

How Does Changing Powder Affect Group Size?

Jeff Siewert, Systems Engineer

Introduction

All reloaders "know" that changing propellant type can affect the group size (dispersion) of the ammunition they make. Why this is so is more than a matter of propellant burnout prior to muzzle exit or some other easily definable characteristic. This white paper details the investigations undertaken to better understand this phenomenon and why it occurs.

Background

In my earlier days as a Ballistics Systems Engineer, I was on a business trip to teach a class on projectile design and troubleshooting at Federal Cartridge in Anoka, Mn. At the hotel, I happened to run into Alan Serven, who at the time was a sales representative for Hercules (now Alliant) Powder. Our discussion turned to the effect propellants can have on the size of the groups produced. At the time, **my** opinion was that powder simply provided the "push" for bullets and as long as the propellant burned out prior to shot exit and provided the desired muzzle velocity within the established pressure limits, one powder was as good as another. As a result of this study, I no longer believe that. This "white paper" documents the study I did to better understand why propellants affect group size.

I was graciously provided a limited set of dispersion data by Hornady on their 6.5mm 140g ELD-M versus propellant types. The powders used were: Varget, H4350, Hybrid H100-V and W760. I compared the provided dispersion data to the predicted dispersion data and herein document my findings.

Interior Ballistics

The first step in this study was to ensure that the results from the lumped parameter interior ballistics model I was using replicated measured pressure-time history reasonably closely. To characterize propellants for use in this study, the predicted peak pressure and muzzle velocity were compared to published data from Hodgdon's annual reloading guide for each powder. I used the data contained in their 2018 manual for the W760 simulations and their 2021 manual for my simulations with Varget, H4350, and Hybrid H100-V. Figure 1 shows a comparison between measured and predicted pressure-time history for 54.0g of W760 propellant in a 30-06 cartridge case firing 178g Hornady ELD-X projectile.

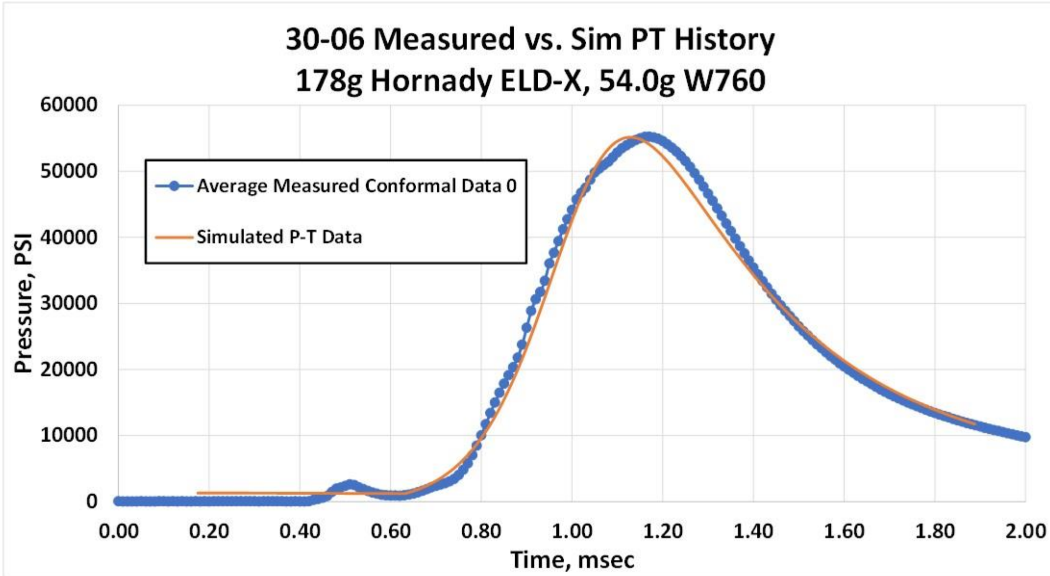


Figure 1: Comparison of Measured & Predicted Pressure-Time for W760

For purposes of balloting simulations, it's important to match peak pressure and muzzle velocity, as well as the pressure rise rate, as based on prior experience, those parameters influence the structural dynamic behavior of the bullet-barrel combination. At least qualitatively, the propellant model for the W760 propellant is in good agreement with measured data, as shown in Figure 1. Similar characterizations were performed for each of the other propellants examined.

Figure 2 shows the predicted average pressure-time histories for the propellants and respective charge weights studied. Statistical variations were generated for each powder based on their muzzle velocity standard deviation during firing.

