Do Muzzle Tuners Work?

By Jeff Siewert

In early November 2023, I decided to conduct a study on the effect added masses on the end of barrels could have on the group size of bullets fired from said barrels. It was felt that the mass added to the end of the barrel would indeed reduce the transverse motion of the barrel (movement perpendicular to the bore axis), but the more important question was: "would a reduction in transverse barrel motion result in smaller group sizes?"

Background

The study of in-bore balloting dates to at least the early 970's when dispersion problems arose during the development of the 30x173mm API designated the PGU-14. A lumped mass and beam element model of this projectile was created and a structural dynamics code written was subsequently used to solve the excessive dispersion exhibited by early developmental versions of this projectile.

In the intervening years, this code has been further developed and enhanced, adding the capability of analyzing the interaction between a flexible projectile a flexible gun barrel with externally applied masses, variable pressure-time forcing functions, Monté Carlo draws for initial projectile position and preferred ranges for initial in-bore orientation. The balloting code ultimately provided engineering basis for dispersion reduction efforts on projectiles ranging from 5.56mm to 155mm on 50+ different projectiles since then and continues to be used to this day on all types of ammunition. The model assumes both the projectile and the barrel operate in a mechanically elastic regime. In Monté Carlo mode, the balloting program collects the initial angle of attack in the vertical and horizontal plane, as well as the angular rates imparted to the projectile at muzzle exit in the horizontal and vertical planes, along with the associated cross velocities in both axes to enable computation of the true dispersion for 500 simulated shots.

For projectiles exhibiting average dispersion (the average of Sigma X & Sigma Y) greater than approximately 0.10 mrad, the dispersion predictions of balloting model historically have been fairly close to firing observations provided an accurate account of the in-bore clearances and pressure-time history is available. Below 0.10 mrad, (typical dispersion for small caliber projectiles) the mean and standard deviation of the in-bore clearances are SWAG's (Scientific Wild Ass Guesses) based on bullet construction, bullet type (military ball vs. target vs. hunting) and other engineering judgements. The model has never been able to characterize the effect of varying free run to the rifling, but then again, that analytical task has never been undertaken.

Projectile Model Description

The projectile used for this study was a 30 Caliber, 178g Hollow Point Boat Tail (HPBT) made by Hornady, item #30715. Figure 1 shows a comparison of the physical representation of the referenced projectile (above the horizontal centerline) and the lumped mass and beam element model of that projectile (below the centerline).

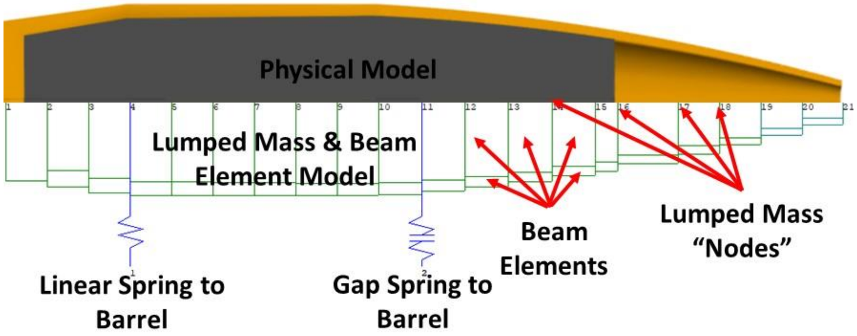


Figure 1: Physical Model and Balloting Model of 178g, 30 Cal HPBT Projectile

The mass of each "segment" of the model is assumed to be concentrated at projectile nodes located along the projectile axis, which are connected with beam elements comprised of cylinders having the same density and elastic modulus of the projectile body components. The composite projectile model is "connected" to the barrel lands by a linear spring at the aft bourrelet, and a "gap" spring at the forward bourrelet. For the purposes of this study, support spring stiffness values previously derived from 3-D FEA models on similarly constructed projectile were used. The projectile is assumed to be "perfectly built" (no principal axis tilt, non-symmetric products of inertia or corresponding CG offset) and is constrained to bend only in the plane of in-bore yaw, which rotates in-bore with respect to the barrel per the defined twist vs. travel profile.

Barrel Model Description

The lumped mass and beam element model used for this study is shown in Figure 2. The springs connecting the barrel to "ground" in recoil, horizontal and vertical axes is shown on the left-hand side and the added mass of the muzzle tuner is shown on the right-hand side.

