Engine Air/Fuel Ratios

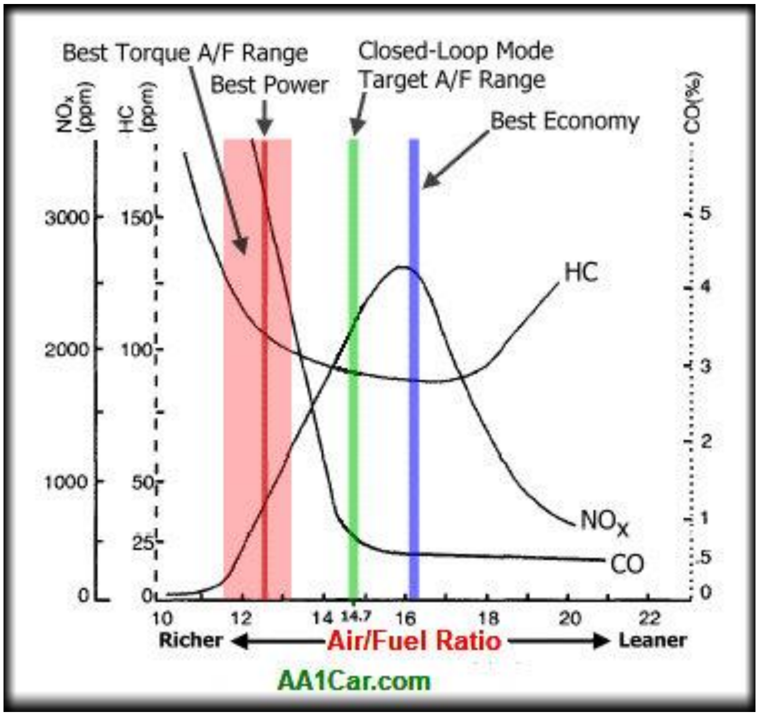
by Larry Carley copyright 2019 AA1Car.com

The Air/Fuel ratio (A/F) is the mixture ratio or percentage of air and fuel delivered to the engine by the fuel system. It is usually expressed by weight or mass (pounds of air to pounds of fuel). The Air/Fuel ratio is important because it affects cold starting, idle quality, driveability, fuel economy, horsepower, exhaust emissions and engine longevity.

For a mixture of air and fuel to burn inside an engine, the ratio of air to fuel must be within certain minimum and maximum flammability limits otherwise it may not ignite. Too much air and not enough fuel , or too much fuel and not enough air may create a mixture that fails to burn when the spark plug fires. The result would be an ignition misfire, loss of power and increased emissions (unburned hydrocarbons or HC primarily).

THE CHEMISTRY BEHIND AIR/FUEL RATIOS

When the Air/Fuel mixture is perfectly balanced chemically, there is just the right amount of oxygen to burn all of the fuel. This ratio is called a STOICHIOMETRIC fuel mixture. All of the oxygen in the air and all of the hydrocarbons in the fuel will be consumed, leaving nothing but water vapor (H_2O) and carbon dioxide (CO_2). Under light cruise conditions and low engine load, most engines like a stoichiometric A/F mixture because it produces the lowest HC and carbon monoxide (CO) emissions and good fuel economy.



This chart shows how different Air/Fuel ratios affect emissions, fuel economy and performance.

The ideal or stoichiometric Air/Fuel mixture for various fuels will vary depending on the fuel and its chemical makeup. The amount of oxygen required in the A/F ratio will depend on the number and type of carbon and hydrogen bonds in the fuel, so different fuels have different optimum A/F ratios.

Gasoline contains a mixture of various long chain hydrocarbons. One of its main ingredients is octane (C8H18), but it also includes many other HCs. The actual formula will vary depending on the season (winter or summer), the refining process and the emission regulations the fuel must meet in various areas. Generally speaking, gasoline will contain about 15 percent straight-chain C4 to C8 alkanes, 25 to 40 percent branched C4 to C10 alkanes, 10 percent cycloalkanes, up to 25 percent aromatics, 10 percent straight-chain and cyclic alkenes, and less than one percent benzene.

