CATALYTIC CONVERTER

THEORY, OPERATION AND TESTING

The gasoline used in the modern automobile is a complex blend of both straight and branched chain hydrocarbons. In simpler terms it is a mixture of different types of bunches of hydrogen and carbon. We will use the fictitious molecule C_8H_{17} to approximate the blend of different hydrocarbon compounds found in gasoline. In more simple terms one gasoline molecule* contains 8 atoms of carbon for every 17 atoms of hydrogen and nothing else*.

ONE GASOLINE MOLECULE*

GASOLINE IS --> C_8H_{17}

8 CARBON ATOMS + 17 HYDROGEN ATOMS BONDED TOGETHER

**There is no such thing as a single gasoline molecule. Gasoline is a very complex blend of several different molecules. C_8H_{17} is used to represent the average "gasoline molecule".*

COMPOSITION OF AIR

1 PART OXYGEN (O_2) AND 4 PARTS NITROGEN (N_2)

When gasoline is mixed with air and ignited in the combustion chamber it burns, and in doing so reorganizes the hydrogen, carbon and oxygen atoms. As these atoms are reorganized they can form CO, CO_2, H_2O, NO (and other NOx), and of course if some of the gasoline is left unburned, C_8H_{17} or other forms of generic HC.

Optimum combustion occurs at an A/F ratio of about 14.64:1. If all of the fuel vaporizes and takes part in combustion and no NOx is formed we would have perfect combustion. Perfect combustion would result in the formation of nothing CO_2, H_2O.

Perfect combustion: Air + Fuel → CO_2 + H_2O (and nothing else)

Unfortunately as more and more CO_2 is formed the temperature goes up. As the temperature increases, NOx is formed. NOx formation uses up the oxygen that is needed for CO2 formation

Real World combustion: Air + Fuel → CO_2 + H_2O + NOx + CO (and unburned HC, O_2 & N_2)

NOx emissions are at there highest between 14.64:1 and about 16.5:1

HC emissions increase whenever the mixture is richer or leaner than about 14.64:1. Under lean conditions, the fuel charge will sometimes fail to ignite and result in high HC emissions. This is known as a lean misfire. Under rich conditions, some of the fuel fails to burn because there is not enough oxygen.

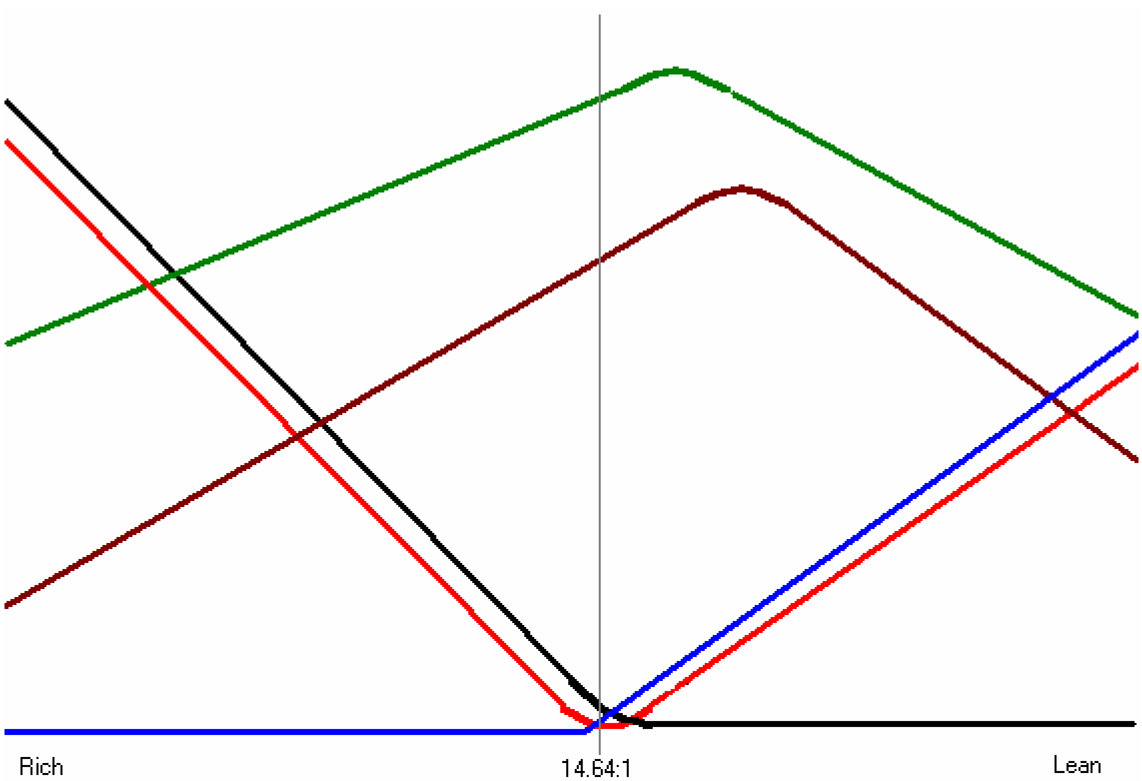
KEY CONCEPTS:

1. ***The amount of oxygen present determines what emissions the fuel will produce when burned.***
2. ***As we approach perfect combustion the increased temperature causes additional pollutants to start forming***
3. ***We can never achieve perfect combustion inside the engine***

CO emissions increase under conditions richer than 14.64:1 and when NOx emissions increase near 14.64:1.

The amount of energy (power) released during this reorganization of atoms (combustion/chemical reaction) depends upon the ratio of gasoline to oxygen and the new compounds that are formed. The following is a list of the amount of energy (power) that is released when different compounds are formed. This list shows how much energy is released when one molecule of each compound is formed.

Carbon monoxide	CO = 110.5 KJ/mole (releases heat / exothermic)
Carbon dioxide	CO_2 = 393.5 KJ/mole (releases heat/exothermic)
Water (steam)	H_2O = 241.8 KJ/mole (releases heat / exothermic)
Unburned fuel	HC = 0.0 KJ/mole (releases heat / exothermic)
Nitric oxide	NO = -90.4 KJ/mole (absorbs heat / endothermic)



As the air/fuel mixture approaches 14.64:1, the high combustion temperatures (2500 degrees and higher) inside the combustion chamber cause the nitrogen and carbon to compete for oxygen. This prevents perfect combustion from taking place inside the combustion chamber.

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KEY CONCEPTS:

1. ***An air/fuel mixture of 14.64:1 is the best compromise but it does not provide perfect combustion.***
2. ***A 14.64:1 mixture gives the lowest CO and HC levels but it also produces very high NOx levels.***
3. ***A 14.64:1 mixture also results in low oxygen levels.***

Lower compression ratios and retarded spark timing can decrease combustion temperature and reduce emissions. Unfortunately this also destroys performance and fuel economy. Exhaust gas recirculation (EGR) can reduce temperature and NOx emissions, but it can cause driveability problems and increase HC emissions (from misfires).

THE CATALYST

Catalysts are needed to reduce emissions to acceptable levels without dramatically reducing performance and fuel economy. This is true of HC, CO and NOx, but NOx is the emission that is most dependent on the catalyst for emissions compliance.

There are actually two types of catalysts. Reduction catalysts cause NOx to be reduced into O_2 and N_2. Oxidation catalysts cause HC and CO to oxidize with any available oxygen into CO_2 + H_2O. Unfortunately oxidation will only occur when there is enough free oxygen, and reduction will only occur in a relative absence of free oxygen.

