Effect of Equipment on Distance – Golf Balls

1. Executive Summary

This document summarizes the results of research on the effects that various ball design features have on distance. Particular attention is paid to PGA TOUR average distance, as this is the most reliably measured and tracked manifestation of drive distance through time. Simulations were then conducted to study the effect of how changing ball parameters such as size, weight, speed or aerodynamics (lift and drag) affected distance. These studies were expanded to a larger cohort of golfers to estimate the effect of changing ball parameters across various skill levels

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2. Fundamentals of Drive Distance

The basics of golf ball drive trajectories are well-understood. At impact, kinetic energy is imparted to the ball. Based on the construction of the ball and club, some kinetic energy is lost in the collision, typically about 6-8% of the pre-impact energy of the clubhead.

After impact, there are three forces acting on the ball in flight: gravity, and aerodynamic drag and lift. Drag, or wind resistance, is the most significant source of energy loss in the drive: where 6-8% of the pre-impact kinetic energy is lost during the collision between the ball and the club, 85% of the ball's initial kinetic energy is lost to drag by the end of a long carry.

Lift is critical in fighting the effect of gravity in order to extend flight time. Under typical circumstances, lift approximately triples the time of flight (compared to a zero-lift ball), leading to significantly longer distance. Lift and drag are both proportional to the cross-sectional area (or the square of the diameter) of the ball. Both aerodynamic forces increase with ball spin, though in a nonlinear way. Finally, lift and drag are affected by the dimple design through what are called the Coefficient of Lift (CL) and the Coefficient of Drag (CD). For example, increasing the CD by 10% increases the drag force on the ball by 10%.

Both aerodynamic lift and drag are proportional to the square of the velocity; a golf ball going twice as fast generates four times as much aerodynamic force. Changes that affect aerodynamic forces would therefore be expected to have a greater effect on longer drives than on shorter drives or iron shots. This is not the case with the speed effects and ball construction.

One final note is the role of ball weight; a heavier ball (at the same speed) contains more kinetic energy. Essentially this means that the ball can carry more speed in the face of wind resistance; the relative effect of drag on the heavy ball is slightly less, and the ball travels further.

3. Basic Parameters of Ball Design and their Effect on Shot Distances

3.1 Ball Speed

The single most substantial factor in how far the ball travels, independently of the player's launch conditions or other factors, is ball speed. It affects both drive and iron distances and is the major factor limiting how far recreational players hit the golf ball.

3.2 Launch Conditions

As ball spin increases, there is an increase in the aerodynamic drag on a golf ball (as well as an increase in the lift). This increased aerodynamic drag reduces distance.

The size (diameter) of the golf ball also affects the aerodynamic forces. Increasing the size of the golf ball increases the aerodynamic forces on the ball, including drag, thereby reducing distance.

3.3 Weight

The weight of the golf ball magnifies the effects of aerodynamic forces. A lighter golf ball doesn't travel as far (e.g., the Cayman ball).

3.4 Dimples/Cover

The size, shape, and distribution of dimples on a golf ball dictate the amount of aerodynamic lift and drag produced. A golf ball with high drag because of its dimple design, will not travel as far as one with low drag. A golf ball with reduced lift will also lose distance, though this can be mitigated to some extent with a high loft driver. Conversely, an extremely high lift ball with a ballooning trajectory will also have a lose distance under normal conditions.

Within limits, lift and drag can be controlled independently in the design of a ball cover. This is not an absolute; a ball with extremely low drag tends to have poor lift qualities, particularly at lower speeds. However, a ball with 'normal' drag can be made with either high or very low lift.

3.5 Relative Effect of Various Parameters

In order to better illustrate how these parameters affect performance, simulations were carried out varying each characteristic individually. Note that the changes in characteristics made in this section and in the remainder of this document were studied in isolation: for example, studying the effects of decreased ball weight did not include the mitigating cross-effects of higher ball speed due to lower ball inertia from rest. The effect of the various changes was evaluated using the baseline aerodynamics of a typical tour ball. The assumed launch conditions associated with each type of shot are given in Table 1.

Table 1 Assumed launch conditions used to study effects of parameter changes on different shot types.

Shot Type	Speed, ft/s	Angle, deg.	Spin, RPM
1w (Driver)	260	9.5	2560
5i	189	16	5280
8i	172	19	6480
PW	131	19	10080

The effects of reducing ball speed, spin, diameter, weight, and drag coefficient on all shot types are shown in Figure 1 through Figure 5.

With respect to Figure 1, it is clear that reducing ball speed has a significant effect on all shot types.

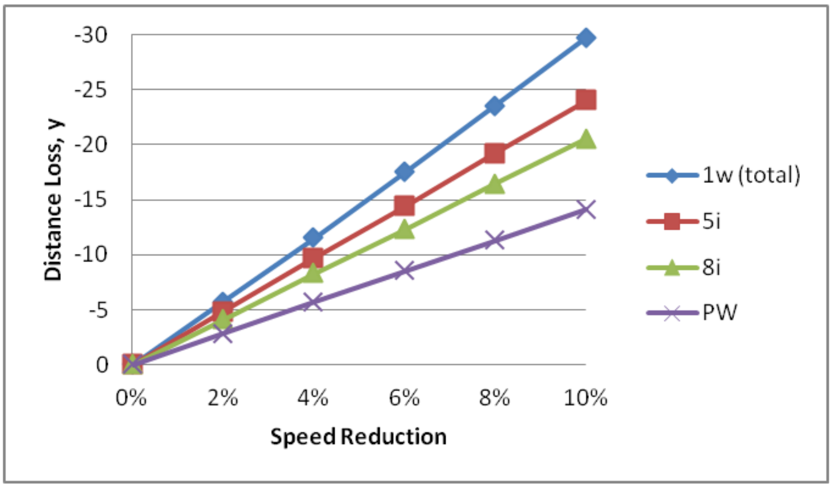

Figure 1 Effects of decreased ball speed on shot distance for different shot types. Effects of large speed reduction are significant for all types of shot. (Carry distance unless otherwise noted.)

Figure 2 through Figure 5 show much smaller effects on iron distances from changes in spin, ball diameter, weight and C_D, although the effect on drive distance is significant.

