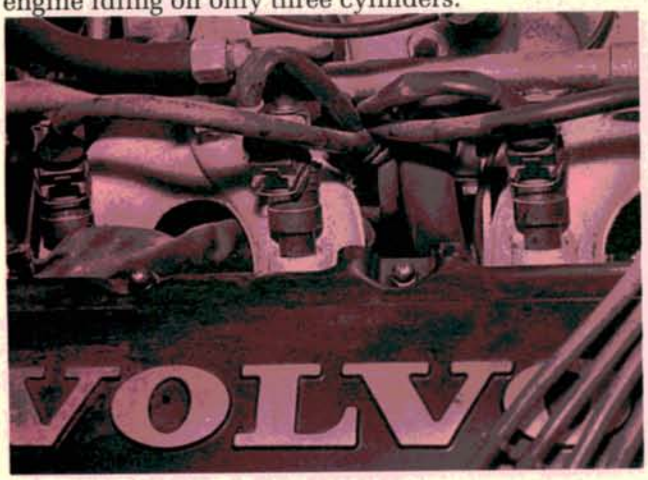
Dead Hole

You've got a car with a dead hole. One of the spark plug wires has damaged insulation, and the spark is going directly to ground. The fuel and air in the cylinder are not being burned. Four cylinder cars are not happy when one of the foursome goes completely to sleep. But can the 4 gas give you clues about the cause of the dead hole? Let's simulate a bad miss caused by weak or missing secondary spark. The tailpipe readings tell us a lot, and can lead us to diagnosing our problem. These readings are from an LH equipped Volvo. Notice how the LH system tries to react to the miss, mistaking high O_2 for a lean mixture. Too bad it can't measure HC.

HC - HC went high, from 25 PPM to 1257 PPM
CO - 0.49% Our original tailpipe reading was 0.04. But we have a lot of unburned oxygen in the tailpipe so the ECU richens the mixture.
O_2 - 3.5% (Our dead hole is sending both HC andO_2 down the pipe unburned)
CO_2 - 10.0%—down from reading of 15.5

Dead Hole/Dead Injector/Catalyst Lit

This time, we'll disconnect the injector on our LH-Jetronic car. Now we have a dead miss on the same cylinder caused by a different problem. But we revved the car between tests to normalize the engine after simulating the ignition miss in the previous test. This relit the converter. Our first readings with the injector disconnected were surprisingly low, even with a miss. The HC readings were somewhat higher than normal, but CO remained very low. CO_2 was also pretty high. The unburned oxygen becomes a clue, however, since it's passing through untouched. The catalyst and fuel system are responding amazingly well (at least on the short term!) to an engine idling on only three cylinders.



HC - 55 PPM (higher than normal, but not outrageous)
CO - 0.08%
O_2 - 3.8%
CO_2 - 13.9%

Dead Hole/Dead Injector/ No Catalyst Cleaning

We decided that the previous readings were foolers, so we shut the car down long enough to allow the catalyst to "go out." This time, the tailpipe readings without catalyst cleaning were much more what we expected with one injector disconnected. Again we disconnected the number 1 injector and made our tests before the catalyst could relight. Sometimes, when you're dealing with a car that can think on its feet, you have to fib to it a bit to get at the truth of the matter. Notice that even though our miss is caused by a disconnected injector, our HC emissions go up, although not as much as they did from the ignition miss.

HC - 150 PPM
CO - 1.80 (trying to compensate for high oxygen content in exhaust)
O_2 - 3.0 (lots of unburned oxygen)
CO_2 - 13.0 (once again lower than original 15.5)

Coolant Sensor Problems

One of the most important signals sent to the ECU comes from the CTS, or Coolant Temperature Sensor. What happens when we have a warm engine combined with a lying CTS? We dialed in a cold signal to the ECU on an engine fully warmed and running at its designed operating temperature.

By the way, a similar problem will occur if something as simple as a coolant thermostat sticks open or part way open. In that instance, the CTS may not be at fault at all. It's just that the engine never gets warm enough to get the ECU to stop sending a cold enrichment signal.

HC - 288 PPM (The mixture is too rich to burn efficiently in a warm engine)
CO - 9.37% (cold enrichment signal)
O_2 - 0.7% (This makes sense since the fuel air ratio is too rich—there isn't enough oxygen to go around)
CO_2 - Only about 9-10% (very inefficient)

4 Gas Quick Tips

Here are a few quick suggestions and pieces of information that may help you organize your thoughts about 4 gas analysis.