Rhodium is generally the most efficient reduction catalyst. Platinum and palladium are used for oxidation.

2-way catalytic converters are oxidation catalysts. They oxidize CO and HC but do not reduce NOx. 3-way catalysts oxidize and reduce. They oxidize CO & HC and reduce NOx.

Proper air /fuel mixture control and exhaust oxygen content is required for proper 3-way catalyst performance. In general, oxidation and reduction can not both occur at their highest efficiency at the same time.

Reduction efficiency is not at it's highest unless the oxygen content is very low. This usually doesn't happen unless the air/fuel mixture is at least a little bit rich. Oxidation only reaches it's highest efficiency when the oxygen content is fairly high. That happens when the mixture is at least slightly lean.

KEY CONCEPTS:

1. ***A catalyst can not clean up CO and HC unless there is enough oxygen in the exhaust.***
2. ***A catalyst can not clean up NOx unless the level of oxygen in the exhaust is very low.***
3. ***There is no fuel mixture that allows CO, HC and NOx to all be catalyzed at maximum efficiency.***

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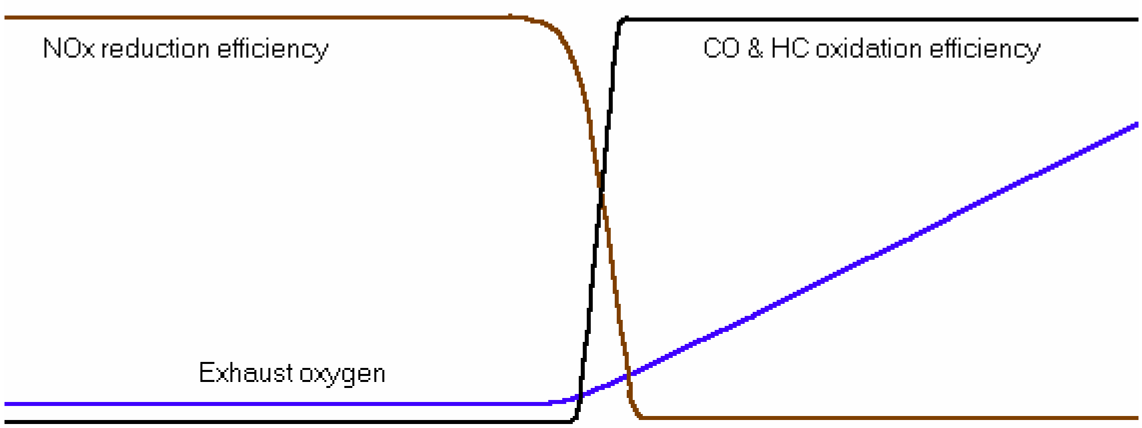
A dual bed catalyst has two separate chambers. Air can be injected in the middle of the catalyst to increase oxygen content in the back half of the converter. The engine can then be run slightly rich to improve NOx reduction in the front half of the converter. The air that is injected allows high efficiency oxidation of CO & HC in the back half of the converter. This type of converter can allow NOx reduction to occur in the front bed at maximum efficiency while CO and HC oxidation are occurring in the rear bed at maximum efficiency. It is the injection of air in front of the rear bed that allows both oxidation and reduction to occur at maximum efficiency.

For the dual bed catalyst to operate at maximum efficiency, it must have very low oxygen levels in the exhaust entering the front bed. This only occurs when the engine is running slightly rich with no misfires or deposit problems. It must also have enough air injected in front of the rear bed to allow oxidation of the CO and HC.

The front bed of a dual bed catalyst does also oxidize CO and HC. Even a rich mixture will leave some oxygen in the exhaust. The catalyst uses this small amount of oxygen to oxidize CO & HC into CO_2 & H_2O. As NOx is reduced, oxygen from that NOx is freed up. If this extra oxygen was allowed to accumulate it would start to limit NOx reduction. But the oxygen from the NOx is used to oxidize CO and HC. This limits oxygen build-up in the front bed and keeps NOx reduction at maximum efficiency.



<u>KEY CONCEPTS:</u>

1. ***A dual bed catalyst depends on air injection to provide the oxygen to clean up CO & HC when the mixture is rich.***
2. ***Air is only injected into the rear bed.***

Many cars do not have air injection. Without air injection and a slightly rich mixture these cars must depend on something else to manage the oxygen in the catalytic converter. Cerium is an element that attracts oxygen. Under high oxygen conditions the cerium will absorb oxygen and allow NOx reduction to occur with greater efficiency. Under low oxygen conditions the cerium will release it's stored oxygen to increase the oxidation efficiency of CO and HC. Cerium is very important in any 3-way catalyst. Even dual bed catalysts benefit from cerium. The cerium can allow the front bed of a dual bed catalyst to continue reducing NOx at close to maximum efficiency without a rich mixture.

Cerium has it's limitations. It will only absorb small amounts of oxygen and it can only release as much oxygen as it has absorbed. Cerium allows the catalyst to operate efficiently under slightly rich and slightly lean conditions only for very short time periods. If the air/fuel mixture is continuously cycled from slightly rich to slightly lean, cerium can allow it to constantly operate at maximum efficiency.

The main purpose of the O2 sensor is to keep the oxygen level in the exhaust constantly changing. If the oxygen level in the exhaust stabilizes, the catalytic converter efficiency will drop considerably. In order for a catalyst to best clean up NOx the A/F ratio must be richer than 14.7:1 however, NOx emissions from the engine are highest when the engine is lean. For the catalyst to best clean up CO & HC the A/F ratio must be lean, but CO and most HC is created when the engine is rich! Three way catalysts (TWC s) overcome this problem by using cerium for oxygen storage. This oxygen storage trick will greatly increase the efficiency of the TWC if the oxygen level is cycling slightly rich and slightly lean.

The only way that proper exhaust oxygen level and oxygen cycling can be maintained is with O2 sensor feedback. This is called closed loop. After the computer has determined the proper fuel metering (injector on time), the O2 sensor is used for feedback to fine tune fuel metering and to make the oxygen content in the exhaust fluctuate slightly.

KEY CONCEPTS:

1. ***Cerium is required for proper catalyst operation (especially without air injection).***
2. ***Cerium can not do its job if the air/fuel mixture is not cycled properly.***
3. ***Proper oxygen sensor function is required for proper catalyst function.***

Oxygen variables:

Conventional 5-gas training and a review of the standard 5-gas graph indicate that CO and O_2 levels do not rise or fall together. Anytime CO increases, O_2 falls. Likewise anytime O_2 increases, CO decreases. The past two decades of advancing automotive technology have revealed numerous exceptions to these commonly held beliefs. So much for conventional 5-gas graphs and training!