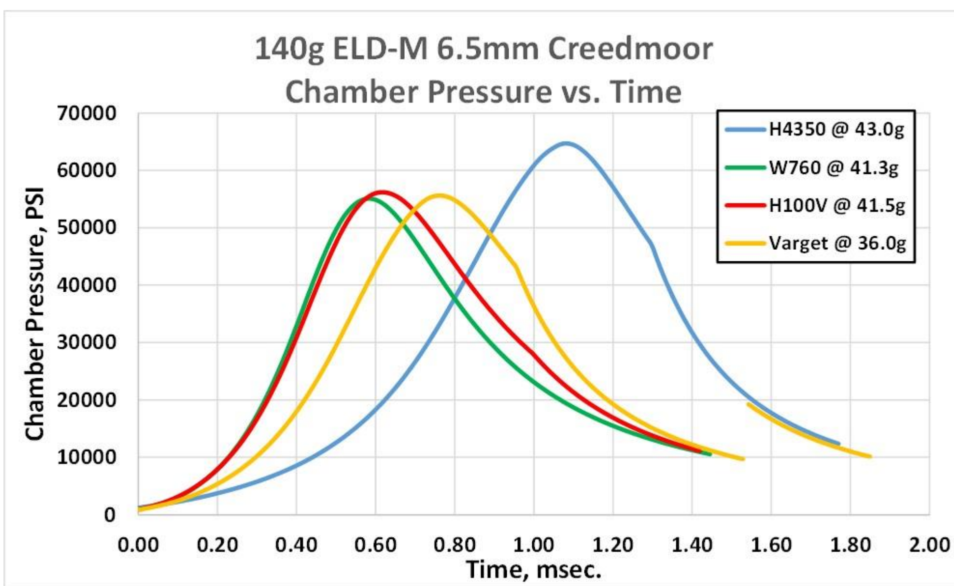


Figure 2: Comparison of Pressure-Time History for Studied Powders

To obtain representative muzzle velocity standard deviations from which to draw for the balloting simulations, the user must import interior ballistics profiles representing the average performance, along with plus and minus 1, 2, and 3 standard deviations from the mean. Figure 3 shows the mean performance for the 6.5mm, 140g ELD-M when fired with 43.0g of H4350 propellant, along with the plus and minus 1, 2, and 3 standard deviations from the mean.

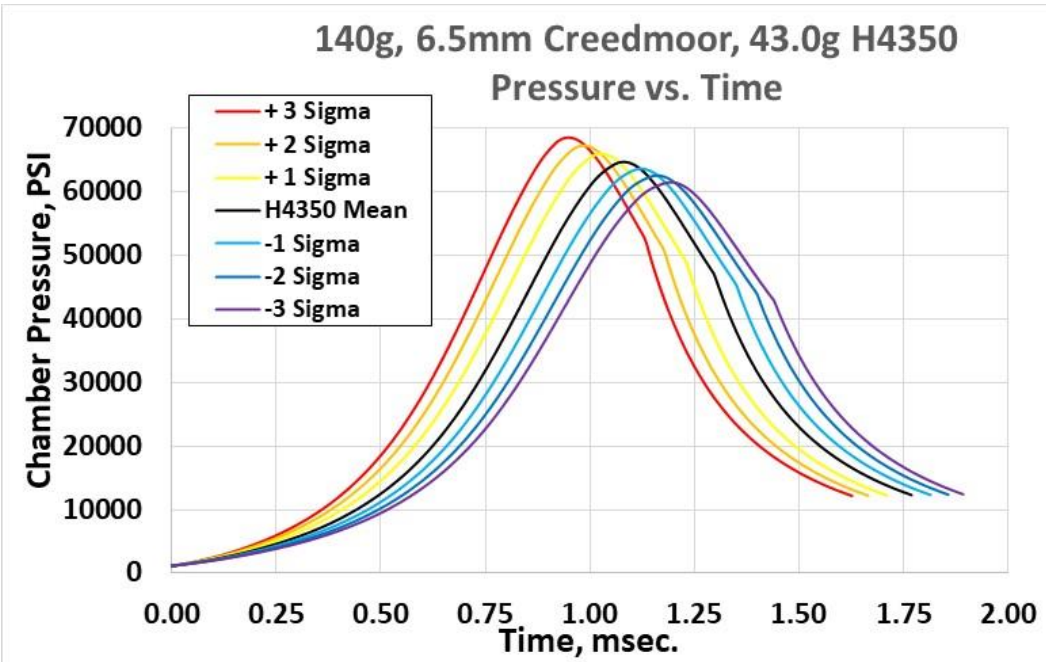


Figure 3: H4350 Pressure vs. Time w/ Standard Deviations

A summary of the propellant characteristics used in this study is shown in Table 1.

Propellant	Charge Mass, grain	Loading Density, g/cc	Mean Muzzle Velocity, FPS	MV Sigma, FPS	Pmax, PSI
H4350	43.0	1.03	2881	8	66879
Varget	36.0	0.88	2644	4	63708
Hybrid H100-V	40.0	0.94	2704	10	62950
W760	41.3	0.98	2564	15	59080

Table 1: Summary of Propellant Performance

The “Loading Density” column in Table 1 is of particular interest because generally speaking, propellants filling the case to a load density between 0.95 and 1.05 are most likely to have small muzzle velocity standard deviations arising from propellant migration in the case at the start of the interior ballistics cycle from ignition. Surprisingly, Varget seems to violate that general rule.

Projectile Balloting Models

The balloting simulation uses lumped mass and beam element models of the projectile and barrel to replicate the interaction of a flexible projectile in a flexible gun tube. In addition to the statistically variable pressure-time forcing functions, bore curvature and variable initial conditions of the projectiles are input. Before we go any further in the study of the interaction between propellant and the projectile structure, the reader should be aware that the run-to-run variability in the predicted projectile dispersion is in the ballpark of 3% of the long-term average due to the vagaries of the Monté Carlo draw of projectile orientation and pressure-time forcing functions.

