Using an Air/Fuel Monitor

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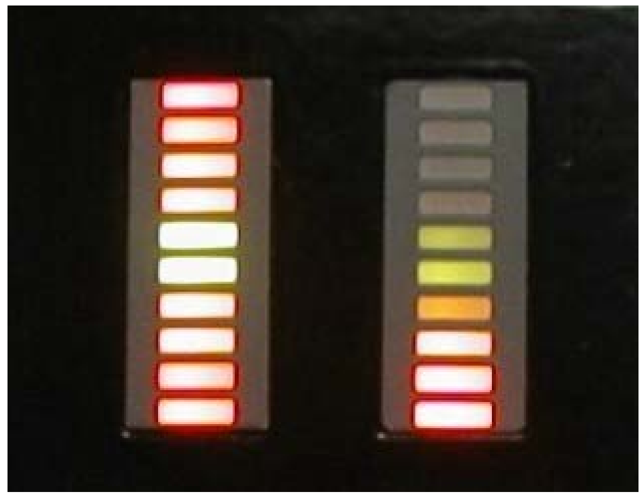
The construction of an Air/Fuel Monitor is described in a separate note. The operation of the monitor on my '76 TR6 is described here. Commercially available units would probably perform similarly. At this point, the monitor has only been installed for a few weeks, since the first of December 2001. The weather has been unseasonably warm so I was able to do a lot of road tests. I wanted to get these data out to other folks so that those living in the north and interested in duplicating the monitor can do so when their car is laid up due to the weather. Hopefully they'll be all set to test everything on the first decent day in the spring.



The monitor display is mounted to the right of the ignition switch as shown above on the left. A close-up of the display is shown on the upper right. The colors appear much brighter and crisper than the photo. The left column of Light Emitting Diodes (LEDs) is for the rear carb and the right column for the front carb. The leanest mixture is with all LEDs off. As the mixture becomes richer, lights begin to turn on from the bottom.

The O2 sensor voltage level corresponding to each LED is shown in the table below. The correct reading is that which corresponds to the highest LED that is on. For example, if the bottom two red and the lowest yellow are the only LEDs on, then the mixture is about15:1. If all except the top two red lights are on, the mixture is about 13.2:1. I don't have specifications as to the likely variations from sensor to sensor. However, I suspect that the variation is probably on the order of plus or minus one LED level. The point is, don't try to read the data too precisely --- the monitor is not a precision test instrument. It will however provide useful carb tuning information.

LED	Voltage Range	Lambda	Air/Fuel Ratio	Output Torque	Observations
	>945mV	<0.80	<12	<98%	Too rich, power loss
	900-945 mV	~0.85	~12.5	100%	Maximum power
	855-900 mV	~0.90	~13.2	99%	Good operation

	810-855 mV	~0.93	13.8	98%	Good operation
	540-810 mV	~0.97	14.3	98%	Good operation
	225-540 mV	~0.98	14.4	97%	Good operation
	180-225 mV	~1.0	14.7	97%	Good operation
	135-180 mV	~1.02	~15	96%	Good operation
	90-135 mV	~1.04	~15.3	95%	Maximum economy
	45-90 mV	1.05-1.25	15.4-18	74-94%	Pretty lean
All out	<45 mV	>1.25	>18	?	Too lean, misfires

