Identifying the Critical Factors That Contribute to Bowling Ball Motion on a Bowling Lane

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Abstract

The physics behind bowling ball motion on a bowling lane has become increasingly complex, in line with the technological advances in bowling ball coverstocks and cores. Over the last two decades, these advances have contributed to an unprecedented increase in scoring, which threatens to jeopardize the integrity of the sport.

In late 2005, with the intent of modifying existing or creating new specifications for bowling equipment, the United States Bowling Congress (USBC)—the national governing body of the sport of bowling—initiated the Ball Motion Study, a comprehensive investigation to decipher and statistically validate the properties of a bowling ball that contribute to ball motion on a bowling lane. Through the use of multiple regression, the mission of the study was accomplished. Many of the results matched what would be expected by physics, but some were surprising to both the bowling ball manufacturers and USBC.

Following review of the results with USBC's Equipment Specifications & Certification Committee and a majority representation of the bowling ball manufacturers, USBC has approved a new specification for one of the identified significant variables, and has begun investigating modifications to the specifications for several other influential factors identified in the study.

Keywords: Bowling, multiple regression, p-value, ANOVA, multicollinearity, leverage value

1. Introduction

The United States Bowling Congress (USBC), the national governing body of the sport of bowling, aims to ensure the integrity and protect the future of the sport by providing programs and services which enhance the bowling experience. Over the past twenty years, the technological advancements in bowling ball coverstocks and cores, coupled with improved lane surfaces and oiling patterns, have contributed to an increasing rate of honor scores and the overall scoring pace—thereby jeopardizing the credibility of the sport of bowling. As shown in Figure 1, the number of 300 games per capita has increased from about one for every 3150 members (1900 – 1980) to about one for every 27 members (2007).

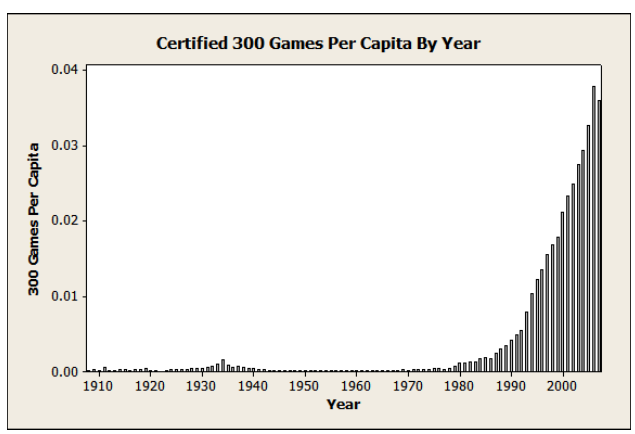

Figure 1. 300 Games Per Capita By Year. The number of perfect games has escalated dramatically over the last 20 years, even though USBC membership has declined.

The Equipment Specifications & Certification Department within USBC is responsible for setting and governing the specification limits of all equipment and machinery used in the sport. Their research has conclusively shown that an increased entry angle into the pins directly relates to better pin carry and, thereby, higher scores (see Figure 2).

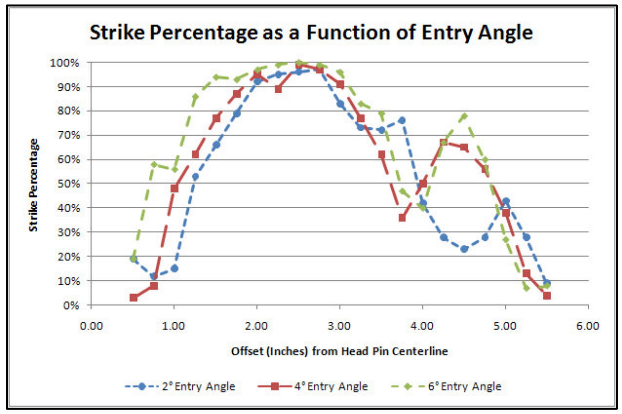

Figure 2. Strike Percentage Versus Angle of Entry. Larger entry angles reap higher strike percentages at most offsets from the centerline of the head pin.

Bowling ball coverstocks and cores have seen the greatest advancements in technology of all bowling equipment. Figure 3 illustrates the timeline of bowling ball technological advances—with each new coverstock increasing the friction between the ball and the lane, and each core evolution increasing the dynamic imbalance of the ball. As the friction between the ball and the lane have increased and the cores have become more dynamically imbalanced, entry angles have increased dramatically—with no additional effort or skill by the bowler. While significant advances in coaching and training have also contributed to increasing scores, USBC believes that the technological advances in bowling balls are responsible for much of the increase in scoring. Therefore, in order to achieve the mission of USBC, the Equipment Specifications & Certification Department set forth to identify which bowling ball properties contribute to ball motion and to determine whether current or new specifications for bowling balls should be modified or developed.

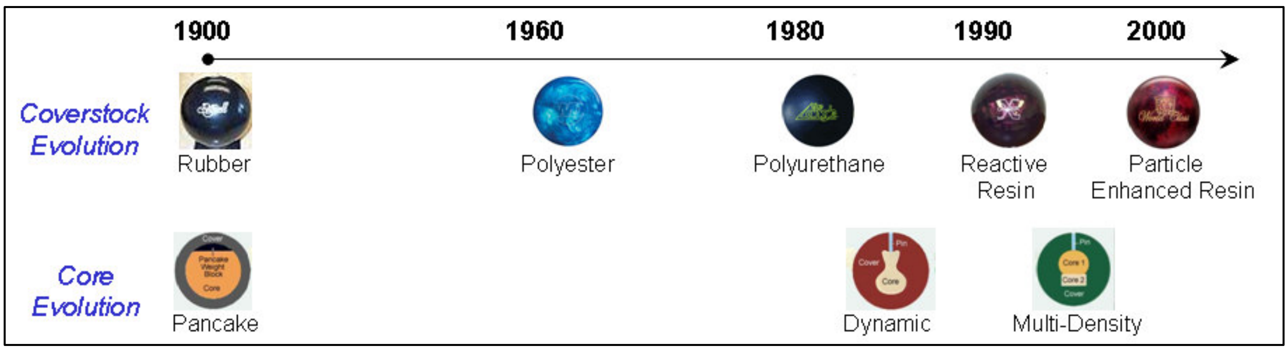

Figure 3. The Evolution of Bowling Ball Coverstocks and Cores since the Founding of USBC in 1895. The last 20 years has seen technological advances through the use of CAE for core design and the use of advanced polyurethane and resin materials for coverstocks.

