

High Tunnel Greenhouse

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Senior Lab Project Report



Abstract

The University of Idaho Extension office would like a high tunnel greenhouse design to withstand the extreme weather conditions in the Buhl, Idaho area. This experiment was performed to determine if a style of high tunnel end-type and wind speed plays a significant role in drag force on a high tunnel greenhouse. To perform this analysis, four models were created and tested inside of a wind tunnel at two different wind speeds, 30 and 60 mph. The models were gothic and Quonset styles with and without windbreak features. The data collected from this experiment was then used in a factorial analysis. This analysis showed that there were significant differences in drag force caused by each wind speed, model types, and their interaction. An additional ANOVA and Tukey test was conducted with the 60 mph data, due to design parameters, to determine statistically significant differences between model types. This testing showed that each type was statistically different. The two models with the least mean force were the gothic and Quonset with windbreaks. The Quonset, with a windbreaker, had the lowest mean of 4.4 N and the Gothic, with a windbreaker, had a mean of 5.9 N. The Gothic with a windbreaker was chosen for the final design due to the small practical difference between the drag force means, its ease of construction, and snow shedding abilities.

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Introduction

Background:

A grower in the area of Buhl, Idaho has constructed several high tunnel greenhouses but is looking for a new design that will be more resilient in the high winds and snowfall of the area. The client would like to extend the life of the greenhouse frame to at least ten years and the plastic covering for five to ten years in order to improve the economy of the design. In the past, greenhouses have failed due to both high wind speeds and heavy snow loads. Since the greenhouse must be oriented with its flat end facing into the wind because of the available land plot, the ends of the greenhouse have blown in during high wind gusts. The sustained wind speeds in the greenhouse location can range between 25 and 30 mph, and the wind can gust up to 75 mph. However, building regulations necessitate designing to a 105 mph wind gust standard at these conditions. The heavy snow loads experienced by the greenhouse will most likely require the use of a Gothic high tunnel frame design, which sheds snow more effectively than the Quonset design. The Gothic frame is shown in Figure 1 and the Quonset frame is shown in Figure 2 below. The design must also take into account accommodating large entrances in the ends. Using these specifications, we will determine the best high tunnel design for the client.



Figure 1: Demonstrating the Gothic Frame Style. *Photo taken from Gothic Arch Greenhouse's Website*



Figure 2: Demonstrating the Quonset Frame Style. *Photo taken from Atlas Manufacturing's Website*

Motivation:

The completion of this experiment will influence design decisions to mitigate the impact of wind on the high tunnel greenhouse. This benefited the project by substantiating decisions to alter traditional high tunnel greenhouse designs in order to withstand high wind speeds. Typical greenhouse designs seldom incorporate features directly related to minimizing wind forces. The experiment enabled the testing of new greenhouse configurations that could help the greenhouse withstand the necessary wind speeds. We were able to test the two prevalent high tunnel designs, the Quonset and Gothic frames, as well as modifications to the designs in order to determine which will best meet the requirements (Blom, Brown, and Hughes 1991). This will benefit the client by developing a greenhouse that can withstand high wind speeds, thus minimizing repair costs.

The effect of wind on greenhouses is often approximated to calculate a resultant wind force. Studies have also been performed to analyze the effects of wind on multiple greenhouses, typically how they interact when situated side by side to each other (Moriyama, 2010). However, no experiment has directly tested both the prevalent existing greenhouse designs as well as the design ideas in a wind tunnel. This experiment yielded previously unavailable data which allowed the design to be optimized for the project.

Objective:

The objective of this experiment was to determine a frame design that minimizes the forces on the greenhouse due to wind. This experiment considered current greenhouse designs as well as several new designs. Through testing and analysis, it was determined if any design had significantly lower drag forces than the others under different wind conditions.

The experiment hypotheses are as follows:

Null Hypotheses:

H_0 : Wind speed and end type do not yield a significant difference in drag force.

H_{01} : There is no interaction effect between end type and wind speed.

Alternative Hypotheses:

H_A : At least one factor (wind speed/end type) is significantly different in drag force.

H_{A1} : There is an interaction effect between design type and wind speed.

