EXPERIMENTAL DETERMINATION OF THE EFFECTS OF CLUBHEAD SPEED ON DRIVER LAUNCH CONDITIONS AND THE EFFECTS ON DRIVE DISTANCE FOR BALLS USED BY THE PGA TOUR

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Steven J. Quintavalla, Ph.D.
USGA Research Engineer
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ABSTRACT

The question of what distance may be achieved at different swing speeds for golf balls used on the PGA Tour is addressed. Experimental data are presented, including coefficient of restitution results from "tour balls" against a standard clubhead, as well as distances computed at fixed launch conditions, optimal launch conditions, and those resulting from mechanical golfer impacts at different clubhead speeds. In each case, it is demonstrated that there are diminishing returns to overall distance with increasing swing speed, a result of the impact properties and the aerodynamic behavior of golf balls.

INTRODUCTION

Experiments have shown that the coefficient of restitution of impact between a golf ball and a clubhead is a smoothly declining (nearly linear) function of clubhead speed (Chou, et. al., 1994; Cochoran, 1998; Lemons, 1998). This is understood to be a function of the hysteretic, rate-dependent nature of the elastomeric materials used in golf ball construction (Tavares, et. al., 1998; Quintavalla, Johnson, 2003; Quintavalla, 2004).

After impact, the trajectory of the golf ball is governed by well-understood aerodynamic forces as well as gravity:

$$\sum F_x = -\rho A \frac{|V|^2}{2}\left(C_D \cos\theta + C_L \sin\theta\right) = m\ddot{x}$$

$$\sum F_y = \rho A \frac{|V|^2}{2}\left(-C_D \sin\theta + C_L \cos\theta\right) - mg = m\ddot{y}$$

where ρ is the air density, A is the cross-sectional area of the ball, V is the free stream velocity, C_L and C_D are the lift and drag coefficients, respectively, g is the force of gravity, and m is the mass of the ball. The angle θ is the angle of the velocity vector with respect to the horizontal, and can be expressed according to the velocity components

$$\theta = \tan^{-1}\left(\frac{V_y}{V_x}\right)$$

It has been shown (Bearman, Harvey, 1976) that the two aerodynamic coefficients, C_D and C_L, are related to the dimensionless Reynolds number (Re) and spin ratio (Ω).

$$Re = \frac{2 \cdot |V| \cdot r}{\nu}$$

$$\Omega = \frac{|\omega| \cdot r}{|V|}$$

where ω is the spin of the ball, expressed in radians per second, r is the radius, and ν is the dynamic viscosity. The relationship between C_L and C_D and these numbers is complex, and has been discussed elsewhere (Quintavalla, 2002). Examples of the C_L and C_D surfaces are shown in figure 1.

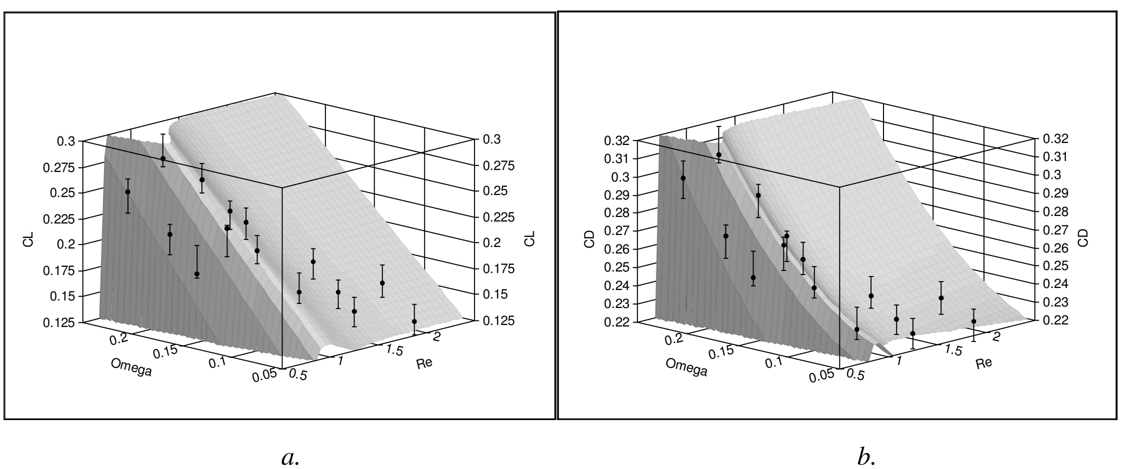

Figure 1: Coefficients of lift (a) and drag (b) as functions of the dimensionless variables Reynolds number (Re) and spin ratio (Omega).

