Regulating the Performance of Baseball Bats

by Alan M. Nathan

The game of baseball as played today at the amateur level is very different from the game I played growing up in the early 1960s. In my youth, wooden bats were the only option. Now, almost no one outside the professional level uses wooden bats, which have largely been replaced by hollow metal (usually aluminum) or composite bats.

The original reason for switching to aluminum bats was purely economic: aluminum bats don't break. However, in the more than 40 years since they were first introduced, they have evolved into superb hitting instruments that, left unregulated, can significantly outperform wooden bats. Indeed, they have the potential of upsetting the delicate balance between pitcher and batter that is at the heart of the game itself. This state of affairs has led various governing agencies (NCAA, Amateur Softball Association, etc.) to impose regulations that limit the performance of non-wooden bats.

The primary focus of this article is to discuss the science behind the regulation of bat performance. This will require a precise working definition of what we mean by "bat performance" as well as a consideration of the properties of a bat that determine its performance. That will lead naturally to a discussion of why aluminum is better, how to measure performance in the laboratory, and the approach used by the NCAA to regulate the performance of bats.

Qualitative Features of the Ball-Bat Collision

We start with a brief introduction to the important features of the ball-bat collision. First refer to Figure 1, which was captured from a high-speed video clip from a laboratory experiment done at the University of Massachusetts Lowell Baseball Research Center. It shows the baseball in contact with the bat at the exact moment when the ball is compressed to its maximum. Notice how distorted the ball becomes as it wraps itself around the cylindrical surface of the bat. The process of compression followed by recovery is very inefficient, as the strands of wool that make up most of the volume of the ball rub together, creating a lot of heat. That heat represents energy that is lost, or dissipated, to the kinetic energy of motion of the ball. The technical term that characterizes this dissipation of energy is the called the "coefficient of restitution," or COR, and the fraction of the initial energy that is dissipated is 1-COR2.

Figure 1

A less technical term for this phenomenon is the "bounciness" of the ball, which can be explored by dropping it onto a hard rigid surface, such as a thick steel plate, and observing how high it bounces. A perfectly elastic ball, such as a superball, will bounce nearly to its initial height. Such a ball would have almost no energy dissipated and a COR close to 1. A completely inelastic ball, such as one made of putty, would hit the plate and die. Such a ball would have all its energy dissipated and a COR of 0. For a baseball at typical collision speeds, about ¾ of the energy is dissipated, so the COR is about 0.5, halfway between perfectly elastic and completely inelastic.

As we will see, the COR of the ball plays a significant role in the efficiency of the ball-bat collision. (By the way, from time to time baseball pundits speculate whether the ball is "juiced", usually during periods when home run production greatly exceeds expectations. In our language, "juiced" means an elevated COR.)

Next refer to Figure 2, which shows a motion analysis experiment done at the Washington State Sports Science Laboratory. High-speed cameras were used to track the incoming slow-pitch softball and three different markers on the bat, with the different symbols showing the locations at 1/1000-second intervals. By looking at the distance between successive points, you can get some indication of the speed.