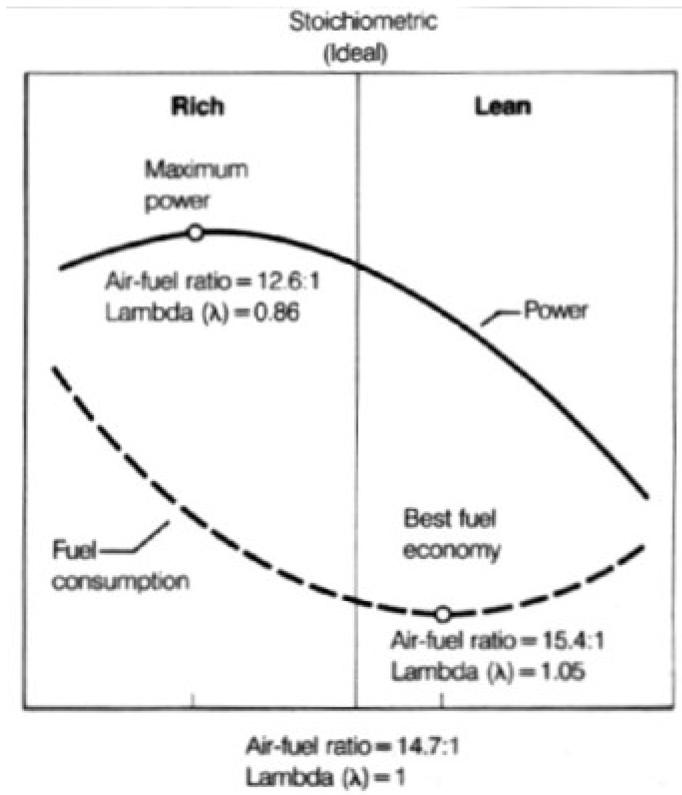
First results: The first test runs were made with the needles set one turn below the full up position. This was a good setting but on the lean side based on previous tests - see accompanying note Part III. The following monitor output was observed on a half dozen test runs of about 5 miles with speeds up to 60 mph:

- When the car was first started, all the LEDs were on. After a couple minutes warm up, the O2 sensors start to respond and some of the lights went off.
- At idle, all but the top LED was on in the left column and the right column varied with the top LED on sometimes and off at other times.
- When accelerating under load at low RPM sometimes the mixture got so lean that all the LEDs went out and then after a couple of seconds the mixture started to become richer to the point where most the LEDs were back on.
- Both the displays moved together most the time.
- Sometimes the mixture when very lean with all the LEDS out when decelerating --- like when going down a steep hill. There was some mild exhaust popping in this situation.
- When running steady on level highway at about 60 mph the LEDS jumped around a lot with from 1 t 5 LEDs on
- The needle for one carb was then adjusted one turn leaner. The monitor showed a significantly leaner mixture for that carb on the subsequent test run.

This was not what I expected. I assumed the mixture would be pretty steady and I'd be able to adjust the needles to the desire point and we'd be finished. Wrong!

The good news was that the display recognized a difference between the carbs when they were adjusted differently.

Upon further reflection, the carb performance observed before the monitor was installed exactly matched the monitor data. At idle for example, the mixture was set so that the idle speed didn't change or increased slightly when the air valve was raised a quarter inch or so. Raising the air valve makes the mixture leaner. For the idle speed to increase when the air valve was raised, the mixture must be richer then the maximum power point on the curve on the right. We had clearly set the needle for an idle mixture near that maximum power point --- around a 12.6 A/F mixture matching all but the top most light on the monitor being on.



Another test I did earlier was to run the engine under severe load and see if the engine misfired matching low power and a weak mixture --- leaner than 15.4:1. It did if the needle was set a turn or so lower.

With the same needle setting a very rich mixture at idle and a very lean mixture when accelerating under load was achievable. I should have expected that the mixture and lights would jump all over the place.

Numerous test runs were made at various needle settings. In earlier tests it was noted that popping occurred when decelerating. Several exhaust air leaks at joints were repaired when the down pipe with the O2 sensors was reinstalled. This reduced the popping some. However, noticeable popping still occurred when the mixture was set leaner then one turn below the maximum up position.

When the needles were set more than one turn below maximum up position, the engine could be made to misfire when under severe load ---- 4th gear in OD going uphill at 1500 to 2500 RPM. I was able to get it to misfire several times under these conditions when the needles were set a half turn below the maximum up position.

Modify the dampers: The carb performance was pretty good with the needles set from one-half to one turn below the maximum up position. There was very little of the exhaust popping when decelerating and only an occasional misfire under severe load. However I was concerned about how easy it was to make the mixture very lean under load. If the gas pedal were tapped while driving at 55 mph, most the LEDs would go out. It was possible to make it go so lean under heavy load that all the LEDs would go out.

Then I though --- the air valve damper is supposed to keep this from happening. The theory is that if the air valve is restricted from lifting as the throttle is opened, the velocity of the air moving past the jet will increase and more fuel will be sucked out of the jet. As the air valve moves up, the velocity of the air moving past the jet decreases, but the opening in the jet is increased because the needle is tapered. So, we have two effects that cause a more fuel to be mixed with the air --- air velocity and jet opening. Apparently, the velocity effects are greater than the jet opening effect so if the lifting of the air valve is delayed, the mixture will be richer that it would be if the air valve were allowed to move freely.

