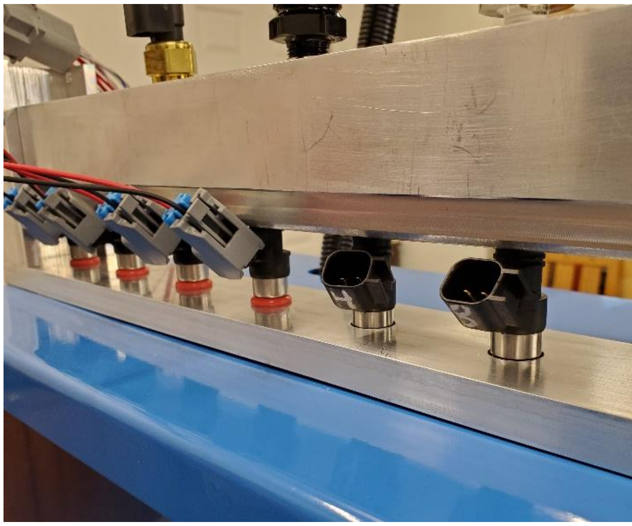
The Best Tuning Cheat Code Out There

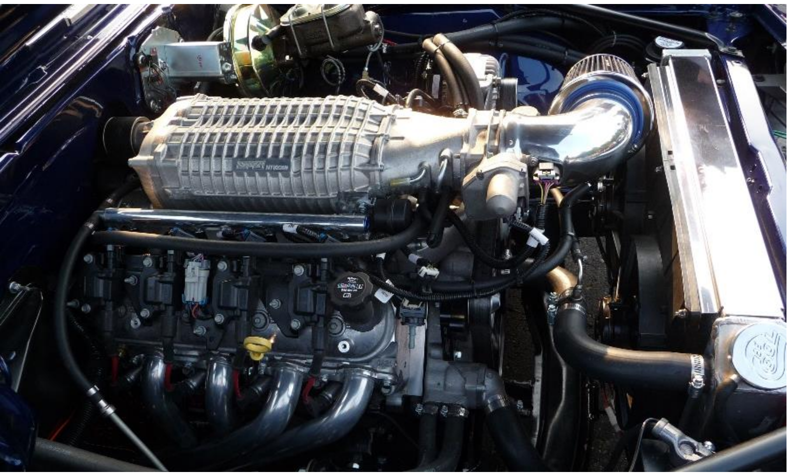
Greg Banish



Pssst! Hey kid, want to know how to dominate this whole engine tuning game? I've got a secret I want to share with you that will show you how some of the pros make engine tuning look so easy.

It's safe to say that performance enthusiasts have embraced electronic fuel injection. That's not to say that carburetors can't do the job, but Detroit hasn't rolled a new one off the production vehicle assembly line in almost 40 years. In that time, we have seen the evolution of EFI systems move from crude to precise in their control of fuel metering and ultimately the air-fuel ratio seen by the spark plug in the cylinders.

The fuel injectors themselves have also evolved. Not only has their physical size diminished enough to allow some very creative placement options in our intakes, manufacturers offer flow rates that allow us to make amazing amounts of horsepower with just a single injector per cylinder. I fondly remember my early days of playing with fuel injection in the late 90's where a 42 lb/hr (roughly 440cc/min) injector flow rate was considered "big." I have more recently tested direct replacement options for many port injection applications that deliver over 286 lb/hr (3000cc/min) depending upon the pressure being used.



Supercharging means the engine needs a lot more fuel from the injectors. Starting with the right injectors and data can make the tuning process much easier.

We all know that more airflow equals more power from our engines, and whenever we add more air, we need to add more fuel too. At the outset of a project, we like to run the math and figure out just how big our fuel injectors will need to be in order to support our target horsepower level. We basically take the desired horsepower and multiply it by an estimated BSFC (Brake Specific Fuel Consumption) number to get total fuel flow. We can then divide this by the number of injectors in the system, usually one per cylinder, and get a minimum injector flow rate. Finally, we throw in a safety factor of about 20% to make sure we don't need to run the injectors completely static to satisfy the engine's needs. We want to give each injector enough time to flow the necessary fuel, close completely, and reopen for the next shot after a brief pause. This also give the injector drivers inside the ECU a chance to cool a bit. It ends up looking something like this:

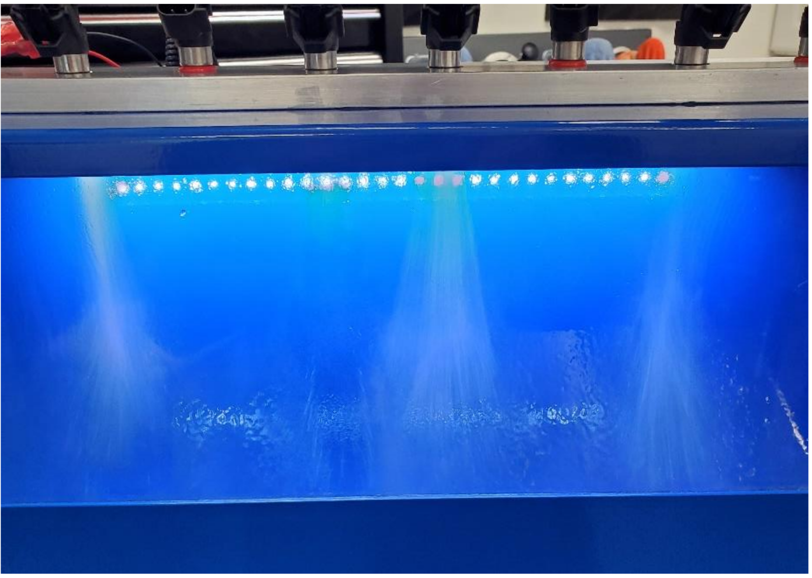
Total Fuel Flow (lb/hr) = *Target Horsepower* (hp) * *BSFC* (lb/hp-hr)

