LEGO DOE PROJECT REPORT

Business Process Analytics SCM – 517

MSBA – WP Carey School of Business

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INTRODUCTION

As part of our project, we utilized a LEGO kit to design and optimize a race car, applying the principles of Design of Experiments (DOE) to achieve the best possible performance at minimal cost. LEGO is a widely recognized system of interlocking plastic bricks and components, allowing for the creation of diverse structures, vehicles, and innovative designs.

The LEGO DOE project integrates the creativity of LEGO construction with the systematic approach of experimental design and engineering. The primary goal is to design a race car capable of traveling the maximum distance down a ramp, fostering both technical and practical learning.

This initiative provides a hands-on, interactive experience for applying key concepts in engineering, statistics, and experimental design. It emphasizes creativity, critical thinking, and problem-solving while encouraging purposeful exploration and innovation. Through this project, participants cultivate curiosity, resilience, and practical expertise in a dynamic and engaging way.

Objective:

The objective of this project is to design and optimize a race car using LEGO components that can achieve the maximum distance down a 30-degree ramp while adhering to cost constraints outlined in the provided Bill of Materials.

Factors:

The following factors were considered for experimentation:

- **Wheel Base:** The distance between the front and rear wheels.
- **Axle Base:** The distance between the left and right wheels.
- **Wheel Size:** This factor had two levels—small wheels and large wheels.
- **Weight Distribution:** Two configurations were tested: placing the weight towards the back of the car versus the front.

Response Variable:

The distance traveled by the car down the ramp (measured in centimeters).

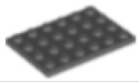
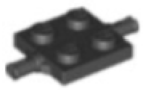
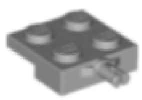
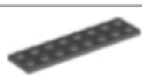
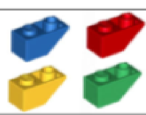
Constraints:

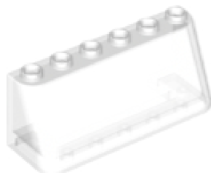
- Only the provided LEGO blocks to be used for the design.
- Each design was required to include a windshield and a steering wheel.

Challenges:

- The ramp surface was uneven, which affected the consistency of the trials.
- Starting the car with zero velocity was difficult.
- Maintaining stable hand movements during the car release introduced variability in the results.

Bill of Material:

Parts of Car	Count	Price Per Unit
	5	500
	4	2000
	4	1500
	4	500
	10	200
	6	1000
	3	1000
	4	1200
	8 total (ignore the colors)	100 each
	1	100
	6	1000
2 x 4 brick	6	600

	1	500
	1	1000
4 x 8 plate	1	2200
	6	500

EXPERIMENTAL SETUP

Our experimental setup included the following:

- A makeshift ramp with a height of 15 cm and a length of 30 cm, forming a 30-degree angle.
- A smooth and consistent surface at the bottom of the ramp to facilitate uninterrupted car travel.
- A measuring tape to ensure precise distance measurements.

The experiments were conducted by varying the following factors:

Factor	Low Level	High Level
Wheel Base	3.5 cm	5 cm
Axle Base	1.5 cm	3.4 cm
Wheel size	Small	Big
Weight Distribution	Back	Front

Measures to Ensure Consistency

- A fixed starting point was marked at the top of the ramp for all trials.
- A level was used to verify the ramp’s angle before each experiment.
- The experiments were conducted in a controlled indoor environment to minimize external factors such as wind or uneven surfaces.

DESIGN OF EXPERIMENTS

Design of Experiments (DOE) is a powerful tool in engineering and product development, enabling systematic analysis of the factors influencing a system's performance. In the SCM 517 course, the Lego DOE project provided a hands-on opportunity to apply these principles to optimize the performance of a race car.

We employed a **full factorial design** with two levels for each factor, resulting in 16 unique combinations ($2^4 = 16$), each replicated three times. This design allowed us to evaluate both the main effects of individual factors and their interactions, which can significantly impact performance.

