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UNIVERSITY OF GALWAY

School of Engineering

Design, Construction and Testing of a Battery-Operated Electric Truck

Final Report

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1 Introduction

The aim of the Truck Race 3000 project was to design a truck capable of transporting a payload across a 3-meter distance in the quickest time achievable using only a Meccano set. The ultimate objective was to determine the most efficient design by conducting extensive testing of various designs with different payloads, ultimately selecting the most efficient design.

The formula used to calculate the score of the Truck Race is:

$$Score = \frac{M_{Payload}}{t}$$

Where $M_{Payload}$ is the Payload Mass and t is the time it takes for the Truck to travel 3 metres.

1.1 Restrictions

The Truck Race 3000 included the following restrictions:

- The payload must be easily removable and must not be a part of the truck
- The payload must not touch the ground
- The payload can be selected by the group
- The motor must be powered by 4 AAA batteries
- The motor power switch must be easily accessible
- No other materials, parts or tools are allowed to be used during the construction of the Meccano kit apart from the following; "rubber band(s), Blu Tack, insulating tape, string, thread, cable ties
- The motor provided must be used

1.2 Testing Process

The test would be conducted in the following manner:

- The test takes place in G037 in the Alice Perry Engineering Building.
- The time is measured as the time taken for the truck to travel between two parallel lines of tape on the floor, marking out 3 metres.
- The team can run multiple tests over the course of the three minutes allocated to them. In between each test, if the payload mass is changed, it must be re-measured.

1.3 Goals/Aims

The goals of the Truck Race 300 were the following:

- Using engineering design principles, construct an electric truck from the Meccano kit which is as efficient as possible.
    - Efficiency is measured as a score calculated as the ratio of weight carried to time taken to travel the three metres
    - The higher the efficiency score, the better the truck

1.4 Design Philosophy

The design approach decided upon was based on three fundamental tenets:

1.4.1 *Practical Testing and Data Collection*

The majority of the data used in this project was obtained through practical tests, following a scientific methodology. These tests gathered important data and provided crucial insights into how best to optimise the truck design.

1.4.2 *Computational Modelling and Optimisation*

Much of the data gathered under the principle of Section 1.4.1 was later used to create a physically accurate computational model, which was used to inform further design choices. This was critical, as it allowed greater efficiency of time and allowed efforts to be targeted towards solutions suggested by the computational model.

At the same time, the team acknowledged that computation was no replacement for physical experimentation, and physical testing constantly remained the team's primary method of data collection.

1.4.3 *Flexible Design*

At the beginning of the design process, the team understood that one of the main obstacles for progress is being stuck in one's ways. With this in mind, the team constantly suggested new ideas and design configurations, being unafraid of the additional work it would take to create and test new designs. This commitment to flexible, ever-changing design allowed the team to create an exceptional electric vehicle, even under time constraints.

2 Design Approach

In the pursuit of an optimal motorized truck design, two distinct concepts were developed. Concept 1 [see Fig.?] features a configuration with four wheels, placing the powerplant at the front of the vehicle, while carrying the entire payload on the rear. This design incorporates a 1:1 gear ratio.

In Concept 2 [see Fig.?], a similar four-wheel truck was designed, but with a centrally positioned motor. Half of the payload is distributed to the front and the other half to the rear. This concept utilizes a 2:1 gear ratio.

Key design variables that were considered include:

- The number of wheels
- The location of the powerplant on the truck
- The chosen gear ratio
- The selection of components
- The payload mass
- The choice between forward wheel drive and rear wheel drive

These variables collectively form the foundation of our design strategy.

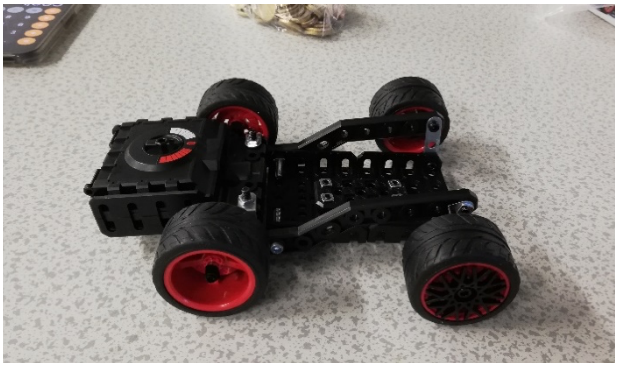

Figure 2: Design Concept 1

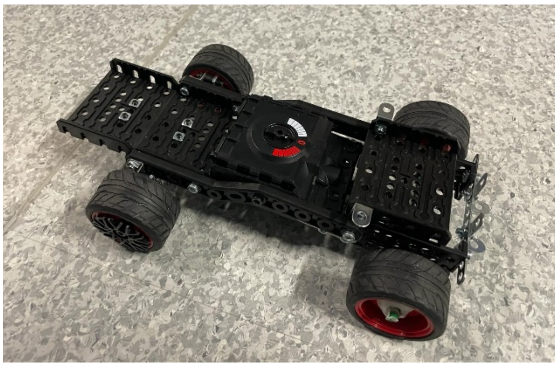

Figure 1: Design Concept 2

2.1 Number of wheels

Deliberation took place between constructing either a 3-wheel or a 4-wheel truck. The 3-wheel configuration involves two driver wheels positioned on a common axle, directly linked to the motor, accompanied by a single driven wheel located at the front of the vehicle. Alternatively, the 4-wheel option entails placing two wheels at each end of the truck, with one pair serving as the driver and the other as the driven components.

The selection of wheels is imperative to the design of the truck as it dictates the trucks balance, weight and traction force. Leading to the overall performance of the truck.

As the normal force is greater with a three-wheel drive, lessening the rolling resistance coefficient, the three-wheel truck would be faster. However, a four-wheel drive offers more stability, allowing for a larger payload. [1,2,3]

2.2 Powerplant position

Powerplant position dictates where the motor will sit on the truck. The position can vary from the rear, middle or front of the vehicle. As the driver wheels were attached to the powerplant, the truck may either push or pull the payload.

In a front engine-front wheel drive, the power is transmitted through the gears & shafts to the front axle. Pulling the truck & payload avoids skidding tendency and creates better road adhesion. However, front-wheel-drive can have a disadvantage in acceleration if the payload is near or on the front axle. [4,5]

With a rear engine rear-wheel-drive, the rear tires are better able to take simultaneous acceleration due to load transfer. Secondly, the division of weight between the front and rear wheels has a significant impact on the truck performance, and it is much easier to get a 50/50 weight distribution in a rear-wheel-drive vehicle than in a front wheel drive vehicle, as more of the engine can lie between the front and rear wheels. [6]

2.3 Gear ratio

Gear ratios feature in almost every mechanical motor and mechanism. A gear ratio is established when 2 or more gears are connected and interlocking in a rotational system. In this case, it can impact the output speed and the output torque of the truck's motor. The first concept design for this truck did not feature any advanced gear ratio as it was a direct drive approach, i.e. the gear ratio was 1:1 and therefore had no impact on the performance of the truck. The second concept did feature a gear ratio consisting of 2 meshing bevel gears at a 90-degree angle, one connected to the motor and the other connected to the axle.

The gear ratio can be expressed simply as

$$\frac{Speed\ of\ driven\ shaft}{Speed\ of\ driver\ shaft}$$

However, in this project the exact speeds of the driven and driver shafts were not known from the beginning, so the gear ratio was calculated using the following method that utilises the number of teeth in each gear to find it.

The gear ratio is the ratio of the number of rotations the output gear makes when the input gear completes one full rotation. The smaller the gear, the more rotations it will make in comparison to its connecting gear. For 2 gears to be meshing correctly, they must have the same pitch and therefore it is only the size of the gears that play a role in determining the ratio between them. Given the same pitch, the size can be expressed as the number of teeth per gear, *N*. In the following formula, N_2 represents the number of teeth on the driven gear, and N_1 represents the number of teeth on the driver gear:

$$Gear\ Ratio = \frac{N2}{N1} = N2\!:\!N1$$

A larger gear ratio would lead to increased torque from the motor to the axle, but a reduction in speed. It follows that a smaller gear ratio would lead to increased speed output but not as much torque. The torque on each gear is directly proportional to the number of teeth, and the speed of each gear is inversely proportional to the number of teeth, as the following formula demonstrates:

$$\frac{T2}{T1} = \frac{N2}{N1} = \frac{\omega 1}{\omega 2}$$

Where T is the torque on the gears, N is the number of teeth and ω is the speed of the gears.

The materials for this project included two suitable gears, one with 26 teeth and one with 52 teeth. This allowed for possible gear ratios of 1:2, maximising speed, or 2:1, maximising torque. Determining the correct gear ratio for this truck was an important design factor that had to be considered when aiming to maximise its efficiency.

2.4 Selection of components

The components of the truck which can vary include the body & frame, tires, the truck bed floor, the hood, and the tailgate.

Certain factors such as material weight, size and quality must be considered in the selection. Included in the Meccano set were both metal and plastic components. Plastic components are often lighter in weight, however, do not provide the same strength as metal components. These decisions are crucial to the truck design as they can greatly impact the weight of the vehicle. [8]

2.5 Payload mass

The payload mass that the truck carries is a crucial part of determining the value s, the performance of the truck. As outlined in Section 1, a larger payload would lead to a higher performance score but would also negatively impact the time taken for the truck to travel the required distance. Finding the correct balance between payload carried and time taken was an important design consideration for this project.

A larger and heavier payload would increase the weight (W) of the truck. Weight is defined as

$$W = mg$$

where m is the mass of the payload and g is acceleration due to gravity, with a value of 9.81 m/s.

This force has a number of consequences on the performance of the vehicle. Increasing the weight would lead to an increased power-to-weight ratio, changes in weight distribution across the truck and affect the trucks centre of gravity. For this project, the centre of gravity is not hugely important but the impact of varying the payload mass on the power-to-weight ratio is, as is its impact on the weight distribution.

The power-to-weight ratio is the amount of power a vehicle has in relation to its weight. A vehicle with higher power-to-weight ratio is likely to accelerate faster than a vehicle with a lower ratio. In this design, acceleration plays an important role in determining the speed and time of the truck [9]. A high power-to-weight ratio could be achieved by finding the most efficient payload mass to apply to the truck through testing and analysis later on.