Figure 4 shows a comparison between the physical model of the 6.5mm projectiles studied (top half of the images) along with the lumped mass and beam element model used by the balloting code and springs that support the projectile in the barrel as it is accelerated along the tube (bottom half of the images). The studied projectiles are the 6.5mm 140g ELD-M and the 6.5mm 130 CX.

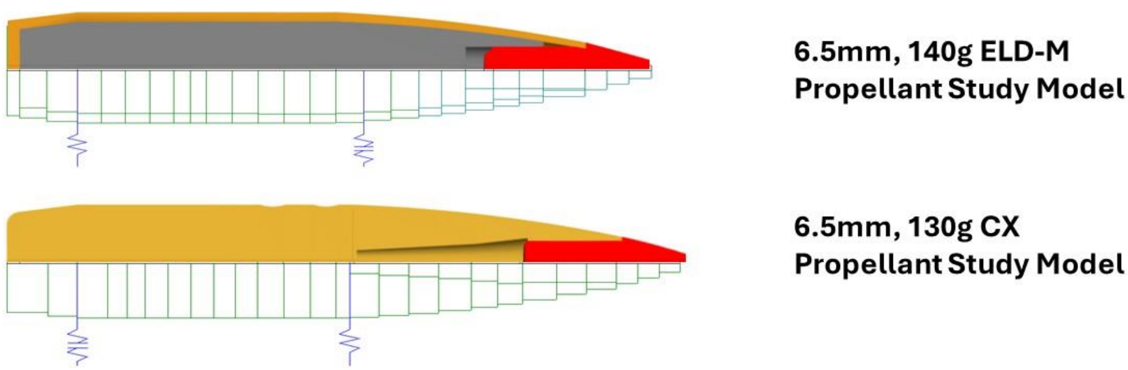


Figure 4: 6.5mm Bullet Physical and Balloting Models

The support springs connecting the projectile to the internal bore surface of the barrel are key players in determining the dynamic response of the bullet to the longitudinal and lateral accelerations imposed on the bullet structure by the firing event. For this study, values determined by FEA for other, similar projectiles were used. In the previous FEA analyses, the contact stiffness was shown to be a function of the rifling geometry (standard rifling or polygonal) as well as the bullet construction. For this analysis, an average of the stiffness values determined over the lands and grooves was used, the only consideration being the bullet construction. Table 2 shows the spring support stiffness values used for this study for the ELD-M and CX bullets.

Bullet	Bourrelet	Stiffness, lb/in
6.5mm 140g ELD-M	Rear	1,000,000
6.5mm 140g ELD-M	Forward	1,000,000
6.5mm 130g CX	Rear	2,000,000
6.5mm 130g CX	Forward	2,000,000

Table 2: 6.5mm Bullet Bourrelet Stiffness Values

Barrel Balloting Models

The balloting simulation also requires lumped mass and beam element models for the barrels being assessed. Figure 5 shows the physical model (above the centerline) and the lumped mass and beam element model used by the balloting simulation for the “tapered barrel” assessments.

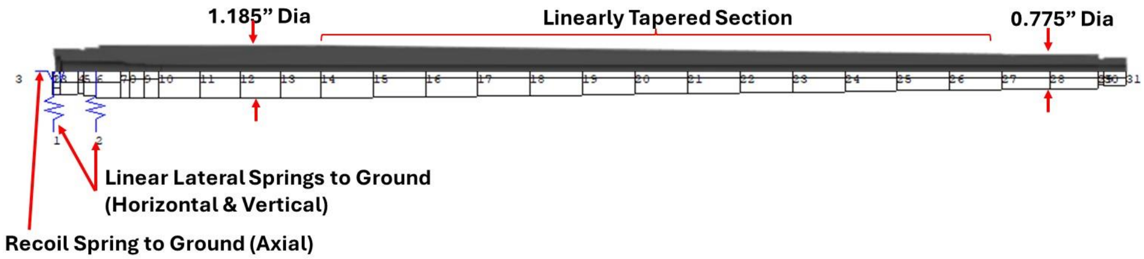


Figure 5: 6.5mm “Tapered” Barrel Physical and Balloting Models

Figure 6 shows the physical model (above the centerline) and the lumped mass and beam element model used by the balloting simulation for the “heavy barrel” assessments.

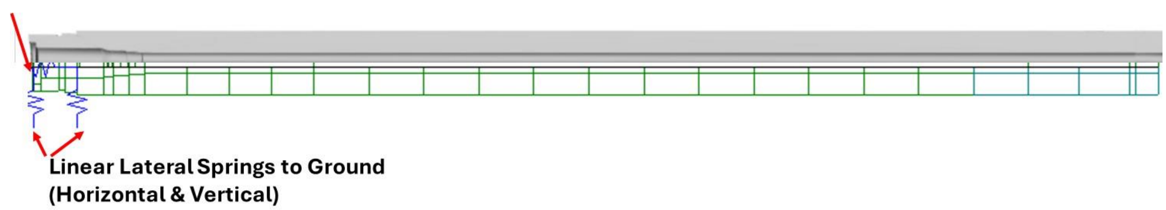


Figure 6: 6.5mm “Heavy” Barrel Physical and Balloting Models

For a few of these analyses, the support springs were moved from the aft (chamber) end of the barrel to a mid-barrel location to assess the effect of moving the barrel clamping location on the resulting projectile exit states (angular rate and cross velocity) distribution and concomitant dispersion.