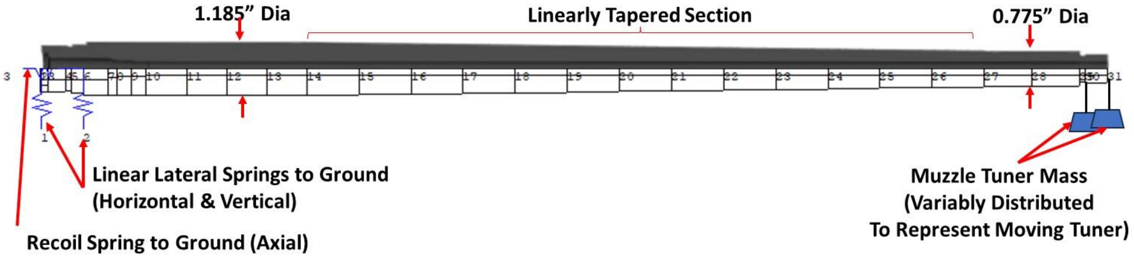


Figure 2: Physical Model and Balloting Model of 24", 30 Cal Rifle Barrel

To simulate the adjusting of the tuner mass, the distribution of the total tuner mass was parametrically distributed between barrel nodes 30 and 31 on the far right-hand side. As with the projectile model, the barrel beam elements are assumed to be comprised of right circular cylinders made of the density and elastic modulus of steel with dimensions corresponding to the model shown above with a total length of 24 inches. The tuner is assumed to have a total mass of 1.0 lbs which is distributed in 10% increments between the barrel nodes at the far right-hand side of the barrel.

Bore Centerline

The bore centerline profile can have anywhere from a little effect to a major effect on the dispersion exhibited by the system depending on the details of the conditions simulated. For this analysis, three different bore centerline profiles were evaluated; a “crooked” barrel, a “good” barrel and a bore profile believed to be “benign”. The bore profiles used in this analysis are shown in Figure 3.

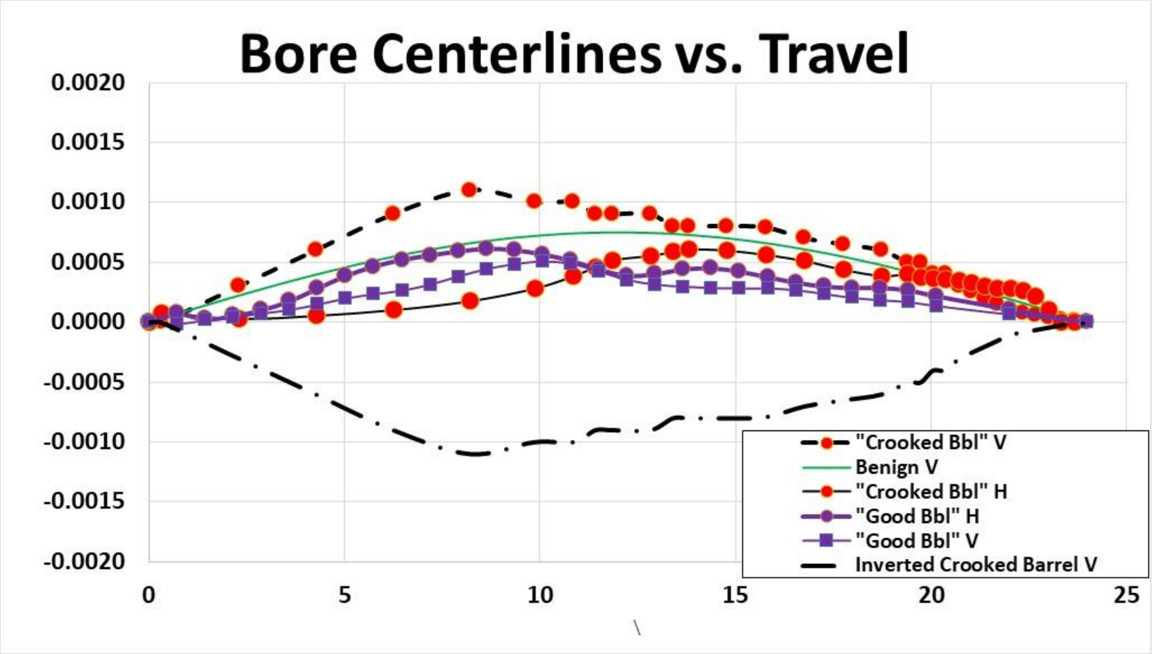


Figure 3: RSS Bore Centerline Profiles.

