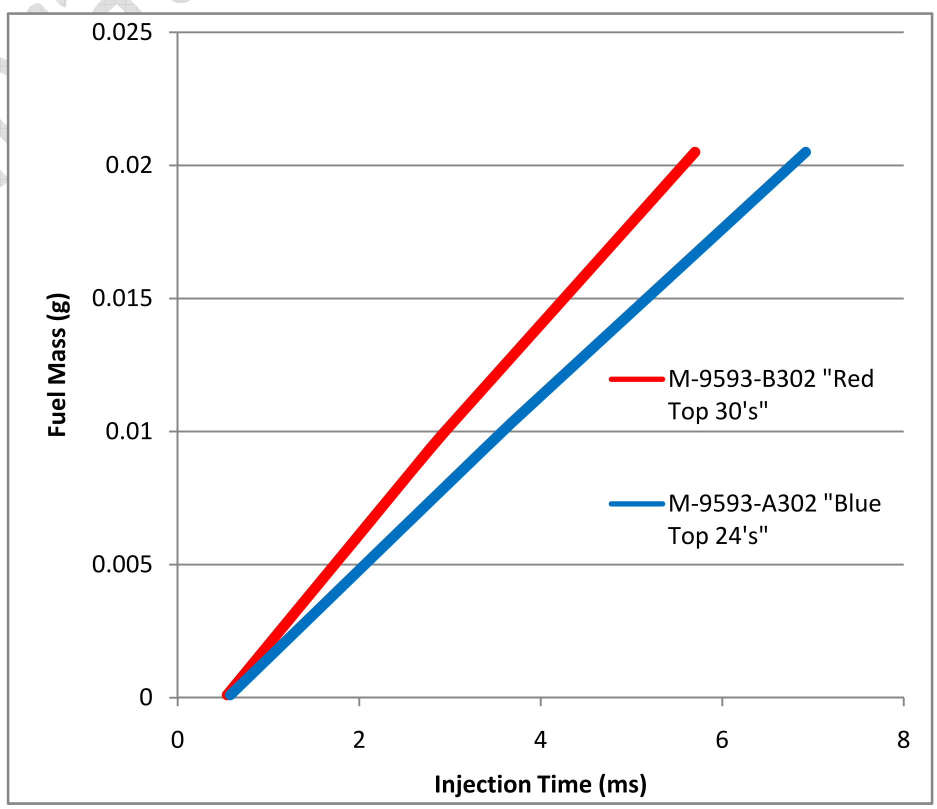
Are all Fuel Injectors Created Equal?

By Greg Banish

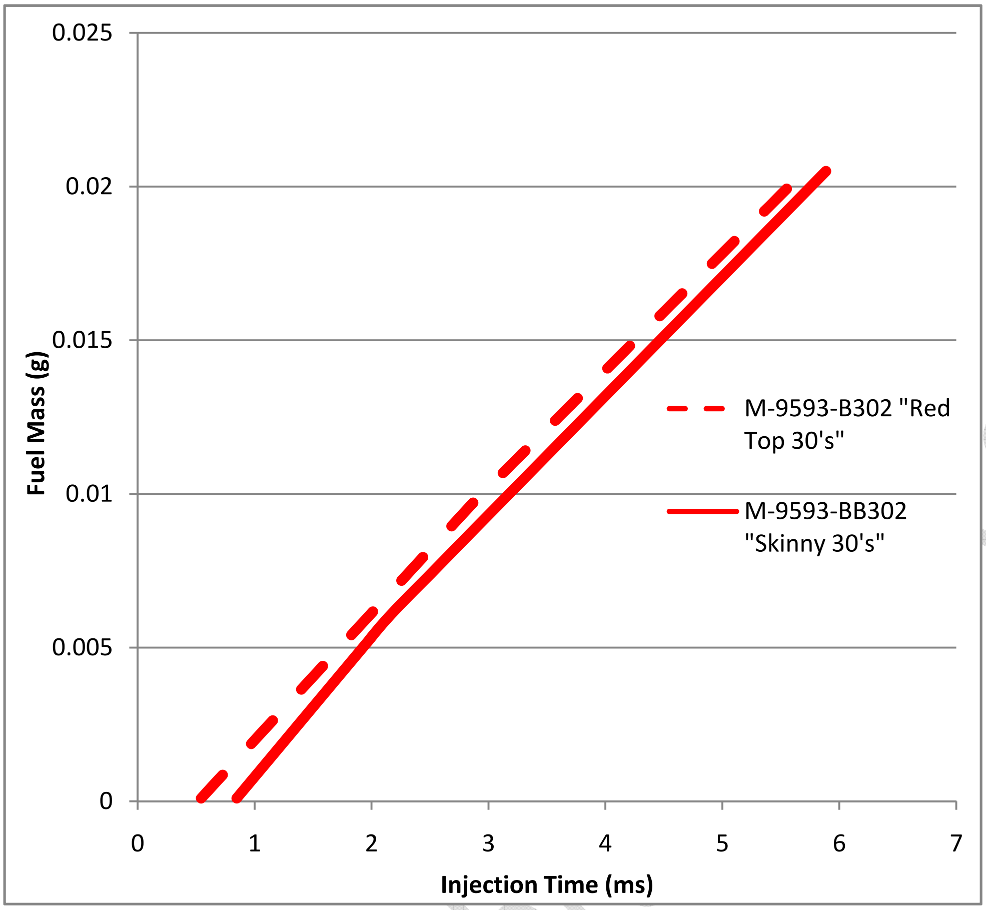
Are all "same size" injectors the same? In short, not a chance.