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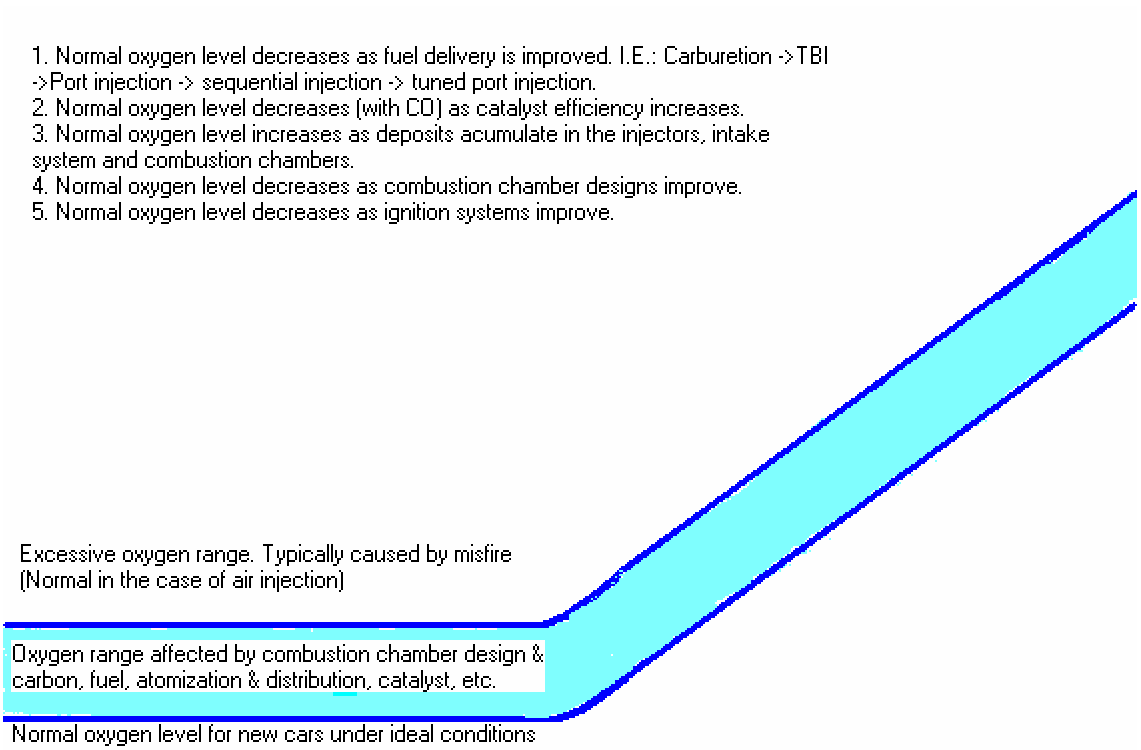
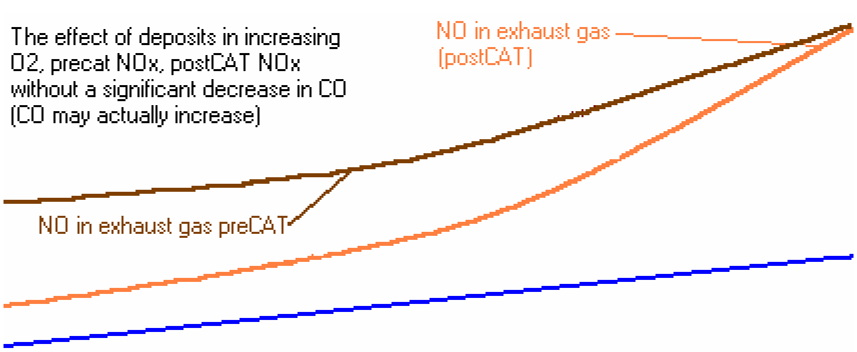
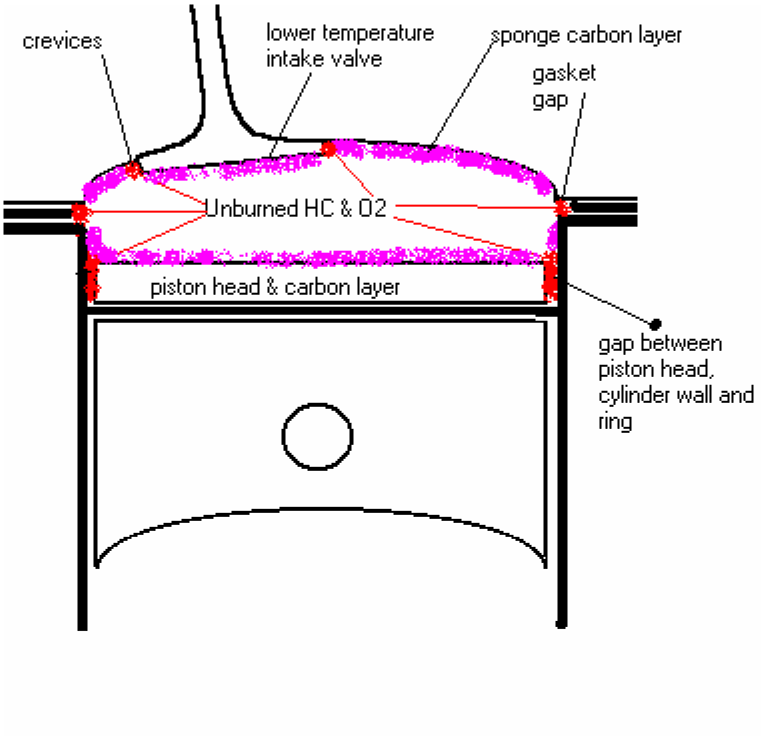


The above graph depicts the wide variation in exhaust oxygen levels that are NOT attributed to component failures. I emphasize that the exhaust oxygen changes of this type are not associated with a corresponding change in CO. Advancements in fuel injection and combustion chamber design have dramatically lowered the exhaust oxygen level of newer cars. This has greatly improved the catalysts ability to reduce NOx emissions.

Some late model cars depend heavily on the catalyst to reduce NOx at extremely high levels (90+%). This simply is not possible unless the oxygen level is low enough. If carbon deposits or other problems increase the exhaust oxygen level, a perfectly good catalyst will operate at reduced efficiency.





During the compression stroke, air and fuel "hide" in the sponge carbon that forms inside the combustion chamber. The flame front of combustion is quenched or snuffed out as it approaches this carbon layer and the comparatively cool surfaces of the combustion chamber. Any gap, crevice or carbon layer serves as a hiding place for air and fuel.

Automotive engineers have responded to this by moving rings higher on the piston and reducing other gaps and crevices. The combustion chamber swirl effect of some newer designs help reduce flame quenching with a corresponding drop in HC and O2 levels. Increasing thermostat temperatures and combustion chamber surface temperatures is another way that this issue has been addressed.

These design modifications have helped reduce the normal exhaust O_2 and HC levels. However, carbon deposits are still a significant problem. The PCM responds to the elevated O_2 level by adding fuel. This additional fuel tends to increase the CO and HC level. The catalytic converter uses the elevated O_2 levels to increase oxidation of both CO and HC. This tends to eliminate any increase in tailpipe HC and CO. The carbon layer also acts as an insulator and increases compression by taking up space in the combustion chamber. The result of this is an increase in NOx production. The increase in NOx production is exaggerated by a simultaneous decrease in the catalyst's ability to reduce NOx. While the catalyst's ability to oxidize CO & HC was enhanced by the O_2 increase, it's NOx reduction efficiency was inhibited. The ability of a catalytic converter to reduce NOx is almost completely eliminated as the O_2 level approaches 2.0%.