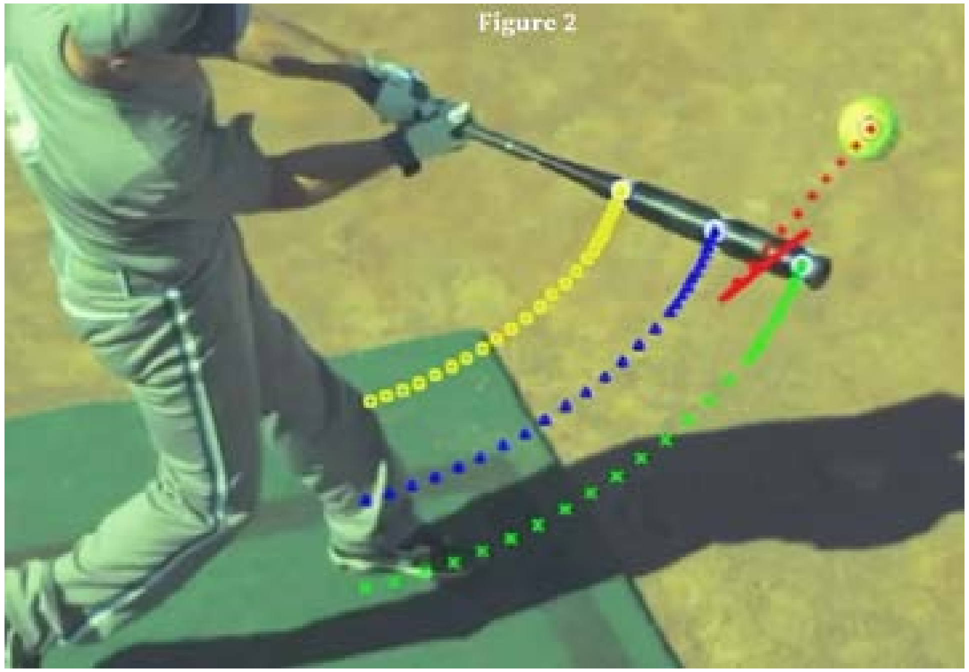


Figure 2

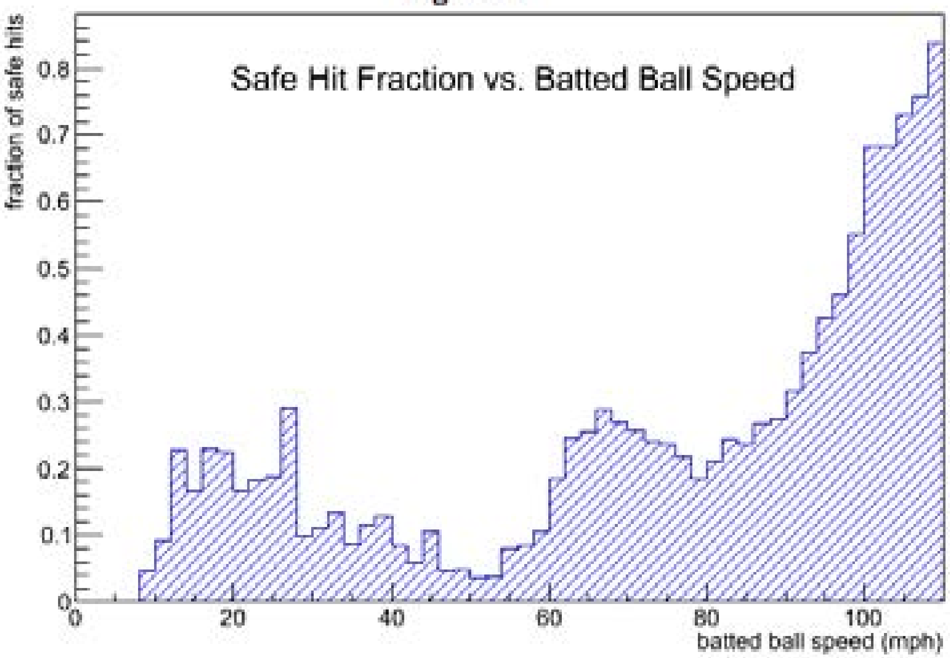
First, note the incoming pitch is moving very slowly, as is appropriate for slow-pitch softball, whereas the outgoing batted ball is moving significantly faster. From this we learn that bat speed plays a very important role in determining the batted-ball speed. Next, note the bat is moving at progressively higher speeds as one moves closer to the barrel tip, an indication the bat is being rotated. In fact, careful analysis of the video shows the bat is being rotated about a point very close to the knob of the bat. Finally, note the bat slows down significantly after making contact with the ball. This is a consequence of Newton's "action/reaction" law. The bat exerts a force on the ball, so the ball must exert an equal and opposite force on the bat, slowing it down.

Defining Bat Performance

Any discussion of bat performance needs to begin with a working definition of the word "performance." We probably have some intuitive feeling about what this means, but that is not good enough for present purposes. After all, if we want to regulate the performance of non-wood bats, then at the very least we need to quantify what we mean by performance. So, let's sharpen up the question by asking a slightly different question.

Suppose we say, "Bat A outperforms bat B." What exactly do we mean by that statement? Among people who have thought about this question, a consensus has emerged that a good working definition of performance is batted-ball speed in a typical game situation, which I will denote simply by BBS. Generally speaking, if you want to improve your chances of getting a hit, then you want to maximize BBS, regardless of whether you are swinging for the fences or just trying to hit a well-placed line drive through a hole in the infield. The faster the ball comes off the bat, the better are the chances of reaching base safely.