I played with the air valve a little and found that there was more than 1/16 inch movement before the damper started to restrict the air valve movement. This corresponds to about two turns of needle adjustment. It was decided to modify the damper in an attempt to reduce the undamped air valve movement.

The photo above shows the damper with an extra piston beside it. If you look really close you'll see that the piston on the damper is longer than the original shown beside the damper. The original design allows 0.075 inch movement of the piston hence 0.075 undamped movement of the air valve. The original piston is 0.367" diameter, 0.375" long with a 0.200" hole. The replacement is .0370" diameter (0.003" larger), 0.425" long (0.050" longer) with 0.228"(0.028" bigger) hole. This longer piston reduces the undamped motion from ~0.075" to ~0.025" and the larger piston diameter increases the damping force. Note that the inside diameter of the air valve guide rod is 0.375 inches so the 0.0370 inch piston diameter gives 0.005 inch clearance.

If you examine a damper closely you'll see that the hole in the piston is much larger than the damper rod. You'll also note that there is a beveled washer at the top of the piston. When the air valve starts to rise, the piston is pushed up and the beveled washer seals the space between the hole on the inside of the piston and the rod. The piston pushing against the oil in the damper cylinder restricts the air valve motion. Some oil gradually slips by in the space between the outside of the piston and the cylinder allowing the air valve to move up slowly. During deceleration the piston must drop rapidly to avoid making the mixture overly lean causing exhaust popping. When the air valve starts to drop, the damper piston drops on the rod, moving away from the beveled washer allowing the oil to move in the space between the large center hole in the piston and the rod. The intent is for the damper to restrict and delay upward motion of the air valve while allowing the air valve to descend rapidly. The longer piston restricts the opening at the top for the fluid to get to the center hole when the piston drops. The inner hole size was increased in a effort to minimize the flow restrictions through the center hole and hopefully allow the air valve to drop with little resistance. (Another way to modify the damper to achieve similar results is to place a 0.050" thick washer between the lower end of the piston and the C clip.)

The performance with the modified damper was as hoped ----- the mixture was much less prone to going overly lean when the accelerator was stomped while the engine was heavily loaded at lower (1500 - 2500) rpm. I ran quite a few tests on these things to make sure that the modifications really helped and were not my imagination. The test that was most convincing was to put a modified damper in one carb and the standard damper in the other. The monitor showed a clear difference in mixture under acceleration.

During the first tests of the modified damper ATF was used in the damper. ATF is thinner than engine oil and I hoped it would minimize any delay in the piston dropping during deceleration. SAE 30 oil was tried next. The pistons seemed to go up a little slower (good) but seemed to drop just as fast (also good).

I believe that the American carbs solve this problem of a lean mixture when accelerating by using the accelerator pump. When the accelerator is advanced rapidly, the accelerator pump pumps (dumps) additional fuel into the carb throat.

Misfire test: Dick Taylor suggested I disconnect one of the plug wires and observe the results on the monitor. The results were that the monitor associated with the side with the disconnected wire showed a leaner mixture. Not surprising ---- since one of the cylinders wasn't firing, the amount of oxygen in the exhaust increased. The difference between the two sides decreased when the RPM was increased. I can't explain that.

Engine Specifics: Before going further, it's appropriate to list the engine and carb specifics. The car is a '76 TR6. The carbs are original and are the same as those used in the accompanying notes on overhauling, tuning and powder coating carbs. The carbs have had very little use, my guess is less than 50K miles. There is not noticeable throttle shaft or shaft bush wear nor any noticeable metering needle or jet wear. The engine has been overhauled within the last 20K miles. The head is from a '73. The compression measures 150 psi to 160 psi on all cylinders. There is no EGR valve and the air pump and associated hardware have been removed. The camshaft is standard. The exhaust is the Falcon stainless dual sport system. The ignition is the standard point system with 6 volt coil. The timing is set to ~TDC at idle. The vacuum retard is connected and operational. The carb bypass valves are functioning properly and adjusted to open as easily as possible with increased vacuum.