After conducting the experiments, we performed a statistical analysis to determine the effects of each factor and their interactions on the car's performance. The insights gained enabled us to identify the optimal configuration.

The primary objective was to design a Lego race car that could travel the maximum distance down a 30-degree ramp while adhering to cost constraints. Through this project, we were able to:

1. Apply DOE principles to a real-world scenario.
2. Analyse complex interactions among design factors.
3. Optimize performance while balancing cost considerations.
4. Enhance practical engineering and analytical skills.

We utilized **Minitab** to perform a detailed analysis of the data and to support our conclusions.

Factorial Regression: Distance versus Axle Base, Weight Distribution, Wheel Size, Wheel Base

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value
Constant		76.04	1.51	50.38
Axle Base	-9.17	-4.58	1.51	-3.04
Weight Distribution	12.75	6.37	1.51	4.22
Wheel Size	-8.42	-4.21	1.51	-2.79
Wheel Base	-0.83	-0.42	1.51	-0.28
Axle Base*Weight Distribution	8.00	4.00	1.51	2.65
Axle Base*Wheel Size	-4.83	-2.42	1.51	-1.60
Axle Base*Wheel Base	4.92	2.46	1.51	1.63
Weight Distribution*Wheel Size	8.75	4.38	1.51	2.90
Weight Distribution*Wheel Base	-26.00	-13.00	1.51	-8.61
Wheel Size*Wheel Base	15.67	7.83	1.51	5.19
Axle Base*Weight Distribution*Wheel Size	-0.50	-0.25	1.51	-0.17
Axle Base*Weight Distribution*Wheel Base	16.25	8.13	1.51	5.38
Axle Base*Wheel Size*Wheel Base	0.58	0.29	1.51	0.19
Weight Distribution*Wheel Size*Wheel Base	-16.00	-8.00	1.51	-5.30
Axle Base*Weight Distribution*Wheel Size*Wheel Base	8.75	4.38	1.51	2.90

Term	P-Value	VIF
Constant	0.000	
Axle Base	0.005	1.00
Weight Distribution	0.000	1.00
Wheel Size	0.009	1.00
Wheel Base	0.784	1.00
Axle Base*Weight Distribution	0.012	1.00
Axle Base*Wheel Size	0.119	1.00
Axle Base*Wheel Base	0.113	1.00
Weight Distribution*Wheel Size	0.007	1.00
Weight Distribution*Wheel Base	0.000	1.00
Wheel Size*Wheel Base	0.000	1.00
Axle Base*Weight Distribution*Wheel Size	0.869	1.00
Axle Base*Weight Distribution*Wheel Base	0.000	1.00
Axle Base*Wheel Size*Wheel Base	0.848	1.00
Weight Distribution*Wheel Size*Wheel Base	0.000	1.00
Axle Base*Weight Distribution*Wheel Size*Wheel Base	0.007	1.00

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value
Model	15	24298.6	1619.91	14.81
Linear	4	3817.5	954.37	8.73
Axle Base	1	1008.3	1008.33	9.22
Weight Distribution	1	1950.8	1950.75	17.84
Wheel Size	1	850.1	850.08	7.77
Wheel Base	1	8.3	8.33	0.08
2-Way Interactions	6	13314.5	2219.08	20.29
Axle Base*Weight Distribution	1	768.0	768.00	7.02
Axle Base*Wheel Size	1	280.3	280.33	2.56
Axle Base*Wheel Base	1	290.1	290.08	2.65
Weight Distribution*Wheel Size	1	918.7	918.75	8.40
Weight Distribution*Wheel Base	1	8112.0	8112.00	74.18
Wheel Size*Wheel Base	1	2945.3	2945.33	26.93
3-Way Interactions	4	6247.8	1561.96	14.28
Axle Base*Weight Distribution*Wheel Size	1	3.0	3.00	0.03
Axle Base*Weight Distribution*Wheel Base	1	3168.7	3168.75	28.98
Axle Base*Wheel Size*Wheel Base	1	4.1	4.08	0.04
Weight Distribution*Wheel Size*Wheel Base	1	3072.0	3072.00	28.09
4-Way Interactions	1	918.7	918.75	8.40
Axle Base*Weight Distribution*Wheel Size*Wheel Base	1	918.7	918.75	8.40
Error	32	3499.3	109.35	
Total	47	27797.9		