For most golf balls, at a given spin rate, the coefficients of lift and drag reach a peak value at a Reynolds number of about 1×10^5, and smoothly decline (though with a positive second derivative) at higher Re. Of course, this should not be confused with the overall behavior of drag and lift forces, which increase quadratically with increasing speed (and hence *Re*) according to equations 1 and 2.

EXPERIMENTAL METHODS

The balls chosen for these tests were selected on the basis of use on the PGA Tour through February, 2006 (labeled "A"-"E". In addition to these test samples, a USGA/R&A Calibration Ball, a two-piece, Surlyn®-covered golf ball, was used for setup purposes.

MECHANICAL GOLFER OPERATION

Launch conditions were obtained by striking these ball types using a servo-controlled mechanical golfer, equipped with a USGA conformance driver (Aeson, 9°), as per the USGA Overall Distance Standard ("ODS"). The mechanical golfer was set to swing the club at the speeds shown in table 1. A swing speed of 58.1 m/s (130 mph) was attempted, but could not be obtained reliably at the time of this testing.

Table 1: Swing speeds used in testing. The lowest, 90 mph, is representative of an amateur golfer, where the highest is typical of longer-driving professionals.

Test Condition	Club Speed, m/s (mph)
1	40.23 (90)
2	44.70 (100)
3	49.17 (110)
4	53.64 (120)
5	55.88 (125)

Due to anticipated differences in the clubhead presentation at each speed, some specification had to be made in how the ball would be positioned on the tee. The tee position was first set at the highest speed in accordance with the ODS, to provide the proper launch conditions ("ALC") for the USGA/R&A Calibration Ball. At subsequent speeds, the tee position was changed in order to maintain the vertical position of the impact location on the clubhead, as well as to ensure that the resultant ball trajectory would be straight (ascertained by hitting outdoors). The tee position was left unchanged in the longitudinal (towards the fairway) direction. This completely specified the impact location of the ball on the face at different speeds. The reported results were the average of six hits at each test condition.

The above specification of tee position at different speeds, along with the servo programming used, determined how the launch conditions would change for each ball type from one clubhead speed setting to the next. It is foreseeable that different specifications might lead to different variations in launch conditions. It is generally true that there has been little correlation between clubhead speed and launch conditions (angle and spin) for tour players. The above specifications, then, establish a reasonable means of acquiring different launch conditions for the same driver under different swing speeds. To supplement these launch conditions, then, simulations would also be performed under the assumptions of constant angle and spin, as well as optimum launch conditions. This required that expanded aerodynamic testing be performed over and above the typical Overall Distance Standard testing, as discussed in the next section.

Independently, the coefficient of restitution was tested for, using an unshafted USGA conformance clubhead ("Aeson", 9° driver) as an impact target. The test setup was identical to that for the expired USGA coefficient of restitution test protocol for clubs, with the exception that multiple speeds and ball types were used with the single clubhead. The impact speeds were the same as the swing speeds described in table 1.

AERODYNAMIC TESTING

Balls were tested for aerodynamic behavior using the Indoor Test Range (ITR) (Quintavalla, 2001). Lift and drag coefficients were determined over a broader than usual range of launcher settings, at initial ball launch speeds ranging from 88.4 m/s (197.7 mph) down to 27.4 m/s (61.4 mph), and a wide enough range of spin settings to encompass both ALC and optimum launch conditions. These settings can be found in appendix 2. Balls were tested in the orientation that gave the longer total distance according to ODS. All other operating parameters were set according to the Overall Distance Standard.

EXPERIMENTAL RESULTS

MECHANICAL GOLFER LAUNCH CONDITIONS

The launch conditions obtained using the experimental methods set out above are shown in table 2. The units used in this table are U.S. customary for the convenience of the reader. Some basic trends can be observed from this data. First, a clubhead speed increase of 39% results in a ball speed increase of about 37% in all cases. This is due to the declining coefficient of restitution with impact speed, as discussed in the next section. Second, the launch angle decreases with increasing impact speed, about 0.7 degrees +/- 0.1. Third, the spin rate increases with increasing club speed, 660 rpm on average.