Methodology

Apparatus:

To perform the experiments, the University of Idaho's wind tunnel located in the Gauss-Johnson laboratory was used. This apparatus is summarized in Figure 3. The main principle was to measure the drag force resulting from the air flow through the wind tunnel. The wind tunnel displays drag force, lift force, air speed, and a flow visualization. The models were located inside of the clear box shown in Figure 4. The wind tunnel generated air flow, which produced a drag force on the model that was measured using instrumentation located inside of the plastic box. Styrofoam was used to model the end types for the experiment. Because the Styrofoam was cut, rough surfaces were created, which would have had a large effect on the data collected. To mitigate the additional drag created by the cuts, the models were covered in duct tape to create smooth surfaces to represent the actual designs better. The model was mounted to the force measuring apparatus located within the wind tunnel.

WIND TUNNEL FACILITY

18" Open Circuit Wind Tunnel

Specifications

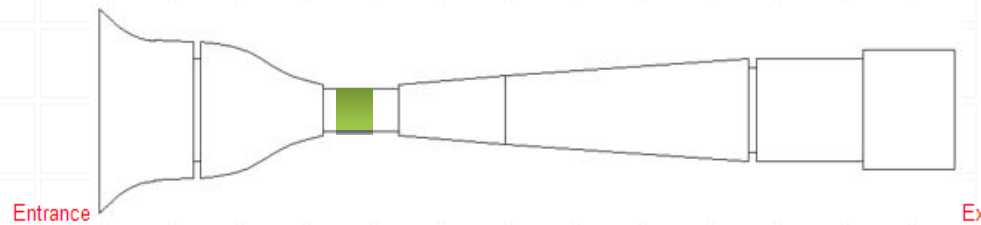
Eiffel type
 18" x 18" x 36" test section
 1 - 160 mph airspeed range
 50 Hp motor

Student Use

Students design and perform their own experiments
 Integrate lab and design projects
 Hands on use
 User friendly

User Friendly Instrumentation

Drag Force
 Lift Force
 Airspeed
 Flow Visualization



<u>Flow Conditioning</u>	<u>Test Section</u>	<u>Transition</u>	<u>Drive Section</u>
Honeycomb and screen pack straighten the inlet flow	Where experiments are performed	Transitions from square to round	48" Axial fan
Contraction reduces spanwise velocity and accelerates the flow to the test section	Made of 3/4" Plexiglass Removable top, bottom, and ports	Slows the flow to the motor	50 Hp Motor
		Smooth transition to prevent turbulence	Acoustic Diffuser to reduce operating noise to 85 dB

Figure 3: University of Idaho Wind Tunnel Detail. *Photo taken from UI Wind tunnel Webpage*

The model was placed in the center of the plastic box with the measuring device connected to the rear. The wind tunnel can collect not only drag, but lift and yaw as well. Therefore, it was important to minimize the lift and yaw so that the data was consistent through all the models. Therefore, the wind pressure was normal to the ends of the greenhouse model as shown in Figure 4.

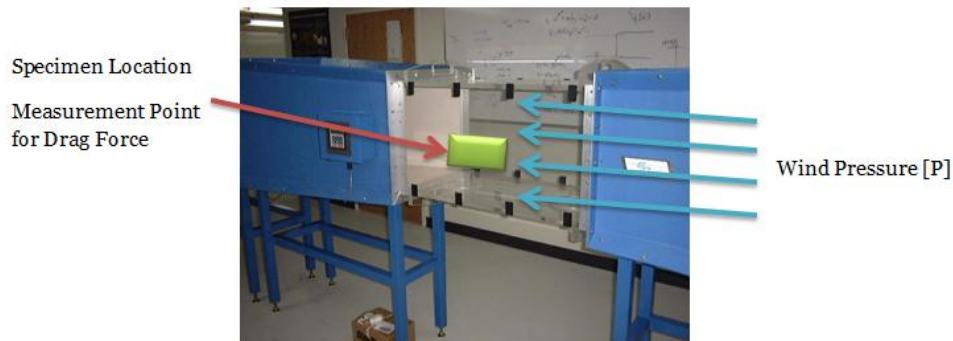


Figure 4: Specimen Location and Measurement Points

Experimental Procedure:

Once the models were completed we tested each model inside of the wind tunnel at the desired wind speed. In order to gain the desired wind speed, we adjusted the frequency of the fan that created the wind pressure. Using a correlation to determine speed, we began collecting data with the wind speeds of 35 and 60 mph. To confirm the wind speed inside the tunnel, a pinot tube was inserted that gave a digital reading. Both the Gothic and Quonset end types were tested with and without windbreakers. Both end types and wind speeds were tested randomly to collect accurate data. Each combination of wind speed and end-type were tested until we obtained four drag forces for each. The tested end types are shown in Figure 5.

