1. Design Brief

Project Title

IMechE Autonomous Vehicle

Project Aim

To design, build, and test a fully self-contained autonomous device capable of accurately engaging with a simulated charging port, holding the connection for a set duration, and returning to the starting position. The system must be built using only mechanical and passive electronic components (no microcontrollers) and adhere to all competition constraints.

Define what success will look like?

- The device autonomously navigates from the starting position to the charging target without external intervention.
- It precisely engages the charging port simulator using its front plunger.
- Maintains contact with the charging port for up to 15 seconds before disengaging.
- Returns to the starting position with minimal deviation from its original path.
- Completes the entire cycle efficiently within a 3-minute time frame.

Design Criteria - Constraints and Requirements

Fuses should be able to withstand a maximum current of 1A, wires should be enclosed and placed away from moving parts. The vehicle should be aesthetically pleasing and have a maximum cost of £50 and should be made of suitable materials that are able to withstand the weights we calculated earlier. Furthermore, the design should adhere to the rest of the specifications stated below.

Rules and Regulations

The device will:

- Have no programmable components
    - Reference: Page 12 (Section 4.1.10)
    - "In the categories Concept Challenge and Foundation Challenge no programmable circuitry is allowed."
- Have a size less than 400mm x 400mm x 400mm
    - Reference: Page 10 (Section 4.1.1)
    - "The device must fit within a working envelope of 400mm x 400mm x 400mm."
- Complete the mission within 3 minutes
    - Reference: Page 16 (Section 6)
    - "The aim of this competition is to design a device that could perform the mission described in less than 3 minutes in total."
- Engage with the wall accurately and for 10-15 seconds for 15 points
    - Reference: Page 16 (Section 6)
    - "The mission description is: start with the reference datum pointer on the centre of the horizontal target, travel towards the wall, contact the plunge simulator on the vertical target (50mm from horizontal surface), remain in contact for up to 15 seconds."
- Return to the centre of the bullseye for 10 points
    - Reference: Page 13 (Section 5, Table 1)

- "Precision in returning to the starting point, with reference to the datum pointer relative to the horizontal target: 0 to 10 points available."

- Have a green light that stays on for the duration of the run
  - Reference: Page 11 (Section 4.1.7)
  - "The device should have a visible green light, to be on for the whole duration of the run."
- Have a red light and sound activate upon contact with the wall and turn off as soon as the device leaves the wall
  - Reference: Page 12 (Section 4.1.8)
  - "When the front plunger – plug simulator engages with the wall, an additional visible red light should be switched on and a sound shall be emitted."
- Be built within a £50 budget
  - Reference: Page 10 (Section 4.1.3)
  - "The datum point element can be purchased from RS Components - part number 397-4954. The pointer shall be included in the BoM, with all the characteristics listed to fulfil the BoM requirements."
  - Note: The budget constraint is implied through the requirement to include all components in the Bill of Materials (BoM) and the general cost constraints mentioned throughout the document.

Quantifiable Objectives (also referred to as Key Performance Targets, Performance Metrics, etc.)

Objective	Target Value
Device Size	390mm x 390mm x 390mm
Time Taken	≤ 150 seconds
Wall Contact Duration	12 seconds
Centre of Mass	Within 20 x 20 x 20 mm of the centre of the body
Cost	≤ £40
No Slip	$F_R \leq \mu N_R$

2. Design Approach

Theory and Methods

- **Theory**: The relationship between motor torque, gear ratio, and wheel torque is given by $T_w = GT_m$. The gear system is used to convert high-speed, low-torque motor output to low-speed, high-torque wheel output.
- **Method**: Use the gear ratio to calculate the torque at the wheels and the corresponding reaction force $F_R = \frac{T_w}{R_w} = \frac{GT_m}{R_w}$. This force will be used to determine the acceleration of the vehicle.
- **Theory**: The motor torque-speed curve is linear, with torque decreasing as speed increases. The relationship is given by $T_m = T_{ms} - \left(\frac{T_{ms}}{\omega_{mNL}}\right)\omega_m$, where T_{ms} is the stall torque and ω_{mNL} is the no-load speed.
- **Method**: Use the motor torque-speed curve to determine the motor torque at any given speed, which will then be used to calculate the wheel torque and acceleration.
- **Theory**: The effective mass m^* accounts for both the linear acceleration of the vehicle body and the angular acceleration of the wheels. The moment of inertia of the wheels is converted to an equivalent mass.
- **Method**: Calculate the effective mass using $m^* = m_v + 6m_w$, where m_v is the mass of the vehicle body and m_w is the mass of each wheel.

Unknowns

- **Friction and Aerodynamic Losses**: These could significantly impact performance, especially at higher speeds or on uneven surfaces.
- **Gear and Motor Efficiency Losses**: These are likely to be moderate but could accumulate, especially in systems with multiple gear stages or high motor loads.
- **Spring System Losses**: These could be critical if the spring is used to control impact forces, as energy losses could lead to unexpected behaviour.
- **External Forces and Environmental Factors**: These could have a large impact if the vehicle operates in non-ideal conditions.

Assumptions

- The motor torque T_m is inversely proportional to the motor speed ω_m following the linear relationship: $Tm = Tms - \left(\frac{T_{ms}}{\omega_{mNLT}} \right) \omega_m$
- The gear system is assumed to be 100% efficient, with no energy losses, so the torque and speed relationships hold perfectly
- The effective mass accounts for both the linear acceleration of the vehicle body and the angular acceleration of the wheels, simplifying the system to a single mass: $m^* = m_v + 6m_w$
- We take iterative steps to take small steps of Δt to update position, velocity, and acceleration.
- We do not consider air resistance
- Motor generates maximum torque when stationary
- The torque-speed curve is assumed to have a linear relationship such that as linear speed increases the motor torque decreases
- Spring follows a linear extension – force relationship.