Table 2: Launch conditions resulting from Tour balls hit by the mechanical golfer at different club head speeds. All results are given in U.S. customary units (conversion factors are listed in appendix 1).

USGA Lot	Club Speed mph	Club Speed S.D.	Ball Speed ft/s	Ball Speed S.D.	Launch Angle deg.	Launch Angle S.D.	Ball Spin rpm	Ball Spin S.D.
BALL A	125.3	0.0	268.2	0.4	9.6	0.2	2536	82
	119.7	0.1	257.6	0.6	9.7	0.2	2398	76
	110.1	0.0	238.7	0.4	9.9	0.2	2314	82
	99.6	0.0	217.4	0.3	10.1	0.2	2142	98
	89.7	0.1	196.0	0.2	10.2	0.3	1932	108
BALL B	125.4	0.0	268.9	0.5	9.4	0.1	2700	63
	119.8	0.1	257.8	0.8	9.5	0.2	2539	83
	110.1	0.0	238.9	0.5	9.6	0.1	2433	63
	99.6	0.1	217.2	0.5	9.8	0.1	2282	81
	89.7	0.1	196.0	0.3	10.1	0.2	2020	75
BALL C	125.3	0.0	268.1	0.7	9.3	0.1	2891	84
	119.7	0.1	257.4	0.7	9.4	0.1	2662	82
	110.0	0.0	238.0	0.7	9.6	0.1	2565	84
	99.6	0.0	216.8	0.6	9.6	0.2	2343	63
	89.7	0.1	195.5	0.7	10.1	0.4	2152	44
BALL D	125.3	0.1	267.7	0.5	9.3	0.1	2769	72
	119.7	0.0	257.0	0.6	9.5	0.1	2581	74
	110.1	0.1	237.4	0.5	9.7	0.1	2460	72
	99.6	0.1	216.0	0.2	9.7	0.1	2282	94
	89.7	0.1	194.6	0.2	10.1	0.3	2081	69
BALL E	125.4	0.1	268.4	0.3	9.6	0.2	2489	100
	119.7	0.1	257.8	0.3	9.7	0.2	2322	92
	110.0	0.1	238.5	0.3	10.0	0.2	2227	100
	99.7	0.1	217.0	0.4	9.9	0.1	2017	100
	89.6	0.1	195.8	0.5	10.2	0.3	1889	96

Coefficient of Restitution

The results of the normal impact between the selected Tour balls and the USGA conformance driver are shown in table 3 and figure 2.

Table 3: Normal coefficient of restitution of impact between golf balls and the USGA conformance driver at different speeds.

Ball Type	Normal Impact Speed m/s (mph)	Coefficient of restitution	Std. Dev.
BALL A	40.2 (89.9)	0.845	0.001
	48.8 (109.1)	0.829	0.005
	58.1 (129.9)	0.801	0.004
BALL B	40.2 (89.9)	0.846	0.002
	48.7 (109)	0.829	0.003
	58.1 (130)	0.803	0.007
BALL C	40.3 (90.1)	0.843	0.002
	48.8 (109.1)	0.821	0.002
	58.1 (130.1)	0.798	0.009
BALL D	40.2 (90)	0.835	0.002
	48.8 (109.1)	0.818	0.002
	58 (129.8)	0.797	0.003
BALL E	40.2 (90)	0.842	0.003
	48.8 (109.1)	0.823	0.002
	58.1 (130)	0.803	0.004