Minimum Injector Flow (lb/hr) = *Total Fuel Flow* (lb/hr) / *# of Injectors*

Safe Injector Flow Rate (lb/hr) = *Minimum Injector Flow* (lb/hr) * *1.20*

For a 600hp supercharged engine, we would take a safe BSFC estimate of 0.6 lb/hp-hr to get a total fuel flow of 360 lb/hr for the system. On a V8 engine, we would need a minimum injector flow rate of about 45 lb/hr. After applying a safety factor of 20%, the real number becomes more like 54 lb/hr for each injector. This is where more people start shopping for injectors.

Of course, we need injectors that physically fit our engine, fuel rail, and connector type. Almost all modern vehicles use high impedance (12-16ohm) injectors with their stock ECU today. There used to be a time when we needed to look at low impedance (2-6ohm) injectors in order to find a high enough flow rate, but we couldn't simply plug them into an ECU that is designed for the higher impedance. Doing so would risk pulling too much current through the drivers that might damage the ECU itself. Today's market is flush with great high impedance options that flow just about whatever we need without endangering the electronics.



There's more to injectors than just a static flow rate. Testing them across a wide range of pulse widths exposes some interesting information that the ECU needs for complete control.

Here's where we start running into problems from a tuning perspective. If we simply grab a random set of injectors with some flow rate and try to make the EFI system work properly by only changing the flow rate in the calibration, we get mixed results at best. If we jumped right to the dyno and started running WOT power pulls all the way to redline, this might work because we begin to approach constant flow out of the injectors. Unfortunately, we can have very different results at idle and part throttle. The reason for this lies in the science of how a fuel injector really works. We can only see that when we take the injectors off the running engine and test them on their own.

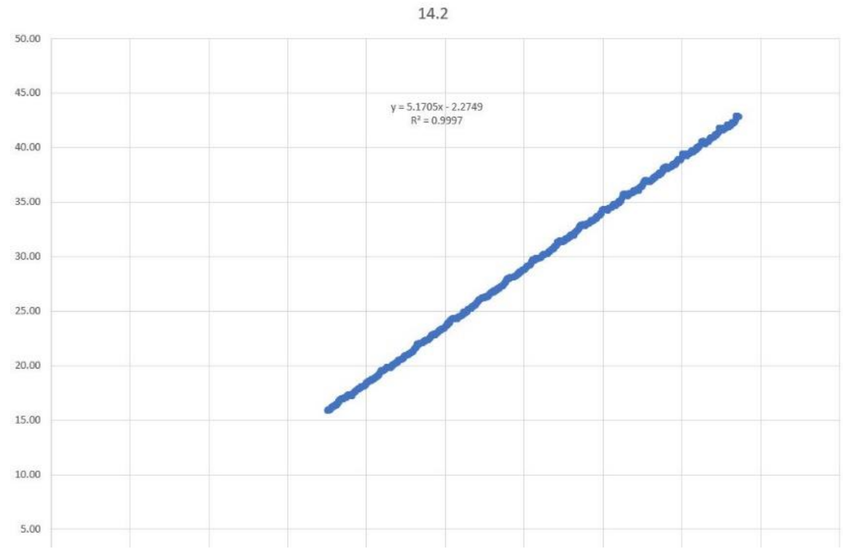
Measuring that behavior requires some specialized equipment that you don't see in every shop today. OEMs use benches especially made for the task costing hundreds of thousands of dollars. The garden variety "clean and flow" benches are not capable of running the necessary tests to get all of this data. Calibrated Success stepped up to the challenge and [made a new unit from scratch] that is capable of running the right test conditions and records the data with enough precision to detect things that are missed in cheap benches at a price that doesn't break the bank for most professional tuning shops. The raw data is processed using an online tool that can deliver results in just minutes any time day or night. For those just looking to have one set measured, they do that in house too.

So, what does "complete" injector data really include?

The Calibrated Success Fuel Injector Characterization Bench is now available to shop owners who wish to generate their own complete data sets in just minutes. It lets them create information specific that exact set of injectors rather than just generic data.