KEY CONCEPTS:

1. ***Some late model cars depend on the catalyst to clean up over 90% of their NOx emissions.***
2. ***This will only occur if the exhaust oxygen level is very low.***
3. ***Deposit build up in the injectors, combustion chamber and other places can increase exhaust oxygen levels.***

Deposit Control , Emissions Failures and catalysts:
Although long ignored, deposit formations are responsible for a significant number of ASM smog test failures. They are also responsible for a variety of driveability problems. These deposits form primarily in the following areas:

1. Combustion chamber
2. The backside of intake valves
3. Throttle body
4. Injection nozzles
5. EGR ports

When there is evidence of deposits in one of these areas, you should assume that the other areas are also affected. Most deposits will increase both the engine's emissions and the converters ability to clean up those emissions. NOx is the emission most affected by deposits.

These deposits increase compression ratio by taking up space in the chamber. They also retain heat and provide a "quenched" area for HC and O_2 to hide from combustion.
NO_x emissions and detonation/pre-ignition are increased due to the retained heat from an even carbon layer; hot spots caused by small chunks of carbon, and increased compression ratio.
HC& O_2 emissions are increased when the atomized/vaporized fuel mixture is absorbed into the carbon layer during the compression stroke, protected from combustion by the flame quenching effect of the carbon layer, and then exits the carbon layer during the pressure drop that occurs on the exhaust stroke.
CO emissions are increased as a result of the increased O_2 levels. The high O_2 level reduces the O_2 sensor voltage. The engine control system responds to this low O_2 sensor voltage by increasing fuel delivery. *Note: pouring water into a running engine to steam blast carbon away can actually increase NO_x emissions because of the small, very hot, chunks of carbon that this method tends to leave behind***.**

CATALYST SELECTION CRITERIA

Engine Displacement
Engine displacement doesn't do much to determine exhaust flow during ASM conditions, but it does affect the maximum exhaust flow for that application. Engine displacement, turbocharging and volumetric efficiency all have a big impact on maximum exhaust flow. When in doubt use a larger catalyst from a quality manufacturer and a reputable distributor.

Gross Vehicle Weight
The gross vehicle weight (GVW) is what determines how much exhaust flow will occur during ASM test conditions. Engine displacement does NOT have as much effect on this as GVW. A small engine will operate under a wider throttle opening than a larger engine so that both engines will have similar exhaust flows. In fact a small engine in a heavy car will be operating under higher combustion pressures and tend to have higher NOx emissions than a larger engine in the same car. Ignoring vehicle weight when selecting a catalyst can result in ASM test failure. Using a converter that is rated for up to 4000 lbs on a 3999 lbs car is asking for trouble. EPA certification only requires that a catalyst be 70% efficient at oxidizing CO & HC, and 60% efficient at reducing NOx. Original equipment catalysts are sometimes sized to achieve over 90% efficiency. When in doubt use a larger catalyst from a quality manufacturer and a reputable distributor.

Non-EGR engines *** Special Needs*****
EGR is one of the most effective ways to reduce NOx emissions. But not all cars have EGR systems. Cars that do not use EGR to reduce NOx emissions must rely more heavily on that catalytic converter to reduce NOx. These cars may require catalyst reduction efficiency of 90% or more. Only the highest quality catalytic converters, operating under the intended conditions can achieve this kind of efficiency. EPA certification only indicates that a converter can reduce NOx emissions by 60%. That is under ideal conditions, and only if the converter is properly sized and properly installed. This means that on cars that do not have EGR the cheaper catalytic converters will often fail to reduce enough NOx emissions to pass an ASM smog test.

Larger catalysts are more likely to work. Increased use of rhodium and cerium can also improve NOx reduction. Your experience with certain brands of converter should also be considered. Custom fit or "direct fit" catalysts tend to pass ASM tests more reliably than universal fit. When in doubt use a larger catalyst from a quality manufacturer and a reputable distributor.

High performance/high compression applications *** Special Needs*****
High performance engines tend to use higher compression ratios. Their camshafts (valve timing) often also tend to reduce EGR flow. Both of these design features increase NOx emissions and require much higher NOx reduction efficiency from the catalytic converter. When in doubt use a larger catalyst from a quality manufacturer and a reputable distributor.

Air Injection *** Special Needs*****
Vehicles equipped with air injection require more careful consideration. Restrictive or poorly designed converters can cause the injected air to back up into the front part of the converter. This will dramatically reduce NOx reduction efficiency. The air injection nozzle that is hidden from sight inside the catalytic converter should be designed specifically to reduce air backing into the front section of the catalyst. The converter must also allow sufficient exhaust flow to prevent this effect. When in doubt use a larger catalyst from a quality manufacturer and a reputable distributor. Also make sure that there are no abnormal restrictions in the rest of the exhaust system (muffler, tailpipe, etc).

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Low power to weight ratio *** Special Needs*******
The engines of under-powered vehicles have to operate at higher throttle openings to achieve the same acceleration or ASM load. This results in higher NOx emissions and generally requires higher NOx reduction efficiency from the catalyst. When in doubt use a larger catalyst from a quality manufacturer and a reputable distributor.

OBDII *** Special Needs*******
The latest on-board diagnostic systems (OBDII) monitor the catalytic converter. They don't actually measure catalyst efficiency. The OBDII system does NOT have the ability to measure CO, HC or NOx. The system uses oxygen sensors to measure the oxygen level before and after the converter. A properly working converter will use up significant amounts of oxygen as it oxidizes CO and HC. The OBDII catalyst monitor looks at the difference between the before and after oxygen sensors as an indication of catalyst integrity. Cerium is not a catalyst but it absorbs and releases oxygen. The oxygen storage of cerium is critical to passing the OBDII catalyst monitor. It is critical that OBDII equipped vehicles use a converter that has adequate cerium and is sold specifically for use on OBDII vehicles.

Oxygen sensor placement is also critical. The sensors must not be relocated. Relocating oxygen sensors can cause the OBDII system to fail the catalyst. Use only catalysts intended for OBDII vehicles from a quality manufacturer and a reputable distributor. Follow the specific OBDII catalyst replacement procedures provided by the converter manufacturer for the application.

California requires that the California Air Resources Board (CARB) certify aftermarket catalytic converters. At the time of this printing time has not permitted CARB to complete testing or certification of any converters. CARB certification will probably eventually be a very good indicator of OBDII catalyst quality.

OBDII systems have methods of adapting to gradual changes in system components and system operation. Because of this, they also have accelerated learn strategies that kick in after the memory has been cleared. These two factors can cause false monitor failures when a converter is first replaced. Many catalytic converters also have a break in period. Some converters may require as much as 100 miles of "break-in" before they operate at their best efficiency. Using a scan tool to turn off a check engine light will often also put the PCM into a rapid learn mode that allows the catalyst monitor to run repeatedly until patterns are relearned. This can cause repeat failures and turn the check engine light right back on, until the break-in period is over.

It is best to treat any OBDII fault codes, EXCEPT catalyst fault codes, that appear after converter replacement as soon as possible. They are indications of faults that could destroy the new converter. Converter fault codes should be addressed differently. They should not be taken too seriously until after the break in period. Break in is usually accomplished within 20 miles and an hour or less.

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The following statement can be used to inform your referring shops of this situation:

Ford, GM, some Chryslers, some Hondas, and possibly other cars, use "exponentially weighted moving averages" (EWMA) to help monitor catalyst function. This strategy has a "fast initial response" after the memory is cleared. This combined with the break-in period that occurs on some new catalysts can cause accelerated catalyst monitors (multiple monitors within a drive cycle). This can possibly result in false failures and false passes during the first few days.

What can damage a new catalyst?