Research

1. Identify Assumptions and Unknowns

- Frictional Losses: If assuming they are negligible, research real-world coefficients of friction for the relevant materials (e.g., wheel-ground contact, gear interfaces).
- Gear Efficiency: Verify whether assumed gear ratios provide expected torque and speed while accounting for mechanical losses.
- Motor Characteristics: Ensure motor torque-speed curve data aligns with practical performance.
- Effective Mass Calculation: Validate whether rotational inertia contributions are correctly approximated in the effective mass equation.
- Vehicle Impact Modeling: Ensure deceleration calculations realistically model elastic or inelastic impact dynamics.

2. Research and Quantification Methods

- Empirical Testing: Conduct experiments or analyze manufacturer data for friction coefficients, motor efficiency, and gear losses.
- Simulation: Use computational tools (e.g., Python, MATLAB, Simulink, Excel) to test assumptions with iterative calculations.

- Comparative Analysis: Cross-check assumptions with similar real-world systems or literature values.
- Sensitivity Analysis: Adjust assumptions slightly and observe the impact on overall performance.

3. Verification of Assumptions

- If frictional losses are assumed negligible, compare theoretical acceleration with actual performance and measure heat generation or resistance forces.
- If gears are assumed ideal, measure real-world torque transmission efficiency and energy loss.
- If impact deceleration is assumed to match theoretical values, test different damping mechanisms to confirm realistic behavior.

<u>Resources</u>

1. Software Tools

- CAD Software (Fusion 360) – Used for 3D modeling to design the device and conduct FEA analysis to ensure device does not break
- Circuit Wizard – To simulate circuits before physical assembly.
- Excel & Python – For numerical model & BoM cost tracking.

2. Testing Equipment

- Multimeter – To measure voltage, current, and resistance, ensuring the electrical circuit functions correctly.
- Mass Scale – To verify that the final weight remains within the expected range.
- Stopwatch & Distance Markers – To measure time and accuracy during test runs.

3. Collaboration & Specialist Support

- Mechspace Mentors – For guidance on manufacturing processes, laser cutting, and circuit assembly.
- Industry Specialists – To provide feedback on mechanical design improvements and efficiency.

<u>Manufacture</u>

Manufacturing Methods:

- Laser Cutting – To manufacture chassis from acrylic or plywood.
- 3D Printing – For custom brackets, housings, and small mechanical components.
- Hand Tools (Saws, Drills, Files) – For manual modifications and fine adjustments.
- Soldering Iron – For secure electrical connections to PCB in the circuits.

3. Concept Design

<u>Basic Concepts</u>

Driving mechanisms:

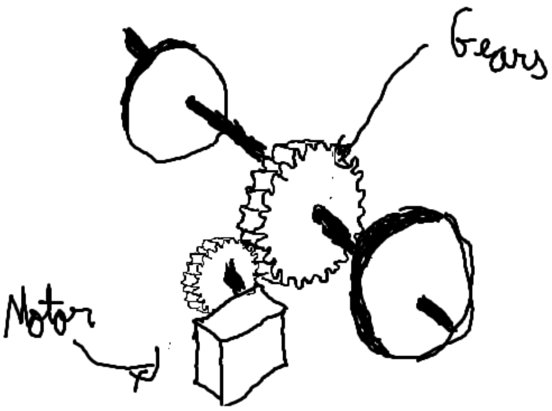


Figure 1

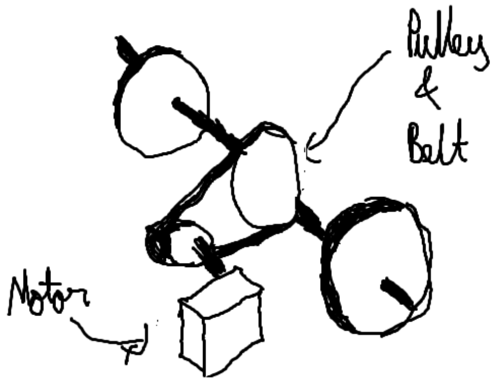


Figure 2

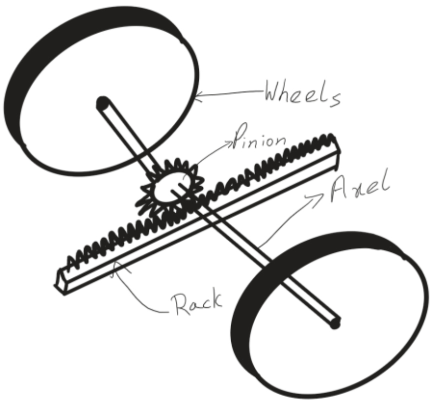


Figure 3

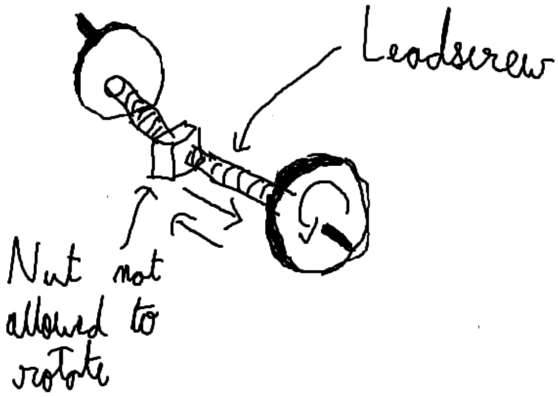


Figure 4

Distance Measuring & Base Ideas:

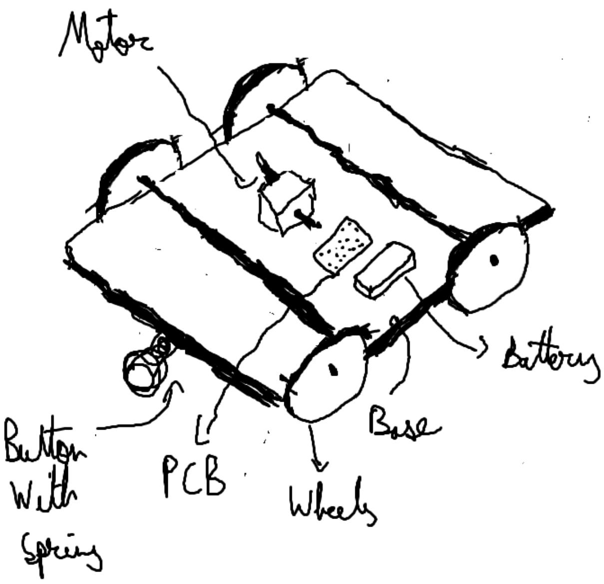


Figure 5

Ball Park Calculations

```
%Model for the position,velocity and acceleration of the vehicle

% Define given parameters
T_m_stall = 0.14709975; % Nm (Motor stall torque)
w_m_NL = 3.141592654; % rad/s (No-load speed)
G = 2.5; % Gear ratio
R_w = 0.04; % m (Drive wheel radius, 80mm diameter)
m_eff = 0.482 + 6*(0.027); % kg (Effective mass)
curve_gradient = T_m_stall/w_m_NL; % Torque-speed gradient

dt = 0.001; % Time step (s)
T_end = 0.2; % Total simulation time (s)
N = T_end / dt; % Number of iterations

% Initialize arrays
t = linspace(0, T_end, N);
w_m = zeros(1, N);
T_m = zeros(1, N);
T_w = zeros(1, N);
F_R = zeros(1, N);
a_x = zeros(1, N);
v_x = zeros(1, N);
P_m=zeros(1,N);
x = zeros(1, N);

% Initial conditions
w_m(1) = 0;
v_x(1) = 0;
x(1) = 0;

% Iterative calculation
for i = 2:N
% Motor torque from torque-speed curve
T_m(i) = T_m_stall - curve_gradient * w_m(i-1);
% Wheel torque considering gear ratio
T_w(i) = G * T_m(i);
% Reaction force at the wheel
F_R(i) = T_w(i) / R_w;
% Acceleration using Newton's second law
a_x(i) = F_R(i) / m_eff;
% Velocity update using integration
v_x(i) = v_x(i-1) + a_x(i) * dt;
% Position update using integration
x(i) = x(i-1) + v_x(i) * dt;
% Motor speed update using velocity and gear ratio
```

```
w_m(i) = G * v_x(i) / R_w;

% Motor power calculation
P_m(i) = T_m(i) * w_m(i);
End

%Normal spring

% Parameters
k = 50; % Spring constant (N/m)
m_star = 0.457; % Effective mass (kg)
ubar = 0.5; % Initial velocity (m/s)
g = 9.81;
% Natural frequency
omega = sqrt(k / m_star);

% Time settings
t_max = pi / omega; % One full oscillation cycle
t = linspace(0, t_max, 1000); % Time vector

% Position, velocity, and acceleration
x = sqrt((ubar^2 * m_star / k)) * sin(omega * t);
v = ubar * cos(omega * t);
a = -ubar * omega * sin(omega * t);

%Driven Spring

a = G * T_m_stall / R_w;
b = G^2 * T_m / (w_m_NL * R_w^2) % Ensure correct grouping if needed

% Correct denominators with parentheses
q_pos = (-b + sqrt(b^2 - 4 * m_eff * k)) / (2 * m_eff);
q_neg = (-b - sqrt(b^2 - 4 * m_eff * k)) / (2 * m_eff);

% Simplify exponentials using exp() function
C = -a / k * exp(real(q_pos));
D = (ubar * k + real(q_pos) * a) / (k * exp(real(q_pos)) * imag(q_pos));
P = a / k;

% Apply element-wise multiplication (.*) for vector operations
disp_driven = exp(a * t) .* (C * cos(b * t) + D * sin(b * t)) + P;
velocity_driven = exp(a * t) .* ((a * C + D * b) * cos(b * t) + (a * D - C * b) * sin(b * t));
acceleration_driven = exp(a * t) .* ( ((a^2 - b^2) * C + 2 * a * b * D) * cos(b * t) ...
+ (-2 * a * b * C + (a^2 - b^2) * D) * sin(b * t) );
```

Concept Selection

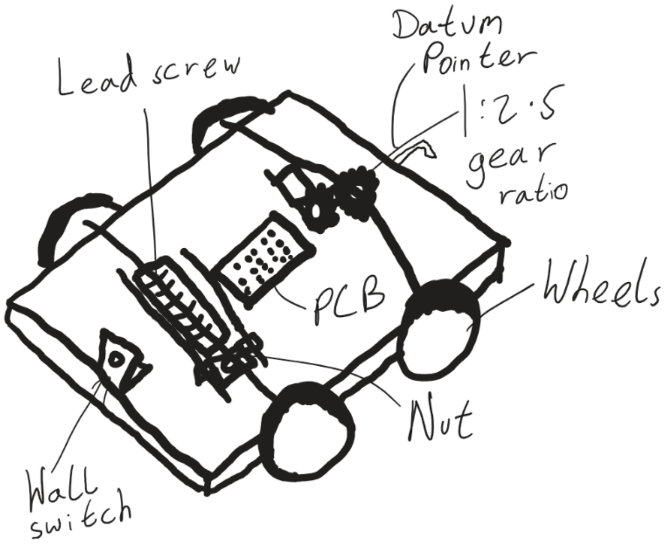


Figure 6

We decided to move forward with the leadscrew mechanism to measure distance. Firstly, its simpler, and hence easier to execute, leaving less room for errors in manufacturing and calculating. Furthermore, the design is symmetric, aiding with the overall air flow over the car, and balancing of the components on the car. The rack and pinion design was not feasible because it didn't fit the compact design. The rack would end up moving off the base platform, making the device no longer follow the regulations. Hence, we settled on using normal gears and cutting out the excess space to reduce weight.

