

Effect of Equipment on Distance – Driver

1. Executive Summary

This document summarizes the results of research on the effects that various driver design features have on distance. When examining the effects, particular attention is paid to PGA TOUR average distance, as this is the most reliably measured and tracked manifestation of drive distance through time.

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2. Fundamentals of Drive Distance

At impact, the kinetic energy of the golf club is imparted to the ball. The net effect of the impact can be summarized by five parameters, collectively referred to as launch conditions. These are:

- ball speed
- vertical launch angle
- spin
- horizontal azimuth direction
- spin axis inclination

These parameters, combined with the ball aerodynamic behavior and the environmental conditions will determine how far and how close to the intended target the ball will travel.

The basics of golf ball drive trajectories are well-understood. Compared to launch angle and spin, ball speed has the largest effect on distance (R20 - Effect of Equipment on Distance - Golf Balls). The primary determinant of ball speed, and consequently drive distance, is the coefficient of restitution (CoR) of the impact between a golf ball and driver.

The coefficient of restitution (CoR) is the measure of the energy lost in the collision. If, in a collision between a ball and a club there was no energy lost, the CoR would equal one. Based on the construction of the ball and club, some of the kinetic energy is lost in the collision.

In terms of driver design, club head flexibility and therefore CoR is directly affected by parameters such as driver face thickness, material and face area. The table below illustrates the effects of the CoR on drive distance.

3. Coefficient of Restitution

It can be shown from the conservation of momentum that the speed of a golf ball increases linearly with coefficient of restitution. For a one-dimensional case:

$$v_{ball} = v_{club}(1 + e) \frac{m_{club}}{m_{club} + m_{ball}}$$

where e is the coefficient of restitution, v is speed, and m is mass. For a two-dimensional case with a low-loft club, ball speed may be approximated by:

$$v_{ball} = v_{club} \cos \theta (1 + e) \frac{m_{club}}{m_{club} + m_{ball}}$$

Where θ is the angle of incidence. The effects on distance may be determined by using the above equation (assuming, for example, a club mass of 205g, a ball mass of 45.7, and an angle θ of 10°), and subject to certain assumptions regarding golf ball aerodynamic properties, dimensions, and spin.

In the result that follows, characteristics of a modern TOUR-specification ball are used in trajectory simulation software including the Overall Distance Standard bounce model.

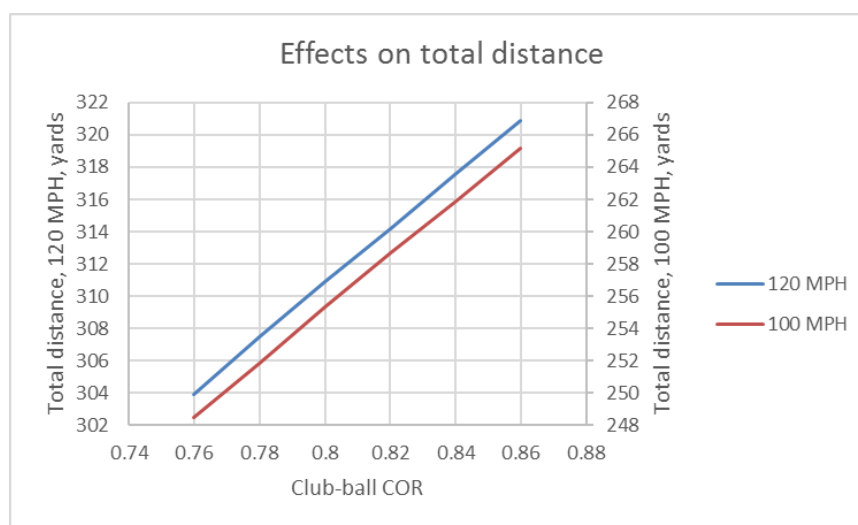


Figure 1 Drive distance as a function of coefficient of restitution at two club speeds.

In this simple case, increasing CoR yields about 1.7 yards per 0.01 CoR. A change of CoR from 0.78 to 0.83 at either speed results in a distance increase of about 8.5 yards.

However, this distance increase is not as uniform as the constant-CoR model implies.

3.1 Impact speed sensitivity

The coefficient of restitution of clubhead-ball impact generally decreases with increasing impact speed. The degree to which this is true varies by the construction of both ball and club. A “0.83” club does not have a CoR of 0.83 at all impact speeds. This is shown in Figure 2 for a typical TOUR-specification golf ball. (Note that the coefficients of restitution are higher than the ‘standard’ values because the ball used is a more resilient golf ball.)

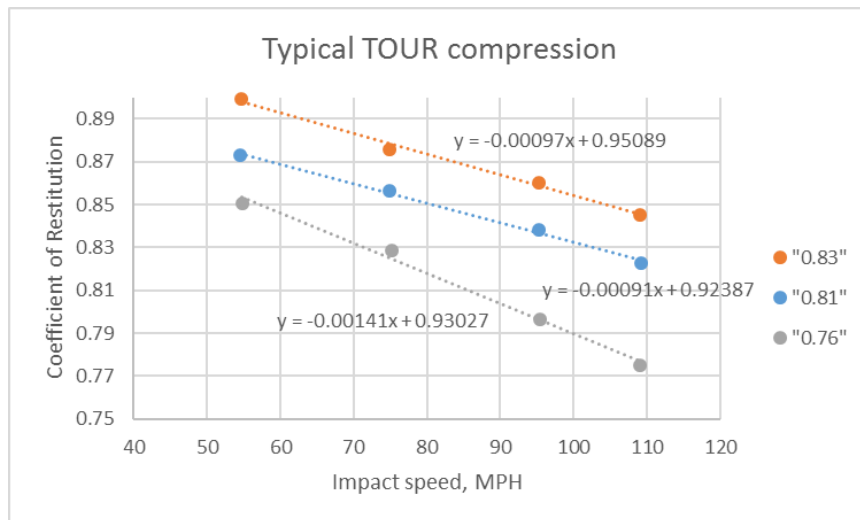


Figure 2 CoR versus impact speed for a TOUR-type golf ball. Note that the CoR of this impact is higher than the number/label because this is a higher CoR ball than the ‘standard’ ball used in the CoR test.