Quality catalytic converters can perform well for hundreds of thousands of miles. One of my own vehicles has over 290,000 miles on the catalytic converter and it is still working fine. However, when subjected to the right conditions, converters can become overheated and destroyed in as little as twelve seconds. Many of the converters that require replacement have failed because of some type of engine operating fault. If the fault is not identified and repaired, the converter can quickly destroy itself. This often happens in less than a month.

Anything that significantly increases the amount of HC and/or CO that is oxidized in the converter will increase the operating temperature of the catalyst. If the car has an air injection system, anything that causes a rich mixture may quickly destroy a new converter.

Any ignition misfire will result in the converter burning the fuel and air that should have burned in the cylinder.

It is a good idea to test the exhaust emissions of vehicles before you replace the converter. Any vehicle that emits over 2.0% CO, or 400 ppm HC, probably has faults other than the converter. Many cars will have emissions much lower than that without a converter. The new catalyst may clean up 90% of these emissions, it may also destroy itself in the process.

Coolant seeping into the combustion chamber or exhaust can also damage catalysts.
The ceramic substrate of the catalyst can be damaged from impacts. Lowered vehicles and off road vehicles are the most susceptible to this type of damage. Some low cost converters can sometimes shift during the expansion and contraction of normal operation. This can eventually result in misalignment and cracking of the substrate. Higher quality converters use retaining ridges and more durable "packing" materials to prevent this.

If any of the following conditions exist, the customer (or referring shop) should be notified that the engine might have existing faults that could damage the new converter:

CO in excess of 2.0% (pre-catalyst)
HC in excess of 400 ppm (pre-catalyst)
Indications of high oil consumption
Indications of combustion/coolant leaks
Indications of O2 sensor faults
Indications of modifications or poor maintenance

Further diagnosis is recommended when the above conditions exist.

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CATALYTIC CONVERTOR TESTS

1.CRANKING TEST

There is typically no CO_2 present in the atmosphere. CO_2 is a product of combustion. Therefore any carbon dioxide emissions measured during typical starter draw test, with ignition disabled must be created in the catalytic converter.

A good catalytic converter should be capable of converting the Hydrocarbon fuel (HC) that is pumped through the engine during the starter test to 13% carbon dioxide.

In order to create 13% CO_2 during a starter draw test the following must occur:

1. The catalytic converter must be completely warmed up.

2. Fuel delivery must be functioning normally. The CO_2 is being created by converting the fuel that is being pumped through the engine.

3. Ignition must be completely disabled.

THE TEST:

1. Start the engine and drive the car to insure that it is warmed up completely.

2. Run the engine at 2000 rpm to insure that the catalytic converter is hot.

4. Turn off the ignition or hit the analyzer kill switch.

5. IMMEDIATLY after the engine stops, disable the ignition (ground the coil secondary or disconnect the coil primary) and crank the engine over while watching the CO_2 levels on the exhaust analyzer.

NOTE:
THE FUEL SYSTEM MUST REMAIN FUNCTIONAL! DO NOT DISABLE RPM SENSOR OR ENGAGE CLEAR FLOOD MODE!
KILL THE IGNITION SYSTEM ONLY!
DO NOT ALLOW THE CONVERTER TO COOL DOWN

4. The CO2 level should reach and maintain 13% in about 10 seconds. If the CO_2 level does not reach at least 13%, or the CO_2 level only spikes to 13%, the catalytic converter is weak.

If the CO_2 level is below 13% make sure that there is sufficient HC and 02 to make the CO_2 from. If the CO_2 level drops below 1% or HC drops below 500 ppm the test will not be valid.

THIS TEST IS DIFFICULT TO PERFORM ON MANY DIS CARS SINCE THE IGNITION IS NOY EASILY DISABLED WITHOUT DISABLING IGNITION. USE THE SNAP THROTTLE TEST ON SUCH CARS

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2. SNAP THROTTLE TEST

When the engine is running at a stoichiometric 14.7:1 fuel mixture with no air injection there is very little oxygen in the exhaust. Cars equipped with Carburetors will have higher normal levels of oxygen due to poorer fuel atomization and vaporization.

During a snap throttle test" CO will increase due to a suddenly rich mixture on acceleration. CO will continue to increase until the O_2 level begins to rise. During this snap acceleration all excess oxygen will be used up by the catalytic converter to convert CO to C O_2. As the O_2 level rises O_2 will be used up by the 'CAT" to convert CO to CO_2 and the CO level will begin to drop as O_2 rises. A good "CAT" will therefore prevent the O_2 level from exceeding 1.2% until the CO level begins to drop.

THE TEST:

1. Drive the car until the engine and catalytic converter are fully warmed up.

2. Disable the air injection system.

3. Run the engine at 2000 rpm and wait for stable exhaust readings with Oxygen level no higher tan 0.5%. Propane enrichment may be used to reduce oxygen level to 0.5%.

4. Snap and release the throttle.

5. Watch the **CO** emissions climb and note the Oxygen level at the instant the CO level peaks. Oxygen level at the instant that Co level peaks should not exceed 1.2%.

Note: It is normal for Oxygen level to rise after CO has peaked.

If the 02 level exceeds 1.2% before the CO level peaks the catalytic converter is weak.

This test works best on cars that have sequential fuel injection -and DXS. The cranking CAT test tends to be difficult to perform on these same cars

3. INVASIVE TESTING

The CAT efficiency can be determined by sampling the exhaust gas before and after the CAT. Kits are available from Thexton (No. 389), OTC and others to tap through single wall exhaust pipes. Other pre-CAT sampling locations may include the EGR port, EGO port and air injection ports. (EGO is not recommended). Record both the before cat and tailpipe exhaust gas with the engine well tuned, preconditioned, no exhaust leaks and no air injection. Fuel mixture may have to be manipulated and/or misfires induced to create the proper oxygen level for proper evaluation.

$$\frac{(\text{HC in}) - (\text{HC out})}{(\text{HC in})} \times 100 = \text{CAT HC efficiency}$$

$$\frac{(CO\ in) - (CO\ out)}{(CO\ in)} \times 100 = \text{CAT CO efficiency}$$

$$\frac{(NOx\ in)-(NOx\ out)}{(NOx\ in)} \times 100 = \text{CAT NOx efficiency}$$

HC oxidation efficiency should be 90% when O_2 in exceeds 1% and O_2 out exceeds 0.5% You may need to induce a misfire to create the proper O_2 levels

CO oxidation efficiency should be 90% when O_2 in exceeds 1% and O_2 out exceeds 0.5%

NOx reduction efficiency should be 90% when O_2 in is less than 0.5%. This test may require loaded node testing and/or disabling EGR. It nay also be necessary to artificially enrich the air-fuel mixture to reduce O_2 content below 0.5%

NOTE: EPA CERTIFICATIONS ONLY REQUIRES CATALYSTS TO OXIDIZE CO& HC AT 70% EFFICIENCY, AND TO REDUCE NO AT 60% EFFICIENCY. THIS MAY NOT BE SUFFICIENT TO ALLOW SOME CARS TO PASS ASM TESTS. SOME CARS MAY REQUIRE 90% EFFICIENCY IN noX REDUCTION. OTHERS MAY BE FINE WITH LESS THAN 50%.