Slope

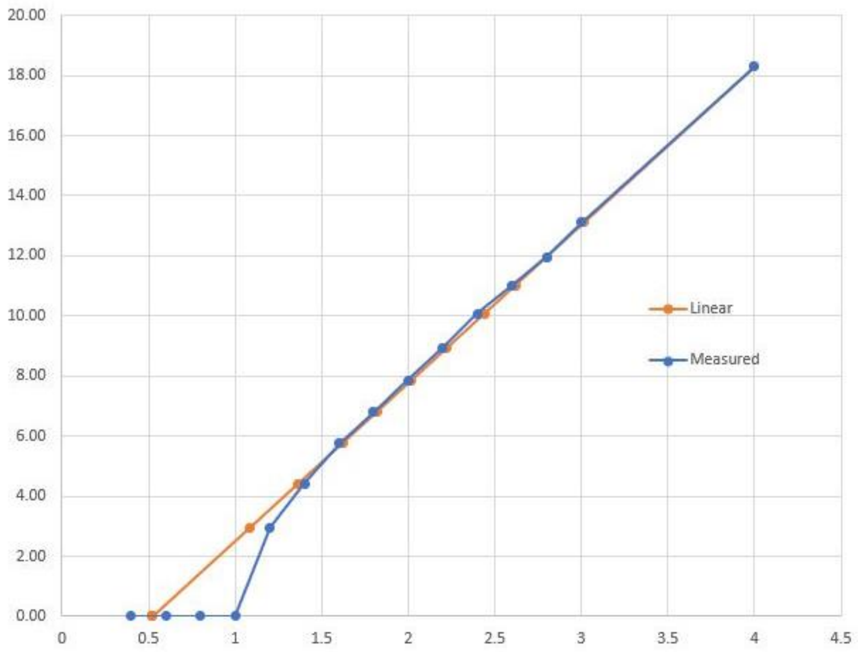
If we run a complete set of tests on just the fuel injector outside of the engine, we can spot a few interesting things. The first is that the linear relationship between delivered fuel mass and pulse width. The longer the injector is open, the more accumulated mass we have. The slope of this line can be measured in mass (milligrams, grams, or pounds) divided by the time (milliseconds, seconds, or hours) that closely matches the advertised flow rate of the injector. Some injector companies simply flow the injectors wide open for some period of time and measure the total delivered fluid, but this static flow measurement isn't exactly what's happening in our engines. Measuring the slope of the line from a series of shorter pulses is more precise.



By taking thousands of data points, a clear linear pattern is found. This reduces the chances of a single data point inducing any significant error.

Nonlinearity

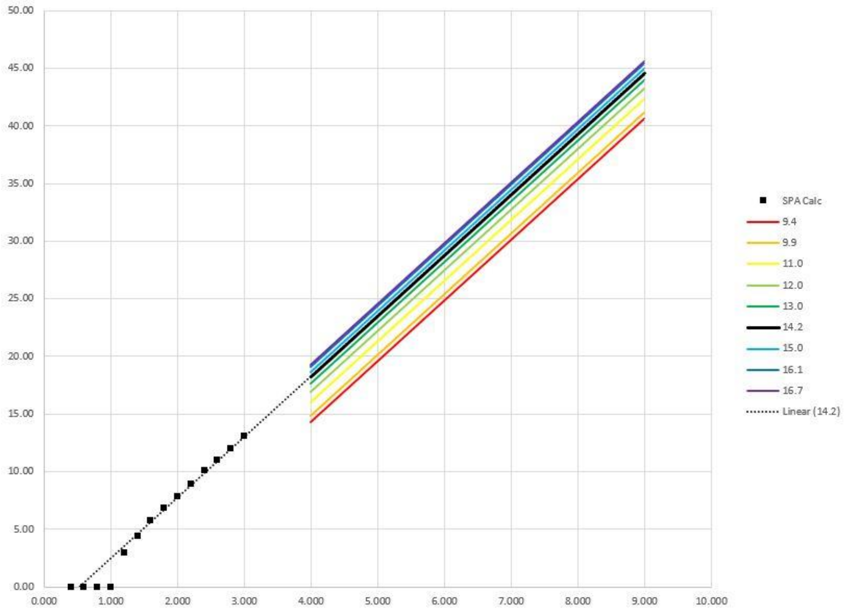
We can also see that this straight line isn't exactly straight when we look close to the bottom. Instead, we see that after a brief pause (more on this in a minute), the instantaneous flow delivered by the injector (slope) is steeper down low before it settles into a more stable linear flow after a few milliseconds. It's the same principle that we see when washing our car in the driveway with a hose. When we first open the valve, water sprays further with more intensity for a second before it settles into the normal flow rate. This is happening every time the fuel injector opens too. The exact shape of this different behavior relative to the straight line we get up top is unique to that particular injector design. Testing on a proper flow bench is able to reveal this nonlinearity if we can collect enough accurate data during these very short pulse widths. The difference between the simple straight line and this actual nonlinear delivery can make for 40% or more error if we were to ignore it.



Looking at individual measurements from a series of very short pulses shows the nonlinear behavior as the fuel injector just begins to flow.

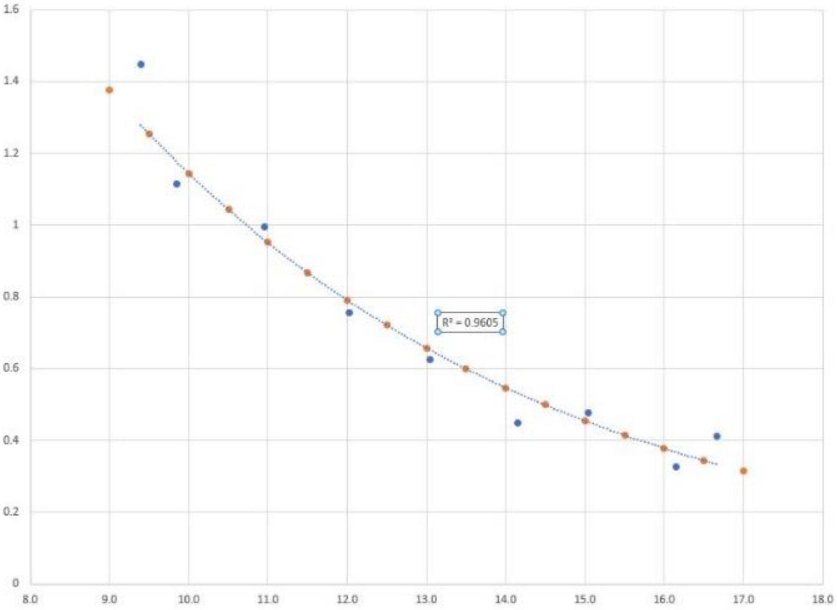
Offset

Finally, by plotting the response across time for a number of different activation voltages, we see that the location of our straight lines can shift. Fuel injectors contain electrical coils that are charged by vehicle operating voltage. There is a delay in opening the solenoid that is proportional to the voltage applied. The lower voltage samples have everything delayed more before they eventually open and begin flowing at the same slope. Higher voltages are able to open the injector in less time, moving their lines to the left.



