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Useless Theory and Boring Math

A detailed look at "Data" for a Common 1000cc Injector

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Several retailers offer the Bosch "117" 48mm injector that is rated to flow "1000cc/min". Among these is one of my engineering clients, Fuel Injector Connection out of Cumming, GA. They had been selling this injector along with "data" that was derived from in-vehicle adjustments by one of their dealers, with some degree of success. As expected, this data got them close, but never really right on the money for true injector characterization. You see, the problem is that it's really not possible to eliminate all the noise factors on a running engine and look exclusively at the fuel injector's performance. Any adjustments made as a result of lambda measurements also depend heavily upon things like combustion instability, incomplete mixing, MAF/MAP/IAT/UEGO sensor errors, accuracy of the airflow model(s), fuel chemistry variation, AND the injector variables themselves of flow rate, offset vs pressure and voltage, and nonlinearity compensations.

$$10 = 3 + X + Y$$ ← *solve for X*

Some of you might recall high school algebra where we had to "solve for X" in a single equation. Whenever we did this, there would only be one unknown, the "X". If you had two unknowns, you needed two equations to find both "X" and "Y" to avoid getting one of multiple possible sets of answers. Yes, your answer for "X" may work in the one case you see, but if the "Y" changes, your value for "X" may prove wrong. Looking at the list of possible noise factors above, we easily have up to 11 variables for the single equation. In short, trying to accurately find the right values for injector flow rate, offsets, and short pulse correction on a running engine is an almost impossible task.

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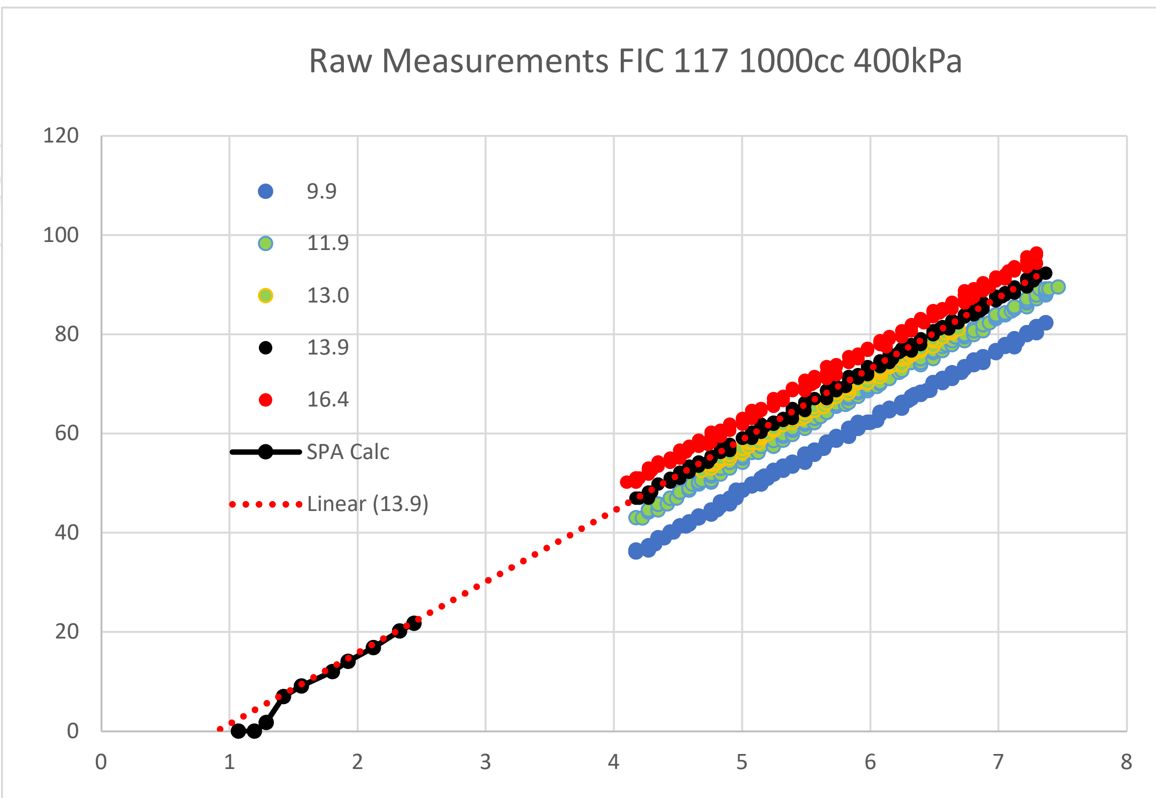
Coming from an OEM background, I looked at what happens there and applied it to the performance aftermarket. OEM calibration engineers do not guess about fuel delivery. Instead, they get exact characterization values from the fuel injector Design and Release Engineer (DRE) before they begin engine testing. The DRE gets these numbers from an offline test bench that only tests the fuel injectors themselves without an engine. The bench is capable of driving the fuel injectors at any combination of voltage, pressure, and pulsewidth in order to draw a complete picture of the relationship between on-time and how much fuel would be delivered. The accuracy of this data is also crucial, so filling and dumping burettes after measuring by eye would be laughable if one wanted data that was within less than a few percent error. Certified laboratory grade flow meters are the norm here for OEM labs. Now you know why I made my own fuel injector test benches. Once we have established that we can accurately measure injector flow at any given point, we can proceed to solving for calibration table values for all the various vehicle manufacturers' models.