Figure 3



This is borne out in Figure 3, a plot of the safe-hit fraction versus BBS, as determined from the publicly available HITf/x data from April, 2009. The plot shows that a batter's chance of getting on base increases sharply from 20 percent at 70 mph to reaching 70 percent at 100 mph, independent of the launch angles. These data make it clear that BBS matters a lot and is a very good candidate for a metric of bat performance. So, we will say that bat A outperforms bat B if a generic batter can achieve higher BBS with bat A than with bat B under typical game conditions.

The Only Formula You Need to Know

Now that we have decided on BBS as our metric of bat performance, we can then ask what BBS depends on. We answer that by writing down the following formula, the only one you will see in this article:

BBS = q*(pitch speed) + (1+q)*(bat speed).

This "master formula" is remarkably simple in that it relates the BBS to the pitch speed, the bat speed, and a quantity q that I will discuss shortly. It agrees with some of our intuitions about batting. For example, we know that BBS will depend on the pitch speed, remembering the old adage that `'the faster it comes in, the faster it goes out." We also know that a harder swing—i.e., a larger bat speed—will result in a larger BBS.

All the other possible things besides pitch and bat speed that BBS might depend on are lumped together in q, which I will call the "collision efficiency." As the name suggests, q is a measure of how efficient the bat is at taking the incoming pitch, turning it around, and sending it out at high speed. It is a joint property of the ball and bat and can assume values between -1 and +1. All other things equal, when q is large, BBS will be large. And of course, the opposite is also true.

Before delving into the properties of the ball and bat that determine q, let's do some numerical estimates. For a typical 34-inch, 31-ounce wood bat impacted at the "sweet spot" (about five to six inches from the tip), q is approximately 0.2, so the master formula becomes:

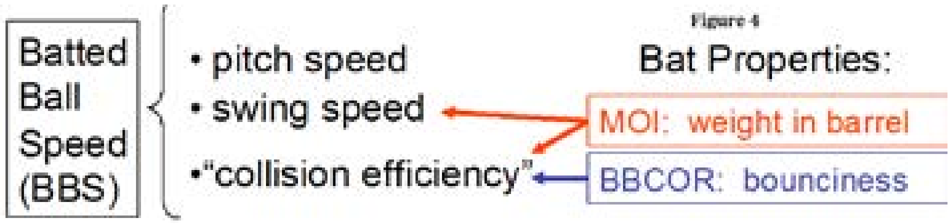
BBS » 0.2*(pitch speed) + 1.2*(bat speed).

This simple but elegant result tells us something that anyone who has played the game knows very well, at least qualitatively. Namely, bat speed is much more important than pitch speed in determining BBS. Indeed, the formula tells us that bat speed is six times more important than pitch speed, a fact that agrees with our observations from the game. For example, we know that a batter can hit a ball off a tee a long way (with the pitch speed zero) but cannot bunt the ball very far (with the bat speed zero). Plugging in some numbers, for a pitch speed of 85 mph (typical of a good MLB fastball as it crosses home plate) and a bat speed of 70 mph, we get BBS=101 mph, which is enough to get you on base about 70 percent of the time. If hitting long fly balls is your thing, a ball hit at that speed and at a launch angle of approximately 270 degrees will carry close to 400 feet. Each one mph of additional pitch speed will lead to about another one foot, whereas an extra one mph of bat speed will result in another six feet. So bat speed matters a lot. We all knew this, but it is good to be able to quantify just how important bat speed really is.

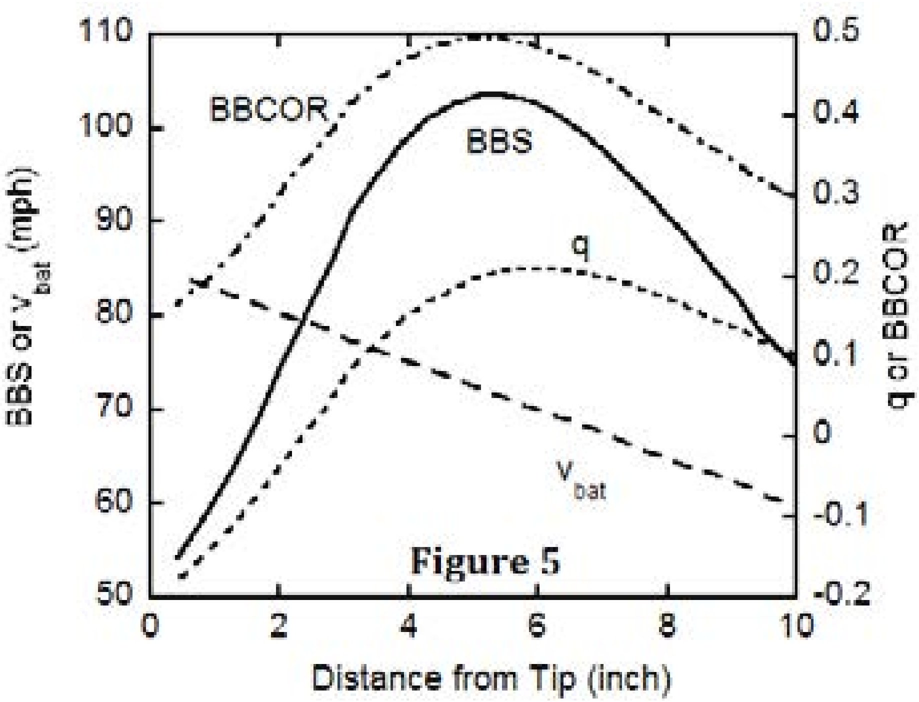
Delving Deeper: The Alphabet Soup of Bat Performance Metrics