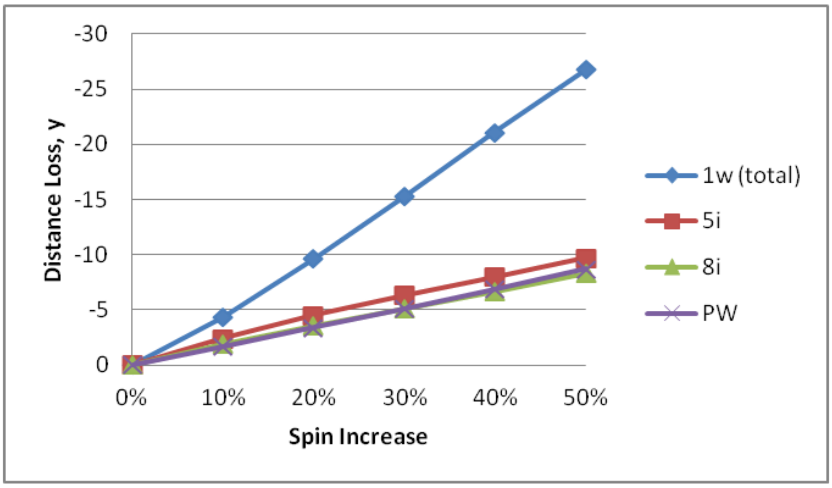

Figure 2 Effects of spin increases on shot distance for different shot types. At large spin rates, 5i-PW curves are approximately parallel. (Carry distance unless otherwise noted.)

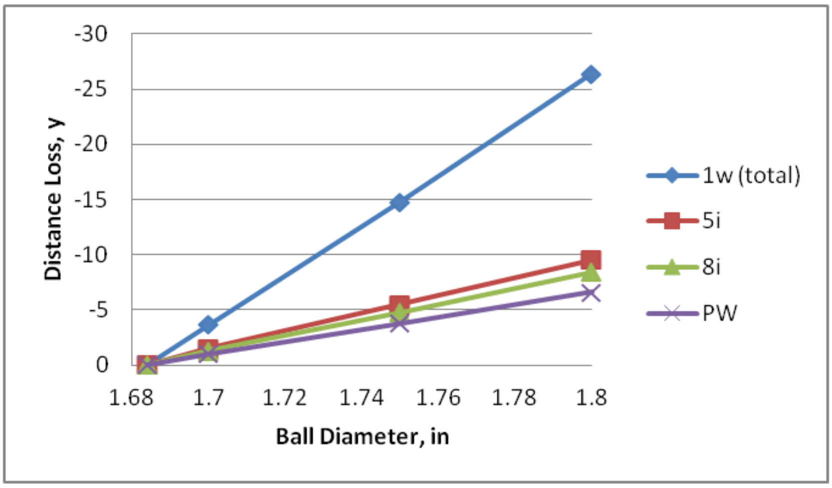

Figure 3 Effects of ball diameter increases on shot distance for different shot types. Distance losses for 5i through PW are better separated as compared to the effects of increased spin. (Carry distance unless otherwise noted.)

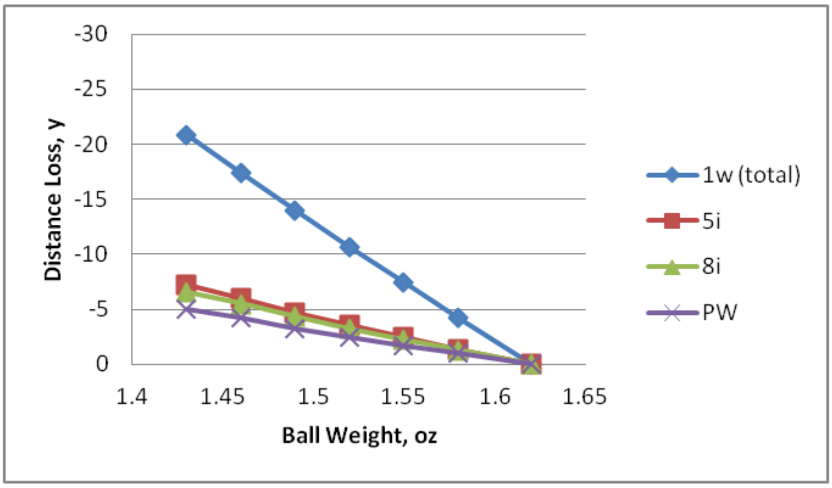

Figure 4 Effects of reduced ball weight on shot distance for different shot types. Note that large changes to ball weight are required to significantly decrease distance. (Carry distance unless otherwise noted.)

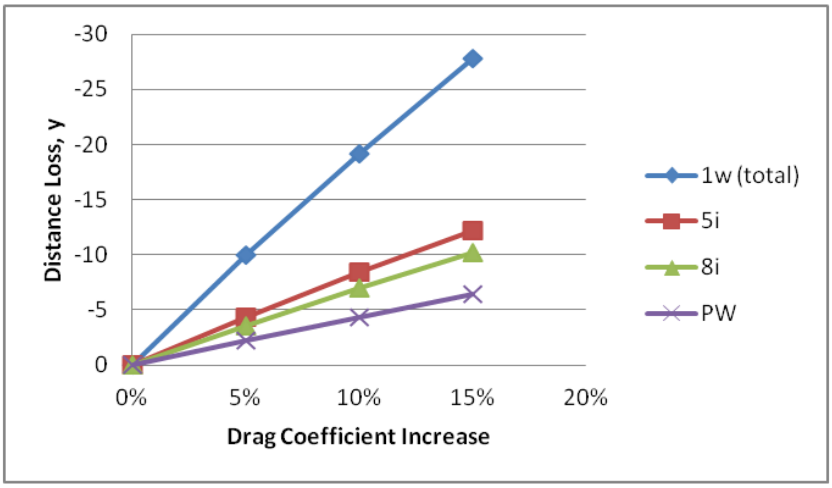

Figure 5 Effects of drag coefficient increase on shot distance for different shot types. Distance change is evident among all shot types. Carry distance unless otherwise noted.

4. Effects of Ball Design Parameter Combinations on Distance

Building on the results presented in Section 3, an exercise was undertaken to understand the relative effects combinations of design changes on distance.