Analysis and Findings

Our analysis revealed the following key insights:

1. **Main Effects:**
   - **Axle Base:** A smaller axle base (1.5 units) significantly increased travel distance, likely due to reduced friction.
   - **Weight Distribution:** Front-weighted configurations consistently outperformed back-weighted ones, likely enhancing stability during descent.
2. **Two-Way Interactions:**
   - **Wheel Base × Weight Distribution:** A significant interaction was observed, suggesting that the optimal wheel base varies depending on the weight distribution.
3. **Three-Way Interactions:**
   - **Wheel Base × Weight Distribution × Axle Base:** This complex interaction indicates that these factors must be considered together to achieve optimal performance.

Practical Significance:

- Although statistically significant, the effect of wheel size was minimal compared to axle base and weight distribution.

- The observed interaction effects emphasize the importance of evaluating factor combinations rather than analyzing factors individually in isolation.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
10.3068	87.49%	81.63%	71.85%

Regression Equation in Uncoded Units

Distance = 126.1 - 19.49 Axle Base + 188.5 Weight Distribution - 38.1 Wheel Size
- 9.01 Wheel Base - 44.25 Axle Base*Weight Distribution
- 4.28 Axle Base*Wheel Size + 3.45 Axle Base*Wheel Base
+ 114.3 Weight Distribution*Wheel Size
- 45.27 Weight Distribution*Wheel Base
+ 9.44 Wheel Size*Wheel Base
- 26.36 Axle Base*Weight Distribution*Wheel Size
+ 11.40 Axle Base*Weight Distribution*Wheel Base
+ 0.41 Axle Base*Wheel Size*Wheel Base
- 25.71 Weight Distribution*Wheel Size*Wheel Base
+ 6.14 Axle Base*Weight Distribution*Wheel Size*Wheel Base

Fits and Diagnostics for Unusual Observations

Obs	Distance Y	Fit	Resid	Std Resid	
2	58.00	76.67	-18.67	-2.22	R
13	39.00	57.00	-18.00	-2.14	R
41	89.00	57.00	32.00	3.80	R

R Large residual

Model Diagnostics

The final model demonstrated strong predictive performance, as indicated by the following metrics:

- **R-squared:** 87.49%
- **Adjusted R-squared:** 81.63%
- **Prediction R-squared:** 71.85%

These values suggest that the model effectively captures a significant portion of the variability in the data and exhibits strong predictive capabilities.

Unusual Observations

- Runs 2, 13, and 41 showed large standardized residuals (>2 or <−2), indicating potential outliers.
- These anomalies were likely caused by measurement errors during the experiments.

MODEL REFINEMENT AND COMPARISON

To evaluate whether the model's accuracy could be improved, we attempted to remove non-significant variables and re-ran the experiment for comparison.

Source	P-Value
Model	0.000
Linear	0.000
Axle Base	0.005
Weight Distribution	0.000
Wheel Size	0.009
Wheel Base	0.784
2-Way Interactions	0.000
Axle Base*Weight Distribution	0.012
Axle Base*Wheel Size	0.119
Axle Base*Wheel Base	0.113
Weight Distribution*Wheel Size	0.007
Weight Distribution*Wheel Base	0.000
Wheel Size*Wheel Base	0.000
3-Way Interactions	0.000
Axle Base*Weight Distribution*Wheel Size	0.869
Axle Base*Weight Distribution*Wheel Base	0.000
Axle Base*Wheel Size*Wheel Base	0.848
Weight Distribution*Wheel Size*Wheel Base	0.000
4-Way Interactions	0.007
Axle Base*Weight Distribution*Wheel Size*Wheel Base	0.007
Error	
Total	

