

TRACKMAN CLUB DELIVERY MEASUREMENTS

RELEVANCE, DEFINITION, ACCURACY, VERIFICATION

TrackMan takes accuracy very seriously and aims to always provide the best product and information possible. TrackMan has spent many hours, resources, and dollars to make sure that the information our customers receive is precise. The following will give the reader some insight into the importance of accurate measurements and how TrackMan verifies the integrity of our data.

REQUEST FOR ACCURACY

TrackMan provides measurements such as Swing Plane and Swing Direction, which relate to a longer duration of the golf swing, but it is the data collected at impact that creates the greatest amount of questions. First, it is critical to understand impact. “The amount of time that the golf club and golf ball are in contact during a given shot is less than 1/2000th of a second. That is less than 0.0005 seconds. To help appreciate how short this is - grab a stopwatch. Generally, stopwatches only show two decimal places after the zero. Now, try to stop and start the clock as quickly as possible. Let’s say you are fast enough to stop it in 0.06 seconds. That’s still more than 100 times longer than the impact interval of a golf shot,” explains TrackMan inventor, Fredrik Tuxen. Of course, such an understanding raises questions about the potential accuracy of measuring data that is so time sensitive. The potential accuracy and the need for limits on what accuracy is acceptable were discussed in the January 2009 TrackMan Newsletter.

The following tables come from the 2009 newsletter article which spoke about defining industry standards for accuracy and why accuracy matters.

Actionable	Data accurate enough to make an objective recommendation that will have an impact on player’s performance.
Marginal	Trained operator may be able to use judgement to make recommendation based on general trends.
Not Actionable	Data not accurate or consistent enough to make a reliable recommendation that will impact player’s performance.

Table 1. Definition of accuracy categories (From January 2009 Newsletter)

Parameter	Actionable	Marginal	Not Actionable
Club Speed	< 2 mph	2-3 mph	> 3mph
Attack Angle	< 1 degree	1-2 degrees	> 2 degrees
Club Path	< 1 degree	1-2 degrees	> 2 degrees
Dynamic Loft	< 1 degree	1-2 degrees	> 2 degrees
Face Angle	< 1 degree	1-2 degrees	> 2 degrees

Table 2. Accuracy requirements

“Because of club delivery’s significant impact on ball flight, it is imperative to require accuracy of Club Path and Attack Angle to be within ± 1 degree with a 95% confidence” stated Tuxen. “What is meant by 95% confidence? That means that 95% of the time the measurement will be within the stated tolerance.” Tuxen continued, “One degree of accuracy might seem a bit strict, but the Attack Angle changes approximately 1 degree during the extremely short time that the club face and golf ball are in contact. Achieving a ± 1 degree accuracy on these data points 95% of the time is extremely difficult. Especially when the player is allowed to hit the ball within a relatively large area, use any club, and have a variety of golf swing flaws or traits.” In order to provide this level of accuracy in all situations, TrackMan introduced the TrackMan III system at the end of 2011.

The TrackMan III and IIIe systems have additional hardware, in order to guarantee the high level of accuracy for the club delivery measurements. “Incorrect data or inconsistent data lead to bad conclusions, which lead to bad information being given to the student. The trust between the student and teacher is a critical part of the learning process and is critical to the instructor’s brand,” concluded Tuxen.

DEFINITION OF CLUB DELIVERY DATA

Equally important as the accuracy discussion is a clear understanding of the definitions being used for club delivery measurements. At first glance, it may seem like a trivial discussion, but experience has shown this understanding is far from trivial. Many poor conclusions have been made simply due to a difference in the definition of what is really being measured. To help improve the understanding of club delivery data, the following definitions are provided.

Attack Angle	The vertical direction of the club head's center of gravity movement, relative to flat ground level, at the point in time of maximum compression of the golf ball*.
Club Path	The horizontal direction of the club head's center of gravity movement, relative to the target line, at the point in time of maximum compression of the golf ball*.
Dynamic Loft	The vertical club face orientation at the impact point on the club face, relative to flat ground level, at the point in time of maximum compression of the golf ball**.
Face Angle	The horizontal club face orientation at the impact point on the club face, relative to the target line, at the point in time of maximum compression of the golf ball**.

Table 3. Definition of club delivery measurements by TrackMan

* Due to changes in the direction of movement of the club head's center of gravity during the impact interval, TrackMan uses the time averaged value which relates closely to the value at maximum compression of the golf ball.

** Due to changes in the impact point and orientation of the club face during the impact interval, the calculated value by TrackMan will relate closely to the value at maximum compression of the golf ball.

It is very important to note that both Club Path and Attack Angle are defined relative to the center of gravity of the club head. This point of measurement is based on the simple fact that the golf ball's movement is a reaction to the club head's mass at the collision. TrackMan measures the movement of the geometric center of the club head and not directly the center of gravity of the club head. However, the difference between the location of the geometric center of a club head and the center of gravity is typically very small (less than 6mm).

