PHASE 3 REPORT

Hydrogen Fuel Cell Powered Motorcycle

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Subject: Hydrogen Fuel Cell Motorcycle – Project Phase 3 Deliverables

Dear Dr. Unsworth,

Enclosed is the final project update on the hydrogen fuel cell motorcycle design. Hydro Motors is pleased to relay the following information in this Phase 3 report:

- Completion of design within project scope
- Total design cost for components within scope
- Recommendations for further development
- Total project cost and schedule followed

The design detailed in this report is the continuation of Concept 1 from the Phase 2 report, with a mid-drive motor, super capacitors, and atmospheric oxygen intake. The motorcycle operates with a maximum power of 20 kW resulting in a top speed of 140 km/h, range of 343 km, and 0-100 km/hr acceleration time of 12.5 s.

A total of 506 Junior engineering hours and 7 Senior engineering hours were dedicated to this project. This results in a total project cost of $89,200, $22,115 over the estimated total project cost of $67,085 which included a $8,640.00 contingency fund.

Any questions or concerns about the report contents or final design can be directed to our sponsor liaison Daniel Gye at dgye@ualberta.ca. Thank you for the opportunity to work on this project with you, and we look forward to hearing your thoughts on the design.

Warmest Regards,

Natalia Brezovan
Project Manager

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Executive Summary

This Phase 3 report describes in detail the final protype design Hydro Motors created for a hydrogen fuel cell powered motorcycle, based on development of Concept 1 from Phase 2. This design uses two 5 kW fuel cell stacks connected in series with integrated systems for air intake and cooling as well as hydrogen recirculation. A supercapacitor is used to provide additional power when the requirement exceeds 10 kW, and a 24 V battery is used for starting up and auxiliary functions. The drive train consists of a 20 kW brushless DC motor connected to the rear wheel using a drive belt and pulleys. The gear ratio between the outsourced drive pulley and custom designed driven pulley is 5. The large driven pulley is designed to reduce weight and verified using finite element analysis (FEA) which confirmed that the pulley remained below yielding and negligible maximum deformation. Lastly, the selected hydrogen tank stores 1.65 kg of hydrogen for a range of 343 km, 0.2 kg greater than the 1.45 kg required for a 300 km range (Edmonton to Calgary).

The table below demonstrates the client design requirements compared with the final design specifications. These performance values were found using Simulink™ to model the dynamic behaviour of the system and verified using hand calculations. 10,000-hour life cycle verification was established with the knowledge that fuel cells only degrade 0.28% per 1000 hours of use [1].

	Client Requirement	Technical Specification
Top Speed (km/h)	120	140
Range (km)	300	343
Lifetime (hours)	10,000	>10,000

To ensure the rider is not subjected to any preventable risk adequate ventilation, secure placement of components, and protective insulating layers should be implemented. Future development recommendations consist of electrical systems and controls design, regenerative braking, and custom chassis design as only high-level integration was included within the 4-month scope.

The total cost of the components is $58,000, over half of which is made up of the two fuel cells totaling $38,000. This project required a total of 506 Junior engineering hours and 7 Senior engineering hours for a total of $89,200, $22,115 over the project cost estimation.

Executive Summary Word Count: 332

1.0 Introduction and Project Objectives

Alternatives to the internal combustion engine have been explored in the automotive industry, as governments and corporations have pledged to reduce their carbon footprint. While automotive manufacturers prioritised battery electrification, the use of hydrogen fuel cells has been limited.

Considering this, Dr. Larry Unsworth of the Department of Chemical and Materials Engineering at the University of Alberta has contracted Hydro Motors to design a hydrogen fuel cell motorcycle powertrain. The design must satisfy desired performance benchmarks of a 120 km/h top speed, a 300 km range, and a 10 000-hour vehicle lifetime. Hydro Motors has successfully developed a powertrain design which exceeds the requirements.

2.0 Key Design Specifications and Revisions

Further refinement of the selected concept throughout Phase 3 resulted in the design specification revisions shown in Table 1, with the updated specification matrix included in Section 6.0.

Table 1: Phase 3 Design Revisions

No.	Design Revision
1	Reduction of required fuel cell quantity (3 to 2): Phase 3 calculations determining the power supply provided by the supercapacitors revealed only 10 kW of power is required from the fuel cell stacks, while an additional 10 kW are supplied from the supercapacitors to meet the maximum power requirement of 20 kW. Therefore, one 5 kW stack was removed, reducing fuel cell power from 15 kW to 10 kW.
2	Selection of new motor: A 20 kW brushless DC motor and compatible motor controller replaced the previous DLC-28 15 kW motor. Since the supercapacitor and fuel cell systems could now supply 20 kW of power combined, a new motor with an increased specified power output was selected.
3	Selection of new hydrogen tank: The compressed hydrogen storage tank selected in Phase 2 was too large to integrate into the chassis and limited the range of the vehicle. A hydrogen storage tank utilizing metal hydride technology was selected to contain the required mass of hydrogen in a smaller container.
4	Selection of new Battery: In Phase 3 it was determined that 24 V is the required voltage needed to start the fuel cell system. The battery selected in Phase 2 would have required an additional DC/DC converter to meet these requirements and was therefore replaced with a new 24 V battery.
5	Removal of Regenerative Braking: In-depth integration of electrical controls were not considered in this project due to lack of feasibility within the given timeline. Due to the sophisticated controls system needed to implement a regenerative braking system it was deemed a further development concept.

3.0 Design Overview

This section provides information on the key components considered in the design of the motorcycle shown in Figure 1. Complete details on these components can be found in referenced appendices and product manuals, and vehicle components are labelled in Appendix Q.

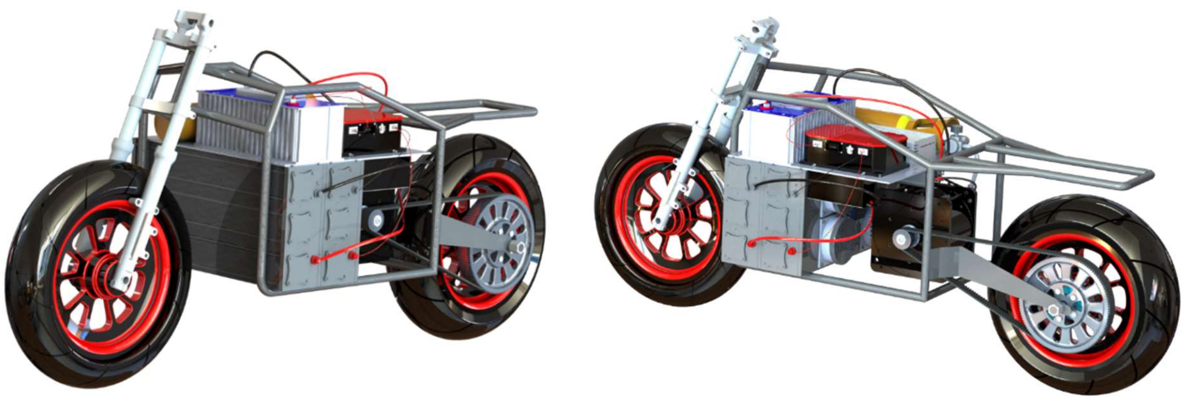

Figure 1: CAD model reflecting possible component configuration

3.1 Components Overview

A general schematic was created to demonstrate how each component functions within the system. The schematic legend is shown in Figure 2 and Table 2 describes the purpose of each component shown in the Figure 3 schematic.

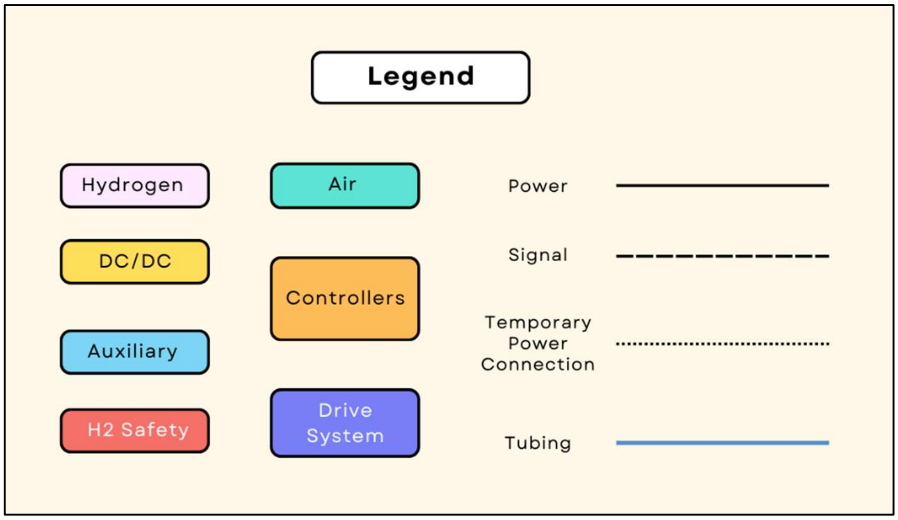

Figure 2: Legend for Fuel cell schematic

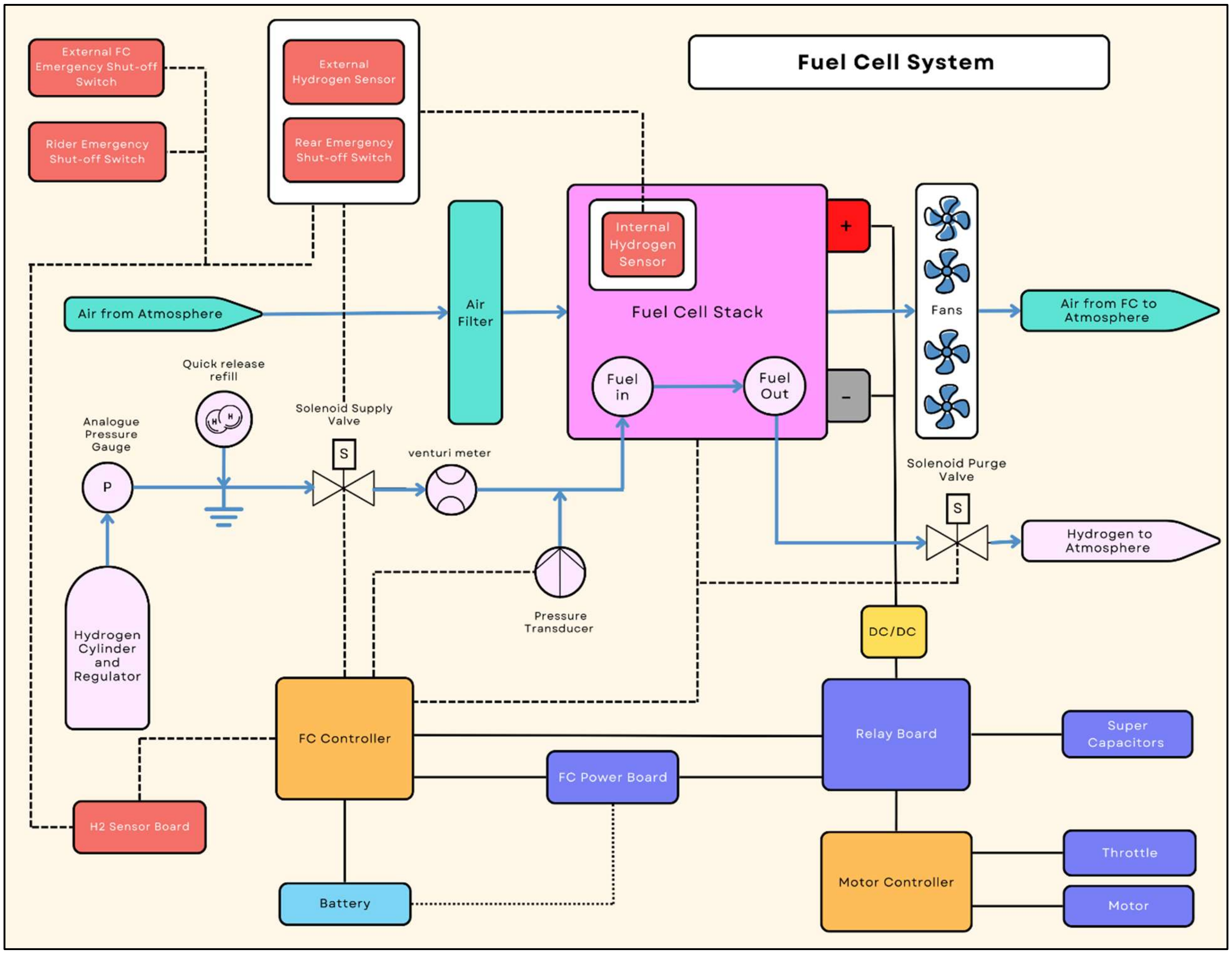

Figure 3: Fuel cell schematic

Table 2: Fuel Cell Schematic Component Details

Component	Details
Fuel Cell Stack	• The fuel cell stack generates direct current (DC) from an electrochemical reaction • The fuel cell takes in hydrogen and air as fuel • The outputs of the fuel cell are hydrogen (recirculated), air, and water vapour.
Hydrogen Flow	• Hydrogen is released from the hydrogen tank, controlled by the fuel cell controller • The hydrogen passes through an analogue pressure gauge • A quick release refill valve is attached to the hydrogen circuit for refueling • Solenoid supply valve is used to control the flow of the hydrogen inputting to the system • Venturi meter is used to recirculate the output hydrogen back into the main line • Pressure transducer is controlled by the fuel cell controller and can control the pressure of the hydrogen • Solenoid supply valve is used to control the flow of the hydrogen output from the system
Air Flow	• Air intake is taken through a series of filters • Air is outputted from a series of fans into the atmosphere
Auxiliary Battery	• The battery jumpstarts the hydrogen fuel cell [2] • Battery powers all auxiliary electronics (lights, dashboard, etc.), safety components, and the fuel cell controller. • When the fuel cell is active, the relay board will switch the primary power source to the fuel cell instead of the battery [3]
H_2 Safety	• Series of internal and external safety features to stop all processes in case of an emergency
Controllers	• Fuel cell controller is used to control stack temperature, blowers, hydrogen flow, purging, and electrical output [4] • Motor controller is used to control torque, speed, and power to the wheels
Drive System	• Drive system compose of the components between the power supply and controllers. • Relay board will switch the primary power source to the fuel cell instead of the battery [3] • The relay board will also control the amount of power output from the fuel cell and super capacitors [3] • Supercapacitors release energy quickly during acceleration cases • Supercapacitors charge using excess fuel cell energy • Throttle is the input to the motor controller letting the rider control the power output • Motor converts electrical energy to mechanical energy

3.2 Power Generation

3.2.1 Fuel Cell

Each 5-kW proton exchange membrane fuel cell stack [5] is integrated with air cooling and hydrogen recirculation. By connecting two of these stacks in series a total of 10 kW of power and 144 V are output from the system. Fuel cells degrade ~0.28% per 1000 hours of use [1], so at the desired 10,000-hour life cycle it will still be operating at near optimal condition.

3.2.2 Supercapacitor

The 48V, 165F supercapacitor [6] stores electrical charge and discharges power quickly in scenarios with power demand greater than 10 kW. It can vary the power output for different discharge durations as shown in Appendix M, and for this motorcycle's 20 kW limiting case the supercapacitor can provide the additional 10 kW needed for approximately 18 seconds.

3.3 Drivetrain

3.3.1 Motor

The selected 20 kW motor [7] can operate at speeds of 3200 – 6000 RPM. It features a peak stall torque of 160 N-m, and a continuous rated torque of 80 N-m, exceeding the maximum torque requirement of 113.5 N-m as calculated in Appendix B. A brushless DC motor was selected as it allowed for instantaneous changes in speed and torque without requiring a transmission.

3.3.2 Pulleys and Belt

After comparing the three different drivetrain methods (shaft, belt, chain) in the decision matrix shown in Appendix E, belt drive was selected for this motorcycle as is common in industry for electric motorcycles. Shaft drive was ruled out due to the high cost, and chain drive was ruled out primarily because of the loud noise it produces compared to the quiet electric motor, with comparable efficiency between belt and chain.

3.4 Hydrogen Tank

Standard hydrogen storage tanks require either very low temperature or very high pressure to counteract the strong repelling force between hydrogen molecules. Metal hydride powders in the selected storage system break apart the hydrogen and allow the atoms to be packed much more densely in the container [8] and reduce risk in a crash scenario because of the lower storage pressure (10 bar).

The selected 56 x 11 cm (H x D) tank [9] stores 1.65 kg of hydrogen, giving the motorcycle a range of 343 km as shown in Appendix H.

3.5 Additional Components

For electrical systems and controls, multiple components were required to be sourced and selected. Further details on these selected components are shown in Table 3.

Table 3: Additional Components in Fuel Cell System

Component	Details
10 kW, 800 V DC/DC Converter [10]	Ensures the DC voltage out of the fuel cell stack matched the super capacitor's rated voltage. • Fuel cell stack outputs a voltage up to 144 V and 10 kW • Supercapacitors output a voltage up to 48 V and 10 kW • Selected DC/DC converted has a nominal power of 10 kW • Selected DC/DC converted is rated for the selected voltage, current, and power requirements • Selected DC/DC converter is compatible with fuel cell systems
24 V Li-Po Battery [11]	Required to jumpstart the fuel cell and to bring the fuel cell stack up to temperature. • A 24 V Li-Po battery was selected due to the requirements from the fuel cell manufacturers manual
CS-MSW Fuel Cell Controller [5]	Controls the fuel cell stack temperature, blowers, hydrogen flow, purging, and electrical output. • Selected fuel cell controller is sold by the fuel cell manufacturer Horizon Educational • Fuel cell controller is compatible with the two 5 kW fuel cells
KBL96251 Motor Controller [12]	Controls torque and speed outputs of the motor • Motor controller controls the torque and RPMs of the motor • Motor controller is rated for the voltage and current supplied by the fuel cell and supercapacitor

4.0 Design Analysis

The design analysis process followed the general procedure shown in the calculation overview flow chart in Figure 4. A brief overview of key analysis is discussed in sections below, and detailed calculations and information are found in the appendices referenced in the flow chart.

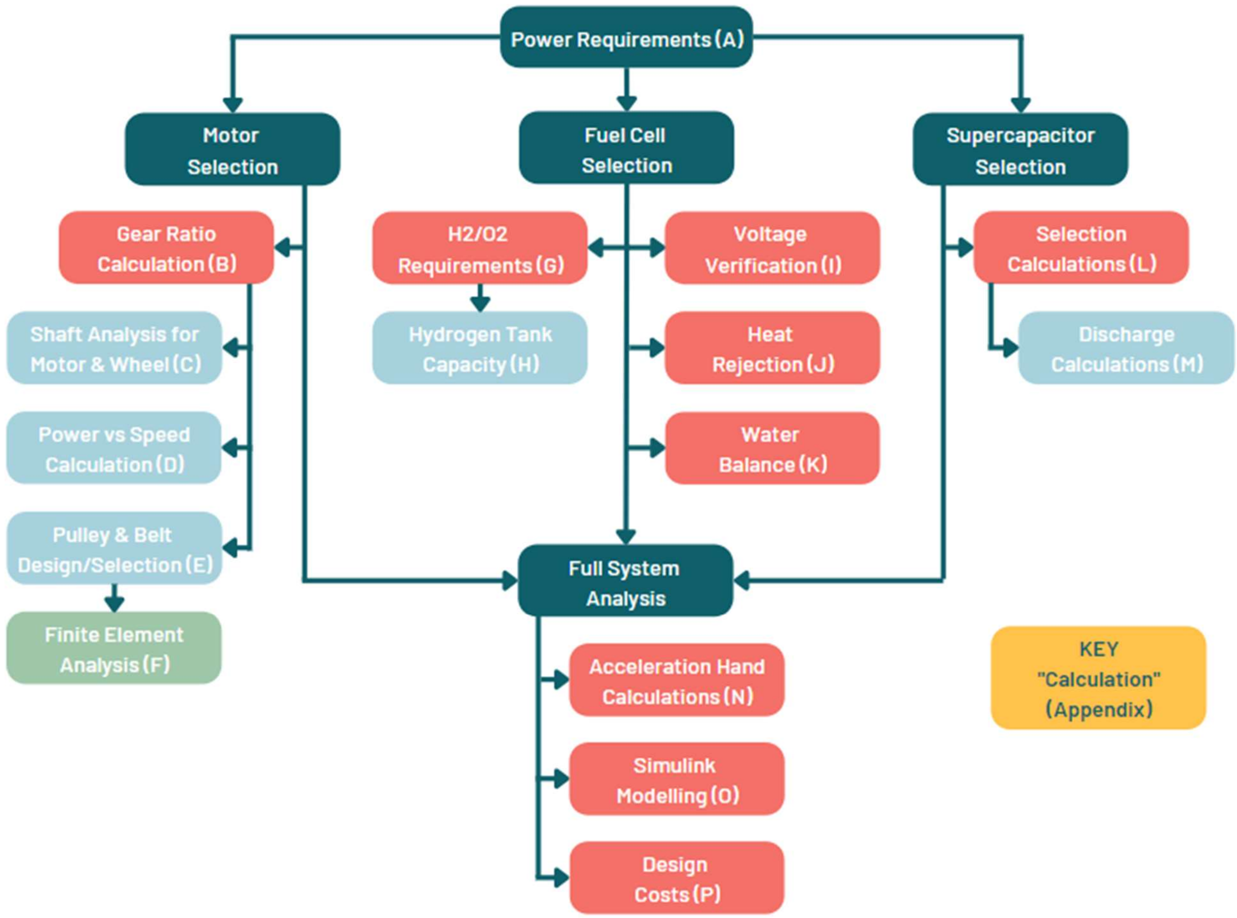

Figure 4: Design process flow chart and reference appendices

4.1 Performance Modelling

4.1.1 Overview of the Model

Simulink™ is a MATLAB based software used to solve non-linear ordinary differential equations. Simulink was used to simplify each component into their fundamental equations to predict how the system performs dynamically and to model and prove the performance of the final design. Figure 5 shows a simplified overview of the Simulink model and Table 4 lists a brief description of individual component function. Further details on the Simulink model and its construction, assumptions, outputs, and validation can be found in Appendix O.

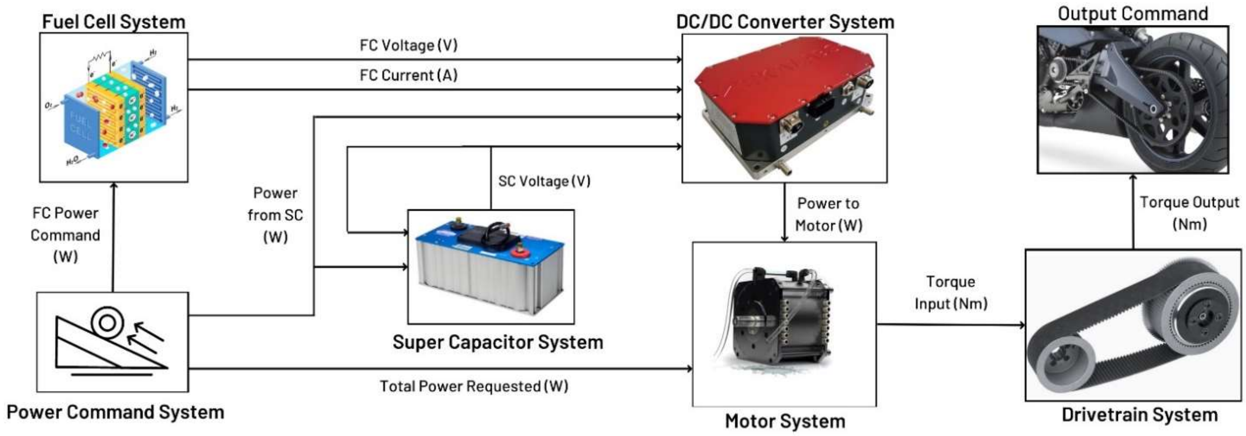

Figure 5: Simplified complete Simulink model

Table 4: Simulink component function details

Simulink Component	Function
Power Command System	• Calculates the power required from the fuel cell and supercapacitor • Has a power stop case when braking is applied
Fuel Cell System	• Simplified the system through modelling as a static system using polarization curve data provided by the supplier • Takes a power input from the power command system and calculates efficiency, current, and voltage • Consists of two fuel cell stacks in series
DC/DC Converter	• Converts the fuel cell voltage to the same voltage of the supercapacitors • Includes efficiency losses
Super Capacitor System	• Assumed linear behavior and ignored self-discharging effects • Simplified by modeling as an RC circuit • Input for the system is the current from the DC/DC converter • Calculates the voltage changes in the supercapacitor
Motor System	• Receives power from the DC/DC converter system • Calculates torque, RPMs, and efficiency losses based off supplier provided data
Drivetrain System	• Uses Simscape drivetrain blocks to model the belt drive, brakes, and wheels • Calculates the torque output from the belt drive • Calculates longitudinal forces, wheel slip, normal force, and axle torque
Output Command System	• Calculates acceleration and velocity

4.1.2 Simulink Results

The plot in Figure 6 shows the changes in voltage and power for the fuel cell and supercapacitor, demonstrating how the system reacts to high demands of power. As the system power requirement exceeds 10 kW (fuel cell maximum output), primarily during acceleration, the supercapacitors activate for ~18 seconds increasing the total power output to 20 kW. 20 kW is the limiting case and max power output from the motorcycle as calculated in Appendix A.

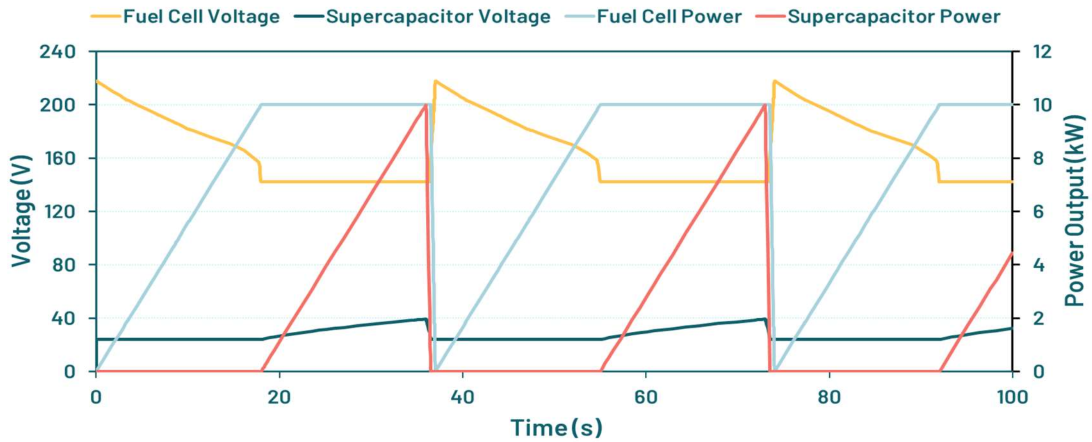

Figure 6: Fuel cell and Supercapacitor power and voltage changes with respect to time

Simulink models different velocities and accelerations as seen from the plots in Figures 7, 8 and 9. These plots correspond to varying power outputs of 5kW, 10kW, and 20kW respectively. Figure 9 demonstrates the increased acceleration rate when the supercapacitor is used due to the power demand exceeding 10 kW. Depending on the power command function, the motorcycle will accelerate and reach different peak velocities. The velocity and acceleration cases show the importance of the super capacitor assisting the motorcycle in cases where more than 10 kW of power is required. Without the supercapacitors, the motorcycle acceleration would be much slower.

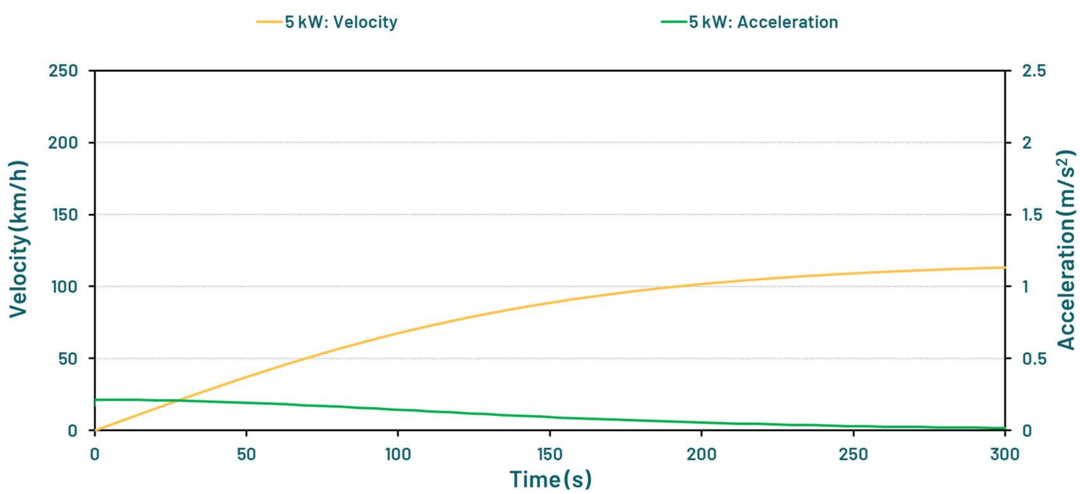

Figure 7: Velocity and Acceleration for 5 kW power from the Fuel Cell

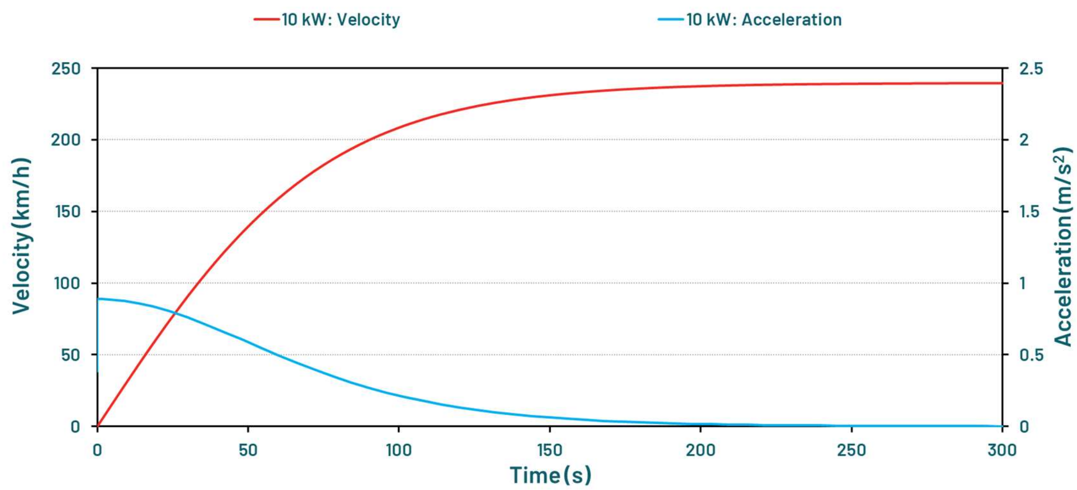

Figure 8: Velocity and Acceleration for 10 kW power from the Fuel Cell

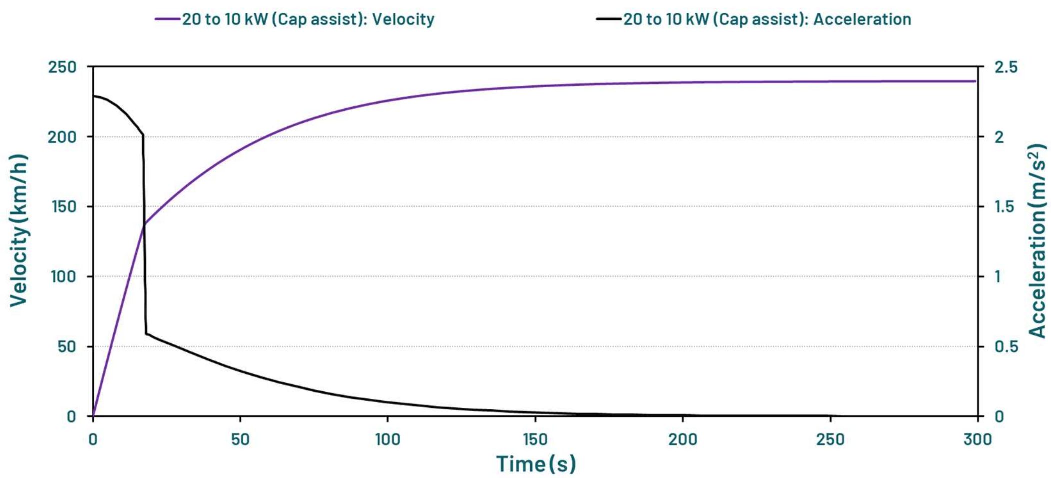

Figure 9: Velocity and Acceleration at 20 kW with capacitor assist then 10 kW from only Fuel Cell

The Simulink model provided the top speeds and acceleration of the motorcycle, and this data is summarized in Table 5.