The bore profile of the “crooked” and “good” barrels were drawn from previously measured straightness profiles and scaled for in-bore travel and peak magnitude.

Pressure Time Forcing Function

One of the primary methods by which changes in barrel pointing can dramatically affect scatter in bullet fall of shot is through an interaction between the barrel structure and variations in bullet in-bore travel time. The balloting code can simulate the shot-to-shot variations in pressure-time history by a Monté Carlo draw, interpolating between nearest adjacent pressure-time forcing functions. Figure 4 shows the variations in in-bore forcing function as a function of travel used for this analysis.

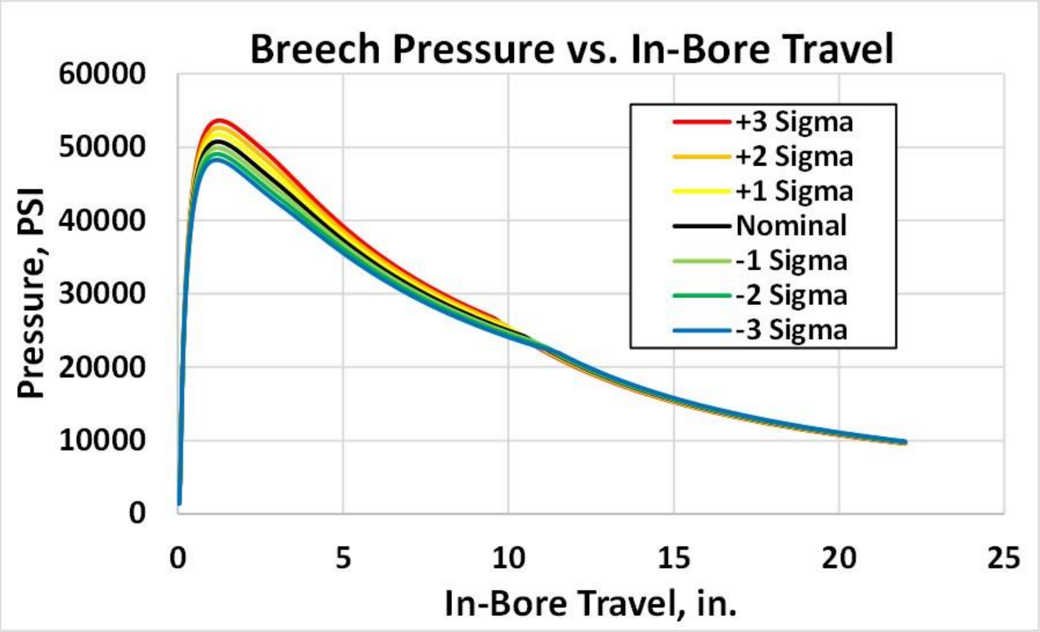


Figure 4: Simulated Variations in Pressure-Travel History for Balloting Analysis

Table 1 lists a summary peak chamber pressure, muzzle velocity and action time of the pressure-time forcing functions used for the balloting analysis.

	Peak Chamber Press psi	Muzzle Velocity ft/sec	Action Time msec
-3 Sigma	48288	2634.0	1.665
-2 Sigma	49084	2646.0	1.652
-1 Sigma	49914	2658.0	1.639
Nominal	50780	2670.0	1.626
+1 Sigma	51684	2682.0	1.613
+2 Sigma	52632	2694.0	1.600
+3 Sigma	53626	2706.0	1.587

Table 1: Summary of Interior Ballistics In-Bore Forcing Functions

The simulated standard deviation in muzzle velocity for the balloting simulation is 12 feet per second, closely mimicking the data shown in Figure 5. This was believed to be on the higher side of typical muzzle velocity variation for reloaded ammunition, but still within useful range. It should be noted that while there is typically fairly good correlation between peak pressure and muzzle velocity for bottle necked cartridges (>0.8 correlation coefficient is common) it never achieves the 1.0 correlation coefficient shown above. Figure 5 shows fairly typical peak pressure vs. muzzle velocity performance for a typical bottle necked cartridge <u>with a single charge mass</u>.