Plotting several sweeps at different voltages together shows how the offset moves but slope stays the same.

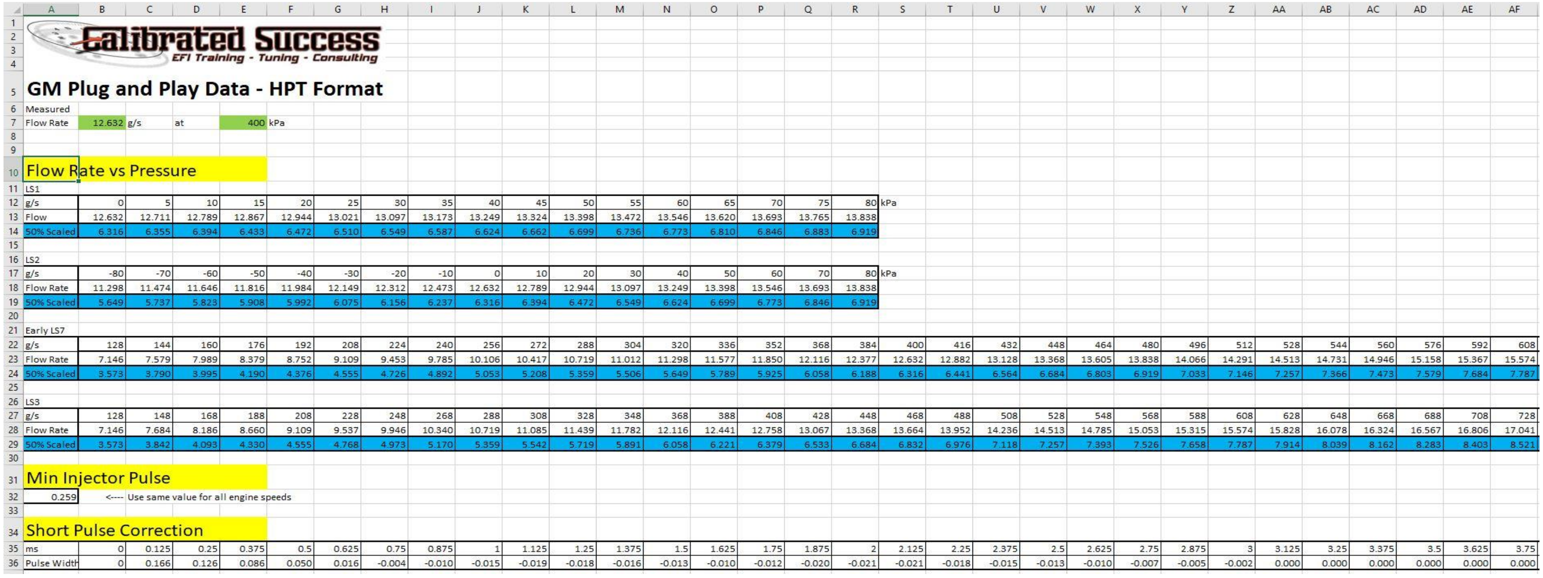
If we plot the X-axis intercept (commonly called the "offset") of these lines against the voltage used to create them, we discover the relationship at work here. In a perfect world all points would fall right on a curve, but the reality of taking data means we always have small amounts of error. The shape of this curve is again unique to the injector design. It actually incorporates both the electrical delay from the coil and the fluid dynamics delay as fuel moves through the body, valve, and tip of the injector. Any modification to the injector tip can change this offset just as much as the linear flow rate. Whenever we are attempting to deliver small amounts of fuel, like idle or when cruising, this offset value can be a large portion of the total injector pulse width from the ECU. Even if we have the right slope, errors in this offset can have the delivered fueling off by enough to flood or starve the engine.



If we plot how the offset moves vs voltage, we can see another clear relationship. Curve fitting is best here so any one data point doesn't force an unrealistic curve.

Bringing It All Together

OEMs are pretty smart. They know how their fuel injectors work too and they added a few extra tables in the ECU to help account for the different variables. Almost all ECUs, even aftermarket standalones, will let us enter the linear injector flow rate. This should match the slope of the line we saw earlier. They'll also let us enter numbers for offset as a function of voltage. Be careful here, as different OEMs will often define the "offset" differently, depending upon how they hand the rest of the nonlinear compensation. We can't always take the published offset value from one manufacturer and use it in another's ECU without baking in some more error. And finally, they may also have a separate function to define the nonlinearity of low flow requests. In an effort to avoid stepping on each other's patents, and probably a need to prove that their software team is smart too, each manufacturer has their own way of modeling this inside their ECU.