There are many different injector manufacturers out there that all make injectors with similar flow rates. Even within some injector manufacturers' offerings, there may be two different variants of a "24#/hr injector" or "30#/hr injector." For the purposes of this article, I've dug into a handful of Bosch fuel injectors that have had their data publically posted on the Ford Racing Performance Parts website. (www.fordracingparts.com) The fine folks at Ford were nice enough to provide us with very detailed analyses of each injector's behavior with respect to opening time, voltage dependency, non-linear flow characteristics and pressure dependencies. Their "Calibration Summary" sheets contain all of this critical information for each unique injector design. The data in these calibration summary reports are the exact values that get entered into one of their PCMs to allow the controller to precisely turn a fuel mass request into the right injector "on time" to deliver that specific fuel mass. It's a critical step in making sure the PCM can accurately deliver the commanded air/fuel ratio.

Using the data provided by an OEM test lab, we can plot the fuel mass delivered versus injection time for each injector. At right, we see what the traditional "Blue Top" 24#/hr injectors look like alongside the "Red Top" 30#/hr injectors when operated at the normal Ford fuel pressure rating of 39.15psi gauge pressure. Notice how the higher flow rate of the "Red Top" injectors requires less time to deliver the same fuel mass to the cylinder. The slope of each line is defined by high school geometry as rise over run, in our case here that's mass over time. This is where we get the "injector slope" value of grams per second or pounds per hour. The 30#/hr injector has a steeper slope as can be clearly seen in this graph. There is also a small delay before the



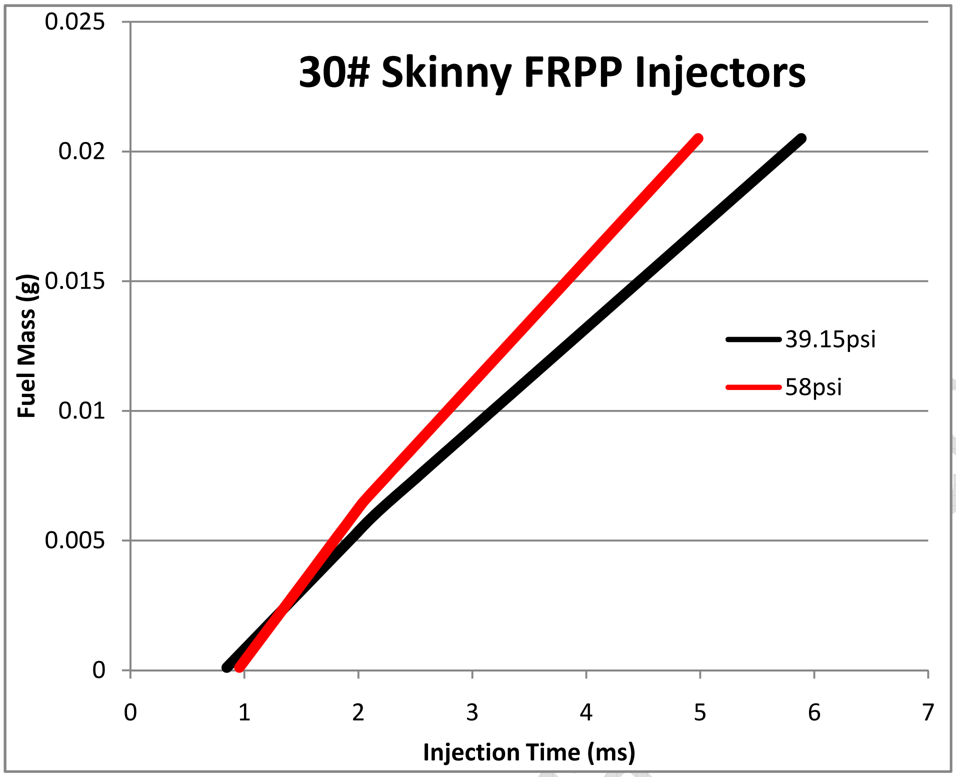
injector opens at all and fuel can begin to flow. A more careful look also shows how that the slope changes slightly with time for both injectors. This is a result of the non-linear flow of fuel through the holes in the injector. More on this later…