Variables and Interactions Removed

1. **Removing Wheel Base**

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
10.3098	87.38%	82.03%	73.30%

2. **Removing Axle Base × Wheel Size interaction**

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
10.7021	86.40%	80.63%	71.23%

3. **Removing Axle Base × Wheel Base interaction**

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
10.7159	86.37%	80.58%	71.16%

4. **Removing Base × Weight Distribution × Wheel Size interaction**

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
10.3020	87.40%	82.06%	73.34%

5. **Removing Base × Wheel Size × Wheel Base interaction**

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
10.3036	87.40%	82.05%	73.34%

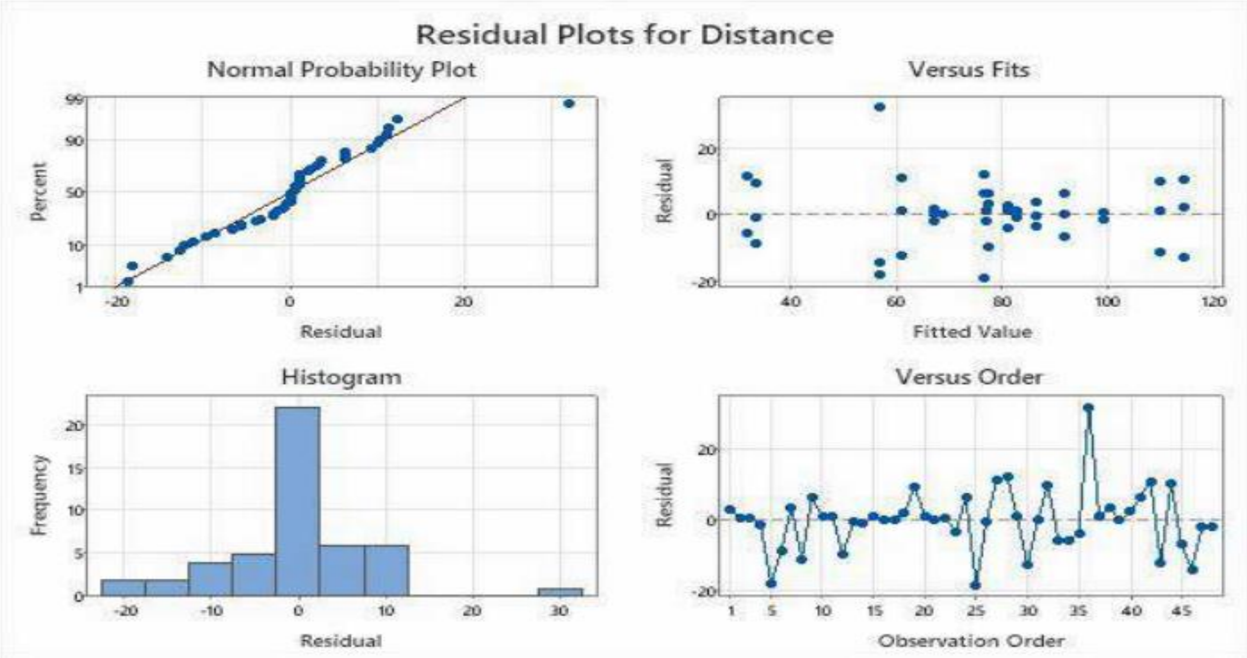
Model Comparison

The results of the refined models are summarized below:

1. **Full Model:** R-squared = 87.49%
2. **Removed Wheel Base:** R-squared = 87.38%
3. **Removed Axle Base × Wheel Size interaction:** R-squared = 86.40%
4. **Removed Axle Base × Wheel Base interaction:** R-squared = 86.37%
5. **Removed Base × Weight Distribution × Wheel Size interaction:** R-squared = 87.40%
6. **Removed Base × Wheel Size × Wheel Base interaction:** R-squared = 87.40%