Guided by our master formula, let's delve a little deeper to find the properties of a bat that determine bat performance. First, let's eliminate pitch speed as a factor, since it has nothing to do with the bat or the batter. That leaves bat speed and collision efficiency as the important factors. Let's simplify things further by only considering bats of a given length. It doesn't matter what the length actually is, but I want to eliminate that as a variable.

So we now come to the following question: For bats of a given length, what properties of the bat determine BBS? And here's the answer. The only properties that matter are the ball-bat coefficient of restitution (BBCOR) and the moment of inertia (MOI), two more additions to our alphabet soup. In the following paragraphs, I'll explain what these properties are and how they contribute to bat performance.



The interplay among the various quantities is shown schematically in Figure 4. For reference in the ensuing discussion, refer also to Figure 5, a plot of BBS, bat speed, BBCOR, and collision efficiency as a function of impact location along the barrel.



Let's start with the BBCOR. As already discussed, the COR is a measure of the bounciness of the ball collision when it collides with a rigid steel plate. But when a ball collides with a bat, the bounciness may be different, so instead one refers to the "ball-bat coefficient of restitution," or simply BBCOR. When a baseball collides with a wood bat near the sweet spot, the bat behaves very much like the steel plate, so

that BBCOR=COR. However, if the ball is hit off the sweet spot, either toward the handle or the tip, some of the energy is transferred to the bat in the form of vibrations, often resulting in a stinging sensation in the hands. With less energy returned to the ball, the BBCOR is smaller than the COR.

Figure 5 shows the dependence of BBCOR on impact location for a typical wood bat. Note that it reaches a maximum of 0.5, corresponding to minimal vibrations, about five inches from the barrel tip. This is as good a definition as any of the "sweet spot", since it both minimizes vibrations and maximizes BBS. Note also that the collision efficiency, q, more or less tracks with BBCOR: A larger BBCOR leads to larger q, and vice versa. The figure also shows the importance of hitting the ball at or near the sweet spot from the rapidity with which the BBS falls from its maximum value, especially for impacts near the tip.

Before turning to the MOI, let's take a look at a simpler impact of a golf driver with a ball, where essentially all the weight of the club is concentrated in the head. For that case, it is the weight of the club head that plays a role in the collision efficiency. All other things equal, a heavier head will hit the ball harder than a lighter head.

Similar considerations hold for a baseball bat, except in that case, the weight of the bat is not concentrated in the barrel but is distributed along its length. For that reason, it is not the weight of the bat that plays a role but rather the MOI, which depends on both the weight and the weight distribution. For a given weight, the MOI is larger when a greater fraction of the weight is concentrated in the barrel end of the bat. In fact, as a rough guideline, you can think of the MOI as proportional to the weight of the bat in the barrel. A larger MOI means a larger q (and vice versa), in complete agreement with our golf analogy. And all things being equal, a batter will get a higher BBS with a larger MOI bat than with a smaller one.

However, as indicated in Figure 4, all other things are not equal in that the MOI affects bat performance in two different ways: It affects both the collision efficiency, q, and the bat speed. So while a larger MOI means a larger q, it also means a smaller swing speed. The inverse dependence of swing speed on MOI agrees with our intuition and is supported by a considerable amount of current research.