4.1 Methods

The data presented in this section were simulated on the basis of starting with a modern ball and modifying its properties. In this exercise the properties were modified in a way that would create a difference in overall distance of approximately 30 yards using ALC (Actual Launch Conditions).

NOTE: This in no way reflects any contemplation of reducing the overall distance limit. Instead using this value allows the parametric analysis to be performed well within the bounds of what can be accurately measured and simulated using the Indoor Test Range (ITR) and software, while providing a sufficient offset in distance performance to understand the effects of individual parameters.

4.1.1 Design Changes

Table 2 shows the design changes that were considered. The number of possible combinations is nearly infinite; this set was chosen to understand first the effects of changing a single factor, and second to get some understanding of the effects of obvious combinations of 2- and 3- parameter changes.

Table 2 Design changes made to study the effect of various golf ball design parameters resulting in an ~30 yard difference

	ΔC_D × 1000	ΔC_L × 1000	V_{ALC} (ft/s)	Spin	Weight (oz.)	Size (in.)
Tour Ball Baseline	**0**	**0**	**260**	**2560**	**1.61**	**1.683**
100% distance change through C_D	36	-	-	-	-	-
Drag 50% / Speed 50%	17	-	246	-	-	-
100% distance change through speed	-	-	23	-	-	-
Drag 50% / Lift 50%	17	-38	-	-	-	-
100% distance change through C_L	-	-58	-	-	-	-
Drag 33% / Lift 33% / Speed 33%	11	-26	251	-	-	-
100% distance change through weight	-	-	-	-	1.34	-
Weight 50% / Size 50%	-	-	-	-	1.47	1.751
100% distance change through size	-	-	-	-	-	1.821
Weight 33% / Size 33% / Speed 33%	-	-	250	-	1.52	1.728
Launch Conditions + C_D	9	-	250	3300	-	-

4.1.2 Effects on Golfers of Different Skill Levels

ALC launch angle and spin are representative of the launch conditions of a typical male tour player (ALC clubhead speed is representative of approximately the 90th percentile). In order to understand the effects of the design parameters on different types of players, each modified ball design was re-examined through simulations based on the following launch conditions:

a. PGA TOUR player launch conditions 2011: all 186 competitors for whom the PGA TOUR reported average launch speed, angle, and spin based on TrackMan measurements.
b. Select Futures Tour players: 23 competitors who participated in USGA drive testing in 2011. This is expected to be reflective of LPGA launch conditions.
c. Average/recreational male players with handicaps of 0-20. Data obtained at the R&A test facility for players of different abilities. 166 participants.

NOTE: It is acknowledged that this launch data does not necessarily represent precisely how players launch the golf ball today. However, it does represent comprehensive data of these cohorts of golfers and while not recommended for prediction of individual performance it is beneficial for comparison of the effects of various parameters across the cohorts.

In order to accommodate the wide range of landing conditions created by the various types of golfer, the bounce and roll portion of the drive was calculated using a correlation derived using data from fairway bounce and roll testing at Pinehurst № 2.

The reported average for a given combination of player type and design type is taken from the average distance result using all simulated launch conditions.

4.1.2.1 Adjustment to Player Launch Conditions

4.1.2.1.1 Ball Speed

Players having identical (measured) clubhead speeds do not necessarily realize the same ball speeds. This may be an effect of actual ball used, the driver used, and/or the club presentation and impact position location typical for a given player.

In cases where the ALC ball speed (V_{ALC}) was changed, therefore, the effects on golfers was simulated by changing the coefficient of restitution of the ball on a basis consistent with the players' measured club speed, and in different cases, the assumption of either a relatively soft (7×10^6 psi) or very stiff (17×10^6) construction.

4.1.2.1.2 Launch Angle and Spin

A wide range of players have been tested on multiple ball types. It has been found that, on average, these golfers had increased spin and decreased launch angle. Adjustments were therefore applied to each golfers' launch conditions in turn.

4.2 Results and Discussion

4.2.1 Effects on Distance

The effects of different parameter changes resulting in an ~30-yard difference are presented in Table 3.

To understand Table 3 take, for example, the row labelled "100% distance change through weight". For this iteration only the ball weight was changed to create a 30-yard decrease in the PGA TOUR baseline drive length. If the same weight change was applied to the other cohort of golfers, it would result in a 20-yard decrease for professional women and men with handicaps between 0 and 10. But it would only result in a 13-yard decrease for higher handicapped men.

Table 3 Effects of different distance changes (yds) on players of different types. R^2 represents the correlation between distance change and clubhead speed.

	PGA TOUR	Prof. Women	Men 0 – 10 hcp.	Men 11 – 20 hcp.	R^2
Tour Ball Baseline (yds)	**293***	**239**	**242**	**211**	**-**
100% distance change through C_D	-27	-19	-19	-15	0.96
Drag 50% / Speed 50% (Soft)	-27	-20	-21	-17	0.96
100% distance change through speed (Soft)	-27	-23	-23	-20	0.87
Drag 50% / Lift 50%	-23	-17	-18	-17	0.54
100% distance change through C_L	-20	-14	-16	-17	0.14
Drag 33% / Lift 33% / Speed 33%	-24	-18	-19	-17	0.70
100% distance change through weight	-30	-20	-20	-13	0.93
Weight 50% / Size 50%	-30	-22	-22	-14	0.90
100% distance change through size	-31	-23	-23	-15	0.84
Weight 33% / Size 33% / Speed 33%	-28	-20	-21	-15	0.94
Launch Conditions + C_D	-22	-18	-18	-14	0.89

*The average drive distance on the PGA TOUR in 2011 was reported to be 290.9 yards.

In general, the results in Table 3 indicate that changing the ball size, weight or drag parameters had a greater effect on distance at PGA TOUR players than the other cohorts of golfers, especially the higher handicap male recreational players. Speed has the biggest effect on distance across all cohorts. A more detailed look at the effects of speed on launch conditions and distance is given in Appendix A.

However, there were two notable exceptions. The first of these is that golf balls having significantly lower lift coefficients resulted in distance changes that were 5-7 yards less than other parameters. Unlike other parameters which showed high R^2 values when the distance change was compared to clubhead speed, in each circumstance where lift was a significant factor in the drive distance change, the change was not well-correlated with player club speed.

