# CONTROLLED FLIGHT OF ROCKET POWERED CARS

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# ABSTRACT

This report investigates the feasibility of constructing a real-world version of the Octane car from the video game Rocket League. By translating the in-game physics of Unreal Engine into real-world physics, various components essential for the vehicle's operation were sized. Specifically, the components to be sized were the engine, rockets, and CMG. the project involved detailed testing to accomplish this, including a simple fall experiment to establish a real-world scale, an engine sizing test to determine power requirements, a rocket test to measure required thrust, and a rotation analysis to configure the CMG. Results showed the engine would require approximately 25kW of power to replicate in-game acceleration, while the rockets were required to generate a thrust of approximately 2.3kN. The CMG analysis showed a power requirement of about 4.6kW to manage the vehicle's orientation using an aluminum sphere with a 15cm radius and a maximum rpm of 800. Overall, replicating the Octane car's functions from Rocket League was determined to be theoretically achievable, however certain challenges remain. Specifically, the two most significant challenges are that further iterative analysis into the mass of the car must be conducted, and a method used to power the CMG must be analysed.

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# INTRODUCTION

Rocket League (RL) is a popular online video game released by Psyonix in 2015. The game features rocket-propelled flying cars which have the objective of knocking a car-sized soccer ball into a goal to score points. The game can be played in many formats and with varying amounts of players, however in most game modes, victory is simple. The player with more points at the end of 5 minutes is the victor.

This report draws motivation from rocket league being a fun game which applies a very interesting spin on game physics. There are many interactions which do not regularly occur in the real-world, such as the collisions between the car and ball, the cars driving on walls, and of course the ability for the cars to achieve controlled flight.

The player can choose from over 100 cars to compete with, however the most popular and most iconic, is known as the Octane and is pictured in figure 1.

*Figure 1 Octane Car from Rocket League*

The goal of this report will be to determine the feasibility of a real-life version of an Octane car from rocket league with the ability to fly and drive in the same way the game allows.

# BACKGROUND

The Octane can do many things a regular car cannot do, but this investigation will center on the differences which are most difficult to replicate in a real-world scenario.

## METHODOLOGY

Three main functions of the Octane will be analyzed, this includes its ability to drive forwards on the ground, propel itself using its rockets, and rotate its chassis midair without any external forces.

The general idea will be to size an Octane chassis, and then use in-game tests to see if the required components for the behaviour of the car could be made to fit the chassis. The components which will be analysed to perform the functions of the Octane will be an engine, rockets, and a control moment gyroscope (CMG). The engine will apply torque to the wheels to allow the Octane to drive on the ground, the rockets will provide thrust, enabling the Octane to fly, while the CMG will enable the rotation of the chassis while in midair to control the flight of the car.

## INFO ABOUT CMGS

CMGs are a technology which allows a body to rotate without using forces from another external body or releasing any of its own mass. They accomplish this by spinning a gimbal inside of the body in the opposite direction the body would like to spin [1]. The main application of CMGs is in satellites. Specifically, any time a satellite requires the ability to change its angle on a regular basis, a CMG is used. Notably, the International Space

Station (ISS) had a failure of one of their CMGs which led to an increase in fuel usage until the CMG could be replaced [2]. CMGs are also used in research applications such as the Hubble Space Telescope (HST) [3] and James Webb Space Telescope (JWST) [4] as both the HST and JWST require the ability to control their own orientation on a regular basis. For the Octane the CMG will likely require much more power than the kind which are typically used in industry. This is because the Octane will need to be able to spin very quickly, whereas satellites are more concerned with cost and reliability than the time taken to rotate between two angles.

## SCIENCEPLUGIN

In total, to size all the components, four tests will be conducted, a simple fall, an engine acceleration test, a rocket thrust test, and a rotational acceleration test.

The tool used to conduct these tests is known as SciencePlugin [5] and has some very useful functionality for this investigation. The tool is capable of outputting various properties of the car including the x, y and z location, the x, y and z velocity components, the rotation about each axis, and the angular velocity about each axis. These values will be critical to the analysis and each test.

SciencePlugin supports both live outputting of data to the screen while in-game, and the ability to record the values of the car at each frame and output the data into a .csv file. All of the tests were recorded using this method and are shown in appendix A. The analysis done in the tests uses a constant framerate of 50fps and assumes each frame is 0.02s

# FINDING A SCALE

The first requirement for sizing the chassis is to find its real-life dimensions. Rocket league is made in Unreal engine and uses unreal units (uu) as an internal length scale. The goal of this section will be to find a conversion from uu to metres.

## KINEMATICS

The method used to find this length scale will be to utilize kinematics. Using SciencePlugin, a fall of a known height can be tested. This fall can be timed, and can then be used in the equation for displacement under constant acceleration,

$$d = v_o t + \frac{1}{2} a t^2 \tag{1}$$

Where $d$ is the displacement, $v_o$ is the initial velocity, $t$ is time taken, and $a$ is acceleration.

Acceleration will be assumed to be gravity on earth, the test will have no initial velocity, and the displacement will be from resting position to ground level, so the equation can be rewritten as,

$$h = \frac{1}{2} g t^2 \tag{2}$$

where h is height, and g is gravity.

## SIMPLE FALL EXPERIMENT

The first experiment will be to record the velocities and height of the car as it falls from a known height. A fall from 500 uu was chosen. The data from the fall is shown in figures 2 and 3 and the fall took approximately 1.22s.

*Figure 3 Simple Fall Height Plot*

The data in the height plot makes sense, as we can see the height starts at 500 units, then falls quadratically to the ground, similar to objects in real life.

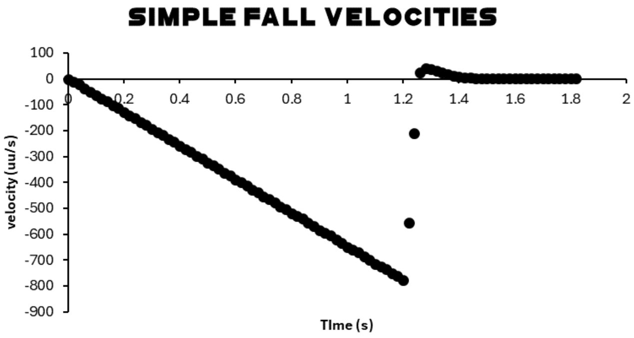

*Figure 2 Simple Fall Velocities Plot*

The velocities plot also makes senses as the start is at 0 and there is a linear decrease in the velocity. This linearity represents a constant change in velocity with respect to time, meaning the gravity in rocket league is constant and does not depend on other factors like velocity or height.

This is a useful result as it means the physics in rocket league follow the same fundamental principles as the real word. Using equation 2, the height of the fall is found to be 7.3m. It therefore follows that 7.3m and 500uu must be the same measurement and so 1m is equal to about 66uu.

### MASS

The second requirement for sizing the chassis was to find the mass of the car. This was done by finding the mass of a scale version of a real car. Specifically, a 2020 Honda civic was chosen for its roughly similar shape and lightweight design. The parameters for the car were found from the manufacturer's website. [2] and were used in equation 2.

To find the real-world length of an Octane, the in-game length was converted using the scale factor. The Octane is around 144 uu [1] which was converted to metres to find that the length of an Octane is approximately 2.17m which was also used in equation 3,

$$m = \left(\frac{L}{L_{Civic}}\right)^3 m_{Civic} \qquad (3)$$

where $m$ and $L$ are the mass and length of the Octane respectively, and $m_{Civic}$ and $L_{Civic}$ are the mass and length of the Honda Civic respectively.

Using the known values, the mass of the Octane is found to be 146kg.

## ENGINE SIZING

The first and simplest component required to emulate the behaviour of the Octane is the engine. The Octane works just like any normal car when driving on the ground. It uses an engine to apply torque to it's wheels and utilizes traction to accelerate forwards.

This section will find the power requirements of an engine capable of mimicking the behaviour of the Octane in-game and select an engine to be used in the chassis.

## ENGINE TEST

Engine sizing was done with the results of the second test. This test had the car start from rest and drive forwards in a straight line using only the accelerator and no rockets. The velocity at each frame was recorded and the kinetic energy was calculated for each frame using equation 4,

$$KE = \frac{1}{2} m v^2 \tag{4}$$

Where $KE$ is the kinetic energy, $m$ is the mass of the Octane and $v$ is the forward velocity of the car. The results of the test are shown in figures 4 and 5.

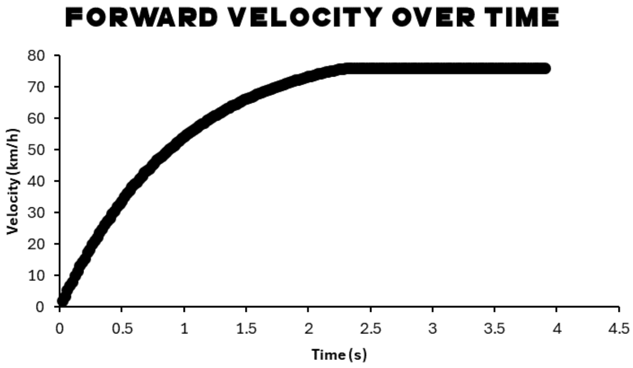

*Figure 4 Driving Test Octane Velocities*

The plot shows a gradual increase in velocity up to a maximum speed of approximately 76 km/h. This makes sense as driving forwards in rocket league eventually brings the player to a maximum speed just like how transmissions in real-life cars limit the maximum speed of the car they are designed around.