Finding the flow rate is easy here, we just look at the slope of the lines measured in milligrams or cc's over milliseconds. Each colored string of data conveniently has almost exactly the same slope, with an offset that moves with activation voltage. This confirms that our basic slope calculation was correct, while letting us draw a clean relationship across voltages. It also exposes the non-linear region immediately after opening that is unique to this injector tip design. That gap between the dotted linear model and black actual measurement can be very important at idle and cruise where fuel mass requirements are small enough to require such short opening events.

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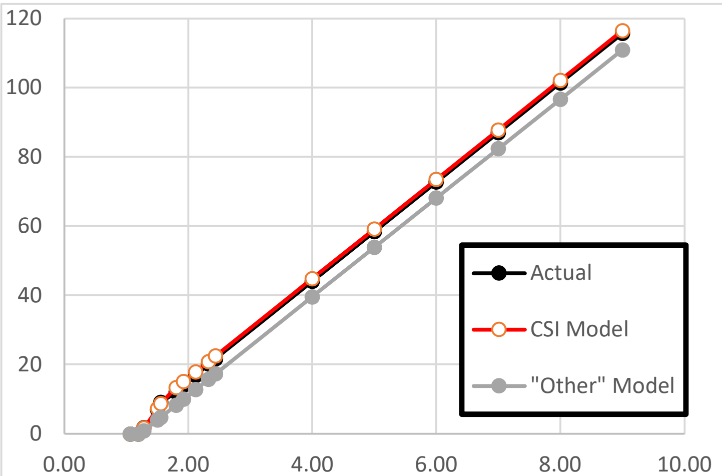
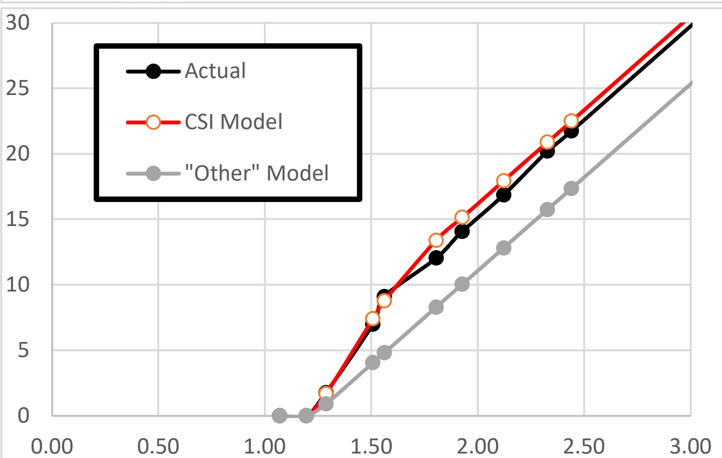
Great, so now we finally have a raw flow measurement that we trust. Now what?