4.2.1.1 A Closer Look at the Effect of Dimples, Lift and Drag

For the golf ball it's the dimple design and the spin of the ball that create lift and drag. From the standpoint of dimples, it is not the number of dimples that dictate the ball's performance. Figure 6 shows a comparison between the number of dimples and the overall distance a ball travels under ALC conditions. Dimple number and distance are not well correlated.

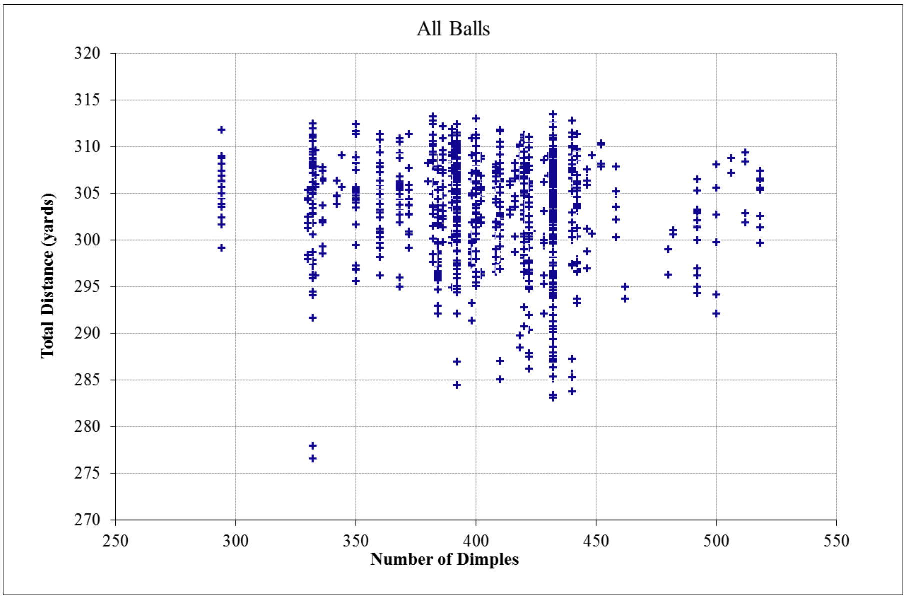

Figure 6 Comparison of the number of dimples to Overall Distance of golf balls tested on the

More precisely it is the area of dimple coverage and the size and shape of the dimples that cause various effects, Figure 7.

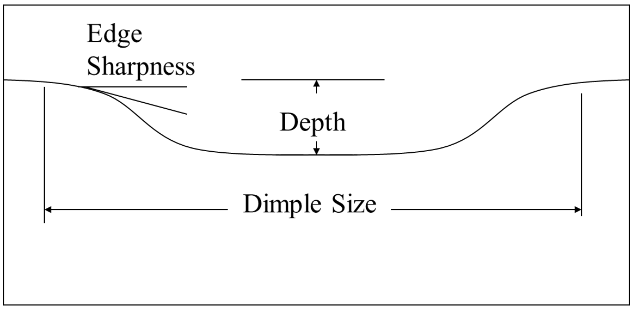

Figure 7 Dimple parameters

To illustrate this, golf balls with broad range of existing dimple patterns / shapes were "worn" through vibratory tumbling. This surface treatment had the effect of altering the edge sharpness, decreasing the relative dimple depth, slightly increasing the diameter of the dimple and slightly decreasing the overall diameter of the ball. The results of increased wear and the subsequent change of the dimple characteristics are shown in Figure 8.

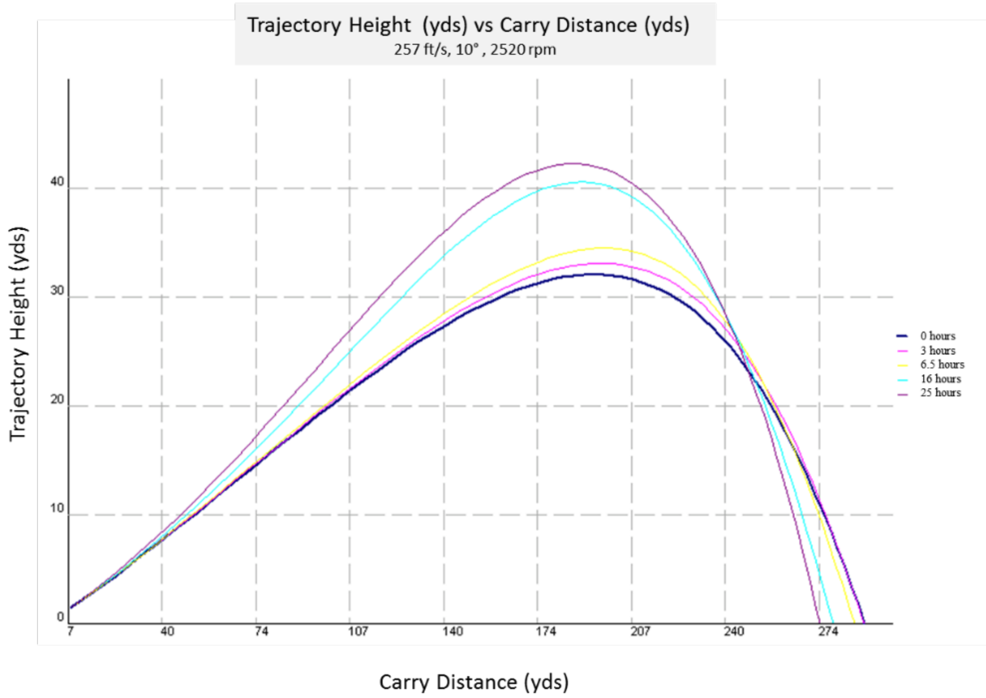

Figure 8 Effects of dimple characteristics on trajectory

Conformance testing of golf balls on the Indoor Test Range (ITR) indicates that the dimples on golf balls create a large range of lift and drag properties, Figure 9. Simply put, lift shapes the trajectory while drag slows the ball down.