Next we see two different versions of the Ford Motorsport "30#/hr" fuel injectors, both manufactured by Bosch. The "Red Top" is the older fat body version and the "skinny" is the newer part that has superseded it. Both injectors flow almost identically at pulsewidths above 2ms, and therefore the slopes of the two lines are parallel on the high end. The big difference here is that the opening delay between the two different injector body designs, with the older design actually opening slightly quicker. Below 2ms, we also see the difference in slopes that results in a noticeable difference in injection time required to deliver the same fuel mass. If the PCM thinks it has the "Red Top" injectors on the engine, but we really have the "skinny 30's" installed, a calculated fuel mass of 0.010g would work out to a predicted injection pulse of about 2.9ms. If we travel along the solid line that represents the skinny injectors that are really installed, we see that 2.9ms of injection time only gets us 0.0088g of fuel, 12% less that the PCM thinks is really being added. This 12% error means that the engine would operate at an air/fuel ratio of 16.6:1 instead of our usual target of 14.64:1 unless some other correction was active. The inexperienced tuner simply makes a 12% adjustment to either the MAF or VE airflow tables to bring the engine back to the target of 14.64:1. This works for correcting the air/fuel ratio at this exact condition (engine temp, air temp, airflow rate, and fuel flow rate), but it's based on a bad assumption for fuel delivery. The result is an air mass calculation that's 12% off all the time. This 12% airmass error can get carried over to the idle control strategy, making it that much more difficult for the PCM to precisely control idle speed with the IAC motor or electronic throttle control system. The proper solution here is to tell the PCM the new injector characteristics that will result in an injection time of 3.1ms in order to deliver the fuel mass target of 0.010g to the cylinder. This means giving the PCM more info than just the offset and linear flow rate.

This starts to get more interesting as we note the typical idle pulsewidth of 2ms or less for this injector on a warm engine. The "bigger" the injector, the more likelihood that the PCM will command a pulsewidth this small at idle or light cruising where this nonlinear behavior plays a big role in the actual fuel mass delivered to the engine. Properly modeling the small nonlinear region of flow can be critical to getting the right fuel mass delivery at idle and cruise, even with two "same flow rate" injectors.

We just looked at two well documented injectors where an OEM's scientific flow lab has properly characterized thousands of each injector to come up with the data presented in the calibration summary sheets. It's just not possible to see the whole story if all you're given is a linear flow rate and turn on time like many internet retailers supply. If you have a set of modified injectors that have been resized or redrilled, you're on your own to guess at what these specs may be, but it's safe to say that we can't simply assume they'll be the "same as the stock injector."