• Maybe the most important rule of all is: Eliminate the obvious! Don't spend time looking for exotic solutions to simple problems. Always eliminate dirty fuel and air filters, contaminated oil, vacuum leaks, and overall neglect before looking for more complicated problems. Most fixes are simple ones.

• The number one cause of high CO is a dirty air filter.

• Catalytic converters need heat (about 550 degrees F) and oxygen to work properly. At idle, a properly tuned engine will produce little oxygen, and exhaust temperatures may drop to well below 550 degrees F. If you take the catalyst out of the picture by allowing it to cool down, don't forget to relight it before final emission testing.

Many cars which fail emissions tests do so because the catalyst isn't up to temperature, or doesn't have enough oxygen to do its job. When testing for catalyst efficiency, start and fully warm the engine. Then run it at 2500 RPM for two minutes.

• Newer ignition components are far more reliable than those used only a few years ago. The most common causes for high HC are less often the result of secondary ignition problems than they used to be. High HC on newer cars is usually caused by an improperly balanced fuel mix—either too lean from a vacuum leak—or to rich from over-fueling of the combustion chamber.

• If you have any doubt about what HC stands for, take the sensing probe of the 4 gas and place it near an open fuel fill neck. HC readings will take off and may peg the analyzer at its maximum HC reading. HC is raw, unburned fuel, in this case, fuel vapor.

This makes your 4 gas a handy tool for finding a leaking fuel line hidden inside a body panel.

• Some vehicles need air injection because they run richer, and need the additional oxygen to increase converter cleaning. With the air injection disabled, these cars will be richer at the tailpipe. With the air injection reconnected, O_2 may be as high as 5 percent, and still be acceptable.

Oxygen readings at the tailpipe will be higher on cars with air injection when the air injection system is operating.

• An ignition misfire will increase O_2 dramatically, since almost all the O_2 in the combustion chamber escapes unused.

• If CO goes up, O_2 goes down.

• An increase in CO does not always result in an increase in HC.

• If O_2 goes up, CO goes down.

• If HC goes up, O_2 will increase. How much it increases depends on the cause of the misfire.

• CO_2 goes down whenever there is an imbalance.

• CO_2 is highest at peak efficiency.

(Information supplied compliments of Lynn Goodman at the National Center for Vehicle Emissions Control and Safety.)

PCV Test (Warm Idle)

Since 20 to 30 percent of the air drawn in by the engine at idle comes from the crankcase through the PCV system, a crankcase loaded with unburned fuel can send CO readings through the roof. To test for crankcase vapor, pull the PCV valve from the valve cover and give the engine a breath of fresh air. If CO drops 1.5 percent or more with the PCV disconnected, then shoots back up when the valve is reinstalled in the cover, stop here and check the crankcase oil for fuel contamination. Change the oil if necessary. If the symptoms persist after the oil change, the rings may be suffering from terminal blow by.

CO and O_2 should change somewhat when the valve starts drawing fresh air. If they don't change at all, check to see if either the PCV valve or the line between the PCV valve and the intake manifold is plugged.

Importance of the PCV Test (Warm Idle)

The PCV test is one of the most important tests you'll run. Some newer cars have computers with adaptive modes. In other words, they keep track of engine conditions, and adjust the fuel mixture to compensate for tiny vacuum leaks and some crankcase contamination. If the car you're testing has higher than normal CO, don't just lean the mixture without finding the reason for your rich readings. If you lean the mixture on an adaptive system to compensate for crankcase fumes, and the vehicle's owner stops on the way home for an oil change at the local Drain 'N Fill, the loss of crankcase enrichment and a lean base mixture may combine to give you a car too lean to restart. Don't forget to check the crankcase for fuel contamination.

K-Lambda System with False Air Before Throttle

We normally think of vacuum leaks occurring at or below the throttle. But what about leaks between the throttle and air sensor? We loosened the screw clamp where the plastic intake tube connects to the rubber sealing boot at the intake sensor on our K-Lambda system. That's all. Just a loose clamp. The resulting misfire was a healthy one indeed. The car chugged, missed badly, and almost stalled several times. We got some very radical readings at the tailpipe this time. Tailpipe readings with the O_2 sensor connected can tell us a lot about how well the car operates in closed loop. Note how the K-Lambda system tried to compensate for the lean mixture.