The oxidation and reduction efficiency of good catalysts vary due to oxygen levels in the exhaust system during normal running conditions of those cars. 2-way catalysts operating with high oxygen levels in the feed-gas should meet the above standards for CO and HC oxidation. All 3-way catalysts operating with low oxygen levels in the feed-gas should meet the above standards for CO & HC oxidation and NOx reduction.

4. LIGHT-OFF TEST

This test must be performed with the engine cold. Start the cold engine and monitor exhaust gas at 2500 rpm during warm up. Exhaust emission readings should be relatively stable except during the following three events:

1. Initial start up & stabilization.
2. Initialization of closed loop.
3. CAT converter “light-off”.

   This can be graphed or “traced” so that the readings before and after converter light off can be compared. Use the same formula shown in the “Invasive Test”.

$$\frac{(HC\ in) - (HC\ out)}{(HC\ in)} \times 100 = \text{CAT HC efficiency}$$

$$\frac{(CO\ in) - (CO\ out)}{(CO\ in)} \times 100 = \text{CAT CO efficiency}$$

$$\frac{(NOx\ in)-(NOx\ out)}{(NOx\ in)} \times 100 = \text{CAT NOx efficiency}$$

HC oxidation efficiency should be 70%-90% when O_2 in exceeds 1% and O_2 out exceeds 0.5%
You may need to induce a misfire to create the proper O_2 levels

CO oxidation efficiency should be 70%-90% when O_2 in exceeds 1% and O_2 out exceeds 0.5%

NOx reduction efficiency should be 60%-90% when O_2 in is less than 0.5%. This test may require loaded node testing and/or disabling EGR. It nay also be necessary to artificially enrich the air-fuel mixture to reduce O_2 content below 0.5%

The oxidation and reduction efficiency of good catalysts vary due to oxygen levels in the exhaust system during normal running conditions of those cars. 2-way catalysts operating with high oxygen levels in the feed-gas should meet the above standards for CO and HC oxidation. All 3-way catalysts operating with low oxygen levels in the feed-gas should meet the above standards for CO & HC oxidation and NOx reduction.

5. MISFIRE TEST

When a misfire occurs the catalytic converter releases a tremendous amount of heat as it oxidizes the unburned HC into H_2O and CO_2. The increased temperature that this causes increases the Catalyst efficiency. This reaction allows us to test the catalyst by inducing a misfire.

THE TEST:

1. Allow the car to run for several minutes at 2500 rpm after it is properly warmed up.

2. Disable one spark plug. Do NOT allow the engine or exhaust system to cool down as you do this. It is permissible to turn the engine of while disabling the spark plug, but this must be done and the engine restarted within 3 minutes. Some engine analyzers will allow you to kill an individual cylinder without turning the engine off.

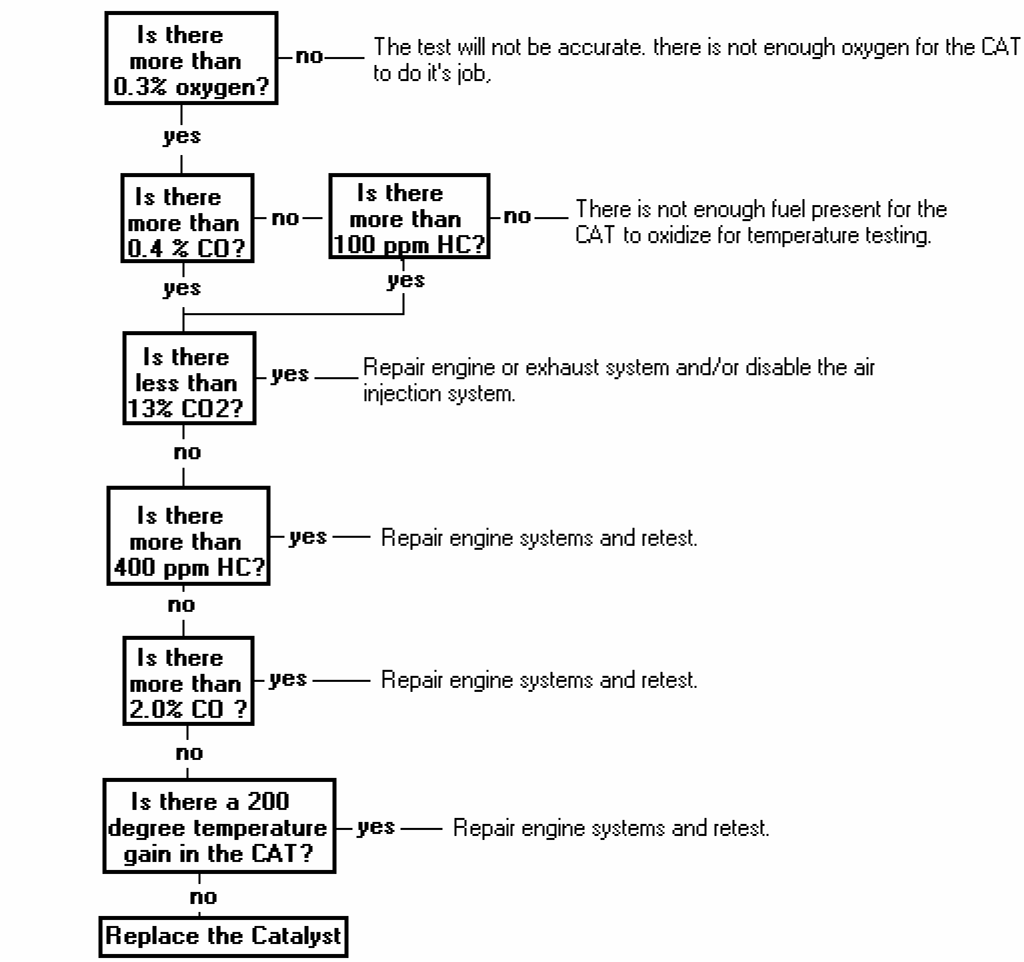
3. Monitor the HC level as you kill the spark plug. The HC will increase dramatically for several seconds. Then, as the catalyst heats up, the HC level drop off significantly. Record the Peak HC level and the level that HC drops to as it gets hot.

A good catalytic converter will be able to reduce the HC emissions to about 50% or less of the peak HC emissions in just a few seconds.

This test must be performed with caution. Do NOT perform this test for extended periods or under a load. A catalytic converter can overheat to the point of melt-down in as little as 12 seconds if all spark plugs are disabled while under load. Do not disable multiple cylinders and do not perform the test under road load or dyne conditions.

5. TEMPERATURE & 4-GAS TEST

Completely warm up the engine and exhaust system. Run the following test using a 4/5-gas analyzer and a infra-red temperature sensing gun.



The accuracy of infra red temperature sensing varies according to the "emissivity" of the surface being sensed. Sometimes it is helpful to paint the surfaces with a quick drying flat black paint before testing. Painting is recommended if the two surfaces have different surface finishes.

NOx failure analysis

1. **Ignition Timing.** Advanced ignition timing increases peak combustion pressures and temperatures resulting in increased NOx emissions. A small increase in base timing can also increase the PCM advance resulting in much greater ignition advance under load. This is a very common cause of ASM NOx failures.

2. **EGR.** EGR reduces combustion temperature and pressure by slowing the rate of combustion. There are numerous things that can go wrong with these systems. Carbon can restrict the EGR passages. The EGR diaphragm can leak. Vacuum controls can leak or become restricted. This system is often intentionally disabled. EGR faults are a very common cause of ASM NOx failures.