Much of the gasoline sold in the U.S. is also blended with ethanol alcohol to extend the fuel supply, improve the octane rating (detonation resistance) and add oxygen for a cleaner burn. Ethanol gasoline fuel mixtures range from 10 percent ethanol (E10) to 85 percent ethanol (E85). E10 ethanol blends are EPA-approved for use in all gasoline engines, while E15 has been recently approved for use in 2001 and newer vehicles. For FLEX FUEL capable vehicles, ethanol/ gasoline mixtures containing up to 85 percent ethanol (E85) may be used.

STOICHIOMETRIC AIR/FUEL RATIOS

For gasoline engines, the ideal or stoichiometric A/F ratio is 14.7, which is 14.7 parts of fuel by weight to one part fuel.

For E10 gasoline (90 percent gasoline with 10 percent ethanol alcohol), the stoichiometric ratio is 14.08:1.

For Flex Fuel applications, the stoichiometric A/F ratio for E85 is 9.7:1.

For an alternative fuel such as neat ETHANOL alcohol (E100), the stoichiometric A/F ratio is 9:1.

For a racing fuel like METHANOL alcohol, the stoichiometric A/F ratio is 6.5:1.

For a NATURAL GAS (METHANE or CH4), the stoichiometric ratio is 17.2:1

For a PROPANE (LP gas or C3H8), the stoichiometric ratio is 15.5:1.

With diesel engines, the stoichiometric A/F ratio for #2 diesel fuel is 14.6. However, because diesel engines use the fuel mixture to control engine speed and power output, they typically run A/F ratios that can range from 18:1 up to 70:1.

RICH AND LEAN AIR/FUEL RATIOS

When the Air/Fuel mixture differs from the stoichiometric ratio, it burns differently and affects engine performance, emissions, fuel economy and longevity differently. Real world driving conditions require different A/F ratios at different times, so the A/F ratio is not something that is static and unchanging,. It is dynamic and changes in response to changing operating conditions.

First, we need to explain the difference between RICH and LEAN Air/Fuel mixtures.

An A/F ratio that contains more air and less fuel than the stoichiometric ratio is called a LEAN fuel mixture. A lean mixture would be one with a ratio greater than 14.7:1 for gasoline.

An A/F ratio that contains less air and more fuel than the stoichiometric ratio is called a RICH fuel mixture. A rich mixture would be one with a ratio less than 14.7:1 for gasoline.

A LEAN A/F mixture typically burns HOTTER and uses less fuel per mile driven, which improves fuel economy. But hotter combustion temperatures also increase oxides of nitrogen (NOX) emissions and the risk of engine-damaging detonation (spark knock).

DETONATION DANGERS OF A LEAN AIR/FUEL MIXTURE

Detonation is an abnormal form of combustion that may occur when the combination of high temperatures and pressures inside a combustion chamber cause the fuel to spontaneously ignite before the spark plug fires. Instead of a smooth outward expanding flame balloon from the spark plug, pockets of fuel ignite and collide with one another producing an audible knocking noise. Detonation is bad because it increases combustion pressure much too rapidly. This produces hammer-like blows on the pistons that can damage pistons, rings, connecting rod bearings and head gaskets. A fuel mixture that is much too lean may even burn a hole right through the top of a piston! So one thing to always avoid is a really lean fuel mixture, especially when an engine is accelerating or working hard under load.

An underlying cause of an overly lean fuel condition may be dirty fuel injectors, low fuel pressure (weak fuel pump or a restricted fuel line or filter) or insufficient fuel flow (pump or injector capacity to small for the application). On modified performance engines (especially those with a supercharger or turbocharger), a higher output fuel pump and/or higher flow fuel injectors are typically needed to keep up with the increased fuel demands of the engine. If the pump or injectors cannot keep up, the fuel mixture can go lean sending the engine into detonation and possible self-destruction!

All late model original equipment engines with computerized engine controls have a KNOCK SENSOR to protect the engine against detonation. If the knock sensor detects vibrations that feel like detonation, it signals the engine control computer to momentarily retard spark timing which lessens the risk of detonation. The engine computer may also enrich the fuel mixture because adding fuel helps cool combustion temperatures and reduces the risk of detonation.

RICH AIR/FUEL MIXTURES, HORSEPOWER AND EMISSIONS

As for RICH A/F mixtures, adding more fuel to the mixture increases power up to a point. A richer mixture also reduces the risk of detonation, which is why engines that are supercharged or turbocharged usually have a richer A/F ratio when the engine is receiving boost pressure. But the trade-off of a richer mixture is increased fuel consumption and higher exhaust emissions (carbon monoxide primarily). The richer the A/F mixture, the higher the percentage of carbon monoxide in the exhaust.