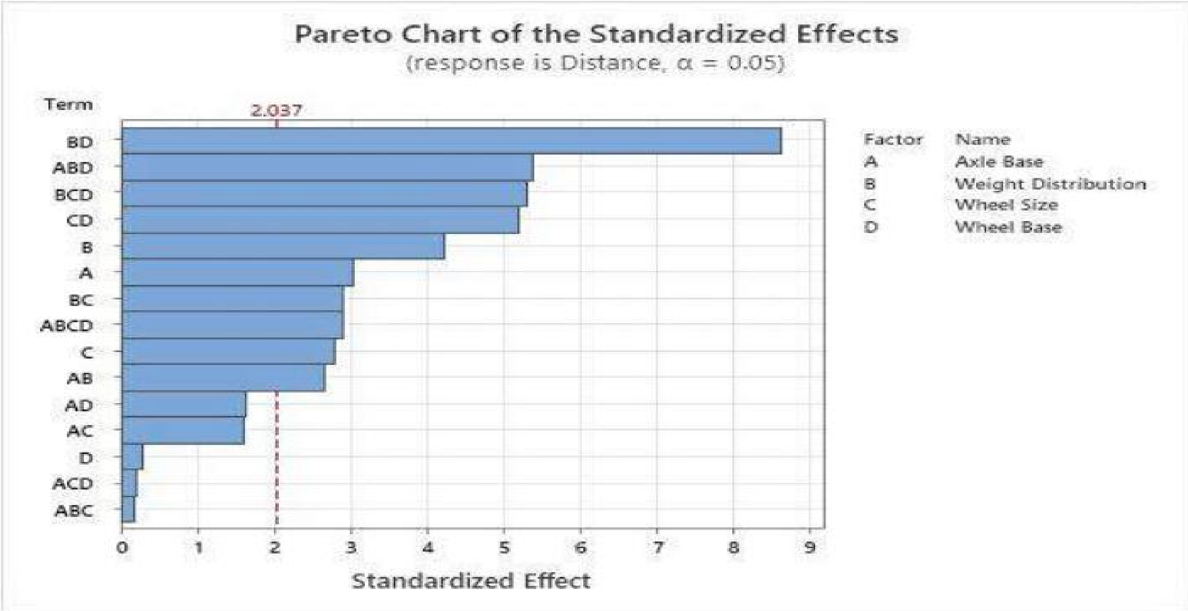
Each removal resulted in a slight decrease in the R-squared value, indicating that all variables and interactions contribute meaningfully to the model's explanatory power. To ensure a comprehensive representation of the system, we opted to retain the full model for further analysis.