Table 5: Power requirements obtained by Simulink for acceleration and speed values

Parameter	Power Requirement	Value
Top Speed (km/hr)	8.9 kW	140 km/hr
Velocity on 8% grade	9.9 kW	50 km/hr
Acceleration (0 to 100 km/hr)	20 kW	12.5 s

4.1.3 Model Validation

Simulink output values were compared to the validation hand calculations shown in Appendices A, D, and N, the discrepancy is shown by comparison of Table 5 and Table 6. and since the differences were within an order of magnitude, the Simulink results were deemed reliable. The hand calculations used simplifications, steady state assumptions, and a constant drag force unlike the Simulink results which use a variable drag force. Differences between the model and the predetermined hand calculations were viewed as acceptable within an order of magnitude.

Table 6: Power requirements obtained by hand calculations for acceleration and speed values

Parameter	Power Requirement	Value
Top Speed (km/hr)	9.14 kW	140 km/hr
Velocity on 8% grade	7.49 kW	50 km/hr
Acceleration (0 to 100 km/hr)	20 kW	12.48 s

4.2 Drivetrain Analysis

4.2.1 Motor Shaft Deflection

To ensure that the diameter of the 304 stainless steel motor shaft would not fail during its application, it underwent bending and torsional deformation analysis as shown in Appendix C. The minimum required shaft diameter to resist bending and torsional deformation were 21.52 mm and 27.73 mm respectively, less than the actual motor shaft diameter of 30 mm.

To radially affix the small front pulley to the motor shaft, the shaft is designed with a keyway of 8 mm in width. Using the same material as the shaft along with a factor of safety of 1.5, the necessary dimensions of the shaft key were determined to be at least 5.71 mm in length and 8 mm in total height.

4.2.2 Rear Axle Deflection

At the rear axle, forces from the weight of the motorcycle and tension from the pulleys attached to the wheel create a shearing load on the axle. With the bolt again being made of stainless steel, its shear modulus was 74 GPa, and it experienced a total shear of 13.63 MPa, which caused a deformation of only 0.0002 radians.

4.3 Pulleys and Belt Analysis

4.3.1 Drive Pulley and Belt Requirement Calculations

To satisfy the gear ratio requirement of 5 calculated in Appendix B, a 61.12 mm pitch diameter, 24 tooth, 8mm pitch, Aluminum 2000 drive pulley was selected. The dimensions required for the pulleys were selected after performing belt selection analysis as shown in Appendix E. The chosen toothed drive belt is 21 mm wide and 1600 mm long with a power capacity of 36.15 kW, greater than the maximum working condition power of 36.08 kW, again with an 8mm pitch to ensure they efficient power transmission between pulleys without slipping or increasing efficiency losses.

4.3.2 Driven Pulley Design

It was determined that a 305.6 mm pitch diameter, 120 tooth, 8mm pitch pulley was required for the driven pulley, again according to Appendix E.

To reduce the weight of the large pulley while ensuring it met design specifications this pulley was custom designed. Speed holes were used to remove material to reduce weight while maintaining the structural integrity and strength of the pulley. Aluminum 6061 was selected as a lighter material and finite element analysis was performed to verify the added holes did not compromise the strength of the pulley.

Figure 10. An Illustration of the designed driven pulley from the hub side

4.3.3 Driven Pulley Manufacturing

A CAD model of the custom pulley was created In Solidworks™ and submitted to a manufacturing company to obtain the quote for material and manufacturing costs shown in Appendix S. The $864.82 cost was entered in the cost breakdown in Section 5.0. A CNC (Computer Numerical Control) milling machine will be used to manufacture this pulley as only a single prototype piece is required. The pulley is designed to have a one-sided flange to simplify manufacturing and allow the milling machine to shape the profile of the pulley teeth without interference on the processing path. Casting would be used for production on a larger scale to significantly reduce costs.

4.4 Finite Element Analysis (FEA)

4.4.1 Background

Finite element analysis (FEA) was completed using Solidworks. The analysis was performed on the drivetrain pulley system shown in Figure 11 as it is subjected to repetitive, high stress throughout operation.

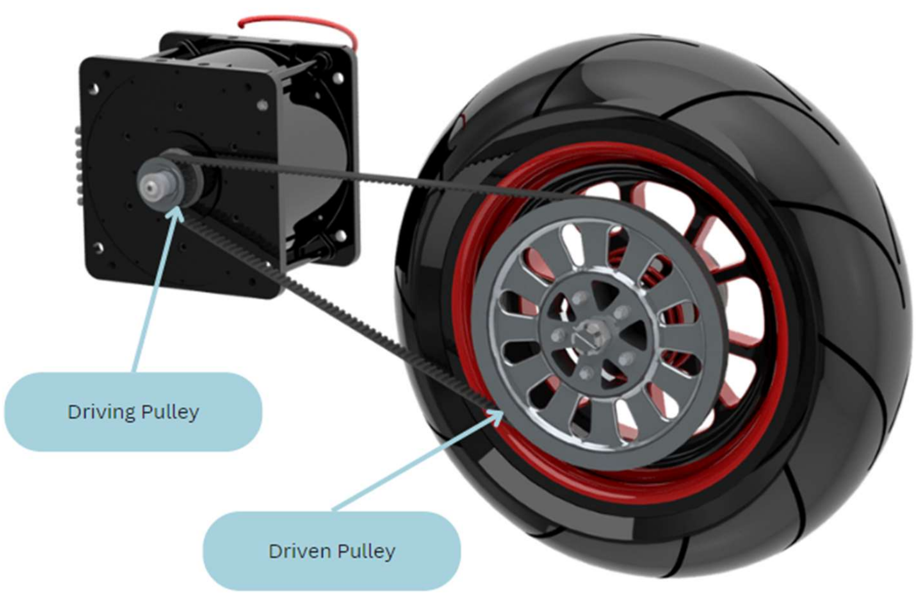

Figure 11: Drivetrain Pulley System

4.4.2 Applied Loads and Boundary Conditions

The rotation of the shaft induced a centrifugal load of 433 rad/s onto the bore hole of the driving pulley, which caused a load at the rim of both pulleys, modelled as a bearing load of 1406 N.

The drive pulley was fixed radially to the shaft using a key, and the driven pulley was fixed to the rear wheel using 5 bolts. This was modelled for FEA as shown in the figures below. Frictional elements that would resist deformation were omitted, as they required a rigid support assumption, a reasonable assumption as the system operated below maximum capacity.

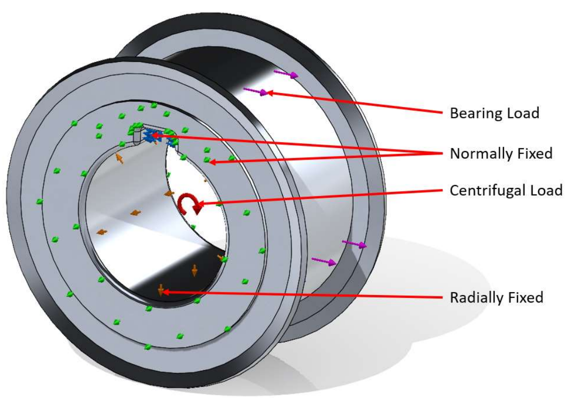

Figure 12 Boundary Conditions on the Driving Pulley

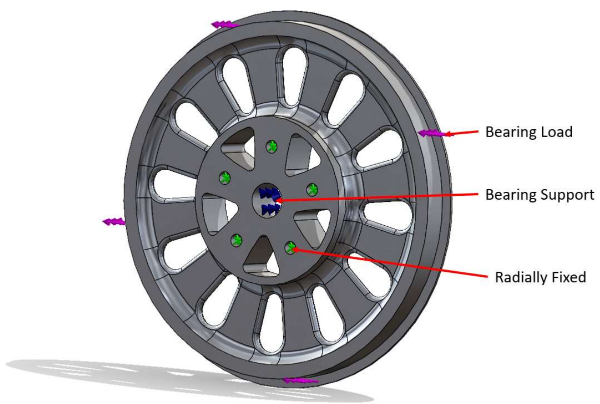

Figure 13 Boundary Conditions on the Driven Pulley

4.4.3 Mesh Convergence

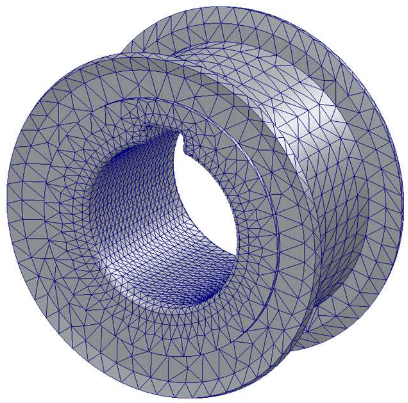

Figure 14 Mesh and Mesh Control Applied to the Driving Pulley

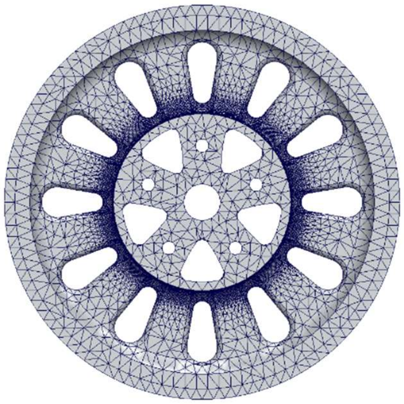

Figure 15 Mesh and Mesh Control Applied to the Driven Pulley

The model was simplified using 3D mesh representation for Solidworks simulation. Meshing was refined in areas of high stress concentrations such as the bore holes, keyways, and fillets. The initial mesh size used was 5 mm and was refined to 1 mm using intervals of 0.5 mm. From mesh convergence studies, mesh independence was achieved through the simulation results for stress having a percent change of less than 5% as seen in Appendix F.

Further details on the mesh sizing, elements, nodes, and convergence percentages are found in Table 7.

Table 7: Results of the Mesh Convergence Study for Both Pulleys

Parameter	Driving Belt Pulley	Driven Belt Pulley
Convergence Error	0.4 %	0.1 %
Mesh Control Size	1.5 mm	1.5 mm
Number of Nodes	38,337	213,960
Number of Elements	44,885	138,846

4.4.4 Simulation Results

The FEA results are shown Figure 16 to Figure 19. Table 8 demonstrates that neither pulley yields under the applied stresses nor had significant displacement. As expected, the maximum stresses occurred at the bore hole on the side where the load from the belt was applied.

Table 8: Numeric results of the FEA

Parameter	Driving Belt Pulley	Driven Belt Pulley
Yield Stress	96.5 MPa	275 MPa
Maximum Stress	2.29 MPa	4.56 MPa
Maximum Displacement	0.621 μm	2.407 μm

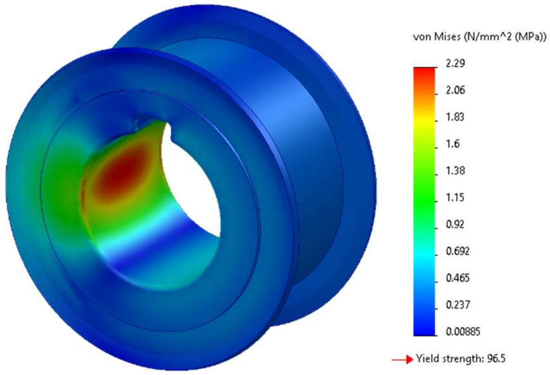

Figure 16 Stress Distribution on the Driving Pulley

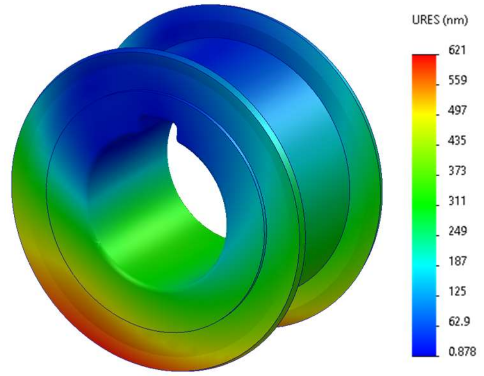

Figure 17 Element Displacement on the Driving Pulley

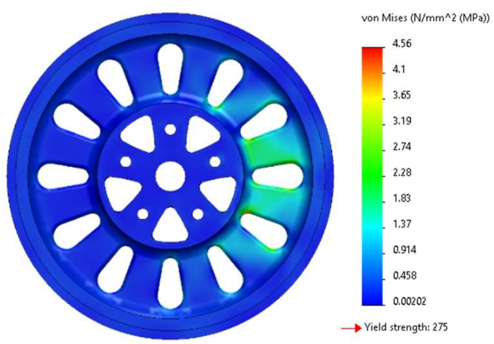

Figure 18 Stress Distribution on the Driven Pulley

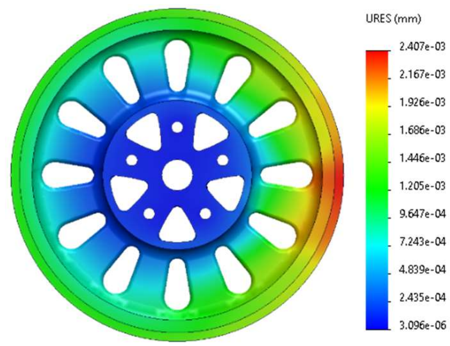

Figure 19 Element Displacement on the Driven Pulley

4.5 Range/H2 required

The quantity of hydrogen required by the fuel cell to operate for a given range was calculated with the procedure shown in Appendix G. The minumum range was 300 km, which satisfies client's request to drive from Edmonton to Calgary without needing to refill fuel. The calculations performed demonstrated that for 300km of operation at 120 km/h, 1.45 kg of hydrogen is required. To ensure the selected tank was capable of storing this mass, verification calculations were performed and are shown in Appendix H.

5.0 Cost evaluation

The cost breakdown is shown in Table 9 below, with references to product links found in Section 11 and quotes available in Appendix S. Note that control boards, custom chassis, rims and tires, and any other components outside of the defined scope are not included in this cost breakdown.

Table 9: Cost breakdown for powertrain components

Description	Qty	Material	Mfg. Method	Cost (CAD)			Supplier	Model	Ref.
				Material	Mfg	Total Cost			
Fuel Cell: PEM 5000W	2	-	Supplier	$18,933.20	-	$37,866.40	Horizon Educational	FCS-C5000	[5]
Fuel Cell Controller	1	-	Supplier	$827.20	-	$827.20	Horizon Educational	CS-MSW	[5]
Hydrogen Storage Tank	1	-	Supplier	$6,665.00	-	$6,665.00	Fuel Cell Store	1021852	[9]
Supercapacitor	1	-	Supplier	$964.93	-	$964.93	Maxwell	BMOD0165 P048 C0B	[6]
24 V Li-Po Battery	1	-	Supplier	$219.99	-	$219.99	Lithium King	6S 22AH	[11]
20 kW Liquid Cooled Motor	1	-	Supplier	$2,538.99	-	$2,538.99	Golden Motor	HPM-20KW-LIQ	[7]
Motor Controller	1	-	Supplier	$499.99	-	$499.99	Kelly	KBL96251	[12]
Drive Pully	1	Aluminum 2000	Supplier	$67.63	-	$67.63	Misumi	HTPA24S8M250-A-HUL	[14]
Driven Pully	1	Aluminum 6061	Turning Milling	$107.92	$756.90	$864.82	Midwest Steel and Aluminum	12 in. d x in h	[16]
Belt	1	Polyurethane	Supplier	$61.75	-	$61.75	Vbelts Direct	210G8M1600	[15]
Solenoid Supply/Purge Valve	2	-	Supplier	$145.35	-	$290.70	Discover Valve	CODE: 102723	[17]
Venturi Meter	1	-	Supplier	$14.94	-	$14.94	Garosa	-	[18]
Pressure Transducer	1	-	Supplier	$270.86	-	$270.86	Grainger	WWG3DRL7	[19]
DC/DC Converter	1	-	Supplier	$6180.00	-	$6180.00	ZekaLabs	10 kW, 800 V	[10]
Pressure Gauge	1	-	Supplier	$163.63	-	$163.63	Omega	PGM-63B-15PSI	[20]
Pressure Regulator	1	Stainless Steel	Supplier	$531.43	-	$531.43	Swagelok	KPR1FJA415A20000	[21]
Tubing	3		Supplier	$8.10	-	$24.30	Homedepot	svki10	[22]
Total Cost						$58,052.56			

6.0 Design Compliance Matrix

The motorcycle design was reevaluated against the initial project requirements in the design compliance matrix shown below in Table 10. The final vehicle design exceeds the speed, range, and lifespan the client had requested. Detailed discussions of the specification matrix can be found in Appendix R.

Table 10: Design Compliance Matrix

Item	Specification	Description	Design Authority	Design Compliance	Importance (1-5)
1	Project Management				
1.1	Budget	Unlimited - exploratory	Client	The design total is $52,572.56	3
1.2	Schedule	The project design should strictly follow the suggested course schedule, December 8 is the final due date	Hydro Motors	Complies	4
2	Overall Design				
2.1	Top Speed	The maximum of the motorcycle should be 120 km/h	Client	Complies: Designed for 140km/h	5
2.2	Maximum Range	The motorcycle must have a range of at least 300 km	Client	Complies: 342 km range	5
2.3	Battery	24v 22Ah Ebike Battery Pack Lithium King Lipo Pack	Hydro Motors	Complies: Not an Lithium Ion Battery	3
2.4	Height	1100mm	Hydro Motors	Complies: 1036mm	2
2.5	Width	715mm	Hydro Motors	Complies: 650mm	2
2.6	Weight (mass of the motor)	16kg	Hydro Motors	Complies: Originally just an estimate, however; final design motor weighed 39kg	2
2.7	Net Weight of Motorcycle	235kg	Hydro Motors	Complies: 195.3kg	2
2.8	Weight of Rider	90 kg	Hydro Motors	Complies	3
3	Functionality				
3.1	Speed Control	The amount of electricity that is sent to the motor will be controlled by the relay board	Hydro Motors	Complies	4
3.2	Velocity Range	The velocity ranges from 0 to 120 km/h.	Client	Complies: Exceeds this range top speed is 140km/h	5
3.3	Fuel Cell System	The hydrogen fuel system will be able to provide the motor 20kW	Hydro Motors	Complies: Provides 10kW and obtains the additional power from the super capacitor	4
3.4	Regenerative Braking System	The supercapacitors will collect extra power generated when motorcycle brakes and release the power when speeding up	Hydro Motors	Did not investigate: Regenerative braking is future recommendation	4
3.5	Heat Exchange System	The temperature should be able to maintain under 100C to allow the hydrogen fuel cell function properly	Hydro Motors	Complies: Operates at 65C	4
3.6	Brake System	The brake system should has Anti-lock ABS Front: 290 mm disc & rear: 220 mm disc	Hydro Motors	Did not investigate	4

3.7	Light	The light on the motorcycle must provide enough visibility when riding and notice the existence of the motorcycle to other vehicles	Hydro Motors	Did not investigate	4
3.8	Suspension System	The suspension system should be able to adjust according to the change in ground and mass and handle 280kg weight capacity	Hydro Motors	Complies	5
3.9	Hydrogen Tank	Metal Hydride Tank will be used to increase the volume capacity of the tank itself	Hydro Motors	Complies: 342 km range	5
4	Assembly and Manufacturing				
4.1	Part Availability	Parts sourced will be available at major retailers	Hydro Motors	Complies: Aside from 1 part that needs to be custom made, the rest are sourced	4
4.2	Ease of Disassembly	The assembly and disassembly of the vehicle will as be simple as possible	Hydro Motors	Complies	4
4.3	Documentation	The maintenance and assembly documents will provided	Hydro Motors	Complies	5
4.4	Operating Condition	The motorcycle should be able to operate item 3.1 to 3.8 in all weather conditions (e.g. rain, sun, wind)	Hydro Motors	Complies	5
5	Safety				
5.1	Power Failure	The bike would go into neutral to ensure that they driver can come to a complete stop under safe conditions	Hydro Motors	Complies	5
5.2	Braking System	Brake pads will be utilized against the disc of the wheel	Hydro Motors	Did not investigate	4
5.3	Allergic	To avoid allergy, rubber should be used	Hydro Motors	Did not investigate	3
5.4	Product Service Life	10,000 Hours	Client	Complies: Conducted FEA on drivetrain. FC degradation is 0.5% per 1000 hours	5
5.5	Thermal Insulation	The driver will be insulated from heat generated by the motorcycle	Hydro Motors	Complies: A protective layer will be used to separate the rider and the components	4
5.6	Capacitor Recharging Life	The lifetime of a capacitor is at least 10,000 hours	Hydro Motors	Complies	5
5.7	Hazard Light	The light should be able to let other vehicles know the position motorcycle to prevent accidents	Hydro Motors	Did not investigate	4
5.8	Hydrogen Fuel Disposal	The additional hydrogen fuel that is used in the chemical reaction will safely released into the atmosphere	Hydro Motors	Complies: Has a purge valve	4
6	Maintenance				
6.1	Ease of Maintenance	The components must be easily removable, installable and accessible	Hydro Motors	Complies	4
6.2	Routine Maintenance	The vehicle will undergo maintenance when required	Hydro Motors	Complies	3

7.0 Risk Assessment

7.1 Fault-Tree Analysis

To ensure that the motorcycle is operating as safely as possible and not subjecting the rider to unnecessary risk a fault tree analysis was performed. As show in Figure 20, all potential risks stem from two main categories: process conditions are not met and if the control system fails.

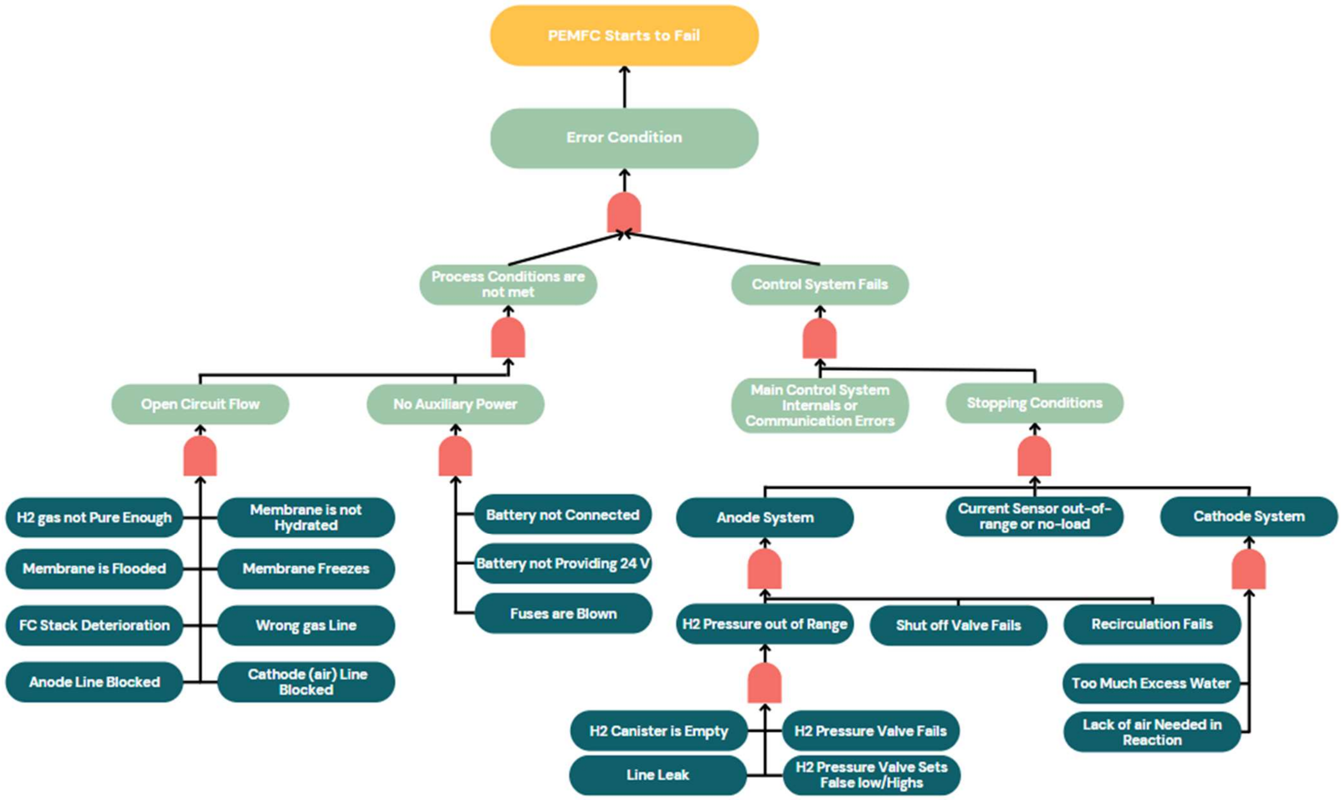

Figure 20: Fault-Tree Analysis

Table 11 shows common faults and their respective preventative measures, or how those faults prevent fuel cell start-up.

Table 11: Preventative Measures for Faults that will Lead to a Damaged PEMFC

Faults that will Lead to a Damaged PEMFC	Preventative Measure/Will it Start
H_2 gas not Pure Enough	Testing purity of H_2 gas using a TCD detector
Membrane is not Hydrated	Recirculation of water system inside of the FC
Membrane Freezes	Heat up the fuel cell to 25°C to ensure that all ice melts
Membrane is Flooded	Drain to ensure that all excess water that is produced is removed from the fuel cell
FC Stack Deterioration	Annual inspections of FC system
Wrong gas Line	Assigned and labeled pipelines to ensure the correct connection
Anode Line Blocked	A sensor to determine if something is blocking the line
Cathode (air) Line Blocked	A sensor to determine if something is blocking the line
Battery not Connected	If the battery is not connected the FC will not start
Battery not Providing 24V	Without 24V the FC will not start
Fuses are Blown	If fuses are blown in the battery, FC will not start
Main control System Internals or Communication Errors	Prevent starting of the FC if any errors are detected
H_2 Canister is Empty	No reaction will occur on the anode side of the reaction; therefore, the FC will not start
Line Leak	The stack must be operated in a well-ventilated area to inhibit potential hydrogen accumulation
H_2 Pressure Valve Fails	Controller will stop the operation
H_2 Pressure Valve Sets False low/High	Annual testing to ensure that there are no faults in the pressure valve
Shut off Valve Fails	Controller will stop the operation
Recirculation Fails	Shut down of system to prevent any flooding in the membrane
Current sensor out-of-range or no-load	Without a current sensor reading, FC will not start
Too Much Excess Water	Drain to ensure that all excess water that is produced is removed from the fuel cell
Lack of air Needed in Reaction	Well ventilated area to inhibit enough air for the reaction

7.2 Hydrogen and Fuel Cell Usage Safety

The analysis for usage safety of hydrogen fuel cell is shown in Table 12 below.

Table 12: Usage Safety Breakdown

Risk	Description	Preventative Measures
Hydrogen		
Asphyxiation	• Colourless, odourless, tasteless gas • Can result in unconsciousness when inhaled	• Provide adequate ventilation
Highly flammable	• Flammable for concentrations of 4-75% by volume • Explosive for concentrations of 15-59% [23]	• Provide adequate ventilation
Explosive	• Stored in a pressurized canister	• Securely fix hydrogen tank • Utilize pressure regulators and relief valves • Ensure tank is designed for transportation
Fuel Cell		
High Voltage	• Voltage exceeds 50V • Shock hazard upon contact • Potential damage to other electronic components	• Utilize electrically insulating layers to prevent contact between components and rider
High Operating Temperature	• Fuel cell is designed to operate at 65°C, potential for burns [24]	• Utilize thermally insulating layers to prevent contact between components and rider

8.0 Further Development Recommendations

Electrical systems and controls were not designed in this project and would be the primary focus for further development, including coding required for control boards and controllers. Additionally, after a sophisticated controls system is established, regenerative braking could be considered to make use of the frictional energy loss upon braking by using it to recharge the supercapacitor, reducing reliance on the fuel cell. This would increase fuel economy as regenerative braking reuses up to 70% of the kinetic energy. [25]

The custom chassis designed shown in this report was for visualization purposes only as only "high level integration" was completed in this project. Further development would include verifying structural integrity and refining the design to reduce drag force and as a result reduce power consumption.