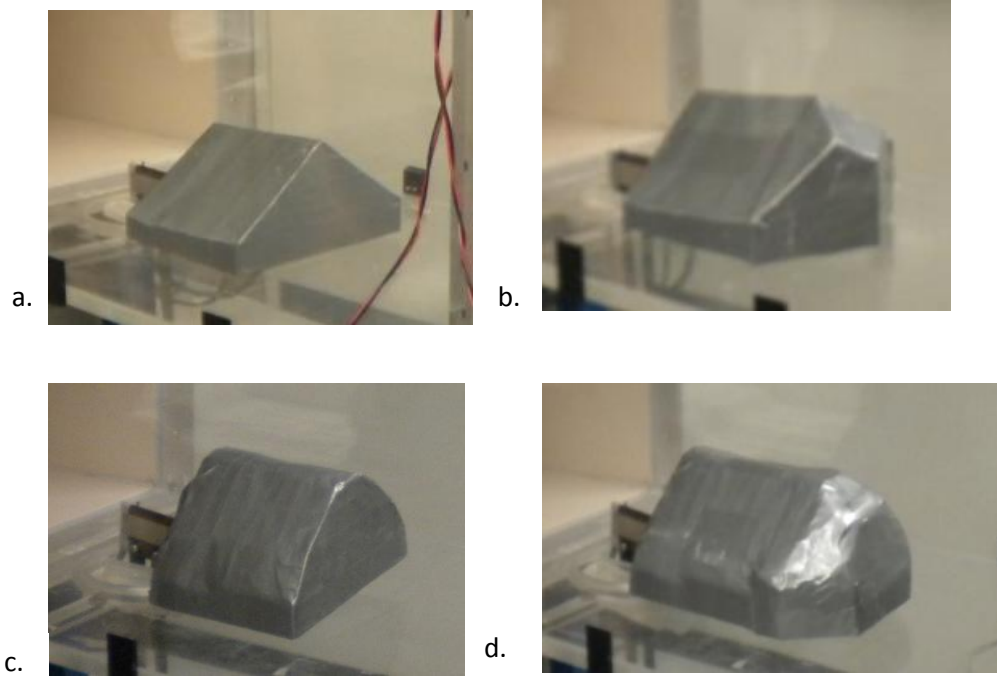


Figure 5: This figure shows the modeled end types: a. gothic without windbreak, b. gothic with windbreak, c. Quonset without windbreak, d. Quonset with windbreak.

Statistical Methodology:

This design procedure required looking into minimizing the amount of force located on the greenhouse. We measured the drag force on the model. The factors included wind speed and frame end design. Wind speed had two levels of 35 mph and 60 mph. The second factor was the frame end design. This factor had four levels; Gothic with and without a windbreak, and Quonset with and without a windbreak. These experimental factors, levels and ranges are specified in Table 1 below.

Table 1: Factors, Levels, and their Ranges

Factors	Levels
Wind Speed	35 mph
	60 mph
End Type	Gothic Without Windbreaker
	Gothic With Windbreaker
	Quonset Without Windbreaker
	Quonset With Windbreaker

The wind tunnel wind speed was varied between the high and low range against each of the end types, resulting in 32 total measurements with four runs for each configuration. A factorial analysis was used as a result of having two independent variables. The wind speeds produced a resultant drag force on the models that was used as the dependent variable for the factorial analysis. The data analysis was performed using the program Minitab version 16.

Once the factorial analysis was completed, the yielded results helped us determine that another ANOVA test, along with a post-hoc test, was necessary to gain the desired insight to the best design.

Accuracy:

The drag force accuracy was of minor concern as this test was to see which design produced the least amount of drag force. Some sources for error came from how the device is mounted. We mounted the models as tightly as possible, but at high wind speeds some shifting occurred. These vibrations may have resulted in minor effects on drag force. Another source was how smooth the Styrofoam models were. Each models' roughness was not identical, which could have resulted in different drag forces. The measurement instrument itself could have been a source of error if it wasn't properly calibrated; it could result in different scales of reading for the high and low settings of wind speed. One way the error was reduced was to attempt to keep other measured quantities constant between the models, such as the lift force. In addition, the accuracy was limited to three decimal places by the pinot tube readout and drag force readout. This leaves a potential error of $\pm.0005$ for each instrument.