Calibrated Success
EFI Training - Tuning - Consulting

GM Plug and Play Data - HPT Format

Measured
Flow Rate 12.632 g/s at 400 kPa

Flow Rate vs Pressure

LS1

g/s	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	kPa
Flow	12.632	12.711	12.789	12.867	12.944	13.021	13.097	13.173	13.249	13.324	13.398	13.472	13.546	13.620	13.693	13.765	13.838	
50% Scaled	6.316	6.355	6.394	6.433	6.472	6.510	6.549	6.587	6.624	6.662	6.699	6.736	6.773	6.810	6.846	6.883	6.919	

LS2

g/s	-80	-70	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	kPa
Flow Rate	11.298	11.474	11.646	11.816	11.984	12.149	12.312	12.473	12.632	12.789	12.944	13.097	13.249	13.398	13.546	13.693	13.838	
50% Scaled	5.649	5.737	5.823	5.908	5.992	6.075	6.156	6.237	6.316	6.394	6.472	6.549	6.624	6.699	6.773	6.846	6.919	

Early LS7

g/s	128	144	160	176	192	208	224	240	256	272	288	304	320	336	352	368	384	400	416	432	448	464	480	496	512	528	544	560	576	592	608
Flow Rate	7.146	7.579	7.989	8.379	8.752	9.109	9.453	9.785	10.106	10.417	10.719	11.012	11.298	11.577	11.850	12.116	12.377	12.632	12.882	13.128	13.368	13.605	13.838	14.066	14.291	14.513	14.731	14.946	15.158	15.367	15.574
50% Scaled	3.573	3.790	3.995	4.190	4.376	4.555	4.726	4.892	5.053	5.208	5.359	5.506	5.649	5.789	5.925	6.058	6.188	6.316	6.441	6.564	6.684	6.803	6.919	7.033	7.146	7.257	7.366	7.473	7.579	7.684	7.787

LS3

g/s	128	148	168	188	208	228	248	268	288	308	328	348	368	388	408	428	448	468	488	508	528	548	568	588	608	628	648	668	688	708	728
Flow Rate	7.146	7.684	8.186	8.660	9.109	9.537	9.946	10.340	10.719	11.085	11.439	11.782	12.116	12.441	12.758	13.067	13.368	13.664	13.952	14.236	14.513	14.785	15.053	15.315	15.574	15.828	16.078	16.324	16.567	16.806	17.041
50% Scaled	3.573	3.842	4.093	4.330	4.555	4.768	4.973	5.170	5.359	5.542	5.719	5.891	6.058	6.221	6.379	6.533	6.684	6.832	6.976	7.118	7.257	7.393	7.526	7.658	7.787	7.914	8.039	8.162	8.283	8.403	8.521

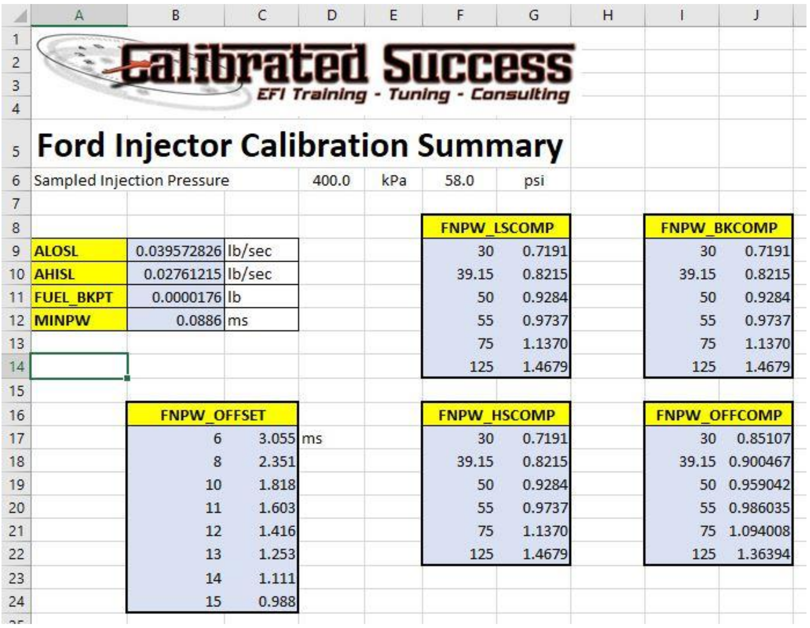
Min Injector Pulse

0.259 <---- Use same value for all engine speeds

Short Pulse Correction

ms	0	0.125	0.25	0.375	0.5	0.625	0.75	0.875	1	1.125	1.25	1.375	1.5	1.625	1.75	1.875	2	2.125	2.25	2.375	2.5	2.625	2.75	2.875	3	3.125	3.25	3.375	3.5	3.625	3.75
Pulse Width	0	0.166	0.126	0.086	0.050	0.016	-0.004	-0.010	-0.015	-0.019	-0.018	-0.016	-0.013	-0.010	-0.012	-0.020	-0.021	-0.021	-0.018	-0.015	-0.013	-0.010	-0.007	-0.005	-0.002	0.000	0.000	0.000	0.000	0.000	0.000

Here's an example of complete fuel injector characterization data in spreadsheet format for GM software. The user can simply copy and paste into their favorite tuning software.



