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

Presented By:

The United States Bowling Congress

Equipment Specifications and Certification Team

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Presentation Outline

⭐ USBC Mission and Guiding Principles

⭐ Basis for the Ball Motion Study

⭐ Ball Motion Study (Phase I)

  ⭐ Planning the Study

  ⭐ Conducting the Study

  ⭐ Analysis of the Results

⭐ Ball Motion Study (Phase II)

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  ⭐ Conducting the Study

  ⭐ Analysis of the Results

⭐ Implementation of New Equipment Specifications

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Mission and Guiding Principles

- As the national governing body of the sport of bowling, the United States Bowling Congress is dedicated to providing programs and services to uphold the game's credibility, preserve its future and enhance the bowling experience

- The Equipment Specifications and Certification Team is dedicated to preserving the character and integrity of the sport, while assuring fairness of play for all United States Bowling Congress members
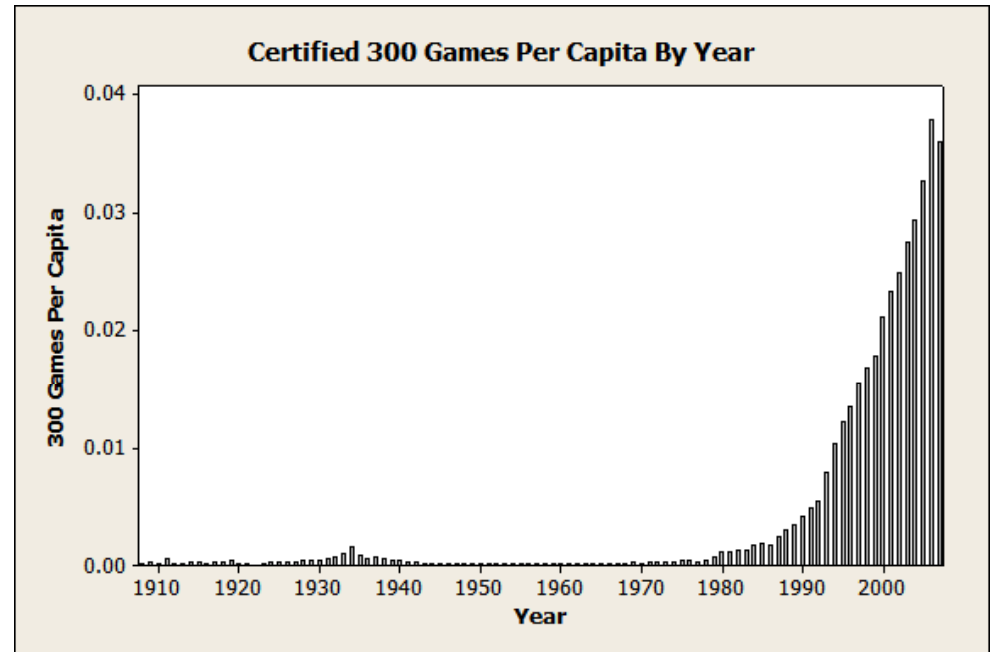
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Basis for the Ball Motion Study

Honor Scores on the Rise

⭐ In many sports, advances in equipment technology have significantly enhanced the ability of participants to score well