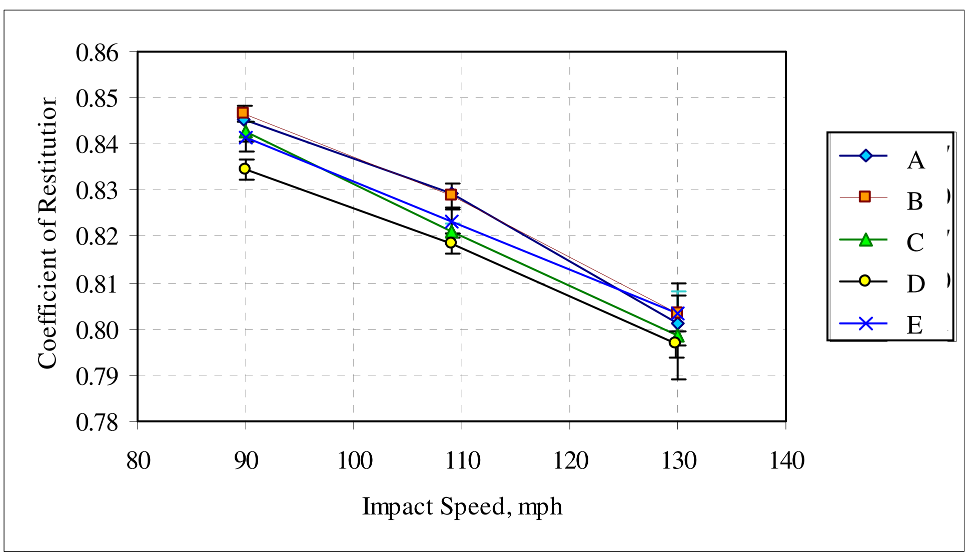

Figure 2: Normal coefficient of restitution of five tour balls at different impact speeds. Speeds are presented in U.S. customary units (conversion factors available in appendix 1).

In all cases, there is a pronounced and steady decrease in coefficient of restitution with increasing impact speed, consistent with earlier published data (Chou, et. al., 1994; Cochoran, 1998; Lemons, 1998). It should be noted, though, that the relative consistency between the rate of change of COR with impact speed is between "solid" golf balls, as experience has shown that the COR of wound golf balls previously tested did not decrease as dramatically as that of solid balls.

DISTANCE SIMULATIONS

Using Mechanical Golfer Launch Conditions

Figure 3 shows the overall distances associated with each ball at the launch conditions listed in table 2. An increase in distance, though with diminishing returns, is shown for all balls. This is more clearly illustrated in figure 4.

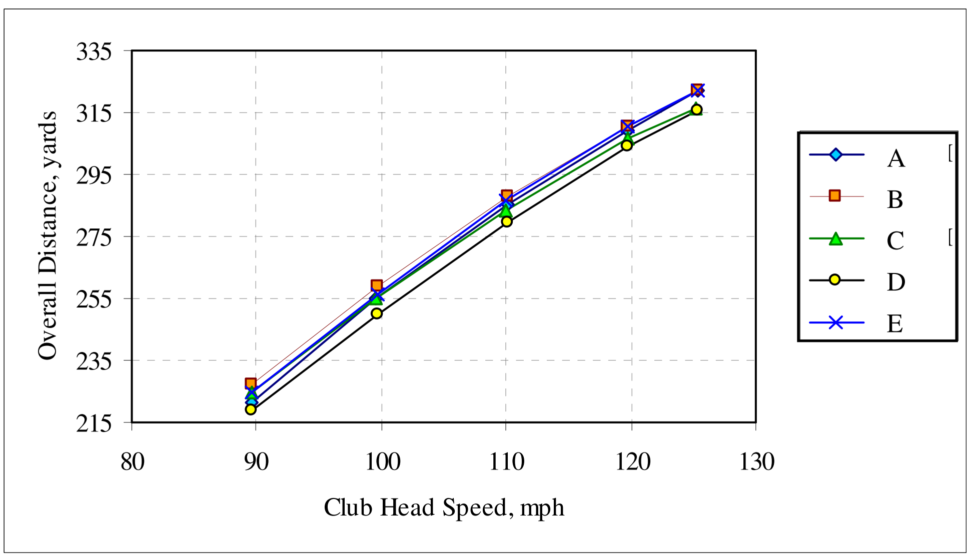

Figure 3: Overall distance as a function of clubhead speed for five tour balls. Figure 4 shows the distance increment for every 10 mph increase in clubhead speed.