2. Planning the Ball Motion Study

In October 2005, USBC—along with representatives from the major domestic bowling ball manufacturers—formed the Ball Motion Task Force. Inclusion of the bowling ball manufacturers allowed USBC to not only utilize the knowledge base of some of the industry's leading minds, but also to fortify the relationship between USBC and the ball manufacturers. The ball manufacturers provided invaluable input regarding the parameters of the testing, selection of the variables to evaluate, and also supplied the bowling balls that were used in the study.

Before testing commenced in July 2006, USBC took several actions to ensure ball motion would be properly measured. The SuperCATS (Compter Aided Tracking) system was installed at USBC’s Equipment Specifications & Certifications building. SuperCATS (Figure 4) employs twenty- three sensors that measure ball position, velocity, and vertical angles down a standard sixty foot lane—providing all the data necessary to accurately capture ball motion. The sensors are placed approximately every two feet, starting at eleven feet from the foul line.

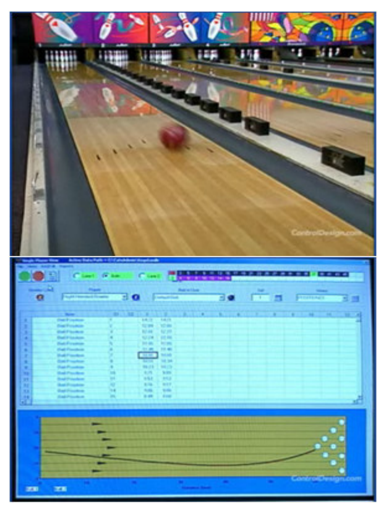

Figure 4. The 23 SuperCATS sensors provide the measurables required to describe ball motion.

Ball motion can be divided into three phases, based on mathematical analysis of the ball's path down the lane:

- Skid Phase, where the ball has not encountered enough friction to begin hooking. This ball path is linear with a negative slope.
- Hook Phase, where the ball has encountered enough friction to transition from a negative slope to a positive slope. This ball path is parabolic.
- Roll Phase, where the ball has stopped hooking and is traveling in a positively sloped linear direction.

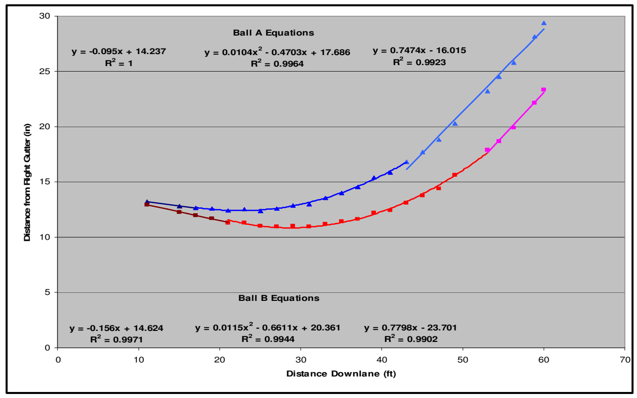

Figure 5. The Three Phases of Ball Motion. Data from SuperCATS is used to determine where on the lane the three phases of ball motion begin and end.

The skid and roll phases were determined by the maximum number of data points that achieved a ninety-nine percent R-squared value for linearity. If a data point was included in either the skid phase or the roll phase and caused the R-squared value of either line to fall below the ninety-nine percent threshold, that point was deemed part of the hook phase. Figure 5 demonstrates the calculation of the three phases of ball motion for two balls, coded A and B.

The Ball Motion Study was one of the largest undertakings in the history of the Equipment Specifications & Certification Department. Therefore, the Ball Motion Study was planned in two phases. In the first phase, a limited performance range of bowling balls was selected for the study, as well as a small number of high-level predictor variables. This served as a method of screening potentially insignificant variables, and allowed USBC to determine, with a minimal amount of resources, whether any trends were apparent in the data. Upon the Phase I results indicating significant trends, Phase II would expand on the predictor variables shown as significant in Phase I, and the performance range of bowling balls included in the study would be expanded.

Ideally, when studying the relationship between predictor variables and a response variable, a Design of Experiments (DOE) is the preferred analytical method. With a DOE, the effects of the predictor variables and their interactions on the response variable can be quantified, along with the derivation of a mathematical prediction equation. However, in the case of the Ball Motion Study, a DOE could not be used because the required specific combinations of predictor variables either do not currently exist or are impossible to manufacture in a bowling ball. Therefore, as an alternative, multiple regression was selected as the analysis tool. Multiple regression still quantifies the effects of the predictor variables on the response variable while also providing a mathematical modeling equation—but the interaction effects are unfortunately lost in the error term.

3. Ball Motion Study—Phase I

To begin Phase I, the Ball Motion Task Force assembled a preliminary y = f (x) cascade, which defined the high-level predictor variables for ball motion. In addition, a list of response variables was generated—all of which could be measured by SuperCATS or calculated from the data provided by SuperCATS.

The eight predictor variables for Phase I were (for more information on how the predictor variables were measured for this study, visit http://www.bowl.com/Downloads/pdf/USBCequipmanual_appendix.pdf):

- Coverstock Type – The technology used in the formulation of the ball's coverstock
- Coefficient of Friction (COF) – The coefficient of friction between a dry (unconditioned) lane and a bowling ball
- Oil absorption Rate – The rate at which lane conditioner is absorbed into the coverstock
- Radius of Gyration (RG) – The RMS distance of the bowling ball's mass to its center of gravity
- Spin Time – The time for a bowling ball to make one full revolution when suspended on the axis of its center of gravity
- Total Differential – The difference in RG between the x- and y-axis of the bowling ball
- Intermediate Differential – The difference in RG between the x- and z-axis of the bowling ball (referred to in industry as Mass Bias Strength)
- Ratio of Total Differential and Intermediate Differential

The nineteen response variables for Phase I were (Figure 6):