9.0 Project Management

The required Junior engineering hours for Phase 3 were estimated as 265, a 241 underestimation as compared to the 506 actual hours worked, estimations were based on time spent on previous phases and the estimation was not sufficiently adjusted for the increased workload for Phase 3. Entering Phase 3 there were a total of 91 contingency hours, 48 originally scheduled for Phase 3 and 41 surplus hours from previous phases. All contingency hours were used for a remaining overage of 152 hours. Figure 21 compares the estimates and actuals for junior engineering hours.

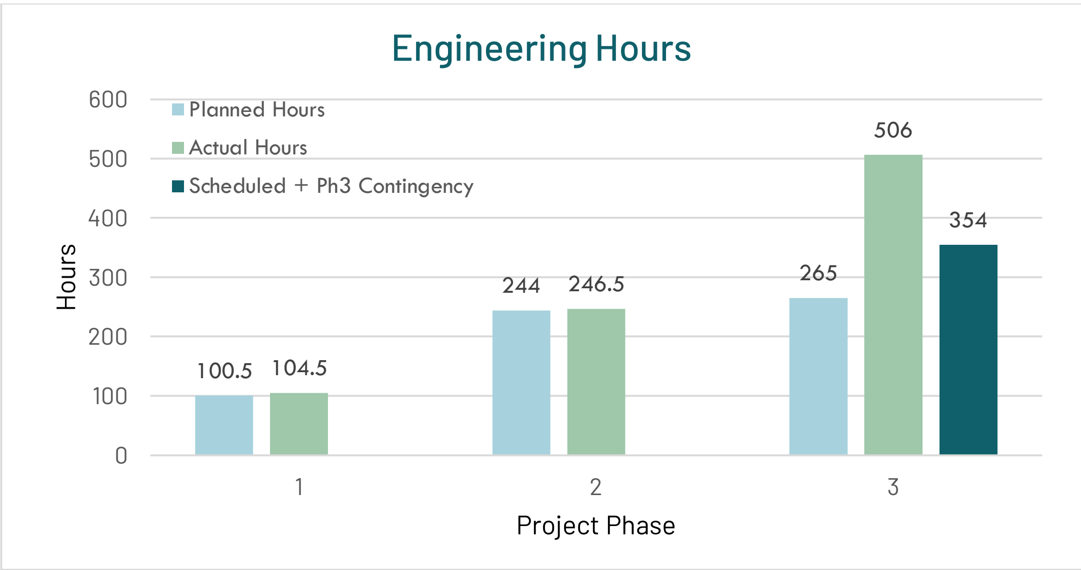

Figure 21: Comparison between actual and planned project hours per phase

The total project cost is calculated from both junior engineering hours from the design team and senior engineering hours from the team advisor. Table 13 shows the total cost breakdown per phase. The initial estimated project cost was \$58,445 + \$8,640 contingency for a total of \$67,085. The actual total project cost was \$89,200, \$22,115 over the initial estimated cost.

Table 13: Project cost by phase comparing estimates and actuals

	Junior Engineer (\$90/hr)	Senior Engineer (\$150/hr)	Estimated Values	Actual Values
Phase 1	100.5	2	\$ 9,545.00	\$ 9,705.00
Phase 2	244	4	\$ 22,560.00	\$ 22,635.00
Phase 3	281	7	\$ 26,340.00	\$ 45,802.50
Sub-Total	678.5	13	**\$ 58,445.00**	**\$ 78,142.50**
Contingency (\$90/hr)			\$ 8,640.00	-\$ 11,057.50
Grand Total			**\$ 67,085.00**	**\$ 89,200.00**

The complete project schedule is shown in the Gantt chart in Appendix P. The updates to this schedule since Phase 2 consist of breaking down categories into more detailed tasks, however the total time estimates were not changed, the hours were simply redistributed. Additionally, at the beginning of the project 48 contingency hours were scheduled for Phase 3, the 41 unused contingency from Phases 1 and 2 meant that at the beginning of Phase 3 there were 89 hours of contingency.

A complete breakdown of tasks completed, and hours worked by each team member is shown in Appendix P.

Note: the Gantt Chart does not include time scheduled or used for meetings. This is shown in Table P-1.

10.0 Conclusion

Hydro Motors has successfully designed a hydrogen fuel cell motorcycle powertrain. Calculations were used to verify characteristics of the required components, and simulation software was able to model the performance of the powertrain altogether. While the client originally desired to retrofit an existing motorcycle with this system, the sizing requirements of current fuel cell technology would make this very difficult. Hydro Motors recommends that the client use this design as a guideline for a future retrofitting project.

Client Acceptance Signature:

Dr. Larry Unsworth, Department of Chemical and Materials Engineering

University of Alberta, December 7th, 2022

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12.0 Appendices

Appendices A through P consist of calculations according to the flow chart shown below.

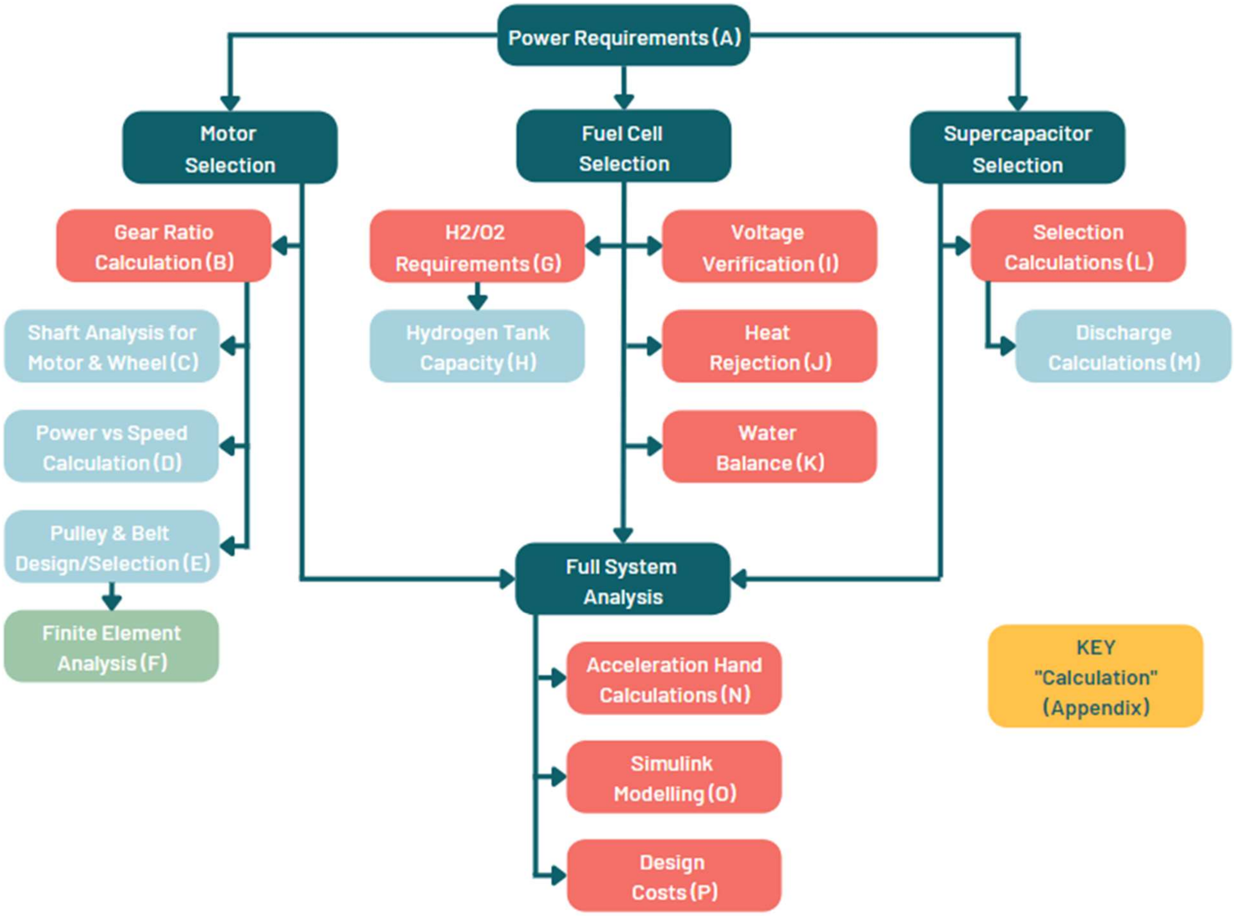


Figure A-1: Design Process Calculation Flow Chart

Appendix A: Power Requirements

Motor Power Calculations

Created by Daniel Gye and James Donick
October 16th 2022

Updated by Daniel Gye
November 27th 2022

Assumptions:

- Vehicle is Moving at constant velocity
- Frontal Area of Motorcycle can be approximated as a triangle
- Density of Air is 1.184 kg/m^3
- Vehicle size dimensions are from a Harley Davidson Fatboy Motorcycle
- Vehicle weight is from a Harley Davidson Fatboy Motorcycle
- Vehicle will travel up a 8% grade with a speed of 50 km/h (Extreme case)
- Drag coefficient will be 0.4007 as obtained from a CFD analysis of sport motorcycles
- Rider maintains a forward lean during operation, keeping half of their head above the windshield
- Rider Weighs 90 kg
- Assume Rolling Coefficient to be 0.01 (Based on Advisor)

In order gauge the efficacy of the Simulink model, hand calculations were performed to obtain values that could be compared to the model's results. The movement of the vehicle at 140 km/h on a flat road was first considered, then the movement of the vehicle at 50 km/h on a 8% grade.

Case 1: Straightaway constant Velocity travel at 140 km/h

Vehicle Characteristics and Constants

$v_{bike} := 985\ \mathrm{mm}$

$h_{bike} := 675\ \mathrm{mm}$

$m_{bike} := 304\ \mathrm{kg}$

$m_{rider} := 90\ \mathrm{kg}$

$g := 9.81\ \dfrac{\mathrm{m}}{\mathrm{s}^2}$

Rolling Coefficient, $\alpha := 0.01$

Velocity

$V_1 := 140\ \dfrac{\mathrm{km}}{\mathrm{hr}} = 38.8889\ \dfrac{\mathrm{m}}{\mathrm{s}}$

$$F_d := \frac{C_d \cdot A_f \cdot \rho \cdot v^2}{2}$$

Drag Force (Fd)

Drag Coefficient

$c_d := 0.4007$

Air Density

$\rho := 1.184\ \dfrac{\mathrm{kg}}{\mathrm{m}^3}$

Frontal Area

$A_f := \dfrac{1}{2} \cdot v_{bike} \cdot h_{bike} = 0.3324\ \mathrm{m}^2$

$$F_{d1} := \frac{c_d \cdot A_f \cdot \rho \cdot V_1^2}{2} = 119.262\ \mathrm{N}$$

Frictional Force (Ff)

$F_f := \alpha \cdot \left(m_{bike} + m_{rider}\right) \cdot g = 38.6514\ \mathrm{N}$

Total Force

$F_1 := F_f + F_{d1} = 157.9134\ \mathrm{N}$

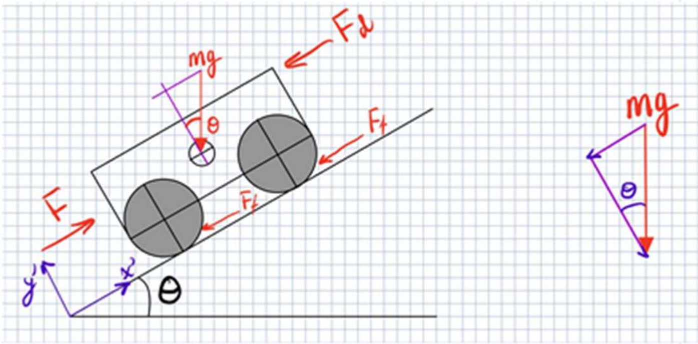
Output Power Requirement

$P_1 := \left(F_{d1} + F_f\right) \cdot V_1 = 6.1411\ \mathrm{kW}$

Case 2: Hill climb at a steep grade (8%), moving at 50 km/h

Angle of hill:

$\theta := \operatorname{atan}\left(\frac{8}{100}\right) = 4.5739\ \mathrm{deg}$



Velocity $V_2 := 50\ \frac{km}{hr} = 13.8889\ \frac{m}{s}$

Drag Force (Fd)

Drag Coefficient
$c_d := 0.4007$

Air Density
$\rho := 1.184\ \frac{kg}{m^3}$

Frontal Area

$A_f := \frac{1}{2} \cdot w_{bike} \cdot h_{bike} = 0.3324\ m^2$

$F_{d2} := \frac{c_d \cdot A_f \cdot \rho \cdot V_2^{\ 2}}{2} = 15.212\ N$

Gravitational Force

$g := 9.81\ \frac{m}{s^2}$

$m_{rider} := 90\ kg$

$F_g := \left(m_{bike} + m_{rider}\right) \cdot g \cdot \sin(\theta) = 308.2264\ N$

Total Force, $F_2 := F_{d2} + F_g + F_f = 362.0898\ N$

Output Power Requirement

$P_2 := F_2 \cdot V_2 = 5.029\ kW$

$P_2 = 5.029\ kW$

$P_2 = 6.744\ hp$

Required Power Calculations

Determining the required output from the fuel cell to power the drivetrain

Assumptions:
- Belt efficiency is 91%
- Central Motor efficiency is 82% (As per manufacturer specifications)
- DC/DC Converter efficiency of 90% (As per manufacturer specifications)

$\eta_{belt} := 91\ \%$

$\eta_{centralmotor} := 82\ \%$

$\eta_{Converter} := 90\ \%$

Case 1 Power Required

$P_{FuelCell1} := \frac{P_1}{\eta_{belt} \cdot \eta_{centralmotor} \cdot \eta_{Converter}} = 9.1442\ kW$

Case 2 Power Required

$P_{FuelCell2} := \frac{P_2}{\eta_{belt} \cdot \eta_{centralmotor} \cdot \eta_{Converter}} = 7.4883\ kW$

Appendix B: Peak and Rear Wheel Torque, and Gear Ratio Calculations

Peak Torque

Calculations to determine the required torque at the rear wheels to overcome the static friction of the vehicle.

Assumptions

Selected Gear Ratio of 5

Peak motor stall torque is 160 Nm as per manufacturer specifications

$\mu_s := 0.68$ Coefficient of static friction between tire rubber and asphalt

$$f_{friction} := \mu_s \cdot (m_{bike} + m_{rider}) \cdot g = 2628.2952 \text{ N}$$

$$T_{starting} := f_{friction} \cdot \frac{1}{2} \cdot D_{wheel} = 567.4489 \text{ N m}$$

$$T_{required} := \frac{T_{starting}}{5} = 113.4898 \text{ N m}$$ Torque required from the motor

Rear Wheel Torque

Calculations to determine the torque at the rear wheel during 0 to 100 km/hr acceleration

$$D_{wheel} := 17 \text{ in} = 431.8 \text{ mm}$$

$$F_{rw} := (m_{rider} + m_{bike}) \cdot a = 967.0752 \text{ N}$$ (Force at the rear wheel)

$$T_{max.wheel} := F_{rw} \cdot \frac{1}{2} \cdot D_{wheel} = 208.7915 \text{ N m}$$

Gear Ratio Calculations

Assumptions

- Efficiency of belt is 0.91
- The worst case of power required is considered (Acceleration 0 - 100 km/h)
- Motor Spins at ~4137 RPM

Find angular velocity of rear wheel gear required to generate the required torque:

$$Power\ (P) := Torque\ (T) \cdot RotationalSpeed\ (\omega)$$

Wheel Characteristics

This is the required torque the wheel must generate during the 0-100 km/h case.

$$T_{max.wheel} = 208.7915 \text{ N m}$$

$$P_{avg} = 13431.6 \text{ W}$$

$$\omega_{wheel} := \frac{P_{avg}}{T_{max.wheel}} = 614.3081 \text{ rpm}$$

Gear ratio

$$SpeedRatio\ (\mathbf{e}) := \frac{DrivenGearSpeed\ (\omega_{out})}{DrivingGearSpeed\ (\omega_{in})}$$

$$e_{w.m} := \frac{\omega_{wheel}}{\omega_{motor}} = 0.1485 \qquad GearRatio := \frac{1}{e_{w.m}} = 6.7339$$

This idealized gear ratio was ultimately not used, as it would have required a rear pulley diameter that exceeded the rear wheel diameter. A gear ratio of 5 was selected instead of 6.73, and thus, future calculations and models were changed to address this.

Appendix C: Shaft Deflection Verification

On the motorcycle, there are components experiencing loads in multiple plains of motion, and as a result, calculations must be performed to verify if the durability of these components is enough to withstand the forces acting upon them. All components were analyzed with a factor of safety of 1.5, as the components are made of highly reliable 304 stainless steel, and the loading and environmental conditions are not severe during vehicle use.

Motor Output Shaft

The Golden Motor™ HPM 20 kW BLDC motor was ultimately selected to propel the motorcycle, and thus, the dimensions and durability of its output shaft needed to undergo verification with the calculations. Due to the presence of a belt and pulley transmission attached to the shaft, it was guaranteed to experience a bending deformation, and so Castigliano's theorem was applied to the shaft.

Motor Shaft Feasibility Analysis

Completed by Daniel Gye on November 22, 2022

Calculations to determine the feasibility and performance of the motor shaft under peak torque.

Constants

Power

$P := 18.4\ \text{kW}$

Torque (extrapolated from supplier provided curves)

$T := 42.4756\ \text{N m}$

Shaft length

$L := 58\ \text{mm}$

Shaft Diameter

$D_{shaft} := 30\ \text{mm}$

Motor Pulley Radius

$r_1 := 29.87\ \text{mm}$

Stainless Steel Elastic Modulus

$E := 190 \cdot 10^3\ \text{MPa}$

Stainless Steel Shear Modulus

$G := 79 \cdot 10^3\ \text{MPa}$

Factor of Safety

$n := 1.5$

Maximum permitted angular deflection at supports

$\varphi := 0.001$

$\varphi_{max} := \dfrac{\varphi}{n} = 0.0007$

Angle of the pulley from the horizontal plane

$\theta := 5.31\ \text{deg}$

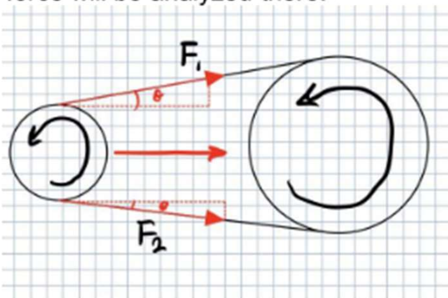
Maximum permitted shaft twist

$\beta := 3\ \dfrac{\text{deg}}{\text{m}}$ (shaft twist permitted per unit length)

$\Phi := \dfrac{\beta \cdot L}{n} = 0.116\ \text{deg}$ Permitted shaft twist

Case 1: Bending moments on the shaft

Due to the presence of an angle at the belt, tensile force is not only acting in the horizontal plane. In addition to this, due to the rotation of the pulley, the tension on the lagging side of the pulley, F2, is only 30% of that of the leading side F1, which creates a net imbalance of horizontal forces. Despite this fact, most of the force acting on the pulley is still in the horizontal plane, and thus force will be analyzed there:



$$F_1 := \frac{T}{r_1} = 1422.0154\ \text{N}$$

$$F_2 := F_1 \cdot 30\ \% = 426.6046\ \text{N}$$

$$F_{1h} := F_1 \cdot \cos(\theta) = 1415.9129\ \text{N}$$

$$F_{1v} := F_1 \cdot \sin(\theta) = 131.5995\ \text{N}$$

$$F_{2h} := F_2 \cdot \cos(\theta) = 424.7739\ \text{N}$$

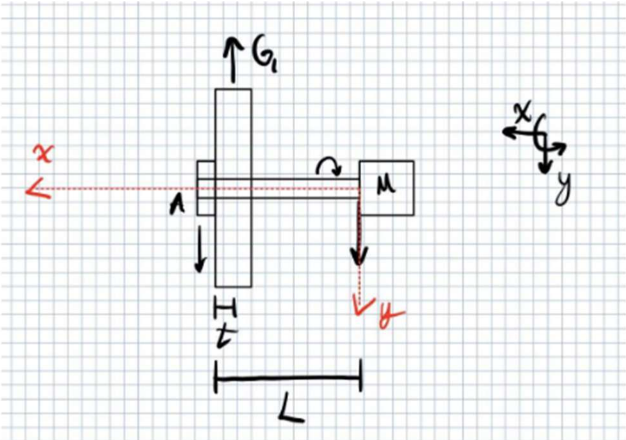
$$F_{2v} := -F_2 \cdot \sin(\theta) = -39.4799\ \text{N}$$

Horizontal and vertical pulley Forces

$$G_h := F_{1h} + F_{2h} = 1840.6868\ \text{N}$$

$$G_v := F_{1v} + F_{2v} = 92.1197\ \text{N}$$

The horizontal pulley force is greater in magnitude, and thus, will be considered in this bending case



G1 represents the horizontal force component of the pulley
A is the fixed support (assumed to be an outer compartment)
M is the motor as well as an additional fixed support

The free body diagram displays the supports at the motor, M, and at the point where the pulley would be anchored on a body component, A. The input force at G1 is 1840.7 N, which means that the support reactions can be calculated:

Obtain the support reactions using moments

$$R_M := \frac{12.5}{50} \cdot G_h = 460.1717 \text{ N}$$

$$R_A := \frac{37.5}{50} \cdot G_h = 1380.5151 \text{ N}$$

Shear flow expressions: with the whole length considered, as well as the thickness of the pulley t, the following expressions can be created:

$$q(x) := R_M (x)^{-1} - G_h (x - 45.5)^{-1} + R_A (x - 58)^{-1}$$

$$V(x) := R_M (x)^{0} - G_h (x - 45.5)^{0} + R_A (x - 58)^{0}$$

$$M_z(x) := R_M (x)^{1} - G_h (x - 45.5)^{1} + R_A (x - 58)^{1}$$

Slope and Deflection Expressions

$$\theta(x) := \int_0^x \frac{M_z(x)}{EI} \, dx + C_1$$

$$y(x) := \int_0^x \int_0^x \frac{M_z(x)}{EI} \, dx \, dx + C_1 \cdot x + C_2$$

$$\theta(x) := \frac{\left(R_M (x)\right)^2 - \left(G_h (x - 37.5)\right)^2 + \left(R_A (x - 50)\right)^2}{2 \cdot EI} + C_1$$

$$y(x) := \frac{\left(R_M (x)\right)^3 - \left(G_h (x - 37.5)\right)^3 + \left(R_A (x - 50)\right)^3}{3 \cdot 2 \cdot EI} + C_1 \cdot x + C_2$$

By applying boundary conditions at to the displacement function y(x) , the values of C2 and C1 can be determined:

Boundary condition 1: y(0) = 0, C2 = 0

Boundary condition 2: y(L) = 0, L = 58

$$y(L) := \frac{R_M \cdot 58^3 - G_h \cdot (58 - 45.5)^3}{3 \cdot 2 \cdot EI} + 58 \cdot C_1$$

$$C_1 := \left(-\frac{1}{174}\right) \cdot \frac{\left(R_M \cdot 58^3 - G_h \cdot (58 - 45.5)^3\right)}{2 \cdot EI}$$

$$\varphi(x) := \frac{R_M \cdot x^2 - G_h \cdot (x - 45.5)^2 + R_A \cdot (x - 58)^2 - \frac{1}{174} \cdot \left(R_M \cdot 58^2 - G_h\,(58 - 45.5)^2\right)}{2 \cdot EI}$$

With the completed angular deflection equation, **φmax** can be applied at the motor support where x=0, and **I** can be found:

Boundary condition 3: Maximum permitted deflection at support A : θ(0) = 0.001. Use this to obtain EI, the product of moment of inertia (I) and the elastic modulus (E)

$$\varphi_{max} = 0.0007$$

$$\varphi(0) := \frac{-\left(G_h \cdot (-45.5\ \text{mm})^2\right) + R_A \cdot (-58\ \text{mm})^2 - \frac{1}{174\ \text{mm}} \cdot \left(R_M \cdot (58\ \text{mm})^3 - G_h\,(58\ \text{mm} - 45.5\ \text{mm})^3\right)}{2 \cdot EI}$$

$$EI := \frac{-\left(G_h \cdot (-45.5\ \text{mm})^2\right) + R_A \cdot (-58\ \text{mm})^2 - \frac{1}{174\ \text{mm}} \cdot \left(R_M \cdot (58\ \text{mm})^3 - G_h \cdot (58\ \text{mm} - 45.5\ \text{mm})^3\right)}{2 \cdot \varphi_{max}} = 2.5352 \cdot 10^8\ \text{N mm}^2$$

$$I := \frac{EI}{E} = 1334.3152\ \text{mm}^4$$

Next, the moment of inertia can be used to obtain the radius and in turn the diameter of the shaft required to obey this case. This value will be compared to that of the manufacturer specified shaft diameter:

$$r_{motorshaft.1} := \left(\frac{4 \cdot I}{\pi}\right)^{\frac{1}{4}} = 6.4201\ \text{mm}$$

$$D_{motorshaft.1} := r_{motorshaft.1} \cdot 2 = 12.8402\ \text{mm}$$

$$D_{shaft} = 30\ \text{mm}$$

$$D_{motorshaft.1} < D_{shaft}$$

The manufacturer's designed shaft is larger than the minimum required diameter to resist bending deformation. Next, the torsional deformation of the shaft under loading must be analyzed.

Case 2: Torsional Deformation of the shaft

In this second case, the input torque, shear modulus, and length of the shaft was used to determine the minimum polar moment of inertia to resist deformation. Then, the polar moment of inertia was used to obtain the minimum required diameter:

$\phi := \frac{TL}{GJ}$ This will be rearranged for J

$$J := \frac{T \cdot L}{G \cdot \Phi} = 15402.9912\ \text{mm}^4$$

$$r_{motorshaft.2} := \left(\frac{2 \cdot J}{\pi}\right)^{\frac{1}{4}} = 9.9511\ \text{mm}$$

$$D_{motorshaft.2} := 2 \cdot r_{motorshaft.2} = 19.9022\ \text{mm}$$

$D_{shaft} = 30\ \text{mm}$

$D_{motorshaft.2} < D_{shaft}$

As seen here, the shaft is once again designed with a sufficient diameter to resist the magnitude of stress it experiences.

Key Sizing Calculations

The Keyway of the motor shaft has a length of 8 mm and an unspecified width. To determine the width and height of the required key, shear failure and bearing failure of the key must be determined. The key will be designed with the same stainless steel as the motor output shaft.

Key failure will occur at the material's ultimate strength for shear and tensile strengths. The ultimate strengths of the stainless steel have a factor of safety of 2.

Yield Strength

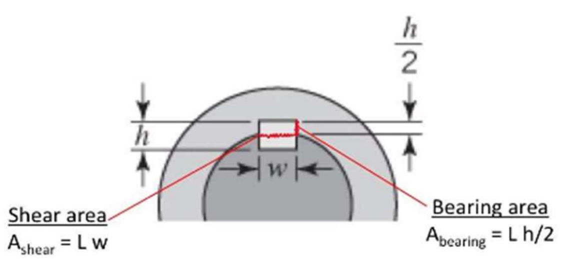
$\sigma_y := 700\ \text{MPa}$

$$\sigma_{permitted} := \frac{\sigma_y}{n} = 466.6667\ \text{MPa}$$

Shear strength (based on maximum shear stress theory)

$$\sigma_{sy} := \frac{\sigma_y}{2} = 350\ \text{MPa}$$

$$\tau_{permitted} := \frac{\sigma_{sy}}{n} = 233.3333\ \text{MPa}$$



Key Shear Stress

$$\tau := \frac{F}{A_{shear}}$$

Key Bearing Stress

$$\sigma := \frac{F}{A_{Bearing}}$$

Key Length

$W_{key} := 8\ \text{mm}$

Radius of shaft:

$$R_{shaft} := \frac{D_{shaft}}{2}$$

Force

$$F := \frac{T}{R_{shaft}} = 2831.7067\ \text{N}$$

Shearing area (Width)

$$A_{shear} := \frac{F}{\tau_{permitted}} = 12.1359\ mm^2$$

$$L_{key} := \frac{A_{shear}}{W_{key}} = 1.517\ mm$$

The key must be at least 2.0226 mm wide

Bearing Area (height)

$$A_{bearing} := \frac{F}{\sigma_{permitted}} = 6.0679\ mm^2$$

$$h_{key} := \left(\frac{2 \cdot A_{bearing}}{L_{key}}\right) = 8\ mm$$

The key must also be at least 2.0226 mm tall

Rear Bolt

The objective of these calculations was to determine the degree of shearing deformation for the one-inch, stainless steel bolt.

Key Sizing Calculations

The Keyway of the motor shaft has a length of 8 mm and an unspecified width. To determine the width and height of the required key, shear failure and bearing failure of the key must be determined. The key will be designed with the same stainless steel as the motor output shaft.

Key failure will occur at the material's ultimate strength for shear and tensile strengths. The ultimate strengths of the stainless steel have a factor of safety of 1.5.