⭐ Today's athletes are well-trained and educated, but USBC also believes technological advances in equipment have artificially inflated scores—thereby jeopardizing the integrity of the sport
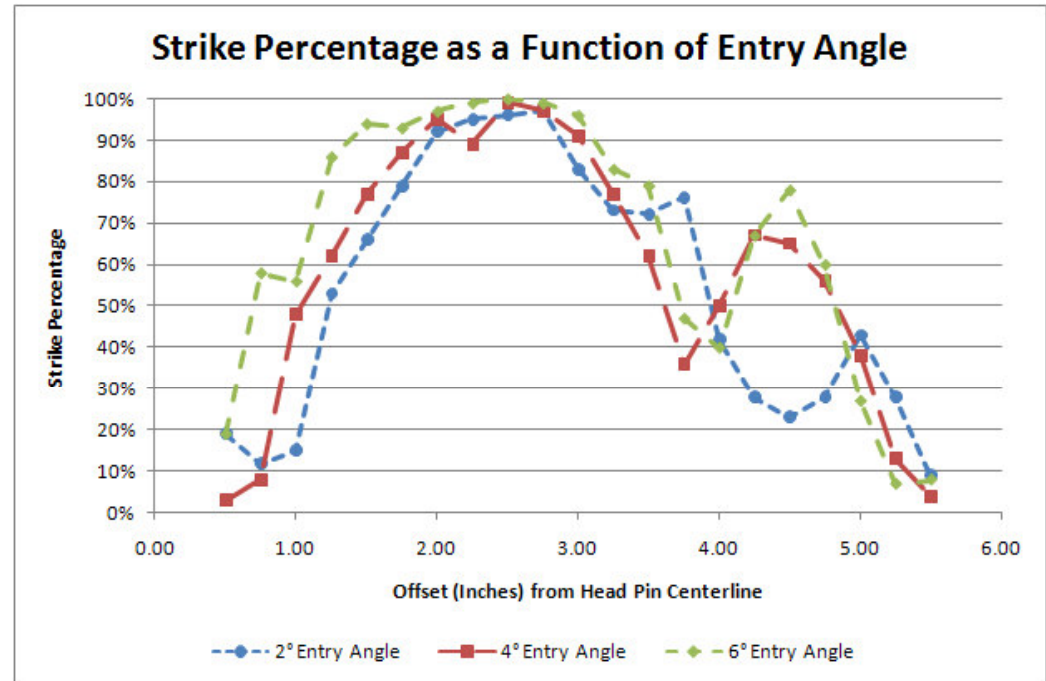
Certified 300 Games Per Capita By Year

1910 – 1980: (1) 300 game for every 3150 members
2007: (1) 300 game for every 27 members

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Basis for the Ball Motion Study

Angle of Entry Versus Strike Percentage

- Studies conducted by the USBC have clearly shown that increased entry angle into the pins significantly improves carry of the corner pins

- Higher carry percentages allow the bowler to roll more strikes—resulting in higher scores

Strike Percentage as a Function of Entry Angle

Y-axis: Strike Percentage (0% to 100%)
X-axis: Offset (Inches) from Head Pin Centerline (0.00 to 6.00)

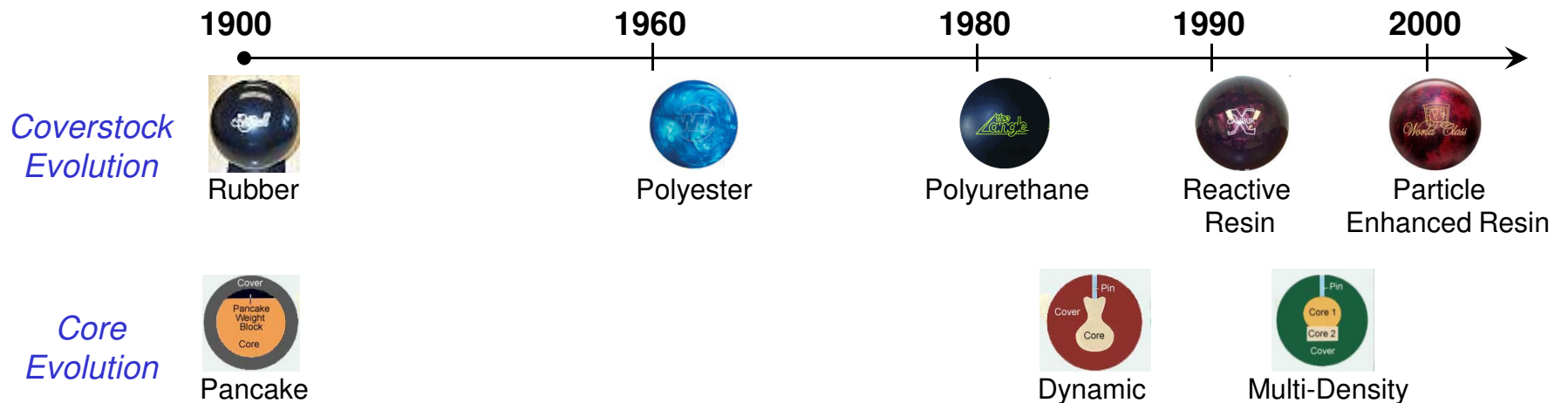Legend: 2° Entry Angle, 4° Entry Angle, 6° Entry Angle

A greater entry angle increases the probability of striking at many offsets from the headpin. Data generated from USBC's BowlScore data collection system