Results:

Upon completing the experiment, the raw data was collected and preliminary results are shown below in Table 2.

Table 2: Descriptive Statistics

Descriptive Statistics			
	Observations	Mean (N)	Std. Dev. (N)
35 mph Gothic without Windbreak	4	3.36	0.0073
35 mph Gothic with Windbreak	4	2.14	0.0173
35 mph Quonset without Windbreak	4	3.68	0.0216
35 mph Quonset with Windbreak	4	1.53	0.0013
60 mph Gothic without Windbreak	4	8.94	0.0423
60 mph Gothic with Windbreak	4	5.89	0.0397
60 mph Quonset without Windbreak	4	10.35	0.0308
60 mph Quonset with Windbreak	4	4.39	0.0309

Even before processing the data, there is a clear difference in mean drag forces between models. The windbreaker had an observable effect on the drag forces. To confirm the significance, a 4x2 factorial analysis was conducted with Minitab and yielded the results shown in Table 3. Within the Minitab analysis the end types were converted to numbers with values 1 and 2 representing Gothic without a windbreaker and Gothic with a windbreaker, respectively. Values 3 and 4 represented Quonset without a windbreaker and Quonset with a windbreaker, respectively.

Table 3: Minitab Factorial Analysis Results

Factorial Analysis Results	
Alpha	R-Squared (adj.)
0.05	99.98%
	P-Value
End Type	<0.001
Wind Speed (mph)	<0.001
Interaction	<0.001

As seen in the table, each calculated p-value fell below the alpha value of 0.05, meaning that all three effects are statistically significant. In addition, the R-squared values are very high and the residual plots behaved in a manner showing that the analysis was very accurate. The residuals can be found in Appendix B. A graphical representation of the main and interaction effects can be seen below in Figures 6 and 7, respectively.