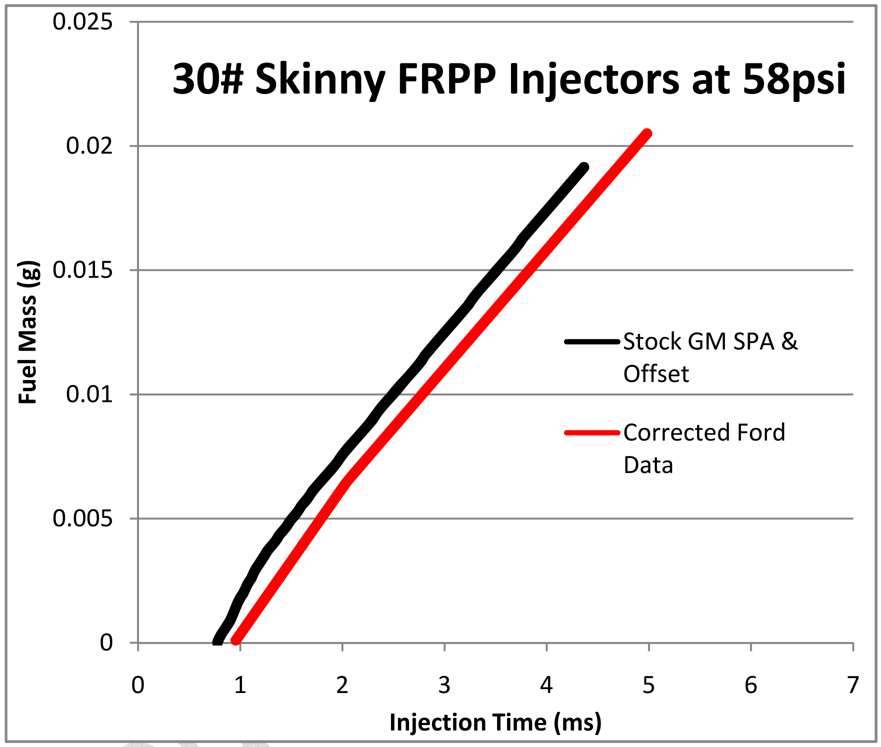


But what about running a fuel injector at higher rail pressure? It's well known that the linear flow rate of an injector is increased as the pressure across that injector is raised. Many amateur (and some professional) tuners wisely correct for this change using the Bernoulli equation (the flow rate increases with the square root of the pressure ratio), but unfortunately stop cold there. The truth is that the increase in pressure also affects the both the opening delay and the nonlinear flow region of injection. In the case of the "skinny 30#" Ford/Bosch injectors, we see that increasing the rail pressure adds slightly to the opening delay but raises the slope (flow rate) at both small and large pulses. The point at which the slope changes (the limit of the nonlinear region) even shifts slightly due to the pressure. Again, the Ford calibration summary sheet clearly spells this out, so it's important to heed their data unless you've got something more accurate. (Good luck!)

Done right, there's no reason why the fuel pressure can't be raised to increase injector flow rate while still maintaining excellent control over the delivered fuel mass and overall air/fuel ratio. In fact, some of the Roush and Ford Racing supercharger kits have used this trick of increasing fuel pressure to gain additional flow through the stock injectors as long as the fuel pump can keep up. They have adjusted both the linear flow rate (high slope in Ford-speak) and nonlinear characteristics (low slope, breakpoint, and offset) to compensate for this change in working pressure while still maintaining tight enough air/fuel ratio control to pass federal emissions standards.

What about putting Ford injectors on a GM vehicle? It's a mechanical fit that's easy to make, with only a wiring connector change or fuel rail spacer required in some cases. The trick is that GM and Ford have different ways of describing the same physics and nonlinear flow characteristic of the same injector. The injector offset can be described as either the intercept of the high slope with zero fuel mass or as the point at which the injector really opens (where the low slope intercepts zero fuel mass). Similarly, GM also uses a short pulse adjustment to make up for the lack of a second injector slope at low masses. Both strategies get the same job done and allow the PCM to properly meter fuel at small pulses in the nonlinear flow region of the injector's capacity. Translating from Ford to GM units and tables can be a bit tedious, but it's necessary if you want to get idle airflow estimates right when calibrating for MAF or VE using a wideband.

So how bad is it if we ignore the shift in offset and nonlinear modeling when changing pressure? I did the math both ways to generate the mass vs. time curves that result from simply replacing the linear injector flow rate in a GM application with a pressure corrected flow rate without changing the nonlinear compensation tables. GM uses a slightly different definition of *offset* than Ford and a *short pulse adjustment/adder table* to replace the *low slope* and *breakpoint* that Ford uses to describe the nonlinear flow region. If I keep the stock short pulse adjustment and offset tables, but swap the injector flow rate, I end up with a different flow vs. time curve for fuel delivery to the engine. I plotted the results of this half-tuned injector behavior against the Ford-supplied data at the elevated pressure. Right away, we see that the offset isn't the same between the reference GM injector (another Bosch 28#/hr injector in this case) and our corrected Ford/Bosch injector at 58psi. This fixed time offset difference is carried across the whole injection time range and results in significant differences in delivered fuel mass at low pulsewidths and still a noticeable shift at the upper end. Below 2ms we also see that the nonlinear flow region is mismatched. The real solution here will be to knuckle down and do the homework to convert the known good Ford data into GM units so that the PCM can accurately deliver the proper fuel mass.



Remember that any time you adjust the MAF or VE tables based on wideband error, your making the assumption that fuel delivery commanded by the PCM closely matches what's really going into the engine. What good is all of the work to perfect a VE table or MAF transfer function if the fuel injector delivery is wrong? Even worse, what if we make the mistake of assuming that the injectors behave one way when they're really doing something else? The result is a false confidence in whatever airflow corrections were made during the calibration process. This bad airflow estimate may be cascaded into other tables such as idle control or spark advance since they're ultimately dependent upon airflow calculations as well.

So what have we learned from this exercise?

- Injectors have nonlinear behavior at short pulses; this requires some additional data to properly tune the PCM.
- The data that describes the nonlinear behavior is not the same for similar flow rate injectors.
- The data that describes the nonlinear behavior is not the same for similar body size injectors.
- Errors in the injector characterization will show up in the calculated airflow tables and create headaches later.

Those looking to learn more about proper injector, MAF and VE calibration can attend one of my Advanced GM or Ford training classes with Calibrated Success, Inc. These courses take a close look at how each PCM comes up with its desired injection times based on airmass estimates and how we can properly tune these values just like an OEM calibration engineer to get stock like performance even with a supercharger, large injectors or a big camshaft. ~Greg