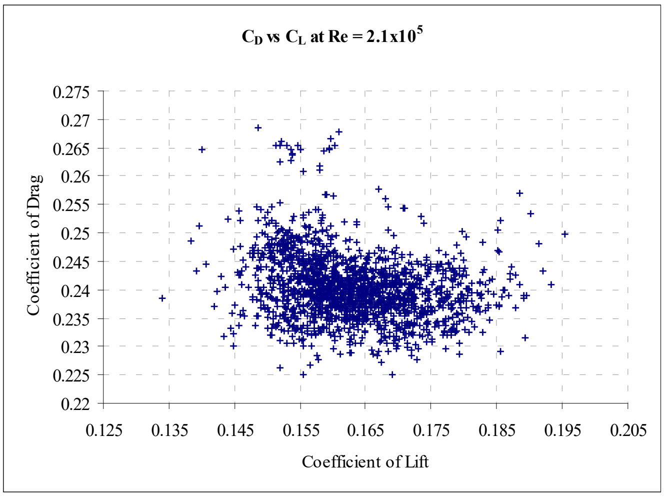

Figure 9 Comparison of lift, C_L, and drag, C_D, coefficients of golf balls tested on the ITR

While there is a very low correlation between C_L and C_D in Figure 9, a look at distance shows that it is drag at high speed is the most important factor in creating distance, Figure 10.

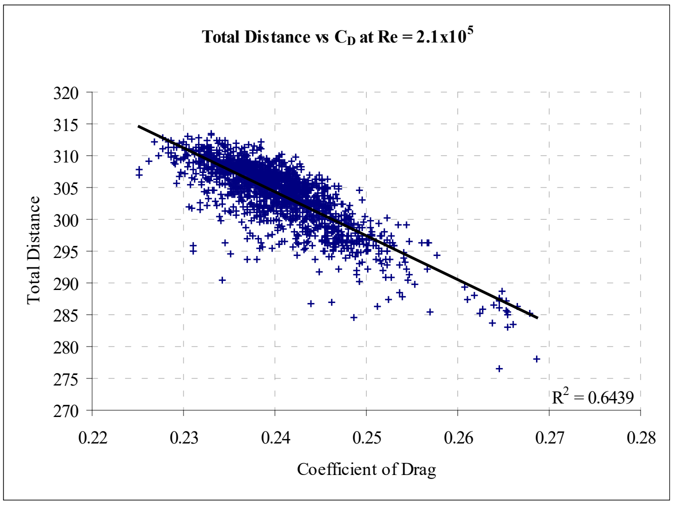

Figure 10 Comparison of drag coefficient, C_D, to Overall Distance of golf balls tested on the ITR

Figures 11 and 12how the effect of C_D and C_L on distance on golf balls launched at the same angle (10°) and spin (2520 rpm) at two different clubhead speeds.

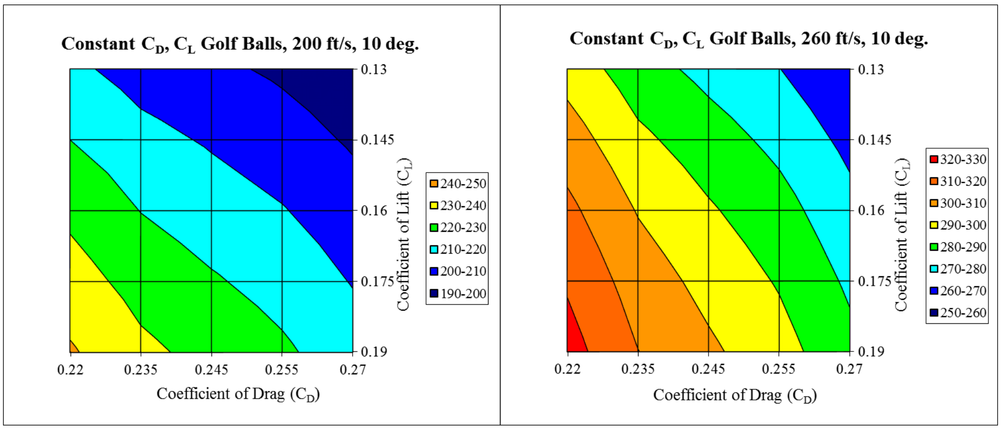

Figure 11 and 12 Effects of Coefficient of Lift C_L and Coefficient of Drag C_D for different ball speeds

Figure 13 shows the distance difference at these two speeds. It can be clearly seen in the figure that the distance difference between club speeds of 260 ft/s and 200 ft/s is due solely to drag.

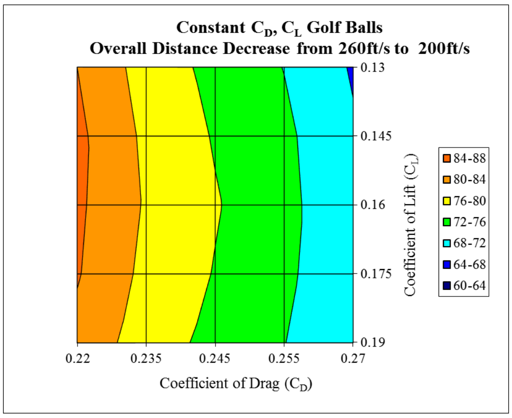

Figure 13 Distance difference at two ball speeds as a function of Coefficient of Lift C_L and Coefficient of Drag C_D

However, the distance difference between club speeds of 260 ft/s and an even lower speed of 180 ft/s, while still primarily the result of drag, a slight effect from lift begins to emerge, Figure 14.

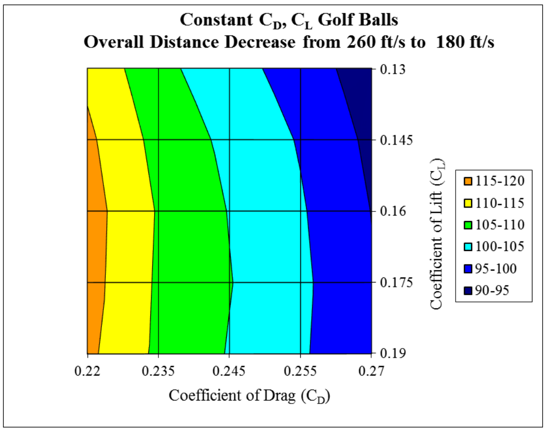

Figure 14 Distance difference at two club speeds as a function of Coefficient of Lift C_L and Coefficient of Drag C_D

4.2.1.2 A Closer Look at Spin

Another important observation can be made from the results of the last design iteration in Table 3; "Launch Conditions + CD". About two-thirds of the distance change in this simulation was a result of speed reduction and drag coefficient increase. Increased spin contributed the final third. A significant part of the distance change caused by increased spin was not seen in the simulated PGA TOUR. This can be best understood by a closer examination of the spin of the golf ball.

