Carburetor Tuning: The Air/Fuel Equation

In part one of this article (Engine Builder, March 2008) we showed why and how we tuned the ignition advance systems of a vintage, carburetor-equipped engine designed for leaded gasoline.

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Now that the ignition spark timing advance curves are optimized for the blend of reformulated and/or oxygenated gasoline your customers are using we will now show you how we use tools such as a 5-gas exhaust analyzer and wideband Lambda air/fuel (A/F) meter to tune the mixture.

The Air/Fuel Mixture
A lean fuel mixture can cause an engine to have a surge or miss at idle and part throttle stumble on acceleration, leading to engine overheating and lack of power. A rich fuel mixture can cause an engine to "load up" at idle, foul the spark plugs, and also lack power or run sluggish.

If the A/F mixture that is delivered to the engine is excessively rich for too long the engine could leave leftover fuel from the combustion process, washing the oil off the cylinder walls. Without the oil to act as an anti-wear agent, the pistons and rings will make metal-to-metal contact with the cylinder walls. Also, if enough fuel gets past the rings and into the crankcase the oil can become diluted and lose much of its lubricating properties and accelerate engine wear.

Theoretically, the ideal stoichiometric A/F mixture (the chemically ideal mixture of air and fuel that is required to provide a complete burn) for a properly tuned engine running on pure gasoline is 14.7:1; that is, 14.7 lbs. of air to 1 lb. of fuel. However, because of operating losses in the induction system due to intake runner and cylinder wall wetting, plus the fact that fuel may not fully vaporize in the combustion chamber, a 14.7:1 A/F mixture is often too lean for actual operating needs. A more realistic light-load, cruise A/F mixture for a stock carbureted engine running on reformulated unleaded gasoline is in the 14.1:1 range.

The A/F mixture always varies from cylinder to cylinder, therefore we tend to tune the average A/F mixture slightly on the rich side to avoid engine misfire in the leanest cylinder. It is possible to target an A/F mixture leaner than 14.7:1 for maximum fuel economy but this can lead to driveabilty problems if any one cylinder is leaner than the others. The power mixture we target for maximum horsepower is in the 12.2:1 - 13.5:1 A/F range, depending on the engine package and its combustion chamber design.

The original equipment carburetor(s) that came on a muscle or classic vehicle's engine was tuned for the leaded gasoline of the day, so in most cases the engine will tend to run lean with the reformulated and/or oxygenated unleaded gasoline of today. The gasoline of today also has lower volatility than the leaded gasoline of days past, which will cause most carbureted engines to need a slightly richer A/F mixture at idle and light load part throttle driving conditions to have the same drivability as it had with the leaded gasoline of the '60s and '70s.

Back in the 1950s and early 1960s, the car manufactures tended to calibrate their carburetors on the rich side of the ideal A/F mixture needs of the engine with the leaded gasoline of the day. Then starting in the late 1960s, the carburetors were calibrated more toward the lean side of the ideal A/F mixture needs of the engine so the vehicle could pass the exhaust emission standards that were just coming into existence.

The modern reformulated conventional and oxygenated gasoline of today will cause the A/F mixture to shift leaner when compared to the leaded gasoline of the 1960s and 1970s. This means if the A/F mixture was lean with leaded gasoline it will be even leaner with today's gasoline blends.

The high performance and replacement carburetors sold today are sold with an A/F mixture curve designed for a generic engine; therefore they must be tuned for both the specific engine and the blend of gasoline they will be used with. These aftermarket carburetors should be designed with an A/F mixture that is rich enough for a wide variety of engine packages with different exhaust systems, but this is not always true. Some of the aftermarket carburetors we see need a lot of tuning work to get the A/F mixture correct for the engine's demands with the reformulated unleaded gasoline of today.

Air/Fuel Mixture Tuning Guidelines
Back in the days of leaded gasoline an experienced tuner would adjust the A/F mixture the engine was getting from its carburetor by reading the color the fuel left on the insulator of the spark plug in the exhaust port and in the first 6 inches of the exhaust header. The reformulated unleaded gasoline we have today has made reading spark plugs almost impossible because it leaves little or no color on the spark plug insulator.