By loading the payload mass too far forward or too far back on the truck, the weight distribution will be altered and impact the performance of the truck. Heavy loads above the motor could affect its output, and unbalanced loads at either end of the truck could lead to it tipping forwards or backwards. It could also flex the plastic components of the truck if too much force was applied to one specific area. Both of these scenarios can be seen below in Figure 3:

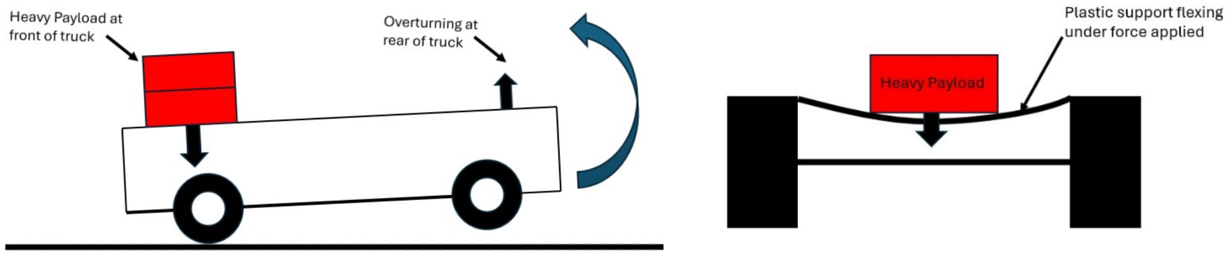

Figure 3: Tipping and Buckling Illustrations

3 Method

3.1 Powerplant Testing

3.1.1 Isolated Testing

3.1.1.1 1:1 Gear Ratio

Two different approaches were taken to test the powerplant. The objective of the tests was to determine the relationship between torque and speed in the motor. For the first attempt, a 1:1 gear ratio was examined

The height of the table was measured, and a piece of string was cut 15cm longer than the table height. One end of the string was wrapped around the output shaft of the motor. It was then secured to the shaft using electric tape. The other end of the string was tied around the top of a water bottle. The empty water bottle was weighed.

The powerplant was positioned lying horizontally, with the output shaft hanging over the edge of the table. The bottle was hung from the output shaft, centimetres from the floor. The motor was turned on to max power. As the output shaft span, the bottle rose upwards. The length of time it took to reach the top of the table was recorded.

Initially, this was attempted using a wheel and tyre to provide a greater circumference for the pulley system [see Fig.?], however the string kept slipping, so the design was amended to feature a bare axel [see Fig.?].

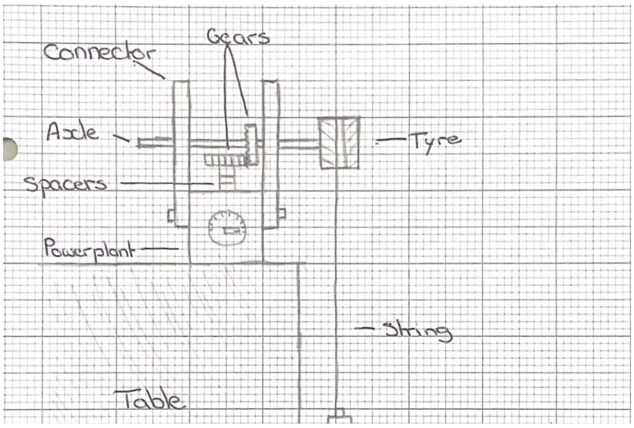

Figure 5: Tyre Pulley System

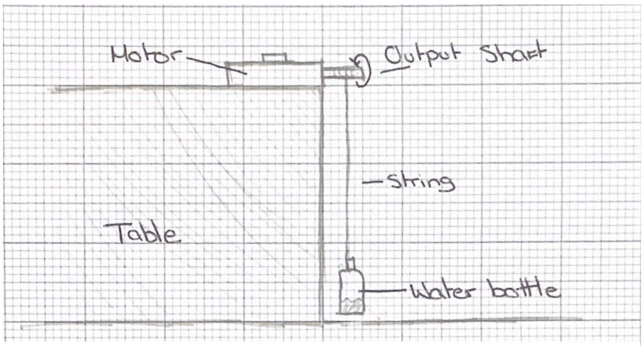

Figure 4: Bare Axel Pulley System

The bottle was filled with a small amount of water and weighed. The same process was repeated. The bottle was continuously filled with water and weighed until it became too heavy for the powerplant to pull up.

The various times were taken and a graph depicting time vs weight was drawn.

3.1.1.2 2:1 Gear Ratio

For the second attempt, A 2:1 gear ratio was explored.

The powerplant stood vertically, with the output shaft facing upward. 3 spacers were placed on the shaft and a 26 toothed gear was placed on the top of the shaft. Two long plastic connectors were fastened to either side of the powerplant. The wheel axle was inserted through both connectors and a 52 toothed gear lies on the axle in between both connectors. Both gears meshed which changed the direction of shaft rotation, acting similarly to bevel gears. [10]

A wheel was then fitted onto the axle, on the outer side of a connector. This acted as the pulley for the weight. The string was wrapped around the wheel and secured using electrical tape. Similar to the first test, the bottle was tied to the other end of the string and was hung off the edge of the table.

The same process was repeated: Water was added to the bottle, the new weight was measured, the motor was turned on, the bottle was lifted from the floor to the top of the table, the time to do so was recorded.

One issue encountered with this testing was that the output shaft and driver axle had different centre lines. This made it difficult for the gears to mesh correctly and caused slipping. This also led to a loss of power and efficiency of the motor. Once this issue had been identified, the centre lines were adjusted and the same tests were ran again.

3.1.2 Vehicular Testing

While the powerplant testing was a great baseline to work off, the team wanted to address the issues of the gears not meshing and also consider the physical differences of interacting with forces using a vehicle as opposed to an isolated system.

This testing was conducted in tandem with the testing detailed in Section 3.2, allowing increased efficiency in how the testing was conducted and allowing us to discover more data in the limited time available to us.

The values of displacement (s, which was a constant of 3m), time (t), wheel radius (r, which was a constant of 0.05m)and mass (m) were gathered. The coefficient of friction between the truck and the floor (μ) was assumed to be 0.5 [11]. From this angular velocity (ω) and Torque (T) were calculated:

$$\omega_{rpm} = \frac{s}{rt} \times \frac{30}{\pi}$$

$$T = mg\mu$$

The results of the initial weight vs time are shown in Fig.6.

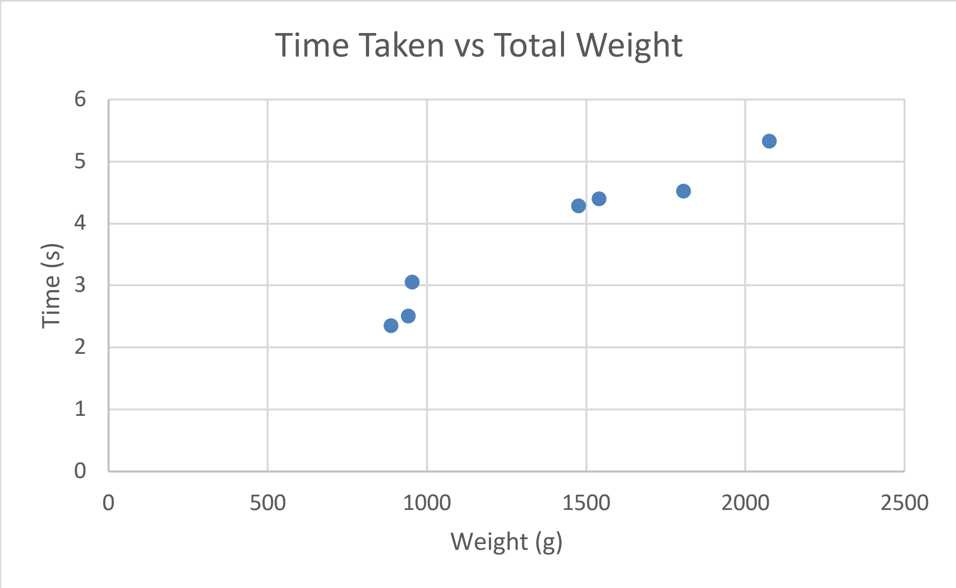

Figure 6: Graph of Time Taken vs Total Weight

The results of angular velocity vs torque are shown in Fig.7.

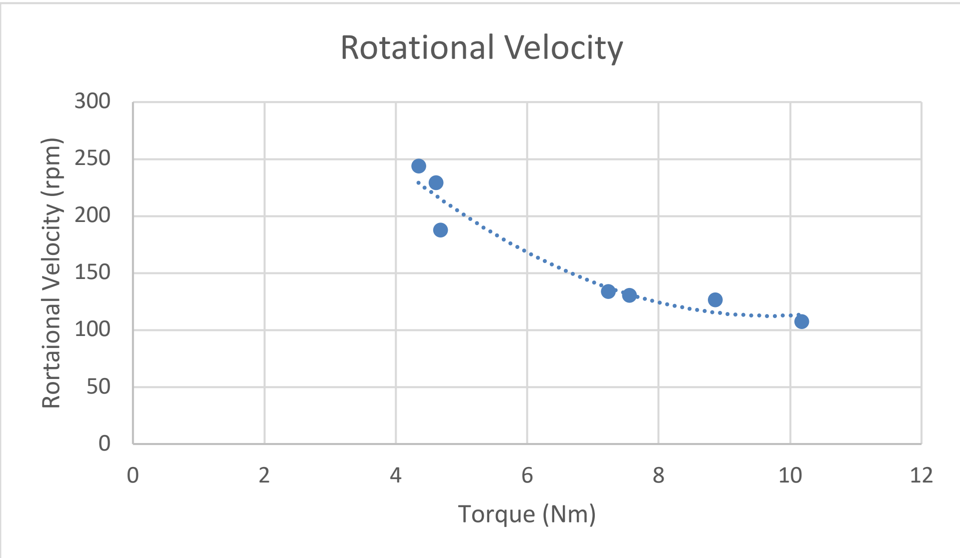

Figure 7: Rotational Velocity vs Torque

These results showed there were some issues with certain assumptions made in the mathematical model shown in Section 3.3. However, it was decided that it would be easier to manipulate the model to provide similar outputs, rather than restructuring the model to provide a better physical representation. This was for a number of reasons:

- These tests were conducted only two days before the testing date, and the creation of the computational model was very time consuming previously
- Initial attempts to restructure the model ran into issues due to the assumptions made in Section 3.2, as in the computational model velocity is crucially not constant and any attempt to make it so would result in something that could easily be calculated using a formula provided by an excel graph, which fails to properly grasp certain nuances.

3.2 Score Testing

Following testing of the powerplant, the truck was physically tested carrying various payloads to determine the ideal conditions to achieve maximum performance. This was done simultaneously with the computational modelling to compare the data.

Both the initial concept with no gear ratio and the second concept with a gear ratio of 1:2 were tested in identical conditions. The second concept was also further modified slightly to improve performance, and this was also tested under the same conditions.