- Negative Slope – The slope of the theoretical line during the skid phase
- First Transition – The distance the transition from the skid phase to the hook phase occurs
- A-Score – The parabolic shape of the ball's curvature during the hook phase ($ax^2 + bx + c$)
- Breakpoint – The apex of the hook phase
- First Transition to the Breakpoint – The length from Breakpoint to First Transition
- Second Transition – The distance the transition from the hook phase to the roll phase occurs
- Breakpoint to Second Transition – The length from Breakpoint to Second Transition
- Total Hook Length – The distance between the First and Second Transitions, characterizing length of the hook
- Positive Slope – The slope of the theoretical line during the roll phase
- Ball Velocity Decrease at 49 Feet / 60 Feet
- Angular Deceleration Rate at 49 Feet / 60 Feet
- Intended Path at 49 Feet / 60 Feet – The total number of boards of hook at 49 feet from the foul line and as the ball enters the pin deck (theoretical calculation)
- Average Path at 49 Feet / 60 Feet – The total number of boards of hook at 49 feet from the foul line and as the ball enters the pin deck (SuperCATS calculation)
- Total Angular Displacement – The total angular change on the lane
- Angle Per Foot – The quotient of Total Angular Displacement and Total Hook Length

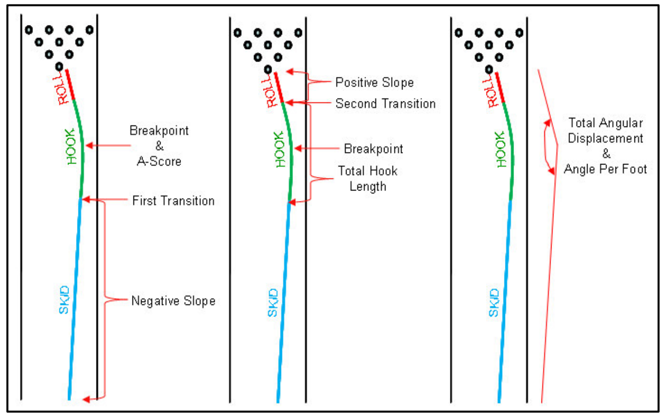

Figure 6. Response Variables for the Ball Motion Study.

For Phase I, ball manufacturers were asked to provide two of their most aggressive particle enhanced or reactive resin bowling balls for testing. The balls were requested to have the following specifications:

- Fifteen pounds in total weight
- Between two and two and one-half ounces of top weight
- Pin-to-CG (center of gravity) distance of between two and three inches
- For asymmetrical core balls, the CG was requested to be within one inch of the midline between the pin and the positive spin high radius of gyration (RG) axis point

The drilling pattern was identical for all test balls. After each ball was drilled, the surface of the ball was taken to 1000 grit by use of Abralon pads. Surfacing the balls was necessary because not every ball comes from the factory at the same box finish. Measurement of the predictor variables was performed after the surfaces of the balls had been standardized. A total of thirty-one bowling balls were used for Phase I.

The bowling lanes used for testing were AMF HPL 9000 synthetic lanes. The lanes were conditioned using the Kegel Standard Sanction lane machine using Kegel Defense/C lane cleaner and Kegel Offense HV lane conditioner. The lane pattern applied to the lane surface was comprised of six two to two loads oiled from the foul line to eight feet and then buffed out to forty-nine feet (this means that thirty units, or microns, of lane conditioner was applied evenly from the second board from the left channel to the second board from the right channel for eight feet, buffed incrementally to eight units of lane conditioner at thirty-two feet, and then buffed incrementally to five units at forty-seven feet).

In order to reduce variation in the testing, Harry—USBC's robotic ball thrower—was utilized for all the testing (Figure 7). Harry has the ability to very accurately repeat programmed ball velocity, spin rate, and trajectory through the use of hydraulic and pneumatic systems. Harry's repeatability and accuracy is constantly monitored by USBC, and at eleven feet from the foul line, his standard deviation for placement and speed are one-third of an inch and one-tenth of a mile per hour, respectively.

The Ball Motion Task Force decided that Harry's programmed bowler characteristics would mimic that of an average advanced bowler:

- Axis tilt of thirteen degrees
- Axis rotation of fifty-five degrees
- Ball velocity of seventeen mph
- Spin rate of 275 rpm
- Positive Axis Point (PAP) of five inches over from the grip midline by three-eighths of an inch up

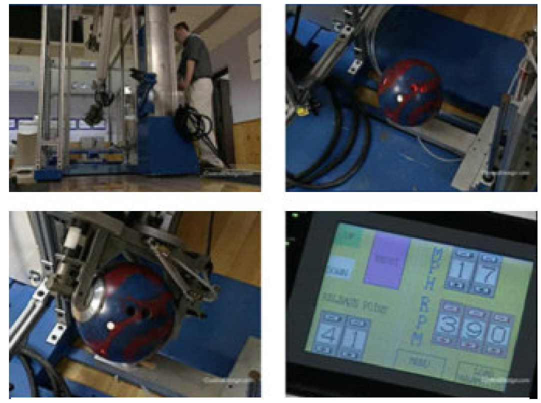

Figure 7. Harry, USBC's Robotic Bowler. Harry uses hydraulics, pneumatics, and a computer system to roll bowling balls with extraordinary precision.

For the data collection, each ball was delivered eight times and the average value for each of the nineteen response variables was calculated. A baseline ball was evaluated at the beginning, middle, and end of each ball's testing to ensure the lane conditioning (oil) pattern did not significantly change between shots.

The multiple regression process followed for each of the nineteen response variables was as follows:

- Regress each of the predictor variables independently with the response variable to determine if there were any potential non-linear effects
- Assess the multicollinearity of the predictor variables in order to eliminate double-counting, inadvertent effect cancellation, or model instability
- Analysis of the ANOVA table of the predictor variables, indicating the significant and non-significant variables, as well as the order of significance
- Analysis of the residuals and unusual observations to verify that the assumptions of the ANOVA analysis were not violated

USBC was interested primarily in identifying which of the eight predictor variables contribute to ball motion; however, mathematical models were also derived to determine if ball motion could be theoretically predicted. For the purpose of determining the predictor variables that most contribute to ball motion, a ranking system was developed based on the ANOVA table generated from the multiple regression analysis for each response variable:

- The predictor variable with the lowest p-value was given a score of eight. The predictor variable with second lowest p-value received a score of seven, and so forth.
- The predictor variable with the largest p-value (or removed because of multicollinearity) was assigned a score of one.
- In the case of a tie for p-values, the raw statistical value (T) was used.