However, a soft or low-compression golf ball has higher sensitivity to impact speed, (Figure 3). An observation from comparing these two charts is that stiffer golf balls gain more from flexible drivers than do softer golf balls.

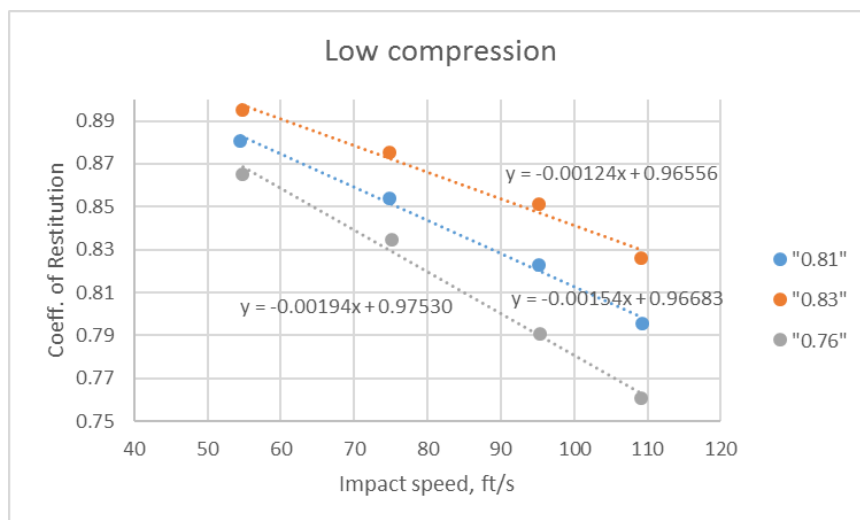


Figure 3 Coefficient of restitution versus impact speed for a modern, low-compression golf ball.

3.2 Ball compression

A previous study using the same flexible impact targets demonstrated that the sensitivity of golf ball CoR to impact speed is strongly affected by the ball's stiffness (or compression), as measured by impact contact time, over a broad range of ball constructions (Golf ball COR sensitivity as a function of ball stiffness, 2011):

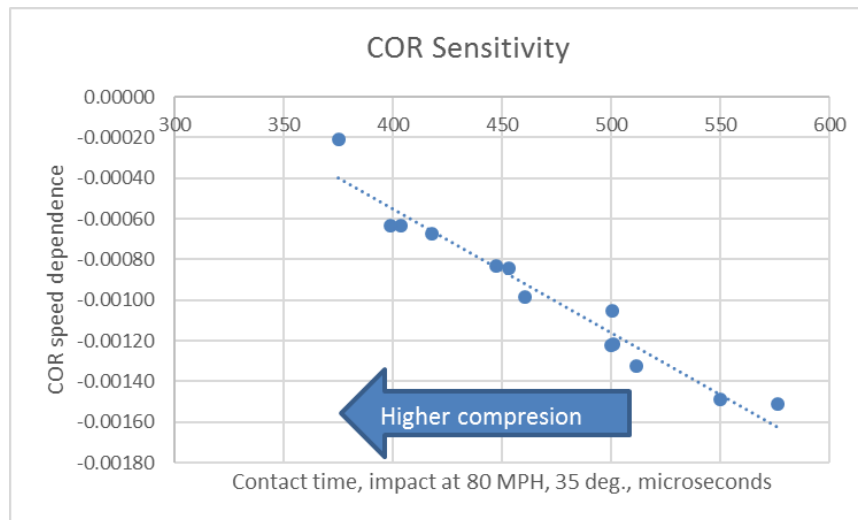


Figure 4 The sensitivity of coefficient of restitution to impact speed. Note that high compression golf balls having short contact times exhibit much lower speed dependence on membrane-type impact targets.

A high-compression golf ball experiences significantly less CoR reduction at high speeds. This is supported by similar work showing that for a flexible impact target, the CoR of a very stiff golf ball was unaffected by impact speed. (Pringle, 2008)

The CoR of the stiffest or highest compression golf ball in the above chart is characterized by:

$$e = 0.8928 - 0.00021v_{initial}$$

Compare this to Figure 3. From this equation, distances can be computed with the ball and trajectory assumptions used in Section 3.1, (Table 1):

Table 1 Effects of club flexibility on distance when ball compression is considered.

Club CoR	Ball compression	100 MPH	120 MPH
Low	Typical	253	304
High	Typical	264 (+11)	317 (+13)
High	High	267 (+14)	323 (+19)

4. Head Size and Moment of Inertia

Section 3 noted that CoR is directly affected by parameters such as driver face thickness, material and face area. All of these parameters have changed over the last several decades.