The method for testing the truck was as follows:

- Firstly, the required distance for the truck to travel, 3 m, was marked out using a measuring tape, establishing a start and finish line.
- Numerous payloads were created using bags of coins and a steel bar, measured on a weighing scale. Coins were added to the bag to create a weight of 250g, which was loaded onto the truck. The truck was placed at the start line, with the front of the truck on the line.
- The truck's motor was switched on to allow it to travel forward and simultaneously a stopwatch was started to measure the time.
- Once the truck reached the finish line the timer was stopped and the motor switched off.
- Values for the payload mass in grams and the time in seconds for the truck to complete the distance of 3m were recorded.
- More coins were added to the bag in increments of 250g to create new weights. A steel bar was also sometimes used in addition to coins for the heavier weights.
- The test was repeated for different payload masses ranging from 250g to 2250g and individual times recorded for each. This data was recorded and compared to the data from the computational model.
- Values for *s*, the performance of the truck, were calculated using Excel and appropriate graphs were created and analysed.

A diagram demonstrating the truck testing method can be seen below, along with images from the testing:

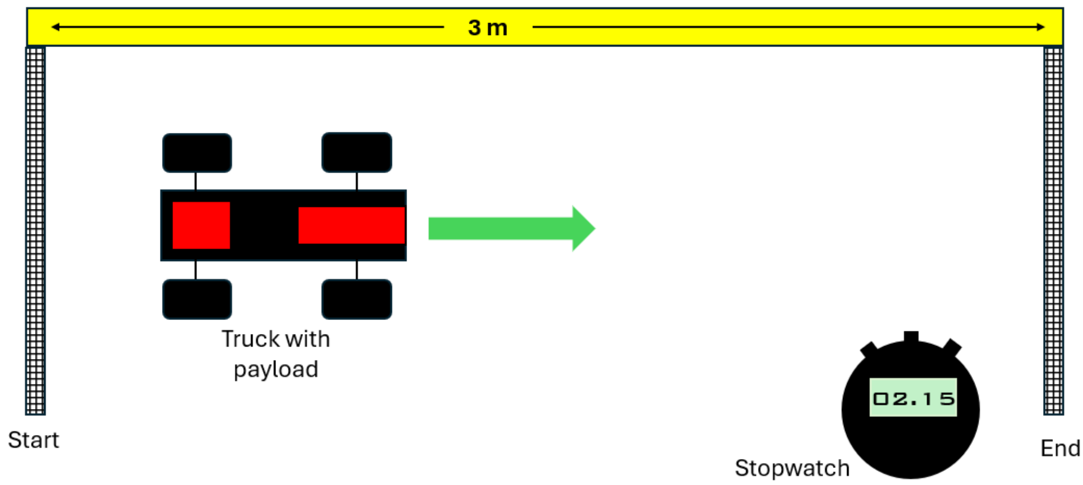

Figure 8: Score Testing Setup

Following the initial testing of the first concept, the second concept featuring a gear ratio of 1:2 was tested using the same method. After analysis of the results of the second test, it was decided that this design could be further improved, whilst keeping the overall structure and gear ratio of the truck intact.

Some adjustments made to the design included an emphasis on weight distribution and the location of the payload mass on the truck. Furthermore, the gears and axles were lubricated gently with WD-40 to decrease any friction forces between the gears and to prevent any apparent rolling resistance between the axle and its bearing. Blue-tack was also added to the wheels at their connection to the axle to prevent any slippage.

3.3 Mathematical model

3.3.1 Overview

In order to enable rapid consideration of different combinations of variables, it was decided to create a computational model capable of real-time calculation and modification.

The considerations for the model were as follows:

- It would run in C or C++
  - This was due to the team learning the C programming language while designing the truck and wanting to put it to use
  - As well as this, C and C++ are compiled programming languages, which enables extremely rapid computation, a useful asset for this project
- It would use all the information gathered from testing to produce a highly accurate model
  - This required using an approach that was iteratively refined to use new insights gleaned from experimentation
  - This also required adding some constants to certain areas of calculations to stand in for untested or inconsistent physical forces
- It would be easily usable
  - This was more for the sake of the team, but it was decided to implement a User Interface rather than running the program in a terminal, to allow easier interaction and interpretation of results

3.3.2 Code

The code that was created was as follows (certain elements omitted for conciseness and simplicity):

```
#include "TruckSimulatorFrame.h"
#include <wx/string.h>
#include <wx/textctrl.h>
#include <wx/stattext.h>
#include <cmath>

int autosim = 0;

TruckSimulatorFrame::TruckSimulatorFrame(const wxString& title)
```

```
    : wxFrame(NULL, wxID_ANY, title, wxDefaultPosition, wxSize(400, 600)) {
    //Code to set-up and display UI omitted for brevity
}

double CalculateMotorTorque(double rpm) {
    double Torque = 1.242-0.0096796*rpm; //This is the linear relationship suggested by
our testing, ignoring the outlier
    if (Torque<0) {
        return -1; //Returns an error if torque is negative
    }
    return Torque;
}

double travelSim(double a, double vMax) {
    //Simulates the truck's movement based off inputs from the main function
    double step = 0.001; // Simulation time step
    double u = 0;        // Initial speed
    double s = 0;        // Distance traveled
    double time = 0;     // Elapsed time

    while (s < 3) {      // Continue until 3 meters are traveled
        if (u < vMax) {
            u += a * step;
            s+=u*step;
            time+=step;
             }
        else {
            s += u * step;
            time += step;
        }
    }
    return time; // Return the total time
}

void TruckSimulatorFrame::OnSimulate(wxCommandEvent& event) {
    autosim=1; //Sets up a variable to allow real time recalculation

//Code gathering UI elements omitted for brevity

    double truckWeight = 0.0;
    double loadWeight = 0.0;
```

```
    double gearRatio = 0.0;
    double wheelDiameter = 0.0;
    double inputTractionCoefficient = 0.55; //[1]

    //This gets the input values from the UI
    truckWeightEdit->GetValue().ToDouble(&truckWeight);
    loadWeightEdit->GetValue().ToDouble(&loadWeight);
    gearRatioEdit->GetValue().ToDouble(&gearRatio);
    wheelDiameterEdit->GetValue().ToDouble(&wheelDiameter);

    double motorRPM = 60/gearRatio;

    double motorTorque = CalculateMotorTorque(motorRPM);
    if (motorTorque == -1) {
          resultLabel->SetLabel(wxString::Format(wxT("Motor Overloaded")));
        return;
    }
    double totalWeight = truckWeight+loadWeight;
    double wheelRadius = wheelDiameter / 2.0; //It's easier to measure the diameter
    double forceAtWheel = motorTorque / wheelRadius;
    double breakingForce = (inputTractionCoefficient * totalWeight * 9.81)*wheelRadius;
    if (breakingForce>1.2*gearRatio /*Initial tests did suggest a much higher maximum force, but in attempting to get the model to line up with results in Section 4.2, the decision was made to set the maximum force to 1.2*gearRatio */) {
        resultLabel->SetLabel(wxString::Format(wxT("Motor Overloaded")));
        return;
    }

    double acceleration = forceAtWheel / (totalWeight+0.3); //The +0.3 is to account for misc forces e.g. friction
    double maxVelocity = ((motorRPM/60)*wheelDiameter*3.1416*1.7)/(totalWeight/2.1+0.8);
    //Testing made it clear that weight had an impact on the maximum velocity, and this equation seems to line up well with reality
    double timeToTravel3m = travelSim(acceleration, maxVelocity)/1.5; //This post-calculation adjustment was needed to line up with the Section 4.2 results
    double score = (loadWeight*1000)/timeToTravel3m;

    //Displays results for ease of iteration
    resultLabel->SetLabel(wxString::Format(wxT("Time to travel 3m: %.2f seconds"), timeToTravel3m));
    ScoreLabel->SetLabel(wxString::Format(wxT("Score: %.2f"), score));
    TorqueLabel->SetLabel(wxString::Format(wxT("Torque: %.2f"), motorTorque));
```

```
    AppliedForceLabel->SetLabel(wxString::Format(wxT("Force  at  the  ground:  %.2f"), forceAtWheel));
    accelerationLabel->SetLabel(wxString::Format(wxT("Acceleration:          %.2f"), acceleration));
}

void TruckSimulatorFrame::OnVariableChanged(wxCommandEvent& event) {
if (autosim==1) {
//Function containing the same logic, activated for real time simulation editing once the simulation has begun
}
}

//Further UI logic omitted for brevity
```

3.3.3 *Explanation*

As this code is quite long and unwieldy, a distilled version of its logic is discussed in this section.

3.3.3.1 Variables

To discuss this code's functionality, we need the following variables:

Variable	Symbol	Default Value
Truck Mass	M_T	Inputted
Load Mass	M_L	Inputted
Total Mass	M_{Total}	Calculated
Gear Ratio	G_r	Inputted
Wheel Radius	r	Inputted
Motor RPM	ω_0	60 rpm
Effective RPM	ω_E	Calculated
Force at wheel	$F_{at\ wheel}$	Calculated
Max Motor Force	$F_{breaking}$	Calculated
Torque	T	Calculated
Maximum Velocity	v_{Max}	Calculated
Coefficient of Traction	μ	0.55

Table 1: Variables for Code

3.3.3.2 Equations and Functions

These variables were implemented to the following functions, which have been formatted as equations or sudo-code for ease of interpretation:

3.3.3.2.1 Motor RPM

$$\omega_{\mathrm{E}} = \omega_0 / G_r$$

3.3.3.2.2 Motor Torque

$$T \ = 1.242 - 0.0096796 \times$$

3.3.3.2.3 Total Mass

$$M_{Total} = M_T + M_L$$

3.3.3.2.4 Forces

$$F_{at\ wheel} = T/r$$

$$F_{breaking} = \mu \times \mathrm{M_{Total}} \times 9.81 \times r$$

3.3.3.2.5 Acceleration and Velocity

$$a = \frac{F_{at\ wheel}}{M_{Total}}$$

$$v_{Max} = \frac{\frac{\omega_E}{60} \times 2 \times r \times \pi \times 1.7}{\frac{M_{Total}}{2.1} + 0.8}$$

3.3.3.2.6 Time to Travel

```
travelSim(acceleration, vMax) {
    //Simulates the truck's movement based off inputs from the main function
    step = 0.001;
    speed = 0;
    displacement = 0;        // Distance traveled
    time = 0;     // Elapsed time

    while (displacement < 3) {      // Continue until 3 meters are traveled
        if (speed < vMax) {
            speed += acceleration * step;
            displacement+=speed*step;
            time+=step;
             }
        else {
            displacement += speed * step;
            time += step;
        }
    }
    return time; // Return the total time
}
```

3.3.3.2.7 Score

$$score = \frac{M_L \times 1000}{time}$$

3.4 Truck testing

Following testing of the powerplant, the truck was tested carrying various payloads to determine the ideal conditions to achieve maximum performance. This was done simultaneously with the computational modelling to compare the data.