3. **Catalytic converter.** Under ideal conditions, a three-way catalyst can reduce somewhere between 50% and 95% of NOx emissions. But, a perfectly good catalyst will not function properly unless fuel control and exhaust oxygen level is correct. Cars that do not have EGR systems tend to depend more heavily on the catalyst for NOx reduction. Catalysts on these cars can sometimes reduce NOx from over 2000 ppm to under 200 ppm. Catalysts are a common cause of NOx failures but they should never be replaced without adequate testing. Anytime a catalyst is replaced, the cause of failure should be confirmed. Fuel metering problems, misfires and other faults can quickly destroy a new catalyst. Fuel mixture and exhaust oxygen level should be considered before testing or replacing a catalyst.

4. **Lean air/fuel mixture.** Lean air/fuel mixtures increase NOx emissions and prevent the catalyst from reducing NOx. This double impact causes tailpipe NOx emissions to much more than typical 5-gas emissions graphs indicate. A lambda fuel mixture calculation should be done to accurately determine fuel mixture.

5. **Fuel injector imbalance.** Fuel injection nozzles can become fouled or restricted. This can cause some cylinders to be lean while others are rich. The combination can cause emissions failures even though the overall mixture is correct.

6. **Carbon deposits.** Carbon deposits increase compression ratio and create hot spots. Both of these increase NOx emissions. Carbon formation is accelerated by rich air/fuel mixture. Because of this, many cars that fail an ASM test with high CO levels, fail with high NOx emissions after the CO problems are repaired. There are many chemical treatments that can be used to remove carbon deposits. Systems that introduce the chemical directly through the fuel injection rail (not the fuel tank) seem to work the best.

7. **Exhaust restriction.** Restricted exhaust increases engine load and increases heat build up in the combustion chamber. This not an extremely common problem and is therefore often overlooked.

8. **Engine temperature.** Engine overheating can easily cause a NOx failure. Simply forgetting to use an auxiliary cooling fan can cause a car to fail an ASM test with high NOx emissions. The heat load of air conditioning compounds this problem. Test all cars with A/C off and an approved auxiliary cooling fan. Most cars that have conventional cooling system problems fixed before having an emissions test so this is not a common cause of emissions failures.

9. **Cooling system restrictions.** Restrictions in cooling passages can theoretically cause individual cylinders to be hot enough to cause NOx emissions failure without any obvious symptoms of overheating. One possible cause of this is freeze plugs that have been left inside the engine block.

10. **Intake air temperature.** This is not as common as rumored. In most cases, computer controlled cars can allow for any foreseeable intake temperature without a NOx failure. If the IAT sensor indicates a temperature that is higher than actual, some cars will under calculate MAF & LOAD resulting in increased computer advance and reduced EGR commands. This can result in a NOx failure on soe cars.

11. **Fuel octane.** Fuels that are lower octane than the car is designed for can dramatically increase NOx emissions. Most cars are designed for low octane fuel so this is not a common problem. Carbon deposits can increase a cars octane requirements. This is best addressed by cleaning out the carbon, NOT switching to high octane fuel.

12. **Spark plug heat range.** This can effectively create a hot spot that in extreme cases can cause a NOx failure.

13. **Spark plug gap.** Increased spark plug gap, especially combined with high performance ignition modifications can have an effect similar to advancing ignition timing. The effect is fairly minor, but can be significant when combined with other problems or modifications.

14. **Compression ratio.** Major engine repairs can and do change compression ratio. Cylinder heads are frequently milled. Different brands of gaskets have different compressed thickness. Increased compression ratio can cause NOx failures.

EGR systems and NOx control

EGR is one of the most effective NOx reduction systems in use. An EGR system that is inoperative or just restricted will usually cause a NOx failure on an ASM/loaded mode test. On many engines, EGR will reduce NOx emissions by 1000 ppm or even 2000 ppm.

1. **Floor jets without a control valve.** This system was used on 1972 & 1973 Chrysler 340-4V and 400-4V. It consisted of two stainless steel metering jets on the bottom of the intake manifold plenum. The jets allowed a small amount of exhaust gas to flow from the exhaust heat crossover into the intake plenum. EGR flow was simply a function of the difference between intake manifold pressure and exhaust pressure. This system can be tested, with the engine off, by opening the throttle and inserting a wire probe into the jets to confirm that they are not plugged.

2. **Basic ported vacuum operated EGR valve system.** This system uses a vacuum operated valve to open a passage between the exhaust system and the intake system. When vacuum is applied to the valve, it opens and allows exhaust gasses to flow into the intake manifold. Ported vacuum is used to open and close the valve so that the valve will not open at idle. Ported vacuum increases as the throttle opens until it is near wide open throttle or the engine is under very heavy load. Under WOT or heavy loads, ported vacuum drops and the EGR valve closes. This system must be tested in two steps. First verify that the engine will stumble and die when vacuum is applied to the valve at idle. This confirms that the valve and passages are working properly. You must also verify that the valve does get a vacuum signal when the throttle is opened. Many of these systems have vacuum delay valves to slow the opening of the valve and reduce tip-in stumbles. They also have temperature vacuum switches to prevent EGR operation at low temperatures (most are coolant temperature operated).

    a. Use a hand vacuum pump to apply vacuum to the EGR valve. The engine must stumble and stall at idle.
    b. Use a vacuum gauge to verify that the vacuum does get to the valve when the engine is revved.
    c. If test #2 fails, also check any delay valves and temperature valves

3. **Vacuum amplifier EGR systems.** These are identical to the above systems except they get vacuum from a vacuum amplifier. The amplifier is uses venturi vacuum to control ported vacuum to the EGR valve. Venturi vacuum is a very accurate signal that is proportional to engine intake air flow, but is too weak to open most valves. The amplifier uses this weak vacuum signal to control the stronger manifold vacuum (ported vacuum on some models) signal to the EGR valve. This is very effective at eliminating tip-in stumble. Vacuum amplifiers fail frequently. Test this system in the same manner as the basic system, but also verify the venturi vacuum and ported vacuum signals to the amplifier. These often have temperature vacuum switches to prevent EGR operation at low temperatures (most are coolant temperature operated, but some are ambient temperature operated).
    a. Use a hand vacuum pump to apply vacuum to the EGR valve. The engine must stumble and stall at idle.
    b. Use a vacuum gauge to verify that the vacuum does get to the valve at high rpm.
    c. If vacuum fails to get to the valve, check for venturi vacuum and manifold/ported vacuum at the amplifier.
    d. If test #2 fails, also check any delay valves and temperature valves.

4. **External backpressure transducer EGR systems.** This system is still the basic system, but uses an inline transducer instead of a vacuum delay valve. The backpressure transducer will leak vacuum unless the desired exhaust backpressure is present. Exhaust pressure is routed to the transducer through a small metal tube or a high temperature silicone hose. The transducer will bleed off any vacuum until exhaust backpressure indicates that the engine is at an appropriate load to handle the EGR flow. The exhaust pressure closes the vacuum bleed and allows the vacuum to reach the EGR valve. This system still uses ported vacuum. It can be tested in the same way as the basic system, except that a condition must be created that increases exhaust pressure in order to verify proper transducer operation.
    1. Use a hand vacuum pump to apply vacuum directly to the EGR valve. The engine must stumble and stall at idle.
    2. Use a vacuum gauge to verify that the vacuum does get to the valve under loaded conditions. You can do this on a road test and sometimes by restricting the exhaust.
    3. If vacuum fails to get to the valve, check for breaks in the small exhaust tube that goes to the transducer. Replace the transducer as necessary.
    4. If test #2 fails, also check any temperature valves.