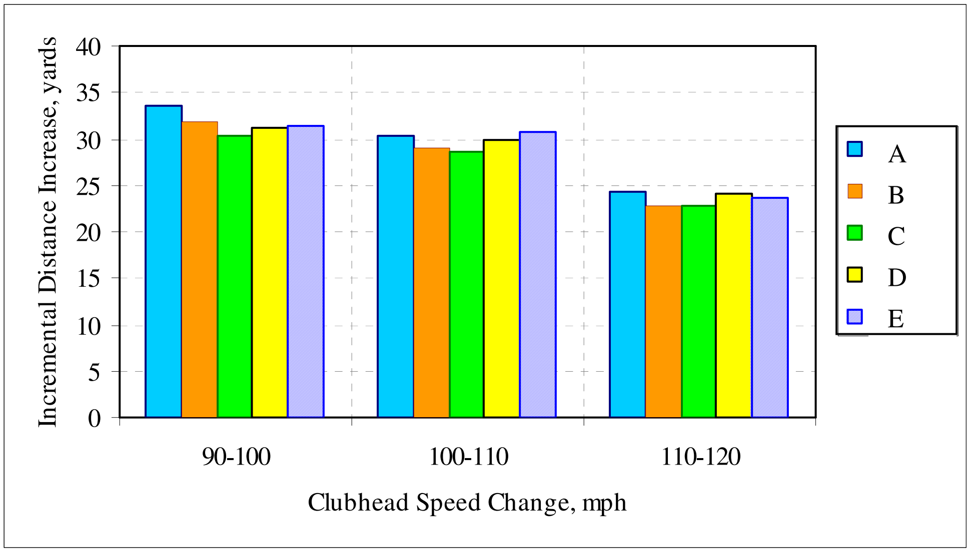

Figure 4: Overall distance increase with each ten mile per hour increase in club speed for five tour balls. This chart shows clearly the diminishing returns with increasing impact speed.

Using Fixed Launch Conditions

In this case, each ball's launch conditions other than speed were held constant (set to the 120 mph impact results for the appropriate ball type) for each simulation. The ball speeds were varied according to table 2. Compared with the results in figure 3, distances varied by less than two yards on average.

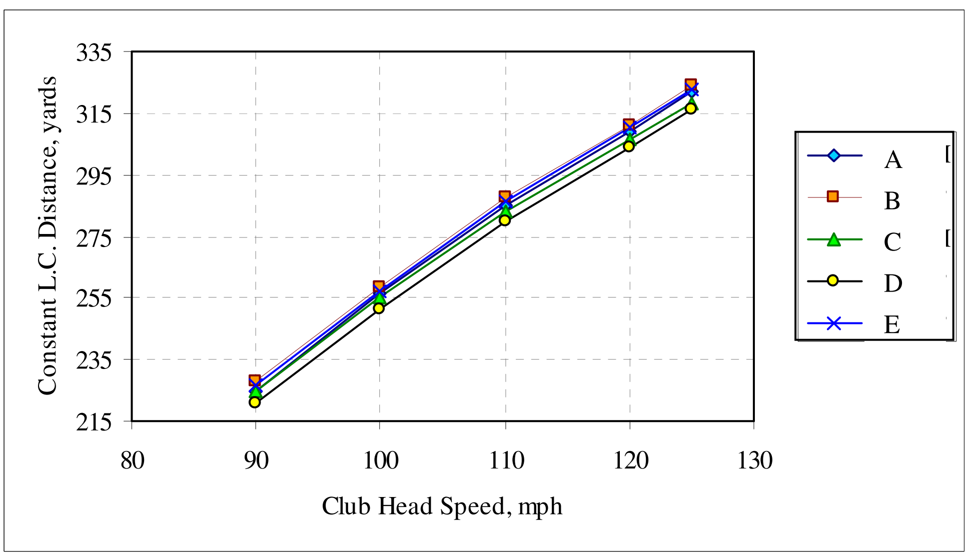

Figure 5: Overall distance as a function of clubhead speed for five tour balls, assuming fixed launch angle and spin rate at each impact speed. Compare distances to figure 3.

Using "Optimum" Launch Conditions

Finally, the golf ball trajectories were simulated under "optimum" launch conditions, those that maximized total distance. At each clubhead speed, the ball speed was again set according to table 2. A separate bounce-and-roll model used for impact, previously determined specifically for the range of landing conditions associated with optimum trajectories, was used.