4 Results

4.1 Powerplant performance

4.1.1 Isolated Testing

The Distance vs Time results found from the powerplant test were used to calculate the speed and torque. The speed was found using the formula: *Speed=Distance/Time*. The Force was then found using the formula: *Force=Mass*Acceleration* taking mass = mass of the truck, and acceleration=acceleration due to gravity. The calculated force was then used to find the torque, as *Torque=Force*Radius*, with the radius of the wheel for radius. A Torque vs. Speed graph was then drawn. [12]

Torque	Speed
0	
0.1	1.9
0.2	1.8
0.3	1.7
0.4	1
0.5	1.2
0.6	1.15
0.7	1.1

Table 2: a table of the results from the testing of the motor. The table details the relationship between torque vs speed.

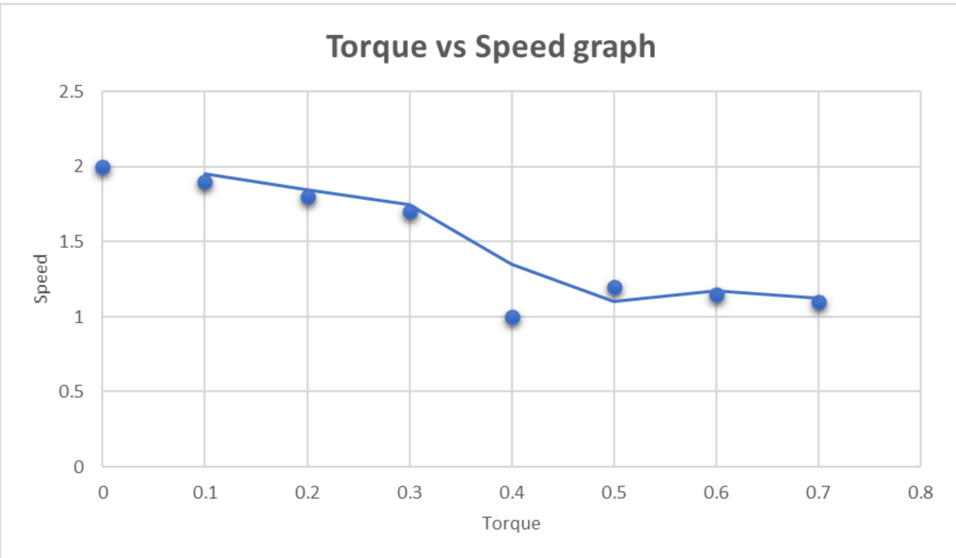

Figure 9: a graph illustrating the relationship between torque vs. speed of the truck. An outlier result can be seen at (0.4,1).

4.1.2 Vehicular Testing

In the vehicle based torque testing, the following results were first gathered:

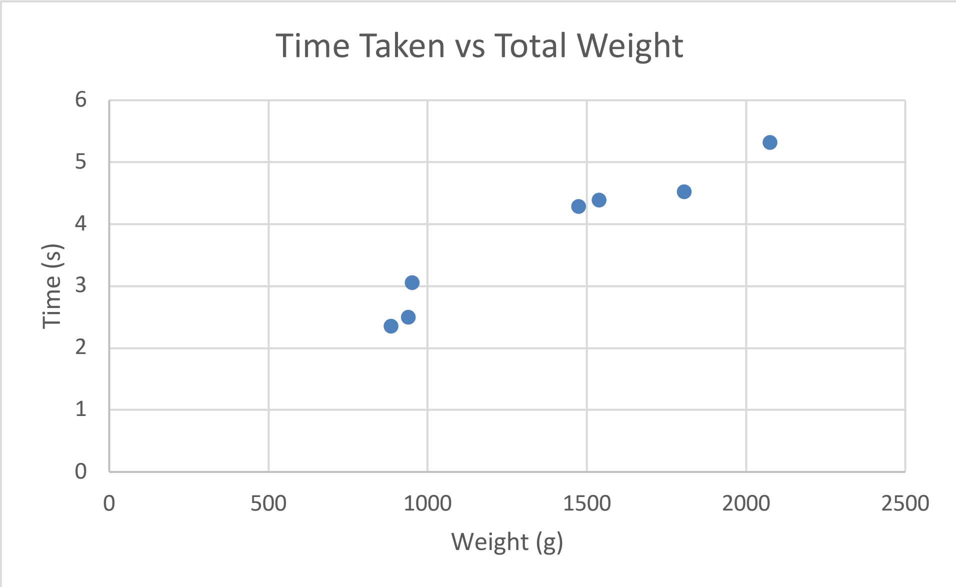

Figure 10: Graph of Time Taken vs Total Weight

This was important, as it showed how as weight was added, time increased, in a near-linear relationship important for comparing the computational model, as well as planning how much weight we would carry.

Then, using the formulae specified in Section 3.2, these results were converted to the more relevant results of angular velocity and torque:

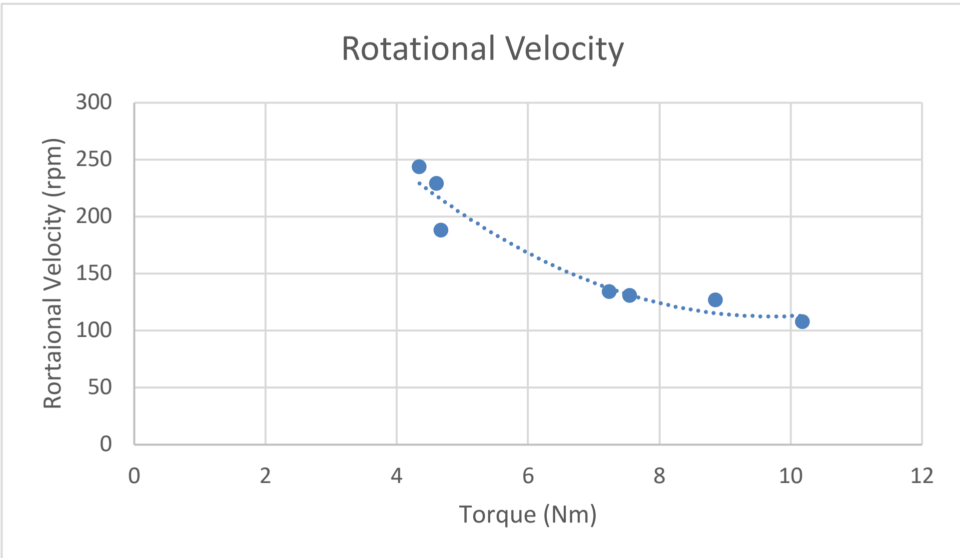

Figure 11: Graph of Rotational Velocity vs Torque

These results showed there were some issues with certain assumptions made in the mathematical model shown in Section 3.3. However, it was decided that it would be easier to manipulate the model to provide similar outputs, rather than restructuring the model to provide a better physical representation. This was for a number of reasons:

- These tests were conducted only two days before the testing date, and the creation of the computational model was very time consuming previously
- Initial attempts to restructure the model ran into issues due to the assumptions made in Section 3.2, as in the computational model velocity is crucially not constant and any attempt to make it so would result in something that could easily be calculated using a formula provided by an excel graph, which fails to properly grasp certain nuances.

4.2 Effect of Payload Mass and Time

As expected, the payload mass applied to the truck was proportional to the time taken for the truck to cross the finish line. As the mass increased, so too did the time, as the graph below shows.

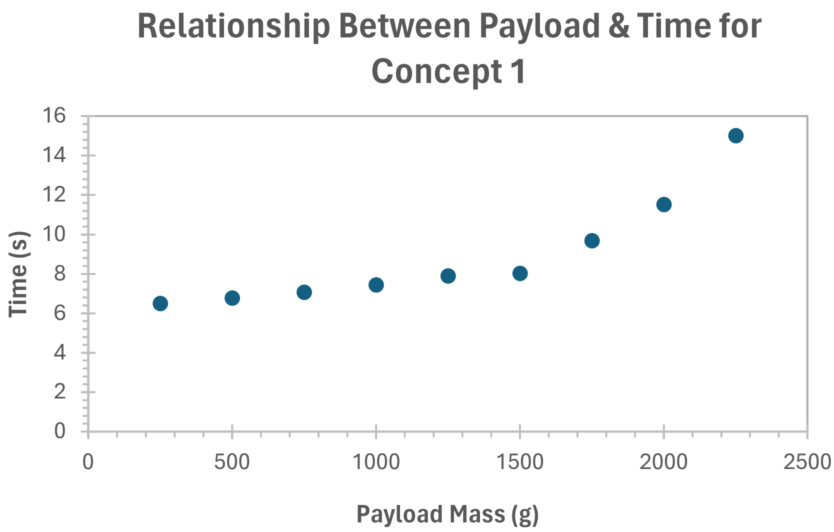

Figure 12: Time vs Payload Mass (Concept 1)

For each test of the truck, there was a payload mass and time that lead to the highest performance score for the truck. However, this did not always occur from using the heaviest weights, as the computational model may suggest. During the testing of the first concept, it was found that a payload of 1500g would result in the best score. This is despite the same truck carrying a heavier weight of 2250g, but the time taken did not lead to a better score.

Following the testing of the second concept, this time utilising a gear ratio of 1:2, the maximum score was achieved with a payload of 1,750 grams. This load was carried across the finish line in 4.09 seconds which led to a score of 224.07 g/s. The graph for this particular test can be seen below.

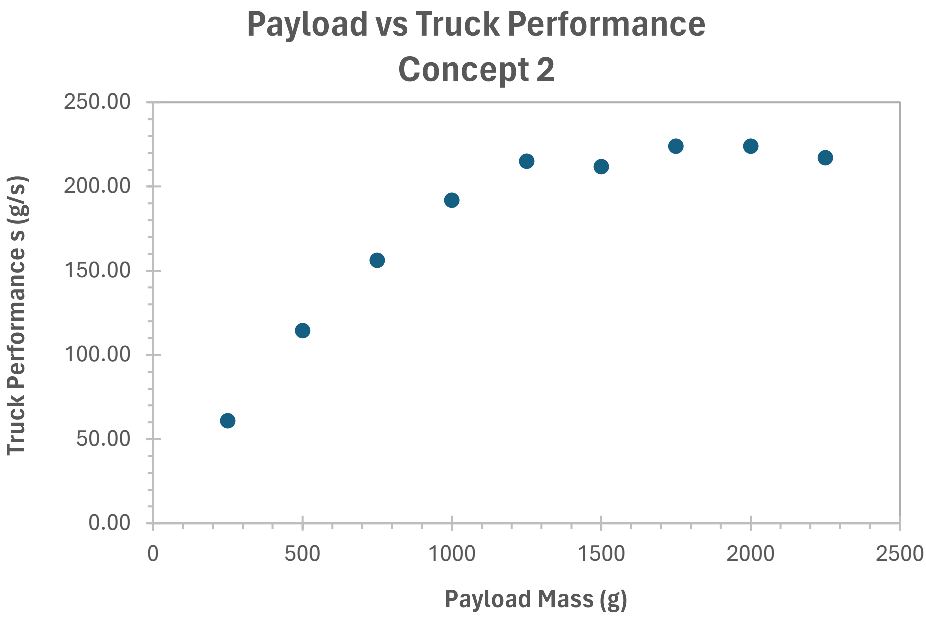

Figure 13: Score vs Payload Mass (Concept 2)

The final test also demonstrated the relationship between payload mass and time, however this final design proved to be much more efficient, leading to the highest performance score found, 447.43 g/s.