4.1 Head Size

Historically speaking driver clubheads were made of wood. Because of the density of wood, that material selection limited the size of the clubhead in order to create a clubhead whose weight was

not unwieldy. The constraints held true in the first viable hollow steel driver. Table 2 shows some historic clubs and their sizes.

Table 2 Historic driver dimensions and volume

Year	Make and Model	Height (in)	Length (in)	Volume (cc)
1976	Spalding laminated wood	1.8	3.8	175
1979	TaylorMade Original Steel	1.5	3.4	119
1985	TaylorMade Tour Burner	1.7	3.5	151
1991	Callaway Big Bertha	1.7	3.9	190
1995	Callaway Great Big Bertha	2.0	4.2	275
1997	Titleist 975D	2.2	4.2	280
Modern	Various	up to 2.8	up to 5	up to 460

The clubhead size of drivers has grown over the last 40+ years, and as stated previously, driven mostly by the materials used. With the increased clubhead size there were corresponding increases in the CoR. Persimmon and laminated wood heads typically had CoRs of about 0.78. The earliest hollow steel heads had only slight improvement in CoR, 0.79. Early titanium models had CoRs of 0.8 or more while modern conforming driver heads push the Characteristic Time limit which is equivalent to a CoR of 0.83.

While the first steel driver heads did not provide a significant improvement in CoR they did represent a significant improvement in Moment of Inertia (MOI).

4.2 Moment of Inertia

When a ball is struck at a location off-centre from the middle of the clubhead (towards the toe or the heel), at least two things happen. First, if the impact location is translated purely in a horizontal fashion, the club head will twist primarily about the vertical axis resulting in (i) a reduction in ball speed and (ii) introduction of tilt in the spin axis (often referred to as side spin) via the gear effect. Recognizing this side spin tendency, the clubhead is generally constructed with a bulge radius that launches the ball in a direction that counteracts this side spin. For example, if a driver is hit towards the toe, a hook spin will be generated. The bulge results in the ball starting to the right (for a right handed player) and the hook spin tending to return the ball to the target. In addition, the bulge results in an oblique impact which likely has a tendency to partially offset the gear effect induced spin.

Table 3 shows the Moments of Inertia of the models presented in Table 2.

Table 3 Historic driver dimensions, volume and MOI

Year	Make and Model	Height (in)	Length (in)	Volume (cc)	MOI (g-cm ²)
1976	Spalding laminated wood	1.8	3.8	175	1577
1979	TaylorMade Original Steel	1.5	3.4	119	1716
1985	TaylorMade Tour Burner	1.7	3.5	151	2050
1991	Callaway Big Bertha	1.7	3.9	190	2235
1995	Callaway Great Big Bertha	2.0	4.2	275	2790
1997	Titleist 975D	2.2	4.2	280	3258
Modern	Various	up to 2.8	up to 5	up to 460	up to 5900

4.2.1 Effect of MOI

The effect of a club's vertical axis moment of inertia (I_{zz}) on drive distance has been simulated using two approaches. The first approach was to consider only the reduction in ball speed as the point of

impact is moved away from the centre-of-gravity (cg). The second method included both ball speed reduction as well as predictions for spin rate and spin axis inclination. These were then used in the trajectory simulation program to determine the resulting carry distance. The two approaches appear to provide a reasonable envelope on drive distance reduction for off-centre impacts although there is a significant difference in the predictions.

Experimental data is was used to evaluate the modelling approaches as well as to provide more detail in a narrow range of club head moment of inertia. The experimental data appears to agree reasonably well with the model predictions. Figures 5 and 6 show the simulation and experimental results for carry distance loss and ball speed reduction using both strategies. Also included on these figures are experimental data points from three different drivers.

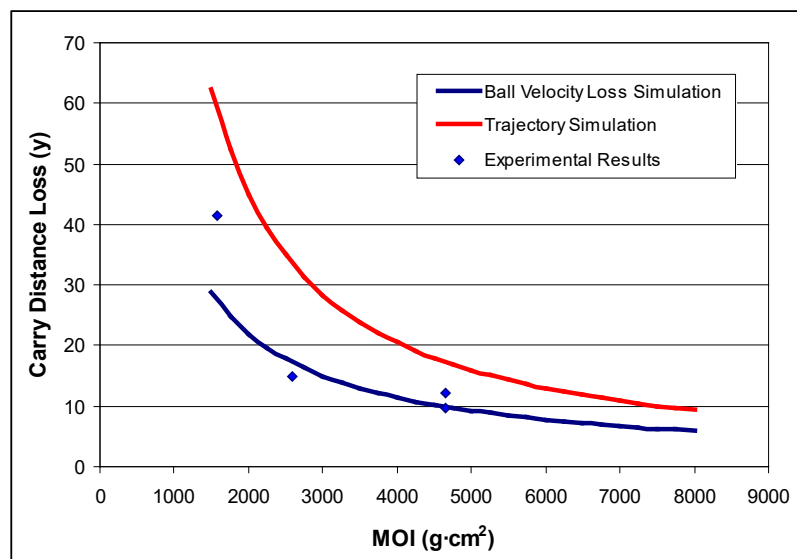


Figure 5 Carry Distance as a function of vertical axis MOI.