Normally, CO levels in the exhaust of a well-tuned engine running at or near its stoichiometric ratio should be zero to less than half a percent. If the vehicle is equipped with a catalytic converter, CO levels at the tailpipe should be zero or very close to zero. Carbon monoxide is a dangerous and deadly pollutant because only a tiny amount can kill!

How the Air/Fuel Ratio Changes

Engine Operation	Air/Fuel Ratio
Cold Start	Extra Rich
Cold Idle	Rich
Warm Idle	Balanced
Light Acceleration	Slightly Rich
Medium Acceleration	Rich
Hard Acceleration	Extra Rich
Cruise Light Load	Balanced to Lean
Cruise Moderate Load	Balanced to Rich
Cruise Heavy Load	Rich
Coasting	Lean to Very Lean
Decelerating	Very Lean to Fuel Off

Air/Fuel ratios are constantly changing from rich to lean to suit changing operating conditions.

WHY THE AIR/FUEL RATIO IS CONSTANTLY CHANGING

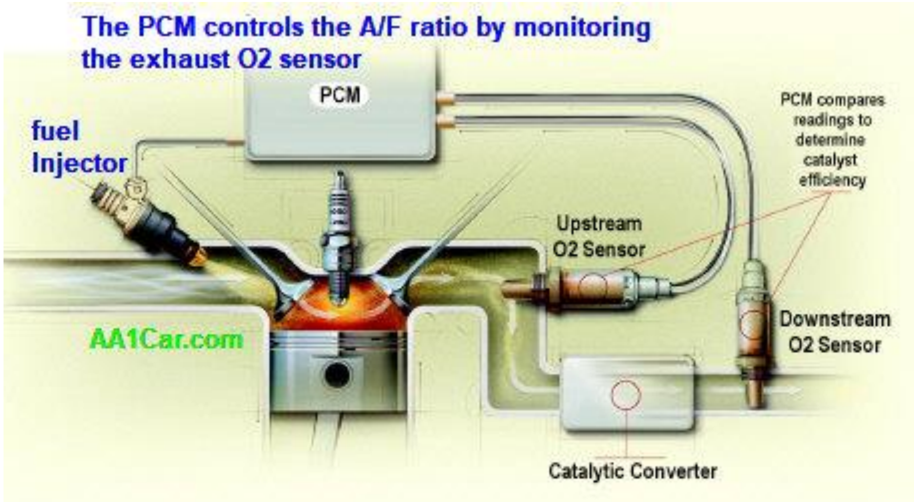
Although stoichiometric A/F ratios produce the best all-round results in terms of fuel economy and emissions, an engine cannot run with a stoichiometric ratio all the time. Sometimes it needs a RICH mixture and sometimes it can benefit from a LEAN mixture. Here is why:

A cold engine needs a very RICH fuel mixture to start (at least initially until it warms up). The cold start period is the dirtiest time for emissions, so auto makers do a variety of things to speed engine warm up and improve fuel vaporization until the engine reaches normal operating temperature. Engines with Direct Gasoline Injection (GDI) are cleaner following a cold start because the fuel is sprayed directly into the combustion chamber under extremely high pressure. This improves fuel atomization so it will mix more readily with the air for a cleaner burn.

On an older engine with a carburetor, the choke provides the initial rich mixture. Closing the choke flap restricts airflow into the carburetor to richen the mixture. As the engine warms up, the choke is gradually opened to allow more air until eventually it is no longer needed and the engine is running at its normal A/F ratio.

On older fuel injected engine, a separate cold start injector provides extra fuel during a cold start. On newer EFI engines, the computer commands a richer mixture when the engine is cranking and first starts. The computer is programmed to deliver exactly the right amount of fuel based on engine temperature and air temperature.

A cold engine also needs a RICH fuel mixture while it is warming up to idle smoothly. The A/F mixture will gradually get leaner as engine temperature comes up and idle speed settles down from a fast idle (around 850 to 1000 RPM) to normal idle speed (typically around 500 to 600 RPM). On a carburetor, this is handled by the choke and fast idle cam.



The PCM uses a feedback control loop from the upstream O2 sensor to fine tune the A/F mixture.