4.3 Effect of Gear Ratio

Upgrading the first concept truck, which had a direct drive system and a gear ratio of 1:1, to the second concept which included a 1:2 gear ratio proved to be a much more successful decision. The second concept truck was much more efficient and quicker carrying its payload over the same 3m distance. Inputting the data found into Excel showed that the average speed to carry the same loads over the same 3m distance was significantly increased with the 1:2 gear ratio, increasing from 0.34 m/s for the first concept with no gear ratio up to 0.46 m/s for the second concept. Following further design modifications on the second concept, a higher speed average of 0.76 m/s was achieved, still utilising the 1:2 gear ratio [see Fig.14]

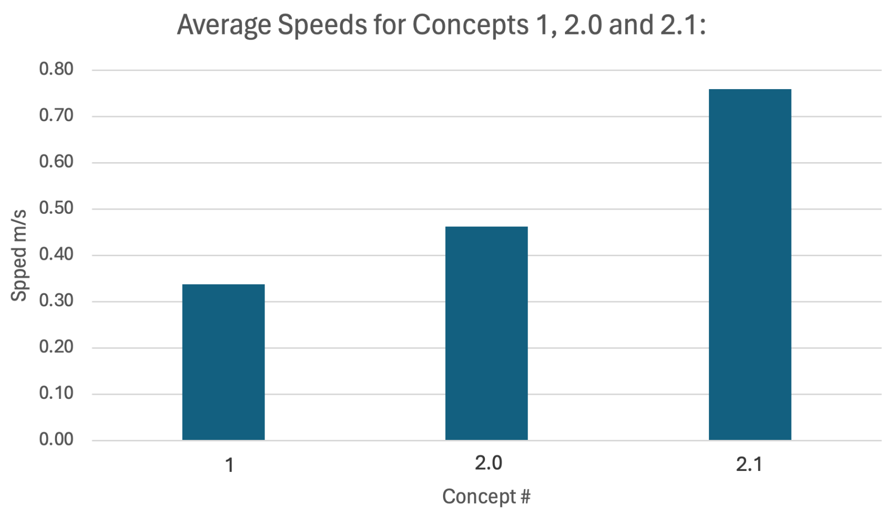

Figure 14: Average Speeds for Concepts 1, 2.0, and 2.1

This increase in speed was to be expected, as there is a direct link between gear ratio and speed. A smaller gear ratio sacrifices torque in order to increase the speed of the driven gear, proven by the following formula:

$$\frac{\omega 1}{\omega 2} = \frac{T2}{T1} = \frac{N2}{N1}$$

Where ω is the speed of the gears, *T* is the torque on the gears, and *N* is the number of teeth on the gears (the gear ratio). Therefore, having a smaller gear ratio will inversely affect the speed but proportionally affect the torque.

The clear advantages of having a gear ratio in the truck design can be seen below in the graph comparing the maximum performance scores achieved by each truck concept. A maximum performance score of 4 g/s was achieved following adjustments to the second concept, referred to as concept 2.1 in the graphs, tables and results. This score was a huge improvement on the initial maximum score recorded with the first concept without gear ratios.

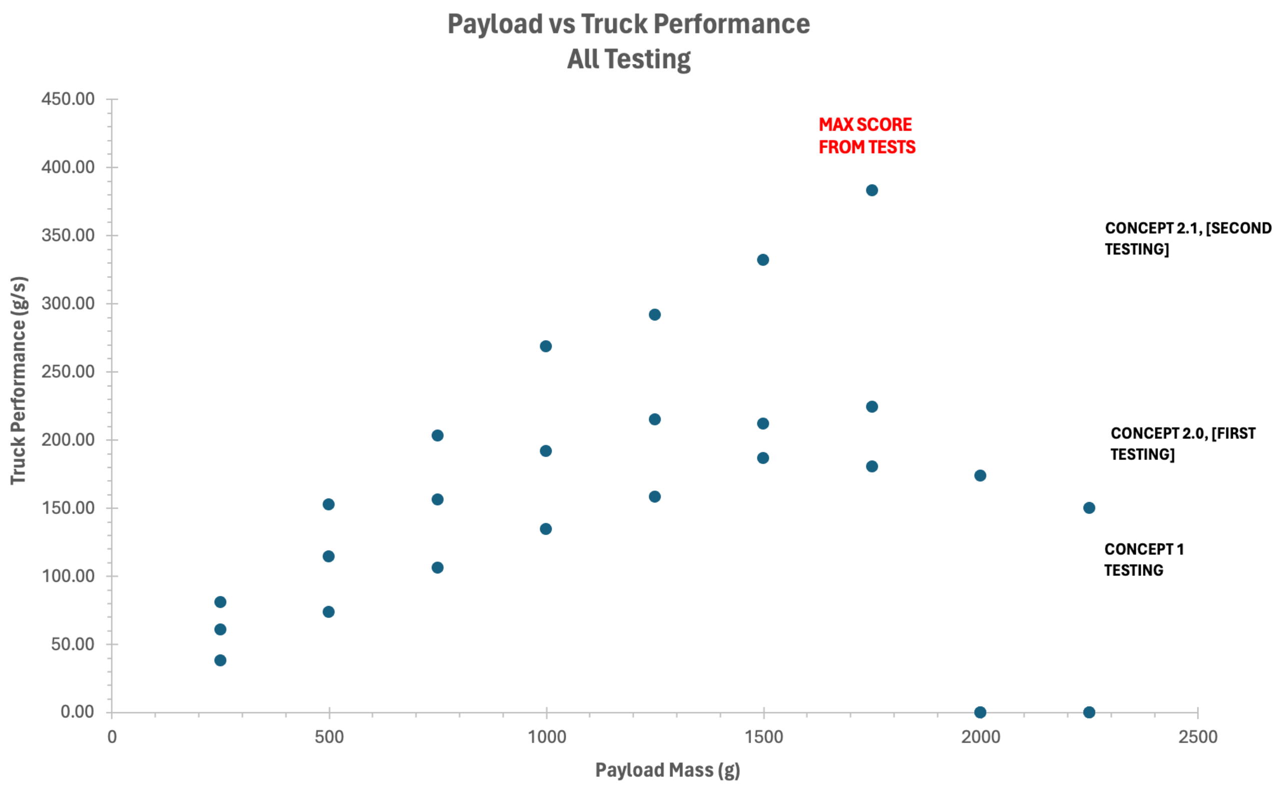

Figure 15: Graph of Payload vs Truck Performance Across All Independent Testing

The table of all results for the 3 separate truck tests can be found below, from which the data for the graphs were taken.

CONCEPT 1 [NO GEAR RATIO]

Payload(g)	Time (s)	s (g/s)
250	6.5	38.46
500	6.78	73.75
750	7.06	106.23
1000	7.44	134.41
1250	7.9	158.23
1500	8.03	186.80
1750	9.69	180.60
2000	11.52	173.61
2250	15.01	149.90
2500	FAIL	N/A
	Max	186.6

CONCEPT 2.0 [1:2 GEAR RATIO]
FIRST TESTING

Payload(g)	Time (s)	s (g/s)
250	4.1	60.98
500	4.37	114.42
750	4.8	156.25
1000	5.21	191.94
1250	5.81	215.15
1500	7.08	211.86
1750	7.81	224.07
2000	FAIL	N/A
2250	FAIL	N/A
2500	FAIL	N/A
	Max	224.07

CONCEPT 2.1 [1:2 GEAR RATIO]
SECOND TESTING

Payload(g)	Time (s)	s (g/s)
250	3.09	80.91
500	3.27	152.91
750	3.69	203.25
1000	3.72	268.82
1250	4.28	292.06
1500	4.52	331.86
1750	4.57	382.93
2000	FAIL	N/A
2250	FAIL	N/A
2500	FAIL	N/A
	Max	382.93

CONCEPT 2.0 [1:2 GEAR RATIO]
FINAL OFFICIAL TESTING

Payload(g)	Time (s)	s (g/s)
1710	3.8	290.58
1110	5	340.64
2010	4.3	472.94
Max/final score		472.94
Distance (m)		
3 constant		

Table 3: Payload, time, score for all testing

4.4 Effect of Batteries

During the physical testing of the truck, it was noted that after changing old batteries out for a new fresh set that performance results started to decrease, despite no other design variables changing. Following some quick checks to ensure that the motor was still functioning correctly, which it was, the conclusion was made that the new batteries sourced must be the issue. Upon further investigation it was found that the new batteries, Panasonic 1.5 V AAA batteries, were approximately 4 grams lighter than their Kodak predecessors, despite being the exact same voltage and size. The Kodak batteries were branded as 'Max Alkaline', and this claim must have been true as they performed remarkably well in comparison to the Panasonic and also Duracell batteries tested.

The same identical test for the truck was completed with Duracell and Kodak batteries, with the Duracell batteries moving a payload mass of 1000g in 9.7 seconds over 3m. The same payload mass was moved over 3m by the Kodak batteries in 6.05 seconds, a significantly decreased time which greatly helped the performance score. This was a surprising yet important discovery found during the testing of the truck.

Figure 16: The tested batteries

4.5 Effect of Location of Payload Mass

The positioning of the payload mass on the truck had a direct impact on its performance in the testing phase of the design. As predicted, too much weight on the front or rear of the truck would cause it to flip upright and overturn. It was also observed that placing any significant weight directly on the rear axle (the driven axle) would result in the truck not moving at its maximum speed, and even halting the trucks movement occasionally. In contrast, a large amount of the payload mass could be comfortably distributed above the front axle, the driver axle, without any impact on the truck's performance. It was found that the potential issue of the plastic components flexing under heavy forces of compression was not an issue in this particular design, which was a welcome discovery.

Figure 17: Demonstration of Payload Distribution

Following the testing it was also confirmed that the truck performed best as a forward-wheel-drive design, as opposed to a rear-wheel-drive design. This is partly due to the location of the payload mass on the tuck, with the front axle being able to support weight placed in front, above and behind it, leading to the motor both pushing and pulling the payload mass. When the same design was reversed and the motor and driving axle were at the rear, the truck struggled to push the entire weight.