However, modern technology has made available at an affordable price both portable 5-gas exhaust gas analyzers and wideband Lambda ("oxygen") sensor based digital A/F meters that can be used to accurately "read" the A/F mixture in an engine by analyzing the content of the engine's exhaust gases. These modern tools can allow you to observe what A/F mixture the engine is getting from the fuel system while driving the car in real world conditions at any rpm and load condition.

The ideal A/F ratio for maximum power or fuel economy may be best calculated at the factory with the engine on a dynamometer, but the readings that are available from a 5-gas exhaust gas analyzer allow you to tune the A/F mixture for what your engine needs in real world driving conditions. The readings from an infrared exhaust gas analyzer will indicate A/F ratio, engine misfire, engine combustion efficiency and excessive combustion chamber heat (detonation) by looking at the following exhaust gases:

CO (Carbon Monoxide): The reading from an infrared gas analyzer that we use to determine the air to fuel ratio when the A/F mixture is on the rich side of stoichiometric. (Note: CO is partially burned fuel.)

The other readings that exhaust analyzers provide are:

HC (Hydrocarbons): The amount of unburned fuel in the exhaust (a indicator of an engine misfire).

CO2 (Carbon Dioxide): A gas that is the product of complete combustion (the best A/F mixture gives you the highest CO2 reading). The ideal ignition-timing advance will also create the highest CO2 reading

O2 (Oxygen): A high O2 reading indicates a lean mixture; an exhaust leak or the engine has a "hot" cam. Note: if O2 content is above 2 to 3 percent, air dilution of the exhaust gases being measured is indicated and the accuracy of the all of the gas readings may be negatively affected.

NOx (Oxides of Nitrogen): A gas created by excessive combustion chamber heat. This gas can be used as a precursor to detonation.

The readings you can get from a 5-gas exhaust gas analyzer can help an experienced tuner calculate what A/F mixture and how much ignition spark timing advance the engine needs to perform at its best.

A wideband sensor lambda sensor based A/F meter calculates the A/F mixture by "reading" the unburned combustible content of the exhaust gases (note: a lot of people call the lambda sensor an oxygen sensor but Bosch calls it a lambda sensor). The wideband lambda sensor measures the amount of oxygen that must be added to or subtracted from the exhaust gas to form a stoichiometric gas mix in its reference chamber, the A/F meter then calculates the A/F mixture of the exhaust gas from that value.

The readings you get from a wideband lambda sensor based A/F meter can be quite accurate, but false readings can be created by an exhaust leak, engine misfire, or an engine with a high performance camshaft at lower engine speeds. These false readings are caused by the Lambda sensor misreading the unused oxygen and/or unburned combustibles that are in the exhaust gas mixture

Tuning with a 5-Gas Analyzer and Wideband Lambda Meter
The use of a portable 5-gas exhaust gas analyzer and/or a wideband sensor based A/F meter can allow a tuner to observe the A/F mixture the engine is getting from its fuel system at any engine operating condition.
A starting point for A/F mixtures for most mild performance engines is:

• **Idle:** 1.0% to 3.0 % CO or a 14.1-13.4:1;

• **Cruise rpm:** 1.0% CO or a 14.1:1 with a mild performance engine; or 1.0% - 3.0% CO or a 14.1 – 13.4:1 with high performance cam; and

• **Power mixture and acceleration:** 6.0% CO or a 12.5:1 for a “normal” engine or high performance engine with improved combustion chamber design such as a Pro Stock or a NASCAR engine; in some cases you may be able to use a slightly leaner power mixture of 4% CO or a 13.0:1.

When we are tuning fuel systems, we use both infrared exhaust gas analyzer and the wideband Lambda sensor methods. This way we can take advantage of the strengths of both tuning methods. The infrared exhaust gas analyzer, while slower in reaction time than a wideband sensor based A/F meter can actually best determine A/F mixture needs. The misfire rate can be observed with the HC (hydrocarbon) reading.

Efficiency can be observed by the CO2 reading (carbon dioxide) reading, and the NOx reading (oxides of nitrogen) can also be used as a precursor to detonation. A wideband Lambda sensor-based A/F meter systems available from companies such as Innovate Motorsports or FAST have almost no delay, while a 5-gas exhaust gas analyzer has a 6 to 10 second delay.