Another important input to the balloting simulation is the bore centerline profile. Figure 7 shows the two vertical bore centerline profiles, “benign” and “moderate” bores.

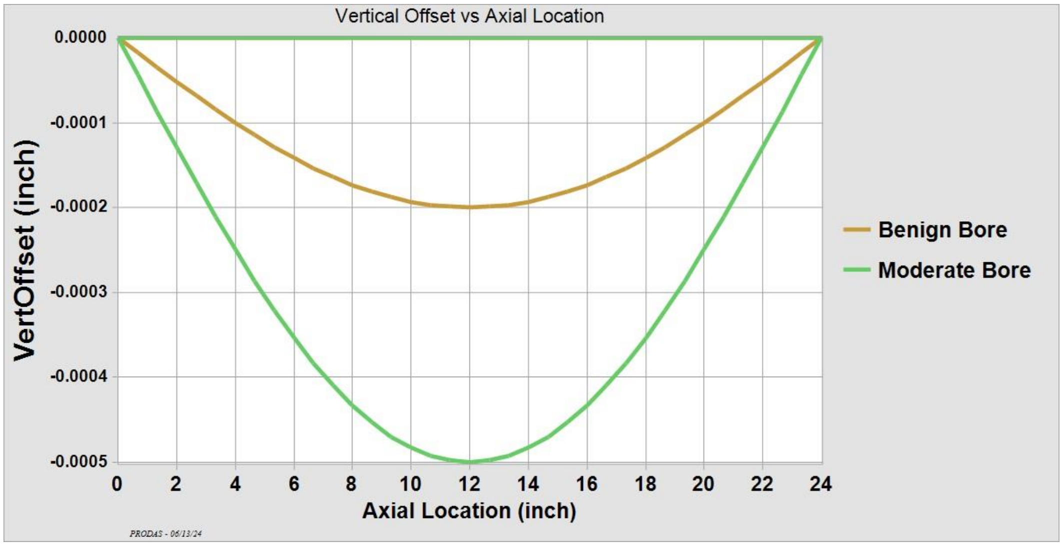


Figure 7: Bore Centerline Deviation vs. In-Bore Travel (Axial Location)

Projectile Initial Conditions

The last important input set for the balloting simulations is the initial conditions for the projectile(s). The two primary input categories that determine the projectile initial position is the bourrelet diameter (mean and standard deviations) along with the establishment of the projectile plane of motion. These inputs are shown in Figure 8 with the blue and red arrows respectively.

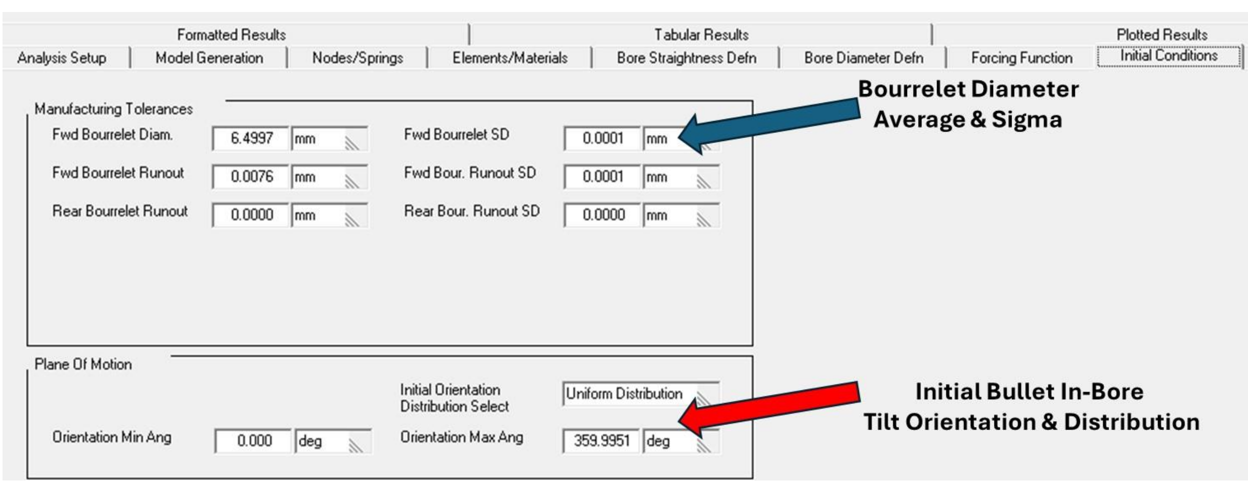


Figure 8: 6.5mm Bullet Initial Conditions Input

Two general sets of initial plane-of-orientation conditions were explored, the first being a limited set of pointing angles, and the second being an unlimited set of pointing angles. For guns with a spring-loaded ejection plunger, it was thought the force applied to the base of the cartridge case by the plunger would result in a preferred initial pointing orientation of the bullet as it was placed into the barrel.

The “uniform” distribution was subsequently determined to be preferred as the limited set of pointing angles typically resulted in a “skewed” fall of shot distribution, which was thought to be inconsistent with observed dispersion patterns.