4.6 Effect of Lubrication

Whilst the performance scores for the second concept were satisfactory, some small but significant design changes were made to create the final truck design, and these changes resulted in a sizable increase in the performance of the truck. The lubrication of the bevel gears and the axle bearings proved to make a rather remarkable improvement to the score, reducing forces of friction and rolling resistance increasing the best previous score by a factor of 2. This score was also aided by the location of the payload mass, as mentioned above.

4.7 Computational Model

The computational was useful in providing a base from which to consider testing different setups of load weights and gear ratios. While not perfectly accurate, it resembled reality closely enough to save significant time in testing. As seen in figure 18 and figure 19, the maximum score (using round weights, as our possible precision is lower than the possible precision of the model) of each of our possible gear ratios varied, but a ratio of 1:2 was proven to be most effective, which convinced us to use this gear ratio.

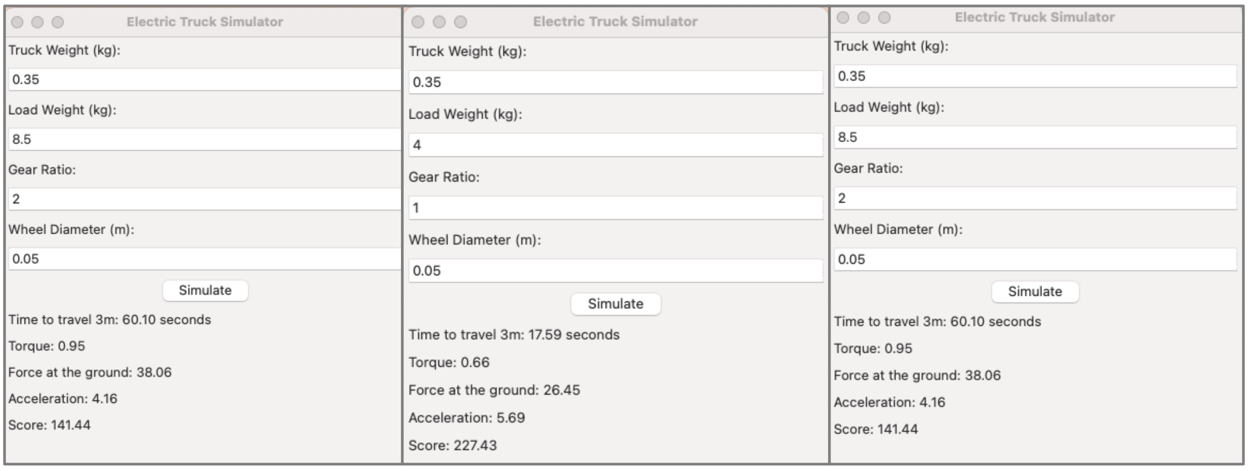

Figure 18: Electric Truck Simulator Output Values

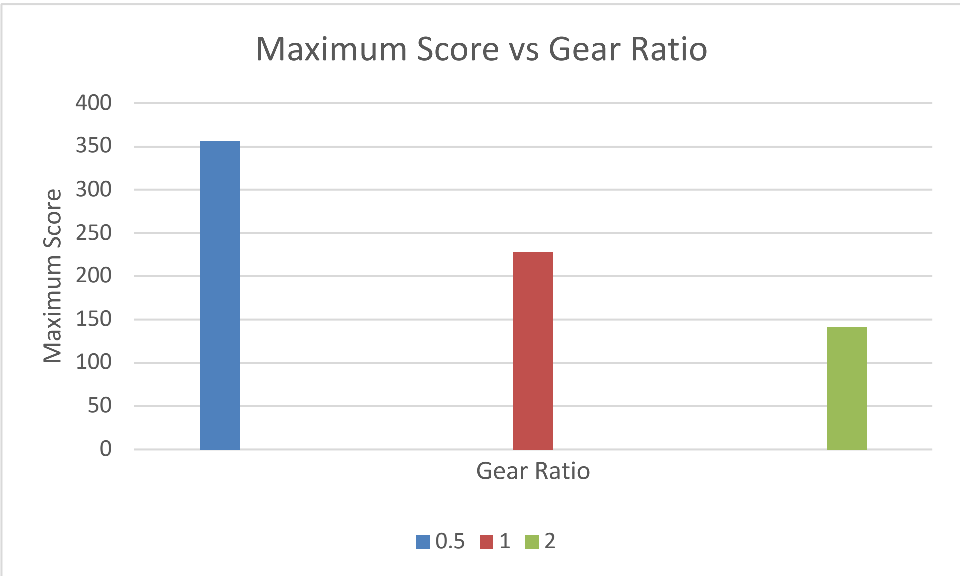

Figure 19: Maximum Score vs Gear Ratio as Calculated by the Computational Model

The simulator also suggested that heavier loads were better for scores [see fig. 20], which the team had already believed, but it was reassuring to receive some mathematical confirmation.

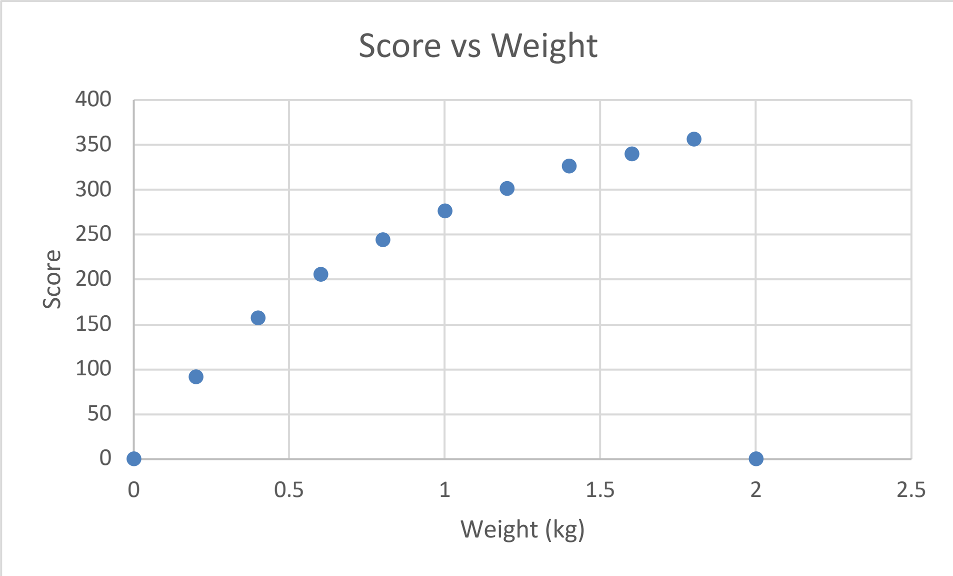

Figure 20: Score vs Weight Carried as Calculated by the Computational Model

4.8 Final test

The final test was executed in the same manner as the previous testing, with the truck travelling a distance of 3m and the time recorded. There was a 3 minute window during which test runs could take place. Given this time limit, this truck design was able to complete 3 full test runs. In this time period there was also 1 unsuccessful test run where the truck was not able to cross the finish line.

The payload masses selected for use in the final testing were based on the results gathered from previous tests on the modified second concept. These results showed that heavier masses would work more favourably in attempting to achieve the highest performance score possible. The same steel bar used in testing, weighing 587g, and two bags of coins weighing 533g and 600g were used as weights for these test runs to avoid losing time re-weighing masses during the limited test window. 3 steel plates, each weighing 100g, were also used during final testing.

The plan for the test runs, which was discussed prior to final testing, was as follows:

- The first run would use both bags of coins and the steel bar, in the hope of replicating the previous best score from testing.
- The second run would only use one bag of coins and the steel bar, as a backup option if the first run proved to be unsuccessful in achieving a high score. It was known prior to testing that this weight would not give a performance score as high as the previous test run, however in the unlikely event that there were any issues with the truck supporting a heavy weight in the first run it was decided that a backup option was needed.
- The third and final test run would attempt to support as much weight as proven possible to potentially achieve a high score. From testing results this was found to be anywhere in the region of 2000g to 2250g. This test run was not expected to achieve a higher score than the first test run but was determined to be still worth doing.

For the first test run, the steel bar was placed at the front of the truck along with the bigger bag of coins weighing 600g. The smaller bag of coins, weighing 533g, was placed at the rear of the truck, giving a payload mass of 1710g. These weights were chosen as they closely matched the weights used to achieve the maximum score in previous testing. In the same manner as the previous testing, the truck motor was switched on and a timer started. Once the truck crossed the finishing line the motor was switched off and the time taken was recorded along with the payload mass.

For the next test run, the larger bag of coins was removed to give a payload mass of 1110g. Unfortunately, on this test run the smaller bag of coins fell over from its designated platform and onto the rear axle. As mentioned before, any weight directly above the rear axle severely impacts the trucks performance and it did not travel the required distance of 3m. This error was quickly fixed, and the run was restarted with the bag of coins staying upright in its position and the truck successfully completing its run, with the time recorded as before.

The third and final test run was completed with a payload mass of 2110g. 3 steel plates, each weighing 100g, were added to the front of the truck underneath the steel bar and bag of coins. This was very close to the maximum weight that could be carried by the truck according to both physical testing and the computational model, but it was decided that the test run was still worth doing. The time taken for the truck to complete the test run was recorded as usual.

Following the final testing the performance score of the truck was calculated for each run, using the formula:

$$Score = \frac{M_{Payload}}{t}$$

Where $M_{Payload}$ is the Payload Mass and t is the time it takes for the Truck to travel 3 metres.

5 Detailed Design

After extensive research, various tests and several different concepts, a final design was decided on. The key features of the final design include:

- Gear ratio
- Powerplant position
- Payload distribution
- Dimensions of truck
- Selection of components

Number of wheels & tyres

5.1 Gear Ratio

Two trucks were built, the first with a 1:1 gear ratio and the second with a 1:2 gear ratio. Both trucks were tested in the time it took to travel three meters while carrying various loads. The second truck proved to have a higher load to speed score than the first truck, proving the theory that the 1:2 gear ratio was more efficient.

Alongside the physical testing, research was conducted on which ratio would be more efficient. It was found that when the gear ratio is 1:1, the amount of torque is the same, and the speed is the same. However, once the gear ratio is increased (1:2, for example), the amount of torque will be cut but there will be a significant increase in the amount of speed. The group decision was that the torque could be sacrificed for an increase in speed, thus the final truck had a gear ratio of 1:2.