HC - 225 PPM

CO - 0.04% (Lean to start since there was less air to move the air sensor. Eventually the ECU tried to compensate by changing the duty cycle at the return line frequency valve, and CO went up to about 2.5%)

O_2 - 9%

CO_2 - 5.2% (Very poor combustion efficiency)

High CO With Vacuum Leak (Warm Idle)

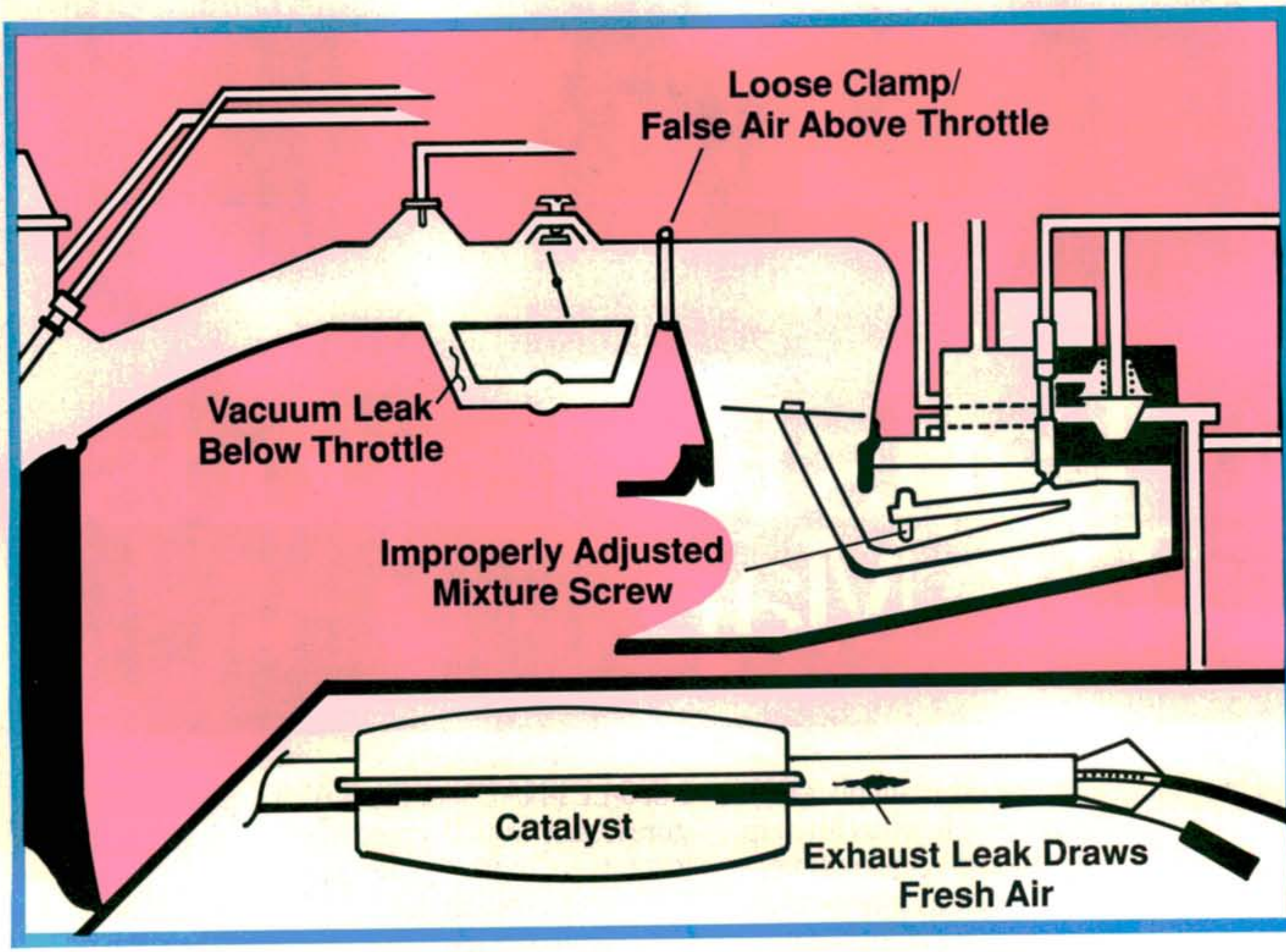
This one can be a little confusing at first glance. Three of our readings are higher than normal. CO, HC, and O_2 are all high. We have plenty of fuel, but we also have a lot of left over oxygen that hasn't been burned in the combustion process. This car has a combination of a vacuum leak and a rich mixture adjustment. The base mixture is too rich, but false air below the throttle plate is raising O_2 emissions. The false oxygen also fools the O_2 sensor into calling for an even richer mixture. Our engine runs badly and misfires on occasion. This situation often shows up when someone attempts to mask a vacuum leak with a richer mixture adjustment.