If the engine you are tuning has an air-gap style intake manifold and/or high performance camshaft you may need to tune the idle and cruise mixtures richer than a stock engine with the same gasoline. The added performance from an air-gap intake manifold and the increased valve overlap from a high performance camshaft can often come at the price of lower fuel vaporization at lower rpm operating conditions.

The richer A/F mixture can help cover up the driveability problems when the fuel is not completely vaporized. The heat the intake manifold gets from the exhaust gas crossover in a conventional intake manifold helps the engine vaporize the fuel as it travels from the carburetor into the cylinders combustion chamber.

A/F Mixture Delivery Circuits

A carburetor has an accelerator pump, idle, main jets, and in most cases a power system that is designed to supply the correct A/F mixture for the demands. The accelerator pump system adds fuel as the throttle valves are opened. Tuning the accelerator pump squirter volume and duration is mainly done by trial and error to obtain the best throttle response, but a 12.5:1 A/F mixture is a good place to start.

An idle system will have an idle jet/restriction that must be changed to supply the desired fuel mixture for idle and off idle engine demands. If the engine you are working on is equipped with a power valve (no metering rods), the main jet size is what determines the A/F mixture that will be delivered to the engine at light-load/cruise speeds.

The power valve restriction (under the power valve) determines what A/F mixture the carburetor will supply when the power valve is open; under high power demands a 6.5˝ power valve will be open, supplying richer A/F mixture any time the vacuum is below its 6.5˝ opening point.

Power valves have a reputation for being a weak link in certain designs, but the carburetor can be retrofitted with backfire protection, which will improve reliability. A carburetor that uses metering rods in the primary jets will use the metering rods to change the A/F ratio for both the power and cruise mixture demands of the engine; the larger the metering rod diameter the leaner the A/F mixture.

After the basic engine condition and tune-up (fuel pressure, timing curve, etc) is confirmed to be correct, as well as checking to be sure there are no vacuum leaks, the next step is to determine what the A/F mixture is at idle through 3,000 rpm. If the cruise mixture is off, first change the jets to get the A/F mixture correct at 2,500-3,000 rpm cruise range. Then check and set the idle mixture. If the A/F mixture is too lean at idle or part throttle and the idle mixture screws do not provide enough adjustment, the correction may involve enlarging the idle jet.

If the mixture is still lean at 1,000 through 1,800 rpm after enlarging the idle jet, the idle channel restriction (if used) may have to be enlarged slightly to allow more fuel to be delivered at part throttle. It is important to note that any changes other than basic adjustments and jet changes should be done by a “carburetor expert” to avoid damaging a vintage carburetor. If the carburetor is damaged a replacement numbers matching carburetor could be quite expensive.

A modular design carburetor, such as a Holley, with a metering block does not use an idle channel restrictor. When we want to richen the part throttle we often must slightly enlarge the idle well in the metering block. When the A/F mixture is too lean at part throttle the engine may miss or stumble on light acceleration and at 5 – 25 mph light throttle cruise conditions.This lean off idle problem has become more prominent as the ethanol content in today’s gasoline is increased and as the gasoline formulation is changed.

If the A/F mixture is too rich at idle and/or part throttle, the idle jet or part throttle idle restriction may be too big. You may need to be replace it with a smaller one. Once you have the idle, part throttle and cruise A/F mixture curves correct, the next step is a road test.

A road test using a portable infrared exhaust gas analyzer and/or a wideband oxygen sensor will allow you to check the cruise speed A/F mixture, followed by a check of the power A/F mixture under load. This type of test allows you to see what the A/F mixture is under real world driving conditions. During this road test you will be able to read and then correct the A/F mixture.

If you see an A/F mixture reading that goes too lean at high engine loads, the first thing to do before you change jet size is to check the fuel pressure. The fuel pressure must stay above 5 psi at wide-open throttle; if not, the carburetor will starve for fuel.

The most common accelerator pump-related complaint we hear is a hesitation on quick acceleration. This hesitation is most often caused by the changes in the gasoline’s volatility and changes in carburetor manufacturing. The accelerator pump duration spring used on most replacement carburetors is not as strong as the spring that was on these same carburetor designs used in the 1960s.