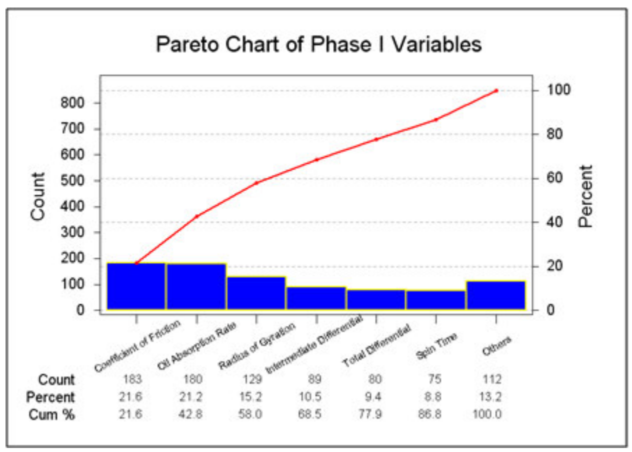

Figure 8. Tally of Scores for Ball Motion Predictor Variables. The results from Phase I clearly show some variables are more influential on ball motion than others.

The scores for each predictor variable were summed over the nineteen regressions. Figure 8 shows the final tally of scores. The following bowling ball properties are the most contributing variables to bowling ball motion on a bowling lane and should be further investigated by USBC:

- Coefficient of Friction
- Oil Absorption Rate
- Radius of Gyration

Figures 9 – 12 summarize the process of determining the mathematical models for the possible theoretical prediction of ball motion. In the illustrated example, the response variable is Intended Path at 60 Feet.

Figure 9 reveals that performing the regression with all eight predictor variables produced significant multicollinearity, suspected to be between Intermediate Differential and Ratio of Intermediate Differential and Total Differential. This was indicated by the Variance Inflation Factor (VIF), which should ideally be less than five, although less than ten is acceptable. Since the Ratio of Intermediate Differential and Total Differential is a mathematical calculation which uses Total Differential and Intermediate Differential (both of which are included as predictor variables), the Ratio of Intermediate Differential and Total Differential was removed from the model. The resultant regression analysis without that predictor variable (Figure 10) yielded desirable values for VIF—thereby, the analysis could continue.

In addition, at this point in the analysis, the predictor variable rankings were determined for the response variable Intended Path at 60 Feet:

- Total Differential got 8 points
- Radius of Gyration got 7 points
- Coverstock Type got 2 Points
- Ratio of Total Differential and Intermediate Differential got 1 point

Next, the Best Subsets algorithm was used to evaluate potential mathematical models. The best model was chosen considering the following criteria:

- Several models with the highest R-squared (adj) values were considered promising. The R-squared (adj) statistic was used because the models being compared have different numbers of terms.
- Mallow's C-p statistic, which is a measure of the "over-fit" of a model, was used to further reduce the number of models. The C-p statistic should be less than or equal to the number of terms in the model.
- The final model was selected by using the lowest standard deviation of the residuals (S).

The boxed model in Figure 11 represented the subset of predictor variables that best model the response variable Intended Path at 60 Feet:

- Coefficient of Friction
- Radius of Gyration
- Total Differential
- Intermediate Differential
- Spin Time

Once the Best Subsets algorithm process was completed, the final model statistics were evaluated. Figure 12 shows the final regression equation for Intended Path at 60 Feet. The R-squared value indicates that the predictor variables in the model account for 56.1% of the behavior of Intended Path at 60 Feet. The remaining 43.9% is from predictor variables not studied, interactions between predictor variables, noise, and measurement and experimental error. While this mathematical model is statistically significant, it is not adequate for useful theoretical predictions.

Predictor	Coef	SE Coef	T	P	VIF
Constant	-16.77	16.04	-1.05	0.307	
Cover	-0.5500	0.5689	-0.97	0.344	1.5
COF	-52.21	27.84	-1.88	0.074	2.6
Oil Absorb	-0.007392	0.007386	-1.00	0.328	2.0
RG	16.554	7.095	2.33	0.029	1.8
Total Diff	133.43	47.23	2.83	0.010	2.3
i-Diff	-28.9	164.1	-0.18	0.862	64.4
Ratio	-0.592	7.626	-0.08	0.939	62.1
Spin Time	-0.1176	0.1012	-1.16	0.258	1.7

Figure 9. Multiple Regression ANOVA Table with All Predictor Variables. Multicollinearity exists.

Predictor	Coef	SE Coef	T	P	VIF
Constant	-17.19	14.79	-1.16	0.257	
Cover	-0.5360	0.5277	-1.02	0.320	1.4
COF	-51.79	26.71	-1.94	0.065	2.5
Oil Absorb	-0.007291	0.007110	-1.03	0.316	2.0
RG	16.620	6.891	2.41	0.024	1.8
Total Diff	136.12	31.51	4.32	0.000	1.1
i-Diff	-41.44	27.22	-1.52	0.142	1.9
Spin Time	-0.11703	0.09873	-1.19	0.248	1.7

Figure 10. Multiple Regression ANOVA Table . The multicollinearity has been resolved. This table was also used to rank the predictor variables.

Vars	R-Sq	R-Sq(adj)	Mallows C-p	S	Cover	COF	Absorb	RG	T-Diff	I-Diff	S-Time
1	42.2	40.3	5.1	1.3094					X		
1	9.0	5.9	23.6	1.6432				X			
2	46.2	42.4	4.9	1.2861				X	X		
2	44.2	40.2	6.1	1.3102					X		X
3	50.5	45.0	4.5	1.2566		X		X	X		
3	47.5	41.7	6.2	1.2936				X	X	X	
4	53.7	46.6	4.7	1.2379		X		X	X	X	
4	52.0	44.6	5.7	1.2610	X	X		X	X		
5	56.1	47.3	5.4	1.2300		X		X	X	X	X
5	54.6	45.5	6.3	1.2509	X	X		X	X	X	
6	56.8	46.0	7.0	1.2450		X	X	X	X	X	X
6	56.8	45.9	7.1	1.2455	X	X		X	X	X	X
7	58.6	46.1	8.0	1.2442	X	X	X	X	X	X	X

Figure 11. Best Subsets Algorithm Output. The boxed model (also in red) is the best mathematical model for Intended Path at 60 Feet.