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Basis for the Ball Motion Study
Technological Advances in Bowling Balls

Bowling Ball Coverstocks and Cores

- As the amount of friction the bowling ball creates on the lane increases, the ability to create larger angles of entry into the pins increases
- As the dynamic imbalance of a ball's core increases, the ability to create larger angles of entry into the pins increases

1900	1960	1980	1990	2000

Coverstock Evolution

Rubber — Polyester — Polyurethane — Reactive Resin — Particle Enhanced Resin

Core Evolution

Pancake — Dynamic — Multi-Density

Basis for the Ball Motion Study
Setting the Goals

- In late 2005, the USBC Equipment Specifications and Certification Team initiated the task to identify which properties of a bowling ball contribute to ball motion

- The results of the study would be used to modify existing or create new specifications for bowling balls, thereby limiting technological innovations that threaten to further erode the integrity of the sport

- The Ball Motion Study would be conducted with full involvement with the major bowling ball manufacturers

- In addition to the Ball Motion Study, the USBC Equipment Specifications and Certification Team has begun task forces on lane beds, lane conditioners, and pins to further quantify the effects of technology on scoring.

Planning the Ball Motion Study

Determination of the Predictor and Response Variables (Phase I)

- Phase I used a limited performance range of bowling balls and focused on eight predictor variables determined from a high-level $y = f(x)$ cascade. From Phase I, the team could determine:
  - Which predictor variables need more in-depth analysis and which predictor variables can be removed from future studies (screening)
  - Whether any trends are apparent using the proposed mathematical methods—thereby, not wasting monetary and time resources on a study that might not produce good results

Planning the Ball Motion Study
Determination of the Predictor and Response Variables (Phase I)

✴ The eight predictor variables were:

  ✴ *Coefficient of Friction*
  ✴ The coefficient of friction between a dry lane bed 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 ball's mass to 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

  ✴ *Ratio of Total Differential and Intermediate Differential*

  ✴ *Spin Time*
  ✴ The time for a bowling ball to make one full revolution when suspended on the axis of its center of gravity

  ✴ *Coverstock Material*

Planning the Ball Motion Study
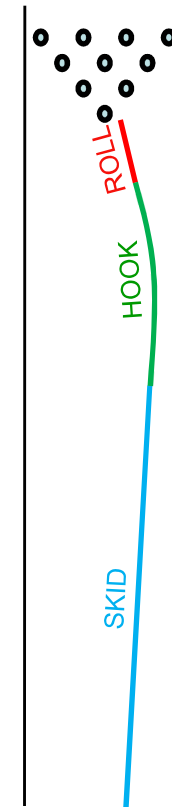## *Determination of the Predictor and Response Variables (Phase I)*

- Nineteen response variables were selected, each of which uniquely characterize the motion of a bowling ball down the lane
  - These variables were measured using the Computer-Aided Tracking System (SuperCATS), which uses 23 sensors located on the bowling lane that track ball characteristics as the ball travels down the lane.
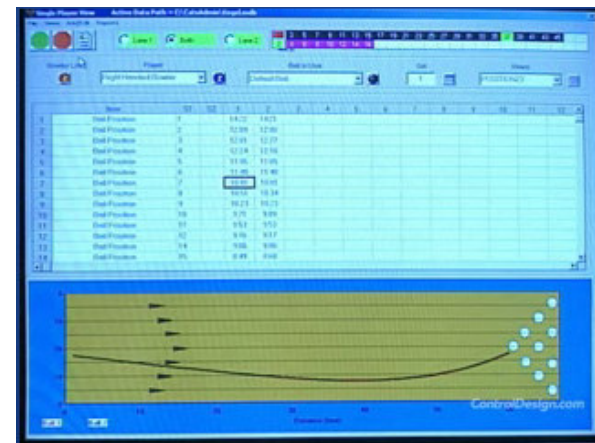
Planning the Ball Motion Study
Determination of the Predictor and Response Variables (Phase I)

⋆ 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.