We use an accelerator pump upgrade kit on most Holley modular style carburetors that consists of a stronger duration spring, a 0.031˝ squirter and a “pink cam” (Ole’s p/n 1330), this makes the accelerator squirt more active.
When we are working on a engine with an Edelbrock Performer or Thunder series carburetor we use an improved accelerator pump (Ole’s p/n 1010). This accelerator pump has a stronger duration spring that allows the pump to be more active and thus help cure most of the accelerator pump related hesitation we see with these carburetors.

Selecting the Correct Carburetor
The big four suppliers of 4 barrel carburetors today are Edelbrock, Holley, Quick Fuel and Barry Grant, each of these carburetor designs have strong and weak spots. The carburetor that we would recommend is based on how the customer will drive their car and the engine package that is in the car.

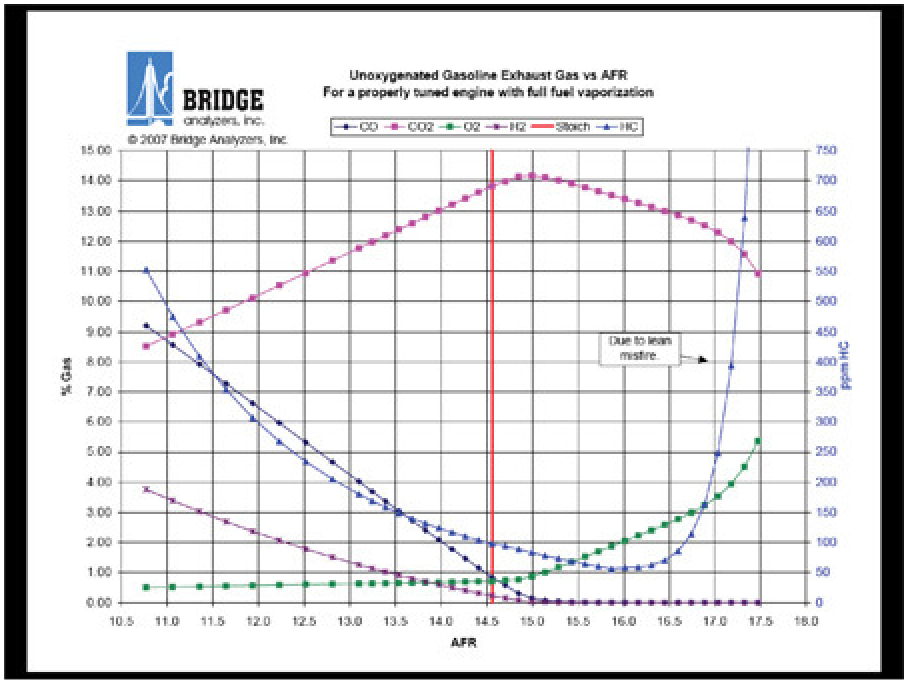
The Carter-designed Edelbrock Thunder and Performer are reliable low maintenance carburetors with great electric chokes but if the driver likes to drive fast around corners they may not bethe best carburetor to select for that application. The off-idle system design in these Carter-designed carburetors can lead to a lean off-idle stumble problem when the engine has a “hot cam” or an air-gap style intake manifold. Enlarging the idle channel restrictor on the 500 thru 650 cfm units will often cure this lean off-idle stumble problem but we have not had the same success solving this lean off-idle stumble problem on the 750 and 800 cfm carburetors of this design.

Modular carburetors manufactured and sold by companies such as Holley, Barry Grant and Quick Fuel are very good carburetors to select when the driver likes to drive fast around corners or when you are tuning for maximum power. Quick Fuel also sells billet metering blocks with changeable idle jets, power channel restrictors and emulsion well restrictions for the Holley style modular carburetors, which allow you to custom tune the fuel curve.

When the customer wants a high performance modular carburetor with an electric choke we often recommend a Holley brand carburetor because their chokes have a choke pull-off built in. When we are tuning a high performance engine with a “hot cam” (over 240 degrees of duration @ .050˝) or any engine with an air-gap style intake manifold, we often recommend a race-designed modular carburetor with a four corner idle system.