Circuitry

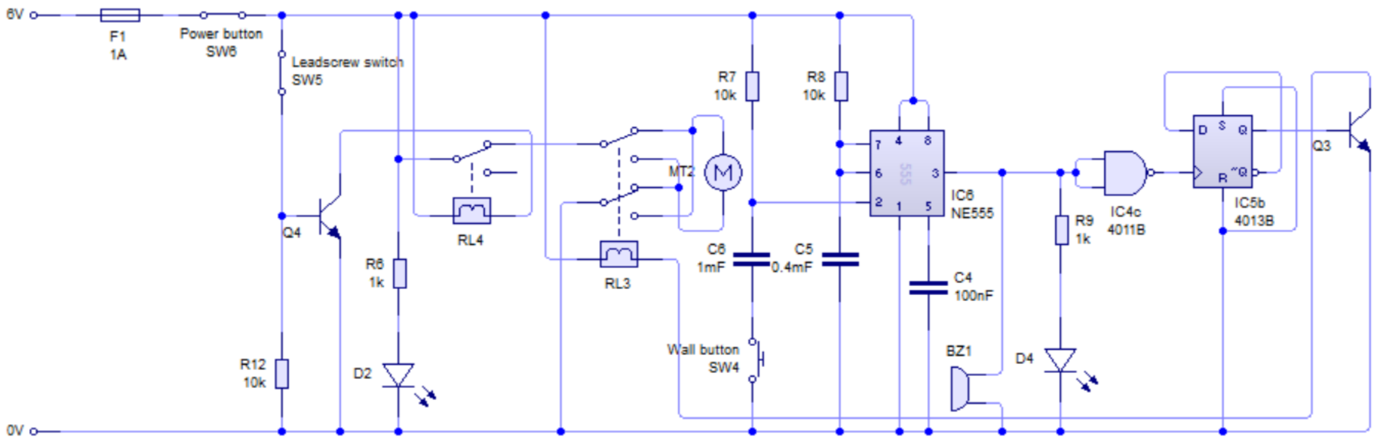


Figure 7

When the power button is pressed, the circuit receives 6V from the battery pack. This causes the relay, RL4, to initially switch causing the motor to rotate and hence moving the nut ever so slightly along the leadscrew. Doing so then opens the leadscrew switch which then switches RL4 back to its original position and makes the motor rotate. Also, when the power button is pressed, the green LED, D2, lights up and remains on until turned off. To note, initially, the motor rotates in the forward direction as RL3 is unaffected. Therefore, the vehicle travels towards the wall at an average speed of 0.06 ms^{-1}. When the vehicle reaches the wall, the wall button is pressed and triggers a 555 timer. This causes the output of the chip to go high for 12 seconds – causing the buzzer to make a sound and a red LED, D4, to light up for the same duration. Then when the output falls from high to low, the 4013 chip triggers due to the falling edge which sends a signal to the relay – causing it to reverse its polarity and hence change directions. Therefore, the vehicle moves back towards the start position. To ensure the vehicle stops at the same position that it started at, we have a switch attached at the start position of the leadscrew so on the way back, when the nut hits the leadscrew switch, the relay, RL4, is triggered causing the motor to be disconnected. This causes the motor to stop and the vehicle therefore returns to its starting position. Also, we measured the maximum current in the circuit using the CircuitWizard simulation software and found that a 1A fuse was most suitable to ensure that no components were damaged in the circuit during testing.

<u>Time delay and stop</u>

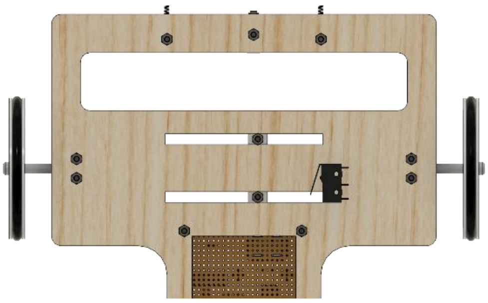


Figure 8

To ensure that the vehicle turns on a buzzer and red LED when in contact with the wall, we used a 555 timer with an RC combination to last 12 seconds. And additionally, as we need the mot or to reverse directions at the end of the 12 seconds, we used a 4013 flip flop IC that is falling edge triggered so when the relay RL3 is triggered, the motor reverses polarity and hence rotates the wheels in the opposite direction. Coming to the stopping mechanism on the way back to the horizontal marker, we used a limit switch which starts closed, opens and when closed on the way back, triggers the RL4 relay – causing the motor to disconnect and stop running.

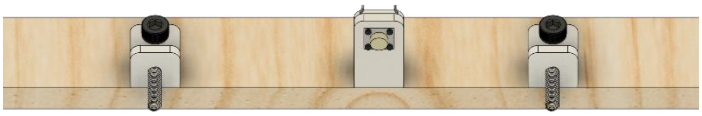


Figure 9

4. Design Specification

<u>Design Specification</u>

The Foundation Challenge Vehicle must be capable of driving itself through a course of 1.4m – 4.0m, insert a charging port within a 50mm height tolerance, hold contact for 12 seconds, and return to within ±50mm of the original start point, all in ≤150 seconds. It must be within 390mm × 390mm × 390mm envelope, with ≥10mm plunger and rear datum pointer (RS Part 397-4954) within 6mm of the track. The mass centre must be within 20mm × 20mm × 20mm of the geometric centre for stability.