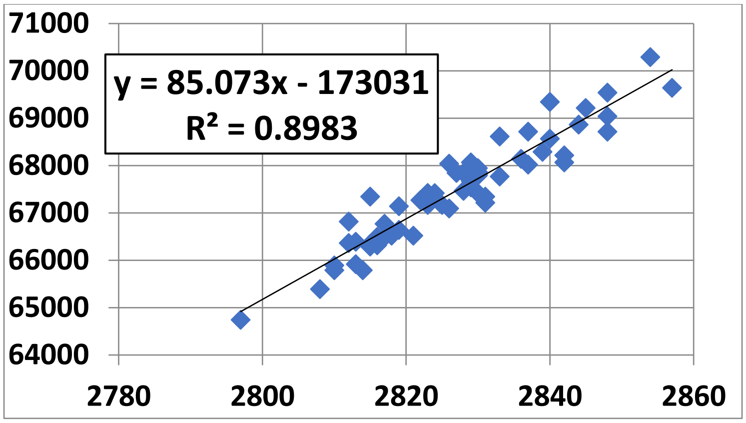
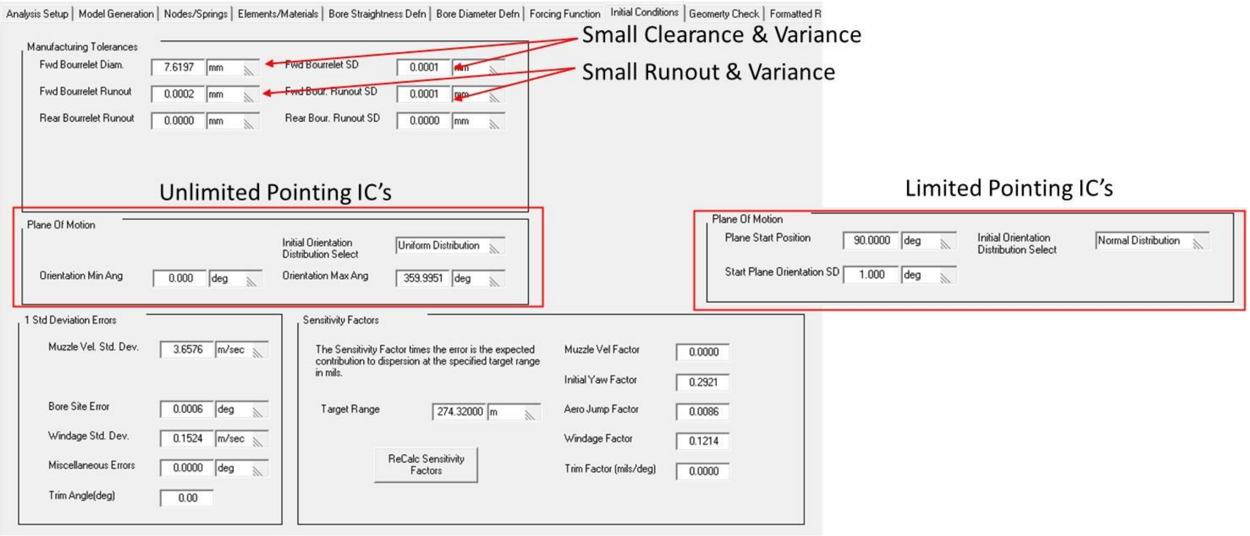


Figure 5: Typical Peak Pressure vs. Muzzle Velocity Performance for Bottle Neck Cartridge

In this particular instance, the pressure-muzzle velocity data comes from a well-known magnum cartridge and the standard deviation in peak pressure is a bit over 1100 PSI while the standard deviation in muzzle velocity is a bit north of 12 FPS.

Projectile Initial Conditions

Yet another factor causing dispersion of projectiles is the variation in initial position of the projectile longitudinal axis with respect to the bore centerline at the origin of rifling. The bullet is presumed to be "perfectly made" (no tilt of the principal axis with respect to the bullet bourrelets) but the bullet can be tilted with respect to the bore centerline and its pointing vector can vary "around-the-clock" as viewed from the breech. At first blush in-bore clearances might seem to be impossible due to the interference fit between the projectile outside diameter and the barrel lands, but small caliber barrel bores grow in diameter elastically in response to the increasing pressure trapped behind the bullet, effective in-bore clearances can indeed arise. This allows the bullet to tip in-bore relative to the bore centerline. Figure 6 shows the inputs for variations in the initial in-bore tilt of the projectile at the top, along with the constraints on the initial pointing vector of the projectile (around the clock as viewed from the breech) shown in the middle of the input page.