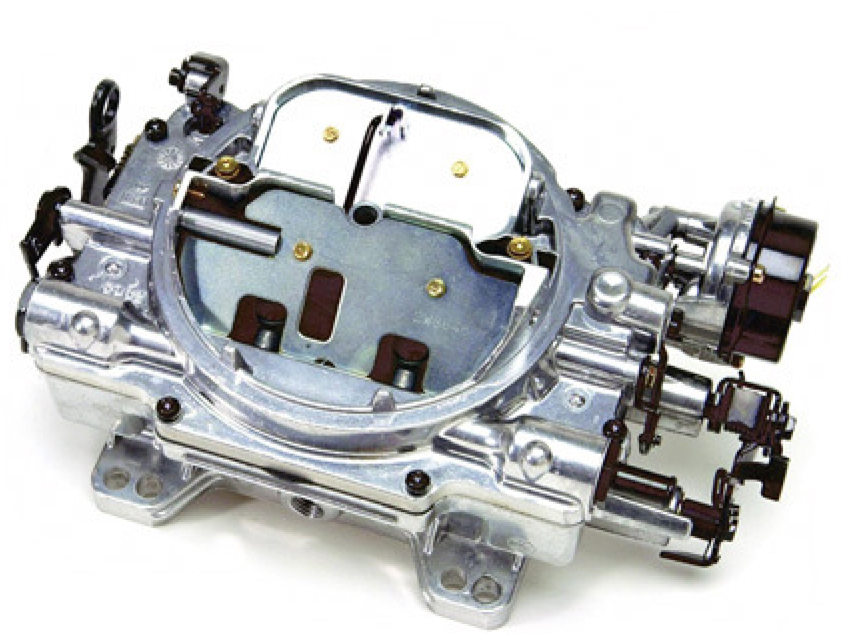
Tuning Results
You can build your customer the perfect engine but unless it is tuned for the correct formulation of gasoline the engine will not perform like it should. The first person that most customers blame if the engine does not perform like they think it should is the person that built the engine. The best way to ensure your customer is satisfied with the dollars they spent to rebuild their engine is to either offer a tuning service or give them a tuning guide.

Once the engine has been tuned so that it has the correct ignition spark timing and the correct A/F mixture for every operating condition the engine will perform like it should. Properly tuned engines will also have fewer alleged warranty claims since a properly tuned engine will not suffer from problems such as the piston rings being washed down from overly rich A/F mixtures, piston damage from detonation or engine tuning related driveability problems.



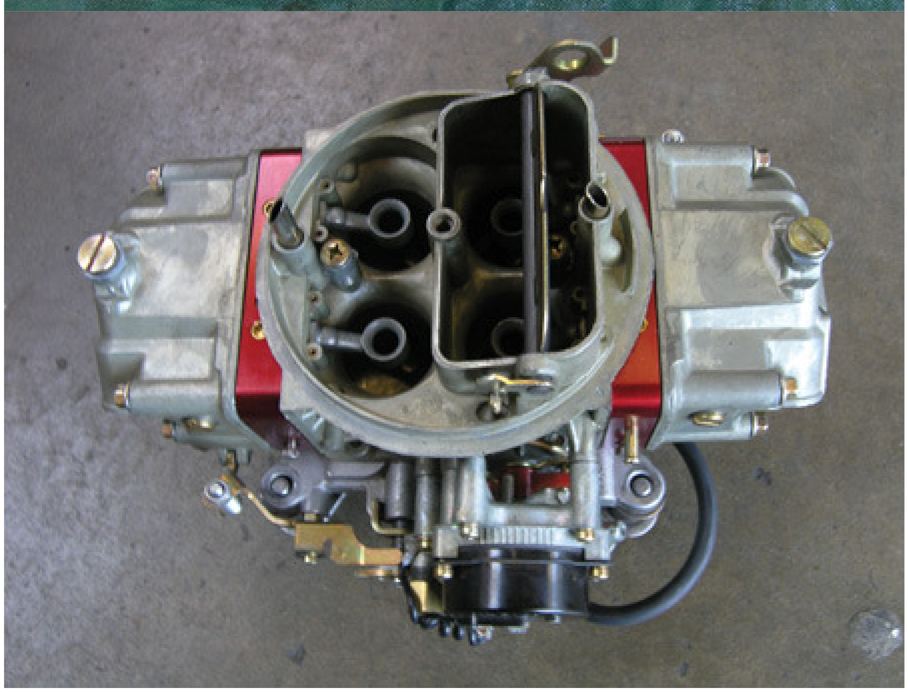
Top: The above chart shows the gases in the exhaust that an infrared exhaust gas analyzer reads and how the gases change as the A/F mixture changes. The 14.7:1 Stoichiometric calculation value is for an engine with perfect fuel vaporization and it assumes you are using “pure” gasoline. Reformulated and/or oxygenated gasoline will have a slightly richer Stoichiometric A/F mixture ratio value.