Power is provided by 3 1.5V batteries, with the need for ≤10A fuse for safety. Wiring should be encapsulated, and there must be a green operational running light with a red one and alarm sounding for ≥1 second when striking the target. The mechanical aspect must utilize analogue parts (no microcontrollers) with gears, motors, and pulleys producing precise motion. Moving parts should be encapsulated, the frame must be hard but not heavy, and the forces of friction should be utilized to avoid slipping of the wheels.

Designed for plywood, MDF, OSB, and industrial floor applications, the machine must handle ≤2mm surface joints and ≤3mm level differences. The overall investment must be ≤£40 with each component specified in a BoM. Markings is based on on plunger accuracy (5 pts), 12-second contact time (10 pts), and return accuracy (10 pts). Adherence to these specifications assures competition compliance as well as the possibility of victory.

5. Design and Analysis Process

<u>Create a Virtual Prototype</u>

Mathematical model:

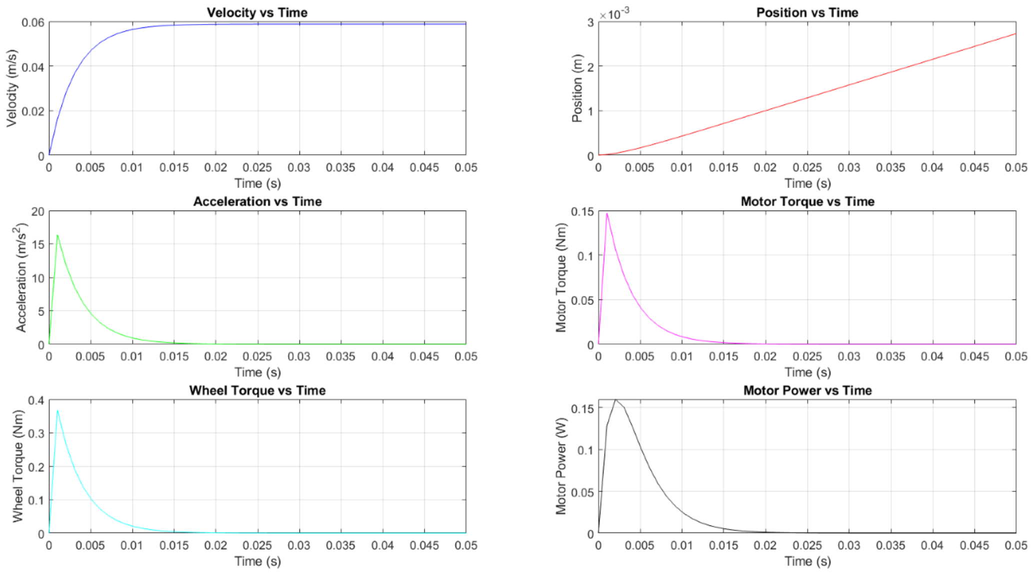


Figure 1a: Graphs showing key metrics of our design's motion over the period

Our design utilises an electric motor which explains the initial spike in motor torque which is mainly ideal for rapid acceleration from a standstill and is beneficial for our design to overcome the static friction between the wheels and the tyres. Motor power also peaks because of overcoming the friction and inertia of the vehicle.

As for the position, velocity and acceleration of the design, an iterative method was used to find each of the metrics over an incremental time:

- At t = 0 position has not changed and the vehicle is stationary, however the motor produces a peak torque at the start causing the torque at the wheels to reach a peak value of 0.375 Nm, thus a peak frictional force between the surface and tyres is produced, causing a peak acceleration of the vehicle.
- Our local frictional force is 4.49N and Fr at the start of the vehicle's motion is 9.19N resulting in slip.
- Motor power peaks at 0.1613W and decreases as the vehicle's inertia increases, resulting in the wheel torque decreasing and thus acceleration reaches 0 within 0.018 seconds.
- This means that our vehicle reaches peak velocity at 0.0588 m/s in 0.018 seconds, which is useful because reaching peak velocity quickly means we do not over-heat the motor over the period that the vehicle runs, and the battery which powers the motor lasts longer.

Formulas used for this:

1) Equation to find the Torque in the motor: $T_m = T_{mS} - \left(\frac{T_{mS}}{\omega_{mNL}}\right)\omega_m$
2) Equation to find the Torque in the wheel: $T_w = GT_m$
3) Equation for the friction at the wheels: $F_R = \frac{T_w}{R_w} = \frac{GT_m}{R_w}$
4) Equation for the acceleration of the vehicle: $a = \frac{F_R}{m^*}$
5) Equation for the subsequent velocity: $v(t_2) = v(t_1) + a(t_1)\Delta t$

6) Equation for position: $x(t_2) = x(t_1) + v(t_1)\Delta t$
7) Equation for power of motor: $P_m(t_1) = T_m(t_1) \cdot \omega_m(t_1)$