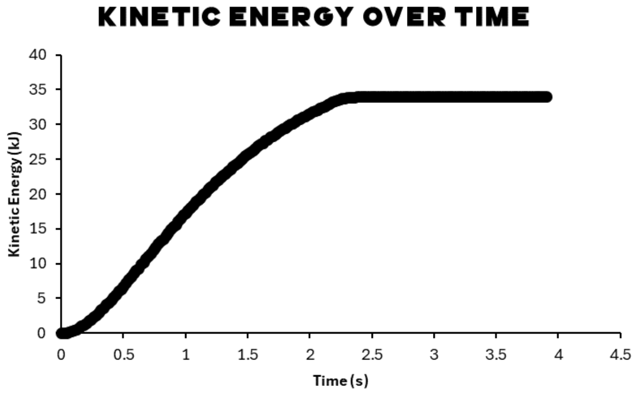

*Figure 5 Driving Test Octane Kinetic Energy*

The Kinetic energy data shows a very roughly linear increase in energy over time with the car capping out at a maximum kinetic energy when it reaches its maximum speed. The change in energy each frame can be determined and converted to a power measurement. The data is shown in figure 6.

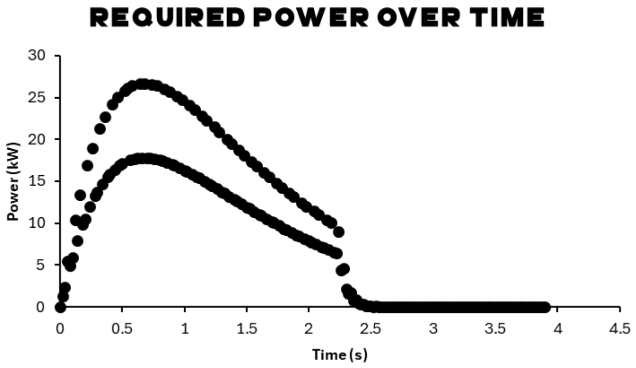

*Figure 6 Required Engine Power Driving Test*

The dataset is rather interesting as it shows two separate curves for the power required. This is because the game engine is adding more velocity to the car between certain frames compared to others. The reason the game engine does this is because the constant framerate of 50fps used for testing likely does not match the tick rate of the internal game engine. Some frames will have more game ticks between them than others. The true power required curve lies somewhere between the two visible curves in the plot. In order to be conservative however, the maximum of this plot was taken and the most power required between two frames was around 27kW.

## ENGINE SELECTION

With the knowledge of the power required for the Octane to accelerate, an engine can be chosen to fit the chassis. A small lightweight engine will be preferable to meet the goals of this section.

Luckily, the University of Alberta Formula SAE team has a similar problem to solve. The engine used inside of the UA-23 car uses a Turbocharged KTM 690 [4] which makes around 40kW of power when stock from the factory [5] and weighs around 40kg [6].This engine will suit the Octane nicely as it leaves plenty of headroom for possible efficiency losses, and is lightweight overall. For these reasons it is chosen as the engine of the Octane.

## THE ROCKET IN RL

This analysis section will focus on the rockets mounted to the back of the car. These rockets propel the Octane forward both on the ground and in the air allowing it to achieve speeds and flight paths that were not previously possible. The rockets will be sized to generate enough thrust to match the acceleration of the car inside of the game.

### ROCKET SCIENCE

The test conducted to determine the thrust of the rockets was very simple. The car will start at rest in the air with all forces, including gravity, disabled. Next, the rockets will be activated and SciencePlugin will be used to record the velocity of the car at each frame. The results of the test are shown in figure 7.

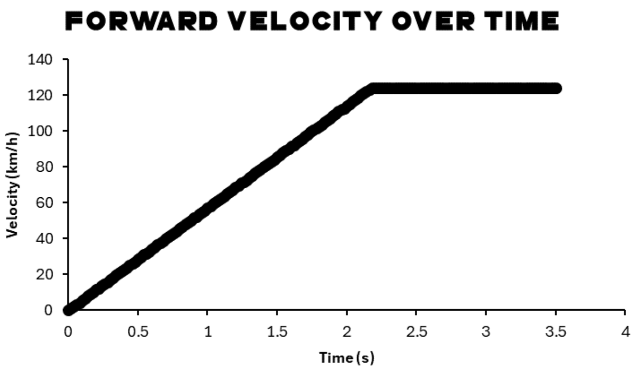

*Figure 4 Rocket Test Velocities*

The results of this test were very conclusive, with the Octane following a strictly linear increase in velocity over time until it capped at a maximum speed. This meant the required thruster force was easy to calculate. First, The slope of the acceleration was determined using the LINEST function in excel, then Newton's second law, equation 5, was used to find the required force.

$$F = ma \tag{5}$$

Where $F$ is the total force of the rockets, $m$ is the mass of the Octane and $a$ is the measured acceleration.

The acceleration was found to be 15.86 $m/s^2$ and the mass is known as 146kg. This resulted in a required thrust of around 2.3kN.

### SOME REAL ROCKETS

With the required thrust known, a rocket can be chosen. Various candidates were analysed, however a pair of 1.5kN rockets, named the "LYNX" hybrid rockets and designed by the company Novart space, were chosen [7]. This is because of their lightweight and compact design as the rocket engine was designed for drone takeoff. Each rocket weighs around 8 kg with fuel inside and has a length less than a metre long [7].

The pair of engines match the visuals in game of two rockets on the back of the Octane and will have a combined thrust of 3kN, while only adding 16kg to the mass of the car. These specifications are more than enough for a real-life Octane.

## OMG IT'S A CMG

The final portion of the analysis focuses on the requirements for a CMG which could allow the Octane to rotate in mid-air and control the direction of its rockets. Specifically, a maximum energy state, and a required power for the CMG will be needed.

### MOMENT OF INERTIA

First, similar to the mass of the car when sizing the engine, the moment of inertia of the Octane will be required. The Octane can rotate about all 3 axes at will, however, its total maximum angular velocity cannot exceed 5.5 rad/s [12]. Because of this, the worst-case scenario axis will be used for further calculations.

The Octane was assumed to be a rectangular prism with dimensions equal to the length, width, and height of the car. The known length will be used, but for the width and height the size of the in-game hitbox is used. The width and height of the hitbox are 84.2 uu (1.27m) and 36.16 uu (0.55m) respectively [13]. The hitbox is visualised in figure 8.

Figure 8 Octane Hitbox Visualisation

It can be seen that the width and height of the hitbox exceed the dimensions of the visual model, meaning the moment of inertia will be a conservative estimate. It can also be seen that the visual model of the car exceeds the length of the hitbox, which is why the known length is used instead of the hitbox length. The worst-case scenario moment of inertia will therefore be around the vertical axis, as the height is smaller than both the width and length.

The moment of inertia of a rectangular prism [14] about the axis running though its height is,

$$I = \frac{1}{12} m(L^2 + W^2) \tag{6}$$

Where $I$ is the moment of Inertia, $m$ is the mass of the car, $L$ is the length, and $W$ is the width. Using the known values the worst-case moment of inertia is found to be approximately 77.6 kg/m$^2$.

### ROTATION ANALYSIS

The experiment to determine the rotational capabilities of the Octane was similar to the rocket test. The Octane was first placed at rest with all forces, including gravity, disabled. Next, the car was rotated about it's vertical axis until it reached the maximum speed of 5.5rad/s. The angular velocity was recorded at each frame and the data is shown in figure 9.

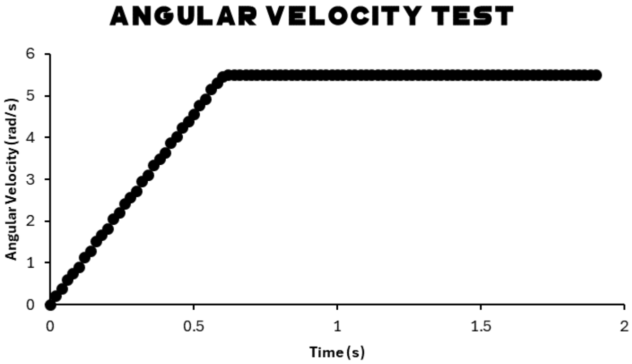

Figure 9 Rotation Test Angular Velocities

This plot looks correct as it starts at no angular velocity and eventually reaches the predicted maximum angular velocity of 5.5 rad/s. It can also be seen that the game adds a constant amount of angular velocity to the car over time. The total angular kinetic energy of the car at each frame can be calculated using equation 7 [15],

$$KE = \frac{1}{2} I \omega^2 \tag{7}$$

Where $KE$ is the kinetic energy, $I$ is the moment of inertia and $\omega$ is the angular velocity. The energy values are shown in figure 10.

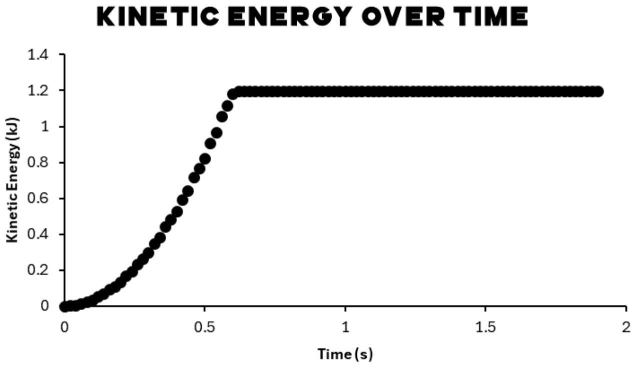

*Figure 5 Rotation Test Energy Values*

From the plot, the kinetic energy added per frame increases until the maximum angular velocity is reached. The car holds approximately 1.2kJ of energy at it's maximum angular velocity. The change in kinetic energy in each frame was determined similarly to the driving test and the results are shown in figure 11.