Manufacturing Tolerances
Fwd Bourrelet Diam. 7.6197 mm
Fwd Bourrelet SD 0.0001 mm
Fwd Bourrelet Runout 0.0002 mm
Fwd Bour. Runout SD 0.0001 mm
Rear Bourrelet Runout 0.0000 mm
Rear Bour. Runout SD 0.0000 mm

Plane Of Motion
Initial Orientation Distribution Select: Uniform Distribution
Orientation Min Ang 0.000 deg
Orientation Max Ang 359.9951 deg

Plane Of Motion
Plane Start Position 90.0000 deg
Initial Orientation Distribution Select: Normal Distribution
Start Plane Orientation SD 1.000 deg

1 Std Deviation Errors
Muzzle Vel. Std. Dev. 3.6576 m/sec
Bore Site Error 0.0006 deg
Windage Std. Dev. 0.1524 m/sec
Miscellaneous Errors 0.0000 deg
Trim Angle(deg) 0.00

Sensitivity Factors
The Sensitivity Factor times the error is the expected contribution to dispersion at the specified target range in mils.
Target Range 274.32000 m
Muzzle Vel Factor 0.0000
Initial Yaw Factor 0.2921
Aero Jump Factor 0.0086
Windage Factor 0.1214
Trim Factor (mils/deg) 0.0000

Figure 6: Projectile Initial Conditions Input

The predicted dispersion was studied with both limited and unlimited pointing initial conditions (IC's) and the results are herein reported.

Results

The answer to the question "Does a muzzle tuner reduce barrel motion?" is a definite "YES". Figure 7 shows the displacement vs. time for Node # 31 at the very muzzle of the barrel. Clearly there is much less motion with the muzzle tuner installed vs. the bare barrel.

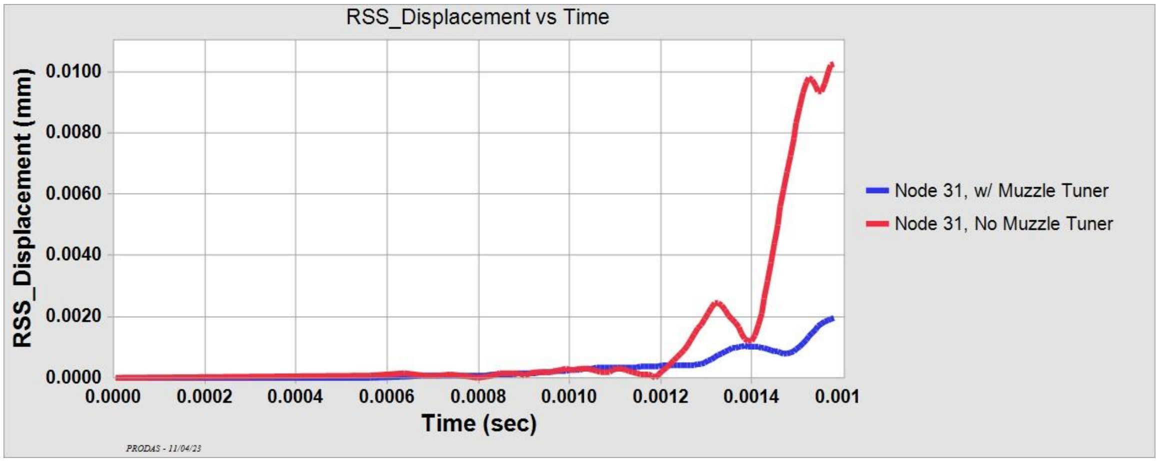


Figure 7: Comparison of Barrel Muzzle Displacement w/ & w/o Tuner

However, a reduction in barrel motion alone is no guarantee of shooting smaller groups. Dispersion arises from both angular rate (bullet wobble at muzzle exit) and cross velocity. Depending on the bullet construction and location of manufacturing defects, the aerodynamic jump from angular rate can either add to or subtract from the throw caused by cross velocity. Energy in the system from bullet travel down the bore must move the barrel if the bore is not straight, and if the application of the tuner mass reduces the motion of the barrel, the energy then goes into the bullet, potentially increasing the dynamic in-bore deflection of the bullet axis relative to the bore axis. The added angular rate at muzzle exit usually results in an increase in dispersion.