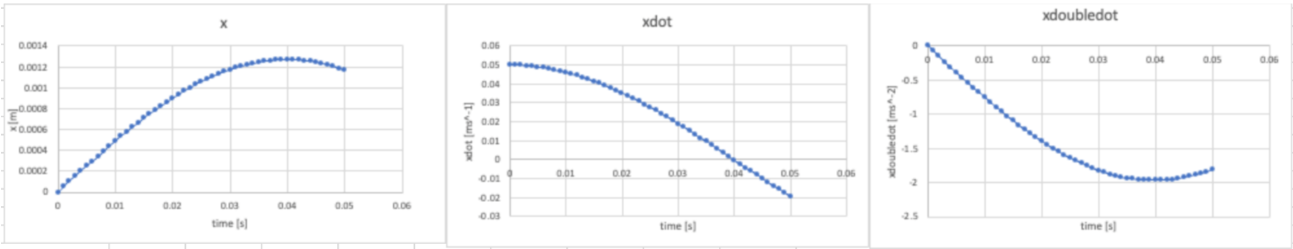
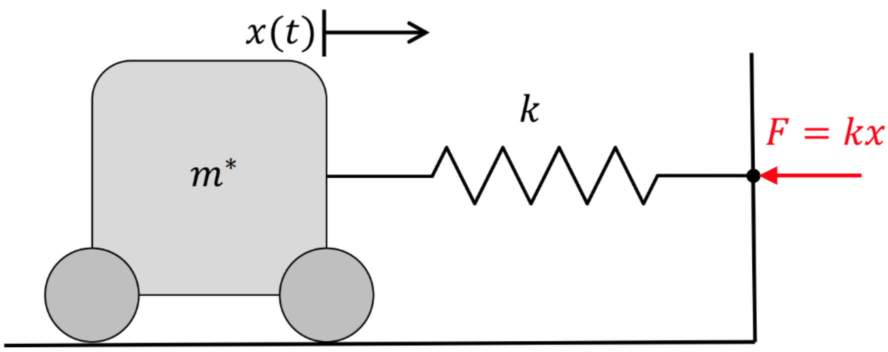


Figure 2a: Graphs showing the deceleration of the vehicle as on impact using a spring where the motor does not continue to run.



For Non–Driven Spring:

- *The equation for the displacement of the spring is governed by the differential equation:* $m\frac{d^2x}{dt^2} + kx = 0$
- *This is a second order differential equation in the form of* $x = Ae^{qt}$
- *Thus, the differential equation is homogeneous and the solutions to the auxilary equation is distinct and imaginary thus taking the general solution form of:* $x(t) = C\cos\left(\sqrt{\frac{k}{m^*}}t\right) + D\sin\left(\sqrt{\frac{k}{m^*}}t\right)$
- *Applying boundary conditions, we can find the Coefficients C and D where at t = 0, x = 0 and* $\dot{x} = \overline{u}$ *we find that* $D = \frac{\overline{u}m^*}{\sqrt{k}}$, *where* $\overline{u}$ *is the maximum velocity that the vehicle reaches which for this design is 0.0588 as stated and C = 0.*
- *Thus, equation for displacement for the spring:* $x(t) = \frac{\overline{u}m^*}{\sqrt{k}}\sin\left(\sqrt{\frac{k}{m^*}}t\right)$
- *Equation for velocity:* $\dot{x}(t) = \overline{u}\cos\left(\sqrt{\frac{k}{m^*}}t\right)$
- *Equation for the deceleration:* $a(t) = -u\sqrt{\frac{k}{m^*}}\sin\left(\sqrt{\frac{k}{m^*}}t\right)$
- *The vehicle reaches maximum deceleration at the same time at which the velocity reaches 0, therefore if the spring were not driven, the vehicle would receive a push back from the wall causing it to slowly roll back.*

For Driven Spring:

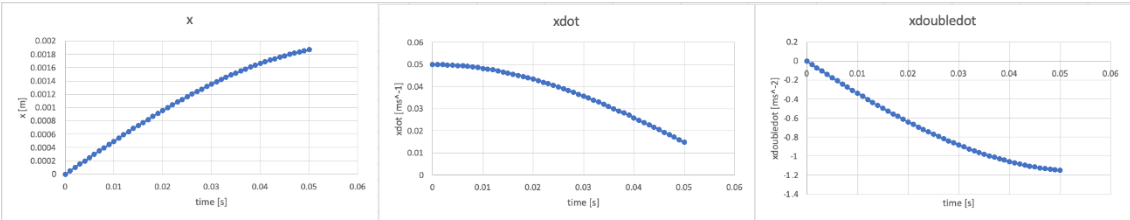
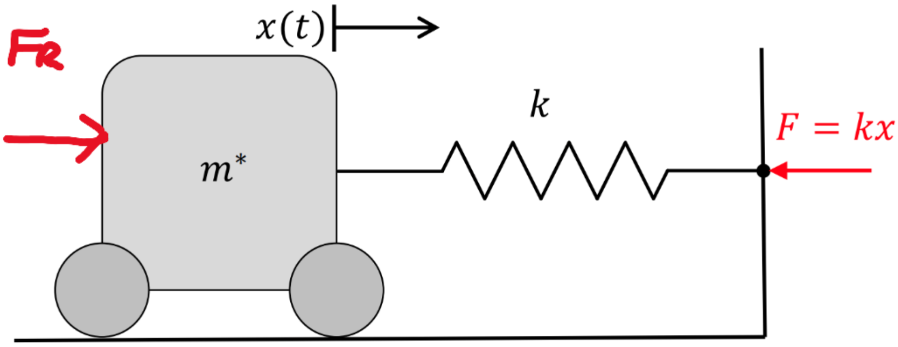


Figure 4a: *Graphs showing the deceleration of the vehicle as on impact using a spring where the motor does continue to run.*



For Driven Spring:

- The equation for the displacement of the spring is governed by the differential equation: $m^* \frac{d^2x}{dt^2} + kx - F_R = 0$
- Formula for friction is: $F_R = \frac{T_w}{R_w} = \alpha - \beta \frac{dx}{dt}$
- α And β represent parameters from the motor speed curve
- Therefore, differential equation can be re - written as: $m^* \frac{d^2x}{dt^2} + kx - \left(\alpha - \beta \frac{dx}{dt}\right) = 0$
- Re-arranging this gives us a non-homogeneous differential equation of: $m^* \frac{d^2x}{dt^2} + \beta \frac{dx}{dt} + kx = \alpha$
- The solution for this auxiliary equation is dependent on the quadratic formula of: $q = \frac{-\beta \pm \sqrt{\beta^2 - 4m^*k}}{2m^*}$
- The nature of the curve is dependent on the result of this equation: $\beta^2 - 4m^*k$
- If $\beta^2 > 4m^*k$ then the solution to the displacement of the spring during the impact is represented by a decaying set of exponential curves whereas if $\beta^2 < 4m^*k$ then the displacement of the spring during the impact is represented by a set of decaying sinusoidal curves
- In our project's specification we use the sinusoidal curves thus we utilise the general solution of: $x_h = e^{-\frac{\beta}{2m^*}t}\left(C \cos\left(\frac{\sqrt{4m^*k - \beta^2}}{2m^*}t\right) + D \sin\left(\frac{\sqrt{4m^*k - \beta^2}}{2m^*}t\right)\right)$ + P
- P = α / k
- Thus this is the equation for the position of the spring during its driven impact: $x = e^{\alpha t} \cdot (C \cos(bt) + D \sin(bt)) + P$
- Subsequently the velocity equation is:

$$\frac{dx}{dt} = e^{\alpha t} \cdot \left((\alpha C + D\beta) \cos(\beta t) + (\alpha D - C\beta) \sin(\beta t)\right)$$

- And the subsequent acceleration for this is:

$$\frac{d^2x}{dt^2} = e^{\alpha t} \cdot \left(\left((\alpha^2 - \beta^2)C + 2\alpha\beta D\right)\cos(\beta t) + (-2\alpha\beta C + (\alpha^2 - \beta^2)D)\sin(\beta t)\right)$$

CAD model

Concept Development

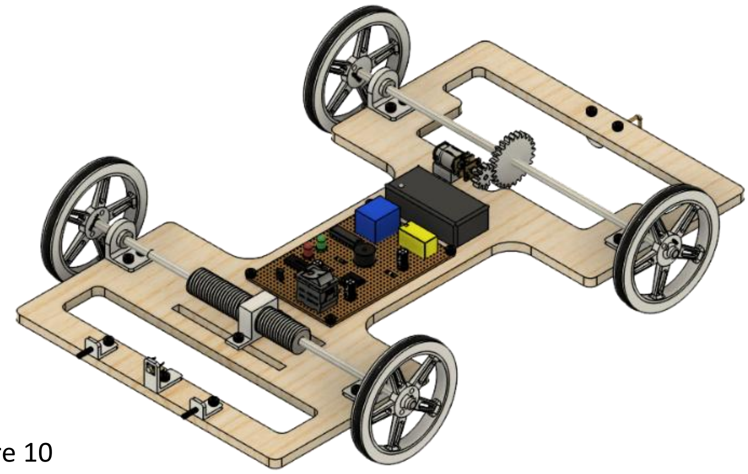


Figure 10

Create a Datum Model to Build Your Assembly Around

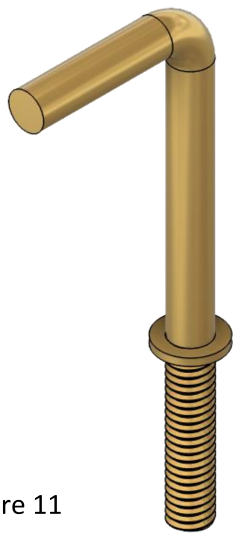


Figure 11

Design for Manufacture

PLA (Polylactic Acid) for 3D printing

Plywood for base

Strength, Stiffness, Stress

The two loads on our car are the reaction force due to the wall, and the weight of the car. The maximum load exerted by the wall is between 1-2N, and the weight of the car is 0.482 kg, hence its weight is 4.72N. To be safe during the FEA analysis, we set the reaction force by the wall as 5N.

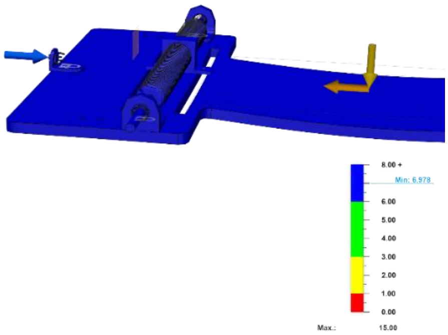


Figure 12

Figure 12 demonstrates the safety factor of the material due to the load. The minimum is 6.978, and the maximum is 15. This demonstrates that the car can support a load 15 times greater than its current load and is hence strong enough for the project. Since the safety factor is significantly greater than the minimum we would have accepted (roughly 1.5-2), we can reduce some material from the base of the car to reduce weight, and therefore overall load.

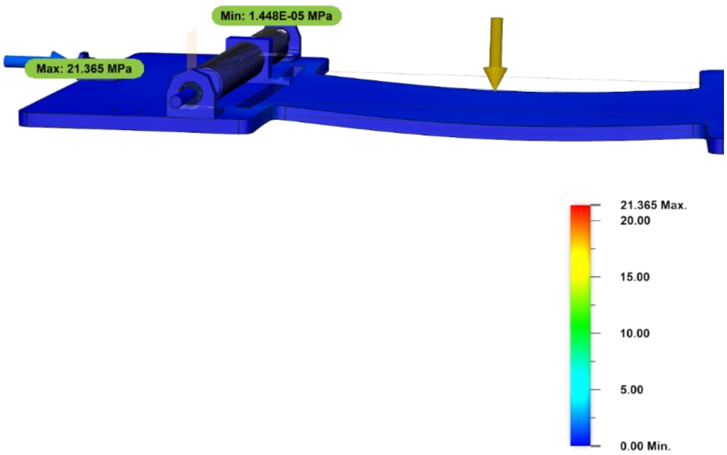


Figure 13

The maximum stress is 21.365 MPA at the button, due to the reaction force from the wall. However, the reaction force was set to 5N as a safety measure, and the actual force is likely half of that. Hence, the maximum stress is well supported by the material, as will be covered below in the displacement diagram.