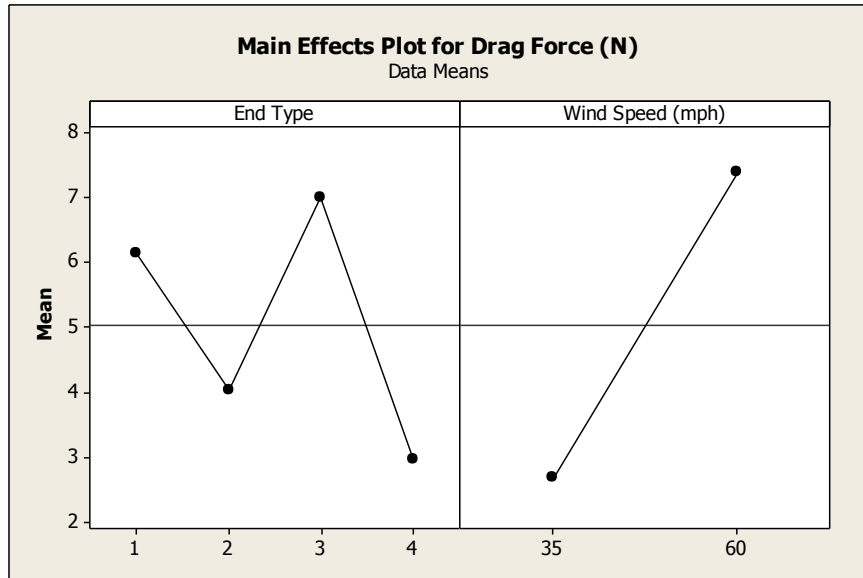


Figure 6: Main Effects Plot

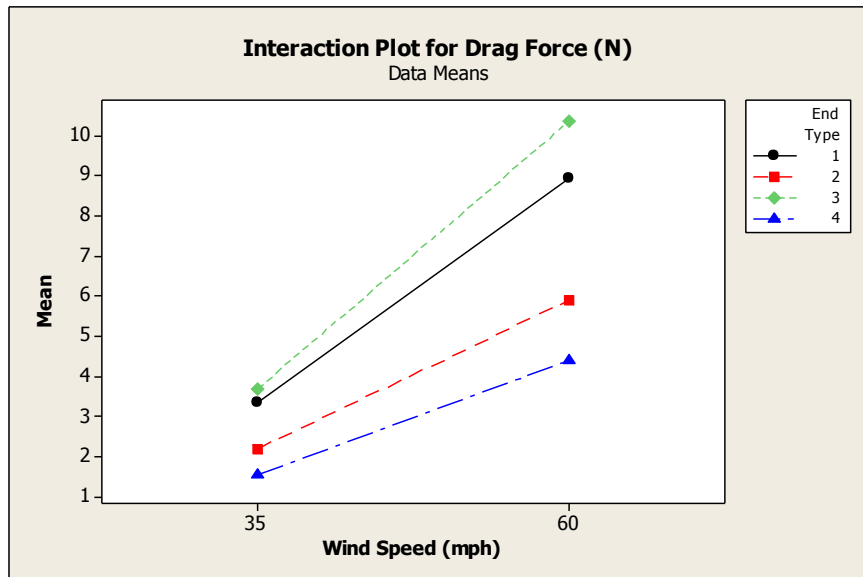


Figure 7: Interaction Plot

As seen in Figures 6, the wind speed and inclusion of a windbreak have an observable effect on drag forces. Figure 7 shows the interaction plot and how the Quonset with a windbreak has the least amount of drag force with the next best being Gothic with a windbreak. It is also seen that a Quonset end type is affected more by the use of a windbreak as opposed to the Gothic type.

In order to prove where the exact significant differences lie within the different end types, the group performed an ANOVA analysis with a Tukey test using data collected at 60 mph. The 60 mph wind speed was chosen as it has both the highest means for each drag force and is more crucial toward the client’s goal of surviving high wind. The information from Table 4 shows the variance between the four different types of models tested and the drag force values for each. In this test, if the p-value falls below the alpha value then that means there is a significant difference between at least one of the four different end types. The results from the additional one-way ANOVA analysis are shown below in Table 4.

Table 4: ANOVA Table Comparing End Types with Drag Force at 60 mph

One-Way ANOVA Results				
	Alpha	P-Value	R-Squared (adj)	
End Type	0.05	<.0001	99.98%	
	Gothic	Gothic Windbreak	Quonset	Quonset Windbreak
Mean (N)	8.9418	5.89	10.345	4.3937

The p-value is below 0.05 meaning there is evidence to say that there is a significant difference between the types. The R-Square values found from the one-way ANOVA tests validates that the test was accurate.

Next, the Tukey’s post-hoc test was performed to understand where the significant differences actually lie between the end types. The following data in Table 5 show the results from the test.

Table 5: Tukey Test Output

Tukey Test Results		
End Type	Mean (N)	Grouping
Quonset Windbreak	4.3937	D
Gothic Windbreak	5.89	C
Gothic	8.9418	B
Quonset	10.345	A

As seen in the table above, the Tukey test results show a statistically significant difference between all of the end types. Each end type was assigned a different grouping letter, with the Quonset with windbreak having the lowest mean drag force and the gothic with windbreak having the second lowest mean drag force. These two means are about half of their corresponding end types' means of drag force. Therefore, there is a proven difference between the drag forces in each of the different end-types which was a large factor in the final decision.

Discussion

After interpreting the results of the statistical analysis, much was revealed about the model types. The discoveries showed that the windbreaks generated mean drag forces that were significantly lower and about half the force as the models that lacked the windbreaks. If the windbreak is a feasible design to build, then it will be considered as a potential solution. This could also lead to the consideration of the effects of other wind directions on a design that includes a windbreak as opposed to only the effects of a head-on wind.

Most of the results from the experiment followed our expectations, such as wind speed and end-type playing a significant role in drag force. What was more interesting was how the Quonset and gothic windbreakers results significantly differed in the amount of force reduced on the end walls. The reduction of almost half the force was not anticipated, with our original expectations only being about a third or a fifth in reduction of force prior to the test. During the test we found that the models without the modifications of a windbreaker began to shake around 50 mph while the models with

windbreaks remained firm. This led us to speculate that the reduction was greater than our original expectations.

A result that was somewhat surprising to us was that the gothic with windbreak didn't see as much reduction in force as the Quonset with windbreak. We think that a gothic windbreak would see a much larger reduction in force if we would have made the point a steeper angle. The factor of the angle is something to consider in the future if we conduct more testing on gothic windbreaks to perfect our model.