Taking A step Back: In the process of fooling around with the modified dampers it became obvious that the hilly winding roads near my home are an excellent place to test the carb operation but a poor place to try to take measurements in a way that different adjustments can be compared accurately. The modifications to the dampers caused the air valve to take a longer time to reach the new equilibrium position after changing the throttle position. These roads are such that a throttle position can't be maintained for more than a minute or so so then carbs never seem to reach equilibrium .

Another thought is that we'd like the carbs to run as lean as possible when we're cruising along at a steady speed where only 10 or 20 HP are required to propel the vehicle. On the other hand, we want a rich mixture when we stomp on the accelerator where we use all HP that is available and want many more HP.

This led me to a different approach ----- split the measurements into two parts: steady state and transient. Once the steady state performance is understood, the dampers can be installed again and an attempt made to understand the transient performance.

Steady State measurements: To measure the steady state performance I removed the dampers and drove on a flat highway and held the accelerator in a position to maintain the RPM indicated. All measurements were in 4th gear direct drive except for 4500 and 5000 RPM where I dropped down to 3rd gear. (There seemed to be a bear convention along the highway when I was making the tests and didn't want to explain that I wasn't speeding, just testing some carb adjustments.) The mixture measurement recorded is the highest LED lighted. The two displays were nearly identical so no differentiation is made. The reading of 0-1 for example means that no LED is on part of the time and 1 LED is flashing on and off. A reading of 1 to 2 LEDs is near maximum economy and about 90% power. A reading of 6 or 7 LEDs or more is very near or at maximum power.

Steady State A/F Reading (number of LEDs on)				
	Needle Adjustment (-1 = one turn below maximum up position)			
RPM	**0**	**-1/2**	**-1**	**-1 1/2**
1500	8	8	6-7	0
2000	7-8	7-8	6-7	0
2500	7-8	7-8	2-5	0-1
3000	6-7	2-5	1-5	0-1
3500	2-5	1-5	1-2	1
4000	2-5	1	1	1
4500	1	1	1	1
5000	1	1	1	1

The first conclusion that one draws from the above table is that the needle adjustment has no effect on the mixture at higher RPM. This is easy to understand if one looks at the chart below. There are about four adjustment turns between each eighth inch distance step in the chart. A 1 1/2 turn adjustment around the 1/4 inch position gives about a 10% change in the open area between the jet and the needle. I guess the needle position for 4000 RPM is about the 1 inch position. A 1 1/2 turn adjustment around the 1 inch position gives about a 2% change in the open area between the jet and the needle. Therefore, one can successfully adjust the performance at idle and low RPM by raising or lowering the needle. The performance at high RPM is controlled by the needle profile. In our case, we get near maximum economy at high RPM which is good both for the pocketbook and pollution. If I were trying to improve the performance so I'd have a hope of out dragging an old lady in a minivan, I would change the needle profile. One can try thinning the needle a bit in just the right places or substitute a thinner needle. I understand some folks have used TR4 SU needles to improve high RPM power. Dick Taylor has made a number of suggestions on how to go about the task of thinning a needle. This is a good future project that might go with putting a modified cam in my '70 TR6. So many toys and so little time......

The other conclusion was of course that the needle height has a big influence on the mixture at lower RPM. Earlier tests showed that the performance changed between the -1 and -1 1/2 needle positions. The table above shows an almost unbelievable difference in mixture between these two needle settings ---- like falling off a cliff. After taking the measurements and writing this up, I went back and repeated these measurement ---- same results.

Needle (B1AF) and Jet Geometry		
Distance from needle top (inches)	Needle diameter (inches)	Open area between needle and jet (sq inches)
0.000	0.0951	0.0030
0.125	0.0942	0.0035
0.250	0.0923	0.0046
0.375	0.0897	0.0061

0.500	0.0864	0.0080
0.625	0.0835	0.0095
0.750	0.0798	0.0114
0.875	0.0771	0.0127
1.000	0.0749	0.0138
1.125	0.0731	0.0146
1.250	0.0712	0.0155
1.375	0.0695	0.0162
1.500	0.0695	0.0162

Transient Performance: The carbs were adjusted to 1 turn below the maximum up position for these tests. SAE 30 oil was used in the dampers. The damper versions tested were:

- No dampers
- Original dampers
- Modified dampers (longer and bigger diameter pistons --- see above)

The first test consisted of driving on the level highway at 3000 RPM in 4th gear direct drive (~55 MPH). After the carb was at equilibrium, the accelerator was stomped to the floor and the mixture observed as the RPM increased to 3500 RPM.