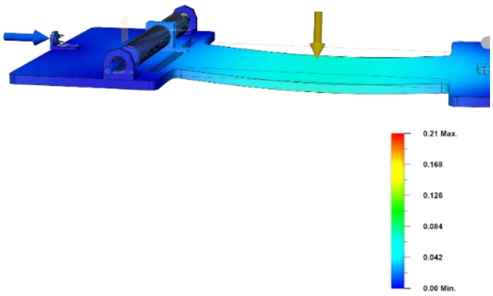


Figure 14

As seen in figure 14, the maximum displacement is at the centre of the base, which is between 0.04 - 0.06 mm. This is nearly negligible and hence reinforces that the car is well suited to handle the loads.

6. Implementation

Data Management – Part Labelling System

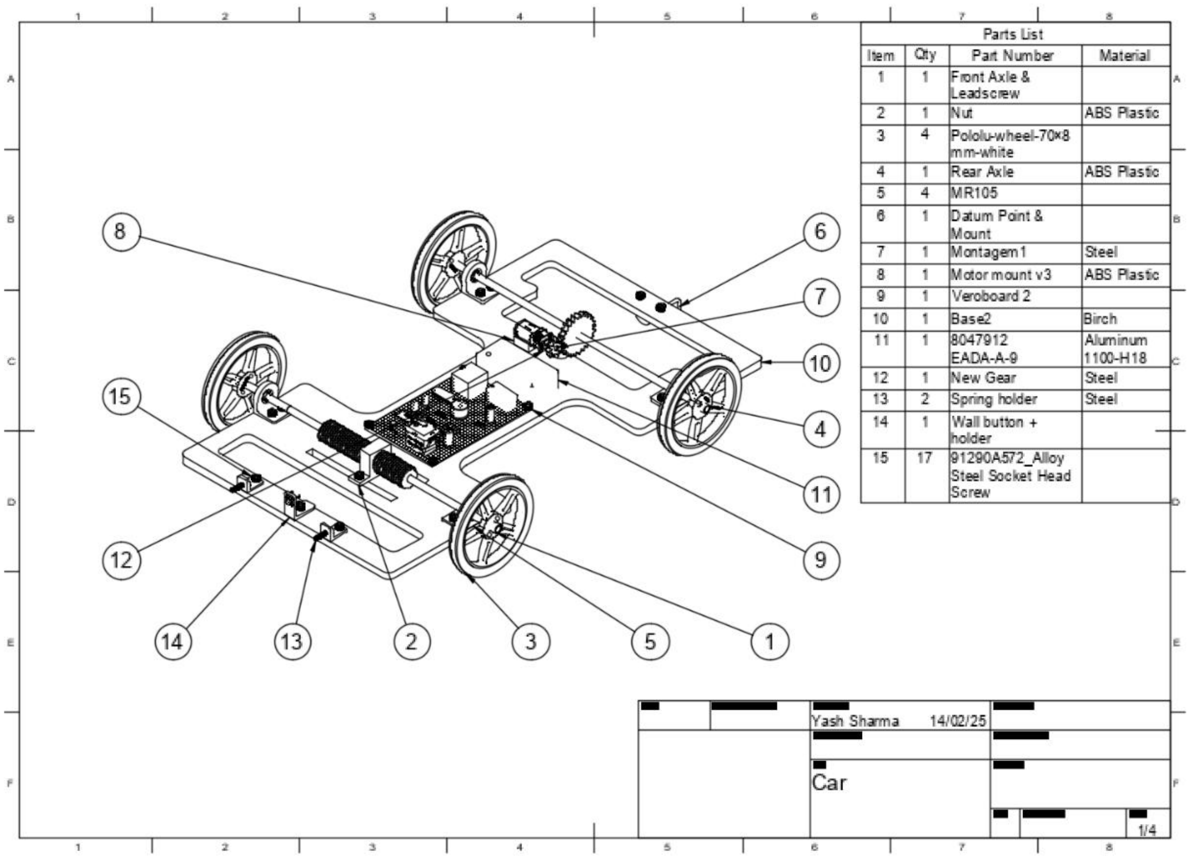


Figure 15

Bill of Materials

Self-Produced		
Component	Number	Cost
Wheels	4	£0.45
Datum mount	1	£0.01
Gears	1	£0.0656964
Nut	1	£0.00429918
Axle Mount	4	£0.062932032
Leadscrew	1	£0.086

Plywood	1	£0.7

Electronics		
Component	**Number**	**Cost**
SPDT Relay	1	£2.49
DPDT Relay	1	£2.70
555 Timer	1	£0.18
CD4013	1	£0.59
BC547	1	£0.53
Motor	1	£1.50
Red LED	1	£0.14
Green LED	1	£0.23
1k Resistor	2	£0.21
10k Resistor	2	£0.28
1mF Capacitor	2	£0.18
100nf Capacitor	1	£0.18
CD4011B	1	£0.29
Buzzer	1	£1.93
Battery	1	£0.96
Battery holder	1	£1.01
Fuse	1	£1.00

Drivetrain		
Component	Number	Cost

Bearings	4	£4.19
Axles	2	£7.78
O rings	4	£3.93
Shaft Collar	4	£3.44

Total: £35.12