On a fuel injected engine, the computer maintains a rich A/F mixture until the oxygen sensor is hot enough for the feedback control system to go into CLOSED LOOP. Once this happens, the computer starts using the oxygen sensor signal to fine tune the A/F mixture. The computer controls idle speed via the idle speed control motor or solenoid on the throttle body that allows air to bypass the throttle plate.

Idle speed is preprogrammed and nonadjustable on computer controlled engines with electronic fuel injection. The only way to change it is to reprogram the computer. But on carburetors, idle speed and the idle mixture are both adjusted by turning screws. Turning the idle mixture adjustment screw in (clockwise) leans the A/F mixture while turning it out (counterclockwise) richens the A/F mixture. The goal is to get the smoothest idle at the recommended idle speed.

FUEL ENRICHMENT

When you step down on the gas pedal to accelerate, pass another vehicle or to climb a hill, the engine needs a RICH mixture to produce more power. On older engines with a carburetor, the accelerator pump and power valve provide extra fuel enrichment when the throttle is opened. On newer vehicles with electronic fuel injection, the engine computer monitors engine load via the mass airflow sensor, throttle position sensor and manifold absolute pressure sensors to change the A/F ratio when you step on the gas. The computer will then increase the pulse duration of the fuel injectors to deliver more fuel to the engine for as long as it is needed. The computer will also use feedback signals from the oxygen sensor(s) in the exhaust to monitor the Air/Fuel ratio as it changes so corrections can be made as needed.

Under light cruise conditions when there is less load on the engine, or when decelerating, most engines can run safely with a LEANER A/F ratio to improve fuel economy. On many applications, the injectors may even shut off entirely while decelerating to further conserve fuel. On engines that deactivate cylinders to improve fuel economy, the injectors on the dead cylinders are turned off temporarily.

TUNING THE AIR/FUEL RATIO FOR MORE PERFORMANCE

When auto makers develop the factory tunes for an engine, they have to meet fuel economy and emission standards. The engines are therefore tuned with leaner fuel curves to meet these goals, which means there is often room for improvement when it comes to making more power.

To increase performance, a RICHER A/F ratio will add power. How much richer the A/F ratio should be depends on the application and how much of a performance improvement you want.

For peak power with straight pump gasoline (no ethanol in the mix), the A/F ratio can go as rich as 12.5:1. If you are using E10 pump gasoline, an A/F ratio of 12:1 will deliver peak power. Going any richer just wastes fuel and will actually decrease power.

Running a race engine at peak power for an extended period of time may win a race IF the engine can hold together long enough to finish the race. But for an endurance race or every day driving, running a peak horsepower A/F ratio may not be the best idea. An A/F mixture of 13.1 to 13.3 will still produce almost as much peak power as a 12.5:1 ratio but with less stress on the engine itself.

For peak power with E85, you can run the fuel mixture as rich as 6.975:1, but for an endurance race it might be safer to go with a A/F ratio of 8.3 to 8.5.

For peak power in a methanol-powered race engine, the A/F ratio can be as rich as 3.5 to 4.0:1. Again, if you want your engine to last all season, it might be wise to back off the mixture a bit and go with a 4.5 to 4.8:1 A/F ratio. It all depends on the application. A naturally-aspirated race engine burning methanol may run best with a A/F of 5:1 while a blown high output Hemi might need a super rich mix of 3.5:1 to keep the engine from melting pistons. The extra methanol in a really high output engine is there mostly for additional cooling inside the combustion chamber.

If an engine is burning propane, peak power can be achieved with an A/F ratio of 13.18:1.

NOTE: The A/F ratio that produces actual peak power in an engine without overtaxing it to the point where damage occurs will depend on a lot of factors besides the chemistry of the fuel itself. Variables that affect the A/F ratio where peak power actually occurs in an engine include compression ratio, spark timing, valve lift, overlap and duration, the design of the combustion chamber, engine temperature, ambient air temperature, boost pressure (in a supercharged or turbocharged engine) and the use of other power adders such as Nitrous Oxide (N2O).