The fact that the MOI affects bat performance in two opposite ways raises an interesting question. If I have two bats with the same BBCOR but with different MOI, which one will have the larger BBS? For example, if I "cork" a wood bat, which reduces its MOI, will the resulting increase in swing speed compensate for the reduction in collision efficiency? Current research suggests that the answer is "no," and that corking a bat does not lead to a larger BBS. By the way, corking a wood bat does have some important advantages, even though higher BBS is not one of them. By reducing the MOI, the batter will have a "quicker" and more easily maneuverable bat, allowing him to wait a bit longer on the pitch and to make adjustments once the swing has begun. So, although corking a bat may not lead to higher BBS, it certainly may lead to better contact more often.

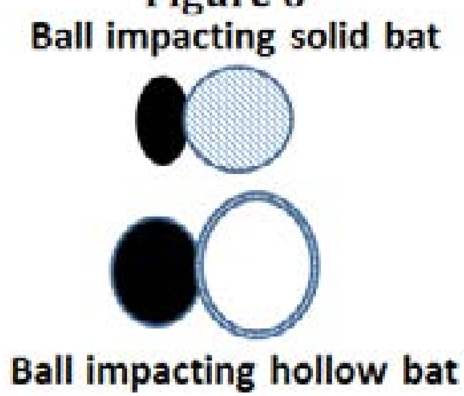
Why is Aluminum Better?

Now let's get to the heart of the matter: Why is an aluminum bat better? To sharpen up the question, let's consider two bats of the same length and weight, one made of wood, the other made of aluminum. What features of these bats will lead to a difference in performance? First, it is very likely that the aluminum bat will have a smaller MOI. Being hollow, as opposed to a solid wood bat, a smaller fraction of its weight will be concentrated in the barrel.

An interesting little experiment you can perform is to take these two bats of the same length and weight (e.g., 34 inches, 31 ounces), one wood and one aluminum, and find the point on the bat where you can balance it on the tip of your finger. You will find that the balance point is farther from the handle for the wood bat than for the aluminum bat, showing that a larger concentration of the weight is in the barrel for the wood bat. What will be the effect of the smaller MOI on BBS? The answer is not much, since there will be a cancelling effect, with the larger swing speed compensated by the smaller collision efficiency. As with the corked bat, there will be no significant change (either increase or decrease) in BBS, although the lower-MOI aluminum bat will have the "quicker bat" advantage.

So, what is the real reason why aluminum generally performs better than wood? The answer is the feature of aluminum bats popularly called the "trampoline effect," which is shown schematically in Figure 6. A hollow aluminum bat has a thin flexible wall that can "give" when the ball hits it, unlike the surface of a solid wood bat. Some of the ball's initial energy that would otherwise have gone into flattening out the ball instead goes into compressing the wall of the bat. While a large fraction of the former energy is dissipated, as we have already discussed, most of the latter energy is very effectively returned back to the ball. As a result, there is less overall energy dissipated, and the BBCOR is larger. The more flexible the wall, the large the BBCOR.

Figure 6



It is not at all atypical for a non-wood bat to have a BBCOR = 0.55, resulting in an increase in BBS of about six mph relative to an otherwise comparable wood bat. For a fly ball on a typical home run trajectory, that will increase the distance by over 30 feet! Indeed, the technology of making a modern high-performing bat is aimed primarily at improving the trampoline effect. For aluminum this is achieved by developing new high-strength alloys that can be made thinner (to increase the trampoline effect) without denting.

The past decade has seen the development of new composite materials that increase the barrel flexibility beyond that achievable with aluminum, giving rise to a new generation of high-performing bats. Left unregulated, aluminum and composite bats can greatly outperform wood bats and upset the delicate balance between pitcher and batter.

As an aside, the trampoline effect also plays a role in other sports, such as golf and tennis. A "wood" driver is no longer made of wood but rather is hollow metal with a thin plate that makes contact with the ball. The trampoline effect results from the flexing of the thin plate. In a tennis racket, the trampoline effect is a result of the stretching of the strings. It is perhaps non-intuitive but nevertheless true that a tennis ball will be hit harder with reduced string tension (as opposed to higher string tension), since the lower tension means more flexible strings, which in turn means more of a trampoline effect.

Measuring Performance in the Laboratory

When testing in the lab, the basic idea is to fire a baseball from a high-speed air cannon onto the barrel of a stationary bat that is held horizontally and supported at the handle. Both the incoming and rebounding ball pass through a series of light screens, which are used to measure accurately its speed. The collision efficiency, q, is the ratio of rebounding to incoming speed. The bat is scanned across the barrel to determine the location of the sweet spot. The MOI is measured by suspending the bat vertically and allowing it to swing freely like a pendulum while supported at the handle. The MOI is related to the period of the pendulum by a standard physics formula. Once q and the MOI are known, these can be plugged into a well-established formula to determine the BBCOR. These three quantities—q, MOI, and BBCOR—can be determined very precisely by these measurements, with no further assumptions.