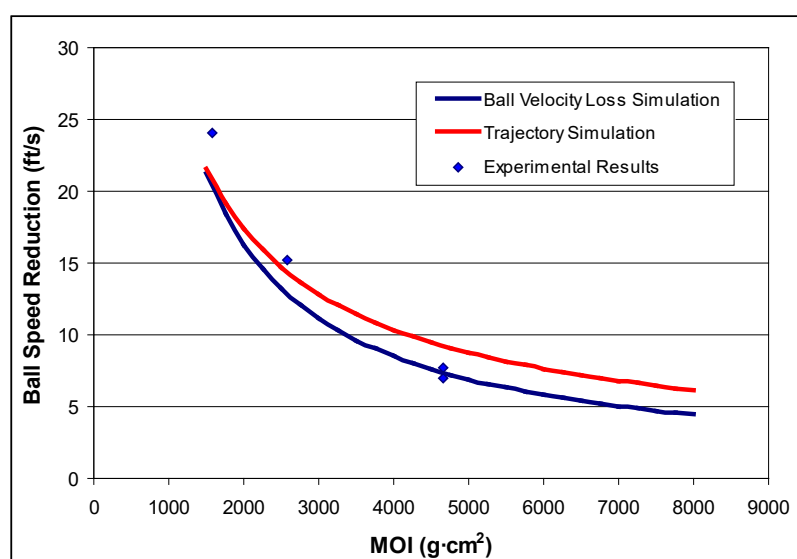


Figure 6 Ball speed reduction as a function of vertical axis MOI

It should be noted that the three clubs used for the experiments were all of different designs and therefore differences between them are not limited to their vertical axis moment of inertia.

To gain further insight into the region of MOI which is highly non-linear (1600 to 2500) a machined clubhead was fabricated with a series of brass weights which permitted variation of only the vertical axis moment of inertia (from approximately 1650 to 2800 g·cm²) whilst keeping everything else the same. The clubhead had a static loft of 11 degrees. The club face had a roll radius of 10" and a bulge radius of 11". A rendering of the club head is shown in Figure 7.

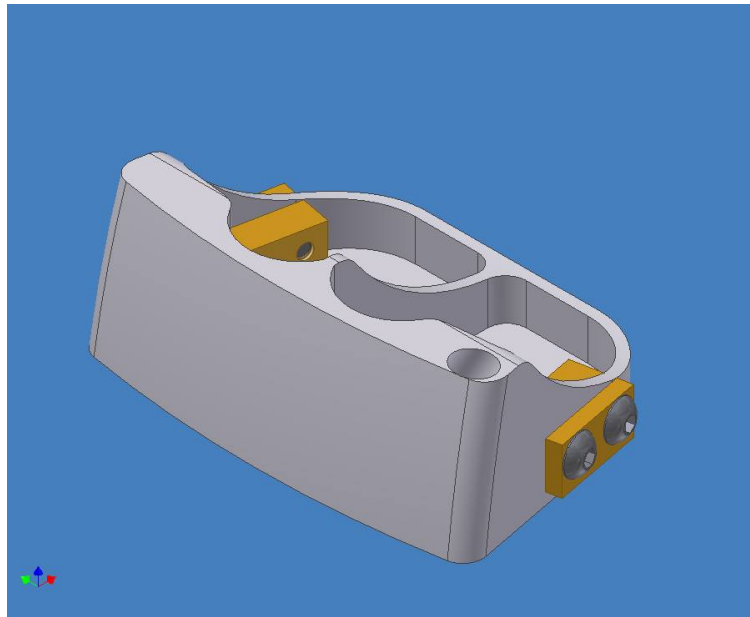


Figure 7 Variable inertia clubhead

4.2.1.1 Procedure for Testing Variable Inertia Clubhead

The following procedure was followed for each of the weight positions.

- 1) The driver was installed in the mechanical golfer. The tee was located precisely at the geometric centre of the club face during impact (carbon paper was used for this purpose). The tee was then moved 7/8" towards the toe and the heel and the impact location recorded. The tee height was adjusted at each of the three locations to ensure that the actual impact was moved horizontally across the face of the club.
- 2) The mechanical golfer was setup using a tour specification golf ball for the following launch conditions using a doppler Radar (Trackman) measurement system:

Ball Speed:	240 ±2 ft/s
Angle:	12 ± 0.5°
Spin	2650 ± 100 RPM

The ball flight was checked to be approximately neutral (neither hooking or slicing) and straight down the fairway.

- 3) Once the golfer was setup for the specified launch conditions, eight shots were recorded. Launch condition data was collected using both a stereoscopic launch monitor and the radar. The carry was also spotted visually and the total distance measured with a laser rangefinder.
- 4) Once the centre shots were recorded, the tee location was moved 7/8" towards the toe, the tee height adjusted as outlined in (1) and eight additional shots recorded.
- 5) The tee was then moved 7/8" from the centre-line towards the heel and eight more shots were recorded.
- 6) The weight position (and hence the vertical axis moment of inertia) was then changed and the process repeated.

4.2.1.1.1 Results and Observations

Tables 4 and 5 summarize the carry and ball speed loss due to the off-centre hits. It should be noted that since the bulge was appropriate only for one particular moment of inertia, the off-centre deviation distance is not relevant and hence is not reported here. The results of the carry distance and ball speed loss are also shown graphically in Figures 8 and 9. The data points in Figures 8 and 9 represent the average distance and ball speed loss for the toe and heel impacts. The range of the respective toe and heel values are indicated by the vertical error bars.