4.2.1.2.1 Study of Golf balls with Various Spin Rates

For this study, a sample of wound and solid balls were tested for oblique impact and aerodynamic performance. It has been shown that the most obvious evolution in the characteristic of popular tour golf balls is their significant reduction in spin and commensurate increase in drive distance. It also appears that the aerodynamics of these balls has also improved.

4.2.1.2.1.1 Driver Launch Conditions

The study used the measured launch conditions of competitors in the 2006 US Open. The golfers with the top 10 carry distances as measured at the 2006 US Open are compared to the ALC values for two popular tour balls of that era, Table 4.

Table 4 Comparison of Player and ALC Data

	Top 10 Carry Distance 2006 US Open	**Tour Ball A**	**Tour Ball B**
Clubhead Speed (mph)	119	120.1	120
Ball Speed (ft/s)	256	257.0	258.2
Launch Angle (deg)	10.2	9.7	9.7
Spin (RPM)	2600	2520	2426

It can be seen in Table 4 that the ALC data compares very well to the carry distance of the top 10 golfers at the 2006 US Open. As a result, for the purpose of this study, the ALC was considered suitable for representing the launch conditions of the high swing speeds of touring professionals over a wide range of golf ball types.

4.2.1.2.1.2 Comparison of Modern Solid Construction Balls to Wound Golf Balls

A variety of golf balls were selected for testing. These included wound balls (Wound Ball A and B) manufactured just prior to the widespread use of solid construction balls at the highest level of the game, two solid construction balls (Multilayer 1 and 2) from the transition period from wound to solid balls, and finally, two solid construction balls (Multilayer 3 and 4) popular at the time.

Each of the ball types was tested with enhanced settings in the ITR. They were then fired obliquely at an infinite mass over a range of angles (ten to seventy degrees) with test speeds consistent with a touring professional and a recreational golfer. Additional test speeds at the ten-degree angle were also included. Finally, each of the ball types was hit on the mechanical golfer according to the ALC procedure.

4.2.1.2.1.3 Oblique Impact

The spin as a function of impact angle for the six ball types is presented in Figure 15 for professional golfer-like impact speeds. The impact velocity as a function of angle is the same as that used for the groove study.

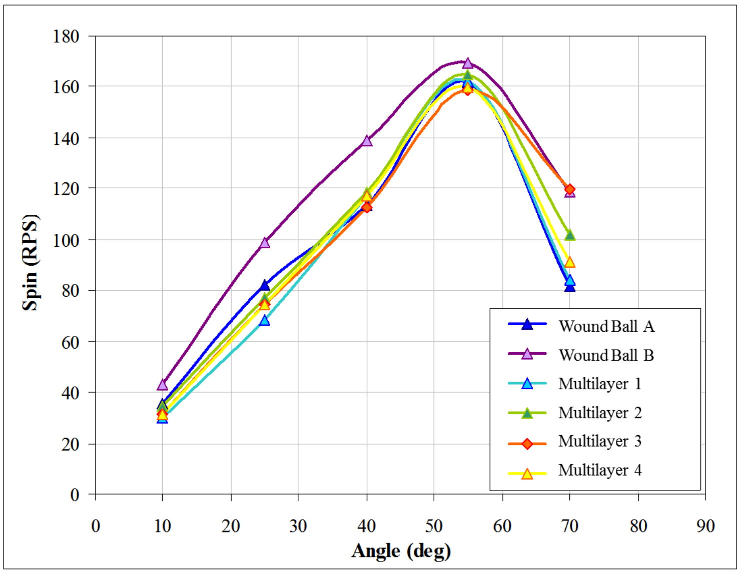

Figure 15 Spin performance of different ball types (professional impact speed)

It can be seen in Figure 15 that the Wound Ball B spins substantially more than the other balls at all but the highest impact angle.

4.2.1.2.1.4 Low Angle Impact

The same group of balls tested above were re-tested at the ten-degree impact angle over a range of impact speeds from professional golfer to recreational golfer. These results are presented in Figure 16.

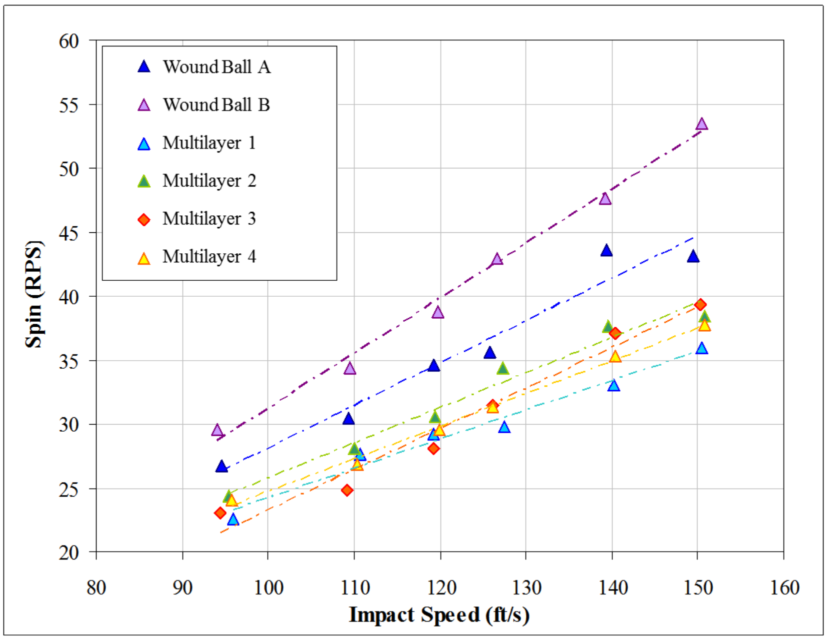

Figure 16 Low impact angle *(10 degrees) spin performance*

It can clearly be seen in Figure 16 that the wound balls spin considerably more than the solid balls for driver like impact angles. Wound Ball B also spins significantly more than the Wound Ball A. It is also evident that as impact speed increases, the difference between the Wound Ball B and the solid balls grows larger. It is therefore reasonable to hypothesize that the broad adoption of lower spinning balls has benefited the higher swing speed player the most.