Yield Strength

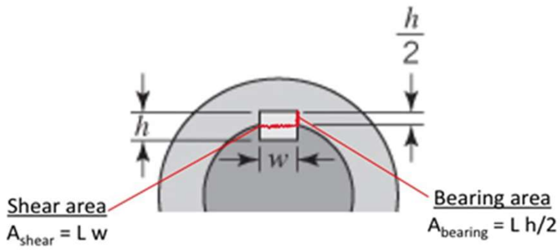
$$\sigma_y := 700 \text{ MPa}$$

$$\sigma_{permitted} := \frac{\sigma_y}{n} = 466.6667 \text{ MPa}$$

Shear strength (based on maximum shear stress theory)

$$\sigma_{sy} := \frac{\sigma_y}{2} = 350 \text{ MPa}$$

$$\tau_{permitted} := \frac{\sigma_{sy}}{n} = 233.3333 \text{ MPa}$$



Key Shear Stress

$$\tau := \frac{F}{A_{shear}}$$

Key Bearing Stress

$$\sigma := \frac{F}{A_{Bearing}}$$

Key Length

$$W_{key} := 8 \text{ mm}$$

Radius of shaft:

$$R_{shaft} := \frac{D_{shaft}}{2}$$

Force

$$F := \frac{T}{R_{shaft}} = 2831.7067 \text{ N}$$

Weight

$$W := m \cdot 9.81 \frac{\text{m}}{\text{s}^2} = 3865.14 \text{ N}$$

Normal Force

$$N := \frac{W}{2} = 1932.57 \text{ N}$$

Weight

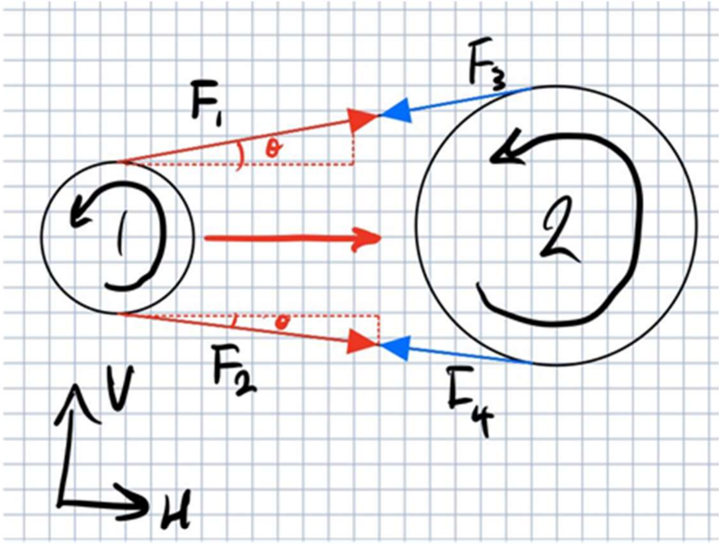
$$W := m \cdot 9.81 \frac{\text{m}}{\text{s}^2} = 3865.14 \text{ N}$$

Normal Force

$$N := \frac{W}{2} = 1932.57 \text{ N}$$

Tensile force on the pulley

The tension from the pulleys was once again included, as the pulleys are directly mounted onto the wheel



Recall: F3 and F4 will have equal and opposite load from F1 and F2 respectively

$$F_3 := \frac{T}{r_1} = 5356.545 \text{ N}$$

$$F_4 := 0.3 \cdot F_3 = 1606.9635 \text{ N}$$

$$F_{3h} := F_3 \cdot \cos(\theta) = 5239.4917 \text{ N}$$

$$F_{3v} := (-F_3) \cdot \sin(\theta) = -1113.6883 \text{ N}$$

$$F_{4h} := F_4 \cdot \cos(\theta) = 1571.8475 \text{ N}$$

$$F_{4v} := F_4 \cdot \sin(\theta) = 334.1065 \text{ N}$$

$$G_{2h} := F_{3h} + F_{4h} = 6811.3392 \text{ N}$$

$$G_{2v} := F_{3v} + F_{4v} = -779.5818 \text{ N}$$

Cross sectional area of the Bolt

The bolt has a 25.4 mm diameter. To determine the shear force it experiences, it will need to have it's cross-sectional area calculated.

$$A := \frac{\pi \cdot D_{bolt}^2}{4} = 506.7075 \text{ mm}^2$$

Shearing Force on the Bolt

During operation of the motorcycle, it will experience all of the forces from the pulley and the motorcycle weight at the same time. The shearing force is the sum of forces from both directions converted into a singular magnitude.

$$F_x := G_{2h} = 6811.3392 \text{ N}$$

$$F_y := N + G_{2v} = 1152.9882 \text{ N}$$

$$F_{shear} := \sqrt{F_x^2 + F_y^2} = 6908.2359 \text{ N}$$

Shear Stress

The total shear stress experienced by the bolt can be determined using it's cross-sectional area and total shearing force.

$$\tau := \frac{F_{shear}}{A} = 13.6336 \text{ MPa}$$

Shear Strain

$$\gamma := \frac{\tau}{G_{stainless}} = 0.0002 \text{ rad}$$

Appendix D: Motor Output vs Motorcycle Speed

The motorcycle speed will increase or decrease depending on the power supplied to the motor from the fuel cell and capacitor, according to the requirement that the motor controller dictates. The calculations performed below used the equations from the initial "Power Requirement" calculations and plotted the power required to achieve various speeds. The different plots reflect different terrain scenarios.

Power - Motorcycle Speed Relationship Calculations

By Natalia Brezovan
October 30, 2022

The calculations shown below are a continuation of the Motor Power calculations performed by Daniel Gye and James Donick on October 16th, 2022

Known values from previous calculations

$A_f := 0.3324\ m^2$	Frontal area	$g := 9.81\ \frac{m}{s^2}$	Gravitational Constant
$m_{bike} := 304\ kg$	mass of bike		
$m_{rider} := 90\ kg$	mass of rider	$\alpha := 0.01$	Rolling Coefficient
$c_d := 0.4007$	Drag Coefficient	$\beta := 5.7106\ deg$	Hill incline
$\rho := 1.184\ \frac{kg}{m^3}$	Air Density	$\eta_{motor} := 0.82$	Motor efficiency
		$\eta_{belt} := 0.91$	Belt efficiency

Equations - No incline

$$P_1 := \left(F_{d1} + F_f\right) \cdot V_1$$

where Fd1 is the drag force, Ff is the friction force, and V is velocity

$$P_1 := \left(\frac{c_d \cdot A_f \cdot \rho \cdot V^2}{2} + \alpha \cdot g \cdot \left(m_{bike} + m_{rider}\right)\right) \cdot V \quad (1)$$

Equations - 10% grade (5.7106 deg) Incline

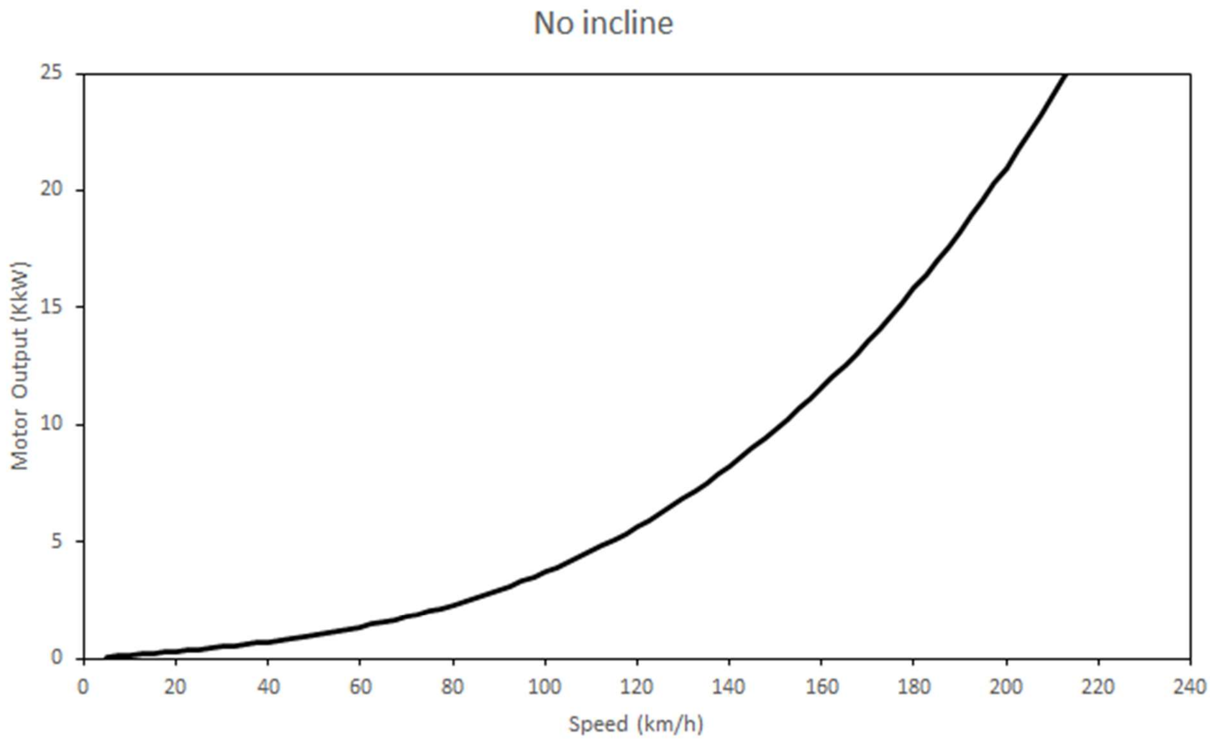
$$P_2 := F_{d2} + F_g + F_f$$

where Fd2 is the drag force, Fg is the gravitational force, and Ff is the friction force.

$$P_2 := \left(\frac{c_d \cdot A_f \cdot \rho \cdot V^2}{2} + \left(m_{bike} + m_{rider}\right) \cdot g \cdot \sin(\beta) + \alpha \cdot g \left(m_{bike} + m_{rider}\right)\right) \cdot V \quad (2)$$

Taking into account the efficiency losses at the motor and belt

$$P_{1eff} := \frac{P_1}{\eta_{belt} \cdot \eta_{motor}} \qquad P_{2eff} := \frac{P_2}{\eta_{belt} \cdot \eta_{motor}}$$



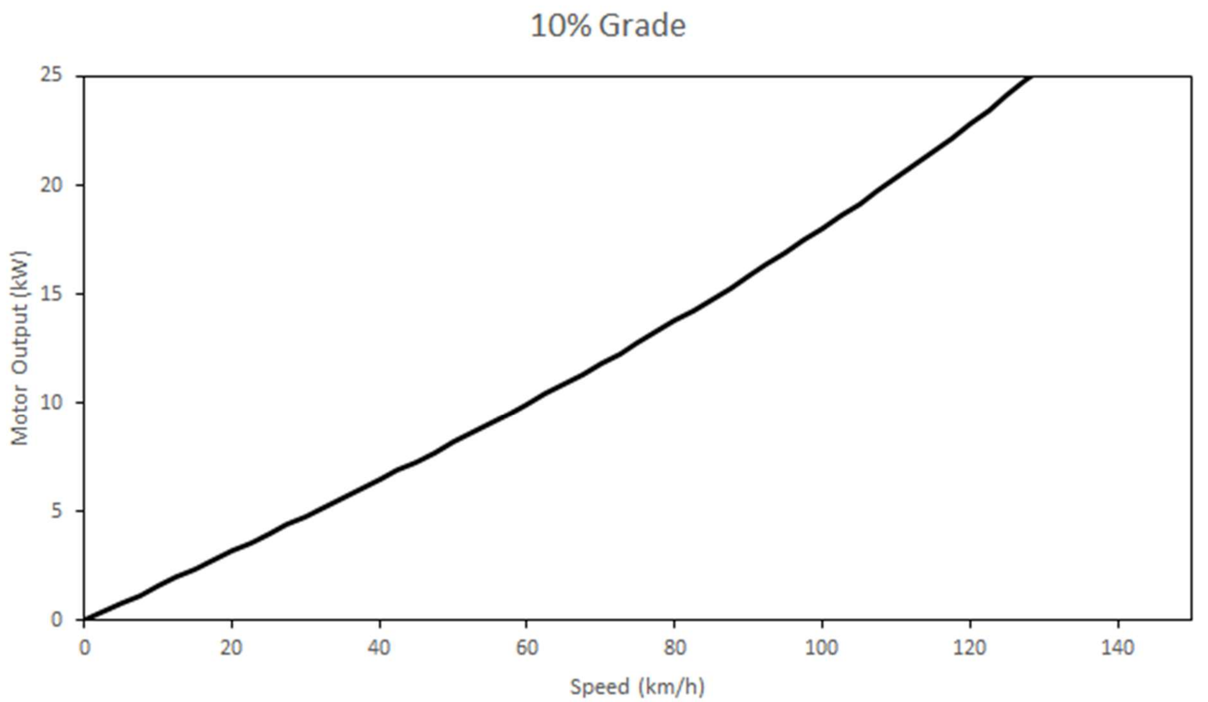


Figure D-1: Motor output vs bike speed plots

Appendix E: Pulley and Belt Calculations

The pulleys and belt will be selected and proved to have enough power capacity for the drivetrain. The calculations below use the equations and manufacturer's data from Design Manual: Timing Belts by MITSUBOSHI BELTING LTD [E1] and input data from Appendix A and Appendix B. All tables in this appendix are taken from this manufacturer's design manual.

Input Data

$P := 16.4\ \mathrm{kW}$ Power input from the Motor

$n := 4100\ \mathrm{rpm}$ The angular velocity of the motor

$ratio := 5$ the gear ratio determined in Daniel's Calculation

$a := 594\ \mathrm{mm}$ center distance: distance between the two pulleys

First, the service factor K_s will be selected to find designed power P_d which is the actual working power on the belt. K_s is sum of service correction factor K_o, speed ratio correction factor Kr and idler correction factor Ki. By referring to the design manuals, the three corrections can be respectively found from Table E-1 to Table E-3.

Table E-1: The service factor Ko selection table

Driven machine	Driving unit / Motor					
	Rated max. output of 300% or less			Rated max. output of more than 300%		
	AC motor (standard motor, synchronized motor) DC motor (Shunt) 2 or higher cylinder engine			Special motor (High torque) DC motor (Series coil) 1-cylinder engine Operation by line shaft or clutch		
	Running time (hr/day)			Running time (hr/day)		
	3~5	8~12	16~24	3~5	8~12	16~24
● Display equipment ● Medical equipment	1.0	1.2	1.4	1.2	1.4	1.6
● Carpenter's lathe ● Band saw	1.2	1.4	1.6	1.4	1.6	1.8
● Packaging machine ● Light load belt conveyor ● Screen	1.3	1.5	1.7	1.5	1.7	1.9
● Liquid stirring machine ● Drilling machine ● Lathe ● Threading machine ● Circular saw ● Planer	1.4	1.6	1.8	1.6	1.8	2.0
● Grinder ● Mixer (Cement/Viscous medium) ● Boring machine ● Milling machine ● Centrifugal compressor ● Vibrating screen ● Rotary compressor ● Injection molding machine ● Shaping machine ● Belt conveyor (ore, coal or sand)	1.5	1.7	1.9	1.7	1.9	2.1
● Extraction pump ● Hoist ● Elevator ● Washer ● Rubber processing machine (Calender, roll, extrusion machine) ● Fan ● Blower ● Conveyor (Apron, pan, bucket elevator) ● Textile machine	1.6	1.8	2.0	1.8	2.0	2.2
● Centrifugal separator ● Conveyor (Flight or screw) ● Hammer mill ● Papermaking machine (Pulper and beater)	1.7	1.9	2.1	1.9	2.1	2.3
● Kiln machinery (Brick or kneading machine) ● Mine propeller ● Air circulator	1.8	2.0	2.2	2.0	2.2	2.4

Table E-2: Speed ratio correction factor Kr selection table

Speed ratio	Correction factor Kr
1.00~1.24	0
1.25~1.74	0.1
1.75~2.49	0.2
2.50~3.49	0.3
3.50 and higher	0.4

Table E-3: Idler correction factor Ki selection table

Idler position	Correction factor(Ki)
When used on belt inner, slack side of belt	0
When used on belt outer, slack side of belt	0.1
When used on belt inner, tight side of belt	0.1
When used on belt outer, tight side of belt	0.2

The service factor, speed ratio correction factor and idler correction factor are respectively selected to be 1.8,0.4 and 0. The sum of them gives 2.2.

$K_s := K_o + K_r + K_i = 2.2$ The overload coefficient Ks

$P_d := P \cdot K_s = 36080\ W$ The designed (working) power, which will be used on belt selection graph to find out the corresponding belt

Second, choose the belt type. From Figure E-1, the temporary belt choice can be selected at corresponding design power and the small pulley revolution. Thus, by observing on Figure E-1, at 4100 rpm and 36kW, the power rating for belt G8M is chosen which has a pitch length *p* of 8mm.

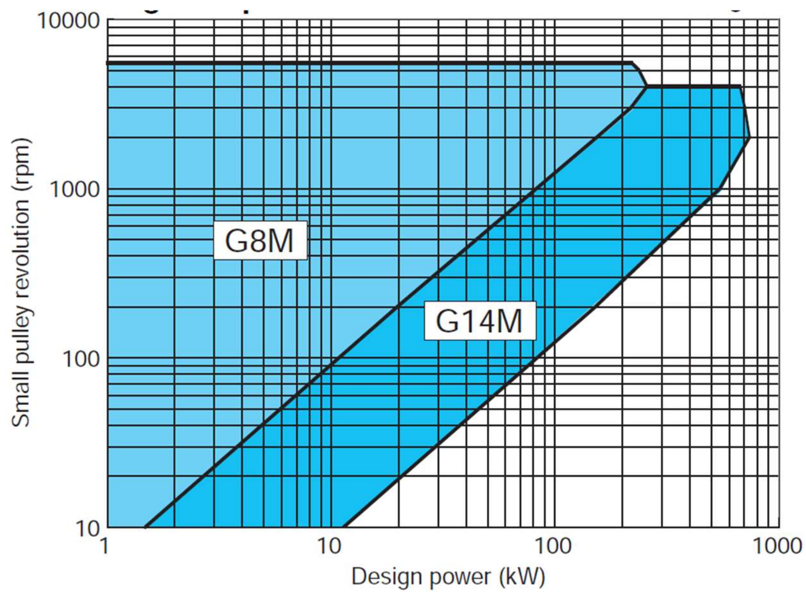


Figure E-1: The Giga Torque GX series belt selection figure

Third, calculate the belt parameters. The allowable minimum number of teeth on the corresponding pulley should be found first from Table E-4. It states the minimum number of teeth required to operate at specific revolution range. It can be found that for the selected tooth profile the minimum number of teeth is 22 for G8M. Therefore, a 24 teeth z_1 pulley can be selected. Consequently, the large pulley pitch diameter, d_{in}, is 12 inches which is lower than that of rear wheel diameter (17inches).

Table E-4: Minimum allowable number of teeth for selected tooth profile

Tooth Profile	Number of teeth	Pitch diameter (mm)	Pitch diameter (inch)
G8M	22 teeth	56.02	2.206
G14M	28 teeth	124.78	4.912

$p := 8\ \text{mm}$	The pitch of the selected belt. Pulley pitch is same to the belt pitch
$z_1 := 24$	The number of teeth on the driven pulley
$z_2 := ratio \cdot z_1 = 120$	The number of teeth on the driving pulley
$m := \frac{p}{\pi} = 0.0025\ \text{m}$	module of the belt and the pulley
$d_1 := z_1 \cdot m = 0.0611\ \text{m}$	the driving (small pulley) diameter
$d_2 := d_1 \cdot ratio = 0.3056\ \text{m}$	
$d_{in} := d_2 \cdot 1000 \cdot 0.03937 = 12.0306\ \text{in}$	Large Pulley Pitch Diameter in inches

Thereafter, the width and length of the belt can be found. It is the minimum belt length required and thus a 1600mm belt fits into the requirement.

Belt Length

Belt Length

$$L := \frac{(z_2 - z_1) \cdot p}{2} + 2 \cdot a + \frac{1}{4 \cdot a} \cdot \left(\frac{p \cdot (z_2 - z_1)}{\pi} \right)^2 = 1.599 \text{ m}$$

To find the correct belt width, the minimum belt width B'w. The P_s, namely the basic power rating for the G8M with a reference belt width of 12mm, can be found on Table E-4. It can be found that the data for G8M at 22 teeth and 25 teeth, 4000 rpm is 15.43kW and 19.47kW, and thus by interpolating, the power rating for 24 teeth is 18.12 kW.

TableE-5: The Giga Torque GX G8M Basic power rating in kW for 12mm width belt

Number of Teeth	22	25	26	27	28	29	30	31	32	33	34	35	36	37	38
φ (inch)	2.206	2.506	2.607	2.707	2.807	2.907	3.008	3.108	3.208	3.308	3.409	3.509	3.609	3.709	3.810
Revolution (rpm) / φ (mm)	56.02	63.66	66.21	68.75	71.30	73.85	76.39	78.94	81.49	84.03	86.58	89.13	91.67	94.22	96.77
10	0.12	0.14	0.15	0.16	0.17	0.17	0.18	0.19	0.19	0.20	0.21	0.22	0.22	0.23	0.24
20	0.19	0.23	0.24	0.25	0.26	0.27	0.29	0.30	0.31	0.32	0.33	0.34	0.36	0.37	0.38
30	0.25	0.30	0.32	0.34	0.35	0.37	0.38	0.40	0.42	0.43	0.45	0.47	0.48	0.50	0.51
40	0.31	0.38	0.40	0.42	0.44	0.46	0.48	0.50	0.52	0.54	0.56	0.58	0.60	0.62	0.64
50	0.37	0.45	0.47	0.50	0.52	0.55	0.57	0.60	0.62	0.65	0.67	0.70	0.72	0.75	0.77
60	0.43	0.52	0.55	0.58	0.61	0.63	0.66	0.69	0.72	0.75	0.78	0.81	0.84	0.87	0.90
70	0.49	0.59	0.62	0.65	0.69	0.72	0.75	0.79	0.82	0.85	0.89	0.92	0.95	0.98	1.02
80	0.54	0.65	0.69	0.73	0.77	0.80	0.84	0.88	0.92	0.95	0.99	1.03	1.06	1.10	1.14
90	0.60	0.72	0.76	0.80	0.85	0.89	0.93	0.97	1.01	1.05	1.09	1.14	1.18	1.22	1.26
100	0.65	0.79	0.83	0.88	0.92	0.97	1.02	1.06	1.11	1.15	1.20	1.24	1.29	1.33	1.38
200	1.16	1.42	1.50	1.59	1.68	1.76	1.84	1.93	2.01	2.10	2.18	2.27	2.35	2.43	2.52
300	1.64	2.02	2.14	2.26	2.39	2.51	2.63	2.75	2.88	3.00	3.12	3.24	3.36	3.48	3.61
400	2.11	2.59	2.75	2.91	3.08	3.24	3.39	3.55	3.71	3.87	4.03	4.19	4.35	4.50	4.66
500	2.56	3.15	3.35	3.55	3.75	3.94	4.14	4.33	4.53	4.72	4.92	5.11	5.30	5.50	5.69
600	3.00	3.70	3.94	4.17	4.40	4.63	4.87	5.10	5.33	5.56	5.79	6.02	6.25	6.48	6.70
700	3.43	4.24	4.51	4.78	5.05	5.31	5.58	5.85	6.11	6.38	6.64	6.91	7.17	7.44	7.70
800	3.85	4.77	5.07	5.38	5.68	5.98	6.29	6.59	6.89	7.19	7.49	7.79	8.09	8.39	8.68
900	4.26	5.29	5.63	5.97	6.31	6.65	6.98	7.32	7.65	7.99	8.32	8.66	8.99	9.32	9.65
1000	4.67	5.80	6.18	6.55	6.93	7.30	7.67	8.04	8.41	8.78	9.15	9.52	9.88	10.25	10.61
1100	5.08	6.31	6.72	7.13	7.54	7.94	8.35	8.75	9.16	9.56	9.96	10.36	10.76	11.16	11.56
1200	5.47	6.81	7.26	7.70	8.14	8.58	9.02	9.46	9.90	10.33	10.77	11.21	11.64	12.07	12.51
1300	5.87	7.31	7.79	8.26	8.74	9.22	9.69	10.16	10.63	11.10	11.57	12.04	12.51	12.97	13.44
1400	6.26	7.80	8.32	8.82	9.33	9.84	10.35	10.85	11.36	11.86	12.36	12.87	13.37	13.87	14.36
1500	6.64	8.29	8.84	9.38	9.92	10.47	11.00	11.54	12.08	12.62	13.15	13.69	14.22	14.75	15.28
1600	7.03	8.77	9.35	9.93	10.51	11.08	11.65	12.23	12.80	13.37	13.93	14.50	15.06	15.63	16.19
1700	7.41	9.25	9.87	10.48	11.09	11.69	12.30	12.90	13.51	14.11	14.71	15.31	15.91	16.50	17.10
1800	7.78	9.73	10.38	11.02	11.66	12.30	12.94	13.58	14.21	14.85	15.48	16.11	16.74	17.37	18.00
1900	8.15	10.20	10.88	11.56	12.23	12.91	13.58	14.25	14.91	15.58	16.24	16.91	17.57	18.23	18.89
2000	8.52	10.67	11.38	12.09	12.80	13.51	14.21	14.91	15.61	16.31	17.00	17.70	18.39	19.09	19.78
2200	9.25	11.60	12.38	13.15	13.92	14.69	15.46	16.23	16.99	17.75	18.51	19.27	20.02	20.78	21.53
2400	9.98	12.51	13.36	14.19	15.03	15.87	16.69	17.52	18.35	19.18	20.00	20.82	21.64	22.45	23.27
2600	10.69	13.42	14.32	15.22	16.13	17.02	17.92	18.81	19.70	20.58	21.47	22.35	23.23	24.11	24.99
2800	11.39	14.31	15.28	16.25	17.21	18.17	19.12	20.08	21.03	21.98	22.92	23.87	24.81	25.75	26.68
3000	12.08	15.20	16.23	17.25	18.28	19.30	20.32	21.34	22.35	23.36	24.36	25.37	26.37	27.36	28.36
3500	13.78	17.36	18.55	19.73	20.91	22.09	23.25	24.42	25.58	26.74	27.90	29.05	30.19	31.34	32.48
4000	15.43	19.47	20.81	22.14	23.47	24.80	26.11	27.43	28.74	30.04	31.34	32.63	33.92	35.20	36.49
4500	17.04	21.54	23.02	24.50	25.98	27.45	28.90	30.36	31.81	33.25	34.69	36.13	37.55	38.97	40.39
5000	18.60	23.55	25.18	26.80	28.42	30.03	31.63	33.22	34.81	36.39	37.96	39.53	41.08	42.63	44.18
5500	20.13	25.51	27.28	29.04	30.80	32.55	34.28	36.01	37.74	39.44	41.15	42.84	44.52	46.20	47.86

$$P_{24} := 15.43\ \mathrm{kW} + (24-22)\cdot\frac{(19.47\ \mathrm{kW} - 15.43\ \mathrm{kW})}{(25-22)} = 18123.3333\ \mathrm{W}$$

$P_s := 18.12\ \mathrm{kW}$ Ps for the G8M type is the reference transmission capacity. The data for 24 teeth is by interpolation

Table E-6 states the reference belt width for G8M belt is 12mm. It is called 'reference' because the basic power rating table is calculated based on the reference belt width. For other widths of the specific belt type, the width correction factor K_b will be used and selected from Table E-7 for 12mm. The belt width of 21mm is first selected as a temporary test and it is 1.75. The belt length correction factor for 1600mm length is 1.14 found on Table E-8. The Km, found on Table E-9, is the engagement factor which is determined by the number of belt teeth engaged on the small pulley when operation. The number of teeth engaged is calculated as follows. At 10 teeth, the Km is found to be 1.

Table E-6: The reference belt width Wp for G8M belt

Tooth Profile	Wp(mm)
G8M	12
G14M	20

TableE-7: The belt width correction Kb factor for 8mm tooth profile

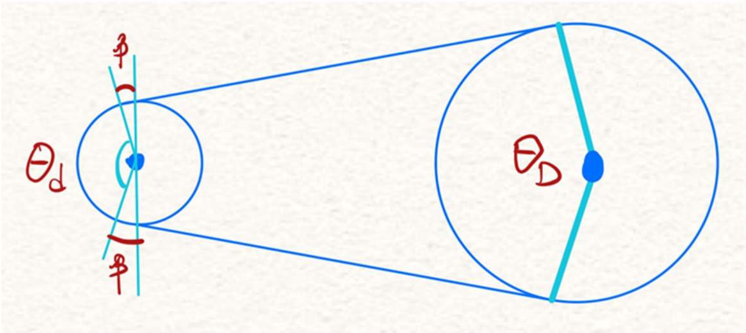
Belt width	mm	12	15	20	21	25	30	36	40	50	60	62	70	80
Kb		1.00	1.25	1.67	1.75	2.08	2.50	3.00	3.33	4.17	5.00	5.17	5.83	6.67

Table E-8: The belt length correction factor Kl for 8mm tooth profile

Length	mm	640	720	800	896	960	1000	1040	1120	1200	1224	1280	1440	1600	1760	1792
Teeth number	T	80	90	100	112	120	125	130	140	150	153	160	180	200	220	224
KL		1	1	1	1	1	1	1	1	1.03	1.03	1.05	1.1	1.14	1.17	1.18

Table E-9: Teeth in Mesh Correction factor Km table

Number of teeth in mesh	6 or more	5	4	3	2
Km	1.0	0.8	0.6	0.4	0.2



$$\beta := \operatorname{asin}\left(\frac{d_2 - d_1}{2 \cdot a}\right) = 11.8547\ deg$$

$$\theta_D := 180\ deg + 2 \cdot \beta = 203.7094\ deg$$

$$\theta_d := 180\ deg - 2 \cdot \beta = 156.2906\ deg$$ wrap angle on the small pulley

$$z_m := \frac{z_1 \cdot \theta_d}{360\ deg} = 10$$ number of teeth engaged

$$K_m := 1$$ Engagement correction Coefficient

Thereafter, with the three correction factors, the minimum belt width B'_w can be calculated. Therefore, it should be at least 20.96mm. By referring to Table E-10 that shows the nominal belt width available on the market, the belt width B_w is determined to be 21mm. Also, the number of teeth on the belt is 200.