Bottom: A wideband Lambda sensor based air/fuel meter is a tool that should be in every tuners' tool box!



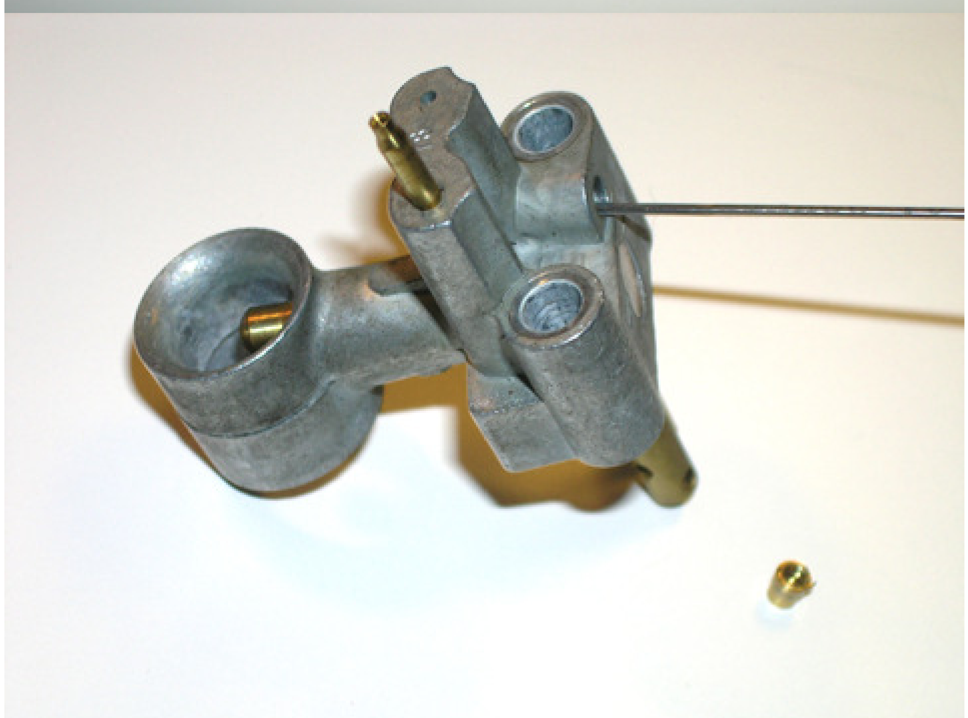
Top: The 650 cfm Edelbrock Thunder carburetor is a very good choice for a mild performance engine.

Bottom: The OTC/SPX Performance exhaust gas analyzer can be used with either the Genisys or Solarity units. This is, in my opinion, the most valuable tool in my tuner's toolbox!



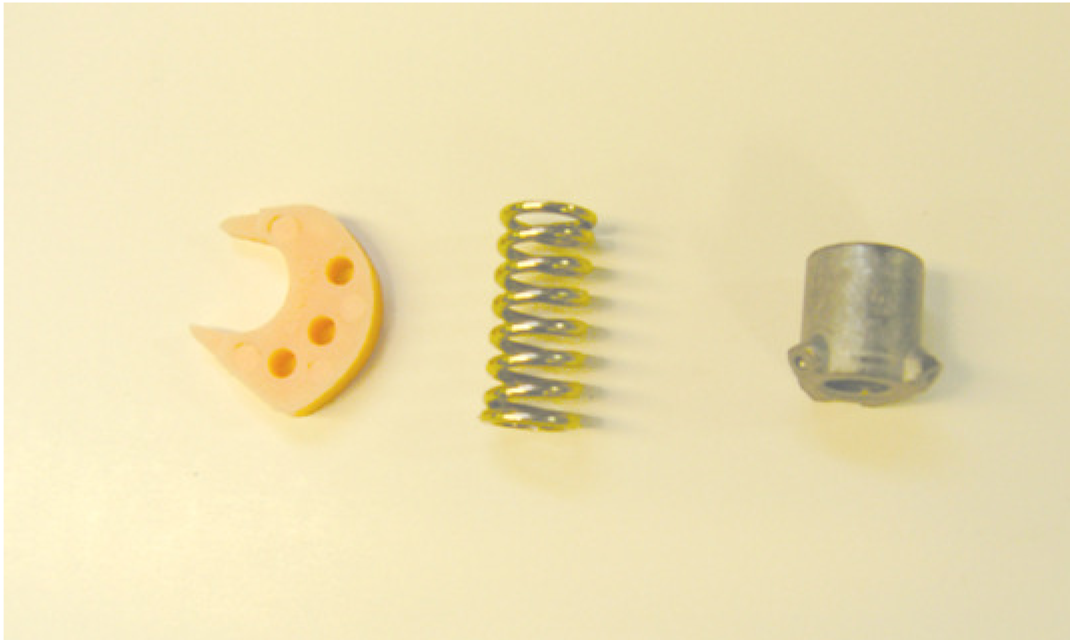
Top: This Unique Innovate tailpipe probe allows you to read the air/fuel mixture without welding a bung into the exhaust system.