Table 4 Reduction in Carry Distance for off-centre Hits (all data in yards)

MOI	Centre			Toe			Heel		
	Mean	±	Loss	Mean	±	Loss	Mean	±	Loss
1680	262.4	2.4	21	246.8	1.3	16	236.8	2.4	26
1850	270.2	2.4	22	251.7	1.8	19	244.9	2.8	25
2180	266.4	1.6	22	251.7	3.3	15	236.2	2.6	30
2410	268.6	2	19	251.4	1.6	17	248.2	3.6	20
2780	258.5	1.8	11	253.3	0.7	5	241.1*	2.4	17

* ball speed for this test was unexpectedly low

Table 5 Reduction in Ball Speed for off-centre Hits (all data in ft/s)

MOI	Centre			Toe			Heel		
	Mean	±	Loss	Mean	±	Loss	Mean	±	Loss
1680	240.1	0.4	17	225.1	0.2	15	220.6	0.6	20
1850	241.6	0.5	16	225.6	0.5	16	224.8	0.4	17
2180	240.4	0.4	14	226.6	0.6	14	225.6	0.9	15
2410	241.7	0.6	14	228.8	0.4	13	226.5	0.5	15
2780	238	0.4	12	229.2	0.6	9	221.9*	0.5	16

* ball speed for this test was unexpectedly low

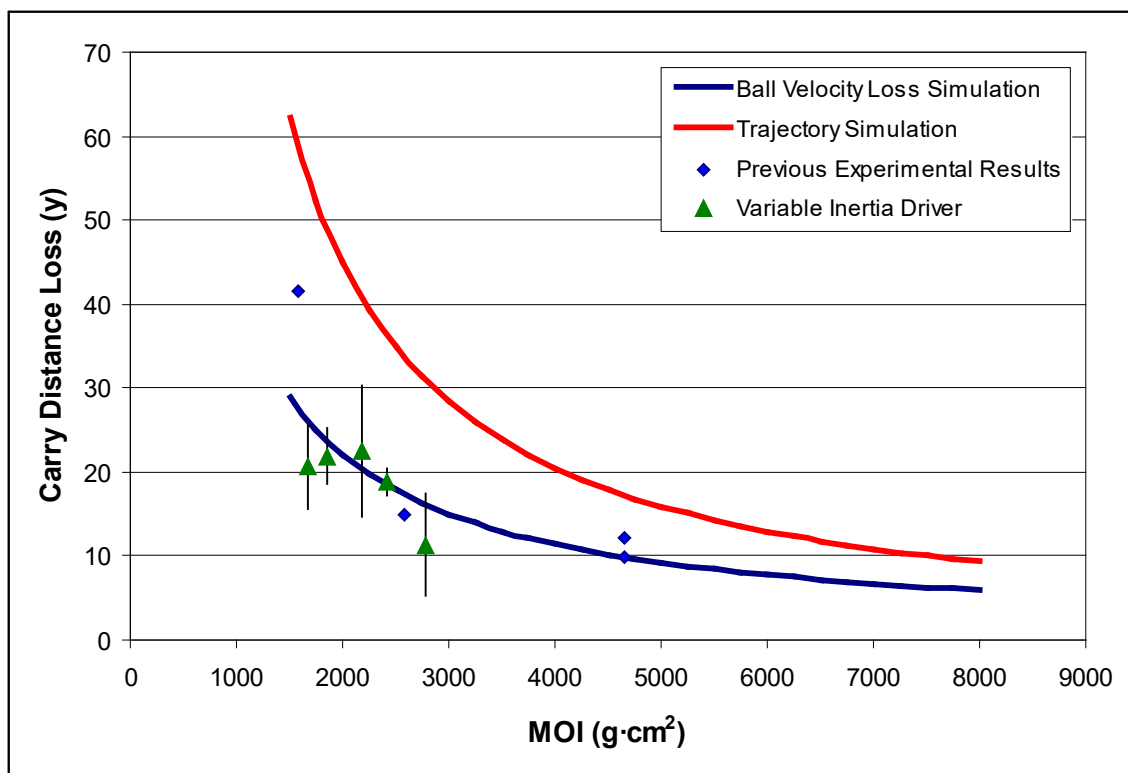


Figure 8 Carry Distance Loss (7/8" Off-Centre Impacts)