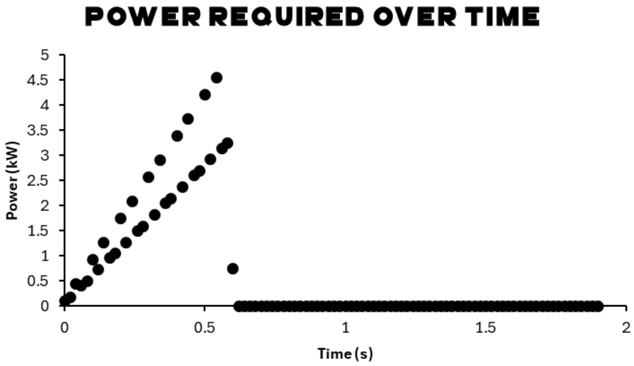

*Figure 6 Power Required Plot Rotation Test*

Like the driving test, there are two distinct curves which form from the data. This is, again, caused by the difference between the game engine's tick rate and the frame rate of the recorded data. The true power required curve lies between the two curves which are seen on the plot. For a conservative estimate, however, the maximum change in energy between any two frames was taken as the required power and was found to be approximately 4.6kW.

## CMG DESIGN

CMGs on the market typically cannot hold 1.2kJ of energy and all CMGs this large are in-house designs. For example, the ISS employs four 100kg steel flywheels which can rotate at up to 6600rpm [16]. This would certainly fulfill the requirements of the Octanes CMG but would also significantly increase the mass of the car. Because of this an in-house design will be needed.

The first requirement will be a motor which can produce 4.6kW to spin the mass inside of the CMG. 5kW motors are readily available from many manufacturers, and a unit from Golden Motor NA was selected. The unit weighs only 11kg and fulfills the needs of the Octane [17].

Next the flywheel size will need to be determined. For simplicity of analysis and to minimize overall size, the flywheel will be a sphere which is capable of being rotated in any direction. CMGs like this do exist but are typically smaller than is required for this application. Aluminum was chosen as the material to be used as it strikes a good balance between being lightweight and space efficient with a density of 2700kg/m$^3$ [18]. Denser materials such as steel or tungsten create less moment of inertia at the same mass and angular velocity. This is because the radius of the sphere will be smaller. Less dense materials such as plastic begin to create spheres which may be difficult to fit inside of the car.

A limit of 39kg was chosen for the sphere so that the CMG will be 50kg in total.

With this, the size of the sphere and the maximum angular velocity of the sphere can be calculated. The formula for the mass of a uniform sphere is,

$$m = \frac{4}{3}\pi r^3 \rho \tag{8}$$

Where $m$ is mass of the sphere, $r$ is the radius of the sphere, and $\rho$ is the density. Solving for $r$, the radius is found to be approximately 15cm. The equation for the moment of inertia of a sphere [19] is,

$$I = \frac{2}{5} m r^2 \tag{9}$$

Where $I$ is the moment of Inertia of the sphere. Substituting eq. 8 into eq. 9 and eq. 9 into eq. 7, A formula for the kinetic energy of a sphere is in terms of it's radius.

$$KE = \frac{4\pi}{15} r^5 w^2 \tag{10}$$

Using the known radius and required kinetic energy, the maximum angular velocity of the CMG will be approximately 800rpm, well within a reasonable range of operation.

# DISCUSSION

Based on the results of each section of the analysis, it seems plausible that a real-life Octane…

**COULD EXIST!**

## ANALYSIS ASSUMPTIONS

There are, however, many caveats based off the assumptions made in the analysis, they are listed in order of use in the table below.

*Table 1 List of Analysis Assumptions*

| Section | Assumption |
|---|---|
| Scale | Rocket league happens on earth and therefore g=9.81m/s$^2$ |
| Engine | The top speed of 76km/h is achievable through transmission design |
| Rockets | The rocket fuel required to operate the pair of Lynx rockets as well as its containment system is negligible in mass |
| CMG | The Octane is a rectangular prism |
| CMG | The CMG will not need a battery and will draw from power generated by the engine |
| CMG | The CMG sphere will be 39kg |

Each of these assumptions is important to its respective analysis section. Some are required for the analysis to hold, and others could be changed or removed with additional analysis. Each requires its own discussion.

The first assumption is necessary as the goal of this report was to determine the feasibility of a "real-world" version of the Octane and not to determine the properties of the in-game world.

The top speed assumption is reasonable as this is a very achievable top speed for a go-kart sized vehicle. Many go karts exceed this top speed [20], and so the transmission design of the Octane could reasonably allow these speeds.

The fuel assumption is reasonable as the required operating time for the rockets is only around three seconds. The Octane can control its flight, but it cannot sustain it.

The rectangular prism assumption is reasonable as it gives a conservative estimate for the moment of inertia of the Octane, the real value is likely much lower.

The lack of a battery is a significant assumption in the analysis of the CMG. The CMG requires a lot of power to operate, and while it is possible to run from an energy standpoint using the engine, this would require a non-trivial electrical system which is much larger than that of a regular car. The power unit in the Octane would likely need to mimic that of a hybrid car, which could add weight to the analysis.

Finally, The CMG was chosen to be 39kg. This mass was chosen arbitrarily to keep the total mass of the CMG in line with the engine and limit the required maximum angular velocity of the sphere. It is possible that a smaller mass could be assumed which would require higher angular velocities to achieve the same behaviour.

## DISCUSSION ASSUMPTIONS

The leap from sizing the engine, rockets and CMG to claiming that a real-world Octane is possible requires certain assumptions about the values that were calculated as well as assumptions about the nature of what it means to be a “real-world” Octane. There are three main points that need to be analyzed.

The first of these is the assumption that the mass of the calculated components is not large enough to undermine the analysis. In total, between the three components, 106k g was added to the car. This is an increase of approximately 70% in the total mass. This initially sounds like a very large increase, but two things must be considered. First is that the mass of the engine of the Honda Civic is accounted for in the original 146 kg, which means the 70% figure is double counting the engines. Without the mass of the selected engine, the increase is only around 40%. The second consideration is that the engine rocket and CMG are all likely quite oversized. For both the engine and CMG, the maximum of the power required plot was taken when the true maximum power was in between the two curves. The moment of inertia was also likely over-estimated by a large amount due to the rectangular prism assumption, and the rockets make 700 N more thrust than is required. Because of this, the mass increase does not undermine the analysis, however a deeper examination on the mass will be required in further analysis.

Second, the real-world Octane is missing two abilities that the in-game Octane has. These are the ability to jump and to flip. Jumping causes the car to gain velocity opposite to the direction that the floor of the hitbox is facing, while flipping causes the car to gain momentum in the direction the player is instructing the car to move. Both abilities are not required for the Octane to sustain flight, but they are very useful for the ability to begin a flight. The real-world Octane will need to drive off a ramp to begin it’s flight. The purpose of the report, however, was to determine if flying and driving in the same way as is seen in-game, and jumping and flipping are only auxiliary to that goal, not necessary.

Finally, the Octane is assumed to have no driver and will be controlled remotely. This is a reasonable assumption as a 30cm diameter Aluminum sphere has been placed at its core, and cars in rocket league are controlled remotely from inputs to the game. It is also necessary to minimize weight, and likely safety as small malfunctions in the CMG could easily cause the car to lose control during flight.

### SENSITIVITY

In the engine sizing analysis, a point between the two curves in figure 4 could have been chosen which would lead to a required power of around 20kW. The chosen engine had a power output of 40kW, and a more suitable engine may be able to be selected which is lighter weight and closer to the 20kW requirement.

The rocket analysis was very straightforward, however, it is interesting to note that the rockets contributed very little to the overall weight. This means a third or fourth rocket could easily be added to bring the thrust to 4.5 or 6 kN.

The CMG analysis hinged heavily on the initial assumption of the mass of the sphere. To reduce the mass further, it could be possible to use a smaller radius sphere and increase the angular velocity. For example, if it is assumed that the mass could spin at the 6600rpm that the ISS employs, the mass of the sphere would only need to be 4kg and the sphere would have a radius of 7cm.

## FURTHER ANALYSIS

As mentioned in the discussion, further analysis is required regarding the mass of the car. Iterative design will need to be employed as the mass of the car is required to size an appropriate engine, rocket, and CMG, but the components affect the total mass.

It may also be possible to emulate the jumping using real world mechanics. The suspension could be loaded in combination with down-facing rockets to allow the car to “jump” in the air and begin its flight.

The landing of the Octane from a flight could also be analyzed, and suspension properties required to absorb the energy of the landing could be considered.

## CONCLUSION

Rocket League is a fun physics based flying car soccer game where the cars fly around to score goals and win the game. The most popular car, the Octane, was analyzed in various scenarios to determine if it’s flight and driving could be emulated in real life.

Three components were analyzed: the engine, the rockets, and a CMG. Each component was sized so that it could model the behaviour of the Octane in-game. Four tests were conducted to determine the relevant physics to size the components: a simple fall test, a driving test, a rocket test, and a rotation test.

The sizing concluded that it is likely feasible for an Octane to exist in real life, requiring a 25kW engine, 2.3kN thrust rocket and a CMG with 4.6kW of power which can hold 1.2kJ of energy.

Further analysis may include iterative design, the ability to jump and possible landing physics.

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# APPENDIX A – TEST VALUES

This appendix has all of the data for each test output from SciencePlugin as well as the calculated values fro each frame. The data is shown in the order of tests done. First the fall test, then the driving test, then the rocket test, and finally the Rotation test.