Table E-10: Nominal belt width Wb

Nominal width	Belt width (mm)
120	12
210	21
360	36
620	62

$$B'_w := \frac{P_d}{P_s \cdot K_m \cdot K_L} \cdot w_p = 0.021\ \text{m}$$

Find the minimum width of the belt.

$$width := B'_w \cdot 1000 = 20.9597\ \text{mm}$$

min belt width in mm

$$z := \frac{L}{m \cdot \pi} = 200$$

number of teeth on the belt

Finally, test if the choice passes the following test. The product of basic power rating and three correction factors give the corrected belt capacity in terms of power (kW). If the result is larger than the design power, the belt width is correct.

$$BeltCapacity := P_s \cdot K_m \cdot K_b \cdot K_L = 36149.4\ \text{W}$$

The belt power capacity after correction

$$P_d = 36080\ \text{W}$$

```
if  Pd < BeltCapacity = Pass
  Pass
else
  Reselect
```

Drivetrain Method Design Matrix

Category	Weighting (1-5)	Belt		Chain		Crank Shaft		Justification
		Score	Weighted	Score	Weighted	Score	Weighted	
Efficiency (1-5)	5	4	20	5	25	2	10	Belt drive: 85-91% Chain Drive: 96-99% efficiency Shaft: 75-80% efficiency [E-2]
Maintenance (1-5)	4	4	16	3	12	5	20	**Belt**: minimal, replacement required upon failure, which would be more expensive than for chain. Less overall damage than chain if it breaks. **Chain:** Frequent lubrication, cleaning, tension adjusting. More overall damage and risk to rider if it breaks **Shaft**: Regular lubrication. If it fails very expensive and complicated [E-3]
Lifetime (1-5)	3	4	12	3	9	5	15	Belt Drive: 70,000-120,000 km [E-3] Chain: 24,000-32,000 km [E-4] Shaft: Engine Lifetime (~130,000-200,000 kms) [E-5]
Noise (1-5)	4	5	20	3	12	5	20	Belt: Quiet [E-6] Chain: Noise and vibrations Shaft: Quiet
Cost (1-5) including labour	3	3	9	5	15	1	3	Belt: ~1000$ [E-7] Chain: 100-250$ [E-8] Shaft: $1500-1700 [E-9]
Total Score			68		58		65	

Appendix E References

[E-1]: MITBOSHI, "Design Manual: Timing Belt," [Online]. Available: https://www.mitsuboshi.com/dcms_media/other/V832-E_timingbelt.pdf.

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[E-3]: Motorbike Writer Drive Systems Comparison [Online] https://motorbikewriter.com/chain-versus-belt-shaft/

[E-4]: Timeless2Wheels [Online] https://timeless2wheels.com/684548/motorcycle-chains-last/#:~:text=If%20maintained%20regularly%20a%20decent,(32%2C000%20%E2%80%93%2048%2C000%20km)

[E-5]: Cardo Systems [Online] https://www.cardosystems.com/blog/belt-drive-vs-chain-drive-vs-shaft-drive-motorcycles-understanding-the-types-of-motorcycle-drive-trains/

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[E-7] Happy Wrench [Online] https://happywrench.com/harley-davidson-drive-belt-replacement-cost/

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Appendix F: Finite Element Analysis

The mesh convergence study was conducted on the mesh for both pulleys from 5 mm to 1 mm with intervals of 0.5 mm. With each iteration of the mesh, the number of elements in the mesh were doubled. For a mesh to converge, the percent changes in the stress results must be less than 5% between the iterations. As seen in the Figures below, at larger mesh sizes there is an increased variation of stress results. However, after further refining the mesh to below 3 mm, the mesh converged. For the driving belt pully, the mesh converged to 0.4% difference between each of the iterations. For the driven pulley, the mesh converged to a 0.1% difference between each iteration. By achieving mesh independence, the results of the FEA can be certified as the number of elements from the mesh is no longer impacting the accuracy of the results.

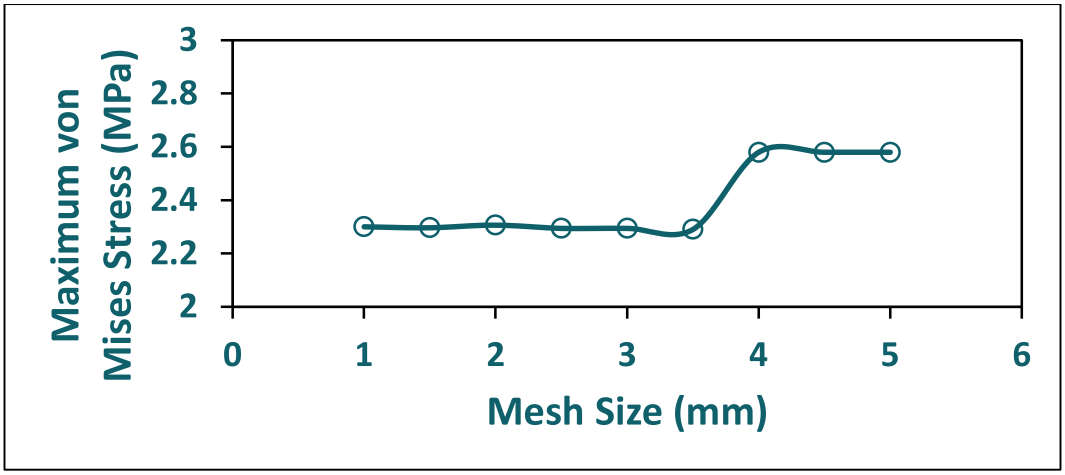


Figure F-1: Plotted Results of the Mesh Convergence Stress Study for the Driving Pulley

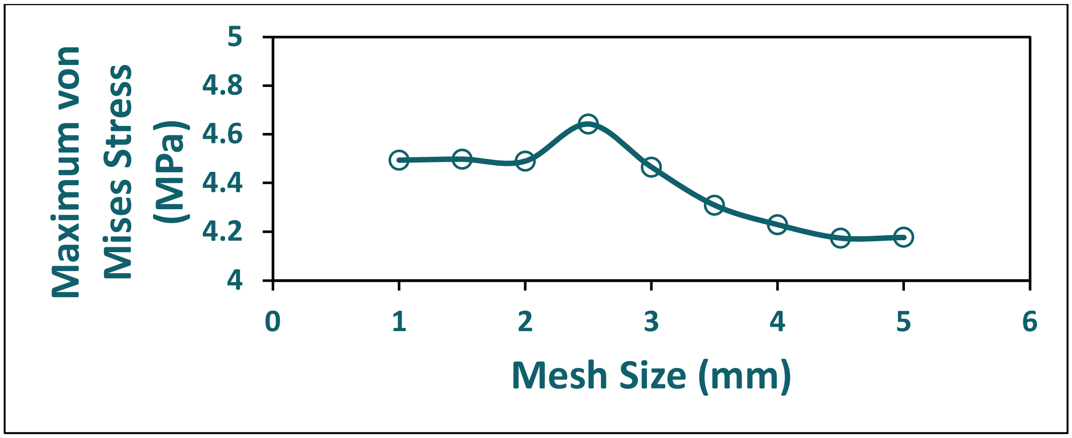


Figure F-2: Plotted Results of the Mesh Convergence Stress Study for the Driven Pulley

Appendix G: Hydrogen and Oxygen Requirements

The amount of hydrogen is calculated to find out the mass of hydrogen required to travel 300km with speed of 120km/s. The oxygen amount is calculated in mass flow rate to show the amount of oxygen required in operation. The operating current and number of cells are found from the manufacturer company.

Technical Data

$I := 70\ \text{A}$	the operating current
$n\_cell := 240$	number of cells in the two fuel cells
$Distance := 300\ \text{km}$	the target travelling distance
$Speed := 120\ \frac{\text{km}}{\text{hr}}$	the speed of the motorcycle
$t := \frac{Distance}{Speed} = 9000\ \text{s}$	time used to travel the taget distance

The amount of hydrogen required in kilograms.

Hydrogen Mass Required

$n_{H2} := 2$	the number of electrons generated per mole of fuel
$F := 96485\ \frac{\text{C}}{\text{mol}}$	Faraday's Constant
$N := \frac{I}{n_{H2} \cdot F} = \frac{7\ \text{mol}}{19297\ \text{s}}$	the mole flow rate in mol/s
$M_{H2} := 2.014\ \frac{\text{g}}{\text{mol}}$	molar mass of the hydrogen
$flowrate := N \cdot M_{H2} \cdot n\_cell = 0.0001607\ \frac{\text{kg}}{\text{s}}$	the mass flow rate of the hydrogen inside the fuel cell for reaction
$m := flowrate \cdot t = 1.4465\ \text{kg}$	the mass of Hydrogen requried

The amount of oxygen required in mass flow rate.

Oxygen Mass Required

$n_{O2} := 4$	the number of electrons generated per mole of oxygen
$N_{O2} := \frac{I}{n_{O2} \cdot F} = \frac{7\ \text{mol}}{38594\ \text{s}}$	the mole flow rate in mol/s
$M_{O2} := 32\ \frac{\text{g}}{\text{mol}}$	molar mass of the Oxygen
$flowrate_{O2} := N_{O2} \cdot M_{O2} \cdot n\_cell = 0.0013\ \frac{\text{kg}}{\text{s}}$	the mass flow rate of the Oxygen inside the fuel cell for reaction

Appendix H: Hydrogen Tank Storage Capacity

These calculations were performed to determine how much hydrogen could be stored in the selected tank, and the corresponding range to the quantity of hydrogen.

Motorcycle Range Calculations

Natalia Brezovan
November 25, 2022

Target Range: 300 km

Based on hydrogen requirement calculations previously performed by Alto G a minumum of 1.45 kg is required.
Sourced Hydrogen Tank: https://www.fuelcellstore.com/hydrogen-equipment/hydrogen-storage?page=2

Storage Capacity of Tank

$PV := mRT$

$m := \frac{P \cdot V}{R \cdot T}$

$P := 10\ \text{bar}$

$R := 4.12\ \frac{\text{kJ}}{\text{kg K}}$

$V := 2000\ \text{L}$

Due to the use of metal hydrides in the hydrogen container the storage capacity is larger than the physical volume

$T := 20\ °\text{C}$

$m = 1.6559\ \text{kg}$

Technical Data:

- ✓ Storage Capacity: 2000 liters
- ✓ Physical Size: 3.3 liters
- ✓ Weight: 14 kg
- ✓ Dimensions (H x D): 56 x 11 cm
- ✓ Recharge Pressure: 5 - 12 bar
- ✓ Maximum Pressure: 30 bar

Confirm Range with this mass of hydrogen

$m = 1.6559\ \text{kg}$

$time := \frac{m}{flowrate} = 10304.5019\ \text{s}$

$Range := Speed \cdot time = 3.4348 \cdot 10^5\ \text{m}$

$Range_{km} := Range \cdot \frac{1}{1000} = 343.4834\ \text{km}$

flowrate from prev calculations performed

$flowrate := 0.0001607\ \frac{\text{kg}}{\text{s}}$

$Speed := 120\ \frac{\text{km}}{\text{hr}}$

Appendix I: Fuel Cell Voltage Calculations

To ensure that the fuel cell can provide the power rating that is specified by the manufacturing company, calculations were completed to determine the voltage and power output from the fuel cells itself. As shown below the power output of each stack is 5017.257 W. This calculation confirms the power rating that the manufacturer states and can be used in this project.

Voltage of the Fuel Cell Calculations

$$H_2 > 2 \cdot H^{+\cdot} + 2 \cdot e^{-\cdot}$$

The dots are just fillers for SMATH as it will not allow superscripts

$$\frac{1}{2} \cdot O_2 + 2 \cdot H^{+\cdot} + 2 \cdot e^{-\cdot} > H_2 \cdot O$$

$$E := E^{o} + \frac{\Delta s}{nF} \cdot \left(T - T_o\right) - \frac{RT}{nF} \cdot \ln\left(\frac{\Pi a_{products}}{\Pi a_{reactants}}\right)$$

Assuming that the process is operating at 65 degrees celcius and air at 1 atm and H2 at 0.5 bar

$$E^{o} := -\frac{\Delta g^{o}}{nF}$$

$$\Delta g^{o} := g_{H2O}{}^{o} - \left(g_{H2}{}^{o} - \left(\frac{1}{2} \cdot g_{O2}\right)^{o}\right)$$

Where:

$$g_{H2O}{}^{o} := -237180 \ \frac{J}{mol} \qquad g_{H2}{}^{o} := 0 \ \frac{J}{mol} \qquad g_{O2}{}^{o} := 0 \ \frac{J}{mol}$$

$$E^{o} := \frac{\left(-237180 \ \frac{J}{mol} - \left(0 \ \frac{J}{mol} + \frac{1}{2} \cdot 0 \ \frac{J}{mol}\right)\right)}{2 \ mol \cdot 96485 \ \frac{C}{mol}}$$

$$E^{o} := -1.2291 \ V$$

$$\Delta s \approx \Delta s^{o} := s_{H2O}{}^{o} - \left(s_{H2}{}^{o} - \left(\frac{1}{2} \cdot s_{O2}\right)^{o}\right)$$

Where:

$$s_{H2O}{}^{o} := 69.95 \ \frac{J}{mol \ K} \qquad s_{H2}{}^{o} := 130.57 \ \frac{J}{mol \ K} \qquad s_{O2}{}^{o} := 205.03 \ \frac{J}{mol \ K}$$

Therefore:

$$E := -1.2291 \ V + \left(\frac{69.95 \ \frac{J}{mol \ K} - \left(130.57 \ \frac{J}{mol \ K} + \frac{1}{2} \cdot 205.03 \ \frac{J}{mol \ K}\right)}{2 \ mol \cdot 96485 \ \frac{C}{mol}}\right) \cdot \left(\left(65 + 273.15 \ K\right) - \left(25 + 273.15 \ K\right)\right)$$

$$-\frac{R_m \cdot (65 + 273.15\ K)}{2\ mol \cdot 96485\ \frac{C}{mol}} \cdot \ln\left(\frac{1}{0.493462 \cdot 0.21^{\frac{1}{2}}}\right)$$

$E := -1.2845\ V$

$V_{cell} := E$

$V_{stack} := n_{cells} \cdot V_{cell}$

$I_{stack} := I_{cell}$

$P_{stack} := n_{cells} \cdot V_{cell} \cdot I_{cell} \cdot E_{eff} \cdot n_{stacks}$

$I_{cell} := 70\ A$

$n_{cells} := 120$

$E_{eff} := 0.4650$

$n_{stacks} := 2$

$P_{stack} = -10034.514\ W$

Appendix J: Heat Rejection

In any chemical reaction, heat is either lost or gained. In a hydrogen fuel cell, as shown below, the hydrogen fuel cell reaction is exothermic and will release heat into its surroundings. This heat will then need to be distributed back into the atmosphere to prevent heat buildup within the motorcycle.

Heat Rejection From the Fuel Cell

Reaction of the Fuel Cell

$H_2 > 2 \cdot H^{+ \cdot} + 2 \cdot e^{- \cdot}$

The dots are just fillers for SMATH as it will not allow superscripts

$\frac{1}{2} \cdot O_2 + 2 \cdot H^{+ \cdot} > H_2 \cdot O$

Rate of $Q := \left(\frac{\Delta h}{n \cdot F} - V_{cell} \right) \cdot I_{cell}$

From thermo tables: enthalpy of fomation of water vapour is: $h_f := -241820 \frac{kJ}{kmol}$

$\Delta h := 1 \text{ mol} \cdot h_f - 1 \text{ mol} \cdot 0 \frac{kJ}{kmol} - \frac{1}{2} \text{ mol} \cdot 0 \frac{kJ}{kmol}$

$V_{cell} := 72 \text{ V}$ Voltage of the fuel cell

$I_{cell} := 70 \text{ A}$ Current of the fuel cell

$n := 2 \text{ mol}$ Number of electrons

$F := 96485 \frac{C}{mol}$ Faraday's constant

$N := 2$ Number of fuel cell stacks

Rate of $Q := Q \cdot N$

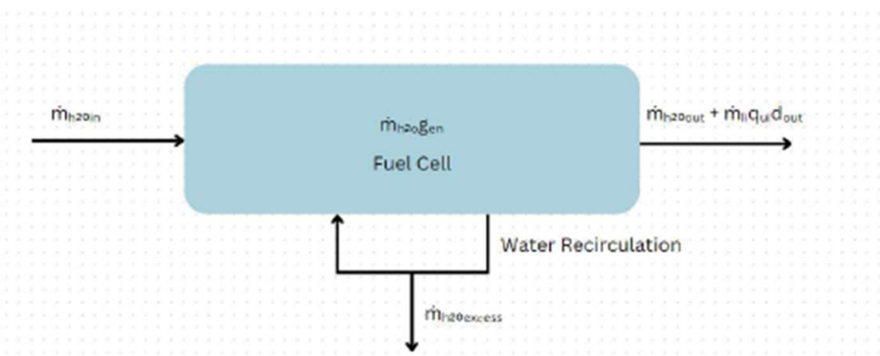
$Q = -10255.4407 \text{ W}$ Heat rejected by the fuel cell

Appendix K: Water Balance

The fuel cell reaction produces water at the cathode and needs to be recirculated back into the anode to ensure that the proton exchange membrane (PEM) is hydrated on both sides of the reaction. If the membrane dries up the fuel cell will no longer be able to operate. As shown below, starting at an equation for the generic transport equation an equation is developed based on the amount of excess water that is produced in the cathode reaction. As shown, the dimensionless variable excess water exceeds 0, which means that the water balance within the conditions of the motorcycle, ambident conditions, as well as location are suitable for this fuel cell. [27][28]

Water Balance

Expression for the Mass Flow Rate of Excess Water (Insert Image)



$$\frac{\delta}{\delta t}\cdot\int_{0}^{CV}\rho \, \mathrm{d} V+\int_{0}^{CS}\rho \, \mathrm{d}\left(\vec{v}\cdot\vec{dA}\right):=m_{H20gen} \qquad (1)$$

Where $\frac{\delta}{\delta t}\cdot\int_{0}^{CV}\rho \, \mathrm{d} V$ represents the rate of change of mass of water inside the control volume

Where $\int_{0}^{CS}\rho \, \mathrm{d}\left(\vec{v}\cdot\vec{dA}\right)$ represents the net rate at which water leaves the control volume

Where m_{H20gen} represent the rate at which mass is generated within the control volume.

Assuming that the process is in steady state, the first term results in 0. The equation ends up resulting in the following:

$$\int_{0}^{CS}\rho_{H20} \, \mathrm{d}\left(\vec{v}\cdot\vec{dA}\right)=m_{H20out}-m_{liquidout}-m_{H20excess}-m_{H20in} \qquad (2)$$

Where :

$$m_{H20excess}:=m_{H20in}-m_{H20gen}-m_{H20out}-m_{liquidout} \qquad (3)$$

Note if $m_{H20excess}$ results in a negative number, the membrane will dry up.

Expressing the variables on the right hand side of equation 3 in terms of ambient conditions and design parameters of the fuel cell.

Reaction inside of the Fuel Cell

$H_2 > 2 \cdot H^{+ \cdot} + 2 \cdot e^{- \cdot}$

The dots are just fillers for SMATH as it will not allow superscripts

$\frac{1}{2} \cdot O_2 + 2 \cdot H^{+ \cdot} > H_2 \cdot O$

Based on this reaction, it can be infered that each mole of diatomic hydrogen supplied requires half a mole of oxygen to form a mole of water

m_{H2Oin} **will be determined**

Let N_{H2} represent the molar flow rate of diatomic hydrogen entering the control volume
First

Let y represent the fraction of excess air supplied

$\left[\frac{(1+y) \cdot N_{H2}}{2}\right]$ represents the actual molar flow rate of oxygen

Let χ_{O2dry} represent the mole fraction of oxygen in dry ambient air (assumed to be 0.21)

Then the molar flow rate of dry ambient air entering the control volume is:

$$\frac{(1+y) \cdot N_{H2}}{2 \cdot \chi_{O2dry}}$$

Therefore the mass flow rate of water entering the control volume along the ambient air in vapour form is:

$$m_{H2Oin} := \frac{M_w \cdot \chi_{H2Oin} (1+y) \cdot N_{H2}}{2 \cdot \chi_{O2dry} \left(1 - \chi_{H2Oin}\right)} \qquad (4)$$

Where M_w is the molar mass of water

Where χ_{H2Oin} is the mole fraction of water in the ambient air

Now to determine m_{H2Oout}

Then the molar flow rate of dry depleted air leaving the control volume is:

$$\frac{\left[\left(1 + y - \chi_{O2dry}\right) \cdot N_{H2}\right]}{2 \cdot \chi_{O2dry}}$$

and the mass flow rate of water leaving the control volume is:

$$m_{H2Oout} := \frac{\left(M_w \cdot \chi_{H2Oout}\right) \cdot \left(1 + y - \chi_{O2dry}\right) \cdot N_{H2}}{\left(2 \cdot \chi_{O2dry}\right) \cdot \left(1 - \chi_{H2Oout}\right)} \qquad (5)$$

Where χ_{H2Oout} is the mole fraction of water in the depleted air

Now m_{H2Ogen} will be determined

$$m_{H2Ogen} := M_w \cdot N_{H2} \qquad (6)$$

Now substituting equations 4, 5, and 6 into equation 3, the mass flow rate of excess water produced becomes:

$$m_{H2Oexcess} := M_w \cdot \left[N_{H2} + \frac{\chi_{H2Oin} \left[\left(1 + y\right) \cdot N_{H2} \right]}{2 \cdot \chi_{O2dry} \cdot \left(1 - \chi_{H2Oin}\right)} - \frac{\chi_{H2Oout} \left(1 + y - \chi_{O2dry}\right) \cdot N_{H2}}{2 \cdot \chi_{O2dry} \left(1 - \chi_{H2Oout}\right)} \right] - m_{liquidout} \qquad (7)$$

The mass flow rate of excess water was expressed in non-dimensional terms by dividing equation 7 and the mass rate of water produced:

$$M'_{excess} := 1 + \frac{\chi_{H2Oin} \left(1 + y\right)}{2 \cdot \chi_{O2dry} \left(1 - \chi_{H2Oin}\right)} - \frac{\chi_{H2Oout} \left(1 + y - \chi_{O2dry}\right)}{2 \cdot \chi_{O2dry} \left(1 - \chi_{H2Oout}\right)} - \left(\frac{m_{liquidout}}{m_{H2Ogen}}\right) \qquad (8)$$

Here M'_{excess} is the non-dimensional form of the excess water rate and is equal to the mass flow rate of excess water per unit mass rate of water produced.

Also as noted earlier, when $m_{H2Oexcess}$ is negative; the membrane will dry up. Therefore in order to achieve water balance:

M'_{excess} must be positive.

$\left(\frac{m_{liquidout}}{m_{H2Ogen}}\right)$ represents the non-dimensional form of the mass flow rate of liquid water carried along with the depleted air as it could not be seperated or removed.

Calculating M'_{excess}

Since χ_{H2Oin} and χ_{O2dry} govern the amount of water and oxygen present in the ambient air, the values depend on the ambient conditions. While the other variables depend on the design conditions.

As stated earlier, χ_{O2dry} will be assumd to be 0.21. As for χ_{H2Oin} it can be calculated using the ideal gas law.

Therefore:

$$\chi_{H2Oin} := \frac{\phi \cdot p_s}{p_{amb}} \qquad (9)$$

Where ϕ is the relative humidity of ambient air, pamb is the ambient pressure, and ps is the saturation pressure of the vapour in ambient air

Using the Hyland and Wexler Equation p_s can be determined.

$$\log\left(p_s\right) := \left(\frac{-0.58002206 \cdot 10^4}{T_a}\right) + 1.3914993 - 0.048640239 \cdot T_a + 0.41764768 \cdot 10^{(-4)} \cdot T_a^2 - \left(0.14452093 \cdot 10^{-7} \cdot T_a^3\right) + 6.5459673 \cdot \log\left(T_a\right)$$

Where Ta is the ambient temperature.

To find χ_{H2Oout} the Redlich-Kwong (RK) equation is used for real gases for each of its constituents:

$$\chi_{H2Oout} := \frac{f\left(p_2, T_1\right)}{f\left(p_t, T_1\right)} \qquad (10)$$

Where pt is the fugacity of pressure, and T1 is the temperature of the depleted air (air leaving the fuel cell.

The fugacity of a gas can be determined using the Redlich-Kwong equation:

$$f := \exp\left(\frac{b}{v-b} + \ln\left(\frac{RT}{(v-b)}\right) - \left(\frac{a}{RT^{1.5}}\right) \cdot \left(\left(\frac{1}{v+b}\right) + \frac{1}{b} \cdot \ln \cdot \left(\frac{v+b}{v}\right)\right)\right)$$

Where $a := \dfrac{0.42748 \cdot R^2 \cdot T_c^{\ 2.5}}{P_c}$ and $b := \dfrac{0.08664 \cdot R \cdot T_c}{P_c}$

Where R is the universal gas constant, Tc is the critical temperature, and Pc is the critical pressure.

Where v is the molar volume

Using equations 8, 9, and 10. M'excess can be calculated when the following are given:

$T_a \quad p_{amb} \quad \phi \quad p_t \quad y \quad T_1 \quad M'_{liquidout} \quad T_c \quad P_c$

Making follow assumptions to determine the value of M'excess that needs to be balanced between both sides of the membrane to ensure that it remains hydrated.

$T_a := 25$

$p_{amb} := 100.3\ kPa$

$\phi := 0\ \%$ For the worst case senario

$T_c := 374\ °C$

$P_c := 3.7858\ MPa$

$p_t := -140.52\ °C$

$y := 0$ Assuming that all air excess air does not influence the reaction

$T_1 := 60\ °C$

$M'_{liquidout} := 0$ Assuming that no liquid exits the fuel cell

$R := R_m$

$p_1 := 3.1698\ kPa$

$p_2 := 31.202\ kPa$

$n := 1\ mol$

Using $PV := NRT$

$$v_1 := \frac{n \cdot R \cdot T_1}{p_1} \qquad v_2 := \frac{n \cdot R \cdot T_1}{p_2}$$

$$v_1 = 0.8739\ m^3 \qquad v_2 = 0.0888\ m^3$$

Calculating for M'excess

$\log\left(p_s\right) = -231.8072$

$p_s := 0$

$\chi_{H2Oin} := 0$ Since the ambient humidity is 0%

$$a = 83.1649\ \frac{m^6\ K^{\frac{1}{2}}\ Pa}{mol^2}$$

$$b = 0.0001\ \frac{m^3}{mol}$$

$$\chi_{H2Oout} := \frac{3158.294}{30125.817}$$

$M'_{excess} := 0.7797$

Appendix L: Capacitor Selection

The calculations shown below were performed to confirm the size of capacitor required for the system according to the manufacturer's procedure specified in Maxwell's "Product Guide" [L-1]

Super Capacitor Power Calculations

Calculations by
Natalia Brezovan
November 6, 2022

Determining which capacitor is required- according to manufacturer's procedure (REF)

$$\boxed{N_{cells} := \frac{V_{max}}{V_R}}$$

Where Ncells is the number of required cells in series
V_{max} is the maximum voltage required
V_R is the rated voltage of a single cell from the manufacturer

$$\boxed{C_{sys} := I \cdot \frac{t}{\left(V_{max} - V_{min}\right)}}$$

where Csys is the approximate total system capacitance
V_{min} is the minimum voltage required
I is an approximate or average current through the capacitor
t is the required run time

After finding the total number of cells and total system capacitance required, the required capacitance for a single cell can be calculated from the equation below and compared to manufacturer specifications to select the appropriate product.

$$\frac{1}{C_{sys}} := \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_n}$$

Since the capacitance for each individual cell is equal (C = C1 = C2 = Cn) the above equation can be rearranged to

$$\boxed{C := C_{sys} \cdot N_{cells}}$$

Where C is the capacitance of a single cell.

Defining Variables

To perform the calculations above Vmax, Vmin, VR, I, and t for this application must be defined.

$I := 210\ A$
$P := \eta \cdot P_e$

Note that since the capacitor is used only for acceleration or brief/sudden power changes this current can be above the maximum continous current (170 A) from the manufacturer. This current is below the max allowable current for the fuel cell of 300 A

$P_e := 10.2\ kW$ Target power value before efficiency losses

$\eta := 0.98$ Efficiency stated by manufacturer

$P = 10.0\ kW$ Based on the motrocycle required power calculations performed previously, the team has set a target maximum value of 10 kW to come from the capacitor in addition to the power supplied by the fuel cell - reducing the size of the fuel cell required.

$I_{max} := 1600\ A$ From manufacturer's specifications of absolute maximum current (peak, not continous)

The equation P = Vmax*I can be rearranged to

$V_{max} := \frac{P}{I} = 47.6\ V$ Where P is power, Vmax and I are defined previously.

$V_{min} := \frac{P}{I_{max}} = 6.2475\ V$ The minimum allowable voltage to ensure the current does not exceed the maximum current specified by the manufacturer

$t := 20\ s$ Chosen to be greater than the time it takes to accelerate from $0 - 100$ km/h

$V_R := 2.7\ V$ From manufacturer specification for BCAP3000 P270 K04/05 cell

Results

$N_{cells} = 17.6296$

$C_{sys} = 101.5658\ F$

$C = 1790.5675\ F$

Verification based on selected system

Based on the manufacturer's product options shown below, the BCAP3000 P270 K04/05 **cell** model was selected.

Rated Voltage (V_{DC})	Rated Capacitance (F)	Typical DC ESR (mΩ)	Terminal	Note: **Cell** model Model Number
3.0	3400	0.15	Threaded/Jove	BCAP3400 P300 K04/05
2.85	3400	0.22	Threaded/Jove	BCAP3400 P285 K04/K05
2.7	3400	0.22	Threaded/Jove	BCAP3400 P270 K04/K05
2.7	3000	0.15	Threaded/Jove	$\boxed{\text{BCAP3000 P270 K04/05}}$

The value of $N_{cells} = 17.6296$ and $V_{max} = 47.6\ V$ led to the selection of the 48V module with 18 of the cells selected above.

ELECTRICAL	BMOD0165 P048 C0B
Rated Capacitance[1]	165 F
Minimum Capacitance, initial[1]	165 F
Maximum Capacitance, initial[1]	198 F
Maximum ESR $_{DC}$, initial[1]	6.0 mΩ
Test Current for Capacitance and ESR $_{DC}$[1]	100 A
Rated Voltage	48 V
Stored Energy[4]	53 Wh
Absolute Maximum Voltage[2]	51 V
Module Over Voltage (OV) Alarm "ON" Range[†]	Nom 48.7 V
Cell Over Voltage (OV) Alarm	Nom 2.70 V
Cell Balance Voltage	Nom 2.30 V
Absolute Maximum Current	1,600 A
Maximum Series Voltage	800 V
Capacitance of Individual Cells[8]	3,000 F
Stored Energy, Individual Cell[8]	3.0 Wh
Number of Cells	18

Appendix L References

[L-1]: Product Guide [Online]: https://maxwell.com/products/ultracapacitors/downloads/

Appendix M: Capacitor Discharge Time

The power and current discharge profiles shown in the plots [M-1] below demonstrate the time the supercapacitor can supply power for a give power value. This interpolation is a continuation of the previous SMath sheet and therefore has the same author.