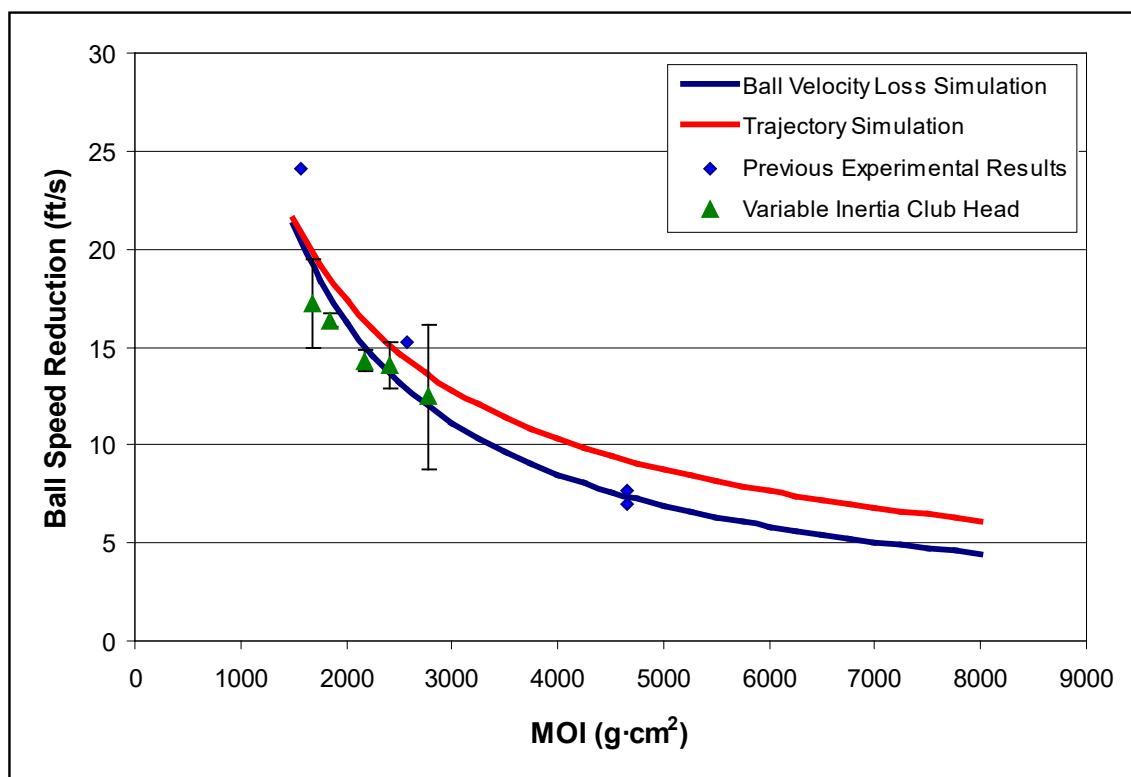


Figure 9 Ball Velocity Loss (7/8" Off-Centre Impacts)

It can be seen in Figure 9 that that ball speed reduction due to off-centre impacts is well predicted by simulation. However, it can also be seen in Figure 8 that the simulation that attempted to capture the spin axis inclination did a poor job of predicting carry distance loss. This simulation used a driver having no face bulge and so the spin axis inclination may have been significantly over predicted. In any case, it appears that the prediction of carry distance loss using only ball speed reduction is the most appropriate (represented by the blue lines in Figures 8 and 9). The carry distance loss reduction for a 7/8" off-centre impact (in yards) may be estimated therefore for the moment of inertia (in g·cm²) by the following equation:

$$\Delta_{\text{Carry}} \approx \frac{29000}{I_{zz}^{0.945}}$$

The measured ball speed reductions compared well with the prediction ball speed reductions as did carry distances based on the predicted ball speeds. Carry distance predictions using spin axis inclination were not as good. It appears that the simulated spin axis inclination significantly over predicted actual performance.

The ball speed reduction is essentially a matter of the basic physics of the impact. The coefficient of restitution of the impact will likely play a role in the impact (since an off-centre impact with a low MOI club is equivalent to a centred impact with a lighter clubhead) but this will be secondary. The measured ball speed reduction is plotted in Figure 10 along with the results of a finite element simulation and a rigid body model (Goldsmith, 1960). It can be seen in Figure 10 that both the experimental data and the two models are in good agreement.

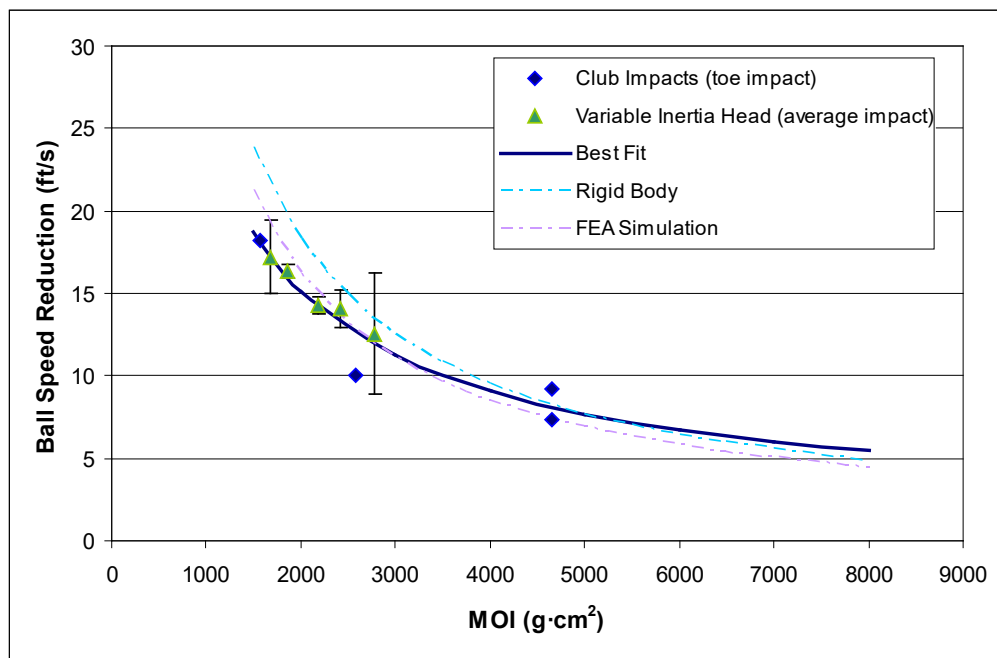


Figure 10 Experimental, finite element and rigid body model of ball speed reduction

4.2.1.2 Launch Angle and Spin

The ball speed reduction is primarily a function of the moment of inertia, the same may not be said of the launch conditions. It is therefore prudent to investigate whether the launch conditions may have any partially mitigating effects the ball speed reduction.