4.2.1.2.1.4 ALC and ODS Performance

Each of the six ball types was hit on the mechanical golfer. Although the performance of the wound balls had likely degraded due to age, their launch speed was still reasonable. The results of the ALC testing are included in Table 5.

ITR tests, with enhanced spin settings, were also performed on the six ball types. The ODS results for the ALC launch conditions are also included in Table 5.

Table 5 Comparison of ALC Data

	Wound Ball A	Wound Ball B	Multilayer 1	Multilayer 2	Multilayer 3	Multilayer 4
Clubhead Speed (mph)	120.2	120.3	120.0	120.0	120.1	120.1
Ball Speed (ft/s)	255.6	254.6	254.3	255.1	257.0	258.2
Launch Angle (deg)	9.6	9.0	9.8	9.5	9.7	9.7
Spin (RPM)	3010	3803	2539	2727	2520	2426
ODS Distance (y)	292.2	287.3	304.2	301.0	305.1	310.5

As was clear from the infinite mass testing, the spin of the wound balls (especially Wound Ball B) is substantially higher than the solid balls. It can also be seen that the overall distance appears to be correlated with the spin. Figure 17 shows the overall distance (corrected for a uniform launch velocity of 258 ft/s) as a function of spin rate.

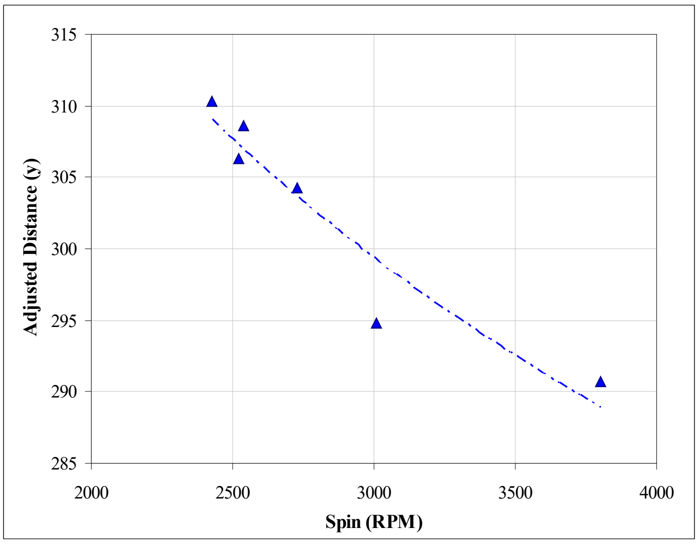

Figure 17 Effect of spin on overall distance (corrected to 258 ft/s launch velocity)

It can be seen in Figure 17 that the overall distance is well correlated to spin. It should be noted that Figure 17 is not intended to indicate that spin is the only factor affecting distance for a given ball speed. However, it does indicate that it is a strong influencer.

The overall distance of the Wound Ball B and Multilayer 4 balls is plotted as a function of spin (with a launch speed of 258 ft/s and a launch angle of 9.5 degrees) in Figure 18.

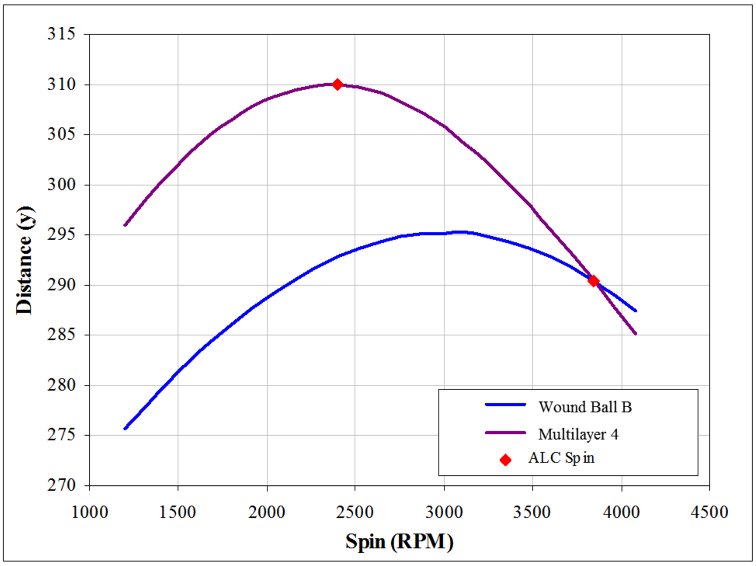

Figure 18 Effect of spin on overall distance (258 ft/s launch speed, 9.5 degrees launch angle)

Figure 18 illustrates that the optimal spin rate for the Wound Ball B is 3100 RPM while that of the Multilayer 4 is 2400 RPM. Clearly (and unsurprisingly) the aerodynamics of the balls were tailored to match the expected spin rate. Figure 18 also shows the large improvements in ball aerodynamics going from the wound to multilayer ball. For example, at 3000 RPM, the Multilayer 4 aerodynamics are ten yards longer than that of the Wound Ball B.

4.2.1.2.1.5 Spin as a Function of Clubhead Speed

It can be seen in Figure 16 that spin for a ten-degree impact is approximately a linear function of the impact speed (when the other impact conditions are held constant). Figure 19 shows that the equivalent launch velocity is also a linear function of the impact speed for infinite mass impacts.