The regression equation is

Intend 60 = - 18.2 - 32.6 COF + 14.9 RG + 134 Total Diff - 46.7 i-Diff - 0.112 Spin Time

Predictor	Coef	SE Coef	T	P
Constant	-18.24	14.49	-1.26	0.220
COF	-32.56	20.39	-1.60	0.123
RG	14.936	6.576	2.27	0.032
Total Diff	133.94	30.98	4.32	0.000
i-Diff	-46.70	26.38	-1.77	0.089
Spin Time	-0.11215	0.09708	-1.16	0.259

S = 1.22997 R-Sq = 56.1% R-Sq(adj) = 47.3%

Unusual Observations

Obs	Fit	SE Fit	Residual	St Resid
6	20.428	0.636	2.706	2.57R
7	17.896	0.364	-2.680	-2.28R

Figure 12. Final Regression Model for Intended Path at 60 Feet. The model has a good R-squared value, but is not adequate for useful theoretical predictions.

For final validation of the regression model, the residuals and unusual observations were analyzed to verify that the ANOVA assumptions were not violated:

- The residuals must be normally distributed
- The residuals must be independent and random
- The residuals must be of equal variance (homoscedastic) across the model
- Unusual observations must not have an over-weighted influence (leverage) on the slope or intercept of the regression line, compared to other data points used to construct the model

Figures 13, 14, and 15 illustrate the analysis of the residuals. Their normality (p-value greater than 0.05 using the Anderson-Darling Test for Normality), independence and randomness (no points out of control and no trends in an Individuals control chart), and homoscedasticity (cloud of data with no patterns when plotting the residuals versus fits) validate that the ANOVA assumptions were not violated.

Evaluation of the unusual observations (listed in Figure 12 and circled in Figure 15) involved comparison of the calculated leverage value for each unusual observation to the calculated critical leverage value. A leverage value exceeding the critical leverage value indicates that data point has an over-weighted influence on either the slope or intercept of the regression line. The critical leverage value was calculated using (2p/n), where (p) is the number of terms in the model and (n) is the number of data points used to generate the model. In this example, the critical leverage value was 0.387, and the leverage values of the unusual observations were 0.287 and 0.087. Therefore, the leverage assumption was not violated, and the mathematical prediction model is considered valid.

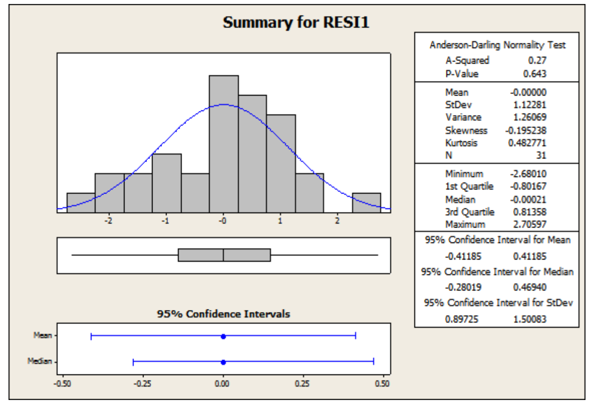

Figure 13. Anderson-Darling Normality Test of the Residuals. The residuals are normally distributed.

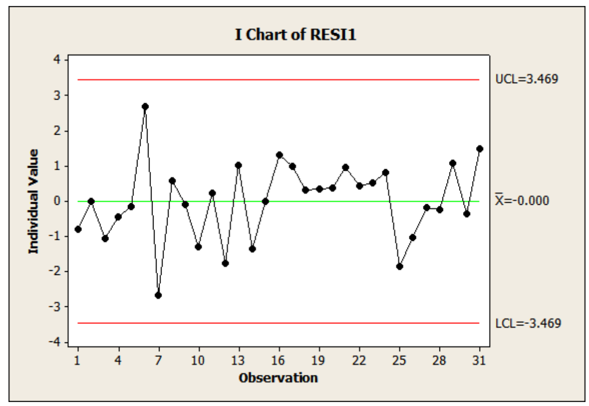

Figure 14. Individuals Control Chart of the Residuals. The residuals are independent and random.

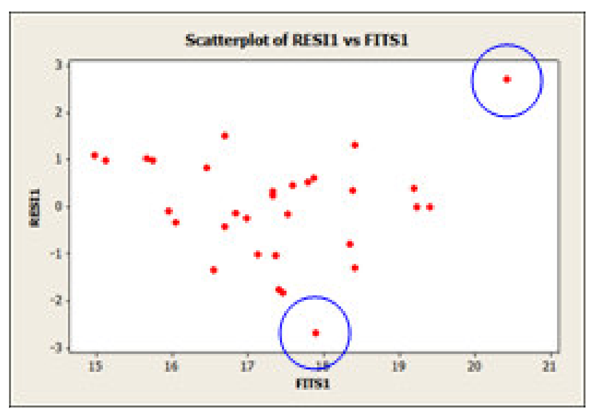

Figure 15. Scatter Plot of the Residuals Vs. Fits. The residuals are homoscedastic.

4. Summary of the Phase I Results

Phase I of the Ball Motion Study was very successful, based on the significant variables identified from the multiple regression analysis. The following is a recapitulation of the Phase I results:

- The three most significant variables that contribute to bowling ball motion on a bowling lane are (in order) Coefficient of Friction, Oil Absorption Rate, and Radius of Gyration. These variables will be further studied Phase II.
- Ratio of Intermediate Differential and Total Differential, because of its multicollinearity with Intermediate Differential, will be removed as a predictor variable for Phase II.
- Coverstock Type was the least contributing variable to ball motion and will be removed as a predictor variable for Phase II.
- Mathematical prediction models were generated for each of the nineteen response variables. Although the models were statistically significant, the R-squared values were not high enough for useful response variable prediction.

5. Ball Motion Study—Phase II

To begin Phase II of the Ball Motion Study, the Ball Motion Task Force developed a more detailed y = f(x) cascade for the significant variables identified in Phase I—thereby adding to the list of predictor variables. In addition, a much broader performance range of bowling balls was solicited from each of the ball manufacturers in order to expand the inference space of the multiple regression analysis. Having the same weight, pin placement, and CG criteria as the balls submitted in Phase I, each manufacturer was requested to submit three balls considered highly aggressive, moderately aggressive, and not aggressive. The balls received ranged from aggressive particle enhanced and reactive resin coverstocks with highly dynamic cores to non-aggressive polyurethane and polyester balls with less- or non-dynamic cores. As in Phase I, each ball was taken to 1000 grit. A total of twenty-two balls were added to the study.