VISUALIZATIONS

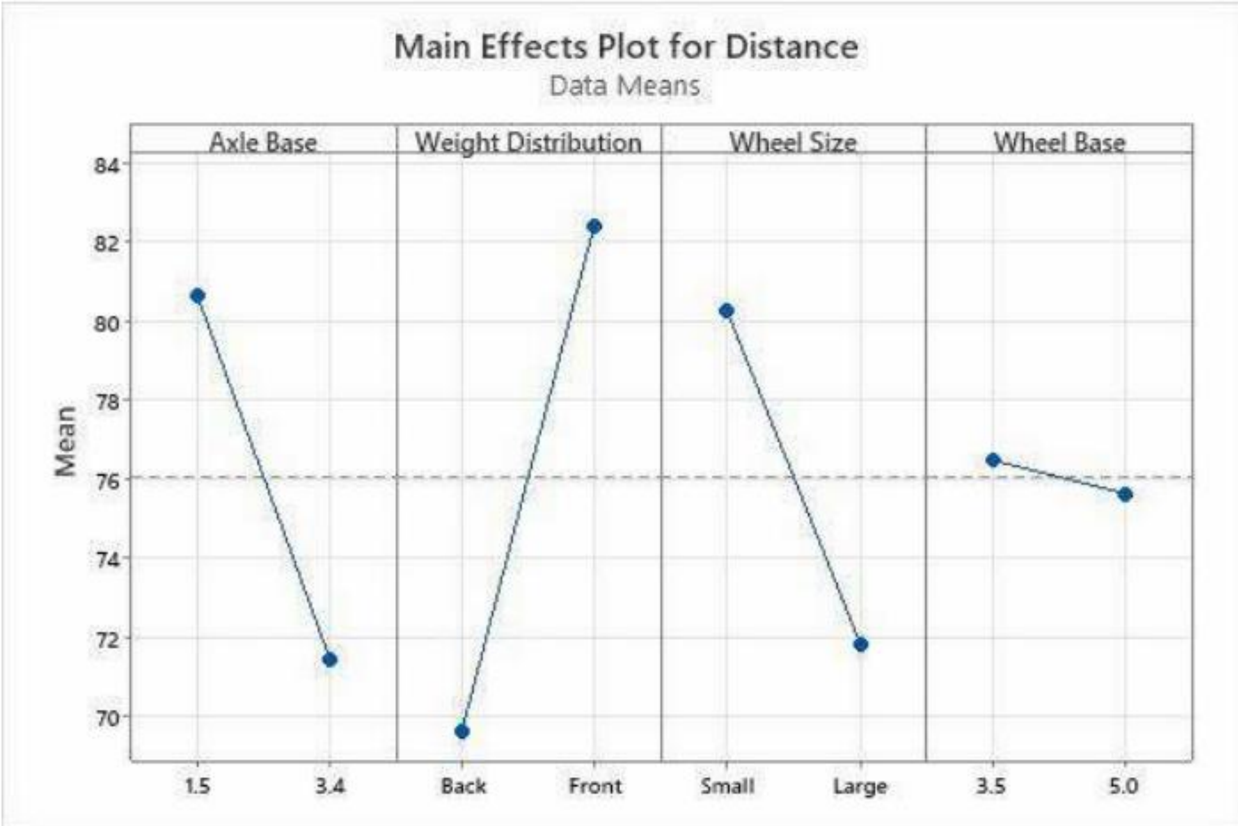


Residual Analysis:

- Normal Probability Plot: Residuals generally followed a straight line, supporting the normality assumption.
- Versus Fits Plot: No clear patterns, indicating constant variance.
- Versus Order Plot: No obvious trends, suggesting independence of observations.



The Normal Plot of Standardized Effects and Pareto Chart confirmed these findings from the tables, with the Wheel Base and Axle Base interaction showing the largest effect.

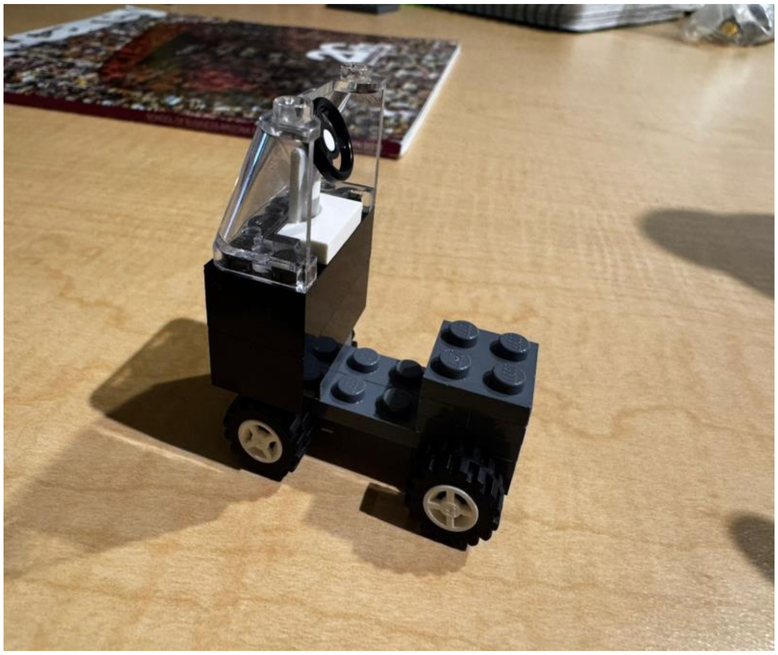


Based on the above analysis we concluded that the car with axle base 1.5 cm and weight distribution in the front and wheel size small and wheel base 3.5 cm has the highest performance

And the car with the axle base 3.4 cm and weight distribution at the back and wheel size large and wheel base 5.0 cm has the lowest performance.