Simulation Results

Once all the inputs were made, initial propellant simulations were made in the benign, tapered barrel. Out of curiosity, I decided to plot the bullet exit states, initial angular rate and initial cross velocity, as a function of standard deviation from the mean for each propellant studied. This yielded some very interesting performance for the 140g 6.5mm projectile, and plots of each of the propellants is shown in Figure 9. The differences among all the propellants is interesting, and the reader should keep in mind that the impact point for an individual shot is the result of a paired set of initial angular rate and cross velocity at a given distance from the mean for a particular, randomly selected interior ballistics (IB) forcing function.

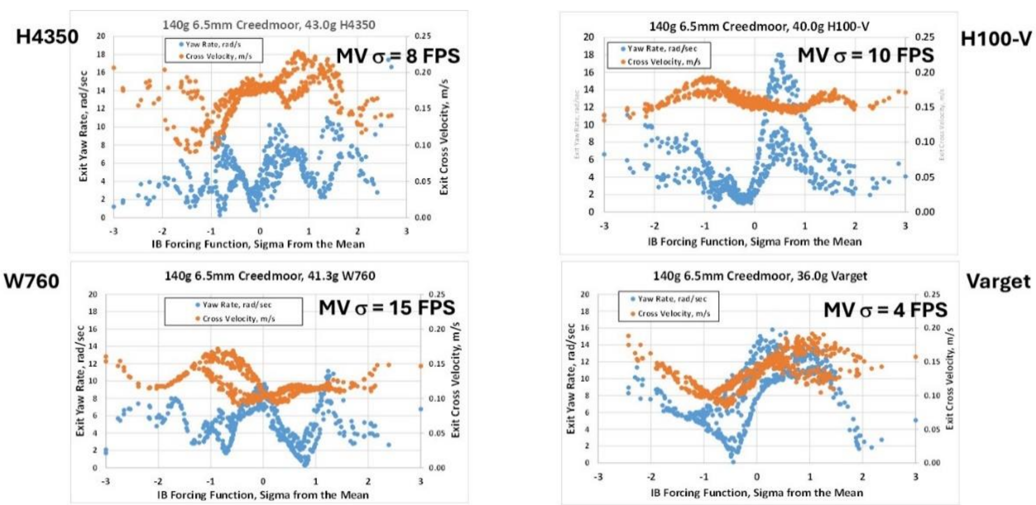


Figure 9: 6.5mm 140g ELD-M Exit States vs. Propellant Type in Benign, Taper Barrel

As seen in Figure 9, all the initial yaw rate plots exhibit significant “waves” in their response to changes in pressure-time history; some zones of pressure-time performance are much more likely to result in larger initial yaw rates, and some velocity zones are far less likely to exhibit high exit rates. The same can be said for the cross velocity behavior, but to a much lesser extent, generally.

Of particular interest in Figure 9 is the exit yaw rate response of Hybrid H100-V, shown in the upper right corner between 0 and +1 standard deviation from the mean. Here the structural response is “bifurcated”, with some shots exhibiting large yaw rates and a similar number exhibiting small yaw rates, with nearly nothing in between. For this particular bullet/barrel/propellant combination in the region between the mean and plus one standard deviation above the mean, approximately 1/3 of shots exit with an angular rate above 10 rad/sec, while 2/3 are below that figure, all while exhibiting a fairly narrow band of cross velocity response. This response anomaly was intriguing and was studied further, as discussed below.

In general, the aerodynamic "jump" from the initial angular rate is in a direction that tends to cancel the "throw" arising from the bullet cross velocity at muzzle exit, provided the cross velocity is caused only by the CG offset of the bullet relative to the bore centerline at muzzle exit. It this case, the exit angular rate and cross velocity should be well correlated, with a correlation coefficient of 0.75 or greater. An examination of the exit states captured from this analysis shows the correlation coefficient of all the propellants studied under any set of boundary conditions was no greater than 0.45. This means that the cross velocity of the bullet/barrel/propellant combinations studied most likely arises from barrel pointing and transverse motion and not the product of CG offset multiplied by the exit spin rate.

Now before you run off and start yelling "See! Nodes ARE real!" keep in mind that the velocity "period" of the structural dynamic response changes are essentially on the order of one or two velocity standard deviations, meaning that you don't have any chance to "tune" your muzzle velocity to a point where the large exit yaw rates don't occur. The effect of changing average muzzle velocity on the structural response is shown in Figure 10, along with several other changes in the "system" parameters.

Since the exit yaw rate structural response "map" of the Hybrid 100-V propellant was so interesting between the mean performance and plus one standard deviation, I decided to explore what bullet-barrel interface parameters could be changed to modify the response in that particular region. Figure 10 shows the "baseline" simulation response (tapered, benign barrel with limited initial projectile tilt plane angles, shown upper left), along with the response with a barrel with straight outside diameter in the upper right. Unsurprisingly, a reduction in both angular rate and cross velocity is seen since this change increases both the bending stiffness of the barrel and increases the barrel mass.