## FALL TEST

| Frame | Time (s) | Height (uu) | Velocity (uu/s) | Velocity (km/h) |
|---|---|---|---|---|
| 0 | 0 | 500 | 0 | 0 |
| 1 | 0.02 | 499.9 | -10.8 | -0.58 |
| 2 | 0.04 | 499.5 | -21.6 | -1.17 |
| 3 | 0.06 | 498.7 | -37.9 | -2.04 |
| 4 | 0.08 | 498 | -48.7 | -2.63 |
| 5 | 0.1 | 496.5 | -64.9 | -3.5 |
| 6 | 0.12 | 495.2 | -75.7 | -4.09 |
| 7 | 0.14 | 493.8 | -86.6 | -4.67 |
| 8 | 0.16 | 491.4 | -103 | -5.55 |
| 9 | 0.18 | 489.6 | -114 | -6.13 |
| 10 | 0.2 | 486.4 | -130 | -7 |
| 11 | 0.22 | 484.1 | -141 | -7.59 |
| 12 | 0.24 | 481.7 | -151 | -8.17 |
| 13 | 0.26 | 477.6 | -168 | -9.05 |
| 14 | 0.28 | 474.7 | -179 | -9.63 |
| 15 | 0.3 | 469.9 | -195 | -10.5 |
| 16 | 0.32 | 466.6 | -206 | -11.1 |
| 17 | 0.34 | 463 | -216 | -11.7 |
| 18 | 0.36 | 457.3 | -233 | -12.6 |
| 19 | 0.38 | 453.3 | -243 | -13.1 |
| 20 | 0.4 | 447 | -260 | -14 |
| 21 | 0.42 | 442.5 | -271 | -14.6 |
| 22 | 0.44 | 437.9 | -281 | -15.2 |
| 23 | 0.46 | 430.6 | -298 | -16.1 |
| 24 | 0.48 | 425.5 | -308 | -16.6 |
| 25 | 0.5 | 417.5 | -325 | -17.5 |
| 26 | 0.52 | 411.9 | -335 | -18.1 |
| 27 | 0.54 | 406.2 | -346 | -18.7 |
| 28 | 0.56 | 397.3 | -362 | -19.6 |
| 29 | 0.58 | 391.1 | -373 | -20.1 |
| 30 | 0.6 | 381.5 | -390 | -21 |
| 31 | 0.62 | 374.9 | -400 | -21.6 |
| 32 | 0.64 | 368.1 | -411 | -22.2 |
| 33 | 0.66 | 357.5 | -427 | -23.1 |
| 34 | 0.68 | 350.2 | -438 | -23.6 |
| 35 | 0.7 | 339 | -454 | -24.5 |
| 36 | 0.72 | 331.3 | -465 | -25.1 |
| 37 | 0.74 | 323.4 | -476 | -25.7 |
| 38 | 0.76 | 311.2 | -492 | -26.6 |
| 39 | 0.78 | 302.9 | -503 | -27.1 |
| 40 | 0.8 | 290.1 | -519 | -28 |
| 41 | 0.82 | 281.3 | -530 | -28.6 |
| 42 | 0.84 | 272.3 | -541 | -29.2 |
| 43 | 0.86 | 258.5 | -557 | -30.1 |
| 44 | 0.88 | 249.1 | -568 | -30.6 |
| 45 | 0.9 | 234.6 | -584 | -31.5 |
| 46 | 0.92 | 224.7 | -595 | -32.1 |
| 47 | 0.94 | 214.7 | -606 | -32.7 |
| 48 | 0.96 | 199.3 | -622 | -33.6 |
| 49 | 0.98 | 188.8 | -633 | -34.1 |
| 50 | 1 | 174.5 | -649 | -35 |
| 51 | 1.02 | 161.7 | -660 | -35.6 |
| 52 | 1.04 | 150.6 | -671 | -36.2 |
| 53 | 1.06 | 133.5 | -687 | -37.1 |
| 54 | 1.08 | 122 | -698 | -37.7 |
| 55 | 1.1 | 104.2 | -714 | -38.5 |
| 56 | 1.12 | 92.19 | -725 | -39.1 |
| 57 | 1.14 | 79.97 | -736 | -39.7 |
| 58 | 1.16 | 61.3 | -752 | -40.6 |
| 59 | 1.18 | 48.63 | -763 | -41.2 |
| 60 | 1.2 | 29.29 | -779 | -42 |
| 61 | 1.22 | 19.13 | -555 | -29.9 |
| 62 | 1.24 | 13.64 | -212 | -11.4 |
| 63 | 1.26 | 13.07 | 24.46 | 1.32 |
| 64 | 1.28 | 13.72 | 40.29 | 2.174 |
| 65 | 1.3 | 14.7 | 37.33 | 2.014 |
| 66 | 1.32 | 15.25 | 31.57 | 1.703 |
| 67 | 1.34 | 15.7 | 25.4 | 1.37 |
| 68 | 1.36 | 16.19 | 17.25 | 0.931 |
| 69 | 1.38 | 16.43 | 12.96 | 0.699 |
| 70 | 1.4 | 16.67 | 8.16 | 0.44 |
| 71 | 1.42 | 16.78 | 5.88 | 0.317 |
| 72 | 1.44 | 16.85 | 4.18 | 0.226 |
| 73 | 1.46 | 16.92 | 2.54 | 0.137 |
| 74 | 1.48 | 16.96 | 1.81 | 0.098 |
| 75 | 1.5 | 16.99 | 1.04 | 0.056 |
| 76 | 1.52 | 17.01 | 0.7 | 0.038 |
| 77 | 1.54 | 17.01 | 0.45 | 0.024 |
| 78 | 1.56 | 17.01 | 0.32 | 0.017 |
| 79 | 1.58 | 17.01 | 0.29 | 0.016 |
| 80 | 1.6 | 17.01 | 0.27 | 0.015 |
| 81 | 1.62 | 17.01 | 0.27 | 0.015 |
| 82 | 1.64 | 17.01 | 0.27 | 0.015 |
| 83 | 1.66 | 17.01 | 0.27 | 0.015 |
| 84 | 1.68 | 17.01 | 0.27 | 0.015 |
| 85 | 1.7 | 17.01 | 0.27 | 0.015 |
| 86 | 1.72 | 17.01 | 0.27 | 0.015 |
| 87 | 1.74 | 17.01 | 0.27 | 0.015 |
| 88 | 1.76 | 17.01 | 0.27 | 0.015 |
| 89 | 1.78 | 17.01 | 0.27 | 0.015 |
| 90 | 1.8 | 17.01 | 0.27 | 0.015 |
| 91 | 1.82 | 17.01 | 0.27 | 0.015 |