The investigation into any effects uses the following strategy: It assumed that optimal launch conditions are achieved for both the centre impact and the off-centre impact and thus the effect of the ball speed reduction is isolated. The optimum launch conditions were sought for the test ball for ball speeds ranging from 210 to 250 ft/s. The optimal launch angle ranged from 15 degrees at 210 ft/s to 12 degrees at 250 ft/s. Optimal spin was approximately 1900 RPM at all ball speeds. It was found that, at optimal launch conditions, the carry distance (and the total distance also) decreased by approximately 1.15 yards per ft/s in ball speed reduction.

This estimate, along with the best fit equation for ball speed reduction as a function of moment of inertia (for 7/8" off-centre impacts) was used to generate a best estimate for the minimum distance loss for a 7/8" off-centre impact as a function of moment of inertia. This is plotted in Figure 11 (solid line). This minimum carry distance reduction estimate may be calculated via:

$$\Delta_{Carry} = \frac{4830}{I_{zz}^{0.74}}$$

Also plotted in Figure 11 is the best fit carry distance reduction line (above equation) and a best fit carry distance for all the data except the laminated wooden driver. It can be seen in Figure 11 that there is excellent agreement between the estimated minimum distance reduction and the best fit of the experimental data with the laminated driver eliminated.

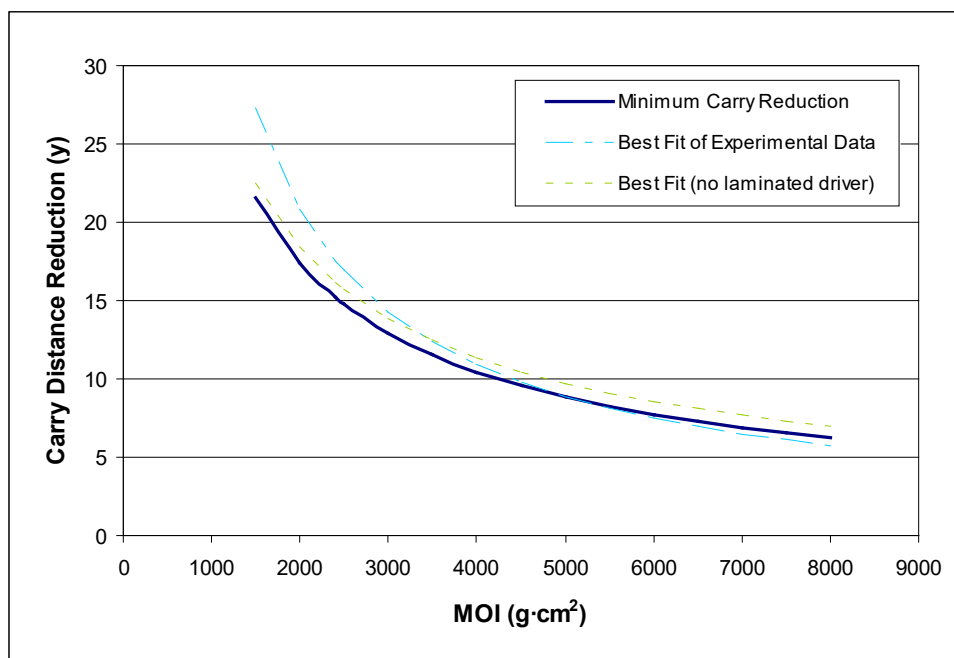


Figure 11 Minimum expected carry distance reduction

4.2.2 Estimating the Effect of Driver Moment of Inertia on PGA TOUR Players

Finite element simulations were performed to estimate the ball speed for different impacts on clubs having different moments of inertia. These ball speeds were then used to estimate the drive distance loss compared to a centre impact. For a centre impact, the drive distance was simulated to be approximately 282 yards. The resulting drive distance loss for clubs having a range of moment of inertia is shown in Figure 12.

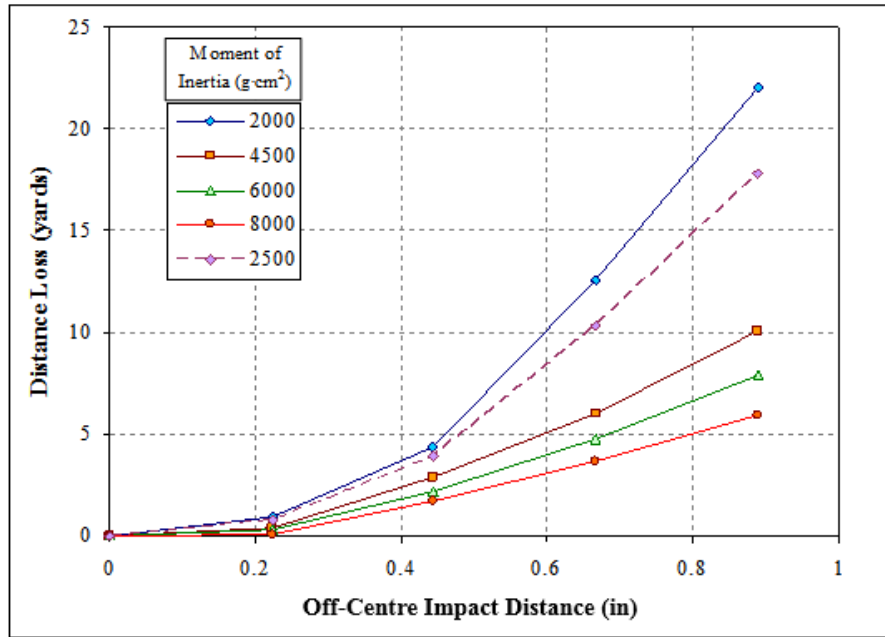


Figure 12 Effect of moment of inertia and impact location on drive distance loss

Each of the individual club responses plotted in Figure 9 can be accurately represented by a function of the form:

$$D = AX^2 + BX$$

where D is the distance loss (in yards) and X is the off-centre impact distance (in inches). The values of A and B for the different club moment of inertia values are given in Table 6.