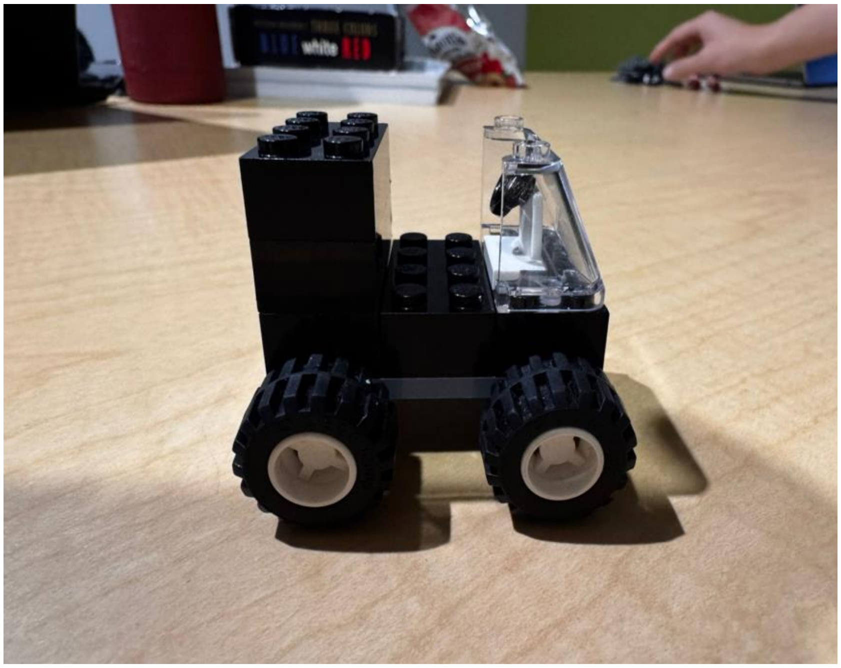
Based on the above graph we can conclude that axle base, weight distribution and wheel size have significant effects on the performance compared to wheel base(as wheel base is closer to the mean).

MODEL DESIGN IMAGES



Best Performing Model:

- Configuration: Wheel Base (3.5), Axle Base (1.5), Small Wheels, Front-weighted
- Performance: 100 cm
- Cost: $10700
- This design optimizes stability and minimizes friction, resulting in maximum travel distance.



Worst Performing Model:

- Configuration: Wheel Base (5.0), Axle Base (3.4), Big Wheels, Back-weighted
- Performance: 25 cm
- Cost: $13600
- This design suffers from increased friction and potentially unstable weight distribution.

Cost-Performance Trade-off:

- While the best-performing model uses more expensive small wheels, its superior performance justifies the additional cost.

SUMMARY

The SCM 517 Lego DOE Project aimed to design and optimize a race car using Lego blocks to maximize its travel distance down a ramp. Our team conducted a full factorial experiment considering four key factors: wheel base, axle base, wheel size, and weight distribution. Through rigorous statistical analysis, we found that axle base and weight distribution had the most significant impact on car performance. Our optimized design achieved a maximum travel distance of 100 cm at a cost of $10700. This report details our experimental approach, findings, and recommendations for balancing performance and cost-effectiveness in Lego race car design.

Intuitively when the weight is added on the back the distance travelled should have been more but in our experiment we got the models works better when the weight is added at the front this could be due to data discrepancy.

In summary, our design of experiments allowed us to effectively investigate how various factors influence the performance of our LEGO race car. Through careful analysis of main effects and interactions, we gained valuable insights into optimizing our design for maximum travel distance down the ramp.

Recommendations:

1. Prioritize narrow axle base and front-weighted designs for maximum performance.
2. Consider the trade-off between wheel size and cost based on specific performance requirements.
3. Utilize the full factorial model for future design decisions, as all factors contribute to performance prediction.