# DRIVING TEST

| Frame | Time (s) | Kinetic Energy (kJ) | Velocity (km/h) | ΔKinetic Energy (kJ) |
|---|---|---|---|---|
| 0 | 0 | 2E-09 | -0 | 0 |
| 1 | 0.02 | 0.027 | 2.139 | 1.344 |
| 2 | 0.04 | 0.073 | 3.534 | 2.326 |
| 3 | 0.06 | 0.183 | 5.583 | 5.489 |
| 4 | 0.08 | 0.281 | 6.92 | 4.911 |
| 5 | 0.1 | 0.398 | 8.234 | 5.852 |
| 6 | 0.12 | 0.607 | 10.16 | 10.43 |
| 7 | 0.14 | 0.767 | 11.42 | 7.979 |
| 8 | 0.16 | 1.035 | 13.27 | 13.4 |
| 9 | 0.18 | 1.231 | 14.47 | 9.829 |
| 10 | 0.2 | 1.441 | 15.66 | 10.49 |
| 11 | 0.22 | 1.779 | 17.4 | 16.9 |
| 12 | 0.24 | 2.019 | 18.53 | 11.98 |
| 13 | 0.26 | 2.398 | 20.2 | 18.97 |
| 14 | 0.28 | 2.663 | 21.29 | 13.25 |
| 15 | 0.3 | 2.937 | 22.36 | 13.71 |
| 16 | 0.32 | 3.364 | 23.93 | 21.33 |
| 17 | 0.34 | 3.658 | 24.95 | 14.7 |
| 18 | 0.36 | 4.112 | 26.45 | 22.71 |
| 19 | 0.38 | 4.423 | 27.43 | 15.53 |
| 20 | 0.4 | 4.739 | 28.4 | 15.81 |
| 21 | 0.42 | 5.223 | 29.81 | 24.2 |
| 22 | 0.44 | 5.551 | 30.74 | 16.42 |
| 23 | 0.46 | 6.052 | 32.09 | 25.02 |
| 24 | 0.48 | 6.389 | 32.97 | 16.88 |
| 25 | 0.5 | 6.731 | 33.84 | 17.08 |
| 26 | 0.52 | 7.248 | 35.12 | 25.85 |
| 27 | 0.54 | 7.77 | 36.36 | 26.12 |
| 28 | 0.56 | 8.121 | 37.18 | 17.53 |
| 29 | 0.58 | 8.65 | 38.37 | 26.44 |
| 30 | 0.6 | 9.004 | 39.14 | 17.69 |
| 31 | 0.62 | 9.359 | 39.91 | 17.74 |
| 32 | 0.64 | 9.892 | 41.03 | 26.67 |
| 33 | 0.66 | 10.25 | 41.76 | 17.79 |
| 34 | 0.68 | 10.78 | 42.83 | 26.7 |
| 35 | 0.7 | 11.14 | 43.54 | 17.78 |
| 36 | 0.72 | 11.49 | 44.22 | 17.76 |
| 37 | 0.74 | 12.02 | 45.24 | 26.59 |
| 38 | 0.76 | 12.38 | 45.9 | 17.67 |
| 39 | 0.78 | 12.91 | 46.86 | 26.41 |
| 40 | 0.8 | 13.26 | 47.5 | 17.52 |
| 41 | 0.82 | 13.61 | 48.12 | 17.44 |
| 42 | 0.84 | 14.13 | 49.03 | 26.04 |
| 43 | 0.86 | 14.47 | 49.62 | 17.25 |
| 44 | 0.88 | 14.99 | 50.5 | 25.71 |
| 45 | 0.9 | 15.33 | 51.07 | 17.02 |
| 46 | 0.92 | 15.66 | 51.63 | 16.91 |
| 47 | 0.94 | 16.17 | 52.45 | 25.16 |
| 48 | 0.96 | 16.5 | 52.99 | 16.63 |
| 49 | 0.98 | 16.99 | 53.78 | 24.73 |
| 50 | 1 | 17.32 | 54.29 | 16.32 |
| 51 | 1.02 | 17.64 | 54.8 | 16.18 |
| 52 | 1.04 | 18.13 | 55.54 | 24.05 |
| 53 | 1.06 | 18.44 | 56.02 | 15.88 |
| 54 | 1.08 | 18.91 | 56.73 | 23.54 |
| 55 | 1.1 | 19.22 | 57.2 | 15.53 |
| 56 | 1.12 | 19.53 | 57.65 | 15.38 |
| 57 | 1.14 | 19.99 | 58.32 | 22.8 |
| 58 | 1.16 | 20.29 | 58.76 | 15.01 |
| 59 | 1.18 | 20.73 | 59.4 | 22.25 |
| 60 | 1.2 | 21.03 | 59.82 | 14.65 |
| 61 | 1.22 | 21.32 | 60.23 | 14.5 |
| 62 | 1.24 | 21.75 | 60.83 | 21.47 |
| 63 | 1.26 | 22.03 | 61.22 | 14.1 |
| 64 | 1.28 | 22.45 | 61.8 | 20.89 |
| 65 | 1.3 | 22.72 | 62.18 | 13.74 |
| 66 | 1.32 | 22.99 | 62.55 | 13.58 |
| 67 | 1.34 | 23.39 | 63.09 | 20.08 |
| 68 | 1.36 | 23.66 | 63.45 | 13.22 |
| 69 | 1.38 | 24.05 | 63.97 | 19.51 |
| 70 | 1.4 | 24.3 | 64.31 | 12.83 |
| 71 | 1.42 | 24.56 | 64.65 | 12.67 |
| 72 | 1.44 | 24.93 | 65.14 | 18.72 |
| 73 | 1.46 | 25.18 | 65.46 | 12.3 |
| 74 | 1.48 | 25.54 | 65.93 | 18.14 |
| 75 | 1.5 | 25.78 | 66.23 | 11.92 |
| 76 | 1.52 | 26.01 | 66.54 | 11.76 |
| 77 | 1.54 | 26.36 | 66.98 | 17.35 |
| 78 | 1.56 | 26.59 | 67.27 | 11.41 |
| 79 | 1.58 | 26.93 | 67.69 | 16.81 |
| 80 | 1.6 | 27.15 | 67.97 | 11.03 |
| 81 | 1.62 | 27.36 | 68.24 | 10.88 |
| 82 | 1.64 | 27.69 | 68.64 | 16.08 |
| 83 | 1.66 | 27.9 | 68.9 | 10.51 |
| 84 | 1.68 | 28.21 | 69.28 | 15.51 |
| 85 | 1.7 | 28.41 | 69.53 | 10.17 |
| 86 | 1.72 | 28.61 | 69.78 | 10.03 |
| 87 | 1.74 | 28.91 | 70.14 | 14.79 |
| 88 | 1.76 | 29.1 | 70.37 | 9.711 |
| 89 | 1.78 | 29.39 | 70.72 | 14.29 |
| 90 | 1.8 | 29.57 | 70.94 | 9.363 |
| 91 | 1.82 | 29.76 | 71.16 | 9.235 |
| 92 | 1.84 | 30.03 | 71.49 | 13.61 |
| 93 | 1.86 | 30.21 | 71.7 | 8.92 |
| 94 | 1.88 | 30.47 | 72.01 | 13.14 |
| 95 | 1.9 | 30.64 | 72.21 | 8.596 |
| 96 | 1.92 | 30.81 | 72.41 | 8.482 |
| 97 | 1.94 | 31.06 | 72.7 | 12.47 |
| 98 | 1.96 | 31.23 | 72.9 | 8.17 |
| 99 | 1.98 | 31.47 | 73.18 | 12.04 |
| 100 | 2 | 31.62 | 73.36 | 7.874 |
| 101 | 2.02 | 31.78 | 73.54 | 7.754 |
| 102 | 2.04 | 32.01 | 73.8 | 11.44 |
| 103 | 2.06 | 32.16 | 73.98 | 7.472 |
| 104 | 2.08 | 32.38 | 74.23 | 11.02 |
| 105 | 2.1 | 32.52 | 74.39 | 7.209 |
| 106 | 2.12 | 32.66 | 74.56 | 7.107 |
| 107 | 2.14 | 32.87 | 74.79 | 10.44 |
| 108 | 2.16 | 33.01 | 74.95 | 6.836 |
| 109 | 2.18 | 33.21 | 75.18 | 10.07 |
| 110 | 2.2 | 33.34 | 75.33 | 6.584 |
| 111 | 2.22 | 33.47 | 75.47 | 6.478 |
| 112 | 2.24 | 33.65 | 75.67 | 9.009 |
| 113 | 2.26 | 33.74 | 75.77 | 4.369 |
| 114 | 2.28 | 33.83 | 75.88 | 4.615 |
| 115 | 2.3 | 33.88 | 75.92 | 2.142 |
| 116 | 2.32 | 33.91 | 75.96 | 1.613 |
| 117 | 2.34 | 33.94 | 76 | 1.686 |
| 118 | 2.36 | 33.96 | 76.02 | 0.795 |
| 119 | 2.38 | 33.97 | 76.03 | 0.819 |
| 120 | 2.4 | 33.98 | 76.04 | 0.386 |
| 121 | 2.42 | 33.99 | 76.05 | 0.289 |
| 122 | 2.44 | 33.99 | 76.06 | 0.313 |
| 123 | 2.46 | 34 | 76.06 | 0.145 |
| 124 | 2.48 | 34 | 76.06 | 0.145 |
| 125 | 2.5 | 34 | 76.07 | 0.072 |
| 126 | 2.52 | 34 | 76.07 | 0.048 |
| 127 | 2.54 | 34 | 76.07 | 0.072 |
| 128 | 2.56 | 34 | 76.07 | 0 |
| 129 | 2.58 | 34 | 76.07 | 0 |

|  |  |  |  |  |
|---|---|---|---|---|
| 130 | 2.6 | 34 | 76.07 | 0 |
| 131 | 2.62 | 34 | 76.07 | 0 |
| 132 | 2.64 | 34 | 76.07 | 0 |
| 133 | 2.66 | 34 | 76.07 | 0 |
| 134 | 2.68 | 34 | 76.07 | 0 |
| 135 | 2.7 | 34 | 76.07 | 0 |
| 136 | 2.72 | 34 | 76.07 | 0 |
| 137 | 2.74 | 34 | 76.07 | 0 |
| 138 | 2.76 | 34 | 76.07 | 0 |
| 139 | 2.78 | 34 | 76.07 | 0 |
| 140 | 2.8 | 34 | 76.07 | 0 |
| 141 | 2.82 | 34 | 76.07 | 0 |
| 142 | 2.84 | 34 | 76.07 | 0 |
| 143 | 2.86 | 34 | 76.07 | 0 |
| 144 | 2.88 | 34 | 76.07 | 0 |
| 145 | 2.9 | 34 | 76.07 | 0 |
| 146 | 2.92 | 34 | 76.07 | 0 |
| 147 | 2.94 | 34 | 76.07 | 0 |
| 148 | 2.96 | 34 | 76.07 | 0 |
| 149 | 2.98 | 34 | 76.07 | 0 |
| 150 | 3 | 34 | 76.07 | 0 |
| 151 | 3.02 | 34 | 76.07 | 0 |
| 152 | 3.04 | 34 | 76.07 | 0 |
| 153 | 3.06 | 34 | 76.07 | 0 |
| 154 | 3.08 | 34 | 76.07 | 0 |
| 155 | 3.1 | 34 | 76.07 | 0 |
| 156 | 3.12 | 34 | 76.07 | 0 |
| 157 | 3.14 | 34 | 76.07 | 0 |
| 158 | 3.16 | 34 | 76.07 | 0 |
| 159 | 3.18 | 34 | 76.07 | 0 |
| 160 | 3.2 | 34 | 76.07 | 0 |
| 161 | 3.22 | 34 | 76.07 | 0 |
| 162 | 3.24 | 34 | 76.07 | 0 |
| 163 | 3.26 | 34 | 76.07 | 0 |
| 164 | 3.28 | 34 | 76.07 | 0 |
| 165 | 3.3 | 34 | 76.07 | 0 |
| 166 | 3.32 | 34 | 76.07 | 0 |
| 167 | 3.34 | 34 | 76.07 | 0 |
| 168 | 3.36 | 34 | 76.07 | 0 |
| 169 | 3.38 | 34 | 76.07 | 0 |
| 170 | 3.4 | 34 | 76.07 | 0 |
| 171 | 3.42 | 34 | 76.07 | 0 |
| 172 | 3.44 | 34 | 76.07 | 0 |
| 173 | 3.46 | 34 | 76.07 | 0 |
| 174 | 3.48 | 34 | 76.07 | 0 |
| 175 | 3.5 | 34 | 76.07 | 0 |
| 176 | 3.52 | 34 | 76.07 | 0 |
| 177 | 3.54 | 34 | 76.07 | 0 |
| 178 | 3.56 | 34 | 76.07 | 0 |
| 179 | 3.58 | 34 | 76.07 | 0 |
| 180 | 3.6 | 34 | 76.07 | 0 |
| 181 | 3.62 | 34 | 76.07 | 0 |
| 182 | 3.64 | 34 | 76.07 | 0 |
| 183 | 3.66 | 34 | 76.07 | 0 |
| 184 | 3.68 | 34 | 76.07 | 0 |
| 185 | 3.7 | 34 | 76.07 | 0 |
| 186 | 3.72 | 34 | 76.07 | 0 |
| 187 | 3.74 | 34 | 76.07 | 0 |
| 188 | 3.76 | 34 | 76.07 | 0 |
| 189 | 3.78 | 34 | 76.07 | 0 |
| 190 | 3.8 | 34 | 76.07 | 0 |
| 191 | 3.82 | 34 | 76.07 | 0 |
| 192 | 3.84 | 34 | 76.07 | 0 |
| 193 | 3.86 | 34 | 76.07 | 0 |
| 194 | 3.88 | 34 | 76.07 | 0 |
| 195 | 3.9 | 34 | 76.07 | 0 |