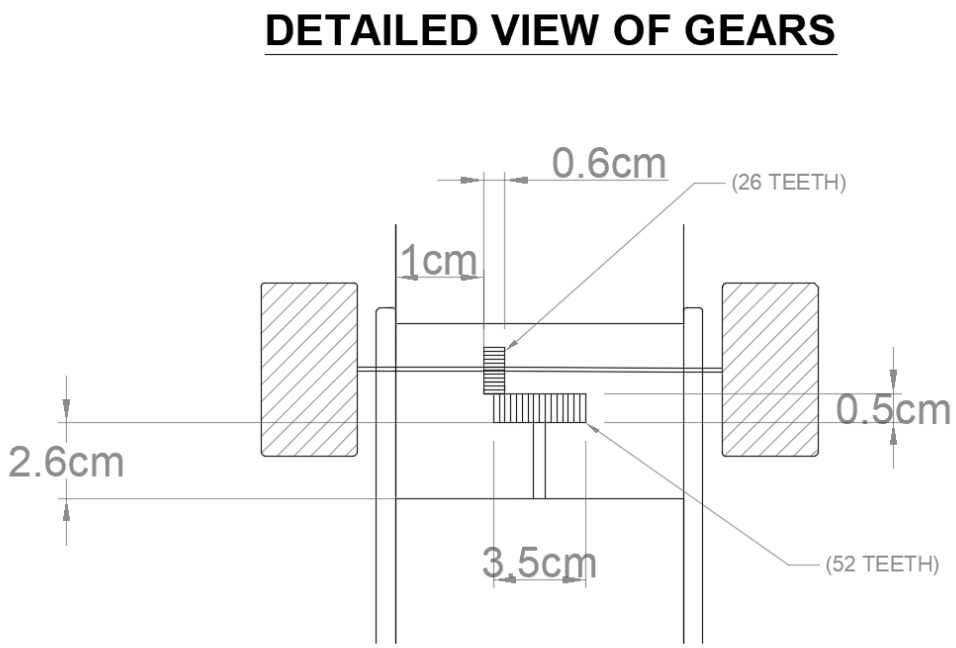

Figure 21: Detailed View of the Gears

5.2 Powerplant Position

Three different powerplant locations were trialled and analysed. In the first design, the powerplant was located at the back of the truck, pushing the entire payload [see Fig.22]

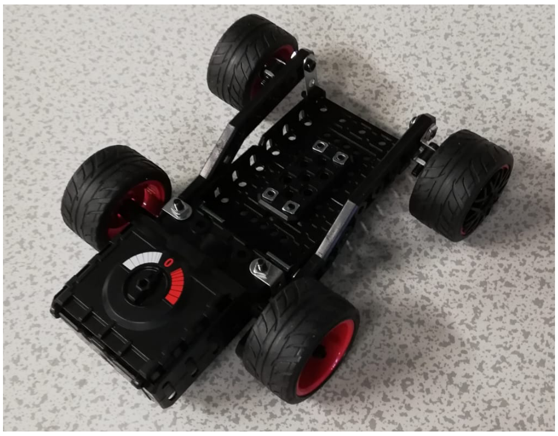

Figure 22: Truck With Powerplant in the Rear

Although this worked well, during the testing phase the same truck was turned around so that the powerplant was now at the front, pulling the payload. According to the test results, it was found that the truck had a higher score when the powerplant was at the front, with the driver wheels pulling the payload.

The second truck was then built with the powerplant in the centre [see Fig.23]. This position allowed for two large platforms to go on either side of the motor, creating more space for larger weights. It was also found that with this powerplant location, a 1:2 gear ratio could be used. Unfortunately, with the first design, as the powerplant was located at the edge of the truck, the wheel axle had to go straight into the motor, forcing a 1:1 ratio.

Each design had its own pros and cons. When the powerplant was at the front or back, the

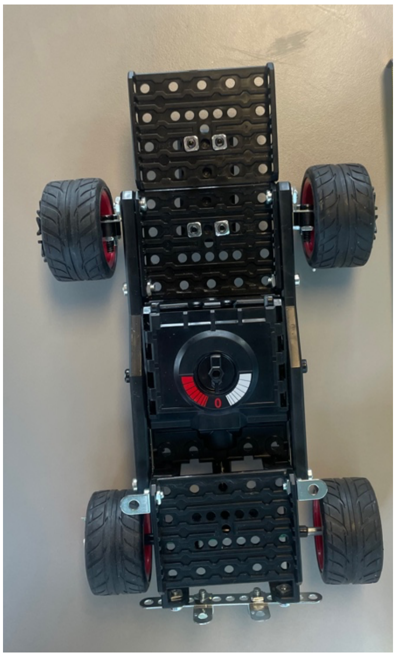

Figure 23: Truck With Powerplant in the Centre

switch was more accessible, making it easier to start and stop the truck. However, the benefit of having a 1:2 gear ratio outweighed this, leading to the final deliberation of the powerplant located in the centre of the truck.

5.3 Payload Distribution

As the powerplant location had been decided on, the payload could go on either side of the motor. The initial assumption was that the truck would work best with an evenly distributed payload, equal amounts of weight on the front and back of the motor. This theory was also backed up by the research that was conducted. Studies indicated that if a payload was unevenly distributed on a moving vehicle, it could cause the vehicle to veer to one side and affect its stability. [13]

However during out-of-lab truck testing, it was found that when the load became greater than 1.7kg the motor would cut out to prevent itself from burning out. It became clear that the back of the truck could not carry the same load as the front of the truck. This was because the driver wheels were to the back of the truck, and the motor was not powerful enough to run when a certain weight was placed over its driver axle.

After this became clear, an unevenly distributed payload was optimal. 2/3 of the weight was placed on the front of the truck. The remaining 1/3 was placed on the back, however it was tilted away from the back wheels. It was found that even if the weight was lying flat along the platform the motor would cut, it had to be placed vertically leaning away from the axle.

5.4 Dimensions

The objective for the dimensions of the truck was clear from the beginning: keep the truck as small as possible but have enough space to carry sufficient loads. It was believed that smaller vehicles often have better acceleration due to their lower weight. Their light masses allow them to reach higher speeds more quickly, as per Newton's Second Law of Motion.

While our initial truck design was the smallest, it was found that if the truck was extended by an extra 12cm in length, it could carry a greater payload without greatly increasing its mass.

Thus, the final dimensions of the truck are as shown in figure 26.

5.5 Selection of Components

Once the general design concept had been chosen, one of the final decisions to be made was the selection of components to be used in the truck [see Fig.24 for the main components of the final design]. The black plastic platforms were optimal for carrying the payload, as they were lightweight, strong, and relatively large.

Plastic connectors were used to hold the platforms and powerplant together. Although metal connectors were tested, they proved too thin to hold the weight of the truck, unable to keep it together. The plastic connectors were longer and less flimsy. They had enough holes for nuts to be inserted both into the powerplant and into the platforms.

The payload guard was built out of 3 shorter metal connectors. The payload guard was designed to prevent the weights from falling off the back of the truck while it was accelerating. In this case, the metal components were better as they were shorter yet strong enough to withstand pressure from the payload.

Through testing & research, both plastic and metal components were used for various reasons in the truck. Each material had individual valuable properties/features such as weight, strength, shape, and size.

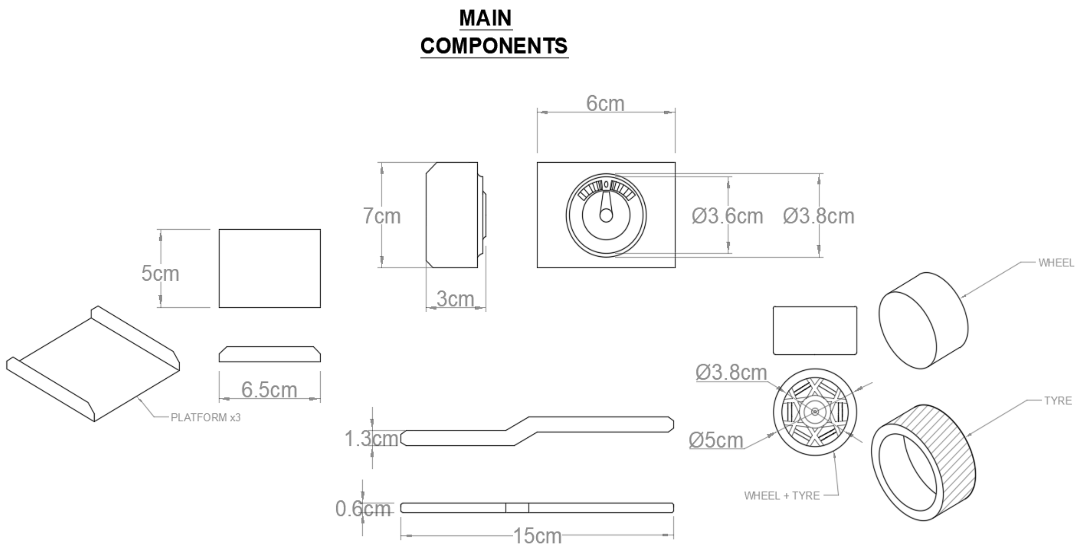

Figure 24: Main Design Components

5.6 Number of Wheels & Tyres

In the earlier design stages, it was decided that a 4-wheel truck was more reliable than a 3-wheel truck. Although certain studies indicate that a 3-wheel truck is faster and lighter, through physical testing it proved too difficult to build one without risking the balance and strength of the truck.

The next question that was faced was "Did all 4 wheels need tyres?". It was evident from the beginning that the driver wheels needed tyres as they provided grip and traction, which was necessary for the initial acceleration of the truck. However, the forward driven wheels did not need the same grip, in fact, it was believed that less grip would allow them to slide faster. This theory was tested, and although it seemed true for smaller weights, once a heavy payload was applied the truck seemed to need the extra torque on the front wheels during its initial acceleration.

Alongside this, with half of back of the truck having tyres and the front without, the truck became uneven, tilted forward. During the testing, it became difficult to balance larger payloads on the front of the truck as they would slip off. Although these tests were interesting, the truck was reverted to its prior design of 4-wheels with 4-tyres.

5.7 Payload Mass

Much of our testing and computation was directed towards the optimisation of our weight carrying. Our tests consistently showed that a higher weight was better, right up to the point at which the motor would cut itself out to avoid burning out (while this issue was mitigated by the processes detailed in Section 5.3, it still proved problematic).

In the end, the optimal weight was found to be 1722g [see ?], although the final testing produced a surprising result, where some last-minute payload redistribution permitted the carrying of 2010g.

The weights used can be seen in Fig.25.