Another common misconception regarding TrackMan definitions is the description of Face Angle. Face Angle is not the leading edge (score lines) of the golf club. Also, Face Angle is not the orientation at the center of the club face (unless impact happens at this point). On the contrary, Face Angle is the direction the club face is pointing at the point of impact on the club face at a moment in time near maximum compression of the golf ball.

VERIFICATION OF ACCURACY

Club delivery data is much more difficult to verify compared to other TrackMan data such as Carry and Side measurements. In the case of Carry and Side, a series of measurements including multiple spotters combined with professional survey equipment is generally sufficient in testing and verifying these measurements.

On the other hand, verifying measurements that happen in such an extremely short amount of time as the impact between a club

and a ball is much more complicated. As we discuss accuracy further, note that there are, in general, two types of accuracies: absolute accuracy and consistency.

Absolute accuracy deals with comparing a measured value to the true measurement. For instance, if the real Club Path is zero, then how far away from zero is the measured value. Determining the 'true measurement' is very difficult for club delivery data, but it definitely involves comparing to other technologies, such as high speed video tracking systems or similar.

Consistency means that if the same shot is repeated with the same club, setup, and everything else, then the measurements among multiple shots will be identical. Verifying consistency does not require testing against other technologies.

In golf, where it is important to know if a player has an "in-to-out" or "out-to-in" club path, it is not enough to have high consistency. You must also have high absolute accuracy.

TrackMan verifies its club delivery measurements in a number of ways. Among these are comparing the results with other trusted technologies (primarily multiple high speed video cameras), as well as collaborating with the R&A, equipment manufacturers, and research laboratories that possess the equipment and know-how to conduct such testing.

The following is an example of a shot simultaneously recorded by a TrackMan Ille, including swing video, and an external ultra-high speed video camera.



A driver shot from TM Ille captured with TPS (top); Ultra-high speed video processed by TrackMan's internal R&D system (bottom).

Notice that the Face Angle (CTR) listed on the ultra-high speed image has a value of -0.3 degrees. This value represents the physical center of the club face. However, when the Face Angle value is adjusted to represent the point of impact, which is 10.9 mm towards the toe, a value of +1.9 degrees is returned. As described above in the TrackMan club delivery definitions, the Face Angle reported by TrackMan is relative to the point of impact and not the center of the club face. By using an apple to apple comparison, you see that the TrackMan value of +1.8 degrees matches up extremely well with the ultra-high speed camera measurement of +1.9 degrees. If an incorrect conclusion was made about the Face Angle that TrackMan was reporting, someone may come to their own conclusion that the value is wrong because they would be comparing the value from the center of the club face (-0.3 degrees) versus TrackMan's value of +1.8 degrees. All of a sudden, this apple to orange comparison becomes a 2.1 degree discrepancy.

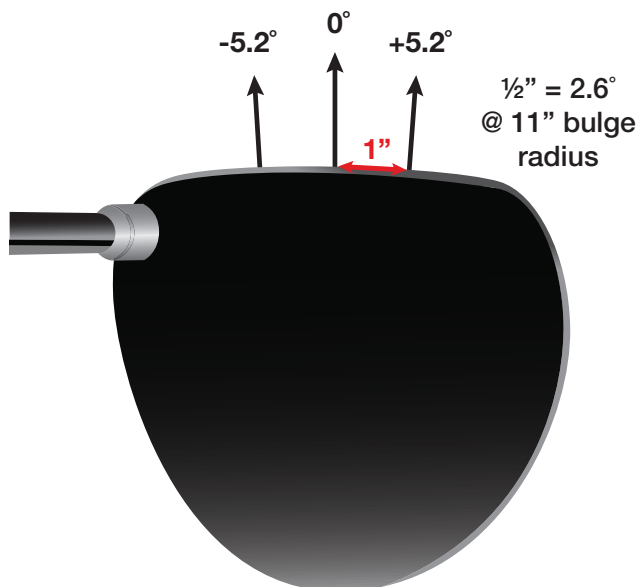


Figure 1. The above picture depicts how the Face Angle at different points on the club face can be dramatically different.

Also, consider the differences between using the center of gravity of the club head versus a point on the club face when reporting the Club Path value. In the above example, the ultra-high speed video returns a Club Path of +1.0 degrees. TrackMan returns a value of +1.3 degrees. Both of these values represent the movement of the center of gravity at impact. If the movement at a point on the club face was mistakenly chosen as the point of reference for the ultra-high speed video analysis, a Club Path value of -1.8 degrees would have been returned. Comparing -1.8 degrees versus +1.3 degrees would have lead to a completely different conclusion about the perceived accuracy of the TrackMan measurement(s).