Supplied by the manufacturer for the selected capacitor (BMOD0165-P048), a 48V module, are the relations shown below. First is the voltage decrease over time with constant power (current increase), and the second plot is the voltage decrease over time with constant current (power decrease). **From interpolation of the power discharge curve - the capcitor can supply 10kW for 20 second. To be conservative in case of inaccuracies in interpolation calculations will be based on 18 seconds.**

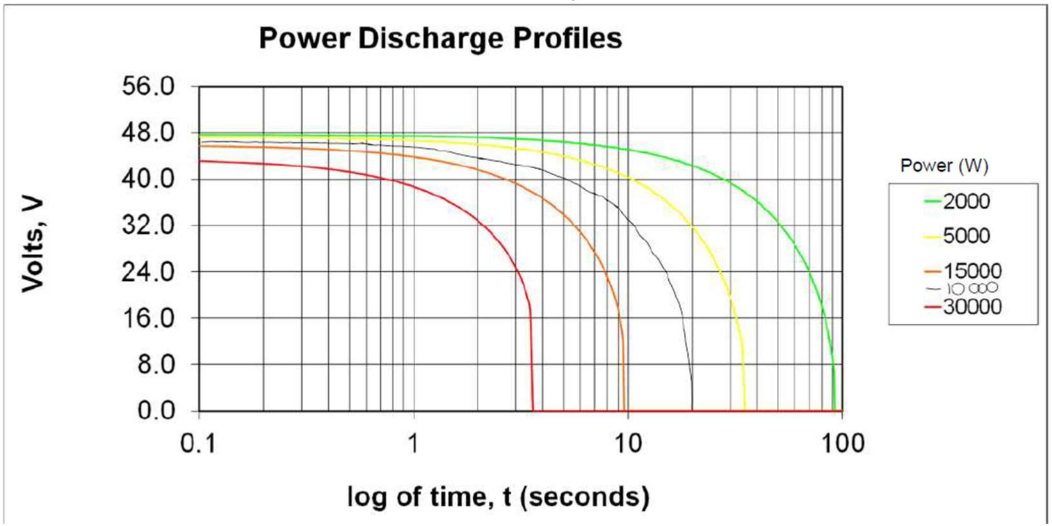


Figure M-1: Supercapacitor Power Discharge

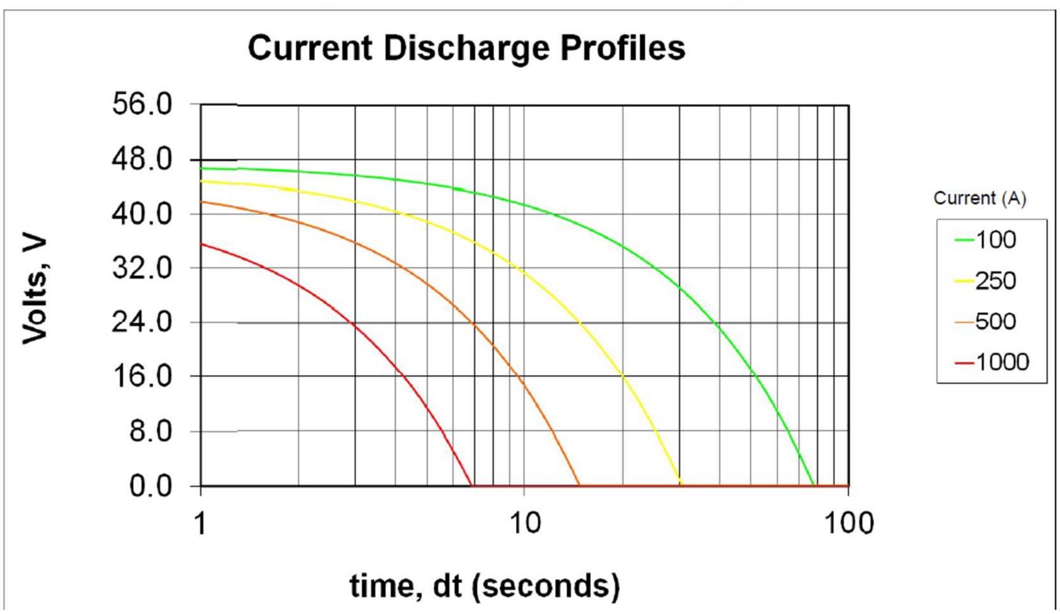


Figure M-2: Supercapacitor Current Discharge

Appendix M References

[M-1]: Discharge Profiles [Online] https://maxwell.com/products/ultracapacitors/downloads/

Appendix N: Acceleration Time (Hand Calculation)

Power to Acceleration

To roughly determine the acceleration time of the vehicle from 0-100 km/h, a rough calculation was completed with the following assumptions:

P can be represented as Average Power over the acceleration of the Vehicle
Acceleration is constant
Neglect the change of drag force
Assume V to be average Velocity over the acceleration test
DC/DC Converter Efficiency is 90%

Using these assumptions, the acceleration of the vehicle can be found using the expansion of the formula relating power, force, and velocity:

$$P := F \cdot V$$

$$P_{average} := \left(m_{rider} + m_{bike}\right) \cdot a \cdot v_{average}$$

$$a := \frac{\Delta V}{\Delta t}$$

$$P_{FuelCell} := 20\ \mathrm{kW}$$

Firstly, the average power was found by multiplying the full 20 kW fuel cell and capacitor load by all the efficiencies encountered in the powertrain:

$$P_{avg} := P_{FuelCell} \cdot \eta_{belt} \cdot \eta_{centralmotor} \cdot \eta_{Converter} = 13431.6\ \mathrm{W}$$

$$V_{initial} := 0\ \frac{\mathrm{km}}{\mathrm{hr}} = 0\ \frac{\mathrm{m}}{\mathrm{s}}$$

$$V_{final} := 100\ \frac{\mathrm{km}}{\mathrm{hr}} = 27.7778\ \frac{\mathrm{m}}{\mathrm{s}}$$

$$V_{average} := \frac{1}{2} \cdot \left(V_{final} + V_{initial}\right) = 13.8889\ \frac{\mathrm{m}}{\mathrm{s}}$$

$$a := \frac{P_{avg}}{\left(m_{rider} + m_{bike}\right) \cdot V_{average}} = 2.4545\ \frac{\mathrm{m}}{\mathrm{s}^2}$$

$$\Delta V := V_{final} - V_{initial} = 27.7778\ \frac{\mathrm{m}}{\mathrm{s}}$$

$$\Delta t := \frac{\Delta V}{a} = 11.3171\ \mathrm{s}$$

The required time to accelerate from 0 to 100 km/h for the vehicle was calculated by hand to be 11.31 seconds. However, this was determined with an optimal gear ratio of 6.73, which was unable to be implemented in the design due to size constraints of the rear wheel diameter. Thus, a gear ratio of 5 was designed, and this would affect how much torque could be fully transferred to the rear wheel.

Torque of powertrain:

Calculations used to determine the required torque of the mid-motor in the Acceleration case. This value will be compared to the power-torque curve provided by the manufacture.

$$P_{motor} := P_{FuelCell} \cdot \eta_{centralmotor} = 16.4\ \mathrm{kW}$$

$$\omega_{motor} := 4136.66\ \mathrm{rpm}$$

(Extrapolated from Motor Specs using input power)

$$T_{motor} := \frac{P_{motor}}{\omega_{motor}} = 37.8587\ \mathrm{N\,m}$$

New Acceleration (0 - 100 km/h)

With the selection of a new gear ratio to accomodate for vehicle size, the new acceleration of the vehicle must be determined

Assumptions

- Gear ratio is 5
- Torque required at the motor for acceleration is the same, and is found using the input power and rotational speed

$$T_{motor} = 37.8587 \text{ N m}$$

New torque at the rear wheel with the newly selected gear ratio

$$T_{new} := T_{motor} \cdot 5 = 189.2934 \text{ N m}$$

New force at the rear wheel

$$F_{new} := \frac{T_{new}}{\frac{1}{2} \cdot D_{wheel}} = 876.7641 \text{ N}$$

New acceleration

$$a_{new} := \frac{F_{new}}{\left(m_{bike} + m_{rider}\right)} = 2.2253 \ \frac{\text{m}}{\text{s}^2}$$

New 0 - 100 km/h time

$$\Delta t_{new} := \frac{\Delta V}{a_{new}} = 12.4828 \text{ s}$$

Appendix O: Simulink Performance Modelling

Simulink

Simulink is a MATLAB based software capable of model-based design. Simulink has a wide range of functions for controls, data processing, vehicle dynamics, etc. Simulink is best used for modeling systems dynamically. For this project, Simulink was mainly used to model a hybrid system and how it responds to different loading cases.

Overview

The Simulink model was created by modeling each of the specific components of the system individually then sending data between them to see how they interact. A top model overview of the entire system is found in Figure O-1. Figure O-1 shows the specific signals and data being transferred throughout the system. From this model, the speed, acceleration, torque, efficiency, and wheel slip can be calculated.

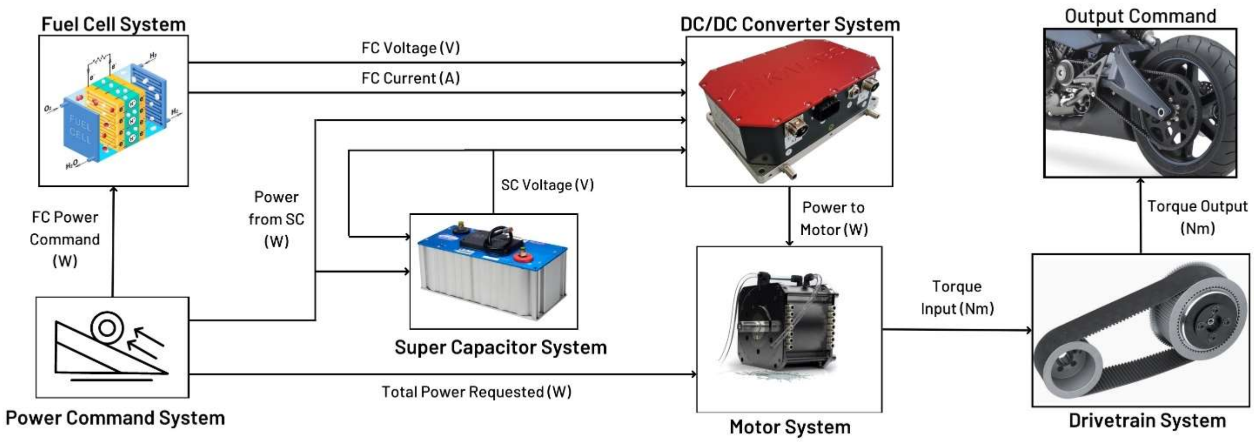


Figure O-1: Simulink System Overview

Power Command System

The initial input to the entire Simulink model comes from the power command, which controls the outputs for all other systems in the Simulink model. This subsystem receives a power input signal from the user which can be constant, time varying, or cyclical in nature. Within the power command system, a switch function is present that stops the system when braking is applied. In most cases, the command will mainly request power from the fuel cell system, but in the event of a power input greater than 10 kW, the power command will automatically request power from the supercapacitors for short durations. In Figure O-2, the full power command model is displayed.

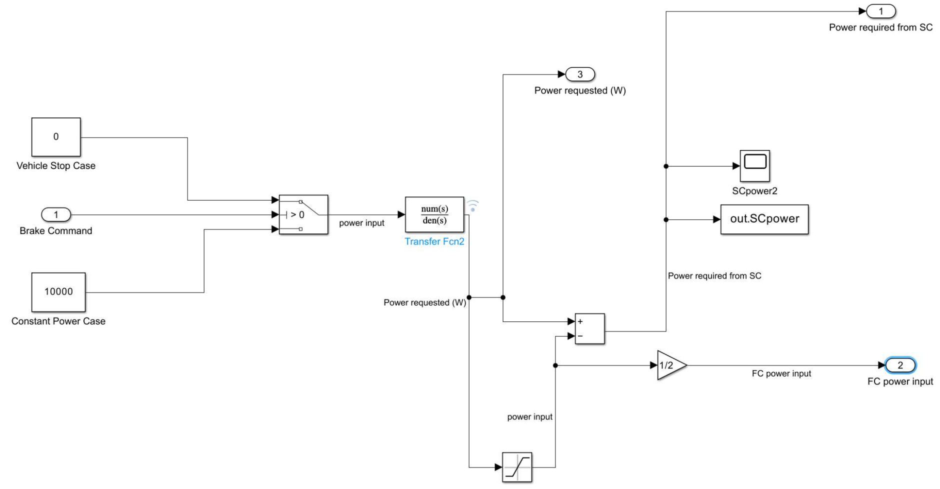


Figure 0-2: Power Command Simulink Model

Fuel Cell System

The second system in the series is the fuel cell system, which receives a power signal from the power command system. Upon receiving a power signal, this system calculates the current, voltage, and efficiency of the fuel cell at the requested power output.

To obtain the values, manufacturer provided polarization curve data was plotted in MATLAB with curve fitting methods and was then converted into Simulink look-up tables. These plots can be found in Figures 0-3, 0-4, and 0-5. Using the tables, the system was able to output specific voltages and currents for the power input signals. To account for the system consisting of two 5 kW fuel cells stacked in a series, the output voltage was doubled. These two stacks together provided the total power output of 10 kW, and the complete fuel cell subsystem can be seen in Figure 0-6.

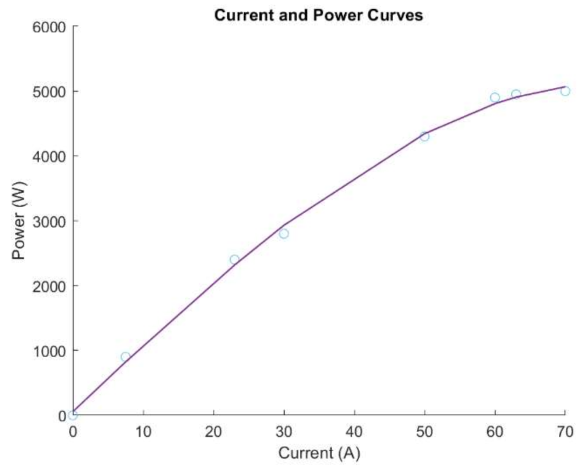


Figure 0-3: Current and Power Curve used in FC Simulink Model

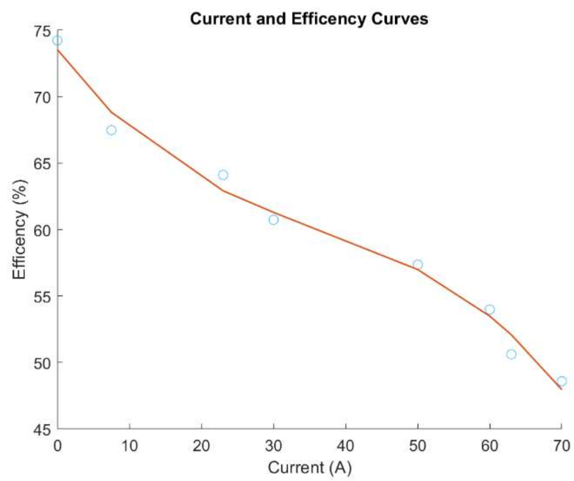


Figure 0-4: Current and Efficiency Curve used in FC Simulink Model

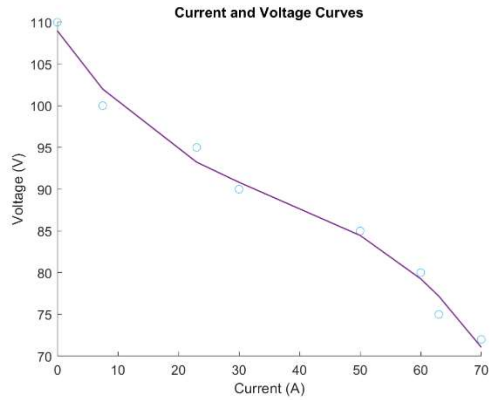


Figure 0-5: Current and Voltage Curve used in FC Simulink Model

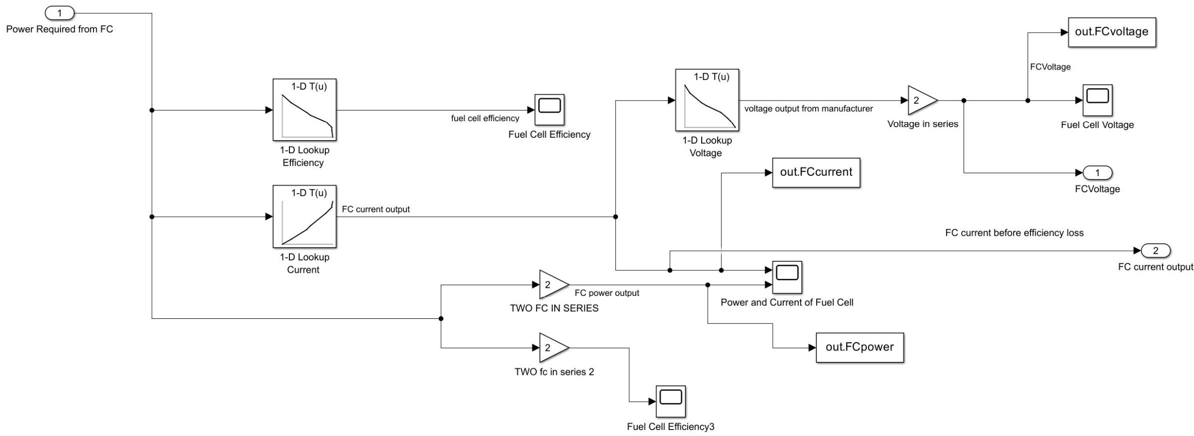


Figure 0-6: Fuel Cell Command Simulink Model

DC/DC Converter System

A DC/DC converter is required to convert the input voltage from the fuel cell to the same voltage as the supercapacitor. Ideally, this system would have been modeled as a buck/boost converter, but this proved to be complex to model. To simplify this process, the DC/DC converter was instead modeled as a system of constant efficiency loss where the output voltage would simply match that of the supercapacitor. The DC/DC converter system can be seen in Figure 0-7.

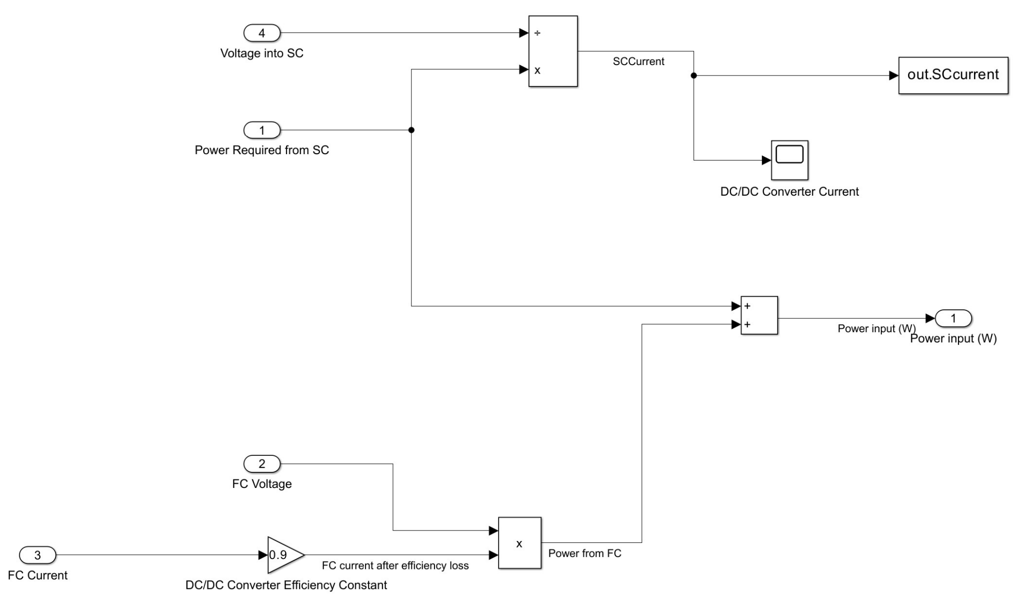


Figure 0-7: DC/DC Converter Simulink Model

Supercapacitor System

The supercapacitor system was another complex component designed around a similar model created by Bertini et. al. at the KTH Royal Institute of Technology. Supercapacitors would ideally be modeled as a series of circuits with multiple resistances and non-linear capacitances as seen in Figure 0-8 [0-1]. However, this would be extremely difficult to model and far too complex for the purposes of this report. To simplify the model, the supercapacitor was assumed to have linear behavior and no self-discharging effects. Through these assumptions, the supercapacitor was modeled as a RC circuit as shown in equation 0-1 and its defined variables are shown in Table 0-1. The final Simulink model for the supercapacitor can be seen in Figure 0-9.

$$V(s) = ESR \times I(s) + \frac{I(s)}{C \times s} \qquad (0\text{-}1)$$

Table 0-1: Variable Definition for RC Circuit formula

Unit	Definition	Value
V(s)	Voltage as a function of time	Variable
ESR	Equivalent series resistance	0.06 Ω
I(s)	Current as a function of time	Variable
C	Capacitance	165 F

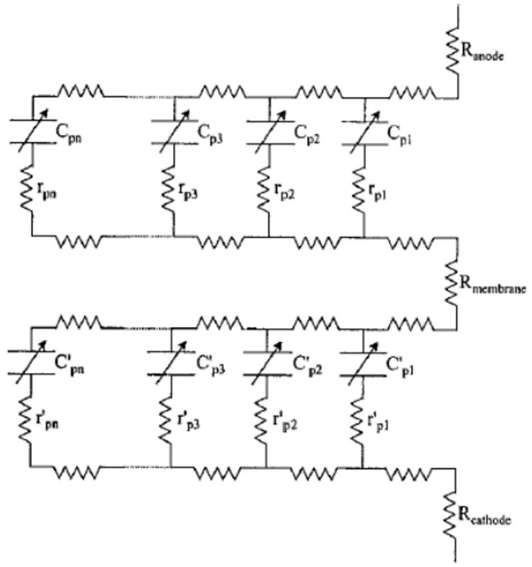


Figure 0-8: Ideal Supercapacitor Circuit [0-1]

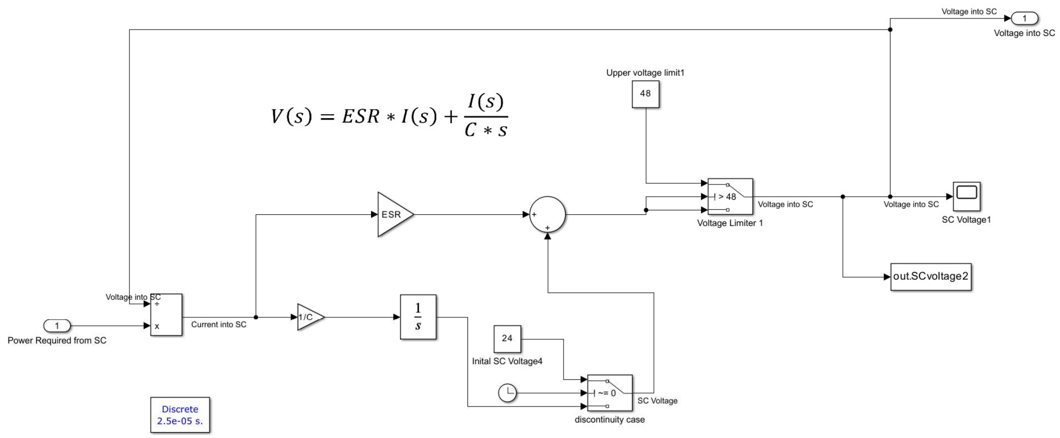


Figure 0-9: Supercapacitor Simulink Model

Motor System

The motor system was designed around the torque, speed, and efficiency data from the manufacturer which can be found in Figures 0-10 to 0-13. The motor data given from the supplier was converted to a series of look-up tables in Simulink. Through the look-up tables, the efficiency and torque could be calculated for different power commands. The motor system model is shown in Figure 0-14.