Calibrated Success
EFI Training - Tuning - Consulting

Ford Injector Calibration Summary

Sampled Injection Pressure 400.0 kPa 58.0 psi

ALOSL	0.039572826	lb/sec
AHISL	0.02761215	lb/sec
FUEL_BKPT	0.0000176	lb
MINPW	0.0886	ms

FNPW_LSCOMP	
30	0.7191
39.15	0.8215
50	0.9284
55	0.9737
75	1.1370
125	1.4679

FNPW_BKCOMP	
30	0.7191
39.15	0.8215
50	0.9284
55	0.9737
75	1.1370
125	1.4679

FNPW_OFFSET		
6	3.055	ms
8	2.351	
10	1.818	
11	1.603	
12	1.416	
13	1.253	
14	1.111	
15	0.988	

FNPW_HSCOMP	
30	0.7191
39.15	0.8215
50	0.9284
55	0.9737
75	1.1370
125	1.4679

FNPW_OFFCOMP	
30	0.85107
39.15	0.900467
50	0.959042
55	0.986035
75	1.094008
125	1.36394

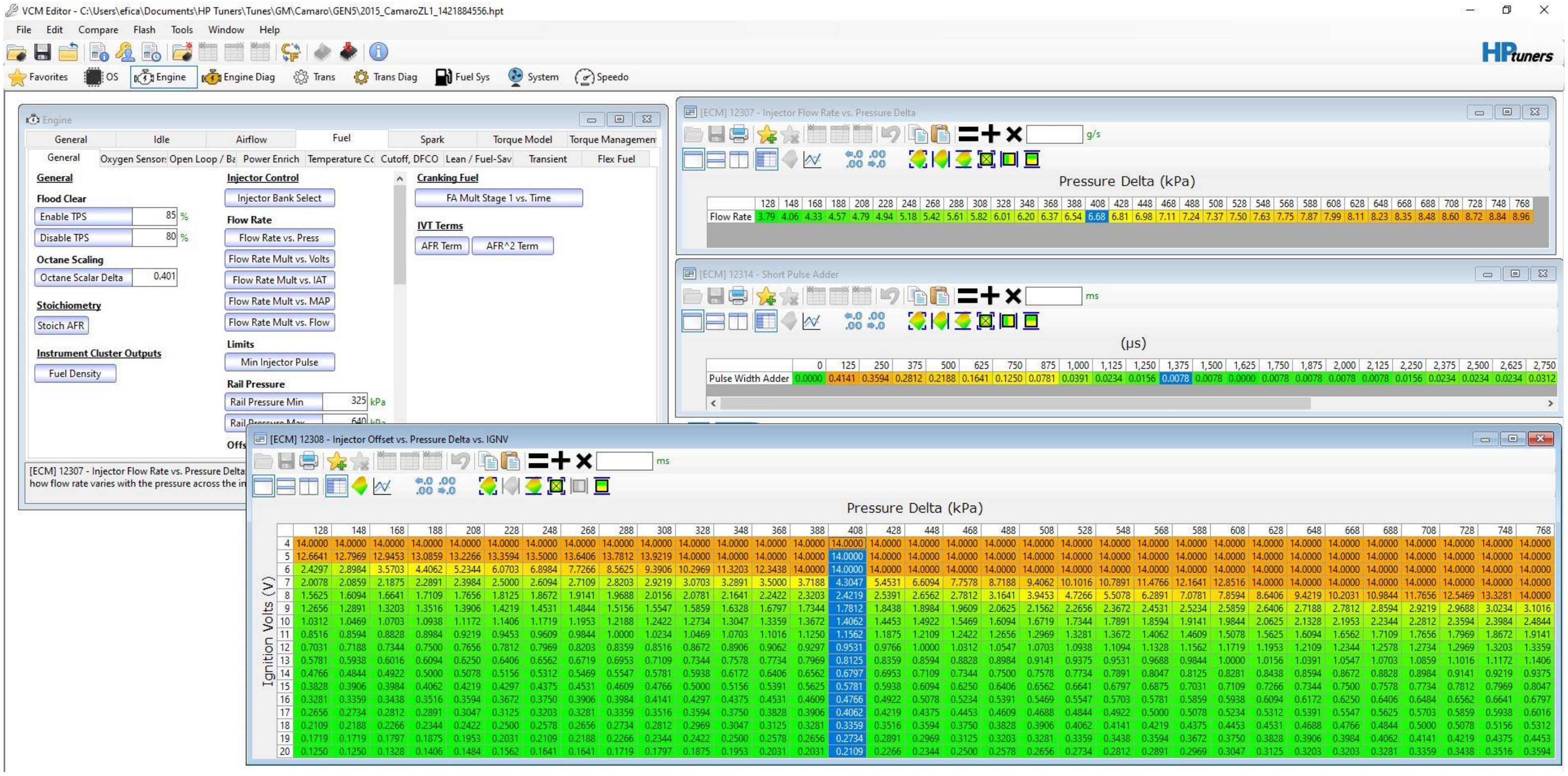
With the right calculations, raw injector measurements can be fitted to almost any OEM format. This is an example of Ford ECU inputs for a specific set of high flow injectors.

If we want to replace the OEM fuel injectors with new higher flowing units correctly, we're going to need ALL of this data too. If we only type in a new flow rate, we can have fits trying to get idle AFRs correct because the error could be coming from MAF/VE airflow, the offset, or the injector's short pulse nonlinearity. Remember high school math where we needed one equation for each unknown in a problem set? This is the real-world application of that.

Sure, we could assume or ignore a change in offset or nonlinearity, but we would be putting that unknown error into our VE or MAF calculations during the tuning process. When the weather changes or we hit a different operating condition, suddenly the AFR is way off again. This doesn't happen to pro tuners who are doing it right because they insist upon having complete injector data from the start.