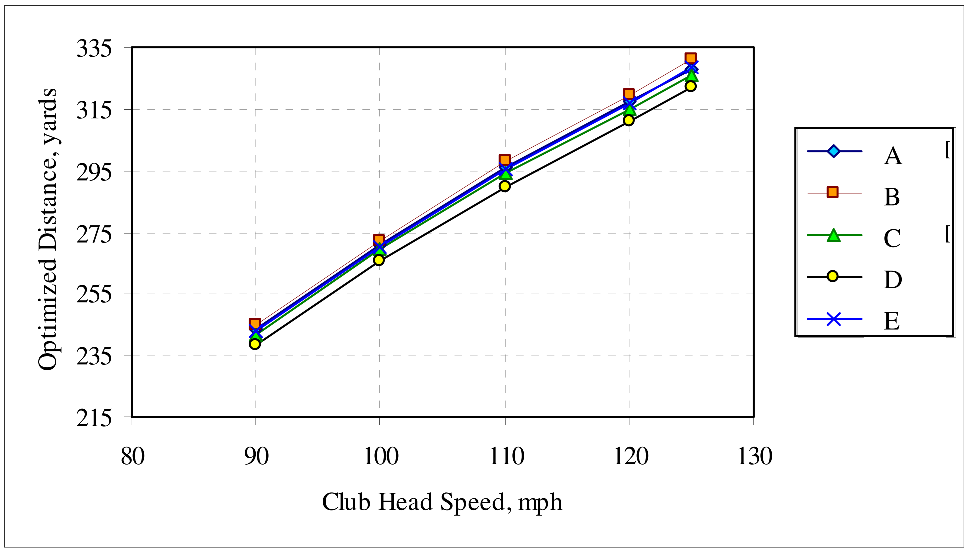

Figure 6: Overall distance as a function of clubhead speed for five tour balls, assuming optimized launch angle and spin rate at each impact speed. Compare distances to figure 3.

Associated with the more aggressive launch conditions is an expected increase in overall distance. It is interesting to note that the distance increase due to optimization at the 125 mph (7.5 yards) is less than half the optimization increase at 90 mph (19 yards).

QUANTIFYING EFFECTS OF AERODYNAMICS AND COR

The results thus far have shown diminishing distance returns with increasing clubhead speed, attributable to aerodynamic forces (which, in general, increase with the square of ball velocity) and the coefficient of restitution (which decreases linearly with impact speed). To understand how important these effects are, we examine one of the longer balls tested, ball "E". Figure (7) shows three possibilities. The first, carried over from figure (5), shows again how distance increases with clubhead speed at constant launch conditions (x's). Next, we show how much the decreasing COR influences this result, by computing the distance at each impact speed assuming a constant COR of 0.842 (which gives higher ball speeds than before). This leads to an identical distance at 90 mph impact, but a 3.9 yard increase by 125 mph. Finally, compare these to the layman's assumption of a linear distance increase. In this case, we assume of 3.05 yards per mph, the slope at 90 mph. This linear (or constant rate) assumption would result in a ball that travels 10.7 yards longer than using the correct COR and aerodynamics at 125 mph.

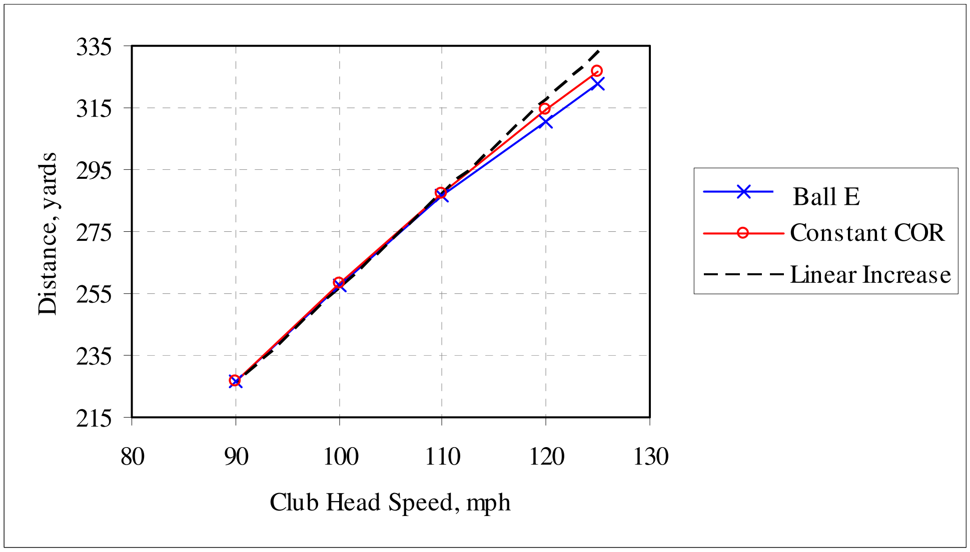

Figure 7: Distance increases using a linear assumption, the assumption of constant COR, and constant launch conditions.

