

PPL PEF Methodology and Testing Procedure

March 28, 2025

Purpose

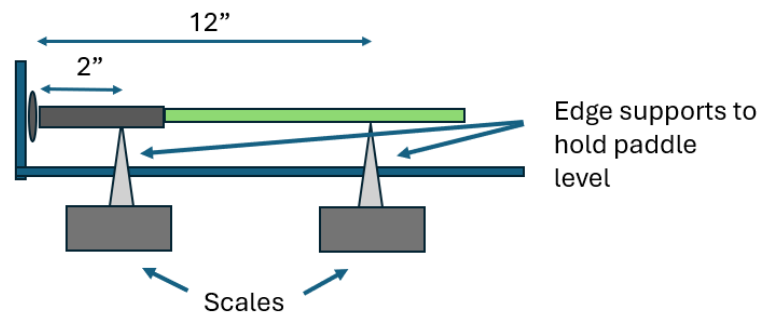
The paddle-ball coefficient of restitution (PBCOR) isolates the paddle's "trampoline effect". This metric quantifies the collective energy lost during the paddle-ball collision and isolates paddle performance from other factors in a collision test, such as inertial effects.

Preparation

1. Qualify balls for use in PBCOR procedure (refer to PPL Ball Qualification Procedure)
2. Condition Paddle and Balls
 - a. Paddles and balls must be stored in a conditioned environment for a minimum of 4 hours prior to any testing or measurements are taken.
 - i. Temperature requirement: $72^{\circ} \pm 2^{\circ} F$
 - ii. Relative humidity requirement: $50\% \pm 10\%$
3. Prepare Scales
 - a. Verify scale calibration using a calibrated weight set
4. Determine paddle face that will be impacted
 - a. Default face to be impacted will be the face with the lowest ADF
 - b. PPL reserves the right to impact either or both faces of the paddle

Procedure

1. Measure and Record the Weight of the Paddle (refer to Figure 1)
 - a. Place the scales 10" apart from their centerlines.
 - b. Place apparatus equipped with two $\frac{1}{16}$ in thick knife edge support blocks that are 10" apart on the center of both scales.
 - c. Tare the scales
 - d. Record weight measurements at both the 2" (W_2) and the 12" (W_{12}) locations to the nearest 0.005 oz



2. Measure and Record the Length of the Paddle
 - a. Use a fixed ruler, or another tool capable of measuring the length of the paddle to the nearest $\frac{1}{32}$ in
3. Determine the Balance Point of the Paddle
 - a. Refer to ASTM F2398–11. The Balance Point (BP) of the paddle is the distance from the butt end of the paddle to the Center of Gravity (CG) of the paddle (refer to Figure 2)
 - i. Use equation 1 to obtain balance point value.