HC - 400 PPM (High)

CO - 3.5% (High)

O_2 - Above 3.0% (High, from false air at intake—If it weren't for high CO we might be fooled into thinking we have a lean miss caused by low fuel pressure—this time we have plenty of fuel, but we also have a large vacuum leak)

CO_2 - 7% (Low, indicating inefficient combustion)



Low CO Caused by Vacuum Leak (Warm Idle)

Let's introduce a vacuum leak at the hose running between the auxiliary air regulator and the intake manifold, like the leak you'd get from a cracked hose. We have too much air to properly support combustion. Unlike the exhaust leak in the BMW, however, this leak is drawing atmospheric oxygen right into the combustion chambers, affecting combustion. To find a problem like this, disconnect the analyzer from the tailpipe and spray light oil around areas suspected of vacuum leaks. Look for engine speed to increase if you score a bull's eye.

HC - High - 250 PPM (Base adjustment may be okay, but incomplete combustion means a lot of HC passes through unburned)
CO - Low - 0.02% (The mixture is lean—too little fuel, too much air)
O_2 - High - Above 2% (We not only have a mixture so lean that it wants to misfire, we're drawing atmospheric oxygen right into the manifold)
CO_2 - Low - About 8.2% indicating incomplete combustion

Lean Miss (Warm Idle)

Let's look at a lean miss on a different vehicle. The readings on this vehicle are different, because the vacuum leak is in a different place, and is a larger leak. But this is a good example of using general symptoms to diagnose a general type of problem. This time there isn't enough fuel to light the fire. That means that much of the HC and O_2 available for combustion pass through unburned. Once again, CO is not a good way to measure a lean miss, since it doesn't change much once the mixture leans above 15/1, and HC alone won't tell us if the miss is a rich or lean miss. Fortunately, O_2 really jumps above 15/1.

HC - 1150 PPM
CO - 0.02%
O_2 - 14.2%—(This is a big leak, and O_2 skyrockets because we have lots of unburned O_2 from the miss, plus air being drawn directly into the manifold)
CO_2 - 3.7% indicating low combustion efficiency

BMW Motronic Measured at Tailpipe

This example shows combustion readings from our BMW which is operating efficiently. This sample was taken at the tailpipe with the catalyst lit. Fuel and air are properly balanced, the ignition system is firing the mixture at the right time, compression is good, and valve timing is correct. We have good clean fuel in the car, fuel and air filters are clean, and there's fresh oil in the sump. In short, we have no problems. But the oxygen reading seems way too high to fit in with our other readings. Maybe there's something else going on which affects our readings.

HC - 10 PPM (Few unburned Hydrocarbons)
CO - 0.06% (Acceptably lean fuel mixture)
O_2 - 3.9% (Low O_2 indicates complete combustion. So why is our O_2 so high in a car that seems to be running well otherwise?)
CO_2 - 14.4% (CO_2 is high indicating good combustion efficiency)

A Bad Exhaust Can Fool You

Sometimes a reading just doesn't fit. The oxygen reading in the previous sample seems high. Oxygen is usually low in a good running engine, and short of having raw air drawn in, it wants to stay fairly stable until the mixture gets lean enough to cause a lean miss. We must be getting oxygen somewhere else. A thorough inspection of the exhaust system turns up a small exhaust leak after the catalyst. The exhaust leak near the tailpipe is drawing fresh, outside air into the exhaust sample. The leak is working almost like a pulse air system, but since it's after the catalyst, it affects only tailpipe O_2. We fix the leak and our readings look like this:

HC - 10 PPM
CO - 0.06%
O_2 - 1.0%
CO_2 - 14.4%

We realize that the readings we've shown are from specific cars, under specific test conditions. If you think you'll be able to match them number for number with other cars coming through your doors, you may miss the point.

We've already shown how the catalyst tried to fool us, and how very adaptive new fuel systems can be as they try to compensate for problems. But we hope the thought process involved in each of these steps will help you establish patterns of logical thought when you use your 4 gas to diagnose driveability and emissions problems.

Using a 4 gas is very much like using an oscilloscope. It takes practice and the time needed to catalog and store your own reference library of known good and known bad readings. We hope this article helps you make the first step in building both your reference library and your 4 gas skills.