ROLL

HOOK

SKID

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Planning the Ball Motion Study

Determination of the Predictor and Response Variables (Phase I)

- The nineteen response variables were:
  - Negative Slope
    - Slope of the theoretical line during the skid phase
  - First Transition
    - The distance at which the transition from the skid phase to the hooking phase occurs
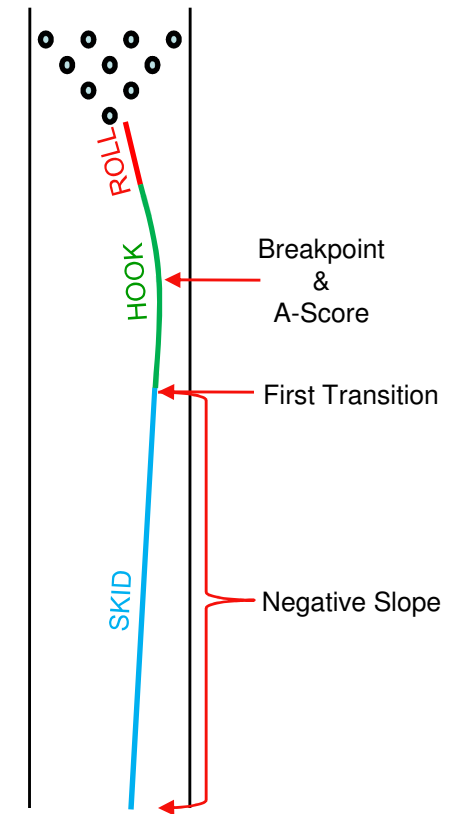 - A-Score
    - Parabolic shape of the ball's curvature during the hook phase $(ax^2 + bx + c)$
  - Breakpoint
    - The apex of the hook phase
  - First Transition to the Breakpoint
    - The length from Breakpoint to First Transition

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Planning the Ball Motion Study
Determination of the Predictor and Response Variables (Phase I)

- The nineteen response variables were (cont'd):
  - Second Transition
    - The distance at which the transition from the hook phase to the roll phase occurs
  - Breakpoint to Second Transition
    - The length from Breakpoint to Second Transition
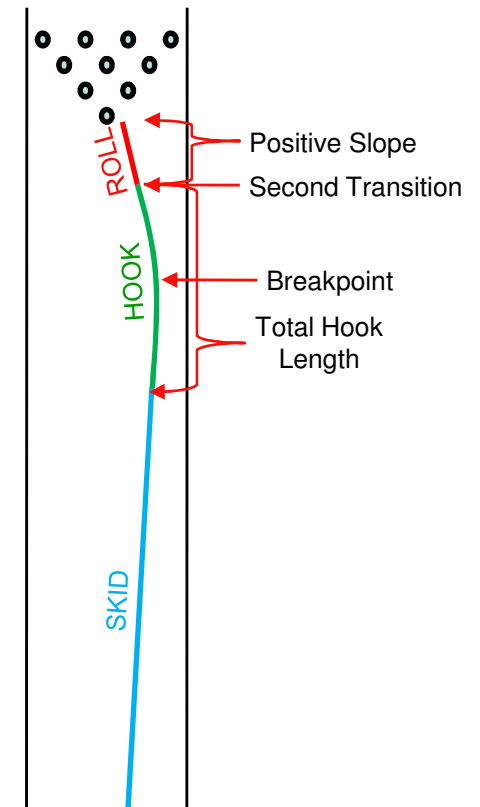 - Total Hook Length
    - The distance between the First and Second Transitions, characterizing the length of the hook
  - Positive Slope
    - Slope of the theoretical line during the roll phase
  - Ball Velocity Decrease at 49 Feet / 60 Feet
  - Angular Deceleration Rate at 49 Feet / 60 Feet

Positive Slope

Second Transition

Breakpoint

Total Hook Length

ROLL

HOOK

SKID

Planning the Ball Motion Study
Determination of the Predictor and Response Variables (Phase I)