The expanded y = f (x) cascade resulted in the addition of the following predictor variables:

- From Coefficient of Friction:
    - Coefficient of Friction was more aptly named Dry Lane Coefficient of Friction, as this variable specifically measures the coefficient of friction between an unconditioned lane and a bowling ball
    - On Lane Friction – The coefficient of friction between an oiled (conditioned) lane and a bowling ball, calculated from the ball's velocity change on the oiled part of the lane.
    - Surface Roughness (Ra / Rs) – The amplitude / spacing of the microscopic spikes on a ball's surface. (Surface roughness is a chemical property of the coverstock of the bowling ball. Therefore, even if the surfaces of two balls are taken to the same grit, the surface roughness of both balls will differ because of the chemical and porosity differences between the coverstocks.)
    - Average Oil Volume at 8 Feet, 32 Feet, and 51 Feet
- From Radius of Gyration:
    - Ball Diameter – The tolerance allowed by USBC for bowling ball diameters (8.500 – 8.595 inches) can influence the ball's radius of gyration.
    - Radius of Gyration on the Positive Axis Point (PAP). USBC research concerning axis migration during ball travel down the lane determined that a ball migrates down the lane on approximately the same RG profile. Therefore, the RG value on the positive axis point gives a clear representation of the RG value the bowling ball is rotating around during its entire path toward the pins.
- From Oil Absorption Rate:
    - Although no new variable was added, an improved test method was developed which reduced the percent study variation calculated in a gauge R&R. For the new test, a single 0.5 µl drop of Kegel Offense lane oil was placed on a random spot on the ball. Once the oil diffused because of surface energy and tension, the diameter was measured in two directions using a micrometer. Time was also recorded from the moment the drop touched the surface of the ball until it was fully absorbed into the ball (the maximum time allowed was thirty minutes). This procedure was repeated four times on random areas of the ball, and the average of the four readings was calculated. With the time, surface area, and amount of oil known, the oil absorption rate was determined for each bowling ball.
- Additional predictor variables added:
    - Environmental Conditions (Ambient Temperature, Ambient Humidity, and Lane Temperature). Although these values are controlled within the Equipment Specifications and Certification building, natural variation by small increments may influence ball motion.
    - Static Bowling Ball Weights (as a result of drilling the finger and thumb holes)
        - Top Weight – The weight difference between the top and bottom halves of the bowling ball
        - Side Weight – The weight difference between the right and left sides of the grip line of the bowling ball
        - Thumb / Finger Weight – The weight difference between the thumb and finger sides of the grip line of the bowling ball

In addition, one response variable was added:

- Frictional Efficiency – The amount of friction the ball encounters over the entire length of the lane, calculated by the total decrease in velocity between the first and last SuperCATS sensors.

In summary, the total number of predictor variables for Phase II increased from eight to twenty, and the number of response variables increased from nineteen to twenty.

The test methodology for Phase II was identical to Phase I—with eight shots per ball, and the evaluation of a baseline ball before, during, and at the end of each ball's testing to ensure that the lane conditioning (oil) pattern had not changed significantly between shots.

Having an increased inference space for Phase II was paramount to the success of the Ball Motion Study. Therefore, before testing commenced, the ranges of selected response variables were measured, which validated that the goal of capturing a wide range of ball performance was accomplished.

Ball Motion Response Variable	Low Value	High Value
Intended Path at 49 Feet (inches)	5.83	14.03
Velocity Decrease at 49 Feet (mph)	1.31	2.53
Angle Change at 49 Feet (degrees)	2.06	4.89
A-Score (unitless)	0.0100	0.0165
Breakpoint (feet)	28.80	39.83
Angle Per Foot (degrees per foot)	1.95	3.04
Average Path at 60 Feet (inches)	13.98	24.58

Figure 16. Response Variable Ranges.

Once all tests were completed, multiple regression was used to analyze the data. As in Phase I, USBC was interested primarily in identifying which of the twenty predictor variables contribute to ball motion; however, mathematical models were also derived to determine if ball motion could be theoretically predicted.

Immediately seen during the initial steps of the multiple regression analysis was the existence of multicollinearity. The predictor variables Oil at 51 Feet and Radius of Gyration at the PAP were both removed from all models, as they were multicollinear with On-Lane Friction and Radius of Gyration, respectively. With the removal of these two predictor variables, the number of predictor variables used in the multiple regression analysis decreased from twenty to eighteen.

For the purpose of determining the predictor variables that most contribute to ball motion, the same ranking system utilized in Phase I was also utilized in Phase II:

- The predictor variable with the lowest p-value for each regression was given a score of eighteen. The predictor variable with the second lowest p-value received a score of seventeen, and so forth.
- The predictor variable with the largest p-value was assigned a score of one.
- In the case of a tie for p-values, the raw statistical value (T) was used.
- The scores for each predictor variable were summed over the nineteen regressions.

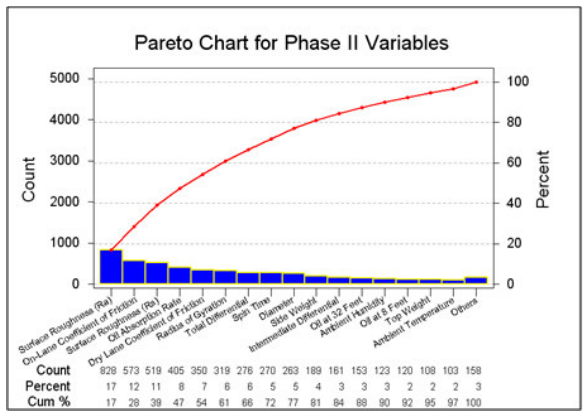

Figure 17. Tally of Scores for Ball Motion Predictor Variables. The results clearly show some predictor variables contribute more to ball motion than others.

Figure 17 shows the final tally of scores, statistically validating the contribution of the predictor variables to bowling ball motion on a bowling lane.

- The predictor variables that contribute the most to ball motion are:
  - Surface Roughness (Ra)
  - On-Lane Coefficient of Friction
  - Surface Roughness (Rs)
  - Dry Lane Coefficient of Friction
  - Oil Absorption Rate
- The predictor variables that are not significant contributors to ball motion are:
  - Static Bowling Ball Weights
  - Intermediate Differential
  - Environmental Conditions

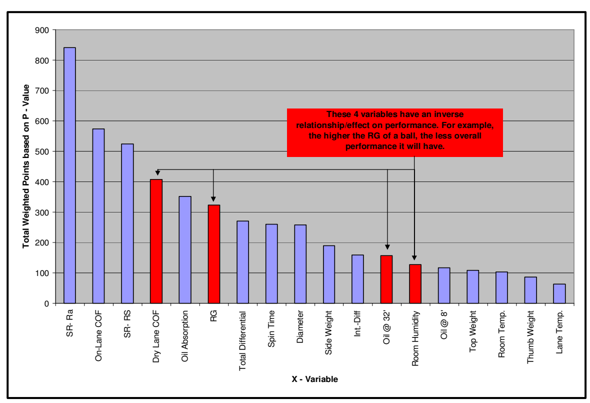

Figure 18. Predictor Variable Relationship to Ball Motion. The variables in red have an inverse relationship to ball motion.