Figure 8 shows the dispersion of the 178g 30 Caliber Hornady HPBT as a function of the percentage of the muzzle tuner mass applied to Barrel Node #31, the muzzle of the barrel. Also shown for reference is the calculated dispersion for each of the barrel profiles with no tuner at all on the far left-hand side of the plot. Note the dispersion trends of the “crooked” bore and “inverted crooked bore” shown in red.

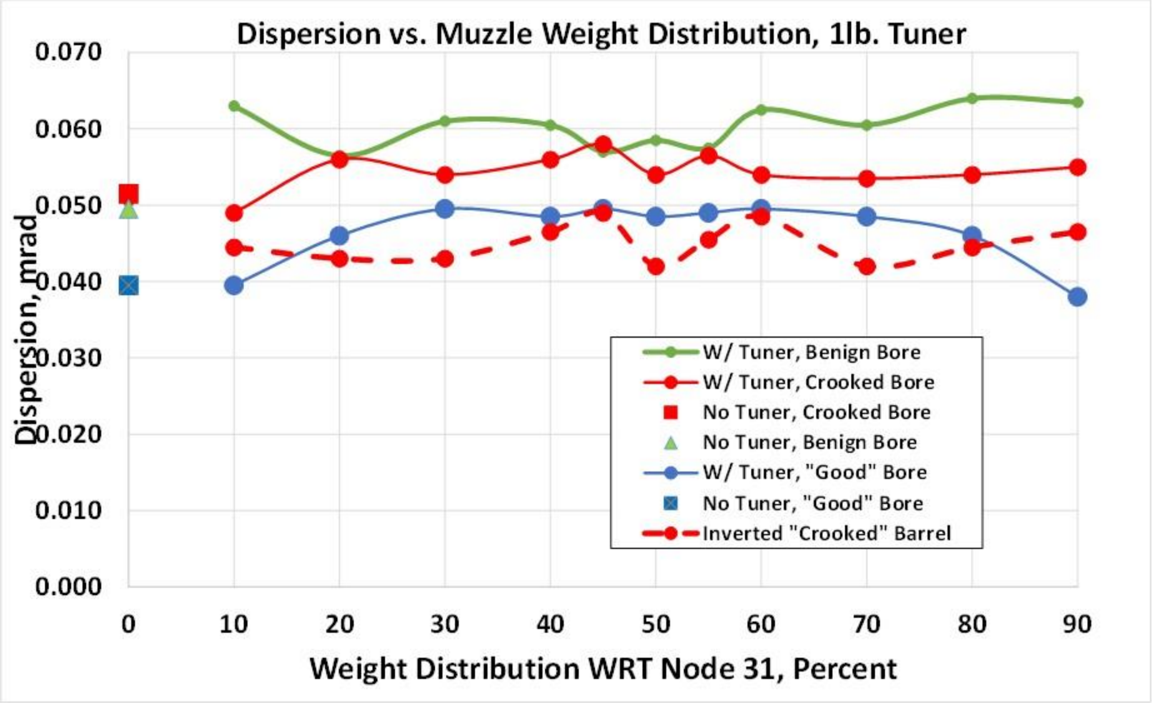


Figure 8: Dispersion vs. Bore Centerline Profile & Tuner Weight Distribution

As can be seen in Figure 8, compared to the barrel without tuner mass applied, there is only one bore profile which exhibits a clear, across-the-board reduction in dispersion with tuner mass applied to the barrel muzzle, namely the Inverted “Crooked” barrel. For the other barrel profiles, there appears to be very limited tuner mass distributions that result in dispersion smaller than the bare barrel.

So, what’s going on with the Inverted “Crooked” barrel? Why does that bore shape result in consistently smaller dispersion than the bare barrel with the tuner mass applied? This bore shape has its maximum bore centerline deviation from straight located vertically below the centerline defined by the bore center at the origin of rifling and the bore center at the muzzle, making the bore closer to straight when the muzzle tuner is applied to the muzzle of the barrel. Taking an average of the dispersion with the “crooked” barrel in its original orientation and an average with the same barrel inverted, the application of the muzzle tuner mass made the dispersion approximately 12% smaller in the inverted orientation. As will be shown shortly, at this dispersion performance level, it will take a large number of shots to prove this improvement in dispersion is real at a 95% confidence level.