Based off the results the Quonset with a windbreaker is significantly better than the Gothic windbreaker, but with a difference of about 1.5 N at 60 mph it does not make a large practical difference. To help determine which design to choose other factors were considered about the designs.

Through external research, it was found that the gothic style has better qualities for shedding snow loads. The feasibility of construction is also an important factor in design selection. These factors were then rated where a higher number meant that the design was better in a particular area than one with a lower score in the same area. The wind data generated lead to the results in the wind load section. The numbers were based off of practical differences, such as the gothic and Quonset without windbreakers were practically better than a square end but were not greatly different between each other and the windbreaker models were better than those without, but also not greatly different from each other. The weighing total was based off of what was considered important for the client, where wind load and snow sheading abilities were considered of most importance and speculated cost and ease of construction were secondary, space was of minor concern for the client. The following table, Table 6, summarizes the selection criteria for the recommended design.

Table 6: End Type Decision Matrix

		End Type Decision Matrix			
	Weight	Gothic Plain	Quonset Plain	Gothic Windbreak	Quonset Windbreak
Criteria					
Snow Load	4	5	3	5	3
Wind Load	5	3	3	5	5
Ease of Construction	2	4	5	3	2
Space Required	1	5	4	4	3
Cost	3	4	5	3	4
	Total:	60	56	64	56

The matrix shows that the research leads to the conclusion that the gothic style with a windbreak would be the most beneficial design for the client’s application. The ease of construction, snow load shedding capabilities, and the significant drag force reduction on the end walls are the main reasons for this decision. The Quonset windbreak design’s advantage of drag force reduction does not outweigh its difficulty of construction and snow shedding capability. Therefore the project will investigate the best methods to build, attach, and accommodate a gothic style high tunnel with a windbreak to meet the client’s specifications.

Some areas that could have been improved in the project are that the models were not level on the ground due to the way the instrument measuring drag force was designed. This led to the added factor of lift force that could fluctuate the drag force considerably if it wasn’t zeroed out. Also, at the higher wind speeds the models would sometimes shift in position and rotate so that they were angled with one side touching the ground and the other side hanging in the air, leading to another factor of error. Being able to measure the drag force with the models flat on the ground would have eliminated these errors in the project. Another area of improvement would be having professional models as the models we made were very rough and required duct tape to help smooth out the rough surface. The way the tape was put on and how much tape was used for each model could possibly have influenced the results.

Conclusion

The testing and statistical analysis justifies the addition of a windbreaker to the proposed design for the high tunnel greenhouse. The wind tunnel testing was successful and gave insight into the wind load characteristics on the structures. Analyzing the data using multiple statistical methods proves that the windbreaks make statistically significant reduction in drag force. Therefore, a windbreak is a worthwhile feature to include in the design. Using these findings along with other external research the decision is to proceed with a gothic style frame with a windbreak. The remainder of the project will be developing the gothic style windbreak and creating a prototype that satisfies the client.

References:

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Moriyama, H, S Sase, Y Uematsu, and T Yamaguchi. "Wind Tunnel Study of the Interaction of Two or Three Side-by-Side Pipe-Framed Greenhouses on Wind Pressure Coefficients." *Transactions of the Asabe*. 53.2 (2010): 585-592. Print.

"Wind Tunnel Facility." University of Idaho. N.p.. Web. 24 Oct 2013.
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Appendix A: Experiment Raw Data

End Type	Wind Speed (mph)	Drag Force (N)	StdOrder	RunOrder	Blocks	PtType
1	35	3.345	1	1	1	1
1	35	3.362	2	2	1	1
1	35	3.358	3	3	1	1
1	35	3.355	4	4	1	1
1	60	9.001	5	5	1	1
1	60	8.919	6	6	1	1
1	60	8.905	7	7	1	1
1	60	8.942	8	8	1	1
2	35	2.119	9	9	1	1
2	35	2.316	10	10	1	1
2	35	2.149	11	11	1	1
2	35	2.143	12	12	1	1
2	60	5.937	13	13	1	1
2	60	5.893	14	14	1	1
2	60	5.840	15	15	1	1
2	60	5.890	16	16	1	1
3	35	3.704	17	17	1	1
3	35	3.652	18	18	1	1
3	35	3.670	19	19	1	1
3	35	3.675	20	20	1	1
3	60	10.380	21	21	1	1
3	60	10.305	22	22	1	1
3	60	10.350	23	23	1	1
3	60	10.345	24	24	1	1
4	35	1.526	25	25	1	1
4	35	1.528	26	26	1	1
4	35	1.525	27	27	1	1
4	35	1.526	28	28	1	1
4	60	4.417	29	29	1	1
4	60	4.414	30	30	1	1
4	60	4.350	31	31	1	1
4	60	4.394	32	32	1	1