↑↑↓↓←→←→ABBA

Here's where we enter the cheat code. There are just too many unknowns to derive the injector variables correctly on a running engine. Instead, we take a known dataset for the new injectors we are installing and copy/paste that data directly into the ECU before we ever start the engine. After we do this, it's safe to assume that any AFR error we measure going forward is from the ECU's airflow model. We just use the measured wideband error to make adjustments to the VE or MAF table accordingly.



Flood Clear
Enable TPS 85 %
Disable TPS 80 %

Octane Scaling
Octane Scalar Delta 0.401

Rail Pressure Min 325 kPa
Rail Pressure Max 640 kPa

[ECM] 12307 - Injector Flow Rate vs. Pressure Delta
how flow rate varies with the pressure across the in

[ECM] 12307 - Injector Flow Rate vs. Pressure Delta (g/s)

Pressure Delta (kPa)

	128	148	168	188	208	228	248	268	288	308	328	348	368	388	408	428	448	468	488	508	528	548	568	588	608	628	648	668	688	708	728	748	768
Flow Rate	3.79	4.06	4.33	4.57	4.79	4.94	5.18	5.42	5.61	5.82	6.01	6.20	6.37	6.54	6.68	6.81	6.98	7.11	7.24	7.37	7.50	7.63	7.75	7.87	7.99	8.11	8.23	8.35	8.48	8.60	8.72	8.84	8.96

[ECM] 12314 - Short Pulse Adder (ms)

(µs)

	0	125	250	375	500	625	750	875	1,000	1,125	1,250	1,375	1,500	1,625	1,750	1,875	2,000	2,125	2,250	2,375	2,500	2,625	2,750
Pulse Width Adder	0.0000	0.4141	0.3594	0.2812	0.2188	0.1641	0.1250	0.0781	0.0391	0.0234	0.0156	0.0078	0.0078	0.0000	0.0078	0.0078	0.0078	0.0078	0.0156	0.0234	0.0234	0.0234	0.0312

[ECM] 12308 - Injector Offset vs. Pressure Delta vs. IGNV (ms)

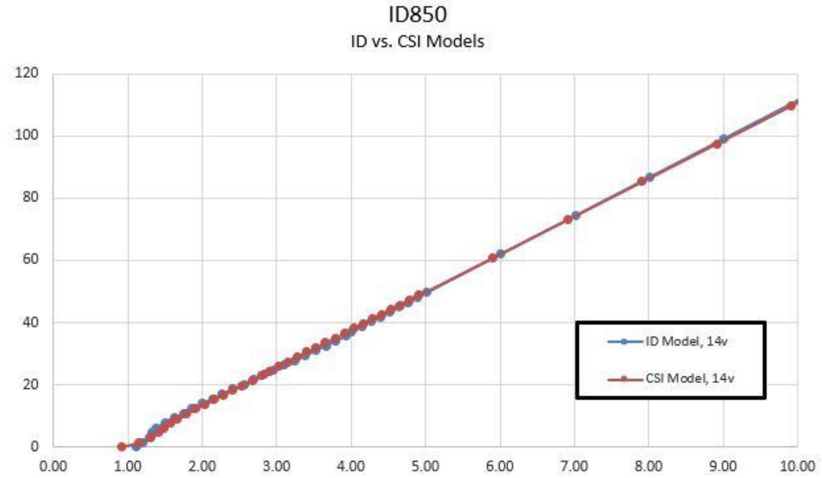
Pressure Delta (kPa)

Ignition Volts (V)	128	148	168	188	208	228	248	268	288	308	328
4	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000
5	12.6641	12.7969	12.9453	13.0859	13.2266	13.3594	13.5000	13.6406	13.7812	13.9219	14.0000
6	2.4297	2.8984	3.5703	4.4062	5.2344	6.0703	6.8984	7.7266	8.5625	9.3906	10.2969
7	2.0078	2.0859	2.1875	2.2891	2.3984	2.5000	2.6094	2.7109	2.8203	2.9219	3.0703
8	1.5625	1.6094	1.6641	1.7109	1.7656	1.8125	1.8672	1.9141	1.9688	2.0156	2.0781
9	1.2656	1.2891	1.3203	1.3516	1.3906	1.4219	1.4531	1.4844	1.5156	1.5547	1.5859
10	1.0312	1.0469	1.0703	1.0938	1.1172	1.1406	1.1719	1.1953	1.2188	1.2422	1.2734
11	0.8516	0.8594	0.8828	0.8984	0.9219	0.9453	0.9609	0.9844	1.0000	1.0234	1.0469
12	0.7031	0.7188	0.7344	0.7500	0.7656	0.7812	0.7969	0.8203	0.8359	0.8516	0.8672
13	0.5781	0.5938	0.6016	0.6094	0.6250	0.6406	0.6562	0.6719	0.6953	0.7109	0.7344
14	0.4766	0.4844	0.4922	0.5000	0.5078	0.5156	0.5312	0.5469	0.5547	0.5781	0.5938
15	0.3828	0.3906	0.3984	0.4062	0.4219	0.4297	0.4375	0.4531	0.4609	0.4766	0.5000
16	0.3281	0.3359	0.3438	0.3516	0.3594	0.3672	0.3750	0.3906	0.3984	0.4141	0.4297
17	0.2656	0.2734	0.2812	0.2891	0.3047	0.3125	0.3203	0.3281	0.3359	0.3516	0.3594
18	0.2109	0.2188	0.2266	0.2344	0.2422	0.2500	0.2578	0.2656	0.2734	0.2812	0.2969
19	0.1719	0.1719	0.1797	0.1875	0.1953	0.2031	0.2109	0.2188	0.2266	0.2344	0.2422
20	0.1250	0.1250	0.1328	0.1406	0.1484	0.1562	0.1641	0.1641	0.1719	0.1797	0.1875