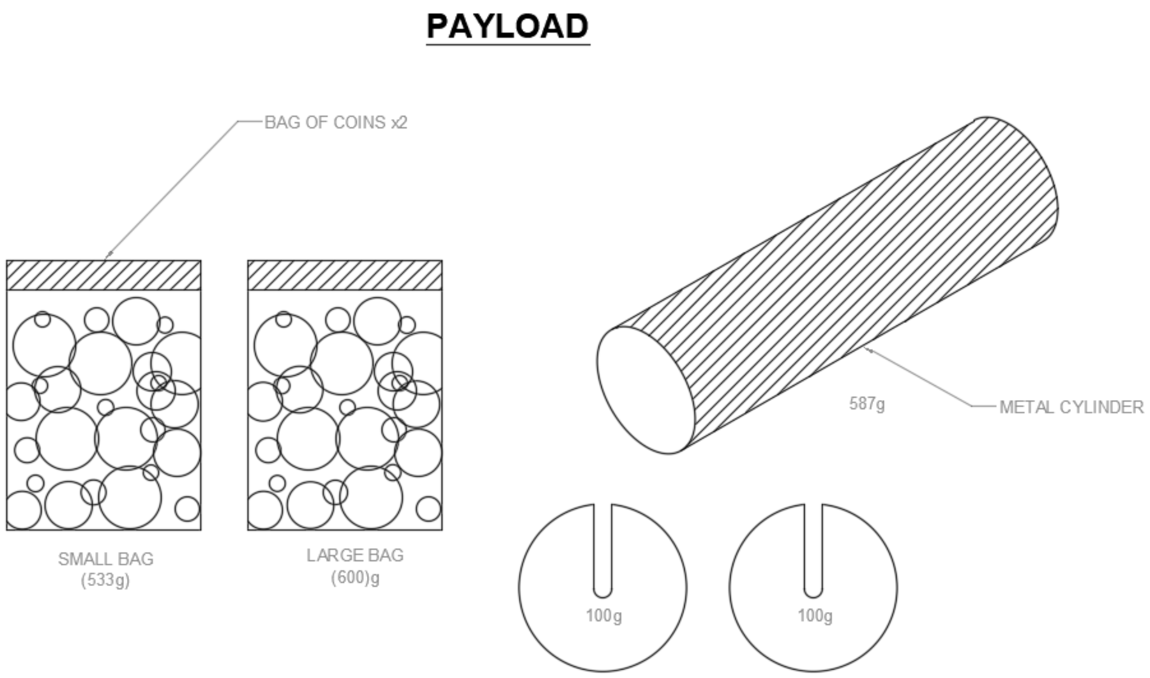

Figure 25: Render of Weights Used

5.8 Overall Design

Our overall final design can be seen in Fig.?.

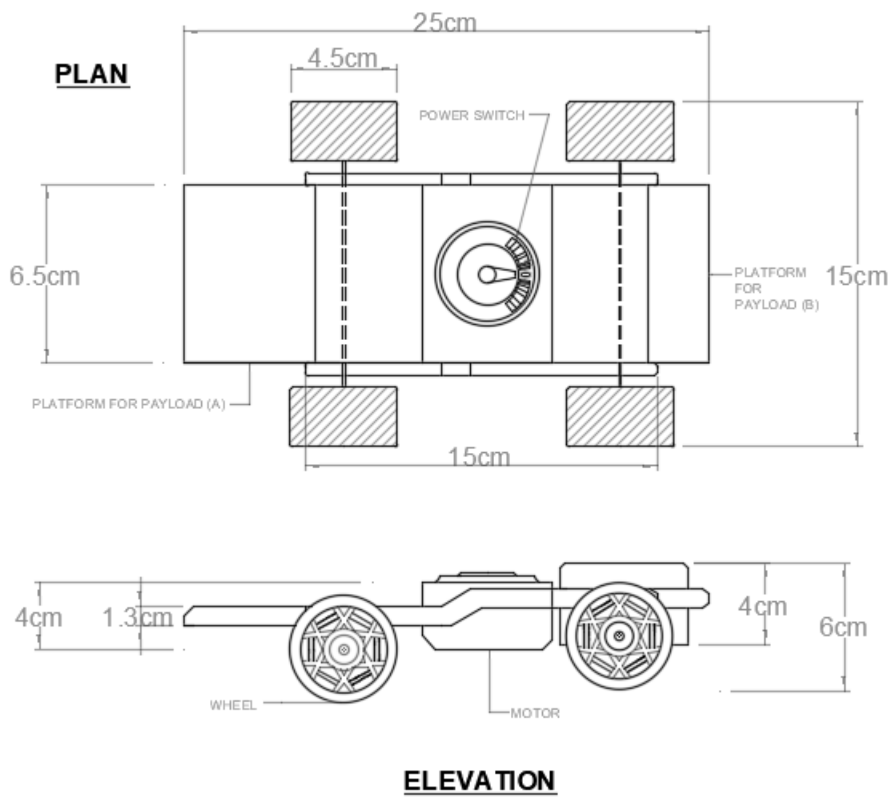

Figure 26: Overall Final Truck Design

6 Conclusions

Following the final testing the performance scores of the truck were examined and analysed. The 3 performance scores recorded from the final testing are shown below:

CONCEPT 2.0 [1:2 GEAR RATIO]		
FINAL OFFICIAL TESTING		
Payload(g	Time (s)	s (g/s)
1710	3.8	290.58
1110	5	340.64
2010	4.3	472.94
Max/final score		472.94
Distance (m)		
3 constant		

Figure 27: Final Testing Performance Scores

The maximum score achieved for the truck was 472.94 g/s. This was an all-time high score for the truck design, surpassing a previous score of 447.43 g/s achieved during initial testing.

This score was the result of weeks of designing, testing, and analysing the truck and its performance under different conditions. Every choice made during the design of this truck impacted on the final results, and these design choices were all influenced by both physical and computational testing. The high score achieved during the final testing reflected the time and work dedicated to this project. The design of this particular truck has all the attributes of a truck that can satisfy the project brief and performs very well in both simulations and real-world testing.

The importance of a gear ratio in the design of this truck was clear from the results and testing of it. Incorporating a gear ratio of 1:2 greatly aided the performance, increasing the speed at which the payload mass could be transported over the required distance. The analysis of weight distribution and its effect on the motor’s ability to perform to its maximum capacity was also a crucial part of the design process. It was also found that small changes can make a significant difference when done correctly, for example the use of lubrication to reduce friction in the truck and the noticeable effect changing between battery brands can have on the overall efficiency of the truck.

7 Recommendations for future work

For future work on the truck or further design the following would be advised:

- Focus on smaller details that make big differences. For example, adding a small amount of WD-40 to the wheel axle had a large impact on the trucks score, yet it was a last-minute change.

- Test more batteries. The 3 different brands of batteries had an immense impact on the truck's performance. Unfortunately, these battery brands were not experimented with until the day before the final test. If there was more time, it would be advised to experiment with other batteries, and try and understand what it was exactly that was causing such a massive difference.

- Give more attention to weight distribution, especially in the computational model. It wasn't fully understood that a greater payload could be added as long as it was not near the back axle until the final test. If this had been realized sooner, there would be a likelihood of a higher overall score.

- Account for oppositional forces in the computational model. This would have increased the accuracy of the model, helping to understand and estimate the actual test results.

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9 Appendix 1 Individual Contributions (compulsory)

A1.1 Eoghan Collins

Eoghan contributed completely to this project, attending all labs and the numerous meetings outside of the designated lab hours. He also created the WhatsApp group and collaborative document to facilitate real-time collaboration. Eoghan was very involved in the physical construction of the truck designs, as well as their design, pitching ideas and collaborating with the team to create the best truck we could. He supplied measuring tape, duracell batteries, lubricant and a measuring scale for the project.

Eoghan also created the computational model and user interface, modifying the model iteratively based on experimental evidence, much of which he stored in excel sheets.

In the report, Eoghan co-authored the introduction, and wrote about the computational model and vehicular torque-velocity testing, as well as listing and setting up citations and finalising the document formatting.

A1.2 Róise Ní Mhurchú

Róise contributed during each weekly lab by helping to design & construct the truck. Róise aided the powerplant testing by weighing out the water and timing each run. Throughout the course of the truck design, Róise took lots of photos and videos of each test, design concept and results. Róise bought electrical tape, Blu Tack and Ziplock bags that were used for the truck. During the report, Róise greatly contributed to the write up of the Design Approach, Detailed Design & Recommendations for future work. Róise drew diagrams of the powerplant tests and created a graph & table of the test results. She also wrote the subsections of Powerplant Testing & Powerplant results.

A1.3 Eoin O'Callaghan

Individual contributions:

- Completion of all CAD drawings
- Contribution in the composition of the Introduction
- All labs and group meetings attended
- Contributed to the construction, designing and testing of the Truck

A1.4 Ruairi O'Neill

Ruairi contributed fully to this project, attending and contributing to every laboratory session. He was also present at every meeting outside of lab hours, providing ideas and participating in the design of the truck. He was heavily involved with the practical side of assembling the truck with his group. For the report, he helped in the Design Approach section and also made up diagrams for the truck. He wrote extensively about the physical testing of the truck in the Methods, Testing and Results section, analysing and recording data in Excel to produce graphs to display the data, and contributed to the Conclusion of the report.

10 Appendix 2 Learning reflection (compulsory)

A2.1 Eoghan Collins

During this project, I learned a lot about iterative design, as well as the mechanics of vehicle design. It was extremely interesting to create computational models for reality, but it was also made clear that no computational model is a replacement for physical testing. It was fascinating how small changes, such as weight-distribution and battery selection had huge impacts on performance. I would have loved to continue the project, delving deeper into the various areas of design and understanding the mechanisms that allow small changes to have huge effects.

I also found that good teamwork is crucial for projects like this. When everyone is engaged and feels comfortable to share, innovate, and collaborate we can get so much more done than in arrangements dominated by one or two people.

A2.2 Róise Ní Mhurchú

Throughout the course of this project, I learned a lot about how vehicles work and small factors that can change a vehicles performance. I widened my knowledge on how traction, torque and payloads affect moving vehicles. I also learned that although research and prior knowledge is helpful for projects, often the best way to learn and improve a design is through trial and error. I think the most important lesson I learned was the importance of a good team. Creating an environment where each member feels comfortable to propose ideas and advise changes yet respecting other opposing opinions. Along with that, I felt the reason our team worked as well as it did was our communication skills. I learned that frequently meeting up outside of labs and having means to contact each other kept our productivity levels high.

A2.3 Eoin O'Callaghan

Through this project I found valuable insights into the non-technical side of Engineering. I found through prioritising attendance for labs, and meeting our group outside of lab times to be very beneficial for my time organisation. I found the group work to be beneficial. I also think that owning up to mistakes and taking responsibility for taking on certain tasks for the group was very important during the completion of the project.

My advice for next years students would be to meet with your group frequently like our group did. It allows the group to be clear about what is to be done. It is very important to discuss different designs, and to share the workload in the report.

A2.4 Ruairi O'Neill

One of the main things I learned from the completion of this project was the importance of recording and analysing data acquired from testing to help influence future design choices. By comparing data from the computational model to the actual real-world test results I was able to examine the effects of different variables on the performance of the truck, which I found very interesting. I also learned the importance of splitting up the workload between the group members, as with a project this long and detailed it would be impossible to complete without closely discussing who does what in each section. Time management was also an important factor to consider in this project, as small progress must be made every week to ensure it was completed on time.