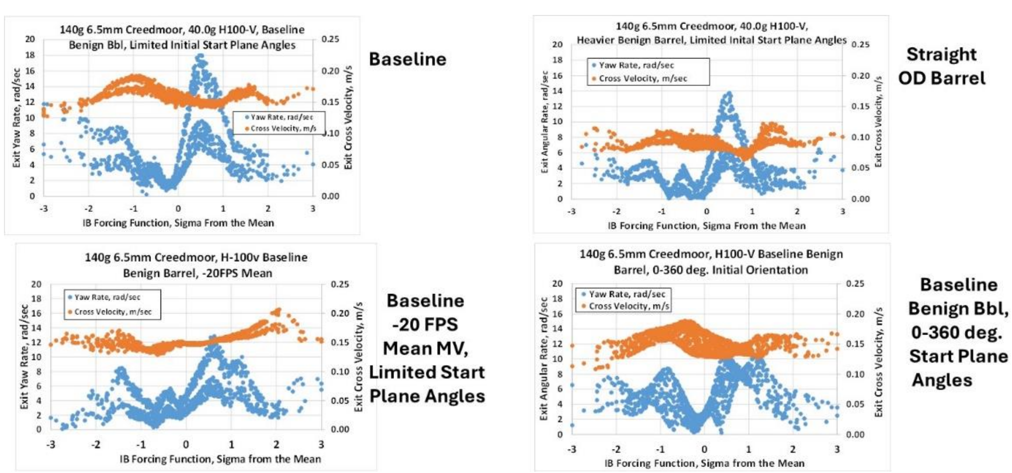


Figure 10: 6.5mm 140g ELD-M Exit States vs. Various Interface Perturbations

In the lower left hand corner of Figure 10, we see the structural response with the same benign, tapered barrel with limited start planes, but the average muzzle velocity has been reduced by 20 feet per second, along with all the velocity standard deviations. This value was chosen because if the response was solely related to the muzzle velocity, a 20 FPS shift in velocity should have moved the bifurcated response to the plus 2-3 sigma range. Interestingly, while there is a reduction in angular rate between the mean and plus one standard deviation, there is still a bifurcation in the yaw rate response in that region.

Subsequently, I decided to change the initial conditions from limited start plane angles to unlimited, meaning the bullet can be randomly point anywhere "around the clock" when the cartridge is chambered. With this set of initial conditions for the projectile, the angular rate "bifurcation" between the mean peak pressure and plus one standard deviation essentially disappeared, being replaced by a broader but lower angular rate response.

Next, it was decided to evaluate the angular rate response for the tapered, benign barrel with the connection between the barrel and "ground" changed from the aft end of the barrel at the chamber to the middle of the barrel. The structural response maps for this analysis is shown in Figure 11. The supports at the aft end are shown on the left-hand side of the figure, while the response for the system with the barrel supports located at the mid-barrel location is shown on the right. There is a clear reduction in exit angular rate and cross velocity with the mid-barrel support location.

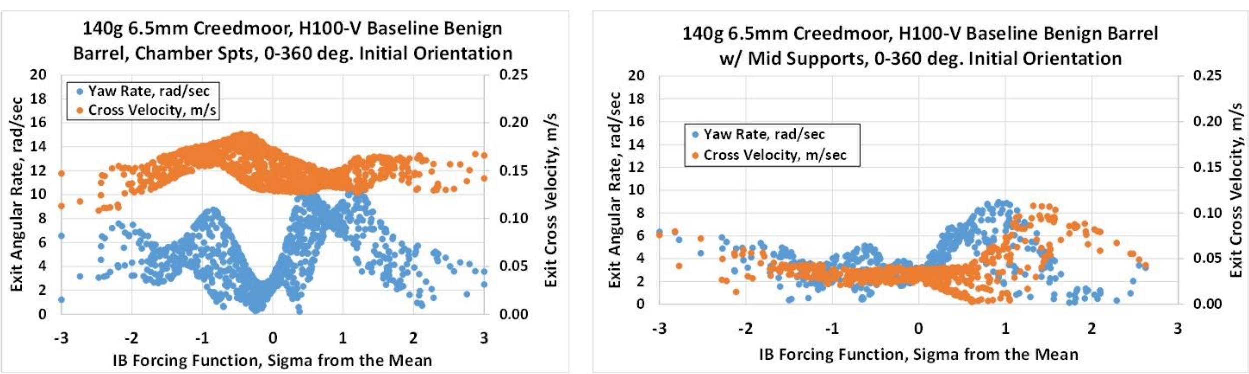
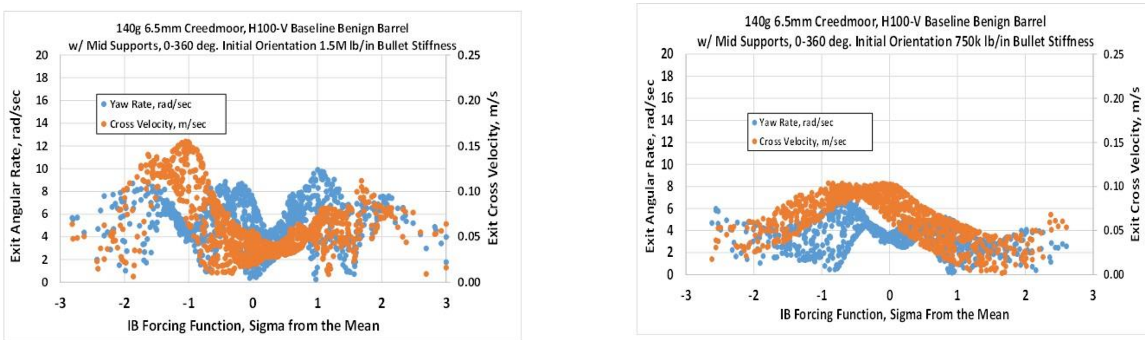


Figure 11: 6.5mm 140g ELD-M Exit States vs. Barrel Support Location

From there, I decided to evaluate the structural response of arbitrarily changing the support stiffness of the projectile. This is a bit of an academic study in that the support stiffness of the bullet is determined primarily by the bullet construction and materials; **it can't be changed in the real world by simply wishing it to be so**. Figure 12 shows the exit state response map for the 6.5mm, 140g ELD-M projectile with 1.5 million lb/in support stiffness on the left, and 750,000 lb/in stiffness on the right. There is a clear reduction in both exit yaw rate and cross velocity with a reduction in support stiffness.