Figure 18 illustrates (in red) the predictor variables that have an inverse effect on ball motion, as evidenced by the sign in the regression coefficients:

- Dry Lane Coefficient of Friction
- Radius of Gyration
- Oil Volume at 32 Feet
- Ambient Humidity

From physics and general observation of ball motion in the field, many the results make sense:

- Bowling balls with high Surface Roughness and On-Lane friction values have higher measurements for intended path (amount of hook) and earlier transitions in the phases of ball motion. These balls are considered and marketed as more aggressive.
- Bowling balls with higher Radius of Gyration values lead to later transitions in the phases of ball motion, and are considered and marketed as less aggressive.
- When lane conditioner is applied farther down the lane at heavier volumes, intended path values (amount of hook) decreases and ball motion transitions occur much later—sometimes not even at all.

Some of the results surprised many of the ball manufacturers and USBC—specifically the low contribution to ball motion of the predictor variables Intermediate Differential and Static Bowling Ball Weights (Top Weight, Side Weight, and Finger / Thumb Weight). Both of these predictor variables currently have upper specification limits set by USBC, and the bowling balls evaluated were all within these stringent limits. While USBC will investigate the relaxation of these specifications, the governing body also realizes that a very possible reason these predictor variables were statistically determined to be low contributors may be that their range was limited by the already tight specification limits. Therefore, premature relaxation or removal of these specifications is not in order.

Finally, mathematical prediction models were also derived for each of the response variables, using the same Best Subsets algorithm from Phase I. These models were validated through the analysis of the residuals and unusual observations, in order to verify that the ANOVA assumptions were not violated. The average R-squared value of the mathematical prediction models was an astounding 74.3%--meaning that, on average, the predictor values explain 74.3% of the behavior of bowling ball motion on a bowling lane. One of the variables of particular interest to USBC—Intended Path at 60 Feet—achieved an R-squared value of 89.3%--a 33.2% increase over Phase I.

6. Validation of the Regression Models and the Trends Observed in the Ball Motion Study

To determine whether the theoretical models could accurately predict ball motion, two bowling balls not used in the study were measured (for predictor variable values) and tested (for response variable values). USBC then compared the tested values to the 95% prediction intervals produced by the mathematical prediction models, which is shown for selected response variables in Figure 19. Overall, the theoretical models correctly predicted more than 80% of the ball motion response variables within the 95% prediction intervals. While this validates the prediction models, USBC will not use the models for theoretical prediction—physical testing will be used as before. However, USBC will continue to refine the models by adding data points as new bowling balls are certified by USBC.

Ball	Response Variable	Test Value	Model Best Fit	95% Lower PI	95% Upper PI	Test Value Within the PI
EB2	Intended Path at 49 Feet	10.62	11.930	9.045	14.822	YES
	Intended Path at 60 Feet	20.40	24.900	19.571	30.224	YES
	Average Path at 49 Feet	11.09	13.840	9.722	17.963	YES
	Average Path at 60 Feet	20.45	25.210	19.475	30.934	YES
	Ball Velocity Decrease at 49 Feet	1.88	2.110	1.669	2.555	YES
	Ball Velocity Decrease at 60 Feet	2.65	2.940	1.980	3.902	YES
	Angular Deceleration at 49 Feet	4.06	3.970	2.702	5.245	YES
	Angular Deceleration at 60 Feet	5.20	4.520	3.020	6.014	YES
WB1	Intended Path at 49 Feet	8.89	9.470	6.233	12.713	YES
	Intended Path at 60 Feet	17.27	24.720	18.457	30.980	NO
	Average Path at 49 Feet	9.21	14.290	9.663	18.910	NO
	Average Path at 60 Feet	17.31	25.140	18.408	30.879	NO
	Ball Velocity Decrease at 49 Feet	2.01	2.220	1.742	2.706	YES
	Ball Velocity Decrease at 60 Feet	2.68	3.310	2.269	4.343	YES
	Angular Deceleration at 49 Feet	3.56	4.240	2.880	5.602	YES
	Angular Deceleration at 60 Feet	4.51	4.700	2.886	6.507	YES

Figure 19. Theoretical Prediction Values Vs. Actual Values for Two Test Balls Not Used in Either Phase of the Ball Motion Study.

Upon review of the results of the Phase II results with the Ball Motion Task Force, several bowling ball manufacturers questioned if the trends in ball motion witnessed in the Ball Motion Study would be consistent on a different lane surface with a different type of lane conditioner (there are many USBC approved lanes surfaces and conditioners). Four balls from the Ball Motion Study were selected for this validation, which was conducted on a Brunswick ProAnvilane surface with Brunswick Authority 22 lane conditioner. Figure 20 shows that the order of strength (measured in boards of hook)—a primary indicator of ball motion—on the Phase II test configuration was the same as on the validation test configuration. This pattern of results was similar for the other response variables.

	Ball (Coded)	Intended Path at 49 Feet (inches)	Intended Path at 60 Feet (inches)
Phase II Test Configuration	EV10	14.03	24.20
	NE21	13.28	23.45
	IC16	11.29	21.32
	PC23	9.37	18.90
Validation Test Configuration	EV10	14.19	25.16
	NE21	9.70	19.00
	IC16	7.28	14.69
	PC23	5.77	12.10

Figure 20. Total Boards of Hook on a Validation Lane Surface and Conditioner. The trends in the validation testing are similar to trends in Phase II.