$$BP = \frac{(2 \times W_2) + (12 \times W_{12})}{W_2 + W_{12}} \quad (1)$$

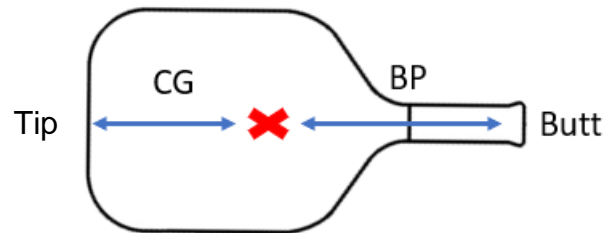


Figure 2

4. Obtain Moment of Inertia (MOI) Value for Paddle (refer to Figure 3)

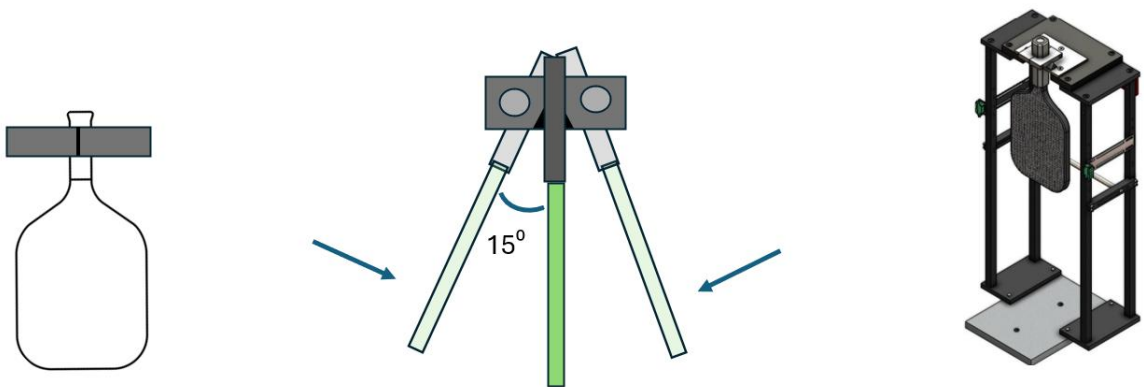


Figure 3

- a. Attach the MOI clamp so the pivot point of the clamp will be 2.0" from the butt end of the paddle.
- b. Place the paddle with clamp on the MOI apparatus.

- c. Populate MOI Software Application with necessary information and run paddle MOI Application to obtain the average frequency of the swinging paddle. Obtain 3 valid readings (within a .01 standard deviation) and take the average of the 3 valid readings (T).

- i. Use equation 2 to calculate the center of percussion (COP).

$$COP = \frac{T^2 g}{4\pi^2} ; \text{ where } g = \text{gravity constant} \quad (2)$$

- d. Use equation 3 to calculate the MOI of the paddle about its pivot point location (in this case, 2.0" from the butt end of the paddle)

$$MOI_{location} = W_p(BP - \alpha)COP - I_c \quad (3)$$

where

$I_c = \text{moment of inertia of the clamp}$

$W_p = \text{weight of the paddle}$

$\alpha = \text{distance of pivot point from the butt of the paddle}$

- 5. Select 6 balls for use in PBCOR procedure
 - a. Balls must meet qualification requirements as defined in PPL Ball Qualification Procedure
- 6. Obtain PBCOR values (the following procedure is based on ASTM F1890 and F2219, refer to them for further reference)

Top View

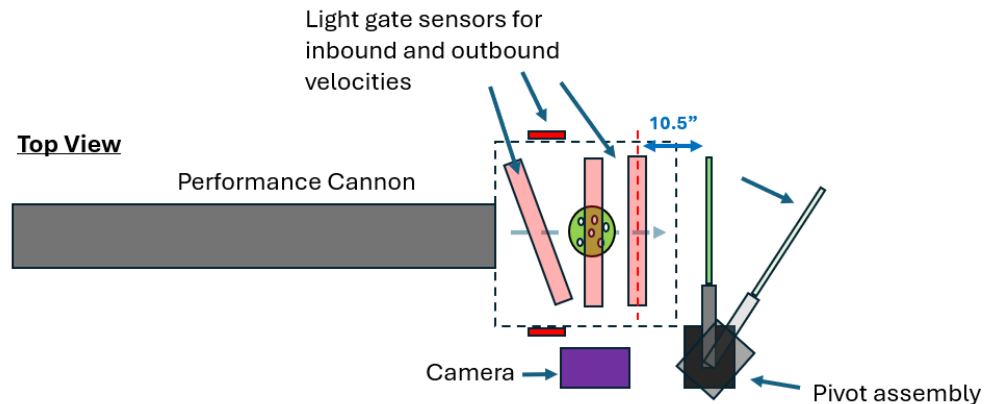


Figure 4

- a. Clamp the paddle in the performance cannon apparatus so that the pivot point of the paddle clamp is 2.0" from the butt end of the paddle. Paddle should be oriented so that the ball will impact paddle face at 90 degree incident angle