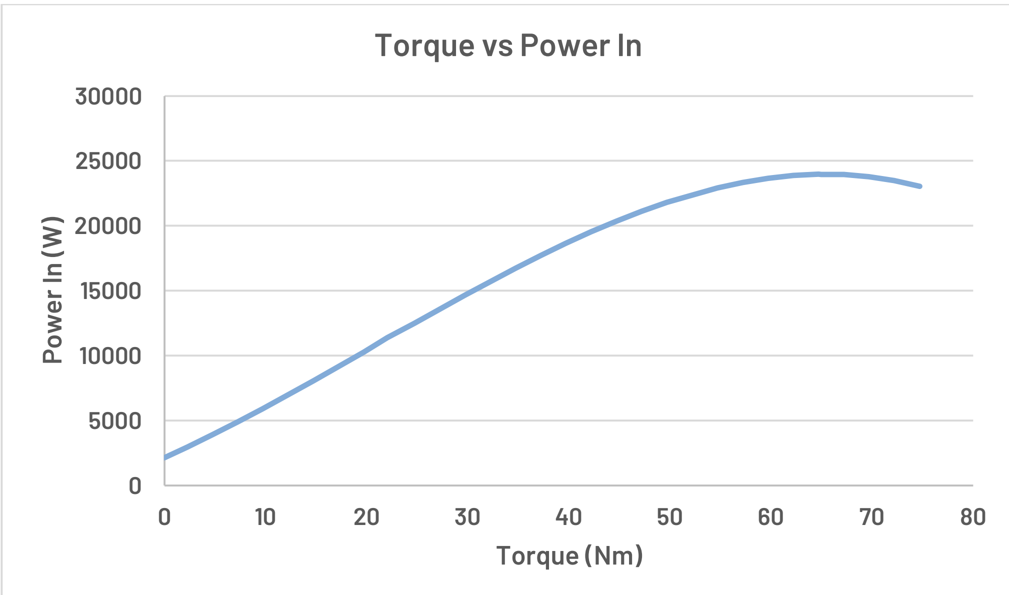


Figure 0-10: Torque vs Power in Data from Motor Supplier

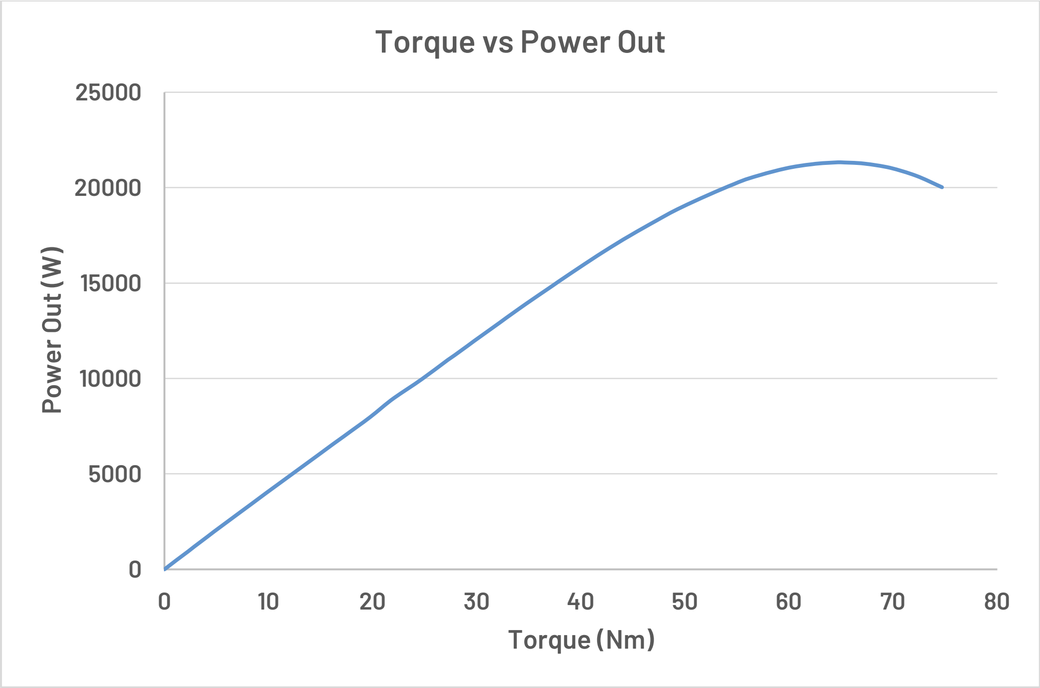


Figure 0-11: Torque vs Power Out Data from Motor Supplier

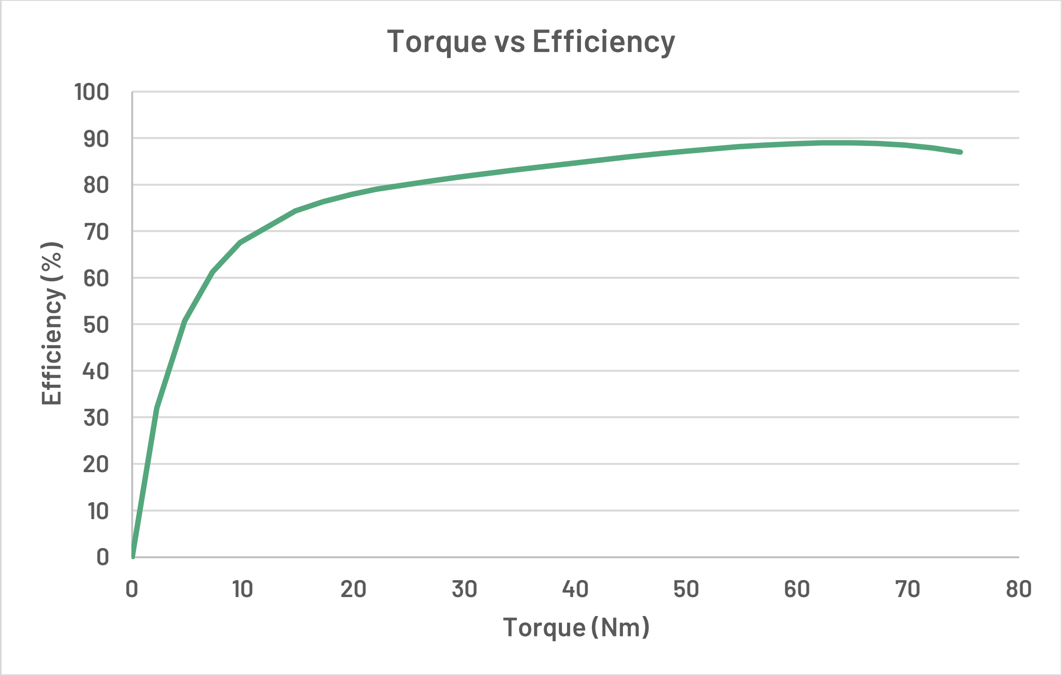


Figure 0-12: Torque vs Efficiency Data from Motor Supplier

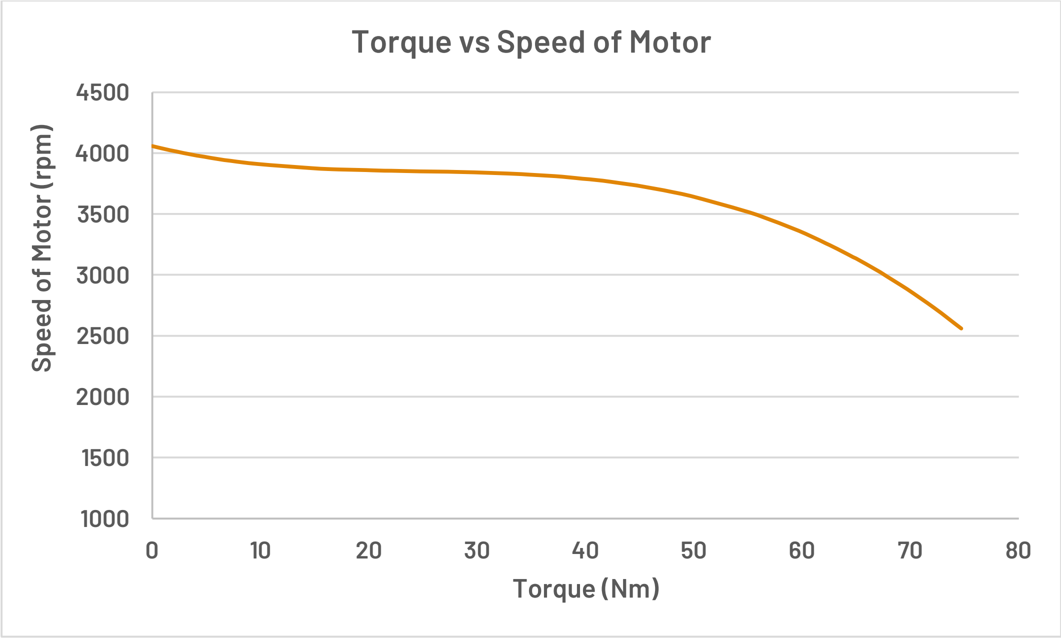


Figure 0-13: Torque vs Speed Data from Motor Supplier

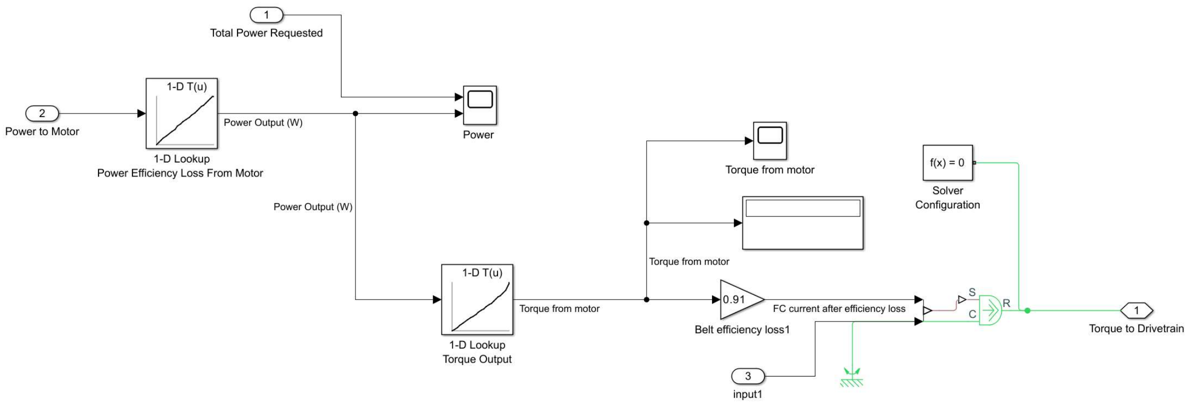


Figure 0-14: Motor Simulink Model

Drivetrain System

Simscape™ was used to model the drivetrain. Simscape is a Simulink feature that allows users to simulate multidomain physical systems [0-2]. By using Simscape functions, models are based off physical components that already contain the fundamental equations they are based on. An overview of the drivetrain model can be found in Figure 0-15. From the model, the torque from the motor is transferred to a belt drive block. From the belt drive, the signal is then transferred to calculate speed, acceleration, longitudinal forces, normal forces, wheel slip, and torque of the axle.

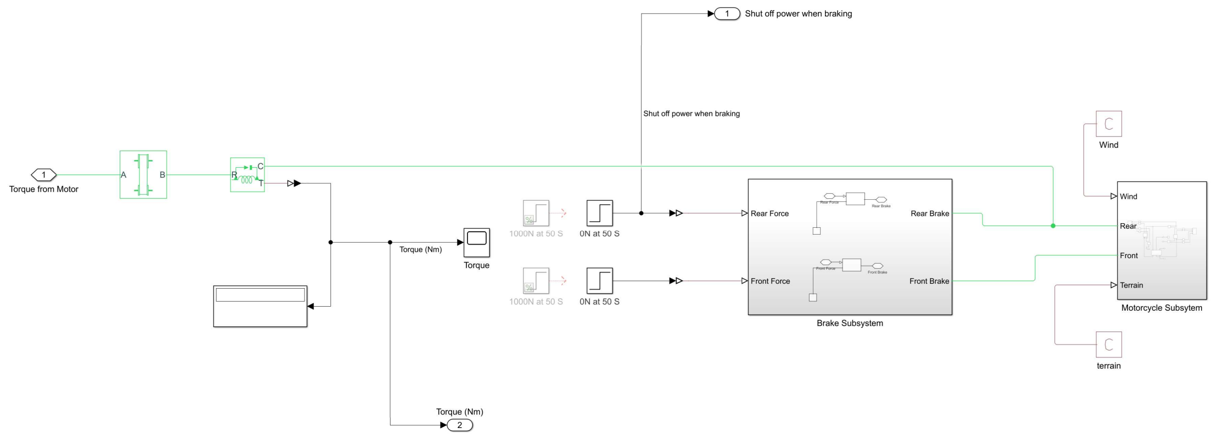


Figure 0-15: Drivetrain Simulink Model

Through Simscape, the motorcycle body, wheels, and braking systems were modelled. The motorcycle body system was designed using MathWorks physical modelling tutorials and can be seen in Figure 0-16 [0-3]. The parameters used in the Motorcycle body can be found in Figure 0-17. Magic Tire Formula blocks were used to model the motorcycle wheels, the constants used can be found in Table 0-2. The braking system was modeled using Simscape's inbuilt Loaded-contact rotational friction blocks as seen in Figure 0-18.

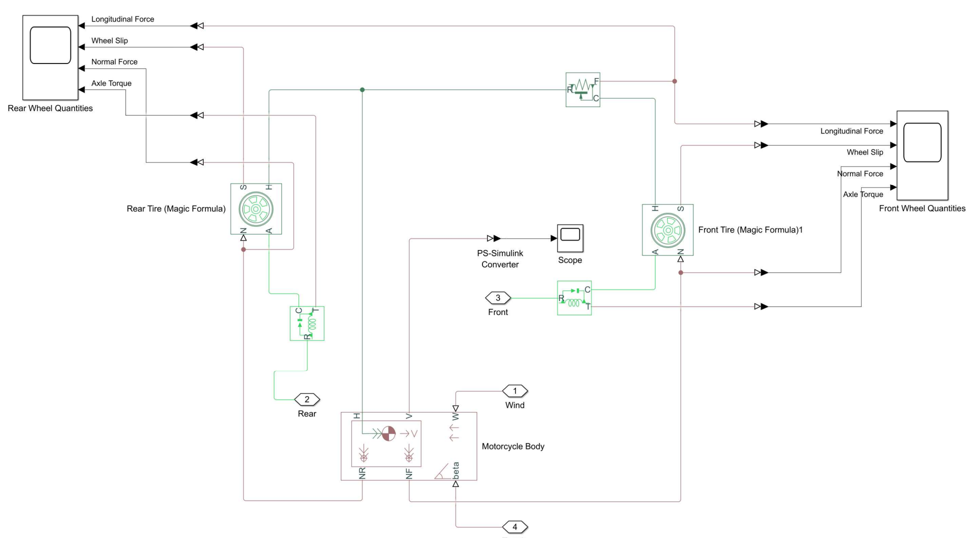


Figure 0-16: Motorcycle Subsystem Simulink Model

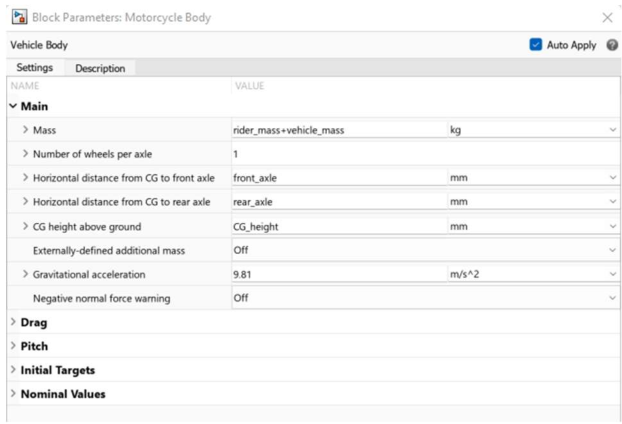


Figure 0-17: Motorcycle Body Parameters for Simscape Block

Table 0-2: Magic Tire Parameters for Simscape Block [0-4]

	Coefficients for Magic Tire Formula Block (Simscape)			
Surface	**B**	**C**	**D**	**E**
Dry Tarmac	10	1.9	1	0.97

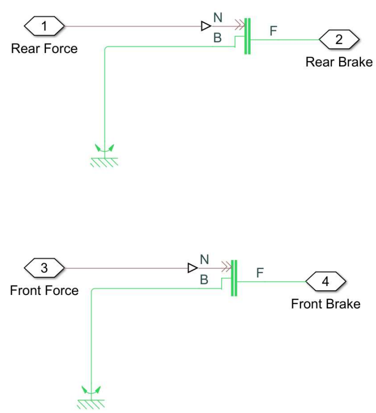


Figure 0-18: Brake Simulink Subsystem Model

From the drivetrain model, the forces at the wheels could be determined for various input power command cases. The braking force and power inputs applied to the system determined the longitudinal force, wheel slip, normal force, and axle torque experienced by the motorcycle. A single case of braking was analysed to demonstrate the function of the drivetrain system. Here, a constant power command signal of 5 kW and a braking force of 1000 N on each caliper is applied at 100 seconds. The speed change of the vehicle when braking can be seen in Figure 0-19. Values for axle torque, longitudinal force, wheel slip, and normal force for both the front and back wheel can be found from Figure 0-20 to 0-27.

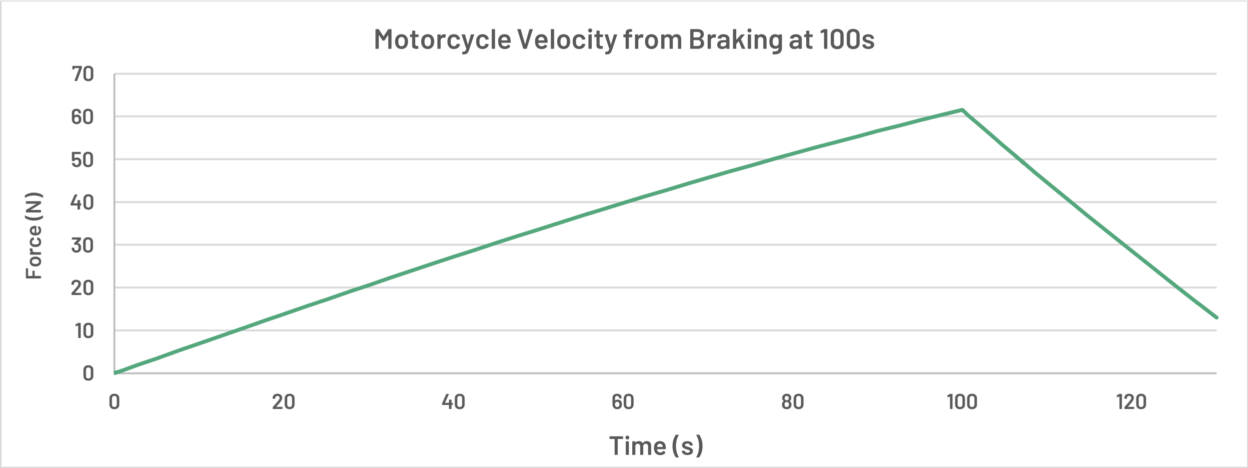


Figure 0-19: Motorcycle Velocity with Braking applied at 100s

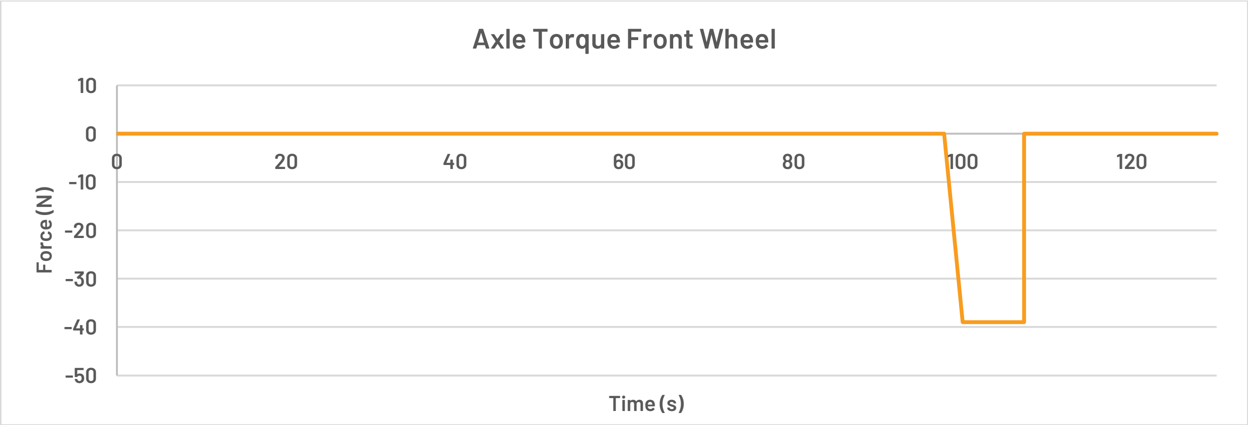


Figure 0-20: Axle Torque at Front Wheel with Braking applied at 100s

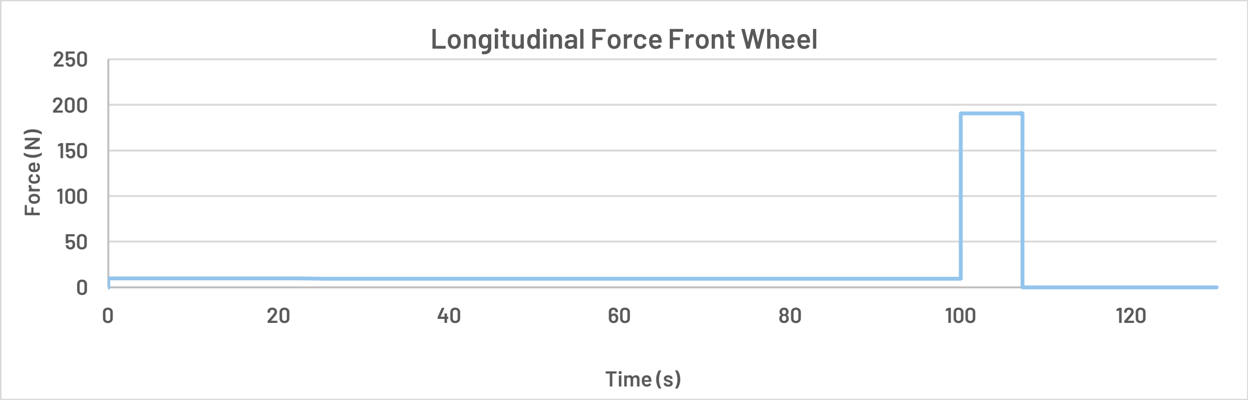


Figure 0-21: Longitudinal Force at Front Wheel with Braking applied at 100s

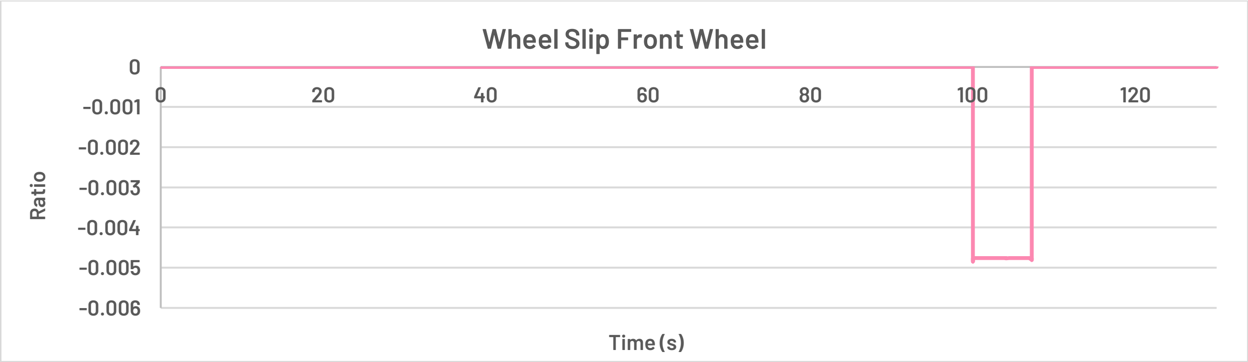


Figure 0-22: Wheel Slip at Front Wheel with Braking applied at 100s

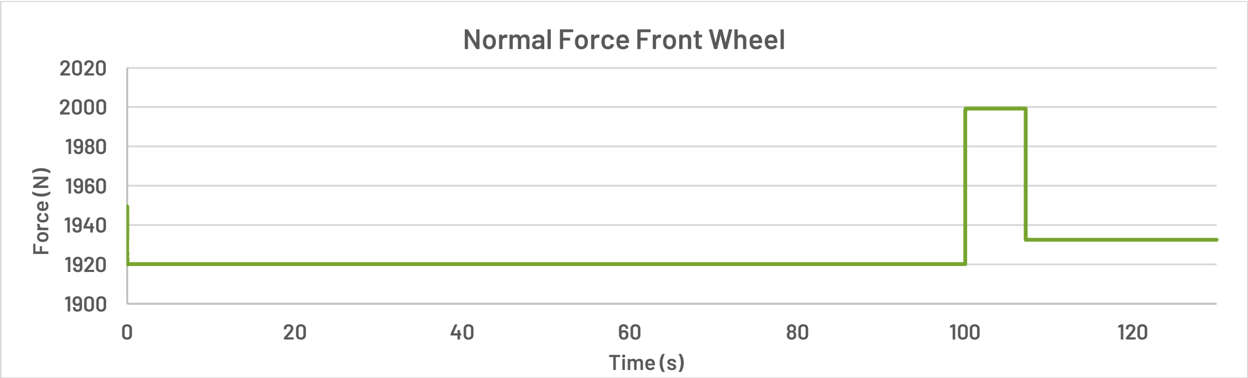


Figure 0-23: Normal Force at Front Wheel with Braking applied at 100s

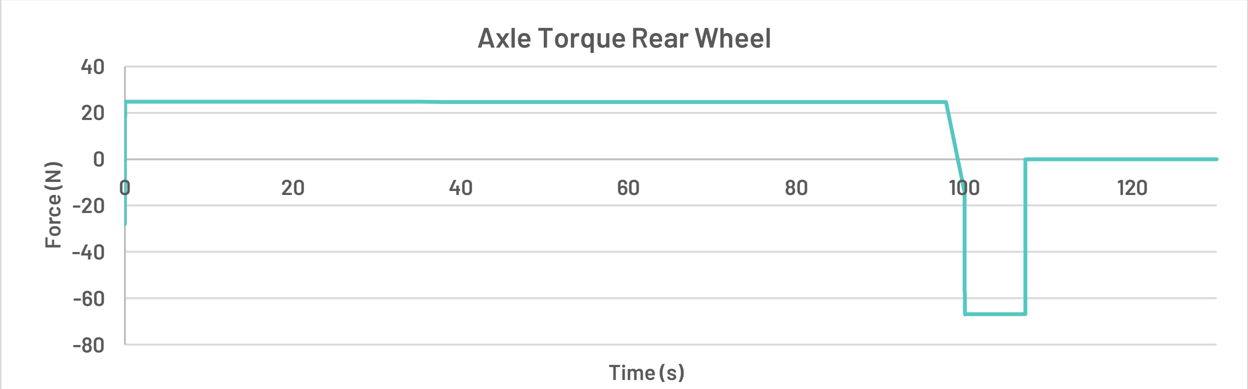


Figure 0-24: Axle Torque at Rear Wheel with Braking applied at 100s

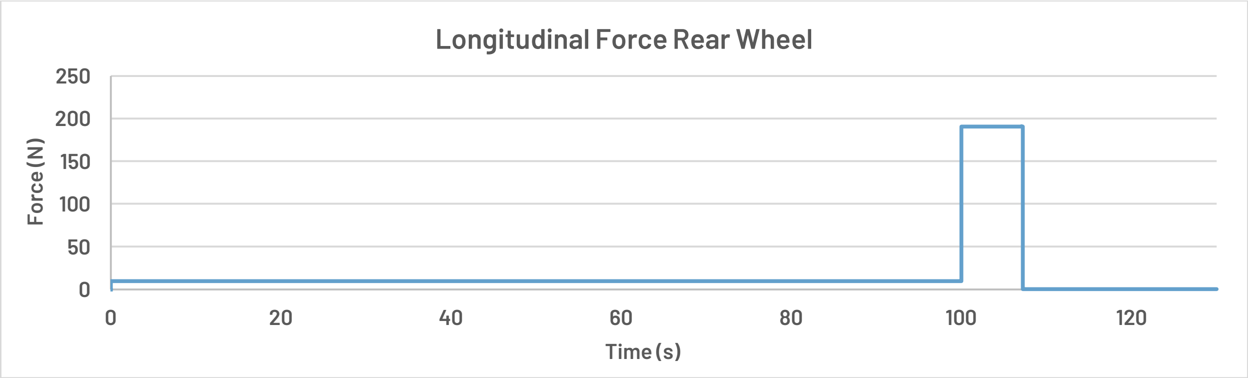


Figure 0-25: Longitudinal Force at Rear Wheel with Braking applied at 100s

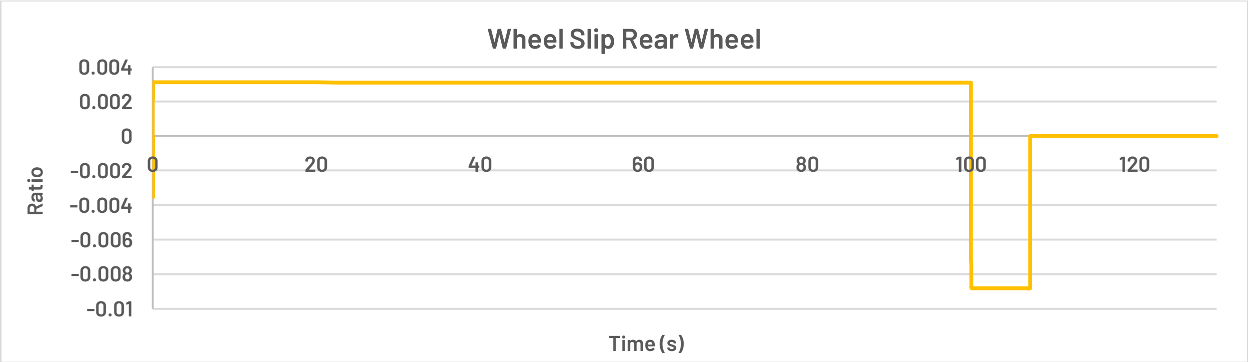


Figure 0-26: Wheel Slip at Rear Wheel with Braking applied at 100s

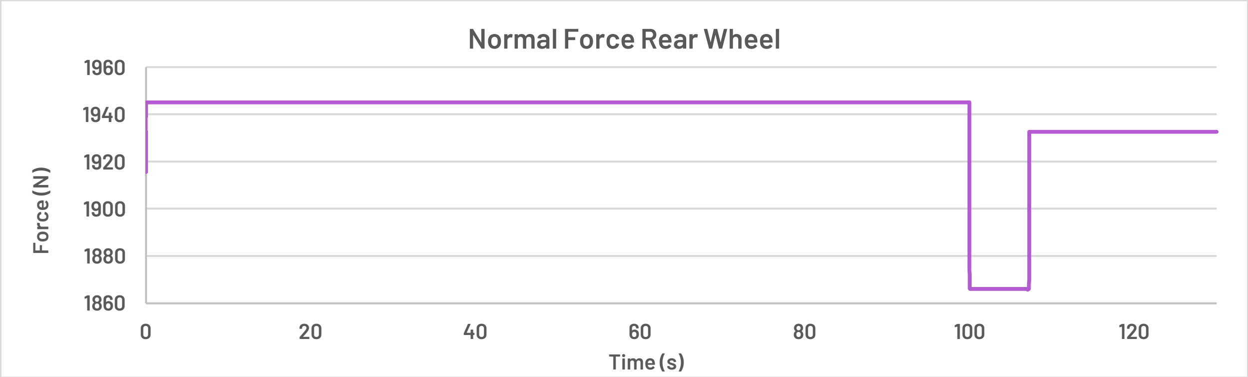


Figure 0-27: Normal Force at Rear Wheel with Braking applied at 100s

Output Command

The output command seen in Figure 0-28 receives data from the drivetrain subsystem and calculates acceleration and velocity for the motorcycle. It first obtains an output acceleration by using equations 0-2 and 0-3, where vehicle mass and force are known.

$$Force = mass \times acceleration \qquad (0\text{-}2)$$

$$F_{applied} - F_{drag} - F_{friction} - F_{gravitational} = ma \qquad (0\text{-}3)$$

Once the acceleration is obtained, it is integrated over time to obtain velocity. This value is back calculated into the aerodynamic drag formula, which increases the drag force term and in turn affects the acceleration. The iterative change in acceleration, velocity, and drag force can be done very quickly calculated by the Simulink model. The velocity and acceleration results for different power command cases are displayed in Figure 0-29.

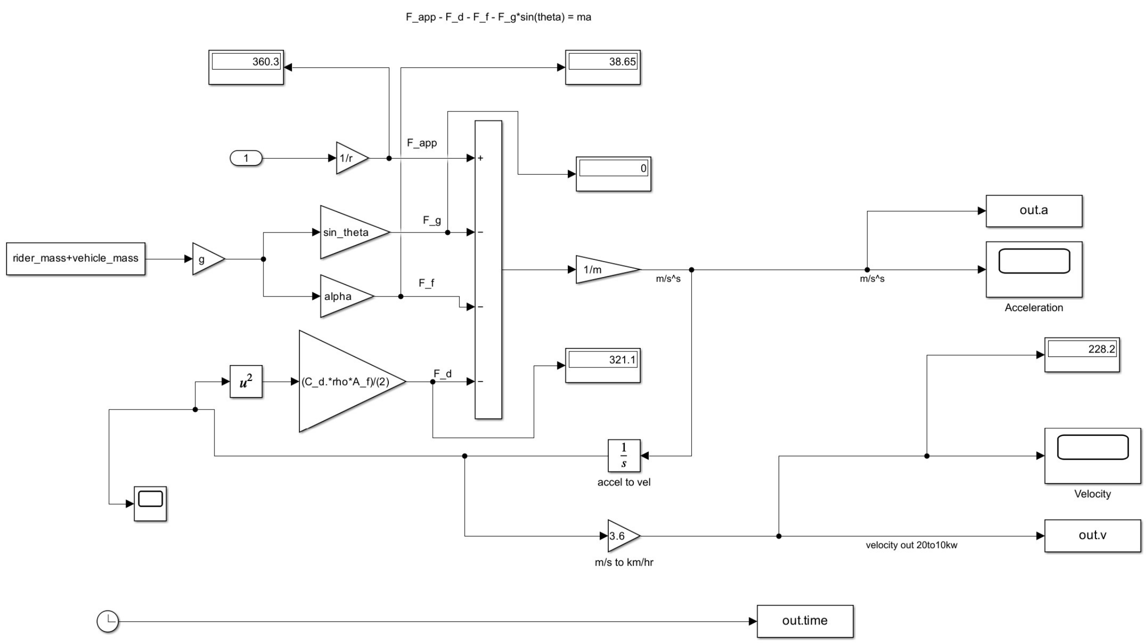


Figure 0-28: Output Command Simulink Model

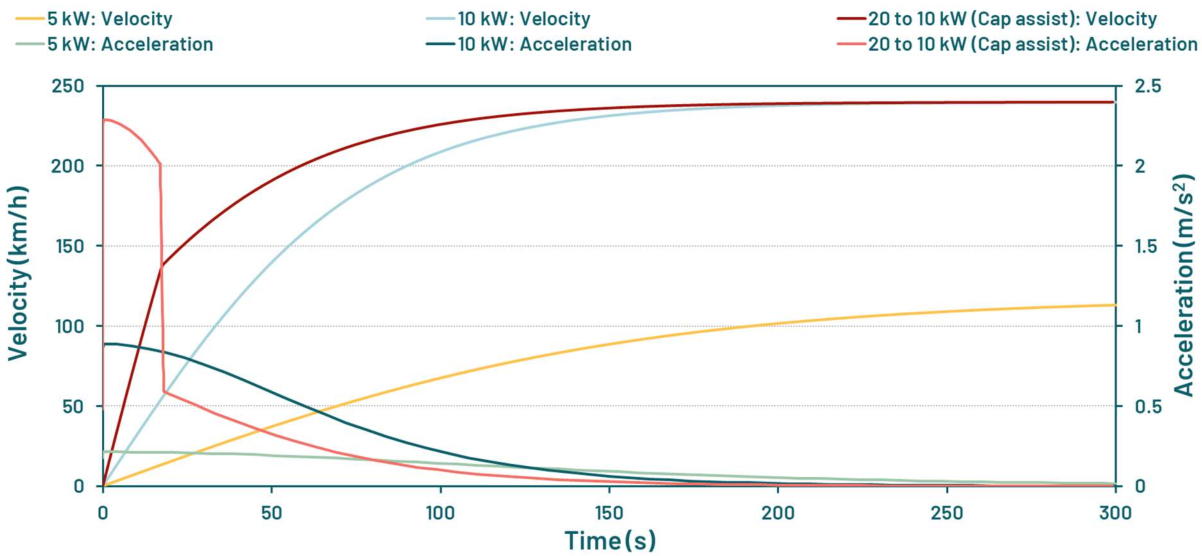


Figure 0-29: Speed and Acceleration Plots for Different Power Command Cases

Appendix O References

[O-1] L. Bertini, "Modeling and Optimization of a Fuel Cell Hybrid System," KTH Royal Institute of Technology, Division of Applied Electrochemistry, Stockholm, 2011.