CONCLUSIONS

The results of these experiments clearly demonstrate the diminishing returns of overall distance with increasing clubhead speeds. This is a direct result of the decreasing coefficient of restitution with increasing impact speed, coupled with the increase in aerodynamic forces with the square of ball speed.

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APPENDIX 1: UNIT CONVERSION

Measure	To convert from	to	Multiply by exactly (approx.)
Distance	m	yards	3937/3600 (1.09361)
Speed	m/s	ft/s	3937/1200 (3.28083)
	m/s	mph	3937/1760 (2.23693)
	ft/s	mph	22/15 (1.46667)
Spin	rev/s	rpm	60

APPENDIX 2: ITR LAUNCHER SETTINGS

Table A- 1: Launcher settings for extended aerodynamic testing of Tour balls. The columns labeled "Speed" and "Spin" indicate those values, in ft/s and rev/s, respectively, as programmed into the Indoor Test Range. Values in m/s and rpm are also shown.

	As Programmed		Alternative Units	
Setting	Speed	Spin	Speed, m/s (mph)	Spin, rpm
1	285	53	59.2 (194.3)	3180
2	285	38	59.2 (194.3)	2280
3	285	23	59.2 (194.3)	1380
4	225	49	46.8 (153.4)	2940
5	225	35	46.8 (153.4)	2100
6	225	20	46.8 (153.4)	1200
7	160	47	33.3 (109.1)	2820
8	160	34	33.3 (109.1)	2040
9	160	21	33.3 (109.1)	1260
10	130	48	27.0 (88.6)	2880
11	130	30	27.0 (88.6)	1800
12	130	21	27.0 (88.6)	1260
13	108	44	22.4 (73.6)	2640
14	108	29	22.4 (73.6)	1740
15	102	23	21.2 (69.5)	1380
16	95	36	19.7 (64.8)	2160
17	93	45	19.3 (63.4)	2700

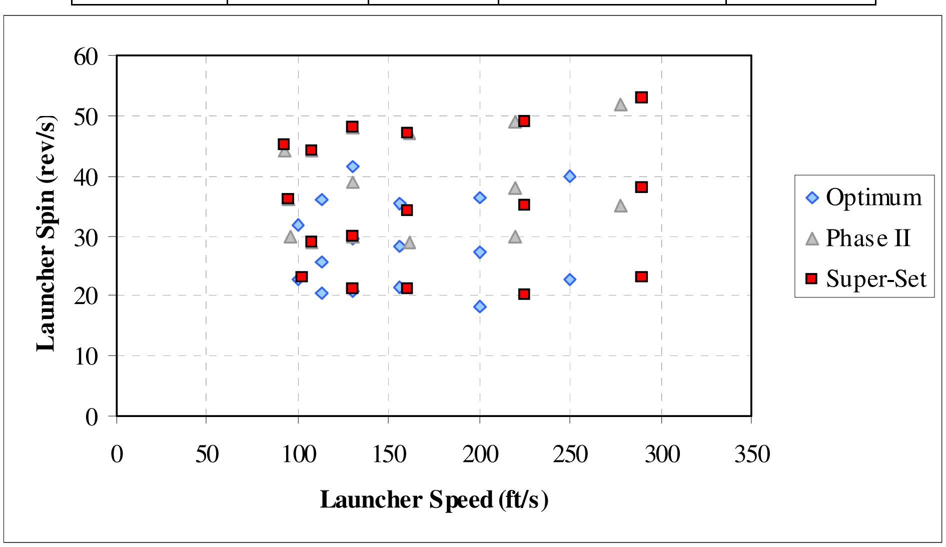

Figure A- 1: Graphical representation of settings used for this test ("Super-Set"). ITR settings traditionally used for Optimum overall distance and the "Phase II" Overall Distance Standard are included for reference.

APPENDIX 3: PGA TOUR STATISTICS

The period 2000-2005 saw significant changes in equipment played on tour. In 2000, the predominant golf ball on tour was a wound golf ball. By 2005, the prevalent ball was a multipiece solid golf ball with a urethane outer cover, and a large-diameter dimple. Over this same period, players switched from drivers that were 250-300cc in volume to more advanced designs at or near 400cc.