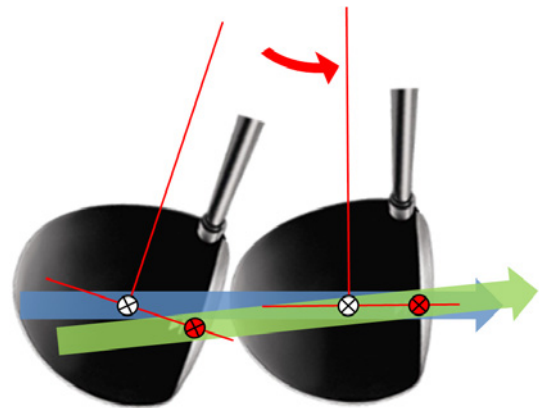


Figure 2. Notice that the center of gravity for the club head (white mark) is moving straight towards the target, while the club face (red mark) is moving out-to-in. This demonstrates how two points on the same object can be travelling in different directions.

Verifying the consistency of the data can be analyzed when shots are hit by an elite level player or a golf robot. The variation of a golf robot from swing to swing is very small. Therefore, it can be assumed that the data output from shot to shot (from a golf robot) should reflect little to no change in the club delivery measurements.

Alternatively, the consistency of the data can be done by having multiple TrackMan systems collect data on the same golf shot at the same time. Please note that this can only be performed with TrackMan III and IIIe systems. A TrackMan II radar can be negatively affected by another radar (all types) positioned directly next to it due to interference.

CHALLENGES WHEN DETERMINING CLUB DELIVERY

Generally speaking, making 3D club delivery measurements using high speed video is not an easy task. Even professionals find it quite challenging. Before you jump in to doing your own high speed camera recordings and try to extract club delivery measurements, here are some precautions:

- Without knowing (the precise) 3D position, orientation, and zoom of the camera relative to the measurement coordinate system, your measurement data will be flawed. A full 3D calibration is required for this, which includes accurate target line adjustment
- The cameras must be so-called 'global shutter' type, which means that all pixels are taken at the same point in time. Cheaper cameras have 'rolling shutter', which is not useful
- Even though it is possible, be very cautious on deriving any club measurements from a single camera. Club delivery is a three-dimensional movement and a camera image is a 2D projection of the 3D event. Consider, for example, the variation of face angle of a 6 iron at different lie angles while keeping the score lines (leading edge) constantly towards the target. From an overhead camera, the lie angle is almost impossible to determine, leading to errors in the face angle determination

- Camera lenses are not perfect, straight lines will not look straight in the captured images – in particular close to the edges of the images distortion is visible. Consequently, the camera(s) need to be lens-corrected. If you change the zoom of the camera, this will in general also change the distortion
- Using markers on the club head, a must to achieving a high level of accuracy, require the exact 3D position of each marker relative to a club head coordinate system to be known. In addition, the marker tracking algorithm needs to be able to precisely track the center of the markers
- Non-uniform light causes objects to appear differently in the images, creating issues for marker tracking
- Once the markers have been tracked, the markers are used to determine the club head 3D position and orientation on a frame by frame basis by matching a rigid model of the club head, which involves fairly complex 3D trigonometry
- Determining the exact time of impact is critical for accuracy of the club data parameters. This should typically involve sub-frame accuracy in the order of 1/5,000 second
- When using multiple cameras, each camera needs to be hardware synchronized so the images are captured at exactly the same point in time

TrackMan detects the club head from the microwave reflection that occurs from the club head. Since the reflection from a club head depends on the shape, material, and orientation of the club head, there are some critical factors when using radar technology for club delivery measurements:

- Variable club heads
- Variable swings (club speed, attack angle, club path, swing plane and/or swing direction)
- Various launch positions of the ball relative to the radar (both side and forward/backwards)

TrackMan has spent a lot of time and effort in making TrackMan club delivery measurements robust for the above variables. The TrackMan III and IIIe has additional, unique hardware added specifically for producing even more robust and accurate club delivery measurements.

ACCURACY OF TRACKMAN

Having carried out multiple tests as described above, TrackMan has determined the accuracy of the club delivery to be as below for TrackMan III and IIIe. Note: the accuracies are at 95% confidence intervals, which are twice as high as compared to the standard deviation (67% confidence interval).

Parameter	Absolute Accuracy (95% confidence)	Repeatability (95% confidence)
Club Speed	±1.5 mph	±0.4 mph
Attack Angle*	±1.0 degrees	±0.6 degrees
Club Path*	±1.0 degrees	±0.6 degrees
Dynamic Loft**	±0.8 degrees	±0.6 degrees
Face Angle**	±0.6 degrees	±0.5 degrees

Table 4. Accuracy of TrackMan III and IIIe.

*The Attack Angle and Club Path assumes that the center of gravity is not located more than 10 mm away from the geometric center of the club head.

**Both the Dynamic Loft and Face Angle refers to the impact location on the club face and assumes that ball impact occurs entirely on the club face. The listed accuracy assumes that the club direction (club speed, attack angle, and club path), ball direction (ball speed, launch angle, and launch direction), and spin rate of the ball are all measured.