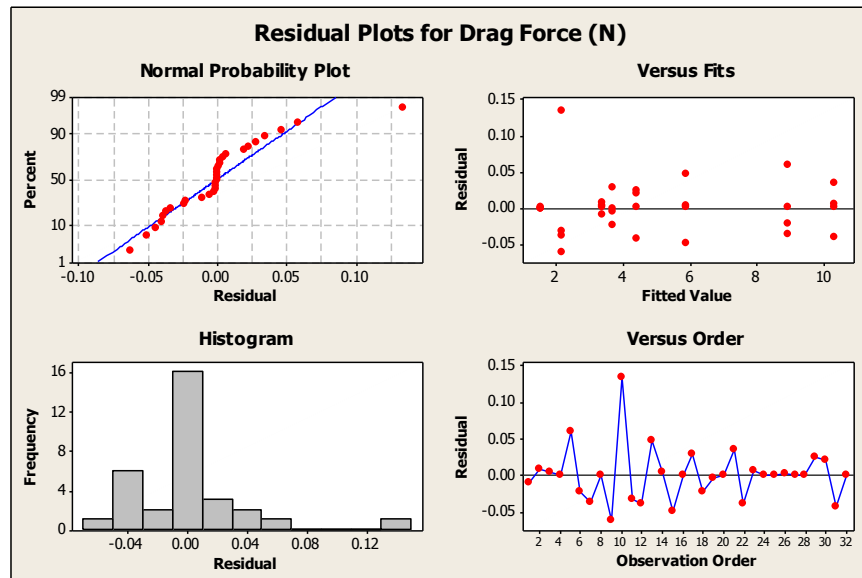
Appendix B: Factorial Analysis Output

Factor	Type	Levels	Values
End Type	fixed	4	1, 2, 3, 4
Wind Speed (mph)	fixed	2	35, 60

Analysis of Variance for Drag Force (N), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
End Type	3	83.556	83.556	27.852	15952.06	0.000
Wind Speed (mph)	1	177.327	177.327	177.327	101562.36	0.000
End Type*Wind Speed (mph)	3	18.015	18.015	6.005	3439.35	0.000
Error	24	0.042	0.042	0.002		
Total	31	278.940				