To determine BBS, the master formula is used along with a prescription for specifying the pitch and bat speeds, the latter of which will depend inversely on the MOI according to some formula. Clearly, assigning a BBS value to a bat requires assumptions about pitch and bat speed, both of which can vary considerably. So it is not possible to predict BBS in any absolute sense. For example, if we are told that a particular bat is a 98-mph bat, that certainly does not imply that 98 mph is the absolute maximum BBS for that bat in the field. However, the BBS value has meaning when making comparisons among different bats. It is only in that relative sense that BBS has any meaning.

Since I am a physicist, I feel compelled to include some brief remarks about how the laboratory measurements can be used to replicate performance in a game situation. To that end, let me bring up three issues where physics plays an important role.

How do we know that measurements done by firing a ball at a stationary bat have anything to do with a game situation where the bat is swung at a moving ball? Physics tells us that the collision efficiency, q, depends only on the relative ball-bat speed. So, if the game situation one is trying to replicate has a pitch speed of 85 and a bat speed of 70, then the laboratory experiment will determine the correct q provided the impact speed is 85+70=155 mph.

The batter's grip in a game situation is not the same as the end support used in the laboratory. Doesn't the collision efficiency depend on how the bat is supported at the handle? The quick answer to that question is "no," but the physics is very subtle. The bottom line is that the ball-bat collision is so rapid that the handle end of the bat does not have time to react before the ball has already left the bat. I have written extensively about this topic, and the interested reader can find lots of information on my web site, http://baseball.physics.illinois.edu/grip.html.

To measure the collision efficiency in the laboratory requires using a baseball, the properties of which can vary. In order to compare one bat to another, how do we take into account variations in the baseball itself, particularly the COR and the stiffness of the ball? As it turns out, this is not a trivial problem. However, guided by our understanding of the physics of the ball-bat collision, techniques have been developed to normalize the laboratory measurements to a baseball with "standard" properties.

The NCAA Bat Performance Protocol

Finally we come to the NCAA bat performance protocol, which has been in effect since the start of the 2011 season. The National Federation of High Schools started using the same protocol starting with the 2012 season. In the interest of full disclosure, I served on the NCAA Baseball Research Panel that devised the protocol in 2008 and recommend its adoption. The panel was charged by the NCAA with developing a standard that would have non-wood bats perform as close as possible to wood. That is, if we have a wood bat (A) and an aluminum bat (B) of the same length, the goal was to have a standard that would assure that the BBS of B would not exceed that of A.

In order to avoid making assumptions about the pitch and swing speed scenarios, which are needed for a direct BBS comparison, it was decided instead to use BBCOR, as measured at the sweet spot, as the performance metric. The reason why BBCOR is a very good surrogate for BBS, at least for comparative purposes, is because the only other property of the bat that matters, the MOI, plays a very small role in determining BBS because of the compensating effect on q and bat speed. It is for this reason that comparing the BBCOR of bat A to bat B is nearly equivalent to comparing the BBS.

Since the BBCOR of a typical wood bat is just under but very close to 0.50 and virtually independent of other construction details of the bat (e.g., the type of wood), the decision was made to set the performance limit for non-wood bats at exactly 0.500. When performing the standard test described in the preceding section, any bat having a BBCOR anywhere along the barrel exceeding this value is not certified for use in NCAA games.

So how well does the new performance protocol work? Prior to 2011, a different performance protocol was used, resulting in non-wood bats outperforming wood bats by as much as five mph. Such a difference in maximum BBS would result in about a 25-foot difference on a long fly ball. Therefore, removing that five-mph gap would be expected to result in a considerable reduction in home run production. And that is exactly what happened. In the two years prior to the new regulations, the average number of home runs per team per game in Division I play was 0.95. In the four years since then, that average has dropped to 0.45, more than a factor of two reduction. Science really does work!

Summary

In this article, I have presented a working definition of bat performance and discussed the features of bats that contribute. I have shown why non-wood bats generally outperform wood bats and shown how to regulate the performance of these bats to make them more wood-like in their performance. Finally, I have shown how the NCAA is currently regulating bat performance, as well as the effect their new protocol is having on home run production.

References & Resources