7. Summary of Phase II Results

Phase II of the Ball Motion Study built on the successes achieved in Phase I. The trends and significant predictor variables observed in Phase I were not only validated, but expanded upon with greater understanding of the complex physics involved in bowling ball motion on a bowling lane. The Phase II results are recapitulated as follows:

- The top five predictor variables that contribute to ball motion are related to the coverstock of the bowling ball:
    - Surface Roughness (Ra)
    - On-Lane Coefficient of Friction
    - Surface Roughness (Rs)
    - Dry Lane Coefficient of Friction
    - Oil Absorption
- The next two predictor variables that contribute to ball motion are properties of the bowling ball's core:
    - Radius of Gyration
    - Total Differential
- The least contributing predictor variables to ball motion are Ball Diameter, Static Bowling Ball Weights, Intermediate Differential, and Environmental Conditions.
- Four predictor variables have an inverse relationship to ball motion:
    - Dry Lane Coefficient of Friction
    - Radius of Gyration
    - Oil Volume at 32 Feet
    - Ambient Humidity
- The average R-squared value of the prediction models was 74.34%, a marked improvement over Phase I.
    - Specifically, for Intended Path at 60 Feet (the response variable illustrated in Phase I), the R-squared value increased to 89.3%—a 33.2% increase from Phase I.
    - The R-squared values for the theoretical models were statistically significant and correctly predict more than 80% of the ball motion response variables within the 95% prediction intervals.

8. Developing a New Specification for Surface Roughness (Ra)

With the Ball Motion Study results fully analyzed, USBC assessed the need for new, tightened, relaxed, or repelled specifications for bowling balls. To preserve the balance of player skill and scoring in the sport of bowling, USBC must take measures on important areas of ball motion that are not being adequately controlled. For example, there are currently two specifications for a bowling ball's coverstock—Dry Lane Coefficient of Friction and Moh's Hardness. However, the results of the Ball Motion Study indicate that Surface Roughness (Ra and Rs) and On-Lane Coefficient of Friction—properties of the coverstock—are extremely influential to ball motion. As a result, the Ball Motion Task Force agreed that development of a specification for Surface Roughness (Ra)—by far the greatest contributor to ball motion—should be initiated immediately, with visitation to the other significant contributors shortly thereafter.

Before developing a new specification for Surface Roughness (Ra), USBC needed to better understand the range of Surface Roughness (Ra) on the market today and develop a graphical representation of how surface chemistry reacts at different grits. Bowling balls from several manufacturers were tested at various Abralon grits (180, 360, 500, 1000, 2000, and 4000) and with a polished surface finish. Figure 21 shows the Surface Roughness (Ra) values for several bowling balls across several grits.

From the results shown in Figure 21, the Ball Motion Task Force agreed to look more closely at the 500 grit Abralon finish. At this grit, which is common in the field, bowling balls begin to show an expanding difference in surface roughness due to shell chemistry. Using inferential statistics for capturing 99% of the current population of bowling balls, a specification was presented to the Ball Motion Task Force and USBC's Equipment Specifications & Certification Committee. The following specification was approved:

- All bowling balls submitted for USBC approval after 04/01/2009 must be below a maximum average Surface Roughness (Ra) of 50 µin at 500 Abralon grit.
- Balls above this value will not be approved by USBC; however, if the initial test results from the two submitted bowling balls are between 35 and 65 µin, the manufacturer will be required to submit eight additional samples for retesting to verify the overall average is below 50 µin.
- Through 04/01/2009, USBC will collect Surface Roughness (Ra) data on all balls submitted for approval. The measurements from these balls will be added to the data set of balls already measured. Should the 99% upper limit of this new data set be significantly different from the initial data set, the specification for Surface Roughness (Ra) will be considered for modification.

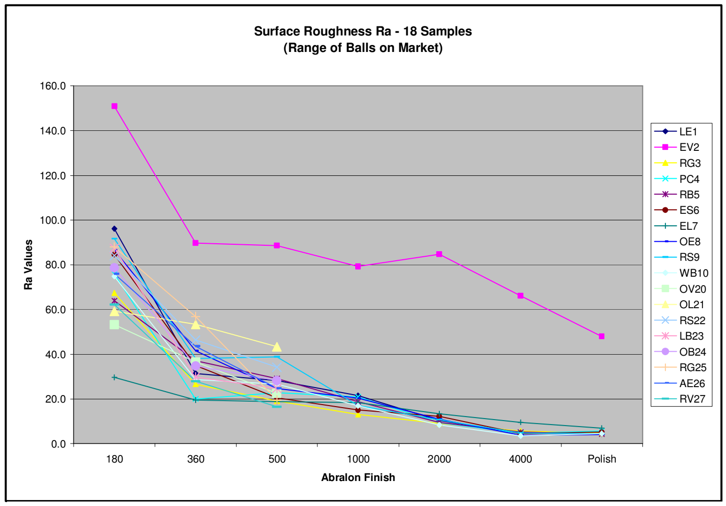

Figure 21. Surface Roughness (Ra) at Various Surface Preparations. Surface Roughness (Ra) is mostly independent of surface finish.

9. Summary

Technological advances in bowling ball coverstocks and cores have increased the complexity of the physics of bowling ball motion on a bowling lane. In addition, unprecedented increases in scoring have accompanied these advances, threatening to jeopardize the integrity of the sport. Through the completion of the Ball Motion Study by the United States Bowling Congress (USBC) in 2008, USBC has a much greater understanding and statistical validation of the critical factors that contribute to bowling ball motion on a bowling lane.

The Ball Motion Study has clearly shown that the properties of a bowling ball's coverstock dominate the ball's movement characteristics on the lane. Other variables believed by some in the bowling industry to have a significant effect on ball motion—such as static bowling ball drilling weights—were deemed insignificant in comparison.

Overall, the five factors that contribute most to ball motion were determined to be:

- Surface Roughness (Ra)
- On-Lane Coefficient of Friction
- Surface Roughness (Rs)
- Dry Lane Coefficient of Friction
- Oil Absorption Rate

As a result of the Ball Motion Study, a new specification for surface roughness (Ra) has been approved by the USBC Equipment Specifications & Certification Committee and will take effect on April 1st, 2009. Surface roughness (Rs) and Oil Absorption Rate will be evaluated during the 2008 calendar year with specifications likely proposed in 2009 or 2010. USBC will also investigate elimination or relaxation of the specifications for bowling ball static drilling weights.

USBC has deemed the Ball Motion Study an enormous success. For many years, the bowling community has disagreed fervently—without data—on the variables that most contribute to the physics of bowling ball motion on a bowling lane. The results of the Ball Motion Study statistically validate the most significant variables and put these disagreements to rest, while allowing USBC to develop and investigate new specifications that will ensure the integrity of the sport of bowling.