- The nineteen response variables were (cont'd):
  - 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)
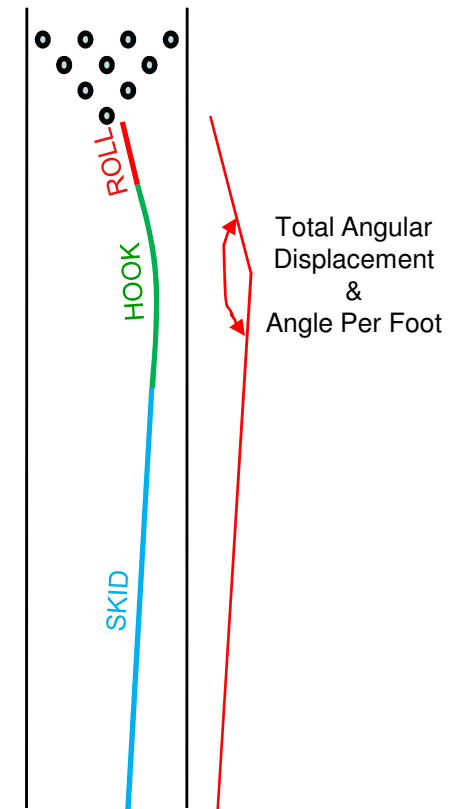 - Average Path at 49 Feet / 60 Feet
    - The total number of boards of hook at 49 feet from the foul line and as the ball enters the pin deck (SuperCATS calculation)
  - Total Angular Displacement
    - The total angular change on the lane
  - Angle Per Foot
    - The quotient of Total Angular Displacement and Total Hook Length

ROLL

HOOK

SKID

Total Angular Displacement & Angle Per Foot

Planning the Ball Motion Study
Final Setup Considerations (Phase I)

- A total of 31 balls were used for Phase I of the study
    - Bowling ball manufacturers submitted bowling balls classified as "high performance"
    - USBC selected additional bowling balls from past certification testing that were determined to be of interest to the study
- Gauge R&R studies were conducted on all measurement systems before the study commenced
    - Crossed gauge R&Rs were used when the condition of the measurement was not destroyed across measurements (radius of gyration, differential, spin time, etc.)
    - Nested gauge R&Rs were used when the condition of the measurement had the potential to be destroyed across measurements (oil absorption, etc.)

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Conducting the Study
Final Setup Considerations (Phase I)

✯ To minimize variation throughout the Ball Motion Study, the robotic bowler "Harry" was used to roll the ball down the lane for each test

   ✯ "Harry" spins the ball to a constant rate of revolution and releases the ball at a programmed velocity and trajectory

(For more information on Harry, visit http://www.bowl.com/bowltv/main.aspx# under the Credibility tab)

✯ Each ball was rolled down the lane eight times to determine the average value for each response variable

✯ A "baseline" ball was used at times during the testing to verify the lane conditioner pattern was unchanged

Planning the Ball Motion Study
Determination of the Analysis Method (Phase I)

- When studying the relationship between predictor and response variables, a Design of Experiments (DOE) is generally chosen because of the ability to quantify the effects of the predictor variables and their interactions on the response variable. DOEs also provide a theoretical prediction equation.
  - Manufacturing and physical limitations make it impossible to produce bowling balls that have specific combinations of the predictor variables required for a DOE
- Multiple linear regression is an alternative numerical method that still quantifies the effects of the predictor variables on the response variable, while providing a theoretical prediction equation.
  - Interaction effects between the predictor variables cannot be studied, as they are lost in the error term

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Conducting the Study

Analysis Method (Phase I)

- Each of the nineteen response variables was analyzed, using the following multiple regression methodology:
  - Predictor variables were independently regressed against the response variable to determine if there were non-linear effects
  - Predictor variables were evaluated for multicollinearity.
    - Variables showing multicollinearity were removed from the model in order to eliminate model instability
  - Predictor variables were ranked 1 to 8, based on the p-value
    - Lowest p-value received a score of 8; highest p-value (or variables removed because of multicollinearity) received a score of 1
  - The best mathematical prediction model was selected using the Best Subsets algorithm for each response variable
  - Residual analysis was conducted to validate ANOVA assumptions

Conducting the Study

Analysis Method (Phase I) – Assessing Multicollinearity & Ranking Predictor Variables

Example Analysis (Response Variable – Intended Path at 60 Feet)

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

Multicollinearity between Intermediate Differential and Ratio of Differentials.

- ☆ This is expected because Ratio of Differentials is a mathematical calculation from Total Differential and Intermediate Differential.
- ☆ Ratio of Total Differential and Intermediate Differential was removed from the model

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

Multicollinearity has been resolved. Variables received points based on the ranking of the p-values

- ☆ Total Differential got 8 points
- ☆ Radius of Gyration got 7 points
- ☆ Coverstock Mat'l got 2 points
- ☆ Ratio of Total Differential and Intermediate Differential got 1 point

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Conducting the Study

Analysis Method (Phase I) – Selecting the Best Model

Example Analysis (Response Variable – Intended Path at 60 Feet)