Now, the trick is to regress that data to fit the method and breakpoints used by the various OEM controllers. By plotting the actual measurements against our newly modeled calibration values, we can see how closely our values line up with the real world. It also lets us compare others' modeled values to our actual measurements to see their errors as well. No OEM model is expected to be a perfect fit, but some are definitely closer than others. For the purposes of this comparison, we'll take a look at two different data sets for the same injector that were modeled in the Ford two slope method to see their residual errors between theoretical and actual fuel delivery.



First, we'll look at the big picture, delivered mass vs pulse width over a large range. At a glance, both models appear to follow the actual measurement's slope, but the "Other" shows an incorrect offset that originates in the non-linear zone below 2ms. Slope is easy to get, it's just mass or volume over time. Properly calculating the offset and short pulse behavior requires more precision from proper test methods and instrumentation.



Zooming in, the differences become more clear. Where the CSI Model closely approximates the nonlinear behavior, the "Other" model completely misses this behavior. The result is large errors in delivered fuel mass at short pulse widths. These errors will get "baked in" to any airflow model work on the MAF or speed density surfaces. Worse, they will make the torque models equally wrong, often leading to throttle control and transmission issues as well.

By looking at the residual error %, we can see just how far off these values were for each model. Where the CSI model was inside of 10% error for all but one point, the "Other" model shows large areas with well over 20% error. Worse, these are right in the "driveability zone" where AFR and torque errors will be the biggest headache. Their 4% error up top would likely just get lost in MAF error.

Actual		CSI Model			"Other" Model		
PW	mg/shot	mg/shot	Ri	%	mg/shot	Ri	%
1.07	0	0	0	0.0%	0	0	0.0%
1.20	0	0	0	0.0%	0	0	0.0%
1.29	1.76675	1.68868	-0.07807	-4.4%	0.91318	-0.85357	-48.3%
1.51	7.00057	7.4018	0.40123	5.7%	4.05473	-2.94584	-42.1%
1.56	9.1051	8.78194	-0.32316	-3.5%	4.81365	-4.29145	-47.1%
1.81	12.0474	13.4004	1.35299	11.2%	8.29813	-3.74926	-31.1%
1.93	14.0784	15.1487	1.07025	7.6%	10.0388	-4.03966	-28.7%
2.12	16.8654	17.9431	1.07765	6.4%	12.8209	-4.04451	-24.0%
2.33	20.2191	20.8865	0.6674	3.3%	15.7515	-4.46765	-22.1%
2.44	21.7509	22.5001	0.74918	3.4%	17.358	-4.39294	-20.2%
4.00	44.1061	44.8553	0.74918	1.7%	39.6152	-4.49087	-10.2%
5.00	58.4363	59.1855	0.74918	1.3%	53.8827	-4.55366	-7.8%
6.00	72.7666	73.5158	0.74918	1.0%	68.1502	-4.61644	-6.3%
7.00	87.0968	87.846	0.74918	0.9%	82.4176	-4.67922	-5.4%
8.00	101.427	102.176	0.74918	0.7%	96.6851	-4.742	-4.7%
9.00	115.757	116.507	0.74918	0.6%	110.953	-4.80478	-4.2%