HOW NITROUS OXIDE AFFECTS THE AIR/FUEL RATIO

Everybody knows that Nitrous Oxide can really add power to an engine. Depending on the dose, N2O can boost horsepower 100 to 400 hp or more! It does this by adding additional oxygen to the Air/Fuel mixture. The air we breathe only contains about 21 percent oxygen. The rest is mostly nitrogen (78 percent) that does virtually nothing to make power during combustion. In fact, some of the atmospheric nitrogen in a combustion chamber will combine with oxygen at high temperature to form NOX pollution. This also steals a little power from the combustion event by reducing the oxygen that is available to burn the fuel.

If Nitrous Oxide is sprayed into the engine, the heat of combustion breaks the N2O molecule apart, freeing lots of extra oxygen to burn with the fuel. The A/F mixture can now be made as rich as 9.5 to 8.0:1 to produce peak power in the engine. In fact, you MUST add additional fuel while injecting N2O to prevent the A/F mixture from going dangerously lean and burning the pistons.

HOW TO CHANGE THE AIR/FUEL RATIO

Various modifications can be done to alter the normal Air/Fuel ratio of an engine to make more power.

On engines that use a carburetor, increasing the orifice size of the main metering jets will increase fuel flow into the main circuit for a richer A/F ratio. Jet sizes are number coded, so referring to a size chart will help you determine the best size for a given set of circumstances. However, this can change depending on air temperature and barometric pressure. Cold air is denser than warm air, so on a really hot day you might want to decrease the jets a couple of sizes so the mixture does not go too rich. Likewise, if you are tuning an engine in someplace like Denver which is a mile above sea level, the air is much thinner (less dense) . This would also require somewhat smaller jets to maintain the same A/F ratio for peak power.

Engine tuning by swapping jets is mostly a process of trial-and-error to see which size jets produce the optimum A/F ratio for best performance. This can be done by changing the jets, make a test run to see how the engine performs, and then changing the jet sizes up or down a size or two until the best results are achieved. Or, to save time, the tuning can be done on a chassis dyno.

NOTE: Changing fuel pressure on a carburetor application will NOT change the A/F ratio (unless you increase pressure so much you force the float needle valve inside the carburetor open and flood the engine).

On engines with Electronic Fuel Injection, the Air/Fuel ratio can be modified by reprogramming the computer to increase fuel delivery by extending the on-time or duration of each injector pulse. There are also interface modules for some applications that alter the oxygen sensor signals to fool the computer into thinking the fuel mixture is leaner than it actually is so it will add more fuel to richen the mixture.

Retuning an EFI system is best done by somebody who knows what they are doing. You can really screw things up if you mess up the fuel calibration map in the computer. The map is actually an algorithm that tells the computer how much fuel to add to the engine based on speed, load, airflow and temperature.

The A/F map is determined by running the engine at various speeds and loads while monitoring the A/F mixture via a wide band oxygen sensor in the exhaust. Depending on what you want, the A/F mixture is then tweaked at various RPM increments to increase power without overloading the engine or wasting fuel. Dyno tuning is also a good way to make sure the A/F mixture is not going dangerously lean at certain points, which could lead to detonation and engine damage.

LAMBDA: ANOTHER WAY TO EXPRESS THE AIR/FUEL RATIO

Another way to express the Air/Fuel ratio is with the Greek letter *Lambda*. The symbol looks like a cursive letter "L" and is basically an engineering or scientific value developed by the people who invented the oxygen sensor (Robert Bosch Corp.). It is also commonly used in Europe. Many exhaust analyzers and emissions test machines will display both the numerical Air/Fuel ratio and/or the Lambda value. The value is determined by measuring the amount of unburned oxygen in the exhaust.

When the Air/Fuel ratio is at stoichiometric (regardless of the type of fuel), the value of Lambda will be ONE (1.00 to be exact).

If the Air/Fuel mixture is LEAN (greater than the stoichiometric ratio, or 14.7 for gasoline), the Lambda value will be HIGHER than 1.00.

If the Air/Fuel mixture is RICH (less than the stoichiometric ratio), Lambda will be LOWER than 1.00.

The Lambda value is calculated by dividing the actual A/F ratio reading by the stoichiometric ratio).

Example: the Lambda reading for an A/F ratio of 16:1 would be (16 divided by 14.7) or 1.088.

Related Articles:

How Electronic Fuel Injection Works

How Fuel Injection Affects Emissions

Fuel Injection Diagnostics

Fuel Injection Problems

Fuel Injection: Diagnosing Returnless EFI

Fuel Injectors (troubleshooting)

How To Diagnose & Repair Carburetor Problems