Other variations in the simulation were considered: increasing the jacket wear due to friction between the land and the jacket, as well as increasing the roll orientation “window” allowable by the bullet as the cartridge is chambered. Figure 9 shows the results of the majority of the conducted analytical studies. The horizontal axis in Figure 9 represents the variation in the roll orientation limits for the projectile as the cartridge is inserted into the chamber; the far left-hand side indicated limited initial roll orientations while the far right-hand side shows much larger (up to 45 deg. standard deviation) for the initial roll orientation for the initial pointing vector of the bullet nose. The solid black line shows the expected dispersion for the 178g 30 Cal HPBT bullet as a function of the allowable roll orientation without a tuner, while the dashed black line shows the dispersion for the same barrel with a muzzle tuner applied to the muzzle.

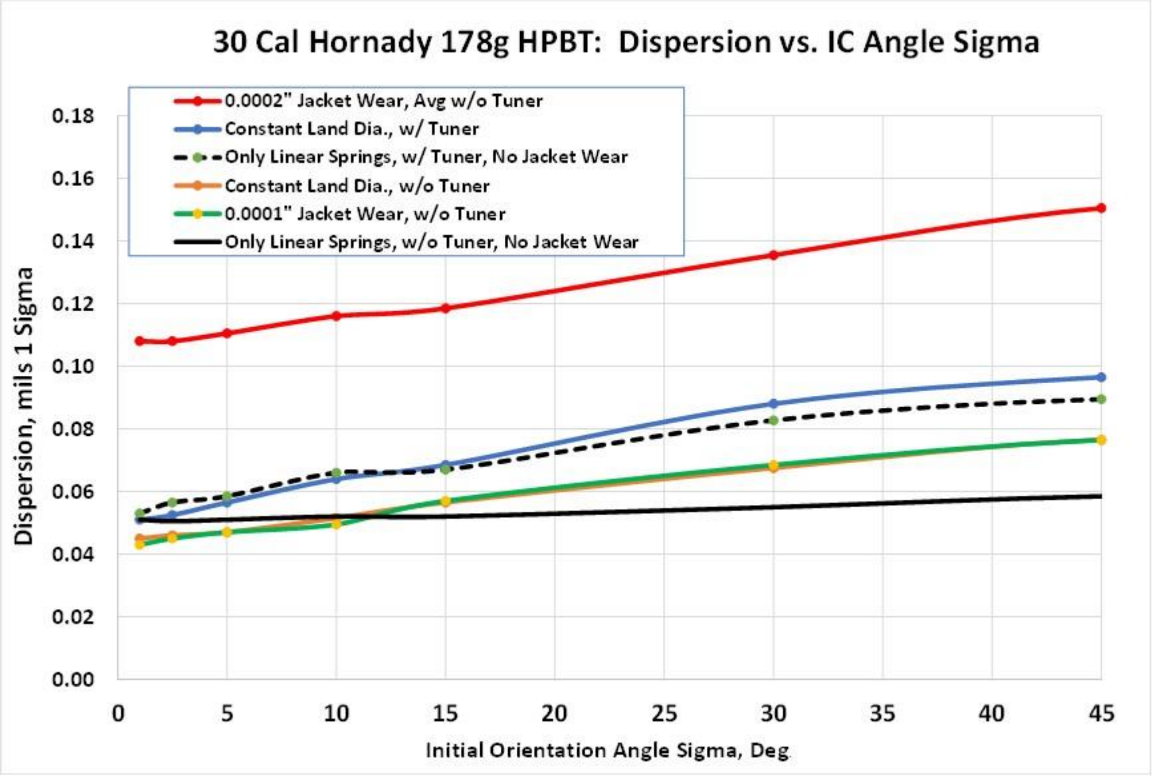


Figure 9: Dispersion vs. Interface Conditions & Limitations on Initial Rotation Angle

We then need to determine how many shots are needed to prove that our groups are either better or worse when using a tuner than with a bare barrel. Using a statistical test known as the “Student’s T test”, it’s possible to determine how many shots are needed to distinguish between the dispersion performance at a statistically significant level. I used the roughly 12% reduction in dispersion performance between the normally oriented “Crooked” barrel and the inverted “Crooked” barrel shown in Figure 8. This analysis presumes the dispersion variation is a fixed percentage of the true dispersion.