1.5m lb/in Stiffness, 0.046 mils 1 Sigma

750k lb/in Stiffness, 0.039 mils 1 Sigma

Figure 12: 6.5mm 140g ELD-M Exit States vs. Bullet-Barrel Support Stiffness

Lastly, I was curious about the response map and expected dispersion of the 140g 6.5mm ELD-M compared to the 130g 6.5mm CX projectile for the two bore centerline profiles at hand. Figure 13 shows the structural response maps of the ELD-M projectile on the left, and the CX projectile on the right. The response of the bullets to the barrel with a 0.0002 inch maximum bore centerline deviation is on the top, while the maps for the same bullets and initial conditions with 0.0005 inches maximum bore centerline deviation are on the bottom.

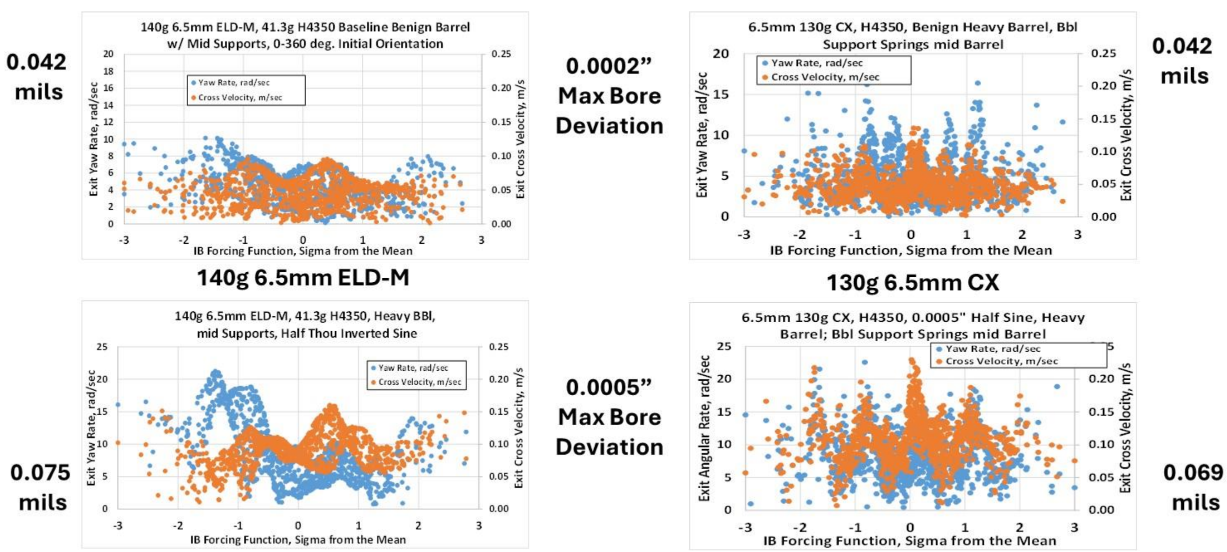


Figure 13: 6.5mm 140g ELD-M & 130g CX Exit States vs. Max Bore Deviation

It is clear in Figure 13 that the exit yaw rate and cross velocity of the CX bullet is more sensitive to changes in pressure-time history than the ELD-M, but the dispersion performance is comparable. The reader is cautioned that these results are for bore centerlines that are half sine waves, the comparative dispersion performance of these bullets may be considerably different. The cleanliness of the barrel is sure to play a significant role in the observed dispersion.

So, how does the results of the balloting simulation compare to the dispersion seen during test? Figure 14 shows the dispersion seen in product testing vs. propellant type and the dispersion predicted by the balloting code.