## ROCKET TEST

| Frame | Time (s) | Velocity (uu/s) | Velocity (km/h) | ΔVelocity (km/h) |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 1 | 0.02 | 17.08 | 0.921 | 0.921 |
| 2 | 0.04 | 43.54 | 2.349 | 1.427 |
| 3 | 0.06 | 61.18 | 3.301 | 0.952 |
| 4 | 0.08 | 78.82 | 4.252 | 0.952 |
| 5 | 0.1 | 105.3 | 5.68 | 1.427 |
| 6 | 0.12 | 122.9 | 6.631 | 0.952 |
| 7 | 0.14 | 149.4 | 8.059 | 1.427 |
| 8 | 0.16 | 167 | 9.011 | 0.952 |
| 9 | 0.18 | 184.7 | 9.962 | 0.952 |
| 10 | 0.2 | 211.1 | 11.39 | 1.427 |
| 11 | 0.22 | 228.8 | 12.34 | 0.952 |
| 12 | 0.24 | 255.2 | 13.77 | 1.427 |
| 13 | 0.26 | 272.9 | 14.72 | 0.952 |
| 14 | 0.28 | 290.5 | 15.67 | 0.952 |
| 15 | 0.3 | 317 | 17.1 | 1.427 |
| 16 | 0.32 | 334.6 | 18.05 | 0.952 |
| 17 | 0.34 | 361.1 | 19.48 | 1.427 |
| 18 | 0.36 | 378.7 | 20.43 | 0.952 |
| 19 | 0.38 | 396.3 | 21.38 | 0.952 |
| 20 | 0.4 | 422.8 | 22.81 | 1.427 |
| 21 | 0.42 | 440.4 | 23.76 | 0.952 |
| 22 | 0.44 | 466.9 | 25.19 | 1.427 |
| 23 | 0.46 | 484.5 | 26.14 | 0.952 |
| 24 | 0.48 | 502.2 | 27.09 | 0.952 |
| 25 | 0.5 | 528.6 | 28.52 | 1.427 |
| 26 | 0.52 | 546.3 | 29.47 | 0.952 |
| 27 | 0.54 | 572.7 | 30.9 | 1.427 |
| 28 | 0.56 | 590.4 | 31.85 | 0.952 |
| 29 | 0.58 | 608 | 32.8 | 0.952 |
| 30 | 0.6 | 634.5 | 34.23 | 1.427 |
| 31 | 0.62 | 652.1 | 35.18 | 0.952 |
| 32 | 0.64 | 678.6 | 36.61 | 1.427 |
| 33 | 0.66 | 696.2 | 37.56 | 0.952 |
| 34 | 0.68 | 713.9 | 38.51 | 0.952 |
| 35 | 0.7 | 740.3 | 39.94 | 1.427 |
| 36 | 0.72 | 758 | 40.89 | 0.952 |
| 37 | 0.74 | 784.4 | 42.32 | 1.427 |

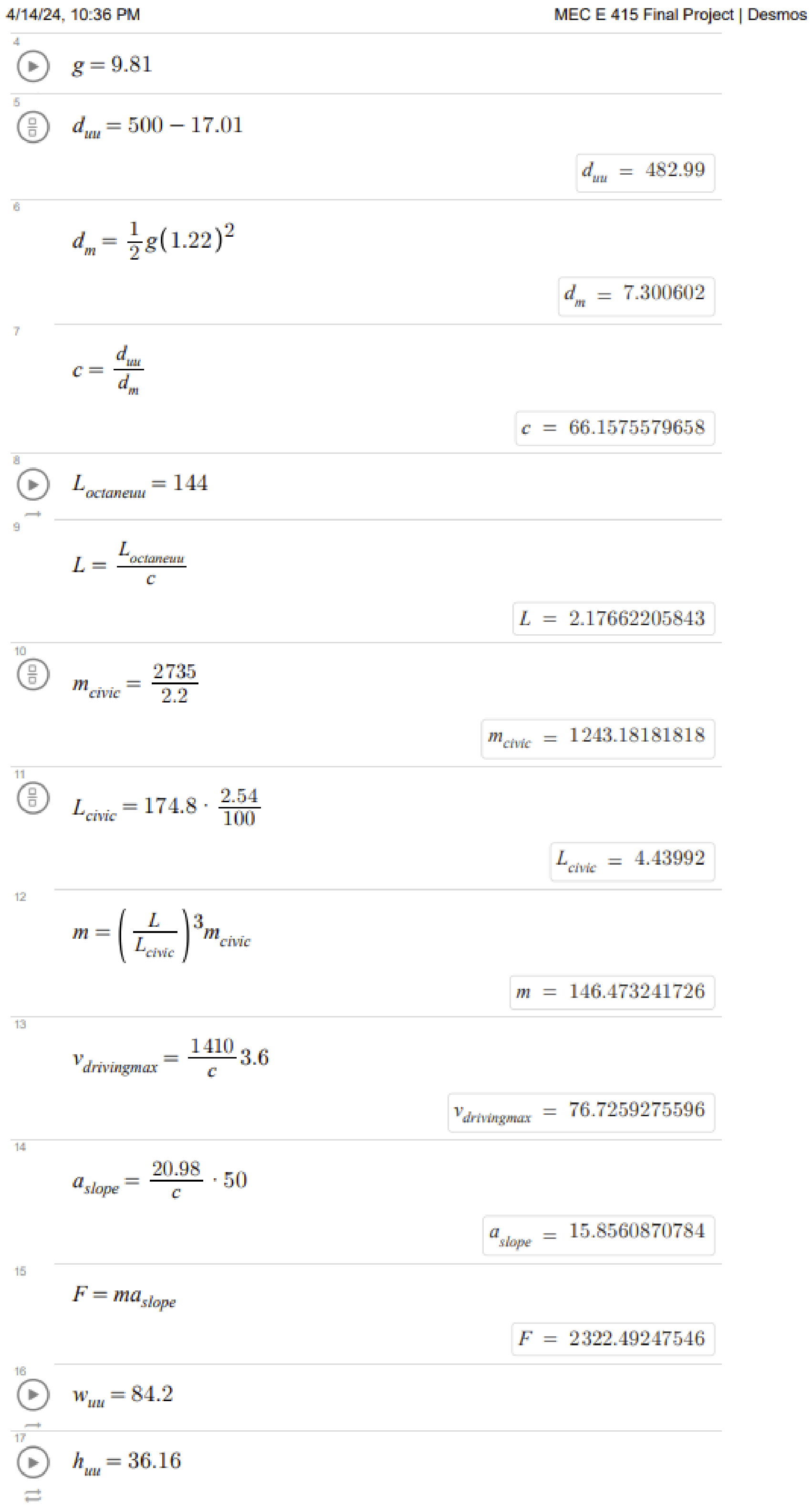
| | | | | |
|---|---|---|---|---|
| 38 | 0.76 | 802.1 | 43.27 | 0.952 |
| 39 | 0.78 | 819.7 | 44.22 | 0.952 |
| 40 | 0.8 | 846.2 | 45.65 | 1.427 |
| 41 | 0.82 | 863.8 | 46.6 | 0.952 |
| 42 | 0.84 | 890.3 | 48.03 | 1.427 |
| 43 | 0.86 | 907.9 | 48.98 | 0.952 |
| 44 | 0.88 | 925.5 | 49.93 | 0.952 |
| 45 | 0.9 | 952 | 51.36 | 1.427 |
| 46 | 0.92 | 969.6 | 52.31 | 0.952 |
| 47 | 0.94 | 996.1 | 53.74 | 1.427 |
| 48 | 0.96 | 1014 | 54.69 | 0.952 |
| 49 | 0.98 | 1031 | 55.64 | 0.952 |
| 50 | 1 | 1058 | 57.07 | 1.427 |
| 51 | 1.02 | 1075 | 58.02 | 0.952 |
| 52 | 1.04 | 1102 | 59.45 | 1.427 |
| 53 | 1.06 | 1120 | 60.4 | 0.952 |
| 54 | 1.08 | 1137 | 61.35 | 0.952 |
| 55 | 1.1 | 1164 | 62.78 | 1.427 |
| 56 | 1.12 | 1181 | 63.73 | 0.952 |
| 57 | 1.14 | 1208 | 65.16 | 1.427 |
| 58 | 1.16 | 1225 | 66.11 | 0.952 |
| 59 | 1.18 | 1243 | 67.06 | 0.952 |
| 60 | 1.2 | 1270 | 68.49 | 1.427 |
| 61 | 1.22 | 1287 | 69.44 | 0.952 |
| 62 | 1.24 | 1314 | 70.87 | 1.427 |
| 63 | 1.26 | 1331 | 71.82 | 0.952 |
| 64 | 1.28 | 1349 | 72.77 | 0.952 |
| 65 | 1.3 | 1375 | 74.2 | 1.427 |
| 66 | 1.32 | 1393 | 75.15 | 0.952 |
| 67 | 1.34 | 1419 | 76.58 | 1.427 |
| 68 | 1.36 | 1437 | 77.53 | 0.952 |
| 69 | 1.38 | 1455 | 78.48 | 0.952 |
| 70 | 1.4 | 1481 | 79.91 | 1.427 |
| 71 | 1.42 | 1499 | 80.86 | 0.952 |
| 72 | 1.44 | 1525 | 82.29 | 1.427 |
| 73 | 1.46 | 1543 | 83.24 | 0.952 |
| 74 | 1.48 | 1561 | 84.19 | 0.952 |
| 75 | 1.5 | 1587 | 85.62 | 1.427 |
| 76 | 1.52 | 1605 | 86.57 | 0.952 |
| 77 | 1.54 | 1631 | 88 | 1.427 |
| 78 | 1.56 | 1649 | 88.95 | 0.952 |
| 79 | 1.58 | 1666 | 89.9 | 0.952 |
| 80 | 1.6 | 1693 | 91.33 | 1.427 |
| 81 | 1.62 | 1711 | 92.28 | 0.952 |
| 82 | 1.64 | 1737 | 93.71 | 1.427 |