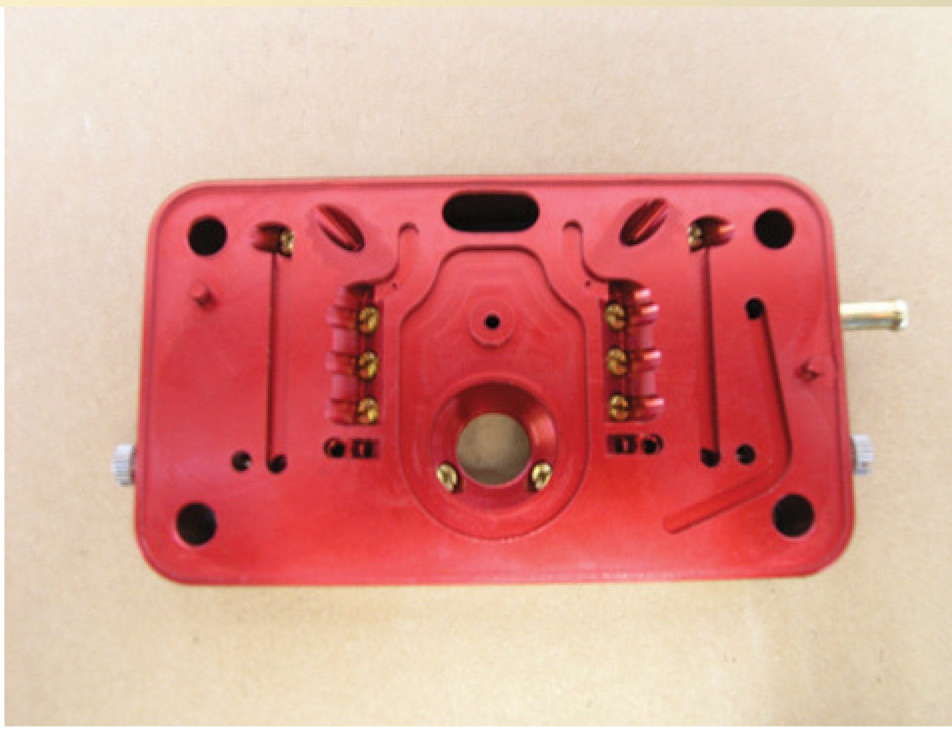
Bottom: This Holley carburetor has metering blocks from Quick Fuel Technology so we could tune the air/fuel mixture curves to match the needs the engine.



Top: The discoloration of this gasket from a modular carburetor is evidence of fuel leakage between the carburetor's fuel circuits. This leakage could have been prevented by tightening the fuel bowl screws every 3,000 miles or so.

Bottom: A ream can be used to slightly enlarge the idle channel restrictor to cure a lean off-idle stumble in a Carter designed AFB/AVS carburetor.





Top: We use the Ole's p/n 1330 pump kit make the accelerator pump more active on many of the Holley carburetors we tune.

Bottom: This very tuner friendly metering block from Quick Fuel Technology can allow a tuner to modify the fuel mixture curve of a Holley carburetor.