Driving distance averages are available for 100 players on the PGA Tour for both of these years (PGA Tour). On average, these players gained 11.6 yards over the five-year period (see figure A-3). However, correlation between the gain experienced by these players and their distance in 2000 is -0.06, a value that is not statistically significant from zero. That is, the longest players could not expect the greatest distance increase resulting from this distance change.

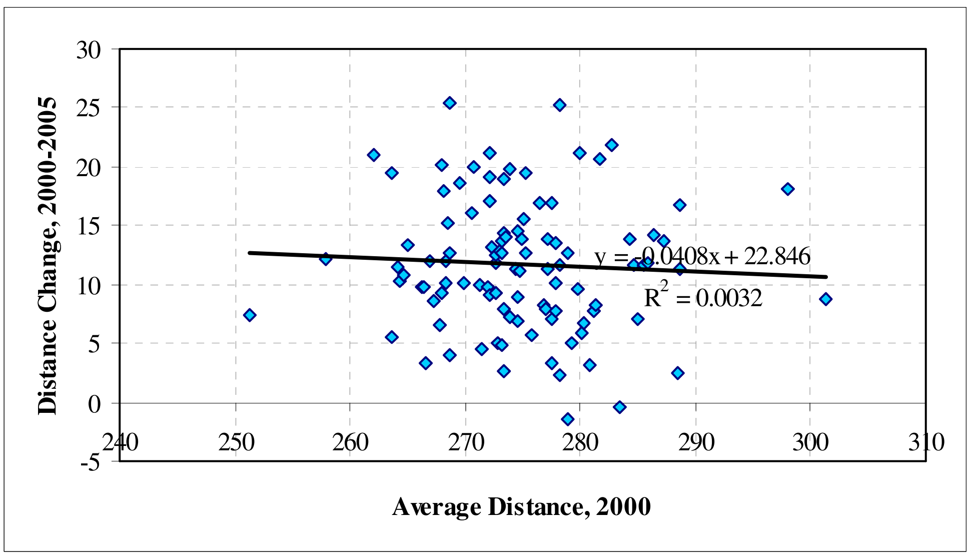

Figure A- 2: Improvement in driving distance for 100 PGA Tour players, 2000-2005, charted as a function of 2000 driving distance. There is no statistically significant correlation between distance improvement over this period and the driving distance average in 2000.

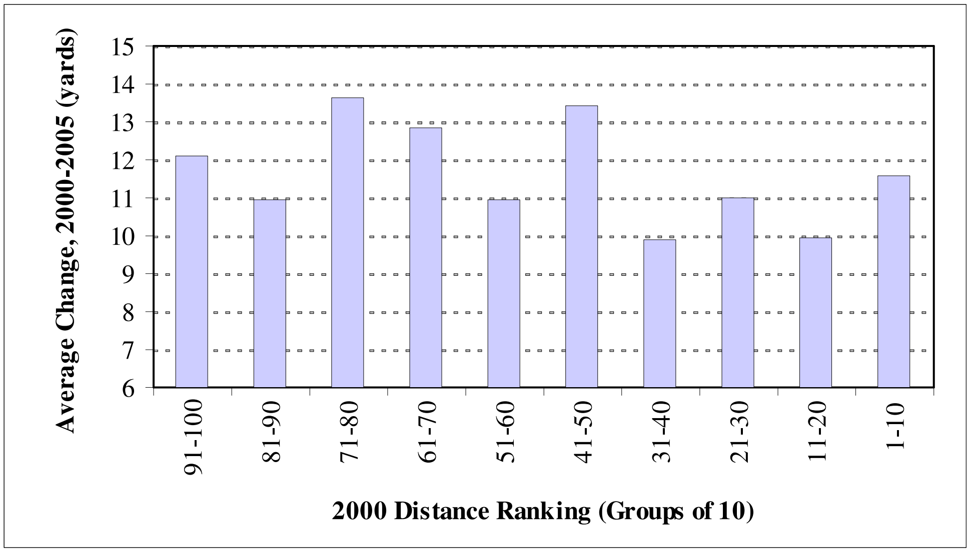

Figure A- 3: Improvement in driving distances by rank, 2000-2005. Bar heights indicate average distance improvement for groups of 10 players.