| 83 | 1.66 | 1755 | 94.66 | 0.952 |
| 84 | 1.68 | 1772 | 95.61 | 0.952 |
| 85 | 1.7 | 1799 | 97.04 | 1.427 |
| 86 | 1.72 | 1816 | 97.99 | 0.952 |
| 87 | 1.74 | 1843 | 99.42 | 1.427 |
| 88 | 1.76 | 1860 | 100.4 | 0.952 |
| 89 | 1.78 | 1878 | 101.3 | 0.952 |
| 90 | 1.8 | 1905 | 102.7 | 1.427 |
| 91 | 1.82 | 1922 | 103.7 | 0.952 |
| 92 | 1.84 | 1949 | 105.1 | 1.427 |
| 93 | 1.86 | 1966 | 106.1 | 0.952 |
| 94 | 1.88 | 1984 | 107 | 0.952 |
| 95 | 1.9 | 2010 | 108.5 | 1.427 |
| 96 | 1.92 | 2028 | 109.4 | 0.952 |
| 97 | 1.94 | 2055 | 110.8 | 1.427 |
| 98 | 1.96 | 2072 | 111.8 | 0.952 |
| 99 | 1.98 | 2090 | 112.7 | 0.952 |
| 100 | 2 | 2116 | 114.2 | 1.427 |
| 101 | 2.02 | 2134 | 115.1 | 0.952 |
| 102 | 2.04 | 2160 | 116.5 | 1.427 |
| 103 | 2.06 | 2178 | 117.5 | 0.952 |
| 104 | 2.08 | 2196 | 118.5 | 0.952 |
| 105 | 2.1 | 2222 | 119.9 | 1.427 |
| 106 | 2.12 | 2240 | 120.8 | 0.952 |
| 107 | 2.14 | 2266 | 122.3 | 1.427 |
| 108 | 2.16 | 2284 | 123.2 | 0.952 |
| 109 | 2.18 | 2300 | 124.1 | 0.873 |
| 110 | 2.2 | 2300 | 124.1 | 0 |
| 111 | 2.22 | 2300 | 124.1 | 0 |
| 112 | 2.24 | 2300 | 124.1 | 0 |
| 113 | 2.26 | 2300 | 124.1 | 0 |
| 114 | 2.28 | 2300 | 124.1 | 0 |
| 115 | 2.3 | 2300 | 124.1 | 0 |
| 116 | 2.32 | 2300 | 124.1 | 0 |
| 117 | 2.34 | 2300 | 124.1 | 0 |
| 118 | 2.36 | 2300 | 124.1 | 0 |
| 119 | 2.38 | 2300 | 124.1 | 0 |
| 120 | 2.4 | 2300 | 124.1 | 0 |
| 121 | 2.42 | 2300 | 124.1 | 0 |
| 122 | 2.44 | 2300 | 124.1 | 0 |
| 123 | 2.46 | 2300 | 124.1 | 0 |
| 124 | 2.48 | 2300 | 124.1 | 0 |
| 125 | 2.5 | 2300 | 124.1 | 0 |
| 126 | 2.52 | 2300 | 124.1 | 0 |
| 127 | 2.54 | 2300 | 124.1 | 0 |
| 128 | 2.56 | 2300 | 124.1 | 0 |
| 129 | 2.58 | 2300 | 124.1 | 0 |
| 130 | 2.6 | 2300 | 124.1 | 0 |
| 131 | 2.62 | 2300 | 124.1 | 0 |
| 132 | 2.64 | 2300 | 124.1 | 0 |
| 133 | 2.66 | 2300 | 124.1 | 0 |
| 134 | 2.68 | 2300 | 124.1 | 0 |
| 135 | 2.7 | 2300 | 124.1 | 0 |
| 136 | 2.72 | 2300 | 124.1 | 0 |
| 137 | 2.74 | 2300 | 124.1 | 0 |
| 138 | 2.76 | 2300 | 124.1 | 0 |
| 139 | 2.78 | 2300 | 124.1 | 0 |
| 140 | 2.8 | 2300 | 124.1 | 0 |
| 141 | 2.82 | 2300 | 124.1 | 0 |
| 142 | 2.84 | 2300 | 124.1 | 0 |
| 143 | 2.86 | 2300 | 124.1 | 0 |
| 144 | 2.88 | 2300 | 124.1 | 0 |
| 145 | 2.9 | 2300 | 124.1 | 0 |
| 146 | 2.92 | 2300 | 124.1 | 0 |
| 147 | 2.94 | 2300 | 124.1 | 0 |
| 148 | 2.96 | 2300 | 124.1 | 0 |
| 149 | 2.98 | 2300 | 124.1 | 0 |
| 150 | 3 | 2300 | 124.1 | 0 |
| 151 | 3.02 | 2300 | 124.1 | 0 |
| 152 | 3.04 | 2300 | 124.1 | 0 |
| 153 | 3.06 | 2300 | 124.1 | 0 |
| 154 | 3.08 | 2300 | 124.1 | 0 |
| 155 | 3.1 | 2300 | 124.1 | 0 |
| 156 | 3.12 | 2300 | 124.1 | 0 |
| 157 | 3.14 | 2300 | 124.1 | 0 |
| 158 | 3.16 | 2300 | 124.1 | 0 |
| 159 | 3.18 | 2300 | 124.1 | 0 |
| 160 | 3.2 | 2300 | 124.1 | 0 |
| 161 | 3.22 | 2300 | 124.1 | 0 |
| 162 | 3.24 | 2300 | 124.1 | 0 |
| 163 | 3.26 | 2300 | 124.1 | 0 |
| 164 | 3.28 | 2300 | 124.1 | 0 |
| 165 | 3.3 | 2300 | 124.1 | 0 |
| 166 | 3.32 | 2300 | 124.1 | 0 |
| 167 | 3.34 | 2300 | 124.1 | 0 |
| 168 | 3.36 | 2300 | 124.1 | 0 |
| 169 | 3.38 | 2300 | 124.1 | 0 |
| 170 | 3.4 | 2300 | 124.1 | 0 |
| 171 | 3.42 | 2300 | 124.1 | 0 |
| 172 | 3.44 | 2300 | 124.1 | 0 |
| 173 | 3.46 | 2300 | 124.1 | 0 |
| 174 | 3.48 | 2300 | 124.1 | 0 |
| 175 | 3.5 | 2300 | 124.1 | 0 |