Vars	R-Sq	R-Sq(adj)	Mallows C-p	S	Cov r F	Abs s C O r F	T - D i R f f G	I - D i f f f	S - T i m e
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
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
6	56.8	45.9	7.1	1.2455	X X		X	X	X
7	58.6	46.1	8.0	1.2442	X X X	X	X X	X	

→

The best model was chosen by considering the following:
- ⭐ Largest R-sq (adj) values
- ⭐ Mallow's C-p statistic equal to or less than the number of terms in the model
- ⭐ Low standard deviation of the residuals (S)

The model highlighted in red was the best model for this response variable
- ⭐ Coefficient of Friction
- ⭐ Radius of Gyration
- ⭐ Total Differential
- ⭐ Intermediate Differential
- ⭐ Spin Time

Conducting the Study

Analysis Method (Phase I) – Interpretation of the Best Model

Example Analysis (Response Variable – 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

The equation of the selected model was evaluated:

- Predictor variables in the model explain 56.1% of the behavior of the response variable.
- The remaining 43.9% is explained by interactions between the predictor variables, factors not considered, noise, and measurement / experimental error
- Unusual observations were recorded for consideration in the residual analysis
- Although the mathematical model is statistically significant, it is not adequate for useful theoretical predictions

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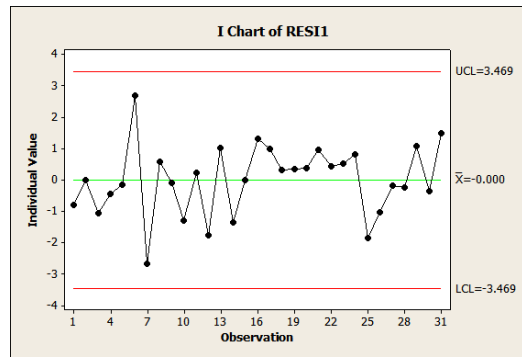**United States Bowling Congress**

Conducting the Study

Analysis Method (Phase I) – Validation of the ANOVA Assumptions

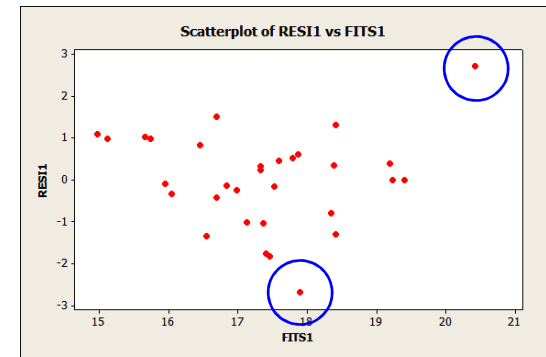Example Analysis (Response Variable – Intended Path at 60 Feet)
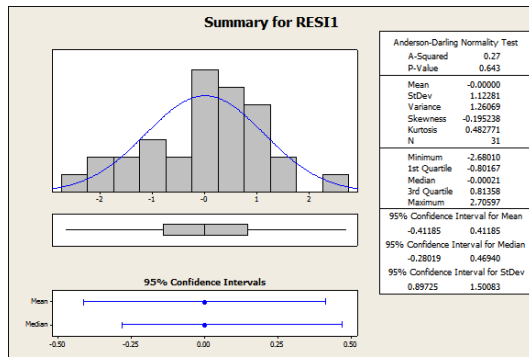
The residuals were normally distributed

The residuals were independent and random

The residuals were homoscedastic—data points 6 and 7 were identified as unusual observations, and required investigation)

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Conducting the Study

Analysis Method (Phase I) – Validation of the ANOVA Assumptions

Example Analysis (Response Variable – Intended Path at 60 Feet)

Leverage values of data points identified as unusual observations must be calculated

- Data points that have a leverage value greater than the guideline for maximum leverage have an over-weighted influence on the slope and / or intercept of the model, and thereby jeopardize the validity of the model

$$Leverage = \frac{2p}{n}$$ Where p is the number of terms in the model and n is the number of data points

Guideline for allowable leverage: 0.387
Leverage for data point #6: 0.267
Leverage for data point #7: 0.087

Therefore, the equal leverage assumption was not violated

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Conducting the Study
Phase I Results