S = 0.0417850 R-Sq = 99.98% R-Sq(adj) = 99.98%

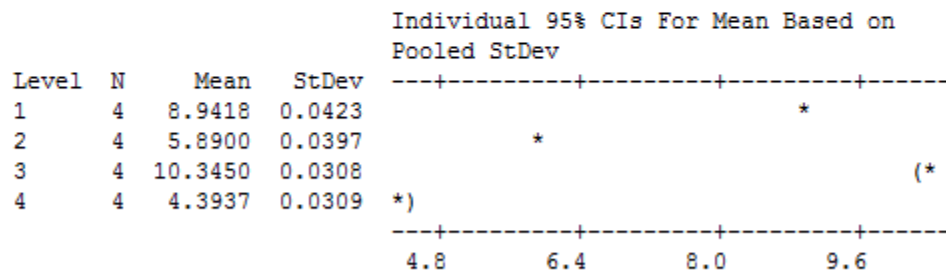


Appendix C: One-Way ANOVA and Tukey Output

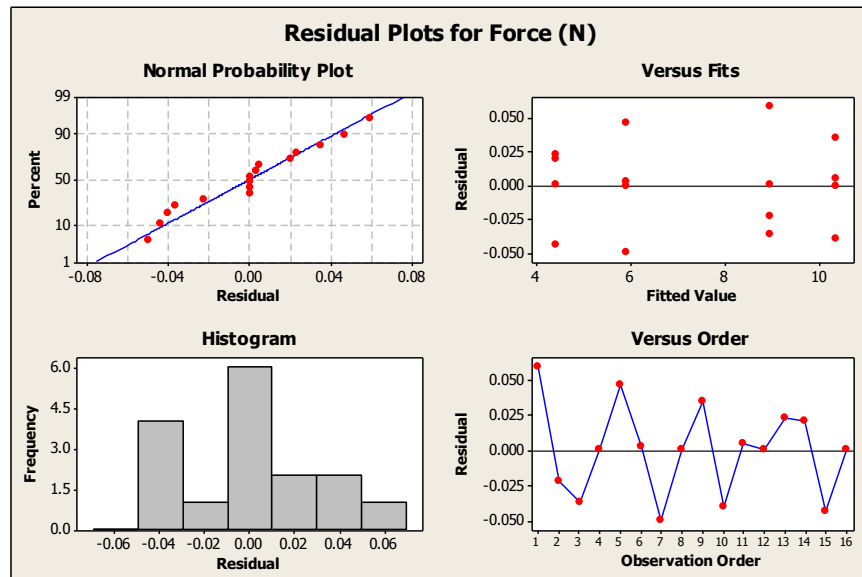
One-way ANOVA: Force (N) versus EndType

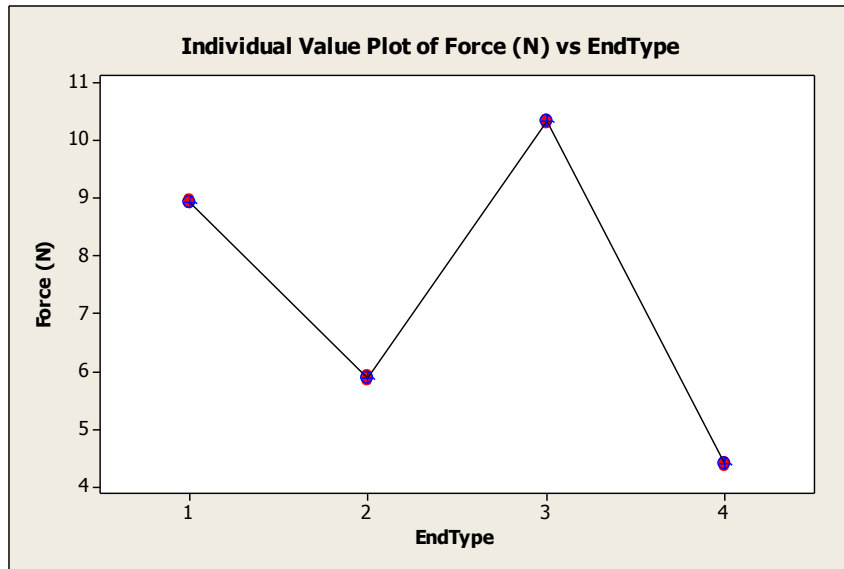
Source	DF	SS	MS	F	P
EndType	3	89.46976	29.82325	22634.10	0.000
Error	12	0.01581	0.00132		
Total	15	89.48557			

S = 0.03630 R-Sq = 99.98% R-Sq(adj) = 99.98%



Pooled StDev = 0.0363





Grouping Information Using Tukey Method

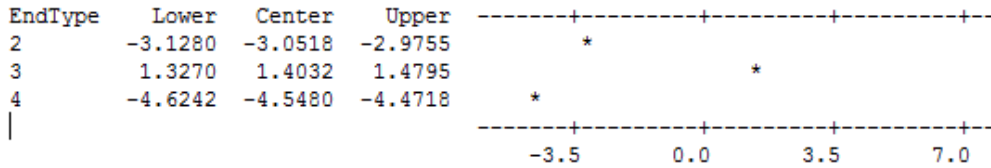
EndType	N	Mean	Grouping
3	4	10.3450	A
1	4	8.9418	B
2	4	5.8900	C
4	4	4.3937	D

Means that do not share a letter are significantly different.

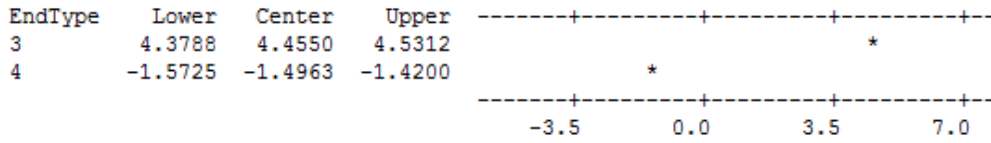
Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of EndType

Individual confidence level = 98.83%

EndType = 1 subtracted from:



EndType = 2 subtracted from:



EndType = 3 subtracted from:

