EFFECTS OF VARIOUS FACTORS ON HYDRAULIC LIFT EFFICIENCY

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Abstract

This report examines the effect of various selected factors on the efficiency of a hydraulic lift system by measuring the input force required to lift an object a certain distance. The experiment tested the effect of the press area of the lift, length of the connecting tube, viscosity of the liquid, and the presence of contamination in the system. The experiment was conducted in a factorial, complete, balanced, and randomised manner with 3 replicates of each treatment tested.

A multiple linear regression model was derived out of the data collected, which found that all variables were considered significant and had an overall high p value of 2.2*10^(-16). The model found that the most efficient hydraulic system (system with the least amount of force required) was one with a small press area, long tube length, low viscosity liquid and as little contamination as possible. To obtain the linear model, a logarithmic transformation was required on the force input data to fit the linear model assumptions. While the findings may be limited for real world application purposes due to certain issues in data collection, it was still determined that the model gives an overall good prediction of the force required to move an object.

1 Contents

2 Introduction

2.1 Significance of Study

Hydraulic systems are an important tool in mechanics due to their ability to efficiently move heavy objects using little amounts of force, thereby creating a large mechanical advantage. They are used in a wide range of fields including lifts, brakes, and heavy machinery. Due to the popularity of hydraulic systems in mechanical devices, it is important to understand how different factors affect the efficiency of a design. This report analyses how elements of a hydraulic pump design can be altered to increase the mechanical advantage to push an object in a hydraulic lift system. Four factors were explored in this test: the area of the hydraulic press, the viscosity of the liquid, the length of the connecting tube and the contamination level of the liquid.

2.2 Aims of Study

The aim of this study is to investigate the amount of force in newtons required to operate a compression tube in order to lift a mass to a height of (5cm) from its resting position and to determine how each of the four variables can be modified to affect the mechanical advantage when operating the lift. The operation of the lift will be tested with a continuous array of contaminants within the liquids ranging from 0% to 10% in 1% increments, this being due to high levels containing more material then liquid and thus being extremely ineffective. The test will also measure the effect of liquids of varying viscosity such as water, oil, honey, milk and paint. Furthermore, the test will modify the length of the tube with 5cm and 10cm modifications. The test will also modify the area of the press with the maximum size being equal to that of the lift.

Along with the main aim of the study there are several other questions from which the study may show an interest.

a) Does the length of the tube have a significant impact on how much force is required to operate the lift?

b) Does the area of the press have a significant impact on how much force is required to operate the lift?

c) Does a liquids level of contamination have a significant impact on how much force is required to operate the lift?

d) Does the viscosity of the liquid have a significant impact on how much force is required to operate the lift?

e) Is there a significant correlation between any two or more elements within the experiment and how it modifies the amount of force required to operate the lift?

f) What is the most efficient combination of the aforementioned variables to affect the mechanical advantage within operation of the lift to the required perimeters.

Variables:

Name of Variable	Type of Variable	Type of Factor	Description
Liquid Contamination	Factor	Continuous	(0%), (5%), (10%)
Liquid Viscosity	Factor	Categorical	(H_2O), (Oil), (Honey)
Press Area	Factor	Continuous	(1/1),(½),(¼),(⅛) pump area to lift area
Tube Length	Factor	Continuous	(15cm) (30cm) (45cm)
Mechanical Advantage	Numeric	Continuous	Force out per Force in
Force	Numeric	Continuous	Newtons

The following variables were chosen due to the assumption they would have a significant impact on the amount of force required to operate the lift and as such would be best to apply modifications towards.

2.3 Assumptions and Limitations

Several assumptions have been made when designing this experiment. One assumption is that the temperature of all the components of every test is at a constant room temperature level. While measures were taken to ensure that all components would be at the same temperature, it cannot be guaranteed that this is always the case. Thus, this experiment assumes that temperature is not a factor that would greatly affect the efficiency of the hydraulic system, and that varying temperatures in components would not have a significant effect. It is also assumed that the results gathered from the simple hydraulic system can also be applied to more complex systems. As the hydraulic system used in this experiment is greatly simplified from most real world systems, there is a possibility that some factors may be more or less effective than found.

Additionally, there are several limitations to the experimental design. One example of this is the contamination level of the liquid. The contamination only considers a single type of contamination, being sand. This results in the experiment only being able to infer how that specific contamination type affects the hydraulic lift, and not any other type of contamination such as air or another solid material. This was decided on as there are so many different types of contaminants, that it would not be feasible to test a large amount of them. The design is also limited in that there are a significant number of ways that human error can affect the calculations, such as when measuring the force or the liquid used, which can possibly cause significant anomalies in the design. Also, the liquid viscosity is limited in that it is treated as a categorical variable. As the means to measure the liquid viscosity were not available for this experiment, it was decided that the liquids were tested based on type (e.g. water, oil, etc.). This allows for some findings to be made on the viscosity, but not any specific data.

3 Literature Review

There are a number of factors which affect the efficiency of a hydraulic lift system. In this experiment, four factors will be observed and experimented upon, namely the area of the pump, viscosity of liquid used, the length of the connecting tube, and the contamination of the liquid. The main law in action within this experiment is Pascal's law, which states that 'when there is an increase in pressure at any point in an incompressible liquid, there is an equal increase at every other point in the container.' For example, if two cylinders are filled with an incompressible liquid and are connected via a tube, and the first cylinder which has an area of 1 square inch is applied a load, this would naturally cause an increase in pressure of the fluid in the entire system. If the second cylinder has a cross-sectional area of 10 square inches, said pressure is applied to every point of that area, allowing it to lift an equivalent load proportional to the larger area. Thus, the larger the cross-section area of the second cylinder, the larger the 'mechanical advantage' of the system, and therefore, a larger mass can be lifted. (Hodanbosi, 1996).

The viscosity of the liquid used also has an effect on the efficiency of the hydraulic lift experiment. Viscosity refers to the consistency and state of a liquid due to internal friction, described as a fluid's resistance to flow (Elert, 1998). As hydraulic liquid flows through the pipeline, or the tube which connects the two cylinders together, a high level of viscosity will naturally cause greater internal friction, causing both the liquid to rise in heat and an increase of resistance to the fluid flow. A similar decrease in effectiveness also occurs with low levels of viscosity, where it may lead to leaking of the liquid and thus reduce volumetric efficiency of the system. Another factor that may affect the viscosity of a liquid is temperature (Anson, 2013). Generally, the viscosity of a liquid decreases as temperature rises in an inverse manner. This is due to the fact that higher temperatures increase the average speed of molecules within a liquid, which decreases the average intermolecular forces (Elert, 1998). Some hydraulic systems show that the oil's viscosity fluctuates when its temperature increases, which is undesirable as this makes fluids compressible and lowers efficiency of the entire system (Mobile Hydraulic Specialties, 2017). Therefore, it is imperative to both choose a liquid with an appropriate level of viscosity and desirable viscosity-temperature properties, as well as taking note of temperature as a nuisance variable, possibly alleviated by conducting the experiment at room temperature.

The third experimental observed factor is the length of the tube connecting the two cylinders. There has not been much literature in the past that has covered how this factor affects hydraulic lift systems, though 'Anson Lifting Platform' notes that the flow of fluid within the tube naturally has pressure loss along the way and keeping the design of the pipe as short as possible while 'reducing elbow' is a method to alleviate this (Anson, 2013). Due to this, it would be experimentally beneficial and of interest to find whether this length would have an effect, if any, to the working efficiency of the hydraulic lift system. A possible effect may be pressure loss due to the distance travelled between the fluid from one cylinder to another. In determining pressure drop in circular pipes, pressure drop (Pa) is directly proportional to the length of the pipe (m), fluid density (kg/m^3), as well as twice the fluid flow velocity (m/s) (Engineers Edge, 2000).

The final factor to consider is the contaminants within the fluid. Contaminants disrupt the resistive properties within a hydraulic fluid, which causes the fluid temperature to rise and therefore affecting viscosity. As stated previously, lower levels of viscosity lead to a reduction of volumetric efficiency within the system, possibly leading to less mechanical advantage overall. Examples of contaminants in the system include air bubbles and generally any foreign particles. (Mobile Hydraulic Specialties, 2017).

4 Methods

4.1 Materials and Equipment:

- Two syringes (on syringe must have a equal or larger diameter than the other)
- One connecting pipe
- Three vices
- Liquid of choice
- Contaminant of choice, i.e. sand
- An adhesive (for creating airtight seal on connecting tube)
- Small wood square
- Weight
- Force gauge
- Drill
- Ruler (For measurements)
- Permanent marker
- String
- Scissors

The ruler, permanent marker, string and scissors are not mentioned in the methods but they are important tools for measuring the diameter of the syringe parts as well as measuring the distance each plunger (pump and lift plungers) moved. The permanent marker and string are used to find the volume of parts of the syringe that cannot be done via a ruler.

4.2 Experimental Design

4.2.1 Experimental Method

1. Both the syringes (the pump and lift) were fixed using vices and the plunger for the pumping syringe was removed. The pump must be able to lift the object (of fixed weight) up a distance (fixed), about 5cm high, without pushing the plunger (of the pump) all the way down.
2. The connecting tube was connected to the hubs of both syringes, making sure that the connection is airtight using an adhesive as a filler
3. A platform was attached to the lift syringe and a weight was placed on top of the platform.
4. The liquid was poured into the simple hydraulic lift system, making sure that there is room for the plunger to be reinserted.

5. A force gauge was held fixed just over the pump, using a vice, with the hook that is being pulled on being connected to the top of the plunger. This was done by drilling a small hole on top of the plunger and then fitting the hook through it.
6. After the experiment is conducted, the liquid was emptied from the cylinder and the next liquid was poured in for the next replicate, ensuring that the cylinder was clean. Steps 4 and 5 were then repeated.

NOTE: The experiment will be done in a room that has its temperature kept constantly at 25 degrees Celsius.

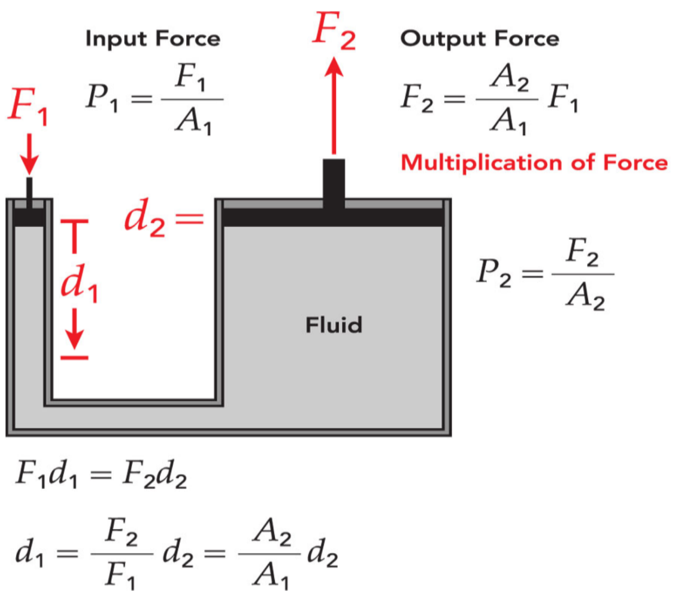

Figure 1: Diagram of a simple hydraulic lift showing the formulas for Pascal's Law (Clippard, 2012).

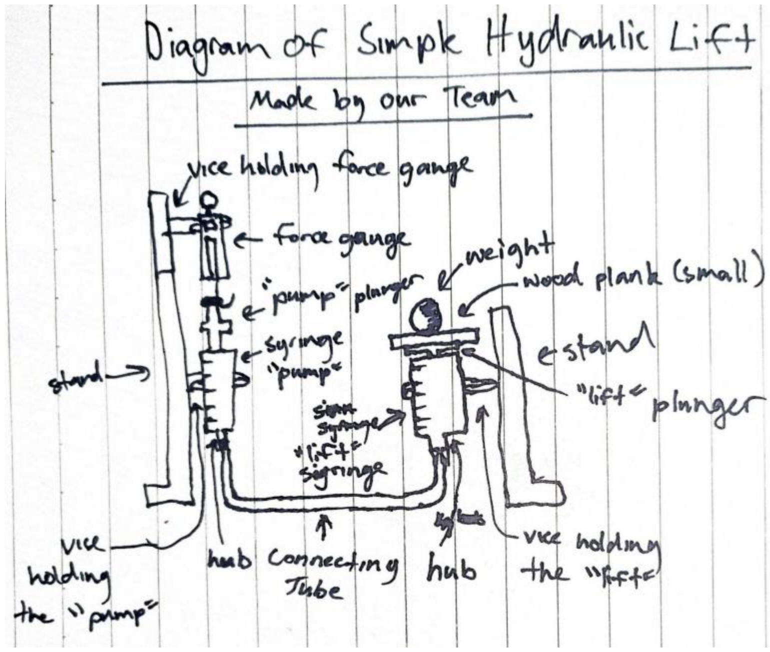

Figure 2: Preliminary sketch of the assembled simple hydraulic lift. This hydraulic lift is based on the simple one shown in Figure 1.

4.2.2 Data Collection Method

The plunger for the pump was pushed down until the object was lifted to its fixed distance. Then the force from the force gauge is measured as well as the distance the plunger from the pump moved. The force acting on the object was calculated using Pascal's law. Afterwards, the output force was divided by the input force to calculate the mechanical advantage, e.g. $Mechanical\ Advantage\ = \frac{F_2}{F_1}$ of 1.5 states that every 1 newton of force being acted on the pump produces 1.5 newtons of force on the lift.

4.3 Methods Reasoning

The simple hydraulic lift was chosen to eliminate as many nuisance variables as possible (including unknown nuisance variables) with the only known nuisance variables being the left-over residues of liquids, contaminants that can enter through the connecting tube, as well as the ambient temperature. The effect of ambient temperature was alleviated by conducting the experiment in room temperature (25 degrees Celsius) via air-conditioning in a closed room. The effect of the left-over residues from previous liquids was alleviated by thorough washing of the tube and syringes with a solvent that the residues can dissolve in and then drying. This was also done between replicates just in case of contamination of the previous replicate. The effect of possible contamination entering was mitigated by creating an airtight seal at all possible sights of entry. The force gauge was fixed over and connected to the pump plunger so that when the pump is pushed down, the gauge measures the force exerted onto it.

4.4 Size and Selection Criteria for the Study Sample

This experiment is a complete experiment with all treatments being done in triplicates to minimise the effect of human error. There are criterias for each of the predictors. Firstly, due to pascal's laws of $F_2 = \frac{A_2}{A_1} F_1$ (clippard, 2012) (Hodanbosi, 1996), where the A_1 and F_1 are the area of the pump and force acting on the pump and; A_2 and F_2 are the area of the lift and force acting on the object being lifted, in tandem with the mechanical advantage formula, $Mechanical\ Advantage\ = \frac{F_2}{F_1}$, it is not ideal to have an area of the pump being larger than the area of the lift and therefore only pump areas that are less or equal to the lift area were experimented on. Also, fluids with extremely high viscosity were not used as it is already known that it takes a lot of force to “compress” them, such as tar. Additionally, the percentage of contamination per volume is relatively small, with a maximum 10% contaminant to liquid ratio, as too high a ratio would be effectively the same as pushing on solids, which just like extremely viscous liquids, will be extremely ineffective. It is also highly unrealistic that a hydraulic system will have 95% sand contamination.

4.5 Potential Sources of Error and Weaknesses

There are multiple areas where error can occur. First of all, there could have been too much adhesive used for the connecting tube gaps which could cause the adhesive to leak in and contaminate the fluid. Unintended air or particle contamination could also occur from undersealing or improper sealing. This has the potential of causing an outlier and possibly an influential point. Also, the method of measuring the force requires a significant amount of human interaction and therefore inaccuracies in the measurements can arise from mismeasuring the force due to human error. Additionally, if the contaminants were not washed out properly when switching fluids then the left-over fluid could contaminate the current fluid which can cause an outlier or influential point in the data. Another source of error can occur from poor assembly of the simple hydraulic lift such as the force gauge being too far from the pump plunger. Most of the effects these errors have on the model will be reduced by conducting the experiment in triplicates, though an outlier can still have an effect on the model.

5 Exploratory Analysis

After the design and conduction of the experiment, the 108 observations were recorded into a results table (Table 1, see Appendix 1) and a coinciding csv file. Initial analysis of predictors and response and their relationships, as well as interactions and main effects, were then conducted.

5.1 Relationships Between Predictors and Response Variables

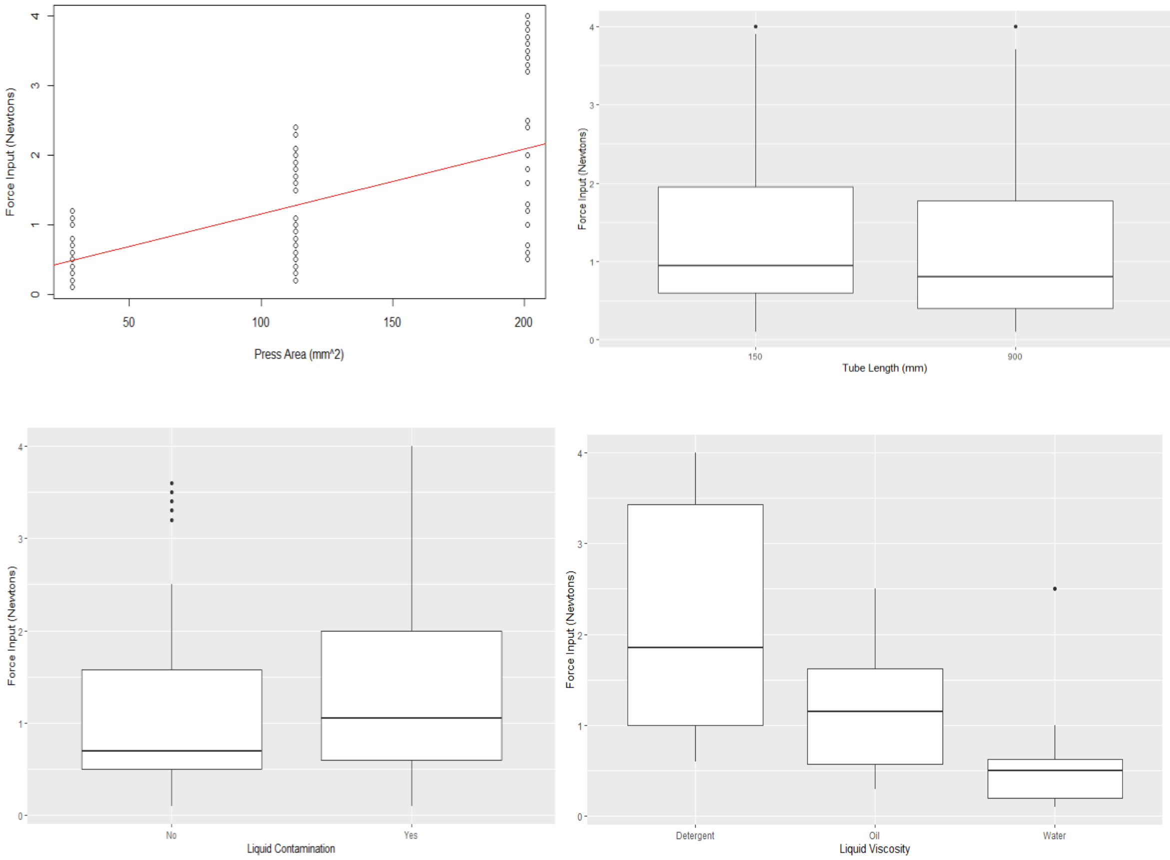

Figure 3: Predictor variables against input force for gathered data

Figure 3 is each predictor variable against force. Tube length, liquid contamination, and liquid viscosity are in the form of box plots as they are categorical factors. This gives some initial insight into the possible relationships between these predictor variables and input force as the response variable. Each predictor and its levels seem to have some effects on input force to lift the mass, indicating that fitting a model using this gathered data to predict input force is statistically practical. Though the outliers within the tube length, contamination, and viscosity plots should be noted. Furthermore, the constant variance assumption was not met for both liquid viscosity and press area, as it was found that variation tended to increase as the liquid used increased in level of viscosity as well as when the press area was increased as shown in Figure 3. The normality assumption was also not met for liquid contamination and tube length, as it was found that the data is right skewed for these factors. However, all other assumptions were met.

Now that it is known that these predictor variables will have at the minimum some effect towards the response variable, potential relationships and the type of these relationships will now be explored. The following plots and figures show two predictor variables against the input force response variable.

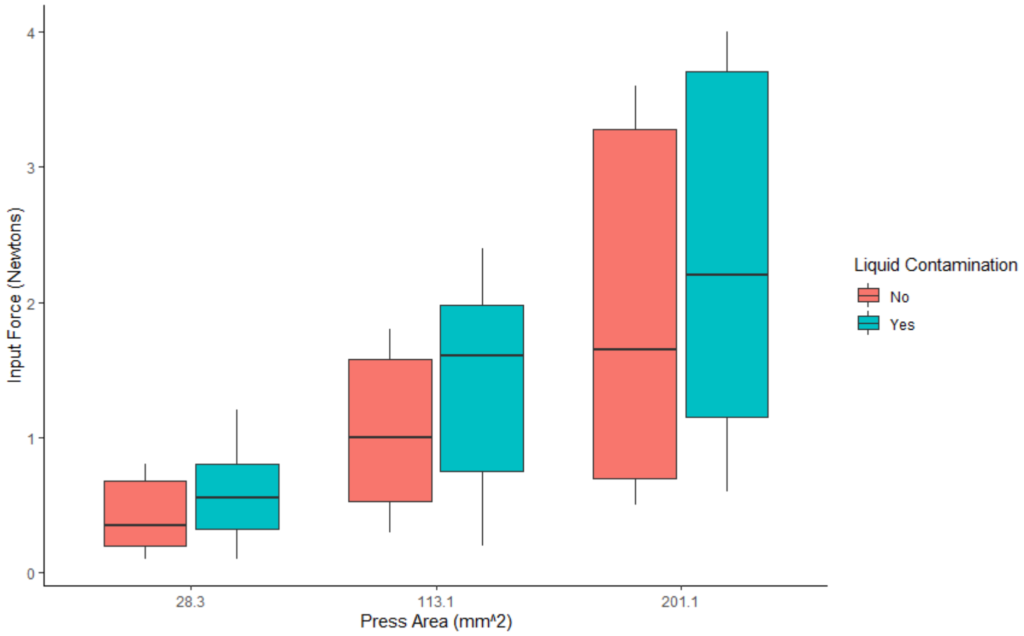

Figure 4: Predictor variables press area and liquid contamination against input force response variable

Figure 4 above shows some insight into how the response variable is affected through the press area predictor variable grouped with liquid contamination levels. As mentioned, the constant variance assumption is not met, with figure 4 visibly showing potential heteroskedasticity, thus indicating that having press area as a predictor of input force in the model is potentially problematic. A spread can also be seen between groups. Therefore, a linear model predicting input force would be problematic when including press area. After some analysis, this plot was again created, however with the y-axis as a log transformation of input force instead. This was done to potentially fix the constant variance issue seen previously. Figure 14 (appendix 2) shows a better variance and confirms that a log transform is potentially more suitable when used in the linear regression model.

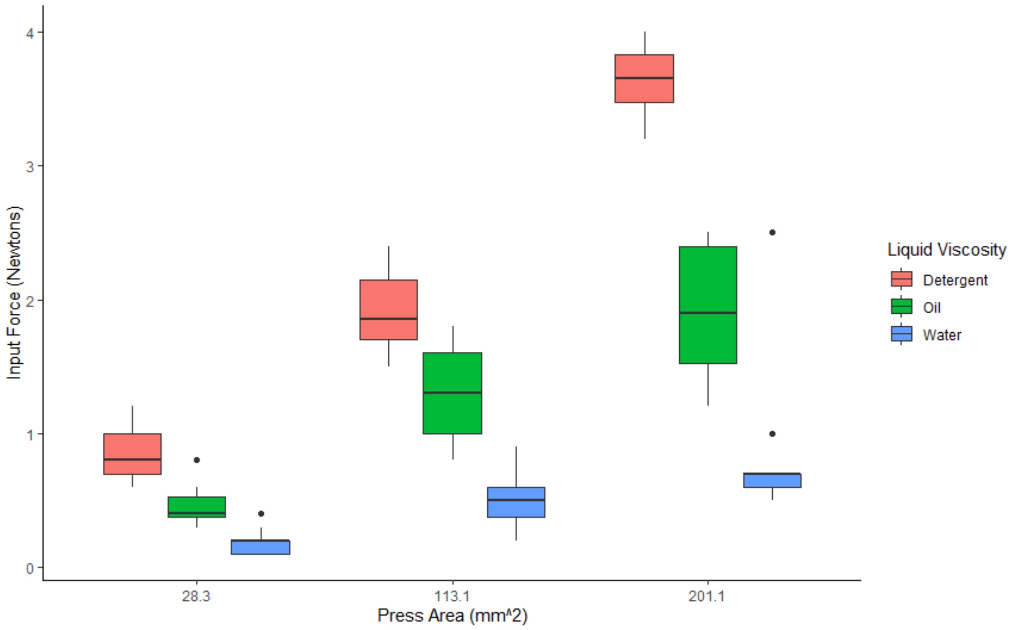

Figure 5: Predictor variables press area and liquid viscosity against input force

Figure 5 has similar issues to figure 4 whereby the potential of heteroskedasticity was again found. This again with figure 4 provides evidence for the possibility of improvement with transformation of the input force response variable, and a log transformation plot of input force was created for liquid viscosity. Again, this fixes the constant variance issue, and further forwards the possibility of a log transformation being suitable for the final model. This is shown in figure 15 (see appendix 2).

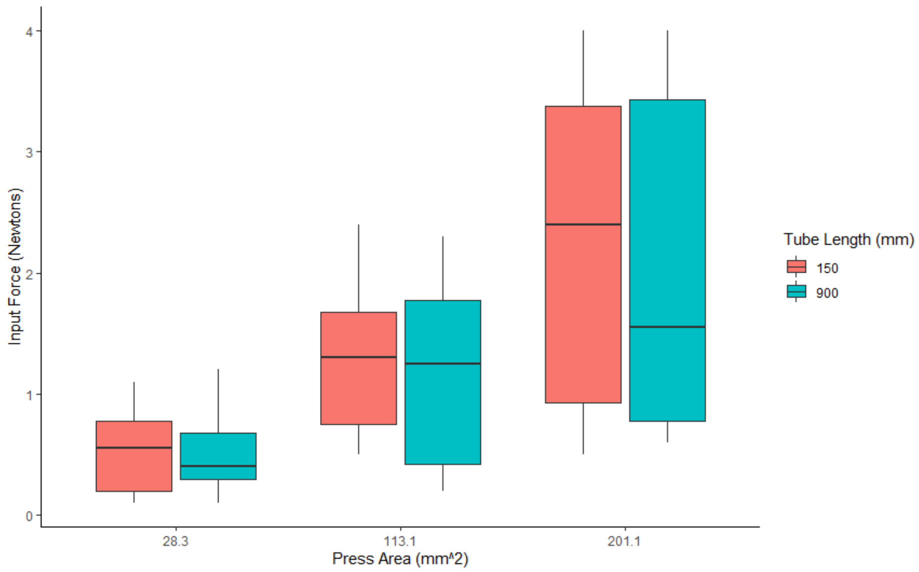

Figure 6: Predictor variables press area and tube length against input force

Figure 6 again shows potential heteroskedasticity with the press area when grouped with tube length levels. The spread also seems to vary between groups, indicating that a linear model on the raw data may be inappropriate. Similar to previous figures, the predictors were again plotted against log transform of input force. This again fixes the stated issues in these initial plots, and therefore provides further evidence of a linear model fitted for the log transformation of input force as being suitable. Figure 16 is a plot with the log transform of input force (see appendix 2).

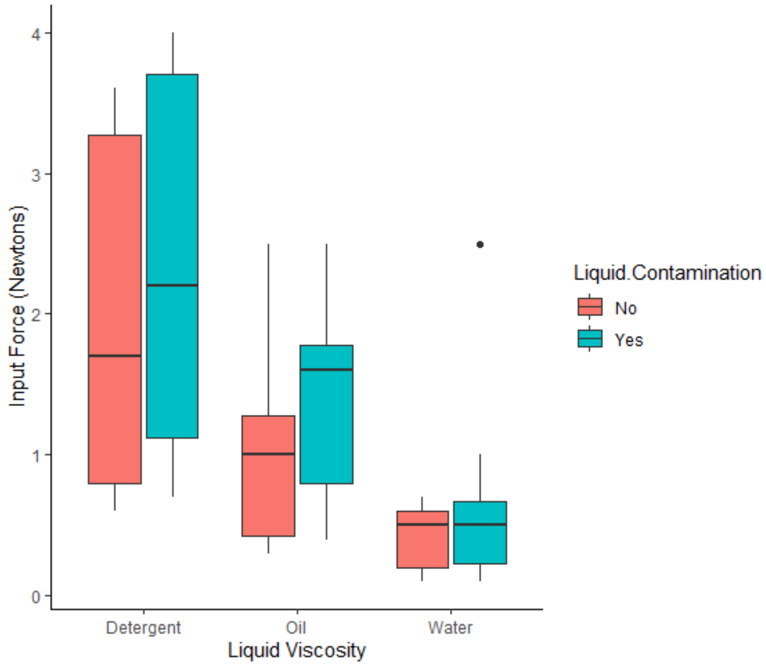

Figure 7: Predictor variables liquid viscosity and liquid contamination against input force

Figure 7 shows potential heteroskedasticity with liquid viscosity when grouped with liquid contamination levels. The spread seems uneven all throughout between and within groups, thus a linear model may be inappropriate for the raw force input data. The predictors were plotted against the log transformation of input force in figure 17 (see appendix 2), which completely fixed these issues with the plot.

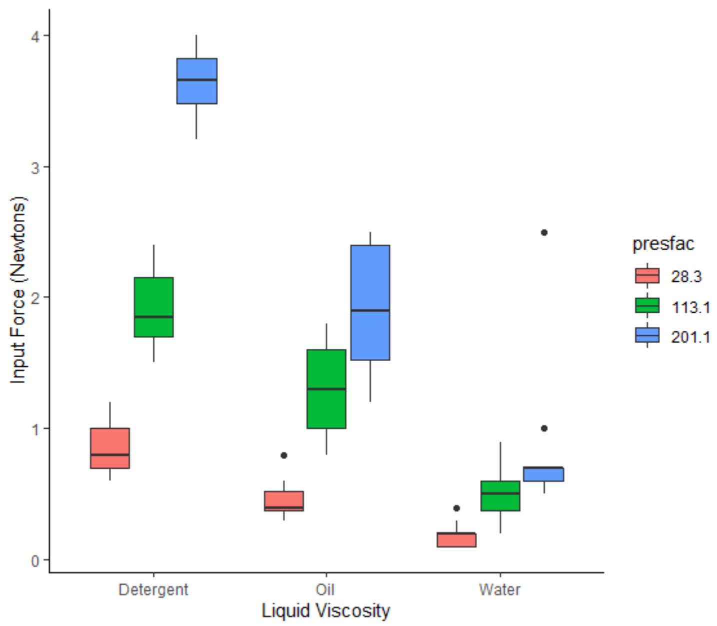

Figure 8: Predictor variables liquid viscosity and press area against input force

Figure 8 again shows potential heteroskedasticity with liquid viscosity when grouped with press area levels. With this in mind, a linear model may be inappropriate for the raw force input data. These predictors were plotted against the log transformation of input force in figure 18 (appendix 2), which fixes the heteroskedasticity issue.

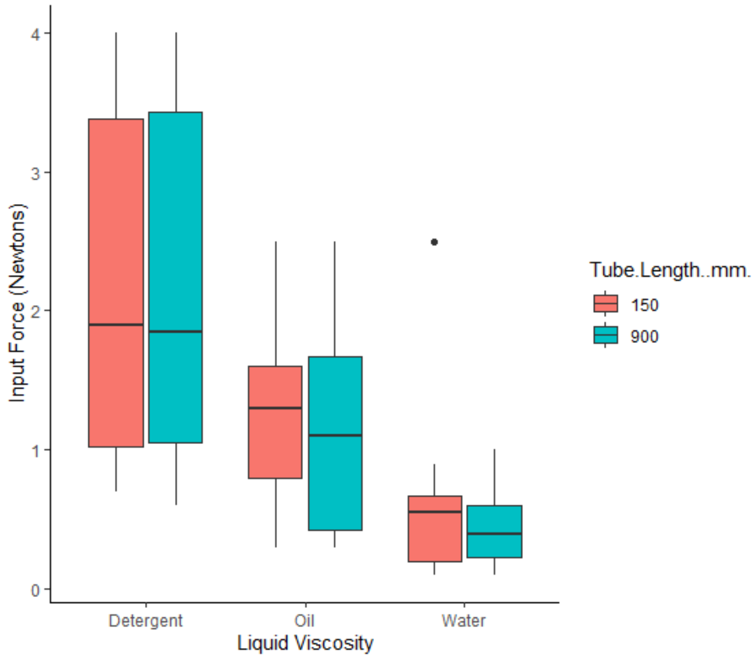

Figure 9: Predictor variables liquid viscosity and tube length against input force

Heteroskedasticity was again found in figure 9 for liquid viscosity grouped with tube length levels. The spread is somewhat uneven between groups, thus a linear model may not be suitable for the raw force input data. These predictors were again plotted against the log transformation of input force in figure 19 (see appendix 2), which fixes these issues.

5.2 Examining Interaction Plots

Interaction effects exist when the effect of a predictor variable on a response variable changes depending on the value of one or more other predictor variables. These are common within ANOVA, regression analysis, and designed experiments. To investigate these potential interaction effects, an understanding of the main effects of each variable was undertaken. The design of the experiment made it possible to conduct analysis on the interaction effects between our categorical variables. To interpret the main effects of these variables, if an interaction term is present in the fitted model, these terms govern the main effects.

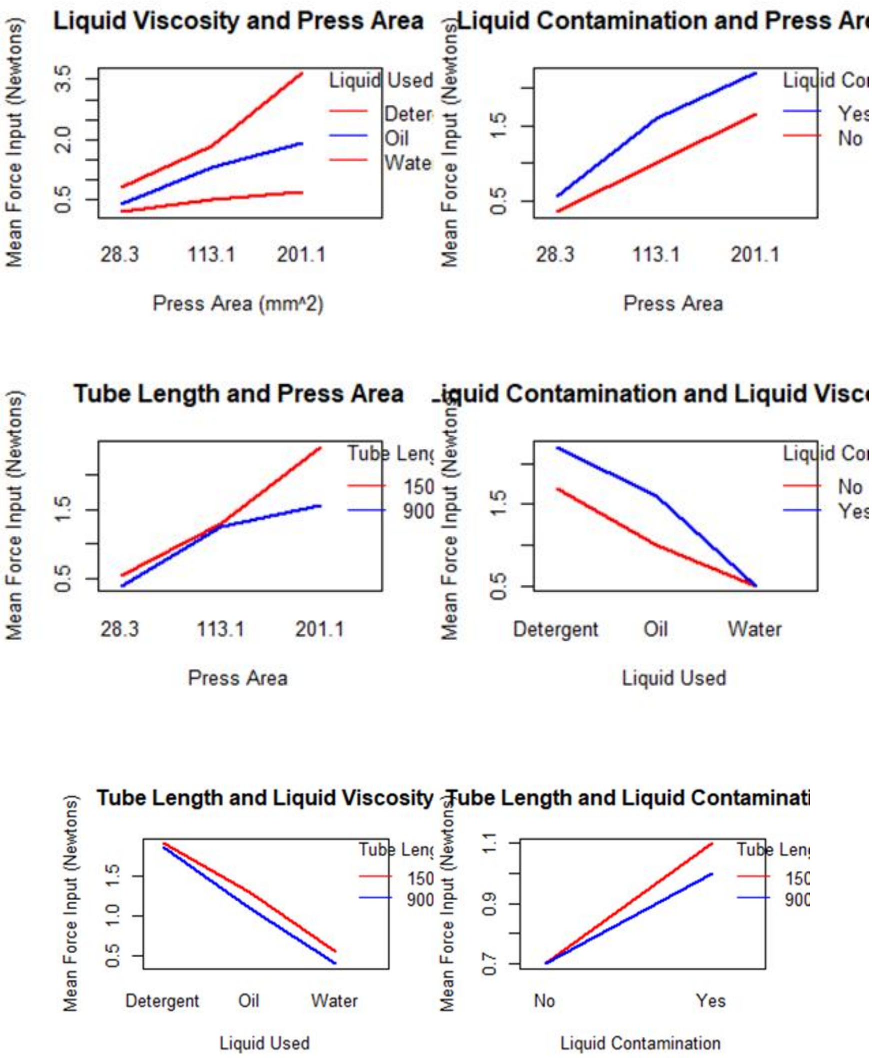

Figure 7: Two-way interaction plots of predictor variables

The interaction plots in figure 7 indicate that there may be interaction present in the gathered data. In the press area and liquid used plot, the steepness seems to decrease as the liquids used lower in viscosity (from detergent down to water), which indicates a form of interaction that could potentially be present in our data and is to be explored when fitting a model.

This is also found in the press area and liquid contamination plot, whereby the steepness of no contamination as the press area increases is almost down to zero (a straight line), which is not the case for when contamination is present within the system. This indicates this interaction term is potentially included in the final model and must be explored.

The press area and tube length plot is quite interesting in that the steepness between tube lengths as the press area is increasing decreases. This interaction term may possibly be included in the final model and must be explored.

The liquid used and liquid contamination plot is similar, with the steepness decreasing from no contamination to contamination being present in the system. There is a possibility of an interaction existing in the data and should be explored when fitting a model.

Penultimately, the liquid used and tube length plot has an almost parallel steepness. A slight interaction may be present here and should be explored when fitting the final model.

Lastly, the contamination and tube length plot does not seem to be parallel when liquid contamination alters in presence in the system. This indicates that the final model could potentially include this interaction term if statistically significant enough.

5.3 Reliability and Accuracy

Our gathered data shows great reliability and accuracy. The methods as presented were followed strictly, though some potential sources of error were still present. For example, human error is potentially present when gathering and obtaining the input force required to lift the mass. As the Newton metre used was not fixed on a hook but rather by hand by only one of our group members, it potentially disrupted some force readings taken and thus could potentially be the source of the unstable variance as well as outliers within the data. Some of the manually created hydraulic systems also malfunctioned during the experiment, and quick repairs had to be made. Unfortunately, this could also be a potential source of outliers or influential points as the systems themselves are relatively different to how it was initially set up before repairs. Lastly, due to resource constraints, to continuously use different liquids with the same systems, washing the tubes and containers were necessary. It is possible that excess, unwanted fluids were left within the system and not completely cleared of the tubes and containers before further treatments were tested, which may potentially deviate data than when it was completely clean initially at the start of the experiment. With the number of controlled variables in the experiment, it is unlikely for any potential errors to be from other sources, and the outliers found in previous figures may be attributed to this. With this in consideration, the data is found to be relatively reliable and accurate in accordance to previous studies mentioned within the literature review.

6 Formal Statistical Methods

The formal statistical methods used in the exploratory analysis were the following,

- ANOVA tests for liquid contamination and tube length while blocking for liquid viscosity
- Linear regression for press area while blocking for liquid viscosity
- ANOVA tests for liquid contamination, tube length and liquid viscosity while blocking for press area

Additionally, for the formal statistical methods a log transformation was performed on the response variable.

Two sets of ANOVA tests were performed on the categorical variables. One set used the press area as a blocking factor while the other used liquid viscosity as a blocking factor. The linear regression of the press area also used liquid viscosity as a blocking factor.

Before these models were suggested the main effects of the four factors on the input force were analysed by performing simple linear regression on the press area and one way ANOVA tests were done for the three other variables. Assumption testing was done for those tests. All assumptions were met except for constant variance for both liquid viscosity and press area. To fix this issue a log transformation on the data was performed, which fixed the assumption of constant variance while having all the other assumptions met. Then a simple linear regression test and one way ANOVA tests were performed again and these were the conclusions gathered.

- There was significant evidence to suggest that there is a linear relationship between press area and log force input
- There was significant evidence to suggest that there exists a difference between the mean log force input between at least two of our liquid viscosities
- There is no significant evidence to suggest that there exists a difference between the mean log force input between short and long tube lengths and the presence of contaminations (yes and no).

Due to press area and both liquid viscosity and press area having significant effects on the log force input it was decided to instead do the two sets of ANOVA tests and one linear regression test mentioned previously. These should answer the four questions mentioned in our aim.

For conclusions to be drawn from these six tests, the following assumptions for both the linear regression model and ANOVA model must be met.

- Constant variation for residuals vs fitted values and residuals vs each of our variables (X’s)
- Linearity. This only applies for the linear regression model so therefore the test is only checking for curvature and unusual observations between residuals vs fitted value
- Independence, are there any trends in our data?
- Normality of the response

After performing the assumption checking for our six tests, none of the assumptions were violated (plots for these tests and Levene test for constant variation in Appendix 2, figures 20-25).

However, there are four outliers for the linear regression model, although the cook's distances for these outliers were not greater than 1 and therefore does not have a significant effect on the test (figure 26). It should be noted that these errors are most likely human errors due to only one group member operating the experiment contraption. These points were not removed as they were not considered leverage points and thus did not affect the test drastically as well as it being unknown the source of these outliers. After the tests used to analyse the effects were done, a final model was made to predict the input force for each combination of factors. Results from the six tests can be seen in figures (27-32).

To determine how the factors tested affect the efficiency of the hydraulic lift as stated in Section 2 of this report, a linear model is to be derived out of the data that was collected through the experimentation. Once the data is thoroughly analysed, a variety of statistical testing methods can be used to determine the best final model for a linear relationship between the predictor variables and the response variable of the design. This model should ideally accurately describe the data by having little bias and offering a good prediction of data without overfitting or underfitting. Due to the usage of both continuous and categorical variables in the experimental design, a multiple linear regression method was chosen to generate this ideal model. This uses Least Squares estimates to find the best fitting model for the data. A linear model found using multiple linear regression can be considered valid if they hold to the following assumptions:

a) There is linearity between the residuals and fitted values for each continuous predictor variable
b) The residuals are independent of one another
c) The residuals have a constant variance compared to the fitted values and each continuous predictor variable
d) The residuals fit a normal distribution
e) There is no multicollinearity between any of the predictor variables.

For the best model to be chosen, it is required that only the necessary predictor variables are included to avoid overfitting. While there are several methods for selecting the best model, it was decided that the stepwise regression was to be used to determine the model choice. Stepwise regression constructs a suitable model by either starting with no predictors and adding a single predictor at each stage until the model does not improve further (Forward selection), or by starting with all predictors and removing one at each stage (Backward elimination). It is also possible to combine the two methods in a process called stepwise selection. Although all methods were tested, for the purpose of this report, it was determined that the stepwise selection starting from the empty model was the most suitable, giving a model that uses the full model and no interactions.

```
Call:
lm(formula = Input ~ Press.Area..mm.2. + Tube.Length..mm. + Liquid.Viscocity +
    Liquid.Contamination, data = ExperimentE.df)

Residuals:
     Min       1Q   Median       3Q      Max
-0.92335 -0.40113 -0.00114  0.31460  0.97665

Coefficients:
                          Estimate Std. Error t value Pr(>|t|)
(Intercept)              0.9740553  0.1246547   7.814 5.15e-12 ***
Press.Area..mm.2.        0.0093432  0.0006401  14.596  < 2e-16 ***
Tube.Length..mm.900     -0.1185185  0.0903227  -1.312  0.19241
Liquid.ViscocityOil     -0.9111111  0.1106222  -8.236 6.27e-13 ***
Liquid.ViscocityWater   -1.6333333  0.1106222 -14.765  < 2e-16 ***
Liquid.ContaminationYes  0.3037037  0.0903227   3.362  0.00109 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.4693 on 102 degrees of freedom
Multiple R-squared:  0.8135,    Adjusted R-squared:  0.8044
F-statistic: 89.01 on 5 and 102 DF,  p-value: < 2.2e-16
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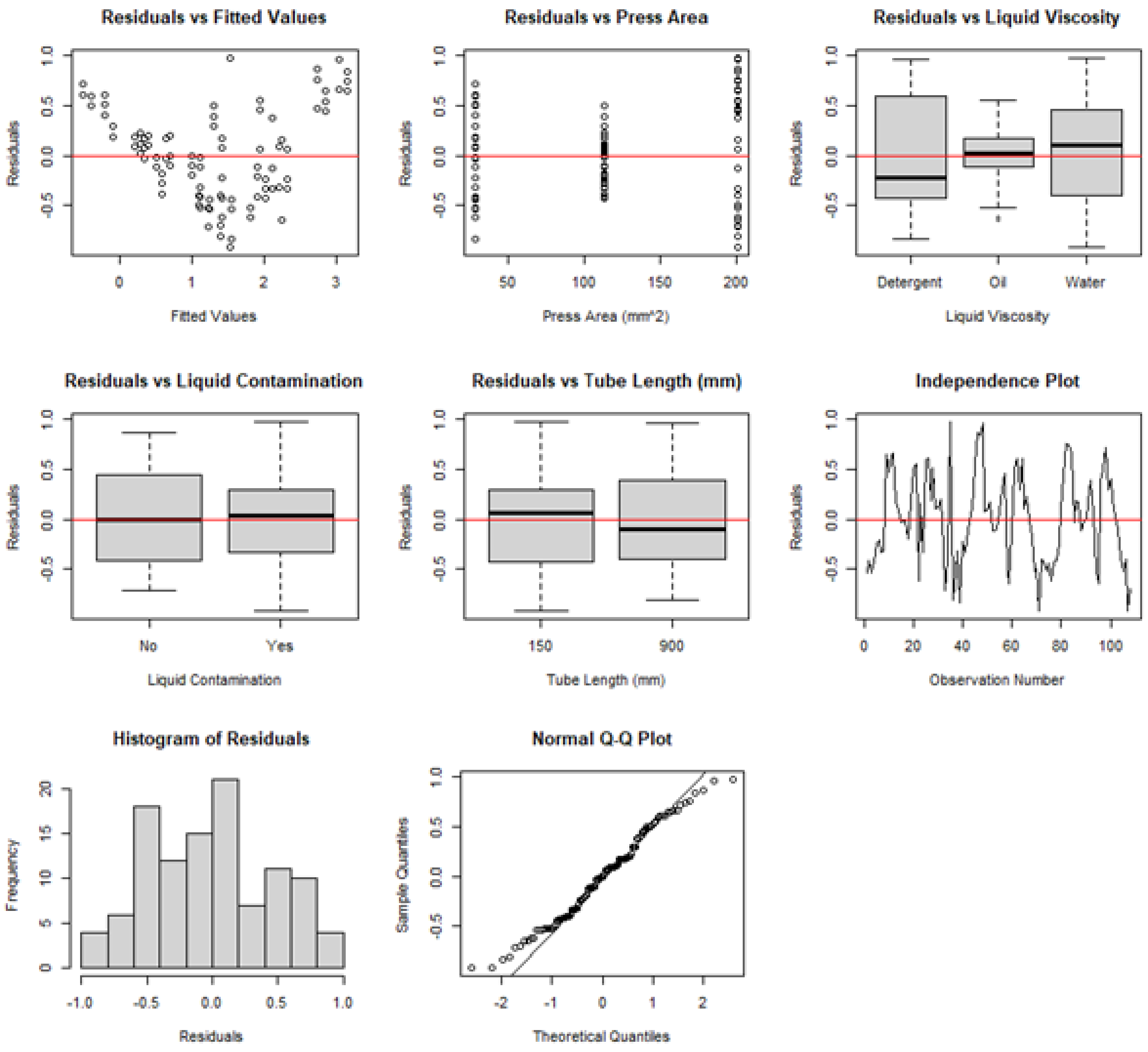

Figure 8 - Initial Model Assumption Plots

As can be seen from testing, this model appears to work well as a predictor in that all predictors were considered statistically significant, with the exception of tube length, and a fairly high R squared value of around 0.81 was achieved. However, upon further analysis, the data violates the assumptions of a multiple linear regression model, especially in terms of linearity in the fitted values and constant variance in the residuals. Additionally, the normality of the residuals is also not particularly well met.

Therefore, a transformation on the force input data is required to make the model fit the assumptions of linearity. While several transformations were considered, it was determined that a log transformation was to be used, as explained in the exploratory analysis section.

6.1 Final Statistical Model

Using the stepwise regression function in R (Appendix 33), it can be seen that the best fitting model is the one that uses all predictor variables with no interactions. While two different models were considered, one with an interaction between press area and contamination, and one with no interactions, the model with no interactions was considered better due to it having a better F-statistic. It can also be seen that nearly all predictor variables are highly statistically significant, with only the tube length being moderately statistically significant. This indicates that the full model with no interactions is the best model to be used.

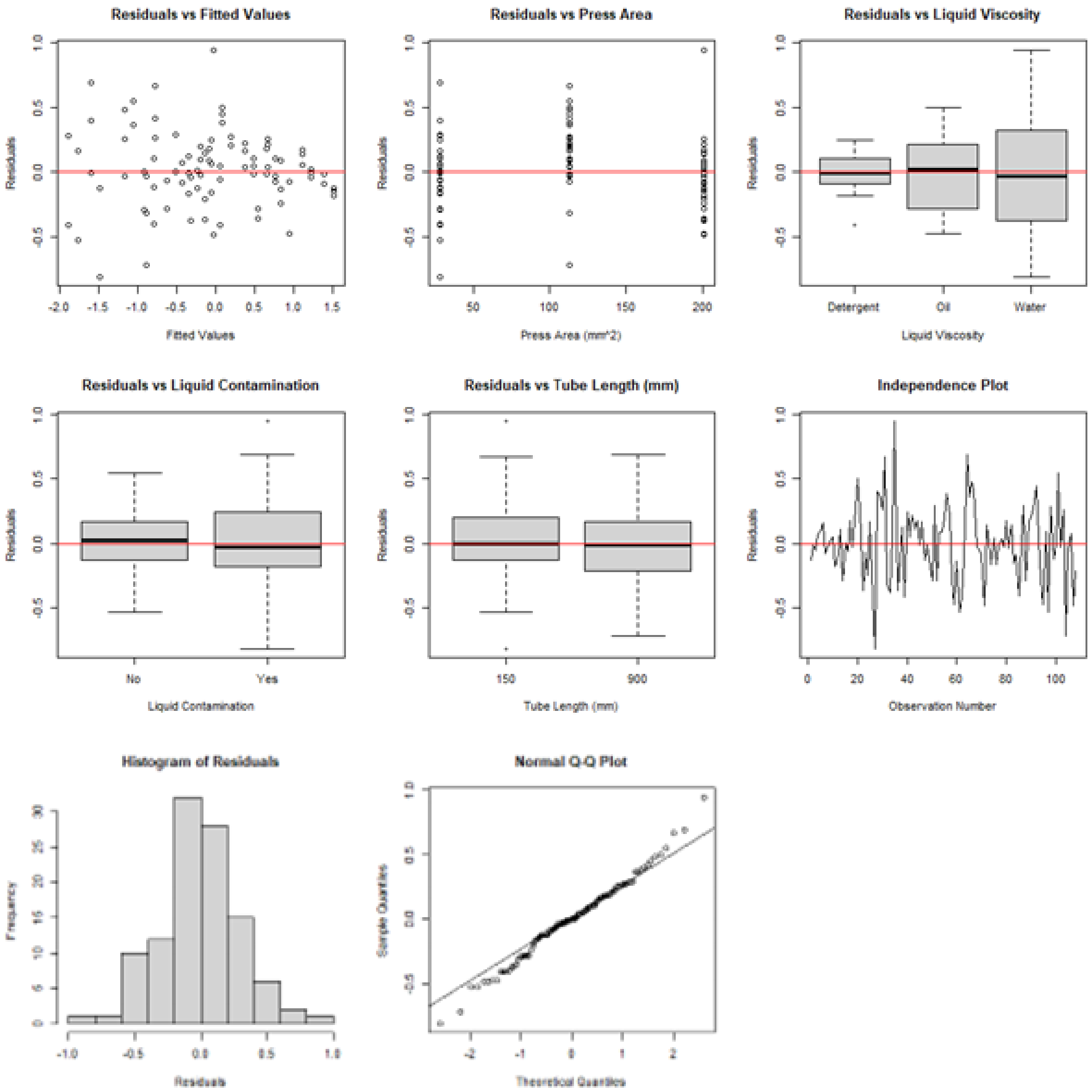

Figure 9 - Final Model Assumption Plots

The assumption plot shows the Independence plot, as well as the Residuals vs Fitted Values and Residuals vs Press Area plots have a mean of around 0, with a seemingly constant variance. The residuals all appear to be random, which further validates the model. The independence plot also seems to have no obvious patterns, meaning that all of the residuals should be independent. Both the Histogram of Residuals and the Normal Q-Q plot also indicate that residuals fit a normal distribution. Although the Q-Q plot appears to have some skew at either end of the plot, it appears to be very minor, meaning that it should still fit the normal distribution. Overall, this means that all the assumptions are met for this model, and therefore it is a valid multiple linear regression model.

```
Call:
lm(formula = LogInput ~ Press.Area..mm.2. + Tube.Length..mm. +
    Liquid.Viscocity + Liquid.Contamination, data = ExperimentE.df)

Residuals:
     Min       1Q   Median       3Q      Max
-0.81315 -0.15498 -0.00507  0.17799  0.94533

Coefficients:
                        Estimate Std. Error t value Pr(>|t|)
(Intercept)           -0.4696013  0.0806573  -5.822 6.78e-08 ***
Press.Area..mm.2.      0.0084513  0.0004142  20.404  < 2e-16 ***
Tube.Length..mm.900   -0.1160532  0.0584429  -1.986   0.0497 *
Liquid.ViscocityOil   -0.5687101  0.0715777  -7.945 2.68e-12 ***
Liquid.ViscocityWater -1.5430763  0.0715777 -21.558  < 2e-16 ***
Liquid.ContaminationYes  0.2840733  0.0584429   4.861 4.25e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3037 on 102 degrees of freedom
Multiple R-squared:  0.9001,    Adjusted R-squared:  0.8952
F-statistic: 183.9 on 5 and 102 DF,  p-value: < 2.2e-16
```

The R summary function was also used to determine the suitability of the model for the purpose of predicting data. This model has a very small p value ($p < 2.2 \times 10^{-16}$) as well as a large F-statistic of 183.9 with degrees of freedom of 5 and 102. This means that the null hypothesis of $\beta_1 = \cdots = \beta_5$ can be rejected and at least one variable in the model is statistically significant. The R^2 value shows that 90.01% of variation in the data can be explained by the model and the adjusted R^2 value shows that it is still 89.52% even when penalising for the number of coefficients. This indicates that the model is highly useful at predicting data. The data shows that all variables in the model were significant, which further indicates that this is a very useful model.

It is also important to detect any unusual observations in the data and determine the source of them to remove any errors in the data. While there are no leverages, nor influential points from Cook’s distance, both the studentized and standardised residuals show that observations 27, 31, 35, 64 and 104 are all outliers. While it cannot be fully explained why these outliers have occurred, it is interesting to note that all five unusual observations are for contaminated water experiments. The most likely reasoning for these outliers is human error, although how this occurred is unknown. As a result, these outliers cannot be excluded from the data. However, due to the very small number of outliers, it should not affect the linear model to a significant degree.

Response: log(Input)	Estimate	Std. Error	t Value	p Value	Strength
Press Area (mm^2)	0.0084513	0.0004142	20.404	< 2e-16	Very Strong
Tube Length (900 mm)	-0.1160532	0.0584429	-1.986	0.0497	Mildly Strong
Liquid Viscosity (Oil)	-0.5687101	0.0715777	-7.945	2.68e-12	Very Strong
Liquid Viscosity (Water)	-1.5430763	0.0715777	-21.558	< 2e-16	Very Strong
Liquid Contamination (Yes)	0.2840733	0.0584429	4.861	4.25e-06	Very Strong

Table 2 - Linear Model Variable Summary

6.2 Effect of Press Area

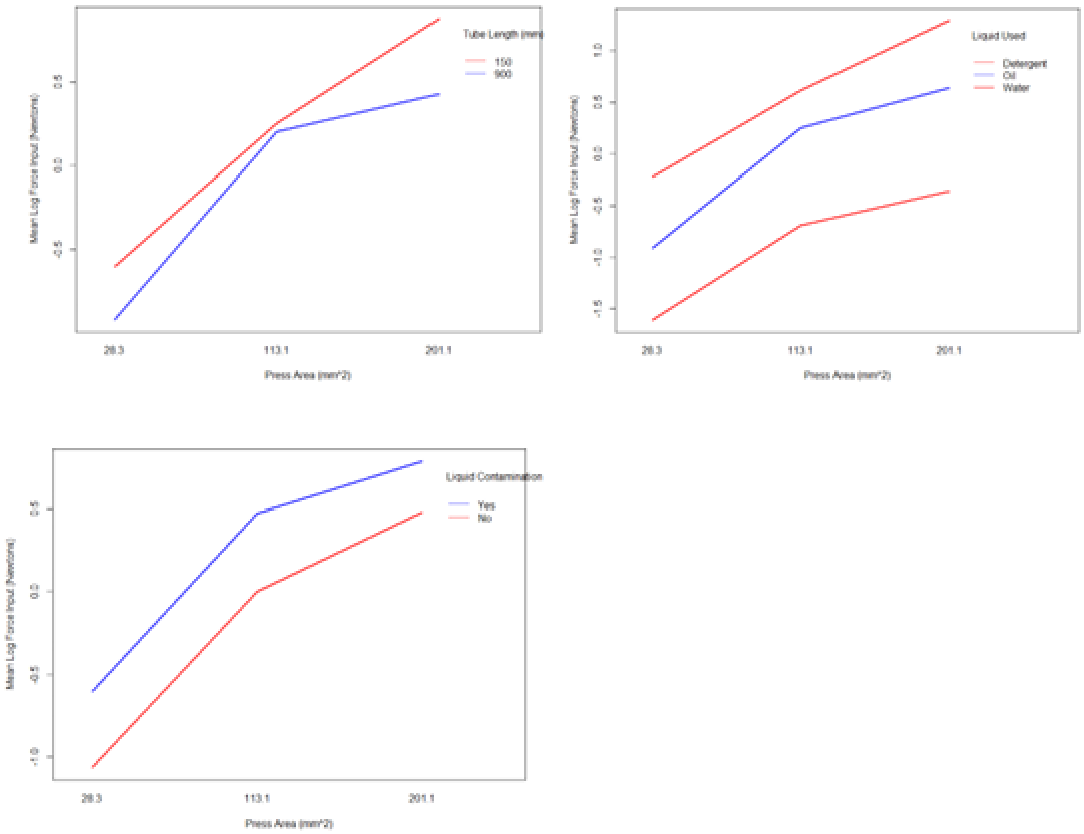

Figure 10 - Log Force Press Area Interaction Plots

The summary table shows that Press area has a strongly significant effect on the log of the required force input ($p < 2 \times 10^{-16}$). It is one of the most influential variables in the force required. For every square millimetre increase in press area, there is a 0.0084 N increase in force required, with a 95% confidence interval between 0.0076 and 0.0093 N. from the interaction plots, it can be seen that the press area is not dependant on any other variable, as there are no clear interactions, although it is worth noting that the 113.1mm^2 input seemed to not have as much of an effect on the 150mm tube and the detergent liquid as it did with the 900mm tube and the other liquids respectively. It is unknown why this occurs, although it could be explained by possible errors in data collection.

6.3 Effect of Tube Length

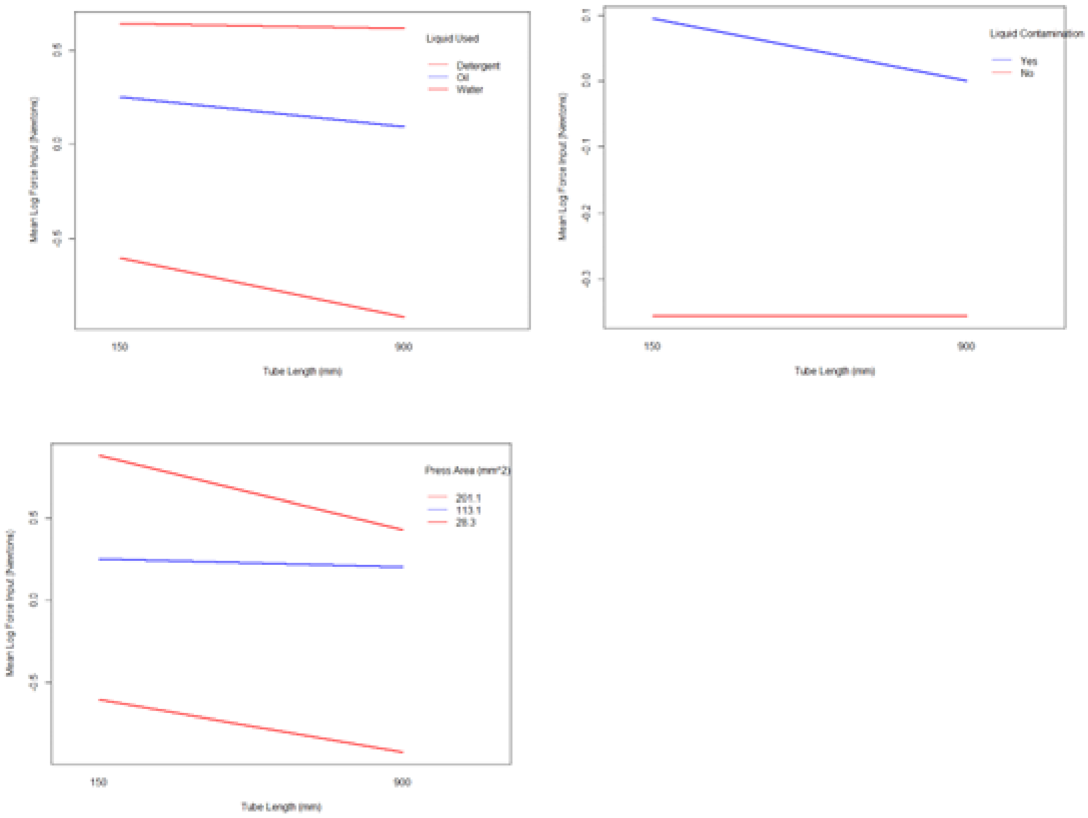

Figure 11 - Log Force Tube Length Interaction Plots

The tube length, while still significant, was much less so than all other variables, with a p value of 0.0497 compared to all other variables that had p values at least ten thousand times smaller. It was determined that the longer tube of 900mm decreased the force required compared to a 150mm tube by 0. 1160532 N on average, with a 95% confidence interval between 0.2319744 and 0.000131888 N in decrease. This is a very large confidence interval, which makes it hard to use the tube length as a predictor. However, the interaction plots also show that there is some interaction between tube length and contamination, in which a long tube length decreases the effect of contamination being present, as well as the tube length having less effect in the 113.1mm2 press area compared to the other sizes. This mostly appears to indicate that a longer tube length tends to help negate problems in contamination.

6.4 Effect of Liquid Viscosity

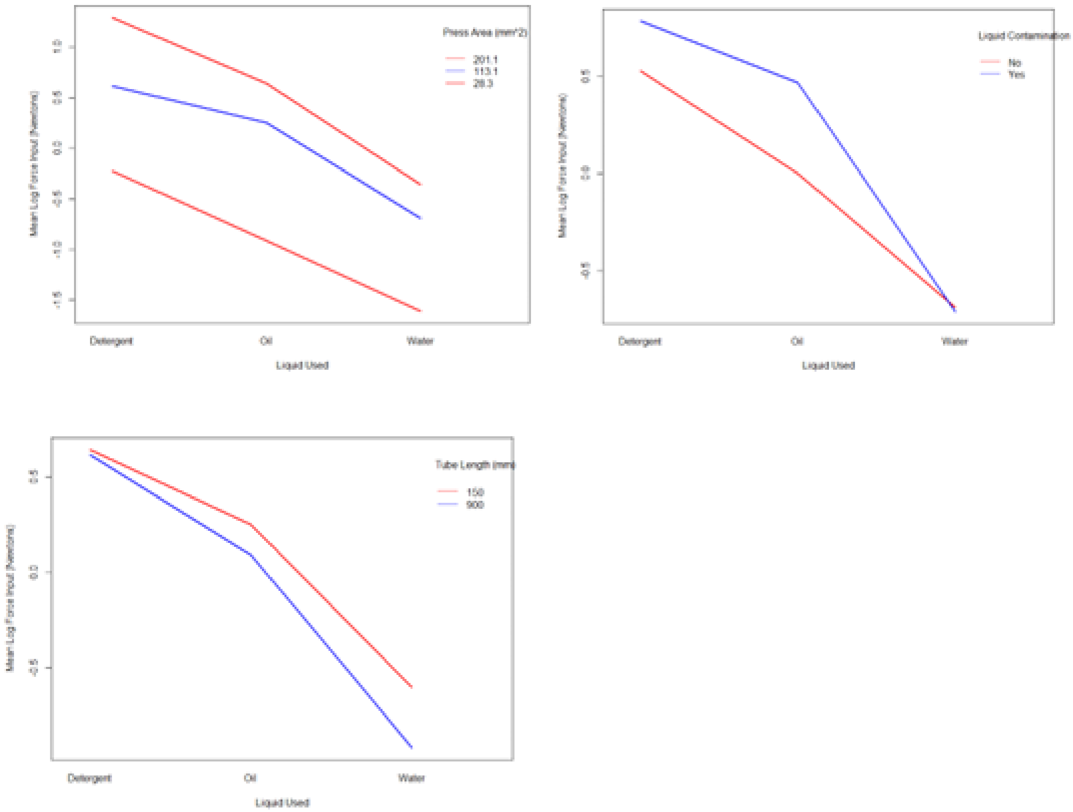

Figure 12 - Log Force Liquid Viscosity Interaction Plots

The liquid used had a strongly significant effect on the required input force for all three types of liquid used, with oil having a p value of 2.68×10^{-12} and water having a p value of 2×10^{-16}. When compared to detergent, on average the oil decreases the force required by 0.5687101 N with a 95% confidence interval between 0.7106841 and 0.4267361 N, and water on average decreased the force by 1.5430763 N with a 95% confidence interval between 1.68505 and 1.401102 N. As the detergent was determined to be the most viscous liquid, followed by the oil and finally the water, it can therefore be seen that the more viscous the liquid, the more force input is required. There are two interesting interactions as seen in the plots above. The first is that water minimised the effect of the contaminant, possibly suggesting that contamination does not affect lower viscosity liquids as much as higher viscosity liquids. The second interaction is that detergent caused a similar reaction in both short and long tube lengths.

6.5 Effect of Liquid Contamination

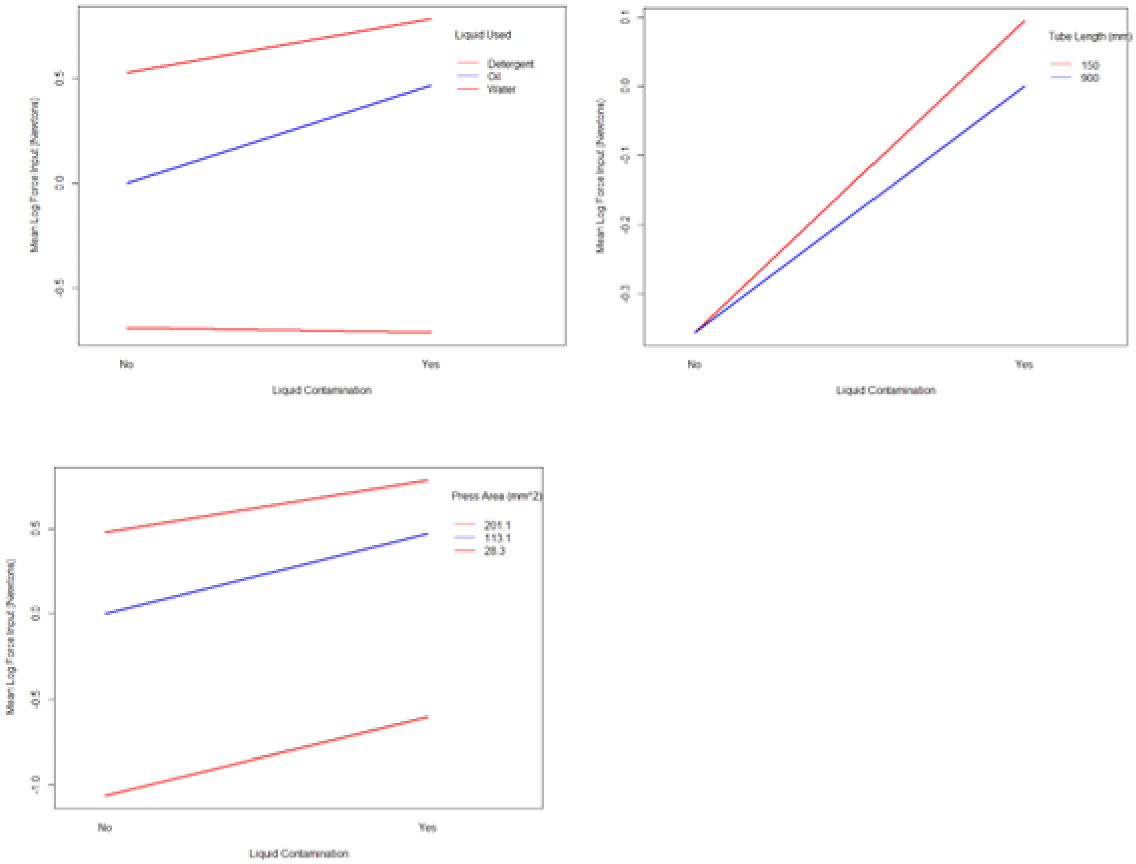

Figure 13 - Log Force Liquid Contamination Interaction Plots

Liquid contamination has a strongly significant effect on the required force input, with a p value of 4.25×10^{-6}. The presence of contamination has an average increase on force required of 0.2840733 N, with a 95% confidence interval between 0.168152 and 0.3999946 N. From the interaction plots, it is very clear that the contamination has interactions with the liquid used and the tube length, which were both already explained in their respective sections. It appears that the presence of contamination has a very large increase in force required in all cases except when water is present.

6.6 Most efficient hydraulic lift

The final model for the effect on the hydraulic lift system is therefore as follows.

$$\log(\widehat{Force}) = -0.469601 + 0.008451Area - 0.116053length_{900mm} - 0.568710oil - 1.543076water + 0.284073contamination$$

Based on the data found in the final model above, the most efficient combination of factors for a hydraulic lift system can be found. This is the system that requires the least amount of force input to move the lift the desired amount. It is clear that the most efficient system is one with a minimised press area (28.3 mm2), a long tube length (900mm), a liquid with low viscosity (water) and no contamination in the system. However, it can be noted that due to the relatively small significance of the tube length, as well as the interaction between tube length and contamination, that the tube length may possibly not have a meaningful impact on the most efficient design.

7 Conclusion

The results have clearly found a linear model that accurately predicts the effect of the four factors on the force required to move a hydraulic lift a set distance. It was determined that all continuous and categorical variables tested had a significant effect on the log of the input force required to operate the lift. A smaller press area, lower liquid viscosity and lack of contamination all lowered the force required by a large amount, while a long tube length also lowered the input force by a lesser, but still significant degree. While the model could possibly be improved to better fit the constant variance assumption, it was still found that a log transformation on the input force worked well in adjusting the data to fit a multiple linear regression model.

A number of recommendations could be made for future study into this topic. One major one would be to further analyse how the data could be further transformed to better fit the assumptions of a linear model as stated above. Additionally, more factors could be analysed further, such as the effect of temperature on the system, as well as having more treatments of each factor. This would allow factors such as tube length to be measured as a continuous variable rather than a categorical variable. The viscosity of each liquid could also be properly measured so that it could also be treated as a continuous variable to determine the exact relationship between viscosity and force required. Finally, improvements could be made to the experimental design to reduce possible variance caused by human error. Overall, it has been determined that the model derived is a good predictor of the factors tested.

8 References

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9 Appendices

9.1 Appendix 1 (Meetings Summary):

Date	Time	Purpose of Meeting	What was achieved during/after the meeting
25/03/22	1pm-2pm	Brainstorming ideas for what experiment to do as well as getting approval	We have decided to do a hydraulic lift experiment.
4/04/22	5:30pm-6:30pm	Allocate Tasks for Report Stage 1 as well as the due date for our draft.	**Methods:** Jesse **Literature Review:** Ryan **Introduction:** Nicole (⅔ of it) and Aiden **Reference:** Aiden **Title Page and Appendices:** Everyone **Draft Due Date**: 13th of April
14/04/22	2:30pm-3:00pm	Sending through our drafts of the initial report.	Drafts are sent through by everyone.
19/04/22	5:30pm- 6:30pm	Going through the report, checking for any errors and making any improvements for the draft	Several more details were added in for the draft along with it being submitted with the checklist
15/05/22	9am-5:30pm	Perform the Experiment and collect all required data. Additionally, discuss how the work will be allocated due to our fourth group member being unwell.	Our group has managed to perform the experiment and collect all required data. However, there was a setback with not being able to obtain a newton metre until midday. Our group has decided upon the following roles: Jesse will do the Coding and meeting summary; Ryan will do the write up for the exploratory analysis; Aiden will do the results/final analysis and conclusion; and

			the whole group will do the abstract.
23/05/22	5pm-6:30pm	Go through the code and to plan out what modal to use.	We went through our code and planned on using a multiple linear regression model. However, there were some changes that occurred between 23/05/22-3/6/22 that were communicated through via text. For example we changed tube length from a continuous variable to a categorical variable due to the nature of the experiment.
1/06/22	7:30-9:30pm	Finalise and edit our slides.	We had proofread each other's slides and finalised them as well as done some right up on our palm cards and practised our speeches.
2/06/22	12pm-3:25pm	Finalise our palm cards and practice presentation.	We proofread each other's speeches; practised speaking and then edited our speeches and repeated.
3/06/22	8pm-12pm	Finalise the Final Report.	Report was mostly edited and finalised. However, a 48 hour extension was required.
4/06/22	9am-10am	Finalise and Submit Report	The final copy of the report was proofread and then submitted.

9.2 Appendix 2 (Graphs and Tables):

Table 1: Data recorded from the experiment

Liquid Contamination	Liquid Viscosity	Press Area (mm^2)	Tube Length (mm)	RunOrder	Input Force (N)
No	Detergent	28.3	150	19	0.7
No	Detergent	28.3	900	56	0.7
Yes	Detergent	28.3	150	31	1
Yes	Detergent	28.3	900	38	1
No	Detergent	113.1	150	34	1.8
No	Detergent	113.1	900	13	1.7
Yes	Detergent	113.1	150	21	2
Yes	Detergent	113.1	900	30	1.9
No	Detergent	201.1	150	32	3.5
No	Detergent	201.1	900	41	3.2
Yes	Detergent	201.1	150	8	3.8

Yes	Detergent	201.1	900	7	3.7
No	Oil	28.3	150	25	0.5
No	Oil	28.3	900	15	0.3
Yes	Oil	28.3	150	24	0.6
Yes	Oil	28.3	900	28	0.5
No	Oil	113.1	150	20	1.1
No	Oil	113.1	900	36	0.8
Yes	Oil	113.1	150	11	1.6
Yes	Oil	113.1	900	9	1.8
No	Oil	201.1	150	53	2.5
No	Oil	201.1	900	16	1.2
Yes	Oil	201.1	150	3	2.4
Yes	Oil	201.1	900	12	1.8
No	Water	28.3	150	54	0.2

No	Water	28.3	900	17	0.1
Yes	Water	28.3	150	6	0.1
Yes	Water	28.3	900	29	0.3
No	Water	113.1	150	1	0.5
No	Water	113.1	900	5	0.4
Yes	Water	113.1	150	44	0.9
Yes	Water	113.1	900	18	0.3
No	Water	201.1	150	43	0.5
No	Water	201.1	900	10	0.7
Yes	Water	201.1	150	4	2.5
Yes	Water	201.1	900	2	0.6
No	Detergent	28.3	150	19	0.7
No	Detergent	28.3	900	56	0.8
Yes	Detergent	28.3	150	31	0.7

Yes	Detergent	28.3	900	38	1.2
No	Detergent	113.1	150	34	1.7
No	Detergent	113.1	900	13	1.8
Yes	Detergent	113.1	150	21	2.4
Yes	Detergent	113.1	900	30	2.3
No	Detergent	201.1	150	32	3.4
No	Detergent	201.1	900	41	3.6
Yes	Detergent	201.1	150	8	4
Yes	Detergent	201.1	900	7	4
No	Oil	28.3	150	25	0.4
No	Oil	28.3	900	15	0.3
Yes	Oil	28.3	150	24	0.8
Yes	Oil	28.3	900	28	0.4
No	Oil	113.1	150	20	1

No	Oil	113.1	900	36	0.9
Yes	Oil	113.1	150	11	1.5
Yes	Oil	113.1	900	9	1.6
No	Oil	201.1	150	53	2.4
No	Oil	201.1	900	16	1.3
Yes	Oil	201.1	150	3	1.6
Yes	Oil	201.1	900	12	2
No	Water	28.3	150	54	0.1
No	Water	28.3	900	17	0.1
Yes	Water	28.3	150	6	0.2
Yes	Water	28.3	900	29	0.4
No	Water	113.1	150	1	0.5
No	Water	113.1	900	5	0.5
Yes	Water	113.1	150	44	0.7

Yes	Water	113.1	900	18	0.4
No	Water	201.1	150	43	0.7
No	Water	201.1	900	10	0.6
Yes	Water	201.1	150	4	0.6
Yes	Water	201.1	900	2	1
No	Detergent	28.3	150	19	0.8
No	Detergent	28.3	900	56	0.6
Yes	Detergent	28.3	150	31	1.1
Yes	Detergent	28.3	900	38	0.8
No	Detergent	113.1	150	34	1.6
No	Detergent	113.1	900	13	1.5
Yes	Detergent	113.1	150	21	2.1
Yes	Detergent	113.1	900	30	2.3
No	Detergent	201.1	150	32	3.3

No	Detergent	201.1	900	41	3.5
Yes	Detergent	201.1	150	8	3.9
Yes	Detergent	201.1	900	7	3.7
No	Oil	28.3	150	25	0.3
No	Oil	28.3	900	15	0.4
Yes	Oil	28.3	150	24	0.8
Yes	Oil	28.3	900	28	0.4
No	Oil	113.1	150	20	1.1
No	Oil	113.1	900	36	1
Yes	Oil	113.1	150	11	1.6
Yes	Oil	113.1	900	9	1.7
No	Oil	201.1	150	53	2
No	Oil	201.1	900	16	1.3
Yes	Oil	201.1	150	3	1.6

Yes	Oil	201.1	900	12	2.5
No	Water	28.3	150	54	0.1
No	Water	28.3	900	17	0.2
Yes	Water	28.3	150	6	0.2
Yes	Water	28.3	900	29	0.2
No	Water	113.1	150	1	0.6
No	Water	113.1	900	5	0.3
Yes	Water	113.1	150	44	0.6
Yes	Water	113.1	900	18	0.2
No	Water	201.1	150	43	0.7
No	Water	201.1	900	10	0.7
Yes	Water	201.1	150	4	0.6
Yes	Water	201.1	900	2	0.7

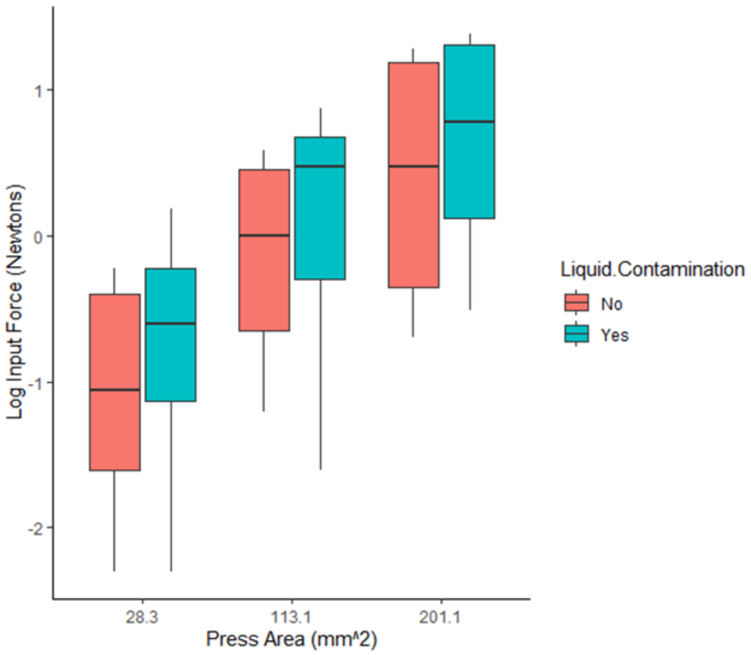


Figure 14: Predictor variables press area and contamination against log input force

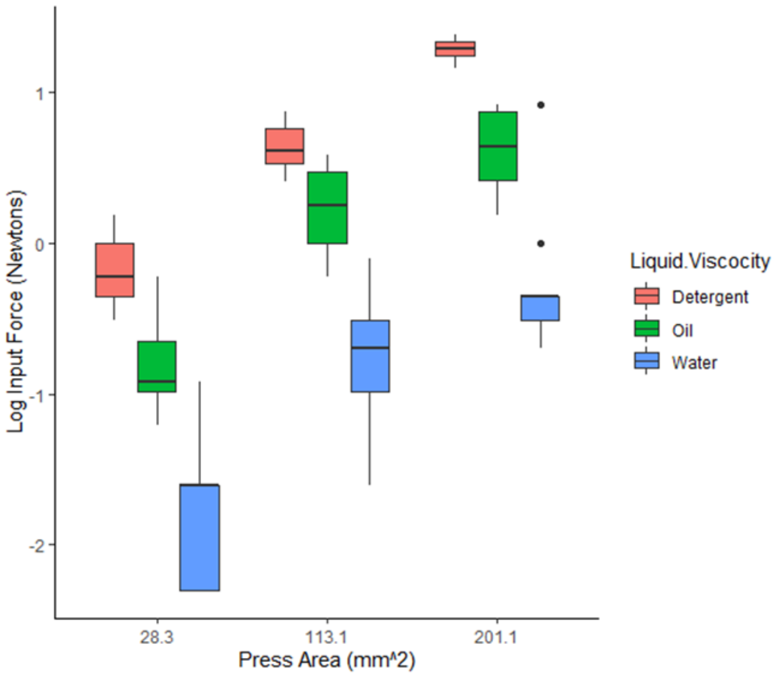


Figure 15: Predictor variables press area and viscosity against log input force

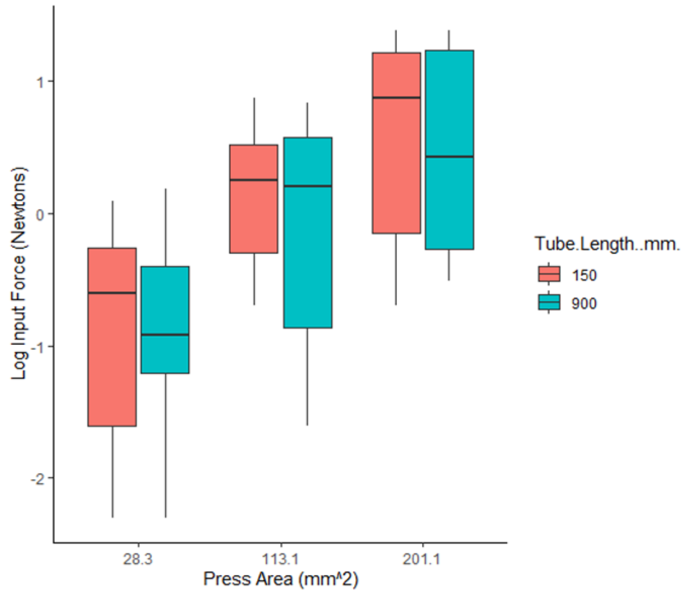


Figure 16: Predictor variables press area and tube length against log input force

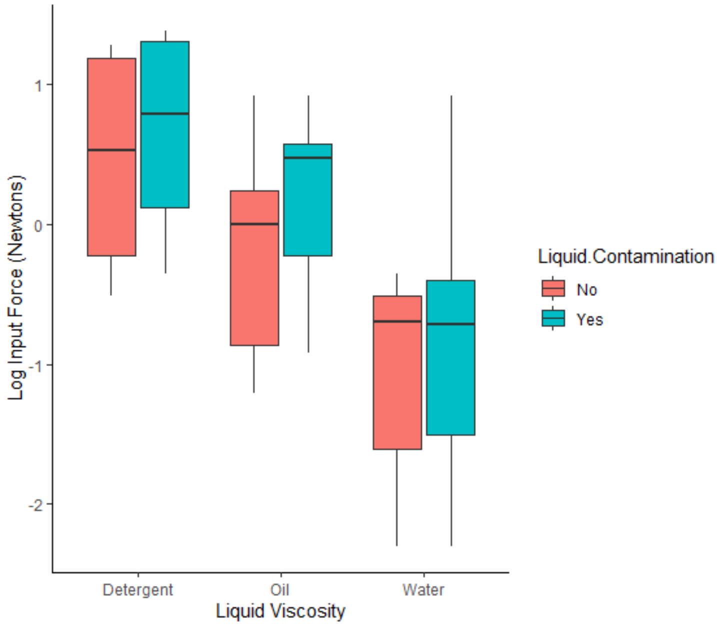


Figure 17: Predictor variables liquid viscosity and liquid contamination against log input force

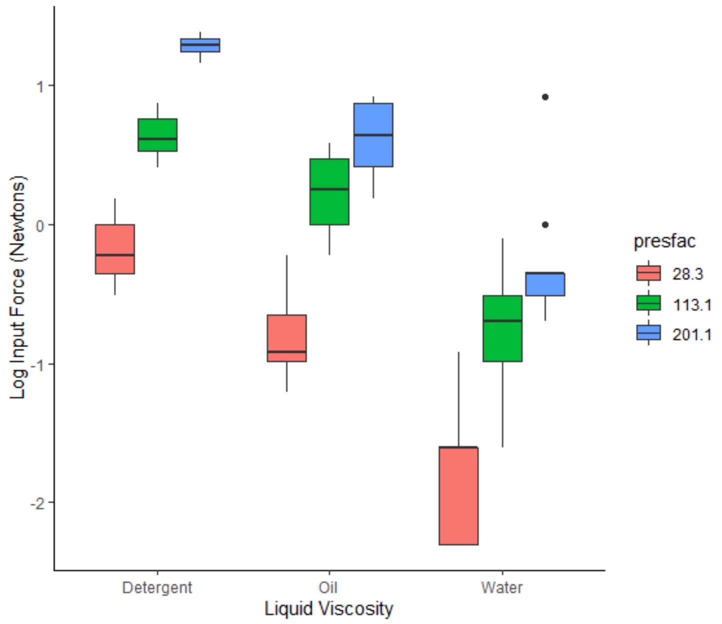


Figure 18: Predictor variables liquid viscosity and press area against log input force

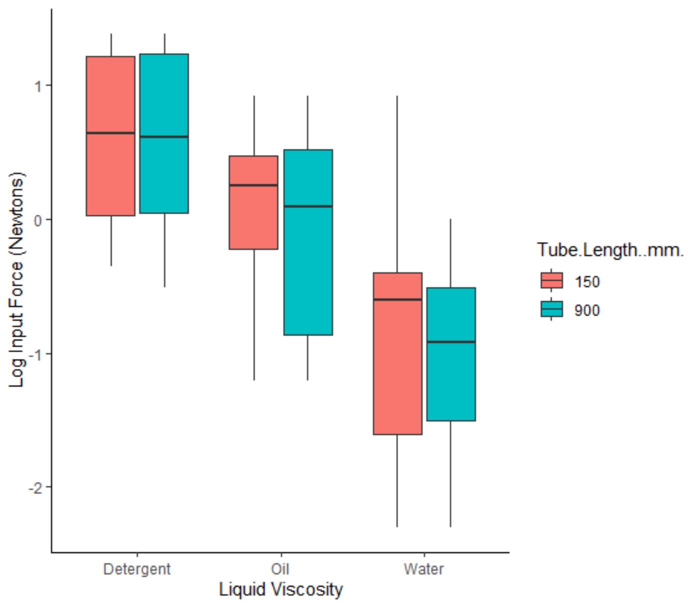
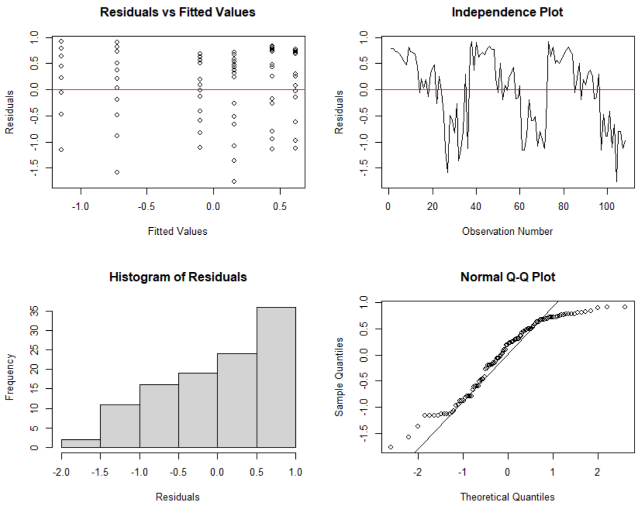
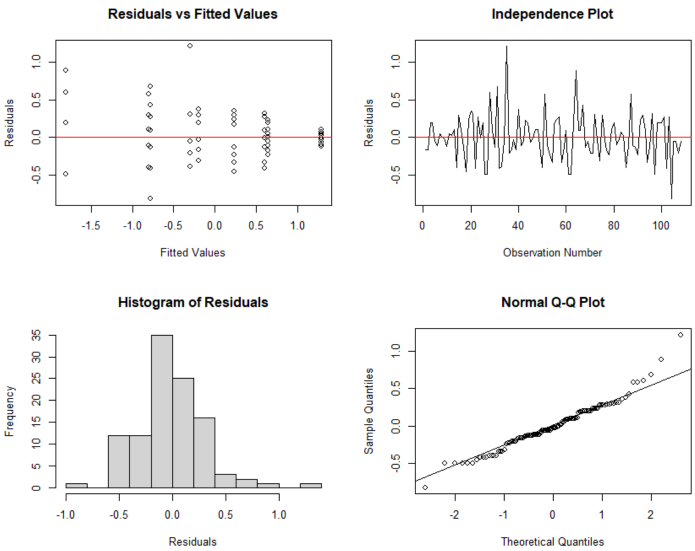


Figure 19: Predictor variables liquid viscosity and tube length against log input force



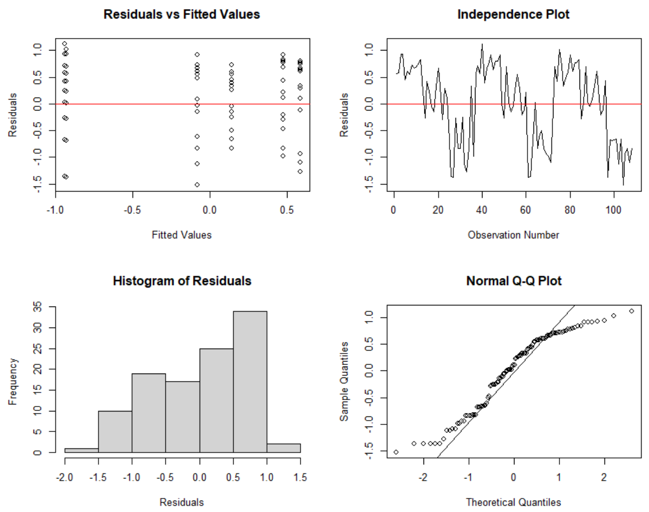

```
> Levene(LogInput, AOVFIT_LC$fitted.values)
      F value  Pr(>F)
group  1.7841 0.06172 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Figure 20 - Assumption Testing For Contamination using Liquid Used as a Blocking Variable



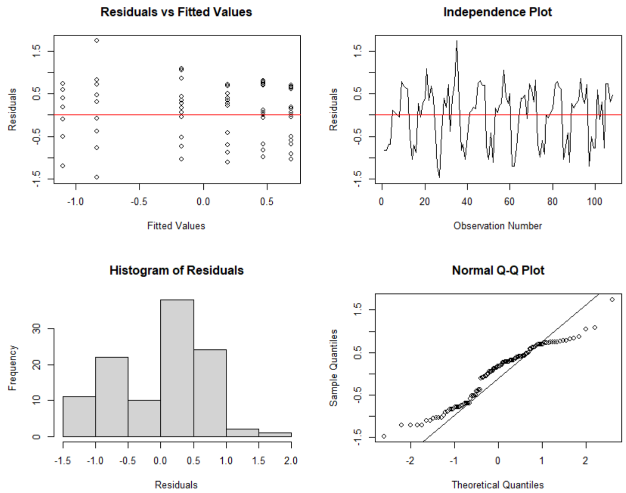

```
> Levene(LogInput, AOVFIT_LU$fitted.values
      F value Pr(>F)
group  1.5133 0.1216
```

Figure 21 - Assumption Testing For Liquid Used Using Press Area as a Blocking Variable




```
> Levene(LogInput, AOVFIT_TL$fitted.values)
      F value Pr(>F)
group  1.3765 0.1965
```

Figure 22 - Assumption Testing For Tube Length using Press Area as a Blocking Variable




```
> Levene(LogInput, AOVFIT_LC$fitted.values)
      F value Pr(>F)
group   0.799 0.6505
```

Figure 23 - Assumption Testing For Contamination using Liquid Used as a Blocking Variable

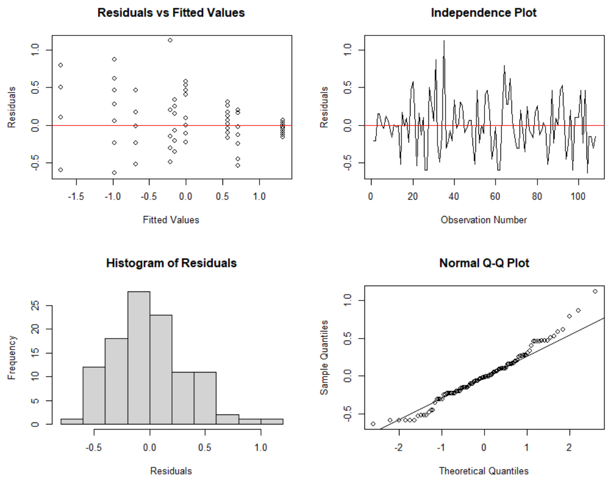
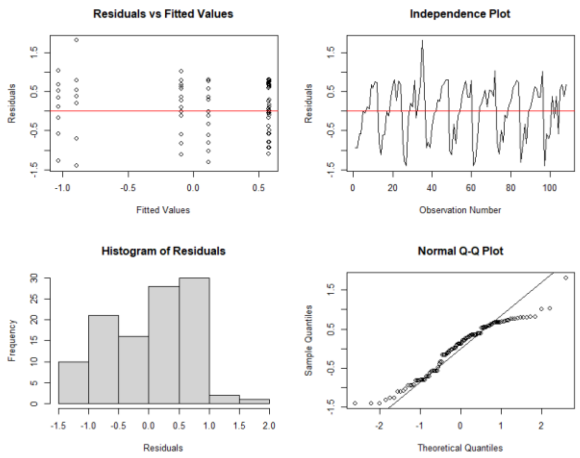


Figure 24 - Assumption Testing For Press Area Using Liquid Used as a Blocking Variable




```
> Levene(LogInput, AOVFIT_TL$fitted.values)
      F value Pr(>F)
group  1.0257 0.4321
```

Figure 25 - Assumption Testing For Tube Length using Liquid Used as a Blocking Variable

```
> # Identifying unusual observations
> which(Unusual_Observations$leverage>(2*(k+1)/n))
integer(0)
> which(abs(Unusual_Observations$standardised)>2)
[1] 31 35 64
> which(abs(Unusual_Observations$studentised)>2)
[1] 31 35 64
> which(Unusual_Observations$cooks>1)
integer(0)
```

Figure 26 - Outlier Tests for Press Area and Liquid Used as a Blocking Variable

```
> A_LCPA.aov <- aov(data = ExperimentE.df, LogInput ~ Liquid.Contamination*presfac)
> summary(A_LCPA.aov)
                              Df Sum Sq Mean Sq F value   Pr(>F)    
Liquid.Contamination           1   2.18   2.179   4.284    0.041 *  
presfac                        2  39.86  19.929  39.182 2.37e-13 ***
Liquid.Contamination:presfac   2   0.28   0.138   0.271    0.763    
Residuals                    102  51.88   0.509                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = LogInput ~ Liquid.Contamination * presfac, data = ExperimentE.df)

$Liquid.Contamination
            diff        lwr       upr     p adj
Yes-No 0.2840733 0.01184032 0.5563063 0.0410014

$presfac
                 diff        lwr       upr     p adj
113.1-28.3  0.9651008 0.56530178 1.3648998 0.0000003
201.1-28.3  1.4634404 1.06364140 1.8632395 0.0000000
201.1-113.1 0.4983396 0.09854059 0.8981386 0.0104559

$`Liquid.Contamination:presfac`
                         diff         lwr       upr     p adj
Yes:28.3-No:28.3    0.4198784 -0.27061397 1.1103707 0.4919812
No:113.1-No:28.3    1.0476603  0.35716795 1.7381526 0.0003661
Yes:113.1-No:28.3   1.3024197  0.61192738 1.9929120 0.0000046
No:201.1-No:28.3    1.5845885  0.89409620 2.2750808 0.0000000
Yes:201.1-No:28.3   1.7621707  1.07167836 2.4526630 0.0000000
No:113.1-Yes:28.3   0.6277819 -0.06271040 1.3182742 0.0968739
Yes:113.1-Yes:28.3  0.8825413  0.19204902 1.5730337 0.0044085
No:201.1-Yes:28.3   1.1647102  0.47421785 1.8552025 0.0000525
Yes:201.1-Yes:28.3  1.3422923  0.65180001 2.0327847 0.0000022
Yes:113.1-No:113.1  0.2547594 -0.43573290 0.9452517 0.8914940
No:201.1-No:113.1   0.5369282 -0.15356407 1.2274206 0.2208407
Yes:201.1-No:113.1  0.7145104  0.02401808 1.4050027 0.0380999
No:201.1-Yes:113.1  0.2821688 -0.40832350 0.9726611 0.8421202
Yes:201.1-Yes:113.1 0.4597510 -0.23074134 1.1502433 0.3877695
Yes:201.1-No:201.1  0.1775822 -0.51291017 0.8680745 0.9754142
```

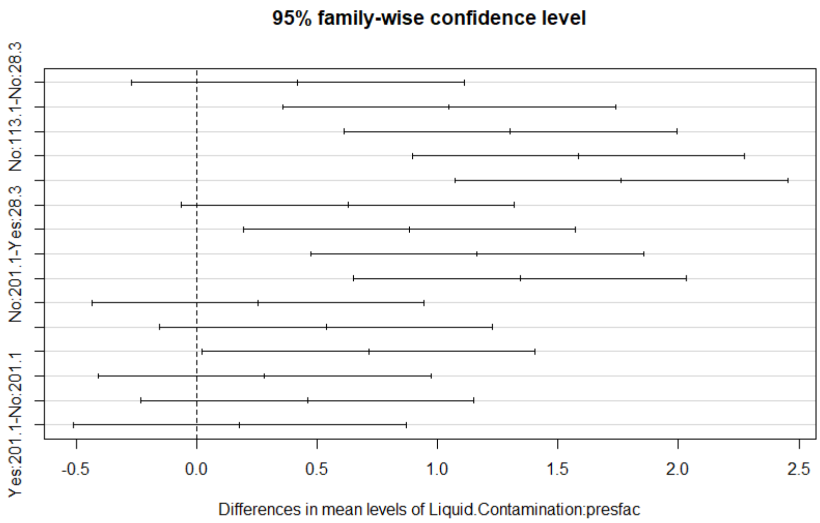


Figure 27: Results for ANOVA Test on Liquid Contamination, using Press Area as Blocking Factor, as well as Tukey Test Results and Tukey Plot.

```
> A_LUPA.aov <- aov(data = ExperimentE.df, LogInput ~ Liquid.Viscocity*presfac)
> summary(A_LUPA.aov)
                         Df Sum Sq Mean Sq F value Pr(>F)    
Liquid.Viscocity          2  43.85  21.923 212.546 <2e-16 ***
presfac                   2  39.86  19.929 193.206 <2e-16 ***
Liquid.Viscocity:presfac  4   0.27   0.069   0.665  0.618    
Residuals                99  10.21   0.103                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = LogInput ~ Liquid.Viscocity * presfac, data = ExperimentE.df)

$Liquid.Viscocity
                      diff        lwr        upr p adj
Oil-Detergent   -0.5687101 -0.7488344 -0.3885858     0
Water-Detergent -1.5430763 -1.7232006 -1.3629519     0
Water-Oil       -0.9743662 -1.1544905 -0.7942418     0

$presfac
                  diff       lwr       upr p adj
113.1-28.3   0.9651008 0.7849765 1.1452251     0
201.1-28.3   1.4634404 1.2833161 1.6435647     0
201.1-113.1  0.4983396 0.3182153 0.6784639     0

$`Liquid.Viscocity:presfac`
                                     diff         lwr         upr     p adj
Oil:28.3-Detergent:28.3        -0.60759701 -1.02342886 -0.19176516 0.0003632
Water:28.3-Detergent:28.3      -1.61258785 -2.02841970 -1.19675600 0.0000000
Detergent:113.1-Detergent:28.3  0.83832069  0.42248884  1.25415254 0.0000002
Oil:113.1-Detergent:28.3        0.42711096  0.01127911  0.84294281 0.0393426
Water:113.1-Detergent:28.3     -0.59031408 -1.00614593 -0.17448223 0.0006029
Detergent:201.1-Detergent:28.3  1.48182207  1.06599022  1.89765392 0.0000000
Oil:201.1-Detergent:28.3        0.79449847  0.37866662  1.21033032 0.0000009
Water:201.1-Detergent:28.3     -0.10618411 -0.52201596  0.30964774 0.9963402
Water:28.3-Oil:28.3            -1.00499084 -1.42082269 -0.58915899 0.0000000
Detergent:113.1-Oil:28.3        1.44591770  1.03008585  1.86174955 0.0000000
Oil:113.1-Oil:28.3              1.03470797  0.61887612  1.45053982 0.0000000
Water:113.1-Oil:28.3            0.01728293 -0.39854892  0.43311478 1.0000000
Detergent:201.1-Oil:28.3        2.08941908  1.67358723  2.50525093 0.0000000
Oil:201.1-Oil:28.3              1.40209548  0.98626363  1.81792733 0.0000000
Water:201.1-Oil:28.3            0.50141290  0.08558105  0.91724475 0.0068258
Detergent:113.1-Water:28.3      2.45090854  2.03507669  2.86674039 0.0000000
Oil:113.1-Water:28.3            2.03969881  1.62386696  2.45553066 0.0000000
Water:113.1-Water:28.3          1.02227378  0.60644193  1.43810563 0.0000000
Detergent:201.1-Water:28.3      3.09440992  2.67857807  3.51024177 0.0000000
Oil:201.1-Water:28.3            2.40708632  1.99125447  2.82291817 0.0000000
Water:201.1-Water:28.3          1.50640374  1.09057189  1.92223559 0.0000000
Oil:113.1-Detergent:113.1      -0.41120973 -0.82704158  0.00462212 0.0550408
Water:113.1-Detergent:113.1    -1.42863477 -1.84446662 -1.01280292 0.0000000
Detergent:201.1-Detergent:113.1 0.64350138  0.22766953  1.05933323 0.0001228
Oil:201.1-Detergent:113.1      -0.04382222 -0.45965407  0.37200963 0.9999951
Water:201.1-Detergent:113.1    -0.94450480 -1.36033665 -0.52867295 0.0000000
Water:113.1-Oil:113.1          -1.01742504 -1.43325689 -0.60159319 0.0000000
Detergent:201.1-Oil:113.1       1.05471111  0.63887926  1.47054296 0.0000000
Oil:201.1-Oil:113.1             0.36738751 -0.04844434  0.78321936 0.1279672
Water:201.1-Oil:113.1          -0.53329507 -0.94912692 -0.11746322 0.0029671
Detergent:201.1-Water:113.1     2.07213614  1.65630429  2.48796799 0.0000000
Oil:201.1-Water:113.1           1.38481255  0.96898070  1.80064440 0.0000000
Water:201.1-Water:113.1         0.48412996  0.06829811  0.89996181 0.0105177
Oil:201.1-Detergent:201.1      -0.68732360 -1.10315545 -0.27149175 0.0000310
Water:201.1-Detergent:201.1    -1.58800618 -2.00383803 -1.17217433 0.0000000
Water:201.1-Oil:201.1          -0.90068258 -1.31651443 -0.48485073 0.0000000
```

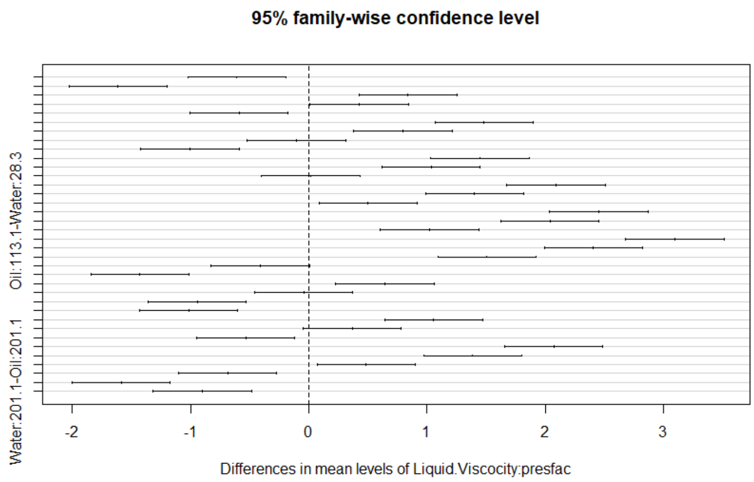


Figure 28: Results for ANOVA Test on Liquid Viscosity, using Press Area as Blocking Factor, as well as Tukey Test Results and Tukey Plot.

```
> A_TLPA.aov <- aov(data = ExperimentE.df, LogInput ~ ExperimentE.df$Tube.Length..mm.*presfac)
> summary(A_TLPA.aov)
                                      Df Sum Sq Mean Sq F value  Pr(>F)    
ExperimentE.df$Tube.Length..mm.         1   0.36   0.364    0.69   0.408    
presfac                                 2  39.86  19.929   37.80 5.2e-13 ***
ExperimentE.df$Tube.Length..mm.:presfac 2   0.20   0.100    0.19   0.827    
Residuals                             102  53.77   0.527                    
```

```
 Tukey multiple comparisons of means
   95% family-wise confidence level

Fit: aov(formula = LogInput ~ ExperimentE.df$Tube.Length..mm. * presfac, data = ExperimentE.df)

$`ExperimentE.df$Tube.Length..mm.`
              diff        lwr       upr     p adj
900-150 -0.1160532 -0.3932027 0.1610963 0.4081589

$presfac
                  diff        lwr      upr     p adj
113.1-28.3  0.9651008 0.55808143 1.372120 0.0000005
201.1-28.3  1.4634404 1.05642104 1.870460 0.0000000
201.1-113.1 0.4983396 0.09132023 0.905359 0.0121693

$`ExperimentE.df$Tube.Length..mm.:presfac`
                           diff         lwr       upr     p adj
900:28.3-150:28.3   -0.01229389 -0.71525648 0.6906687 1.0000000
150:113.1-150:28.3   1.07052967  0.36756708 1.7734923 0.0003441
900:113.1-150:28.3   0.84737806  0.14441547 1.5503407 0.0087717
150:201.1-150:28.3   1.51365048  0.81068788 2.2166131 0.0000001
900:201.1-150:28.3   1.40093649  0.69797390 2.1038991 0.0000012
150:113.1-900:28.3   1.08282356  0.37986097 1.7857862 0.0002832
900:113.1-900:28.3   0.85967195  0.15670936 1.5626345 0.0074574
150:201.1-900:28.3   1.52594436  0.82298177 2.2289070 0.0000001
900:201.1-900:28.3   1.41323038  0.71026779 2.1161930 0.0000009
900:113.1-150:113.1 -0.22315161 -0.92611421 0.4798110 0.9399919
150:201.1-150:113.1  0.44312080 -0.25984179 1.1460834 0.4507834
900:201.1-150:113.1  0.33040682 -0.37255578 1.0333694 0.7475100
150:201.1-900:113.1  0.66627241 -0.03669018 1.3692350 0.0737654
900:201.1-900:113.1  0.55355843 -0.14940417 1.2565210 0.2088318
900:201.1-150:201.1 -0.11271398 -0.81567658 0.5902486 0.9971930
```

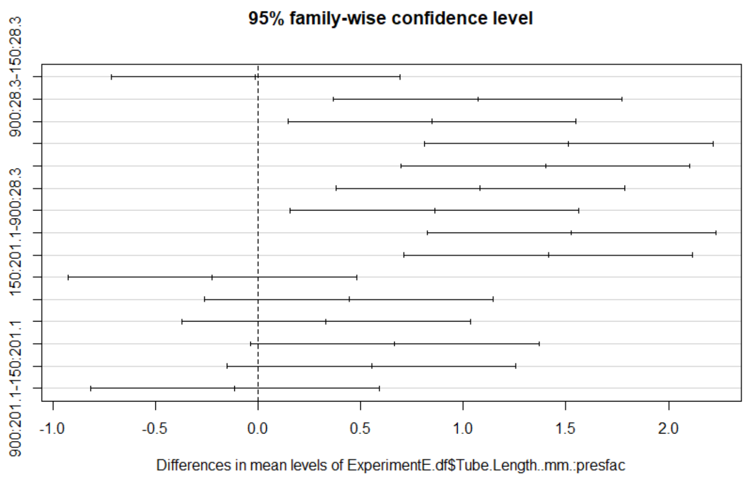


Figure 29: Results for ANOVA Test on Tube Length, using Press Area as Blocking Factor, as well as Tukey Test Results and Tukey Plot.

```
> A_LCLU.aov <- aov(data = ExperimentE.df, LogInput ~ Liquid.Contamination*Liquid.Viscocity)
> summary(A_LCLU.aov)
                                        Df Sum Sq Mean Sq F value   Pr(>F)    
Liquid.Contamination                     1   2.18   2.179   4.624   0.0339 *  
Liquid.Viscocity                         2  43.85  21.923  46.522 4.38e-15 ***
Liquid.Contamination:Liquid.Viscocity    2   0.10   0.048   0.103   0.9025    
Residuals                              102  48.07   0.471
```

```
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = LogInput ~ Liquid.Contamination * Liquid.Viscocity, data = ExperimentE.df)

$Liquid.Contamination
            diff        lwr       upr     p adj
Yes-No 0.2840733 0.02202984 0.5461168 0.0338988

$Liquid.Viscocity
                      diff        lwr        upr     p adj
Oil-Detergent   -0.5687101 -0.9535449 -0.1838753 0.0018882
Water-Detergent -1.5430763 -1.9279111 -1.1582415 0.0000000
Water-Oil       -0.9743662 -1.3592009 -0.5895314 0.0000001

$`Liquid.Contamination:Liquid.Viscocity`
                                diff        lwr          upr     p adj
Yes:Detergent-No:Detergent  0.2193778 -0.4452698  0.884025445 0.9297407
No:Oil-No:Detergent        -0.6408913 -1.3055389  0.023756298 0.0654206
Yes:Oil-No:Detergent       -0.2771511 -0.9417987  0.387496528 0.8304815
No:Water-No:Detergent      -1.5679383 -2.2325859 -0.903290671 0.0000000
Yes:Water-No:Detergent     -1.2988364 -1.9634840 -0.634188811 0.0000019
No:Oil-Yes:Detergent       -0.8602691 -1.5249168 -0.195621542 0.0037646
Yes:Oil-Yes:Detergent      -0.4965289 -1.1611765  0.168118688 0.2609465
No:Water-Yes:Detergent     -1.7873161 -2.4519637 -1.122668511 0.0000000
Yes:Water-Yes:Detergent    -1.5182143 -2.1828619 -0.853566650 0.0000000
Yes:Oil-No:Oil              0.3637402 -0.3009074  1.028387836 0.6072494
No:Water-No:Oil            -0.9270470 -1.5916946 -0.262399364 0.0013636
Yes:Water-No:Oil           -0.6579451 -1.3225927  0.006702497 0.0539985
No:Water-Yes:Oil           -1.2907872 -1.9554348 -0.626139594 0.0000022
Yes:Water-Yes:Oil          -1.0216853 -1.6863329 -0.357037733 0.0002935
Yes:Water-No:Water          0.2691019 -0.3955457  0.933749466 0.8472413
```

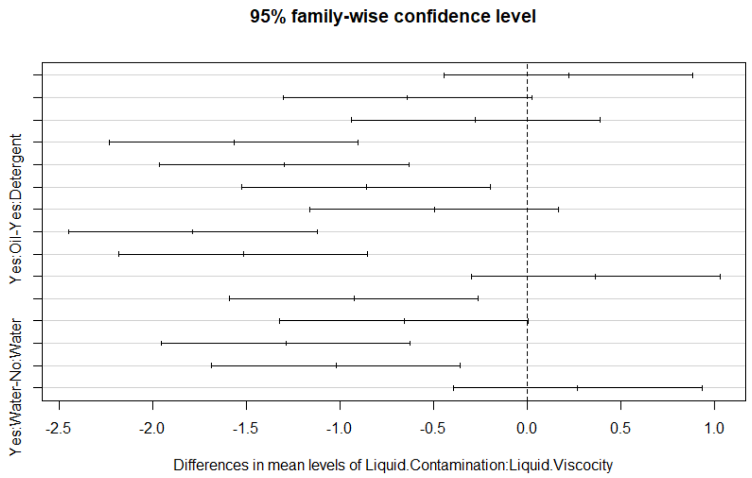


Figure 30: Results for ANOVA Test on Liquid Contamination, using Liquid Viscosity as Blocking Factor, as well as Tukey Test Results and Tukey Plot.

```
> SRPA.w <- lm(data = ExperimentE.df, LogInput ~ Press.Area..mm.2.*Liquid.Viscocity)
> summary(SRPA.w)

Call:
lm(formula = LogInput ~ Press.Area..mm.2. * Liquid.Viscocity,
    data = ExperimentE.df)

Residuals:
     Min       1Q   Median       3Q      Max
-0.63635 -0.20649 -0.01573  0.17216  1.12400

Coefficients:
                                      Estimate Std. Error t value Pr(>|t|)
(Intercept)                         -0.3988433  0.1083487  -3.681 0.000373 ***
Press.Area..mm.2.                    0.0085674  0.0008073  10.612  < 2e-16 ***
Liquid.ViscocityOil                 -0.5141150  0.1532282  -3.355 0.001115 **
Liquid.ViscocityWater               -1.5579152  0.1532282 -10.167  < 2e-16 ***
Press.Area..mm.2.:Liquid.ViscocityOil   -0.0004782  0.0011417  -0.419 0.676215
Press.Area..mm.2.:Liquid.ViscocityWater  0.0001300  0.0011417   0.114 0.909588
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.3417 on 102 degrees of freedom
Multiple R-squared:  0.8735,	Adjusted R-squared:  0.8673
F-statistic: 140.9 on 5 and 102 DF,  p-value: < 2.2e-16
```

Figure 31: Results for Linear Regression Test on Press Area, using Liquid Viscosity as a Blocking Variable.

```
> A_TLLU.aov <- aov(data = ExperimentE.df, LogInput ~ ExperimentE.df$Tube.Length..mm.*Liquid.Viscocity)
> summary(A_TLLU.aov)
                                                   Df Sum Sq Mean Sq F value   Pr(>F)    
ExperimentE.df$Tube.Length..mm.                     1   0.36   0.364   0.745    0.390    
Liquid.Viscocity                                    2  43.85  21.923  44.918 1.02e-14 ***
ExperimentE.df$Tube.Length..mm.:Liquid.Viscocity    2   0.20   0.098   0.200    0.819    
Residuals                                         102  49.78   0.488                     
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = LogInput ~ ExperimentE.df$Tube.Length..mm. * Liquid.Viscocity, data = ExperimentE.df)

$`ExperimentE.df$Tube.Length..mm.`
              diff        lwr       upr    p adj
900-150 -0.1160532 -0.3827339 0.1506276 0.390069

$Liquid.Viscocity
                      diff        lwr       upr     p adj
Oil-Detergent   -0.5687101 -0.9603552 -0.177065 0.0023083
Water-Detergent -1.5430763 -1.9347214 -1.151431 0.0000000
Water-Oil       -0.9743662 -1.3660113 -0.582721 0.0000001

$`ExperimentE.df$Tube.Length..mm.:Liquid.Viscocity`
                                diff        lwr          upr     p adj
900:Detergent-150:Detergent -0.002997377 -0.6794071  0.673412319 1.0000000
150:Oil-150:Detergent       -0.465994140 -1.1424038  0.210415556 0.3489693
900:Oil-150:Detergent       -0.674423461 -1.3508332  0.001986235 0.0511372
150:Water-150:Detergent     -1.476208562 -2.1526183 -0.799798866 0.0000001
900:Water-150:Detergent     -1.612941347 -2.2893510 -0.936531651 0.0000000
150:Oil-900:Detergent       -0.462996763 -1.1394065  0.213412933 0.3562608
900:Oil-900:Detergent       -0.671426084 -1.3478358  0.004983612 0.0528954
150:Water-900:Detergent     -1.473211185 -2.1496209 -0.796801489 0.0000001
900:Water-900:Detergent     -1.609943970 -2.2863537 -0.933534274 0.0000000
900:Oil-150:Oil             -0.208429321 -0.8848390  0.467980375 0.9468879
150:Water-150:Oil           -1.010214422 -1.6866241 -0.333804726 0.0004755
900:Water-150:Oil           -1.146947207 -1.8233569 -0.470537511 0.0000472
150:Water-900:Oil           -0.801785101 -1.4781948 -0.125375405 0.0105418
900:Water-900:Oil           -0.938517886 -1.6149276 -0.262108190 0.0014709
900:Water-150:Water         -0.136732785 -0.8131425  0.539676911 0.9916874
```

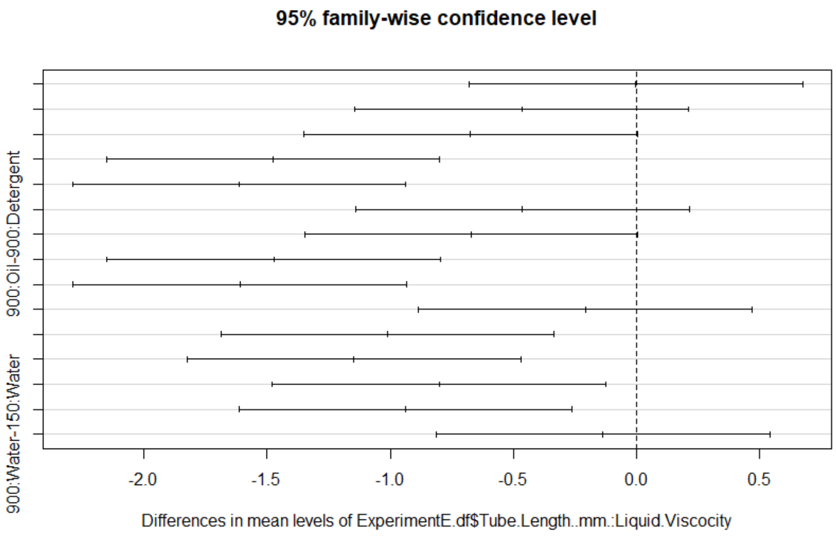


Figure 32: Results for ANOVA Test on Tube Length, using Liquid Viscosity as Blocking Factor, as well as Tukey Test Results and Tukey Plot.

```
> # Stepwise selection of model (starting with empty)
> step(lm(LogInput~1),
+      scope=list(lower=~1, upper=~ExperimentE.df$Liquid.Contamination + ExperimentE.df$Liquid.Viscocity
+                 + ExperimentE.df$Press.Area..mm.2. + ExperimentE.df$Tube.Length..mm.),
+      direction="both")
Start:  AIC=-12.78
LogInput ~ 1

                                     Df Sum of Sq    RSS     AIC
+ ExperimentE.df$Liquid.Viscocity     2    43.847 50.343 -76.434
+ ExperimentE.df$Press.Area..mm.2.    1    38.394 55.796 -67.327
+ ExperimentE.df$Liquid.Contamination 1     2.179 92.011 -13.304
<none>                                             94.190 -12.777
+ ExperimentE.df$Tube.Length..mm.     1     0.364 93.826 -11.194

Step:  AIC=-76.43
LogInput ~ ExperimentE.df$Liquid.Viscocity

                                     Df Sum of Sq    RSS      AIC
+ ExperimentE.df$Press.Area..mm.2.    1    38.394 11.949 -229.760
+ ExperimentE.df$Liquid.Contamination 1     2.179 48.164  -79.212
<none>                                             50.343  -76.434
+ ExperimentE.df$Tube.Length..mm.     1     0.364 49.979  -75.217
- ExperimentE.df$Liquid.Viscocity     2    43.847 94.190  -12.777

Step:  AIC=-229.76
LogInput ~ ExperimentE.df$Liquid.Viscocity + ExperimentE.df$Press.Area..mm.2.

                                     Df Sum of Sq    RSS      AIC
+ ExperimentE.df$Liquid.Contamination 1     2.179  9.770 -249.502
+ ExperimentE.df$Tube.Length..mm.     1     0.364 11.585 -231.098
<none>                                             11.949 -229.760
- ExperimentE.df$Press.Area..mm.2.    1    38.394 50.343  -76.434
- ExperimentE.df$Liquid.Viscocity     2    43.847 55.796  -67.327

Step:  AIC=-249.5
LogInput ~ ExperimentE.df$Liquid.Viscocity + ExperimentE.df$Press.Area..mm.2. +
    ExperimentE.df$Liquid.Contamination

                                     Df Sum of Sq    RSS      AIC
+ ExperimentE.df$Tube.Length..mm.     1     0.364  9.406 -251.599
<none>                                              9.770 -249.502
- ExperimentE.df$Liquid.Contamination 1     2.179 11.949 -229.760
- ExperimentE.df$Press.Area..mm.2.    1    38.394 48.164  -79.212
- ExperimentE.df$Liquid.Viscocity     2    43.847 53.617  -69.629

Step:  AIC=-251.6
LogInput ~ ExperimentE.df$Liquid.Viscocity + ExperimentE.df$Press.Area..mm.2. +
    ExperimentE.df$Liquid.Contamination + ExperimentE.df$Tube.Length..mm.

                                     Df Sum of Sq    RSS      AIC
<none>                                              9.406 -251.599
- ExperimentE.df$Tube.Length..mm.     1     0.364  9.770 -249.502
- ExperimentE.df$Liquid.Contamination 1     2.179 11.585 -231.098
- ExperimentE.df$Press.Area..mm.2.    1    38.394 47.800  -78.031
- ExperimentE.df$Liquid.Viscocity     2    43.847 53.253  -68.364

Call:
lm(formula = LogInput ~ ExperimentE.df$Liquid.Viscocity + ExperimentE.df$Press.Area..mm.2. +
    ExperimentE.df$Liquid.Contamination + ExperimentE.df$Tube.Length..mm.)

Coefficients:
                     (Intercept)     ExperimentE.df$Liquid.ViscocityOil     ExperimentE.df$Liquid.ViscocityWater
                       -0.469601                              -0.568710                                -1.543076
ExperimentE.df$Press.Area..mm.2.  ExperimentE.df$Liquid.ContaminationYes     ExperimentE.df$Tube.Length..mm.900
                        0.008451                               0.284073                                -0.116053
```

Figure 33 - Stepwise Regression of Final Model (Stepwise Selection Empty Model)

9.2 Appendix 3 (Planning Checklist):

Part 1

Please fill in all entries in the following tables and tick boxes to state agreement. It is important as part of your future careers that you take project planning seriously – especially sections relating to ethics (if applicable).

1. We have consulted the unit coordinator and teaching team to discuss this project. ☒

2. This project will not have any physical, emotional or psychological effects beyond those associated with everyday living. ☒

3. We commit to reporting any changes to our plan after any pilot study or at any subsequent stage. ☒

4. This project will not involve issues that are offensive or sensitive. ☒

5. If this project involves peoples' cooperation or assistance, this cooperation will be requested in person. ☒

6. If this project involves a survey or a non-intrusive experiment/study involving peoples' cooperation or assistance, the following statement will be provided to each participant: ☒

   "For a unit in statistics at QUT, we have been asked to choose a topic of interest to us and collect data to investigate it. We are interested in .... and would be grateful for your assistance. These data are for educational purposes only and no individual will be able to be identified in any writing or discussion about the data."

Part 2

It is important that each member of the group reviews this document before submission to verify that they have understood the plan before data collection and assessment commences.

Signed by each member of the group:

1. Aidan Hay (n10777105)

(Name) — (Signature)

2. Ryan Hafizh Indrananda (n10852565)

(Name) — (Signature)

3. Jesse Travaini (n10747028) — Jesse Travaini

(Name) — (Signature)

4. Nicole French (n10212949)

(Name) — (Signature)

If you have four group members, describe the planned additional work in consideration of the fourth member.

The planned additional work for this task will be to include a fourth predictor variable to the design. This fourth variable will be to test how the contamination of the liquid affects the force of the hydraulic pump. This will require a significant amount of extra preparation for the data collection to achieve a complete experimental design.

Aidan Hay

From: no-reply@qut.edu.au
Sent: Friday, 3 June 2022 9:08 PM
To: Aidan Hay
Subject: We've processed your Assignment extension request FORM-AEX-117099

Hi Aidan,

Thank you for your assignment extension request **(FORM-AEX-117099)**.

We have approved your request and the due date for your assignment **Group Project - Final Report**, for unit MXB242 has been extended by 48 hours from the original due date. If your unit outline does not specify that your assignment is eligible for an extension, this confirmation email is not valid and unless you submit by the original due date, the late assessment policy will apply.

You are responsible for ensuring that this assignment is eligible for extension before submitting it after the original due date. Check your unit outline for eligibility.

As you indicated this is a group assignment, you are also responsible for informing other members of your group of this extension.

Be aware that a copy of this email is kept on file. You should not alter this email in any way. Email notifications that have been altered or differ in any way from the original may result in an allegation of student misconduct as set out in the Student Code of Conduct.

Need extra support? You can access free, confidential counselling with qualified professionals. We also offer planning and support if you have a disability, injury or health condition that affects your ability to study. If you are struggling to meet your university commitments, academic support is also available.

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Ref ID: 10777105 FORM-AEX-117099