The p-value rankings from the nineteen regressions were tallied to determine the predictor variables that contribute the most to ball motion.
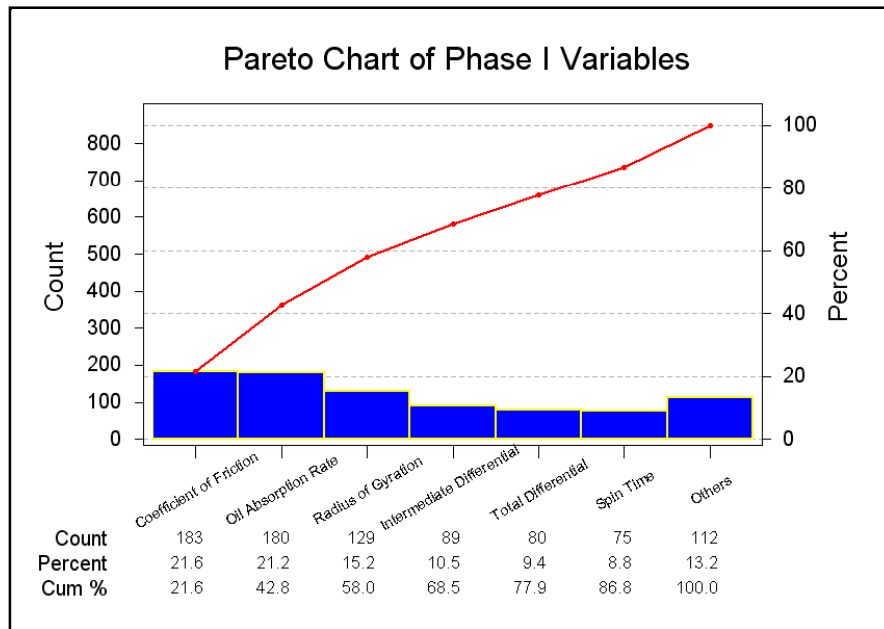
The Phase I predictor variables that significantly contribute to ball motion are:

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

USBC should investigate these variables further

Planning the Ball Motion Study
Determination of the Predictor and Response Variables (Phase II)

- With the success of Phase I, the following enhancements were incorporated into Phase II:
    - A larger performance range of bowling balls (22 balls added)
        - Manufacturers submitted high-, mid-, and low-performance balls
        - USBC included balls of interest from past ball certifications
    - An in-depth $y = f(x)$ cascade on the significant Phase I predictor variable Coefficient of Friction added the following predictor variables:
        - Coefficient of Friction was more aptly named Dry Lane COF
        - On-Lane Friction
            - The coefficient of friction between a conditioned (oiled) lane and a bowling ball, calculated by the decrease in velocity of the ball on the conditioned part of the lane
        - Ball Surface Roughness (Ra / Rs)
            - The amplitude / spacing of microscopic spikes in the ball's surface
        - Average Oil Volume at 8 Feet, 32 Feet, and 51 Feet

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Planning the Ball Motion Study
Determination of the Predictor and Response Variables (Phase II)

- With the success of Phase I, the following enhancements were incorporated into Phase II (continued):
  - A more in-depth $y = f(x)$ cascade on the significant Phase I predictor variable Radius of Gyration added the following predictor variables:
    - Radius of Gyration (RG) about the Positive Axis Point (PAP)
      - The RG about the axis of ball rotation
    - Bowling Ball Diameter
  - Static Bowling Ball Weights (from drilling) added predictor variables:
    - Top Weight, Side Weight, and Thumb / Finger Weight
      - The weight difference, after drilling, between the top and bottom halves of the bowling ball
      - The weight difference, after drilling, between the left and right sides of the grip line of the bowling ball
      - The weight difference, after drilling, between the thumb and finger sides of the grip line of the bowling ball

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Planning the Ball Motion Study
Determination of the Predictor and Response Variables (Phase II)

- With the success of Phase I, the following enhancements were incorporated into Phase II (continued):
  - Ambient conditions were added as predictor variables
    - Lane Temperature
    - Ambient Temperature
    - Ambient Humidity
  - Ratio of Differentials was eliminated as a predictor variable because it was multicollinear in every regression conducted in Phase I
  - Coverstock Type was eliminated as a predictor variable because it was the lowest ranked variable in Phase I
  - Frictional Efficiency (the friction a ball encounters over the entire length of the lane) was added as a response variable
  - A new oil absorption test was developed that reduced the percent study variation from the method used in Phase I

Conducting the Study
Analysis Method (Phase II)