Depending on the targeting metric you choose, the number of shots to prove a dispersion difference can change. Dispersion can be assessed via Extreme Spread, Mean Radius or an average of the standard deviations in X & Y. The average of the Horizontal and Vertical standard deviations in my opinion is the best option, as will be shown shortly. Using the Student's T test, if 95% confidence is an acceptable level of confidence, the required number of shots to be fired for the 12.2% difference in dispersion is shown in Figure 10 for the three dispersion metrics mentioned.

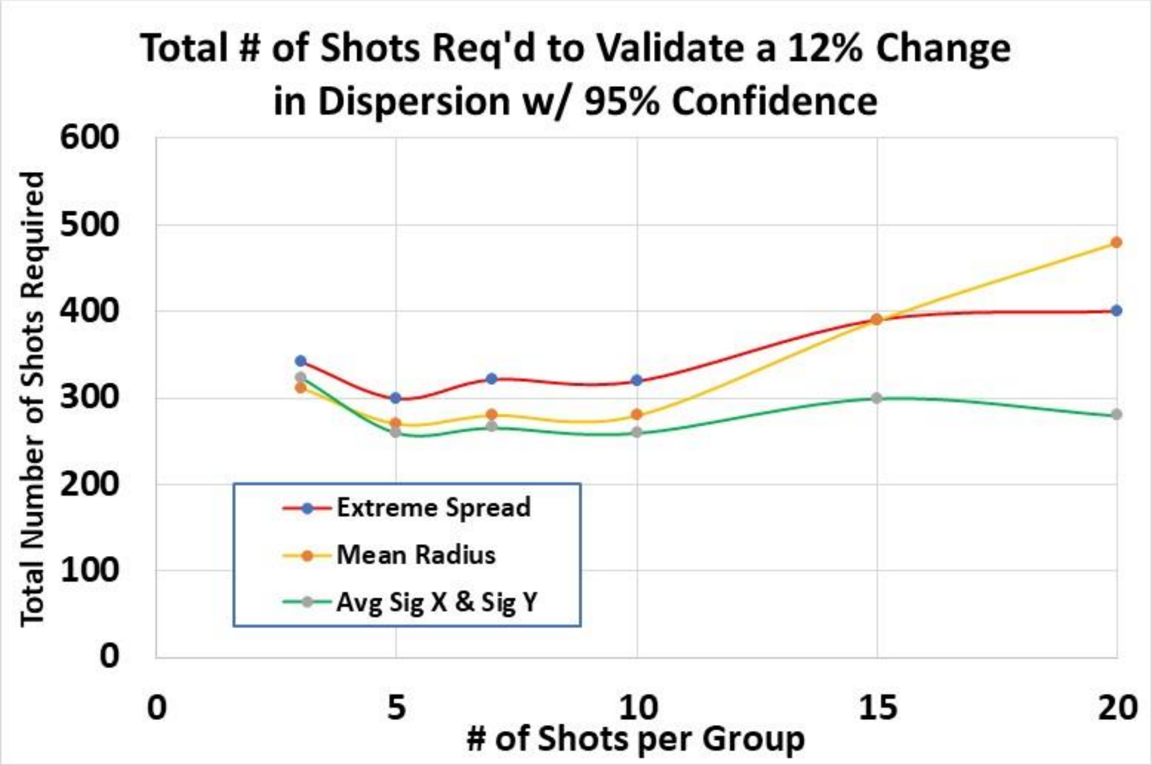


Figure 10: Number of Shots Required to Validate Dispersion Reduction vs. Dispersion Metric

If the dispersion metric chosen is the Average of X&Y Standard Deviations, firing targets with five shot group, approximately 260 rounds would be required (130 test articles plus 130 controls) to validate the 12.2% reduction in dispersion at 95% confidence level. A total of a minimum of 270 rounds would be required for the Mean Radius dispersion metric, and 300 rounds would be required for the same statistical confidence using the Extreme Spread dispersion metric.

Summary

It appears that so called "muzzle tuners" are only able to reduce dispersion in limited situations, namely when the static maximum bore centerline deflection is vertically below the centerline of the straight line defined by the center of the bore at the origin of rifling and the center of the bore at the muzzle. In this situation, the mass of the muzzle tuner, combined with the effects of gravity, tends to make the bore centerline closer to perfectly straight, helping to reduce the interaction between variations in bullet initial position, in-bore forcing function and the resulting barrel motion in a direction perpendicular to the bore at muzzle release. For other orientations of the bore maximum deviations, the expected dispersion is larger, and small movements of the tuner mass are expected to result in only minor changes in true dispersion.