- b. Load and properly orient ball into the cannon. Appropriate orientation will ensure the targeted ball quadrant will be impacted on the pending impact.
 - i. Balls are divided into four quadrants, Q1-Q4. After each impact the appropriate quadrant is marked so that total impacts can be tracked.
 - ii. All balls for PBCOR testing will have undergone a minimum of eight impacts and all balls shall be retired after experiencing a total of 48 impacts (12 impacts per quadrant).
 - iii. To identify the appropriate impact quadrant, review the impact tracking marks. If all quadrants have been impacted an equal number of times, the next quadrant to be impacted shall be Q1. If all quadrants have not been impacted an equal number of times, the next quadrant to be impacted shall be the lowest number quadrant with the fewest number of impacts.
- c. Pressurize the air cannon to a pressure that will produce the desired inbound ball velocity. The inbound ball velocity target shall be 50 mph +/- 1 mph.
- d. Input the relevant paddle, ball and test data into the PBCOR Software Application
- e. Align the paddle in the X and Z direction so that the zero position is at the tip end of the paddle and on the paddle centerline (see Figure 5). A laser alignment tool can be used to identify the cannon's target location.
 - i. It is common practice in the sport to refer to the impact location as the distance from the tip end of the paddle. For example, when hitting on the 6" location, this means a location that is 6" from the tip end of the paddle.

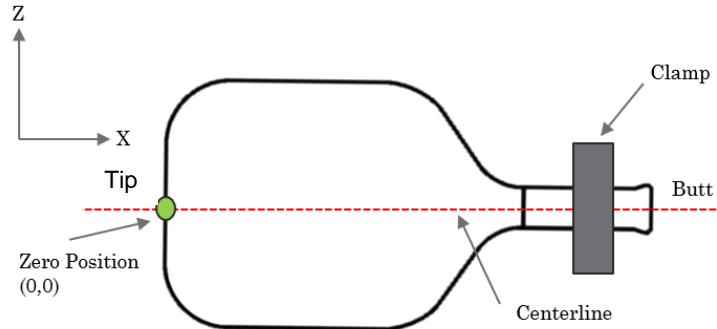


Figure 5

- f. Shoot the cannon with the targeted velocity and at the target location on the paddle
- g. Determine valid shot
 - i. The inbound velocity must be ± 1.0 mph of targeted velocity
 - ii. The path of the rebounding ball must be within 10° of the inbound ball path
 - 1. Rebound angle should be validated using a high-speed camera or an array of light gates.
- h. Observe the PBCOR output from the PBCOR Application

- i. NOTE: Appendix A contains the equations that can be used to verify or manually calculate PBCOR values
 - ii. NOTE: Appendix C contains details regarding how the Qualified Ball's COR properties are accounted for in the PBCOR calculation.
- 7. Utilizing a ball that is different from the ball used for the last impact, repeat steps 6b – 6h until 6 valid PBCOR readings at each impact location have been obtained.
 - a. NOTE: When testing locations near the tip end of the paddle face, paddle out velocity data can be used to determine the PBCOR of that location. Refer to Appendix B for details
- 8. The average of the 6 valid PBCOR readings at each impact location shall be the reported PBCOR value for a particular impact location.
- 9. Continue testing until the paddle's maximum PBCOR value ($PBCOR_{max}$) has been determined
 - a. To find the maximum PBCOR location, ' X_{max} ', a PBCOR scan must be performed along the face of the paddle (refer to Figure 6). Moving in half inch increments down the centerline of the paddle, PBCOR values shall be measured at each location. For clarity, the identification of ' X_{max} ' has been satisfied once the PBCOR values for locations, along the centerline, on either side of X_{max} have been found whose PBCOR values are at least 0.003 less than $PBCOR_{max}$.
 - i. The requirement to find PBCOR values at least 0.003 less than the $PBCOR_{max}$ on both sides of X_{max} does not mean the locations immediately adjacent to X_{max} must have a PBCOR value of at least 0.003 less than $PBCOR_{max}$, rather, it means the PBCOR scan must continue until a location whose PBCOR value is at least 0.003 less than $PBCOR_{max}$ has been found.