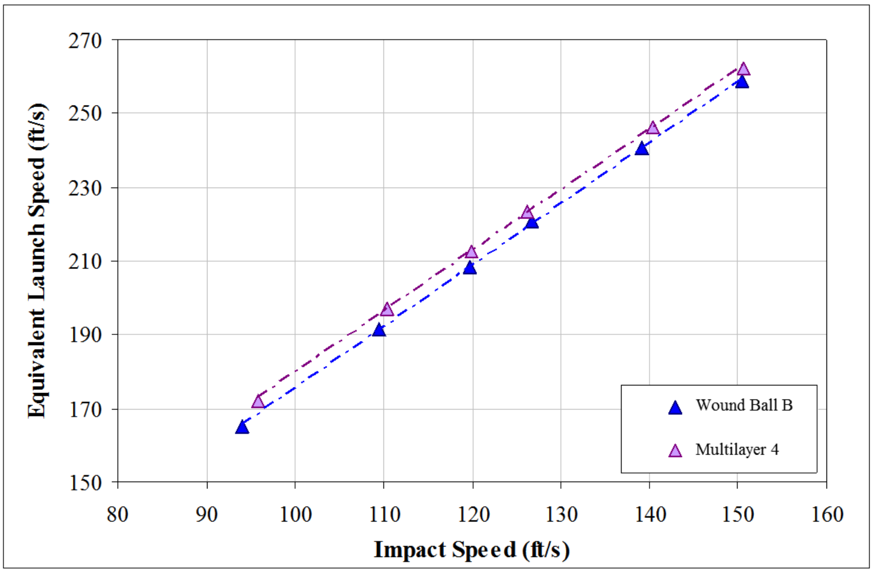

Figure 19 Effect of impact speed on equivalent launch speed (10-degree impact against infinite mass)

Therefore, it can be assumed that the ball speed and spin are linear functions of clubhead speed. Consequently, if the launch angle is fixed, the overall distance will be a function of clubhead speed only. These results have been compiled for two balls: the Multilayer Ball 4 and a fictitious ball that spins like the Wound Ball B but has the aerodynamics of the Multilayer Ball 4. These results, along with the difference between the two balls are plotted in Figure 20.

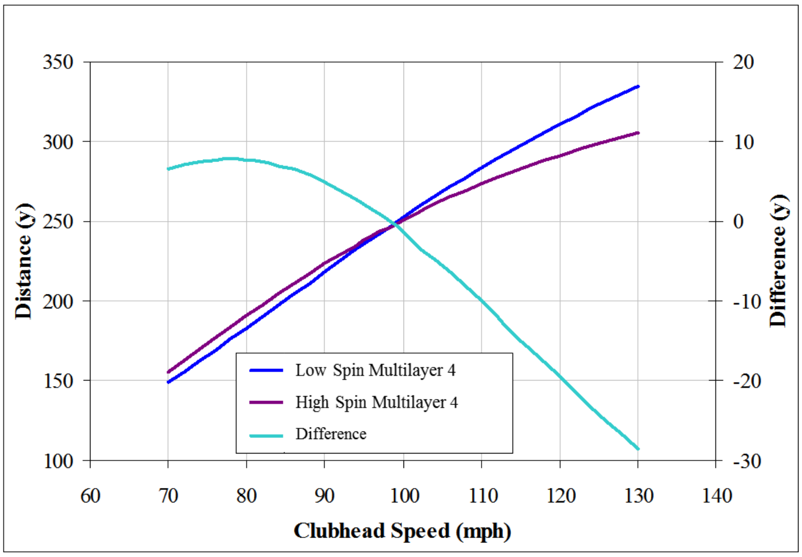

Figure 20 Effect of high and low spinning multilayer balls for different clubhead speeds.

Figure 20 indicates that high swing speed players are primarily affected by this scenario. In fact, the data indicates that low swing speed players might benefit from moving to a high spin ball (at least for the Multilayer 4 ball aerodynamics).

While this is obviously an interesting result, the assumption that the spin is solely a function of clubhead speed is not correct.

4.2.1.2.1.6 Effect of Launch Angle on Distance

Figure 21 demonstrates that distance is strongly a function of both spin and launch angle. It is also obvious that both launch angle and spin are affected by the loft of the driver. It is therefore possible that some of the distance loss predicted in Figure 20 can be offset by moving to a lower loft (and hence lower spin) driver. This phenomenon will be covered in greater detail in “The Role of Equipment – Driver”.

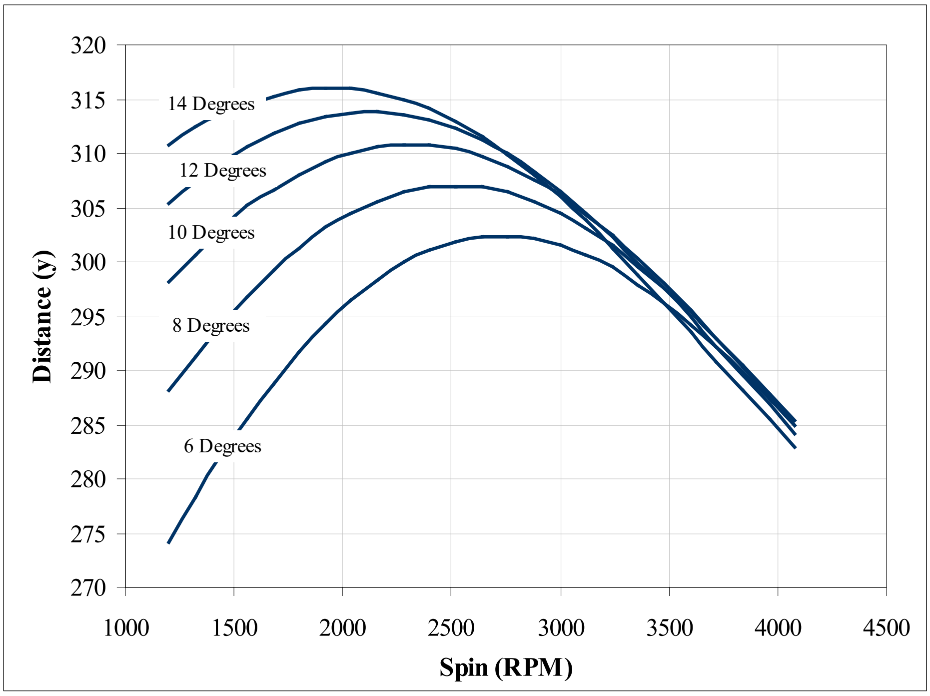

Figure 21 Effect of launch angle on distance (258 ft/s ball speed).

Appendix A – Technical Report

[See additional report]

Appendix B – List of Figures

Appendix C – List of Tables