Table 6 Drive distance loss function parameters

MOI (g·cm ²)	A	B
2000	31.6	-3.1
2500	24.5	-1.6
4500	12	0.8
6000	9.5	0.6
8000	7.1	0.5

4.2.2.1 Simulation of Drive Distance Loss

A Matlab script was compiled to perform a Monte Carlo simulation of the effect of club moment of inertia on drive distance loss given an assumed normal impact location distribution approximately 0.2-in toward the heel of the club with a standard deviation of 0.667, and the effect of impact location on drive distance loss given in Figure 12. In simple terms, the program gets a random impact location (given the statistical distribution) and calculates the resulting drive distance loss. This process is repeated a large number of times (in this case 1,000,000 simulations) resulting in a distribution of drive distance loss.

The result for a club having a moment of inertia value of 2500 g·cm² (in the region where the effect of MOI is very non-linear) as well as a club with a MOI of 4500 g·cm² are shown in Figure 5-9. It can be seen that although large differences are expected for hits well off-centre, the vast majority of impacts are well struck. For example, in 1,000,000 hits, the 2500 g·cm² club would be expected to yield over 2700 drives with distance losses between 40 and 45 yards compared with only 118 for the 4500 g·cm² club. However, even the 2500 g·cm² club is expected to yield 68% of its drives with less than a 5 yard loss which compares reasonably well with the 4500 g·cm² driver that yields 79% of its drives with less than a 5 yards loss. The net result of these two simulations indicates that the 2500 g·cm² driver will average a 5.3 yard loss while the 4500 g·cm² driver will average 3.2 yards; A difference of 2.1 yards. Table 7 summarizes the expected distance loss for each driver MOI level simulated. (Note: the results presented make no attempt to accommodate the effects of club head MOI on driver length or swing speed)

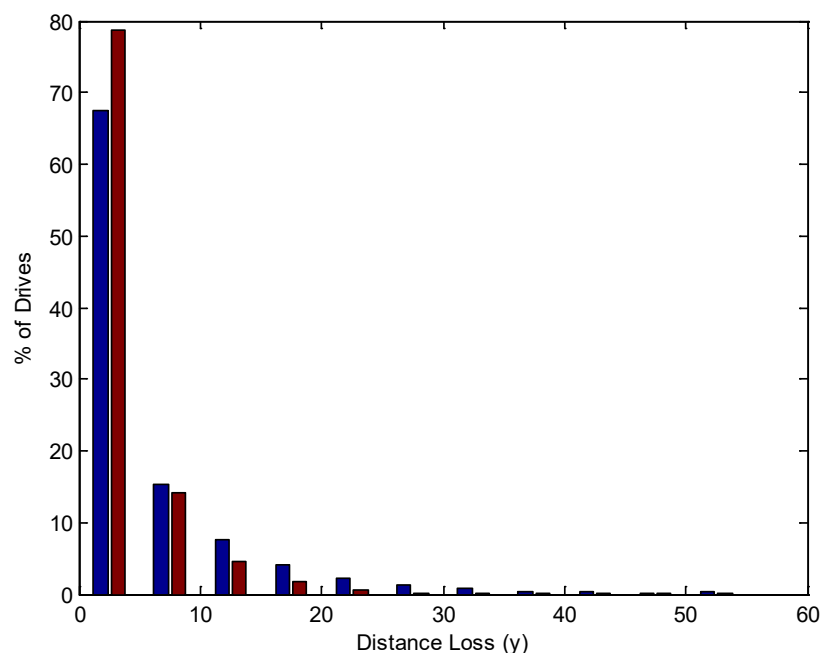


Figure 13 Distribution of distance loss for 2500 g·cm² (blue) and 4500 g·cm² (red) drivers

Table 7 Drive distance loss as a function of MOI for Monte Carlo simulations

MOI (g·cm ²)	Distance Loss (y)
2000	6.4
2500	5.3
4500	3.2
6000	2.5
8000	1.9

The results indicate that the Moment of Inertia has a significant effect on distance on off-centre impacts

5. Other Considerations

5.1 Clubhead Aerodynamics

There is a broad range of aerodynamic performance associated with driver heads. This comes as a result of the introduction of several flat-crown drivers that have dramatically increased drag as compared to other, conventional, rounded-crown designs.

Player testing shows that the difference in aerodynamic drag between these flat-crown drivers and those of the conventional type leads to close to three miles per hour in clubhead speed. This is supported by analytical models that also suggest that eliminating drag entirely (a physical impossibility) would increase swing speed by 2 MPH (given a 120 MPH swing speed with a conventional club). (Quintavalla, Aerodynamic Improvements to Large-Sized Driver Heads, 2008)

5.2 Driver Length

For a given swing speed (in this case hand speed), the shaft length directly corresponds to clubhead speed and consequently to drive distance. The work of six teams of researchers on the effect of club length on drive distance potential has been summarized. (E28-Effect of Club Length on Potential Distance, 2016)

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