## ROTATION TEST

| Frame | Time (s) | Angular Vel (rad/s) | Kinetic Energy(KJ) | Power (kW) |
|---|---|---|---|---|
| 0 | 0 | 6E-04 | 1E-08 | 0.103 |
| 1 | 0.02 | 0.228 | 0.002 | 0.183 |
| 2 | 0.04 | 0.38 | 0.006 | 0.446 |
| 3 | 0.06 | 0.608 | 0.015 | 0.412 |
| 4 | 0.08 | 0.76 | 0.023 | 0.503 |
| 5 | 0.1 | 0.911 | 0.033 | 0.926 |
| 6 | 0.12 | 1.139 | 0.051 | 0.731 |
| 7 | 0.14 | 1.291 | 0.066 | 1.268 |
| 8 | 0.16 | 1.519 | 0.091 | 0.96 |
| 9 | 0.18 | 1.67 | 0.111 | 1.051 |
| 10 | 0.2 | 1.822 | 0.132 | 1.748 |
| 11 | 0.22 | 2.05 | 0.167 | 1.279 |
| 12 | 0.24 | 2.202 | 0.192 | 2.091 |
| 13 | 0.26 | 2.429 | 0.234 | 1.508 |
| 14 | 0.28 | 2.581 | 0.264 | 1.599 |
| 15 | 0.3 | 2.733 | 0.296 | 2.57 |
| 16 | 0.32 | 2.961 | 0.348 | 1.828 |
| 17 | 0.34 | 3.113 | 0.384 | 2.913 |
| 18 | 0.36 | 3.34 | 0.442 | 2.056 |
| 19 | 0.38 | 3.492 | 0.483 | 2.147 |
| 20 | 0.4 | 3.644 | 0.526 | 3.393 |
| 21 | 0.42 | 3.872 | 0.594 | 2.376 |
| 22 | 0.44 | 4.023 | 0.642 | 3.735 |
| 23 | 0.46 | 4.251 | 0.717 | 2.604 |
| 24 | 0.48 | 4.403 | 0.769 | 2.696 |
| 25 | 0.5 | 4.555 | 0.823 | 4.215 |
| 26 | 0.52 | 4.782 | 0.907 | 2.924 |
| 27 | 0.54 | 4.934 | 0.965 | 4.557 |
| 28 | 0.56 | 5.162 | 1.056 | 3.153 |
| 29 | 0.58 | 5.314 | 1.119 | 3.244 |
| 30 | 0.6 | 5.465 | 1.184 | 0.752 |
| 31 | 0.62 | 5.5 | 1.199 | 0 |
| 32 | 0.64 | 5.5 | 1.199 | 0 |
| 33 | 0.66 | 5.5 | 1.199 | 0 |
| 34 | 0.68 | 5.5 | 1.199 | 0 |
| 35 | 0.7 | 5.5 | 1.199 | 0 |
| 36 | 0.72 | 5.5 | 1.199 | 0 |
| 37 | 0.74 | 5.5 | 1.199 | 0 |
| 38 | 0.76 | 5.5 | 1.199 | 0 |
| 39 | 0.78 | 5.5 | 1.199 | 0 |
| 40 | 0.8 | 5.5 | 1.199 | 0 |
| 41 | 0.82 | 5.5 | 1.199 | 0 |
| 42 | 0.84 | 5.5 | 1.199 | 0 |
| 43 | 0.86 | 5.5 | 1.199 | 0 |
| 44 | 0.88 | 5.5 | 1.199 | 0 |
| 45 | 0.9 | 5.5 | 1.199 | 0 |
| 46 | 0.92 | 5.5 | 1.199 | 0 |
| 47 | 0.94 | 5.5 | 1.199 | 0 |
| 48 | 0.96 | 5.5 | 1.199 | 0 |
| 49 | 0.98 | 5.5 | 1.199 | 0 |
| 50 | 1 | 5.5 | 1.199 | 0 |
| 51 | 1.02 | 5.5 | 1.199 | 0 |
| 52 | 1.04 | 5.5 | 1.199 | 0 |
| 53 | 1.06 | 5.5 | 1.199 | 0 |
| 54 | 1.08 | 5.5 | 1.199 | 0 |
| 55 | 1.1 | 5.5 | 1.199 | 0 |
| 56 | 1.12 | 5.5 | 1.199 | 0 |
| 57 | 1.14 | 5.5 | 1.199 | 0 |
| 58 | 1.16 | 5.5 | 1.199 | 0 |
| 59 | 1.18 | 5.5 | 1.199 | 0 |
| 60 | 1.2 | 5.5 | 1.199 | 0 |
| 61 | 1.22 | 5.5 | 1.199 | 0 |
| 62 | 1.24 | 5.5 | 1.199 | 0 |
| 63 | 1.26 | 5.5 | 1.199 | 0 |
| 64 | 1.28 | 5.5 | 1.199 | 0 |
| 65 | 1.3 | 5.5 | 1.199 | 0 |
| 66 | 1.32 | 5.5 | 1.199 | 0 |
| 67 | 1.34 | 5.5 | 1.199 | 0 |
| 68 | 1.36 | 5.5 | 1.199 | 0 |
| 69 | 1.38 | 5.5 | 1.199 | 0 |
| 70 | 1.4 | 5.5 | 1.199 | 0 |
| 71 | 1.42 | 5.5 | 1.199 | 0 |
| 72 | 1.44 | 5.5 | 1.199 | 0 |
| 73 | 1.46 | 5.5 | 1.199 | 0 |
| 74 | 1.48 | 5.5 | 1.199 | 0 |
| 75 | 1.5 | 5.5 | 1.199 | 0 |
| 76 | 1.52 | 5.5 | 1.199 | 0 |
| 77 | 1.54 | 5.5 | 1.199 | 0 |
| 78 | 1.56 | 5.5 | 1.199 | 0 |
| 79 | 1.58 | 5.5 | 1.199 | 0 |
| 80 | 1.6 | 5.5 | 1.199 | 0 |
| 81 | 1.62 | 5.5 | 1.199 | 0 |
| 82 | 1.64 | 5.5 | 1.199 | 0 |
| 83 | 1.66 | 5.5 | 1.199 | 0 |
| 84 | 1.68 | 5.5 | 1.199 | 0 |
| 85 | 1.7 | 5.5 | 1.199 | 0 |
| 86 | 1.72 | 5.5 | 1.199 | 0 |
| 87 | 1.74 | 5.5 | 1.199 | 0 |
| 88 | 1.76 | 5.5 | 1.199 | 0 |
| 89 | 1.78 | 5.5 | 1.199 | 0 |
| 90 | 1.8 | 5.5 | 1.199 | 0 |
| 91 | 1.82 | 5.5 | 1.199 | 0 |
| 92 | 1.84 | 5.5 | 1.199 | 0 |
| 93 | 1.86 | 5.5 | 1.199 | 0 |
| 94 | 1.88 | 5.5 | 1.199 | 0 |
| 95 | 1.9 | 5.5 | 1.199 | 0 |

# APPENDIX B – CALCULATIONS

This appendix contains the numerical calculations for all of the analysis section of the report. It's ordered sequentially, following the logic in the analysis.



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$g = 9.81$

$d_{uu} = 500 - 17.01$

$d_{uu} = 482.99$

$d_m = \frac{1}{2} g (1.22)^2$

$d_m = 7.300602$

$c = \frac{d_{uu}}{d_m}$

$c = 66.1575579658$

$L_{octaneuu} = 144$

$L = \frac{L_{octaneuu}}{c}$

$L = 2.17662205843$

$m_{civic} = \frac{2735}{2.2}$

$m_{civic} = 1243.18181818$

$L_{civic} = 174.8 \cdot \frac{2.54}{100}$

$L_{civic} = 4.43992$

$m = \left( \frac{L}{L_{civic}} \right)^3 m_{civic}$

$m = 146.473241726$

$v_{drivingmax} = \frac{1410}{c} 3.6$

$v_{drivingmax} = 76.7259275596$

$a_{slope} = \frac{20.98}{c} \cdot 50$

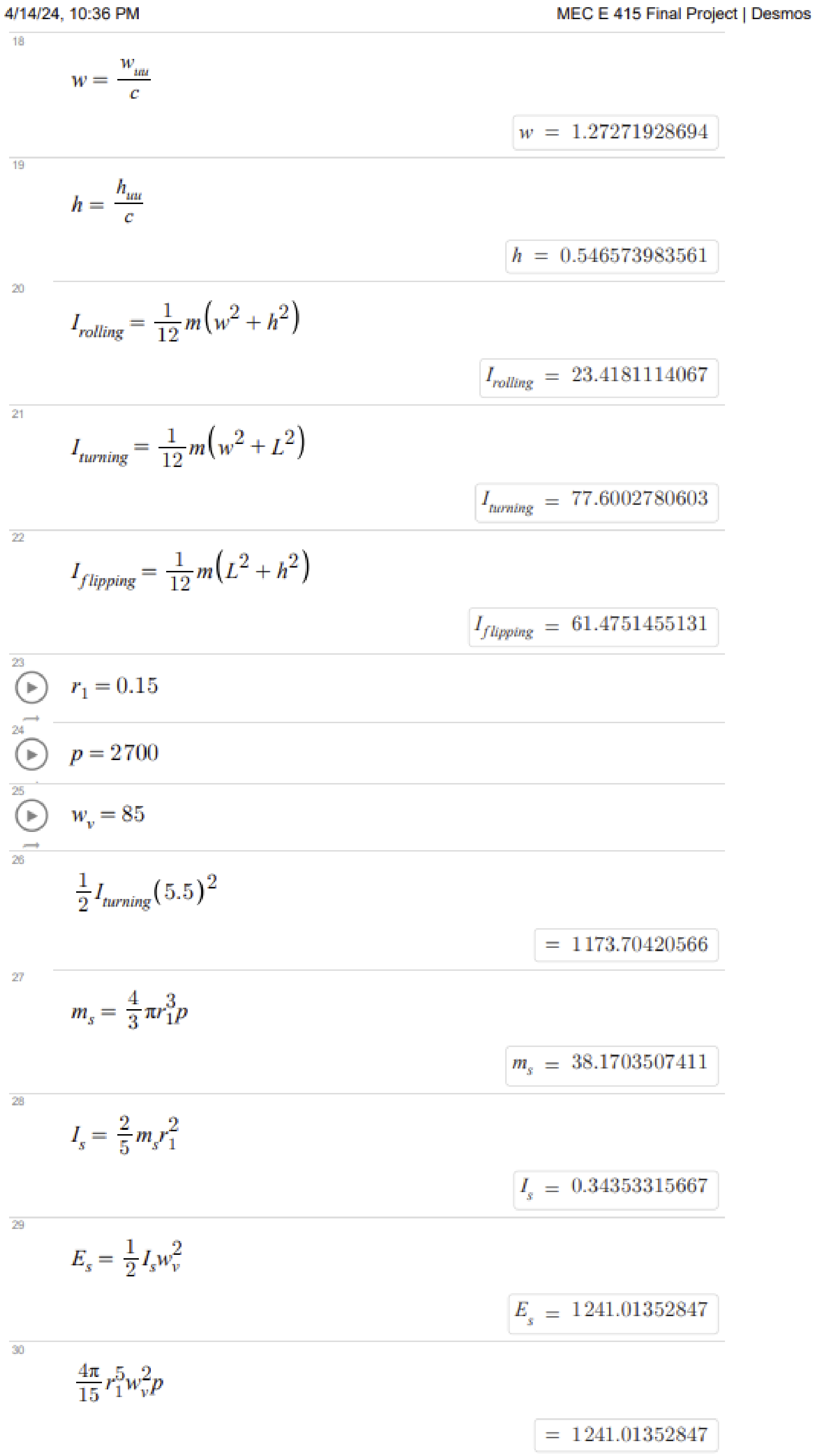
$a_{slope} = 15.8560870784$

$F = m a_{slope}$

$F = 2322.49247546$

$w_{uu} = 84.2$

$h_{uu} = 36.16$



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18 $w = \frac{w_{uu}}{c}$

$w = 1.27271928694$

19 $h = \frac{h_{uu}}{c}$

$h = 0.546573983561$

20 $I_{rolling} = \frac{1}{12} m \left(w^2 + h^2\right)$

$I_{rolling} = 23.4181114067$

21 $I_{turning} = \frac{1}{12} m \left(w^2 + L^2\right)$

$I_{turning} = 77.6002780603$

22 $I_{flipping} = \frac{1}{12} m \left(L^2 + h^2\right)$

$I_{flipping} = 61.4751455131$

23 $r_1 = 0.15$

24 $p = 2700$

25 $w_v = 85$

26 $\frac{1}{2} I_{turning} (5.5)^2$

$= 1173.70420566$

27 $m_s = \frac{4}{3} \pi r_1^3 p$

$m_s = 38.1703507411$

28 $I_s = \frac{2}{5} m_s r_1^2$

$I_s = 0.34353315667$

29 $E_s = \frac{1}{2} I_s w_v^2$

$E_s = 1241.01352847$

30 $\frac{4\pi}{15} r_1^5 w_v^2 p$

$= 1241.01352847$