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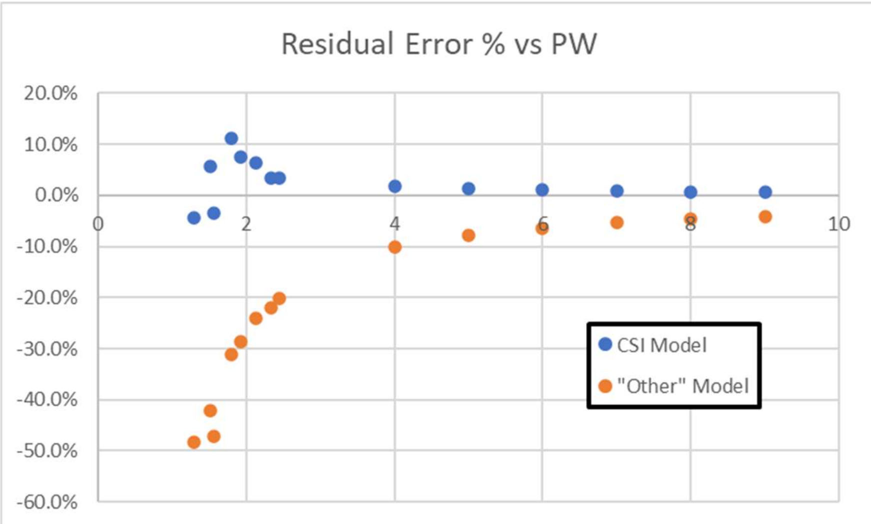
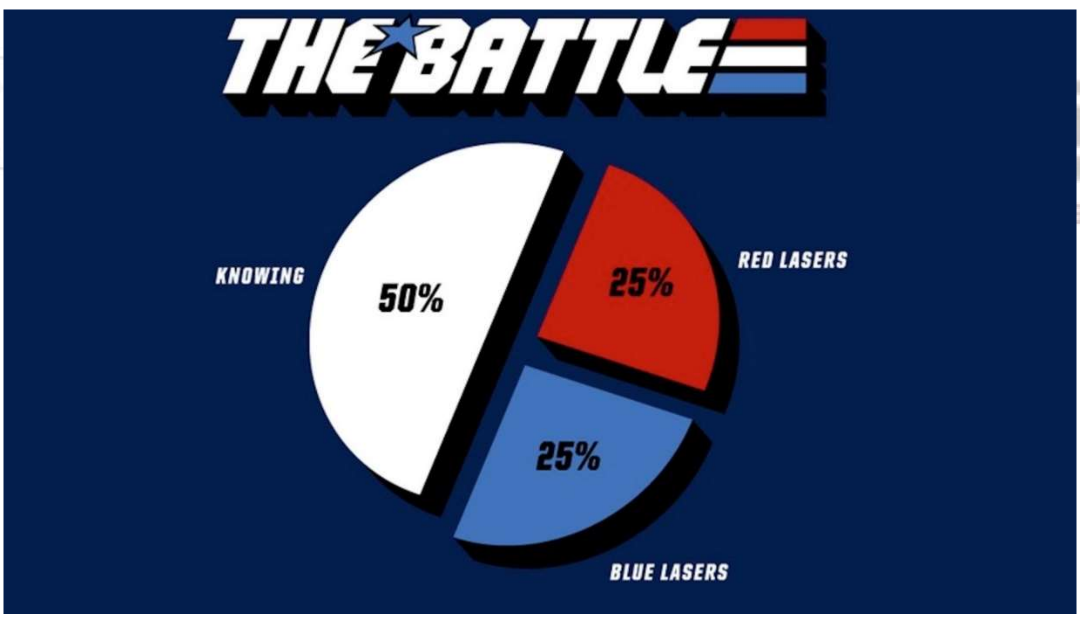


So here we are with two sets of “Data” for the same part number. Sure, there’s going to be some variation from set to set. We expect about +/-6% across the population in the OEM world. Anything more than that is usually either bad parts, bad data or a combination of the two. Because we started with a laboratory grade measurement, we believe the raw numbers. We honestly don’t expect too much variation between one set of undrilled “Bosch 117 1000’s” and another. +/-3% might about the most we’d see, especially if we are averaging the flow of multiple injectors together into a single average data set. Where things got messy was how two different groups normalized that data to the ECU model breakpoints. Without pointing any fingers, all I can say is that Calibrated Success follows the same math used by the OEM in deriving the calibration values from the raw data. We have found that following these procedures results in data that thousands of our customers have found to be exceptionally accurate for the injectors in question.



If you are looking to have a set tested, or would like to enquire about getting your own Calibrated Success fuel injector test bench that can create accurate plug and play data on demand, please contact me directly: greg@calibratedsuccess.com

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