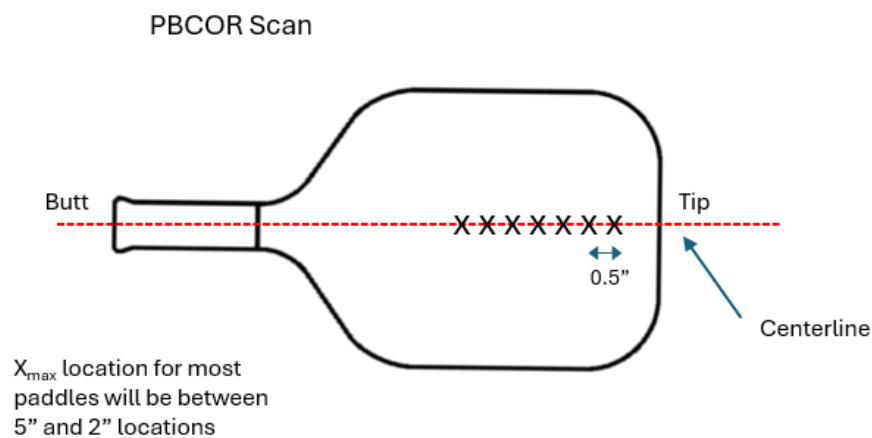


Figure 6

Appendix A

PBCOR Calculation using Ball Out Measurements

PBCOR values can be calculated manually using equation 4.

$$PBCOR = \frac{v_i + v_r}{v_i} \left(\frac{m}{M_e} + 1 \right) - 1 \quad (4)$$

where

v_i = inbound velocity

v_r = rebound velocity

m = mass of the ball

M_e = effective mass

where

$$M_e = \frac{MOI + MOI_p}{Q^2}$$

where

MOI_p = moment of inertia of paddle clamp / pivot assembly

Q = distance between pivot location and impact location

Appendix B

PBCOR Calculation using Paddle Out Measurements

PBCOR values can be calculated manually from Paddle Out Measurements using two methods; equations 5 and 4. The equation 5 method is the straight forward calculation shown immediately below. The equation 4 method, shown further below, uses the Ball Out PBCOR equation except in this instance the ball rebound speed, v_r , is replaced with a Paddle Out-dependent form of the equation, equation 6 or 6'.

$$PBCOR_{paddle\ out} = \left(1 + \frac{M_e}{m}\right) \left(\frac{V_{paddle}}{v_i}\right) - 1 \quad (5)$$

where

V_{paddle} = paddle recoil speed at impact location with units of $\left(\frac{in}{s}\right)$

$$PBCOR_{ball\ out} = \frac{v_i + v_r}{v_i} \left(\frac{m}{M_e} + 1\right) - 1 \quad (4)$$

$$v'r = (MOI + MOI_p) \left(\frac{\omega}{mQ}\right) - v_i \quad (6)$$

where

ω = paddle rotational speed with units of $\left(\frac{rad}{s}\right)$

Substitute the $v'r$ for v_r in equation 4
Equation 6 can be put in terms of V_{paddle} using equation 7

$$V_{paddle} = \omega \times Q \quad (7)$$

The resulting $v'r$ equation becomes:

$$v'r = (MOI + MOI_p) \left(\frac{V_{paddle}}{mQ^2}\right) - v_i \quad (6')$$

Appendix C

PBCOR Correction based on Quadrant COR Measurements

PBCOR can be sensitive to ball variation. To achieve a more repeatable and accurate measure of PBCOR we must apply a correction factor to account for variances in ball performance that have a negative effect on the repeatability of PBCOR.

We have seen that balls have quadrant-dependent COR performance. Our PBCOR equations account for this quadrant-dependent performance by introducing a correction factor. The correction factor is calculated and applied to PBCOR results as follows.

$COR_{expected}$ = average ball COR of the lot of balls which qualified balls have been pulled from

$$PBCOR_{corrected} = PBCOR_{measured} + (COR_{expected} - C_Q)$$

where

C_Q is the quadrant-specific COR value defined in the Ball Qualification SOP