For the no damper case, the mixture went from bouncing around with 1 to 5 LEDs on to no LEDs on for about 1 second then up to 6-7 LEDs on until I let up the accelerator when 3500 RPM was achieved. Note that after the initial lean period of 1 second, the mixture went richer than steady state.

For the original damper case, the mixture went from bouncing around with 1 to 5 LEDs on to one LED on for a very short period, maybe 0.1 second then up to 6-7 LEDs on until I let up the accelerator when 3500 RPM was achieved. Again, after the initial lean period of 0.1 second, the mixture went richer than steady state.

For the modified damper case, the mixture went from bouncing around with 1 to 5 LEDs on to 8-9 LEDs on with no dip. The 8-9 LEDs stayed on until I let up the accelerator when 3500 RPM was achieved. This time the mixture went richer than steady state with no dip.

Additional tests with the modified damper were conducted with a greater loads (4th + overdrive) or going up hills. In those cases there was some early drop in mixture before recovery --- the same pattern as with the unmodified damper, but at a heavier load.

The second test was an attempt to determine how long it took the carb to reach steady state after a change in accelerator position. For this test I I drove the car at 3500 RPM (4th gear direct drive) on flat highway. I took my foot off the accelerator and let the RPM drop to 3000 RPM. This took long enough so that the air valve dropped to the lowest position. I then pressed the accelerator to the point that a steady 3000 RPM was maintained. The mixture went rich and then leaned out to 1 to 5 LEDs on as the air valve reached the steady state position for 3000 RPM. The interval between the time the pedal was pressed and the time the mixture went to the 1-5 LEDs on steady state condition was measured.

For the no damper case, response was nearly instantaneous --- less than1/2 second.

For the original dampers, the recovery took about 3 seconds.

For the modified dampers, the recovery interval was about 15 seconds.

So, what does this all mean? I think a better performance can be achieved by modifying the dampers to reduce the air valve undamped motion (lengthen the damper piston) and increasing the damping force (larger damper piston diameter). The down side of this is that fuel consumption will probably increase significantly for one who drives by moving the accelerator up and down a lot.

Summary of results: I think the A/F monitor reflects the carb operation very well. A competent mechanic probably easily recognizes the information provided by the monitor from the engine performance. Being an incompetent shade tree mechanic, I found the monitor data very reassuring. Also, the lights are really cool. The results were:

- The carbs can supply sufficient fuel over a wide range of operating conditions.
- The mixture varies rapidly as the operating conditions change.
- When the carbs are set for best operation the mixture is towards the rich side at lower RPM.
- The mixture at high RPM is controlled by the needle profile and nearly independent of the needle adjustment.
- The modified dampers improve performance under load and allow a leaner needle adjustment thus improving economy and likely improving pollution performance.
- The carbs perform well over a wide range of adjustment.
- The optimum needle setting seems to be 1/2 to 1 turn below the maximum up position.
- These carbs show little or no needle-jet wear. The optimum setting for carbs with worn needles and jets will probably be with the needle somewhat lower.
- The dampers perform well using SAE30 oil. I suspect that multigrade engine oils will also work as well or better.

Confession: After all the fooling around with this new tool (I choose to ignore the wife's view that it's a new toy), the final carb needle setting of -1/2 to -1 turn is the same as determined by other tests before I built the monitor - see Part III of the carb notes. One difference is that I have more confidence in the settings.

Caution: It's important to reinforce the point that these monitors are not precision test instruments. The monitors accurately indicate if the mixture is lean or rich. However, one can not rely on the specific A/F values indicated in the chart shown above. I don't have any data on the normal variations in the sensors however, I suspect that a variation of at least one LED level and possibly two LED levels between sensors is normal. With the display bouncing all over the place as they do, it's not clear that more precise data would be particularly useful anyway.

TR250-TR6 Carbs: Part I - Disassembly & Theory
Part II ? The Overhaul
Part III ? Reinstall, Tune and Troubleshooting
Powder Coating ZS Carbs
Replacing Fixed Needles with Adjustable Needles
Air/Fuel Monitor
Using Air/Fuel Monitor

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