* The twenty response variables were analyzed using the same methodology as Phase I:
  * Predictor variables were independently regressed against the response variable to determine if there were non-linear effects
  * Two predictor variables were removed because of multicollinearity
    * Oil Volume at 51 Feet (multicollinear with On-Lane Friction)
    * Radius of Gyration at the PAP (multicollinear with Radius of Gyration)
  * Predictor variables were ranked from 1-18, based on the p-value
    * Lowest p-value received a score of 18; highest p-value (or variables removed because of multicollinearity) received a score of 1
  * The best mathematical prediction model was selected using the Best Subsets algorithm for each response variable
  * Residual analysis was conducted to validate ANOVA assumptions

Conducting the Study

Phase II Results

The p-value rankings from the twenty regressions were tallied to determine the predictor variables that contribute the most to ball motion.

Pareto Chart for Phase II Variables
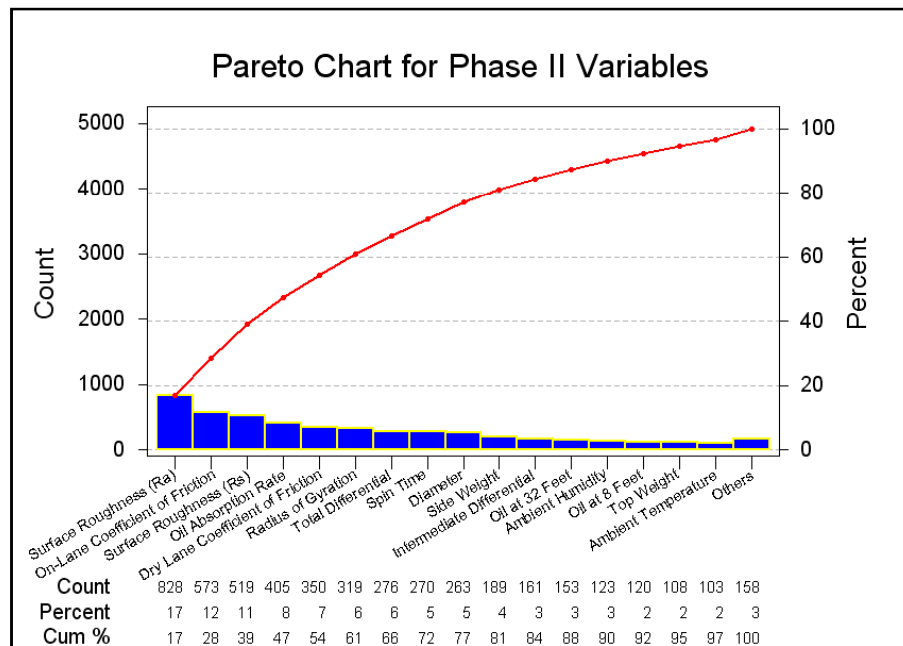
The Phase II predictor variables that significantly contribute to ball motion are:

- Surface Roughness (Ra)
- On-Lane Coefficient of Friction
- Surface Roughness (Rs)

USBC should investigate creation of specifications for these predictor variables

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Conducting the Study
Phase II Results

Additional Notes from Phase II:

- The mean R-squared value for the response variables was 74.35%
  - The highest R-squared value was 89.3% (Intended Path at 60 feet)—an increase of 33.2% from Phase I
- Tests were conducted on an alternative lane surface with an alternative lane conditioner. The trends from this test matched the Phase II trends
- Two additional balls were used to validate the regression models
  - More than 80% of the predicted values fell within the 95% prediction interval for each of the response variables
- Some predictor variables have an inverse relationship to ball motion:
  - Radius of Gyration
  - Oil Volume at 32 Feet
  - Dry Lane Coefficient of Friction

Implementation of New Equipment Specifications

- ✯ USBC has approved a new specification for Surface Roughness (Ra), which will be effective for balls manufactured after April 1, 2009
  - ✯ The specification is based on the 99th upper percentile of the population of balls that are currently on the market
  - ✯ USBC will measure surface roughness of balls submitted for certification over the next twelve months
  - ✯ The surface roughness specification may be modified based on the measurements collected over the next twelve months
- ✯ USBC is investigating new specifications for the other predictor variables identified as significant in this study, and is also investigating relaxation or removal of specifications for predictor variables identified as not significant

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Questions and Discussion

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