5. **Internal positive backpressure transducer EGR valves.** This system is the same as the above system except that the transducer is inside the EGR valve assembly. It will normally leak vacuum until the engine is under a load and/or exhaust pressure increases. **This valve will not hold vacuum at idle or with the engine off.**

    1. Verify that vacuum gets to the EGR valve at high rpm and/or when the throttle is opened.
    2. If test #1 fails, also check any temperature valves.
    3. Verify that if the EGR valve opens at idle the engine does stumble and stall (open manually if necessary)
    4. Verify that the EGR valve does open under open throttle high backpressure conditions. (you may have to restrict the exhaust to verify this)

6. **Internal negative backpressure transducer EGR valves.** This system is the same as the above system except that it will normally leak vacuum until exhaust pressure **decreases**. This valve **will** hold vacuum with the engine off, but not at idle. The exhaust system on these vehicles have a slight vacuum at idle that prevents the transducer from sealing.

    1. Verify that vacuum gets to the EGR valve at high rpm and/or when the throttle is opened.
    2. If test #1 fails, also check any temperature valves.
    3. Use a hand vacuum pump to apply vacuum directly to the EGR valve. The valve should hold vacuum and open when the engine is off.
    4. Manually open the EGR valve with the engine idling. The engine should stumble and stall.

7. **PCM controlled vacuum operated EGR valves (single solenoid).** These are usually basic EGR valves, but some have internal or external transducers. Vacuum is supplied to the EGR valve through a duty cycled or pulse width modulated vacuum solenoid. The valve and actual EGR flow should be tested in the same manner as the basic valves, transducers, and internal transducer valves (depending on which one you have). You must also verify that vacuum does get applied to the valve during ASM test conditions. Some PCM's will not open the valve until the vehicle speed sensor indicates a certain speed. On these cars you may need to perform a road test or a dynamometer test. On systems that have an EGR sensor and self test the EGR system, passing an engine running self test verifies EGR operation.

8. **PCM controlled vacuum operated EGR valves (dual solenoids).** These are the same as the above except one solenoid (normally closed - closed until energized) routes vacuum to the EGR valve and the other solenoid (normally open - open until energized) vents/leaks vacuum. Both solenoids must be energized to open the valve. The control solenoid opens to increase vacuum to the EGR valve. The vent solenoid opens to leak vacuum from the EGR valve.

9. **Digital/electric solenoid EGR valves.** These EGR valves are **not** vacuum operated. Most of these actually have three separate EGR solenoids/valves within one assemble. Each solenoid opens a different size EGR valve. The PCM opens valves individually or in combinations to deliver the desired EGR flow. The assemble typically has four wires. One wire is the 12-volt power feed. This supplies electrical power to all three solenoids. There is a separate ground wire for each of the three solenoids. Grounding any solenoid should cause the engine to stumble at idle. **Do NOT ground the power feed wire!**

EXHAUST BACK-PRESSURE & NOx EMISSIONS

There has been much speculation that exhaust system modifications may cause increased NO_X Emissions and loaded mode smog test failures. The theory is that a free flowing after-market exhaust system will reduce exhaust pressure and therefore reduce EGR flow. It seems logical that any decrease in exhaust back-pressure would decrease EGR flow. EGR is the primary NO_X system, so it stands to reason that reduced exhaust back-pressure would increase NO_X emissions. In the real world this does not always happen. In order for us to accurately diagnose NO_X emissions failures we must understand why.

Other factors besides exhaust pressure are affected by decreased exhaust system restriction. Reduced restriction also improves the flow of heat out of the combustion chamber on the exhaust stroke. This helps reduce combustion chamber temperatures and therefore reduces NOx temperatures. The improved exhaust flow and reduced exhaust pressure also reduces required combustion chamber pressures for a given engine speed and power output. This reduction in pressure also results in reduced combustion temperatures. These factors also result in increased intake manifold vacuum for any given engine speed and load.

The above factors certainly indicate that reduced exhaust back-pressure may reduce NOx emissions. But EGR is still a major influence on NOx emissions so lets look at how EGR flow will really be affected by a change in exhaust restriction.

The amount of EGR flow depends on the following three things:

1. Intake manifold vacuum.
2. Exhaust pressure.
3. Restrictions in the EGR valve and passages (primarily the valve itself).

As exhaust back-pressure decreases due to reduced restriction the intake manifold vacuum tends to increase (assuming horsepower and rpm remain constant). This means that if the EGR valve position does not change, the actual EGR flow would not necessarily change as exhaust pressure changes.

EGR valves with positive back-pressure transducers will leak vacuum and fail to open at idle and with the engine off. Negative back-pressure transducers will hold vacuum with the engine off, but leak vacuum at idle. The transducers are integrated into many EGR valves. Some systems have separate transducer assemblies mounted next to the EGR valve. It is typical for transducers to partially seal under normal engine loads. This partial sealing is part of the normal EGR control.

Non computer controlled cars that use positive back pressure transducers will tend to have a significant change in EGR flow when exhaust systems are modified. The reduced back pressure will delay, or prevent the EGR valve opening in positive back pressure transducer systems. Negative back pressure transducers may actually open the valve sooner! On these cars (primarily GM) reduced exhaust back-pressure could cause hesitation and surge complaints. This is due to early and excessive opening of the EGR valve. This could also increase HC emissions.

Computer systems that have pressure or temperature EGR feedback sensors will generally increase EGR valve opening to compensate for slight to moderate restrictions in the EGR passages, back pressure etc..

Systems that use position sensors have no way of compensating for deposit restrictions.

Computers and conventional EGR systems may respond to slight reduction in throttle position (TPS and ported vacuum signal controls) caused by reduced exhaust back pressure.

If you have a positive back-pressure transducer EGR system, reducing exhaust restriction is likely to cause a significant decrease in EGR flow. Any other system is far less likely to be affected this way. This is consistent with the results that technicians have experienced in “real world” loaded mode emissions testing.

KEY CONCEPTS:

1. ***Increased exhaust backpressure increases NOx emissions***
2. ***Increased exhaust backpressure can cause AIR to back up into the NOx reduction bed of the converter and prevent NOx reduction.***

Conditions that prevent a catalyst from oxidizing HC & CO:

Rich
AIR faults
Low oxygen

Conditions that prevent a catalyst from reducing NOx:

Misfire
Deposits
Lean
Air injection
High oxygen
Exhaust backpressure

What is the engine displacement?
Selecting a converter recommended for engines 20% larger than the one in question is recommended.

What is the vehicle test weight or GVW?
Selecting a converter recommended for cars 20% heavier than the one in question is recommended.

Is the car a performance model, low power to weight ratio, BMW or Volvo?
Add another 25% to the actual GVW or test weight.

Is the car turbocharged or supercharged?
Add another 20% to the actual engine displacement. Add even more if the boost pressure exceeds 6 psi.

Does the engine have EGR?
If not, add another 20% to GVW.

Is the vehicle OBDII equipped?
Make sure the manufacturer recommends the catalyst for OBDII applications.

Does the vehicle have air injection?
Make sure the catalyst is manufactured with a directional injection tube and that the catalyst is rated for a 20% larger engine.