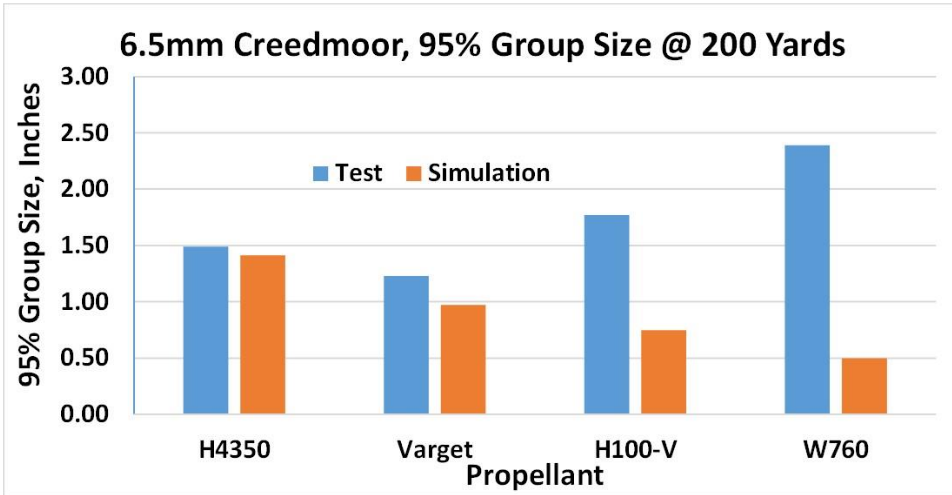


Figure 14: 6.5mm 140g ELD-M Measured vs. Simulated Dispersion

As seen in Figure 14, the dispersion predicted by the balloting code of the 6.5mm 140g ELD-M using the two extruded powders, H4350 and Varget, is in close agreement with the dispersion observed in test. Thirty (30) years of experience with the balloting code has shown if the predicted dispersion is radically different from that observed in test, the most likely cause is something the balloting code doesn't take into account. The H100-V and W760 are hybrid and ball powders, respectively, and my interior ballistic simulations indicate these powders may not be completely consumed at muzzle exit. Unburned propellant grains striking the aft end of the projectile at shot exit (along with accompanying high base pressures at exit) are the most likely explanation for this discrepancy as described in the following paragraph.

Externally applied loads can cause significant additional dispersion if the load is applied in the "wrong" place. If a fixed impulse is applied perpendicular to the longitudinal axis of a projectile for one-half revolution, the angle of attack and trajectory "jump" angle that result are shown in Figure 15. The minimum angle of attack developed by the projectile is seen when applied impulse is located at the projectile center of mass, while the minimum trajectory deviation (the "jump angle") is minimized when applied perpendicular to the projectile normal force center of pressure location. Also shown is the unfortunate fact that the trajectory deviation is maximized when the impulse is applied at the aft end of the projectile, farthest from the normal force center of pressure.

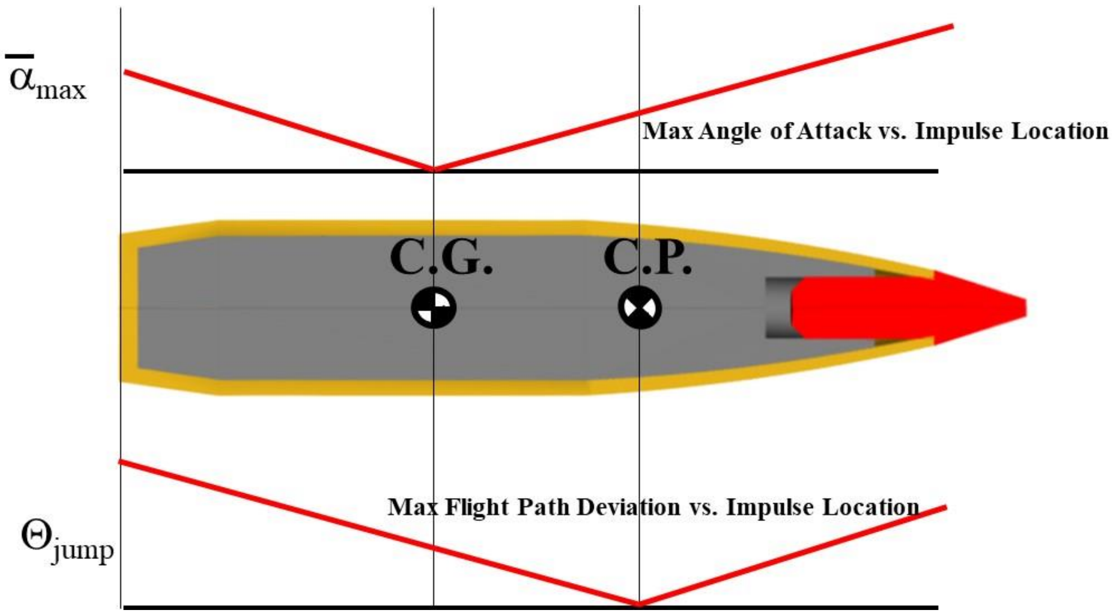


Figure 15: Projectile Angle of Attack & Jump Angle vs. Impulse Location

This behavior implies that if a muzzle brake or suppressor can strip a large portion of the reverse flow at the time the bullet exits the barrel, there is the potential to reduce the observed dispersion. Likewise, if the base pressure at muzzle exit is excessively high or unburned propellant grains strike the projectile at the bullet base, the dispersion of the projectile can be adversely affected.

Conclusion & Summary

The discovery of a unique projectile "structural response map" that changes with the propellant selected came as a complete surprise to me. Prior to this study I was very skeptical that changing propellants could have a significant effect on projectile dispersion. Based on these results, I thus conclude that propellant selection can indeed affect dispersion, and choosing a powder that burns out prior to muzzle exit is a good idea if you want to keep groups small.

In viewing the various response maps, it is easy to see how a reloader could think a dispersion "node" had been found when shooting 3, 5 or even 10 shot sample sizes. Propellant screening testing should thus be viewed as a "will this powder or won't it work" exercise and if the first few shots for a given powder have a wide spread, it's likely best to change powders if your goal is shooting small groups.