Ignition Volts (V)	348	368	388	408	428	448	468	488	508	528	548
4	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000
5	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000
6	11.3203	12.3438	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000
7	3.2891	3.5000	3.7188	4.3047	5.4531	6.6094	7.7578	8.7188	9.4062	10.1016	10.7891
8	2.1641	2.2422	2.3203	2.4219	2.5391	2.6562	2.7812	3.1641	3.9453	4.7266	5.5078
9	1.6328	1.6797	1.7344	1.7812	1.8438	1.8984	1.9609	2.0625	2.1562	2.2656	2.3672
10	1.3047	1.3359	1.3672	1.4062	1.4453	1.4922	1.5469	1.6094	1.6719	1.7344	1.7891
11	1.0703	1.1016	1.1250	1.1562	1.1875	1.2109	1.2422	1.2656	1.2969	1.3281	1.3672
12	0.8906	0.9062	0.9297	0.9531	0.9766	1.0000	1.0312	1.0547	1.0703	1.0938	1.1094
13	0.7578	0.7734	0.7969	0.8125	0.8359	0.8594	0.8828	0.8984	0.9141	0.9375	0.9531
14	0.6172	0.6406	0.6562	0.6797	0.6953	0.7109	0.7344	0.7500	0.7578	0.7734	0.7891
15	0.5156	0.5391	0.5625	0.5781	0.5938	0.6094	0.6250	0.6406	0.6562	0.6641	0.6797
16	0.4375	0.4531	0.4609	0.4766	0.4922	0.5078	0.5234	0.5391	0.5469	0.5547	0.5703
17	0.3750	0.3828	0.3906	0.4062	0.4219	0.4375	0.4453	0.4609	0.4688	0.4844	0.4922
18	0.3047	0.3125	0.3281	0.3359	0.3516	0.3594	0.3750	0.3828	0.3906	0.4062	0.4141
19	0.2500	0.2578	0.2656	0.2734	0.2891	0.2969	0.3125	0.3203	0.3281	0.3359	0.3438
20	0.1953	0.2031	0.2031	0.2109	0.2266	0.2344	0.2500	0.2578	0.2656	0.2734	0.2812

Ignition Volts (V)	568	588	608	628	648	668	688	708	728	748	768
4	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000
5	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000
6	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000
7	11.4766	12.1641	12.8516	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000	14.0000
8	6.2891	7.0781	7.8594	8.6406	9.4219	10.2031	10.9844	11.7656	12.5469	13.3281	14.0000
9	2.4531	2.5234	2.5859	2.6406	2.7188	2.7812	2.8594	2.9219	2.9688	3.0234	3.1016
10	1.8594	1.9141	1.9844	2.0625	2.1328	2.1953	2.2344	2.2812	2.3594	2.3984	2.4844
11	1.4062	1.4609	1.5078	1.5625	1.6094	1.6562	1.7109	1.7656	1.7969	1.8672	1.9141
12	1.1328	1.1562	1.1719	1.1953	1.2109	1.2344	1.2578	1.2734	1.2969	1.3203	1.3359
13	0.9688	0.9844	1.0000	1.0156	1.0391	1.0547	1.0703	1.0859	1.1016	1.1172	1.1406
14	0.8047	0.8125	0.8281	0.8438	0.8594	0.8672	0.8828	0.8984	0.9141	0.9219	0.9375
15	0.6875	0.7031	0.7109	0.7266	0.7344	0.7500	0.7578	0.7734	0.7812	0.7969	0.8047
16	0.5781	0.5859	0.5938	0.6094	0.6172	0.6250	0.6406	0.6484	0.6562	0.6641	0.6797
17	0.5000	0.5078	0.5234	0.5312	0.5391	0.5547	0.5625	0.5703	0.5859	0.5938	0.6016
18	0.4219	0.4375	0.4453	0.4531	0.4688	0.4766	0.4844	0.5000	0.5078	0.5156	0.5312
19	0.3594	0.3672	0.3750	0.3828	0.3906	0.3984	0.4062	0.4141	0.4219	0.4375	0.4453
20	0.2891	0.2969	0.3047	0.3125	0.3203	0.3203	0.3281	0.3359	0.3438	0.3516	0.3594

Copying the spreadsheet data into the tuning software tables ensures that the ECU will be able to calculate the correct injector pulsewidth needed to deliver any amount of fuel requested. With this right, the tuner can focus on airflow errors on the dyno instead of wondering about injector behavior.



Injector Dynamics has a great reputation for data accuracy with their injectors. Our testing confirmed this by returning ECU data that fell almost exactly on top of theirs.

This all, of course, assumes that we have access to a complete characterization data set for the injectors we are using. Given the massive headaches waiting without the right injector data, many pro tuners won't even touch the engine tuning job without it. For the last 20 years, I have been teaching tuners the importance of this lesson. Injector companies like Injector Dynamics and Fuel Injector Connection have taken notice too. Many of them now provide plug and play data to go along with their injectors, some more accurate than others.

Whether you start with injectors that come with trusted, accurate data or you generate your own using the right tools, nailing this critical step will make your life much easier. Your engine will thank you for it, and you'll spend less time tuning too.