[O-2] MathWorks, "Simscape, Model and simulate multidomain physical systems," MathWorks, 2022. [Online].Available:https://www.mathworks.com/products/simscape.html#:~:text=Simscape%20formulates%20the%20equations%20for,Equipment%20Using%20Model%2DBased%20Design [Accessed 6 November 2022].

[O-3] MathWorks, "Student Competition: Physical Modeling Training," MathWorks, 2022. [Online]. Available: https://www.mathworks.com/videos/series/student-competition-physical-modeling-training-107490.html. [Accessed 6 November 2022].

[O-4] MathWorks, "Tire-Road Interaction (Magic Formula)," MathWorks, 2022. [Online]. Avaliable: https://www.mathworks.com/help/sdl/ref/tireroadinteractionmagicformula.html [Accessed 6 November 2022].

Appendix P: Project Management

Meeting Hours

Table P-1 below shows the total hours planned and dedicated to meetings, note that these hours are not included in the Gantt chart.

Table P-1: Actual and estimated time dedicated to meetings

Meeting Hours Breakdown	Phase 1				Phase 2				Phase 3			
	Hr/Wk	3 Wks	x6	Actual	Hr/Wk	4 Wks	x6	Actual	Hr/Wk	7 Wks	x6	Actual
Group Meetings	2	6	36	33	2.5	10	60	33	1.5	10.5	63	63
Advisor Meetings	0.5	1.5	9	10	1	4	24	12.5	1	7	42	9.5
Client Meetings	-	1	6	3	-	2	12	2.5	-	1.5	9	0
Sub-Total	-	-	51	46	-	-	96	48	-	-	114	72.5
Grand Total Planned	261											

Team Member Time Spent Breakdown

Individual team members each tracked the hours they worked for each project task, and this information is shown below in Table P-2. Any section marked with red denotes a task that was performed but not anticipated or scheduled on the Gantt chart. These tasks and underestimating time required for scheduled tasks are the reason for underestimation of the total project cost.

Table P-2: Hours dedicated to the project by team member

Phase 3 Tasks	Natalia	Anita	Daniel	James	Alto	Amos
Meetings						
Group Meetings	11	11	11	9	10	11
Client Meetings						
Advisor Meetings	1.75	1.75	1.75	1	1.5	1.75
FSAE report review	0.5				0.5	0.5
Fuel Cell Supplier Meeting	-	-	-	-	-	0.75
11.0 Fuel Cell						
11.1 Water balance	-	-	-	-	-	4.5
11.2 Air Intake	-	-	-	-	0.5	-
11.3 Connections (specs and type required)	-	-	-	-	-	0.5
11.4 Performance calculations/Evaluation	-	-	-	-	-	1
11.5 Capacitor calculations	5.75	-	-	-	-	-
11.6 Simulink FC modelling	-	33.5	-	-	-	-
11.7 Schematic Diagram	-	3	-	-	-	-
11.8 Heat Rejected from FC	-	-	-	-	-	1.5
Regnerative Braking - not feasible	-	-	-	-	-	3.5
12.0 Hydrogen Tank						

Phase 3 Tasks	Natalia	Anita	Daniel	James	Alto	Amos
12.1 Updated Range Calculations	-	-	-	-	-	0.25
12.2 Source hydrogen tank	1	-	-	4	-	-
12.3 Hydrogen Tank Calculations	0.5	-	-	1	-	-
13.0 Motor						
13.1 0-100 Acceleration Calculation	-	-	3	2	-	-
13.2 Source New Motor + Torque vs Speed	-	-	4.5	-	-	0.5
13.3 Power vs Speed Curves (Straight + Incline)	3	-	0.25	-	-	-
13.4 DC/DC Converter Sourcing	-	-	2.5	-	-	-
13.5 Incline Verification Calculations	-	-	4	-	-	-
14.0 Drivetrain Design						
14.1 Belt Drive Calculations and Sourcing	-	0.5	-	-	15	-
14.1.1 Belt Sourcing					10	
14.1.2 Pulley Sourcing			5		10	3
14.2 Gear Ratio Calculations			3			
14.3 Simulink Drive train Modeling	-	13	-	16	-	-
14.4 Pulley Design	1	1	-	-		-
14.5 Shaft Deflection Analysis	-	-	16.5	-	-	-
14.6 Bearing Calculations	-	-	1	-	-	-
14.7 Shaft vs Belt vs Chain analysis (qualitative)	1.25	-	-	-	-	-
15.0 General Calculations						
15.1 10,000-hour verification	-	-	-	-	-	0.5
15.2 Centre of Gravity Calculations	-	-	-	-	2	-
15.3 Update/Correct Phase 2 Calculations	-	-	3	-	-	0.25
16.0 Safety						
16.1 Hazard Assessment	-	-	-	-	-	1.5
16.2 Risk Mitigation	-	-	-	-	-	3
17.0 CAD						
17.1 Tire	-	-	-	-	3	-
17.2 Rims	-	-	-	-	5	-
17.3 Front wheel assembly	-	-	-	-	0.25	0.5
17.4 Belt	-	-	-	1	3	-
17.5 Pulleys	-	1	0.5	0.5	2.5	-
17.6 Axel Bolt	-	-	0.5	-	-	-
17.7 Chassis	-	2	-	-	-	-
17.8 Update Fuel Cell to match supplier	10	-	-	-	-	-
17.9 Update Motor to match supplier	-	-	-	-	-	4
17.10 Motor Controller (Match supplier)	-	-	-	-	-	1.5
17.11 DC/DC converter	-	-	-	-	-	2
17.12 Hydrogen Tank	-	-	-	2	1	-
17.13 Harnessing	-	-	-	-	-	10
17.14 Purge Valve	-	-	-	-	-	2
17.15 FC Controller	-	-	-	-	-	3
18.0 Finite Element Analysis						
18.1 Pully FEA	-	2	-	11	-	-
18.2 Bolt FEA	-	-	-	3.5	-	-
19.0 CAD Integration						
19.1 Integrate/make all components fit						8
20.0 Manufacturing Considerations						
20.1 Design for Manufacture	-	1	-	-	3	-
20.2 Methods of Manufacturing our Components	-	1	-	-	2	-
20.3 Machining Costs	1	-	-	-	-	-
21.0 CAD Drawings						
21.1 Pulley Drawing	-	-	2	-	-	-

Phase 3 Tasks	Natalia	Anita	Daniel	James	Alto	Amos
21.2 Assembly Drawings (revisit and elaborate)	-	-	-	-	-	2
21.3 Drawing Tree	-	-	-	-	-	1
22.0 Secondary Deliverables						
22.1 Poster & Slides Creation	30.5	18	5	2	1.5	4
22.2 Design Presentation + Practice	2.5	4	4	2	3	3
23.0 Phase 3 Report						
23.1 Critical Design analysis (flow chart)	2.5	-	-	-	-	-
23.2 Product Cost Analysis	4.5	-	-	-	-	-
23.3 Design Compliance Matrix	-	-	-	-	-	1
23.4 Future design recommendations	0.5	-	-	-	-	0.5
23.5 Actual vs Planned Project Cost	1.75	-	-	-	-	-
23.6 Report Writing and Compilation	13.5	10	14.5	2	5	5
23.7 Phase 3 Report Submission	-	-	-	-	-	-
23.8 Updated Project Schedule	6.25					
24.0 Project Closeout						
24.1 Client Acceptance			0.5			
24.2 Review Group Performance	-	-	-	-	-	-
Administration (Meeting agends, Logistics, etc)	4.75					
Individual Hours Total	103.5	102.75	82.5	57	78.75	81.5
Total Hours	506					
Individual Hours Grand Total (Phase 1 +2 +3)	175.5	166.25	139	103.5	130.75	142.5
Team Hours Grand Total (Phase 1 + 2 + 3)	857.5					

Project Schedule

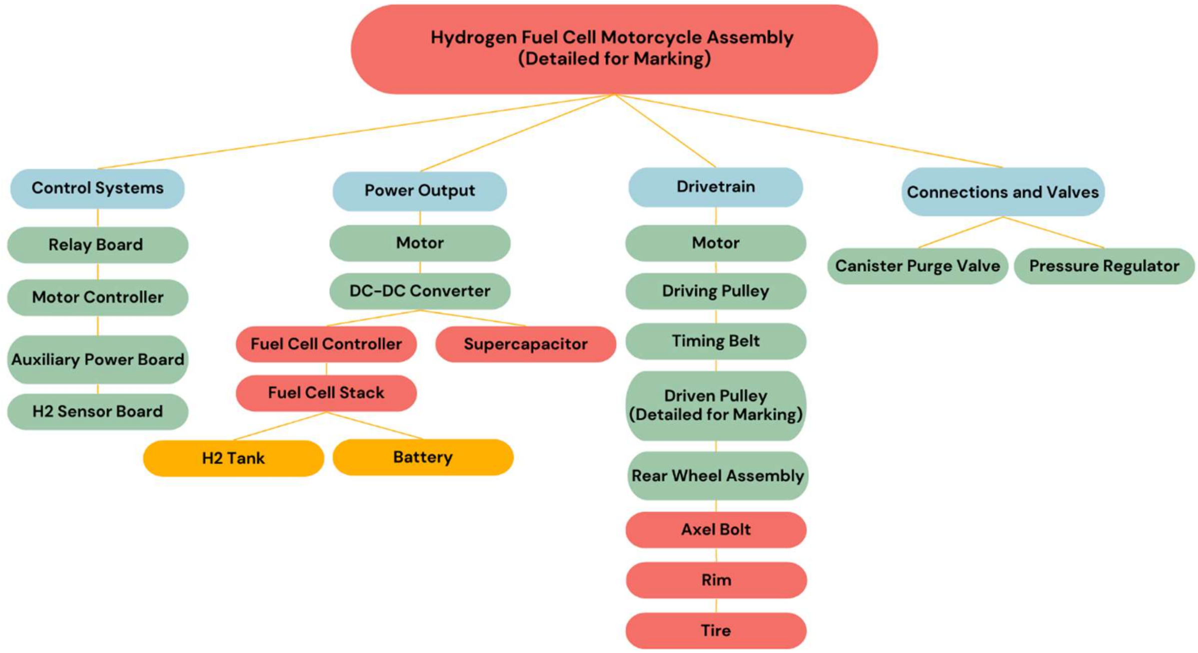
The Gantt chart is appended to this report, and the table below clarifies the "assigned to" information in the gantt chart. Any changes made to the gantt chart since Phase 2 consist of adding more detail to tasks required as the project developed, and tasks became clear. No additional hours were scheduled or changed since Phase 2, simply redistributed.

Table P-3: Team member initials key

Initials	Name
AP	Anita Petrovic
AL	Amos Liu
BG	Bingqing Guo
DG	Daniel Gye
JD	James Donick
NB	Natalia Brezovan

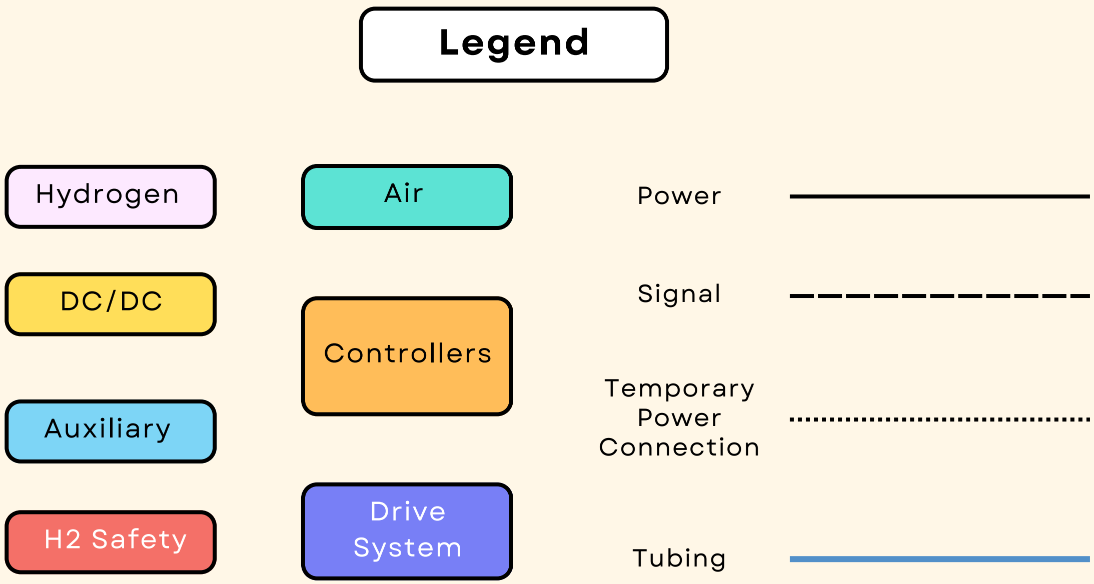
Appendix Q: Drawing Package

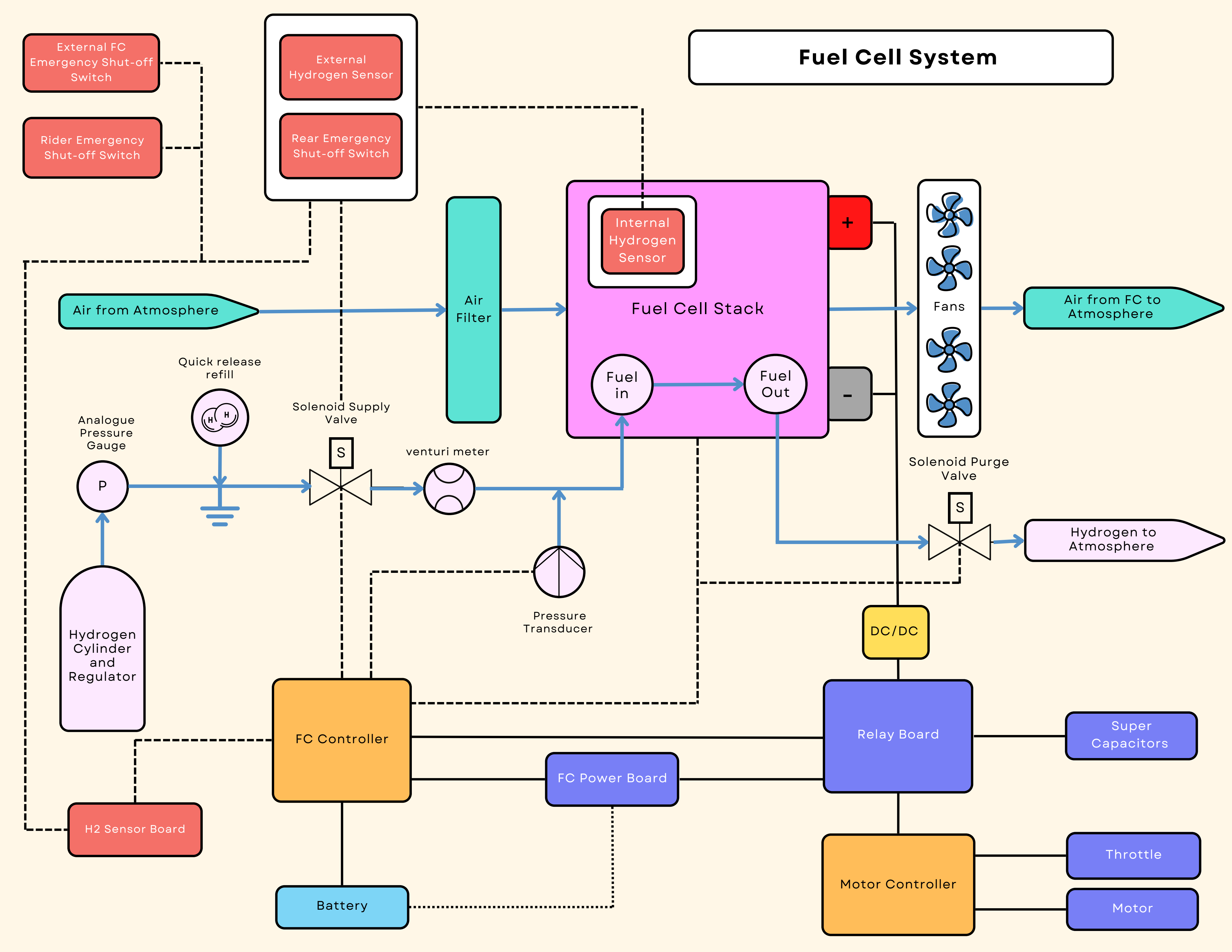
Drawing Tree

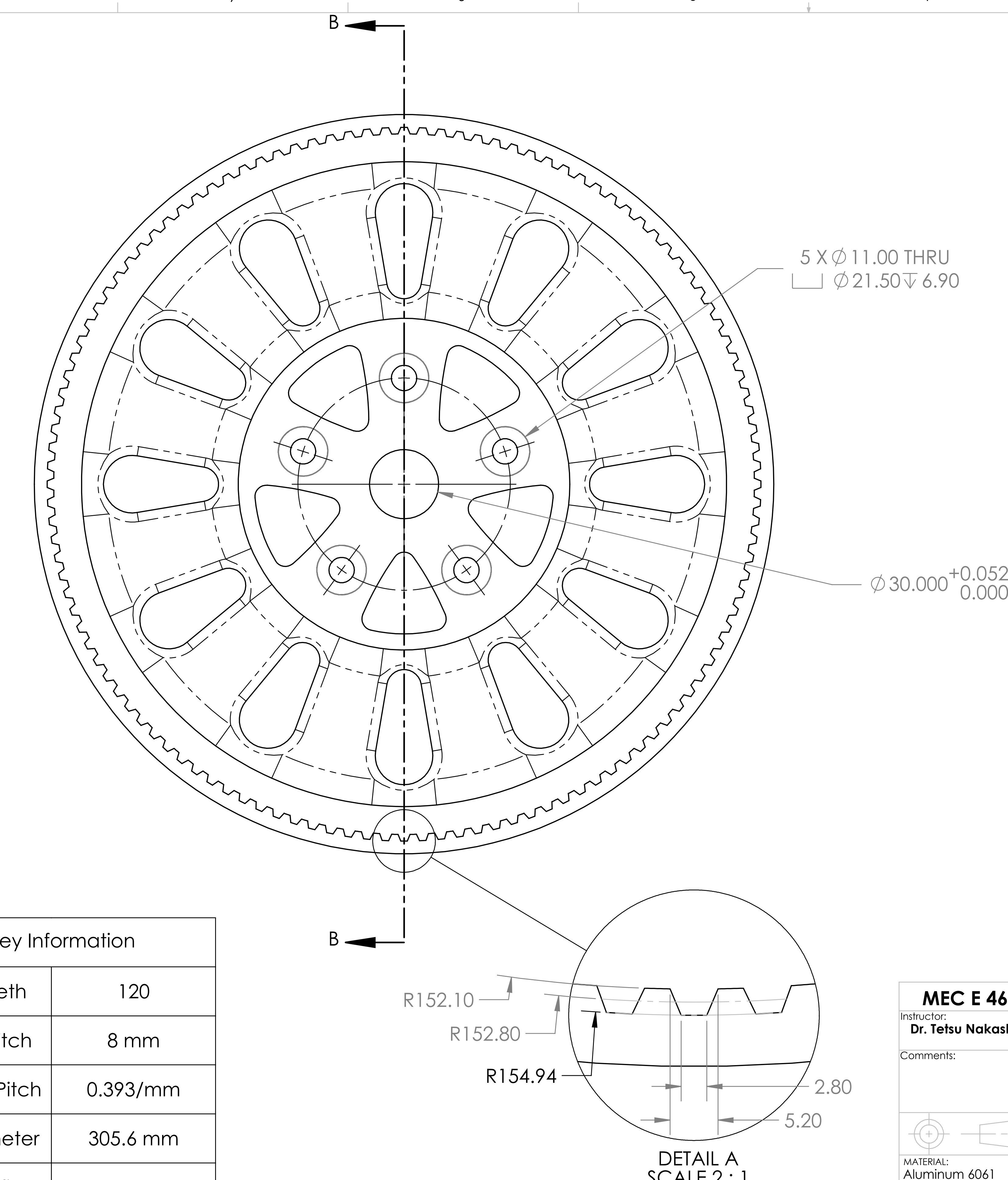


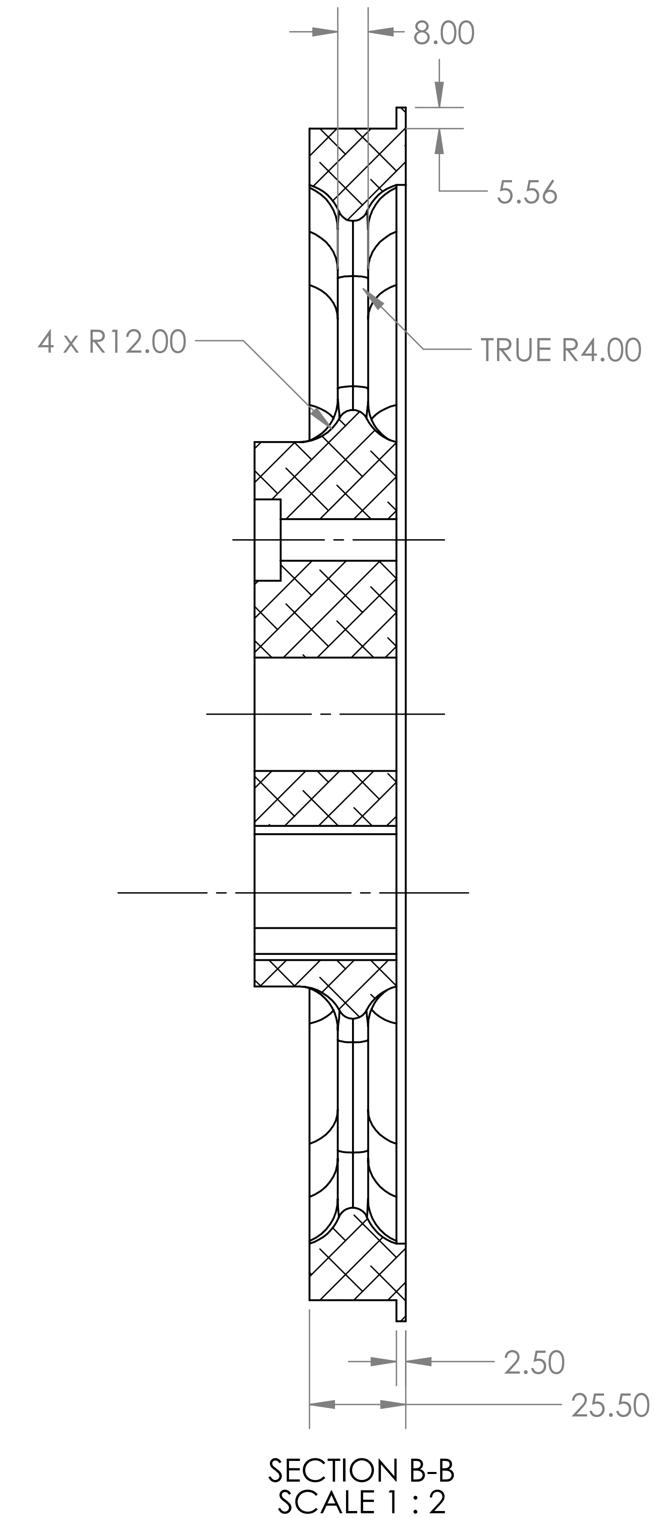
The drawing package appended documents consist of the following, in order:

- System Schematics
- Drawing for custom Designed Driven Pulley
- Full Assembly Drawing with BOM


Legend
Hydrogen
Air
Power
DC/DC
Signal
Controllers
Temporary Power Connection
Auxiliary
H2 Safety
Drive System
Tubing


Fuel Cell System
External FC Emergency Shut-off Switch
Rider Emergency Shut-off Switch
External Hydrogen Sensor
Rear Emergency Shut-off Switch
Internal Hydrogen Sensor
Fuel Cell Stack
+
-
Fans
Air from Atmosphere
Air Filter
Air from FC to Atmosphere
Fuel in
Fuel Out
Quick release refill
Analogue Pressure Gauge
P
Solenoid Supply Valve
S
venturi meter
Solenoid Purge Valve
S
Hydrogen to Atmosphere
Pressure Transducer
Hydrogen Cylinder and Regulator
DC/DC
FC Controller
Relay Board
Super Capacitors
FC Power Board
H2 Sensor Board
Battery
Motor Controller
Throttle
Motor





Pulley Information	
No. of Teeth	120
Circular Pitch	8 mm
Diametral Pitch	0.393/mm
Pitch Diameter	305.6 mm
Tooth Profile	G8M

MEC E 460

Instructor: **Dr. Tetsu Nakashima**

Comments:

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025
SURFACE FINISH µm 0.6
DO NOT SCALE DRAWING

DRAWN BY: **Hydro Motors**

Lab Day

SM By **Hydro Motors**

TA Initials

Hydro Motors
December 5, 2022 2:54:27 PM
November 29, 2022 12:04:13 AM

MATERIAL: Aluminum 6061

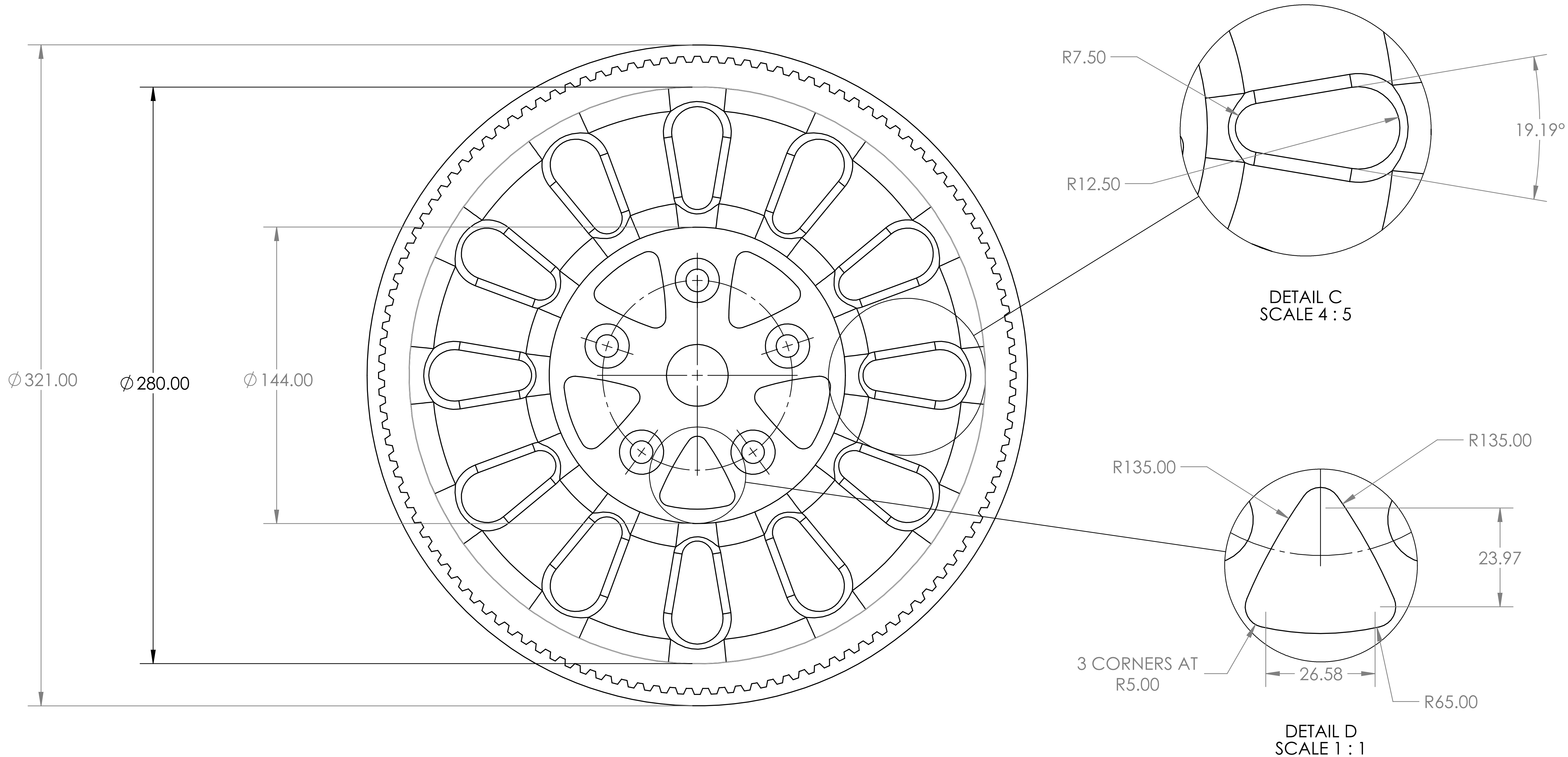
FILE NAME: NEWwheelpully

The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

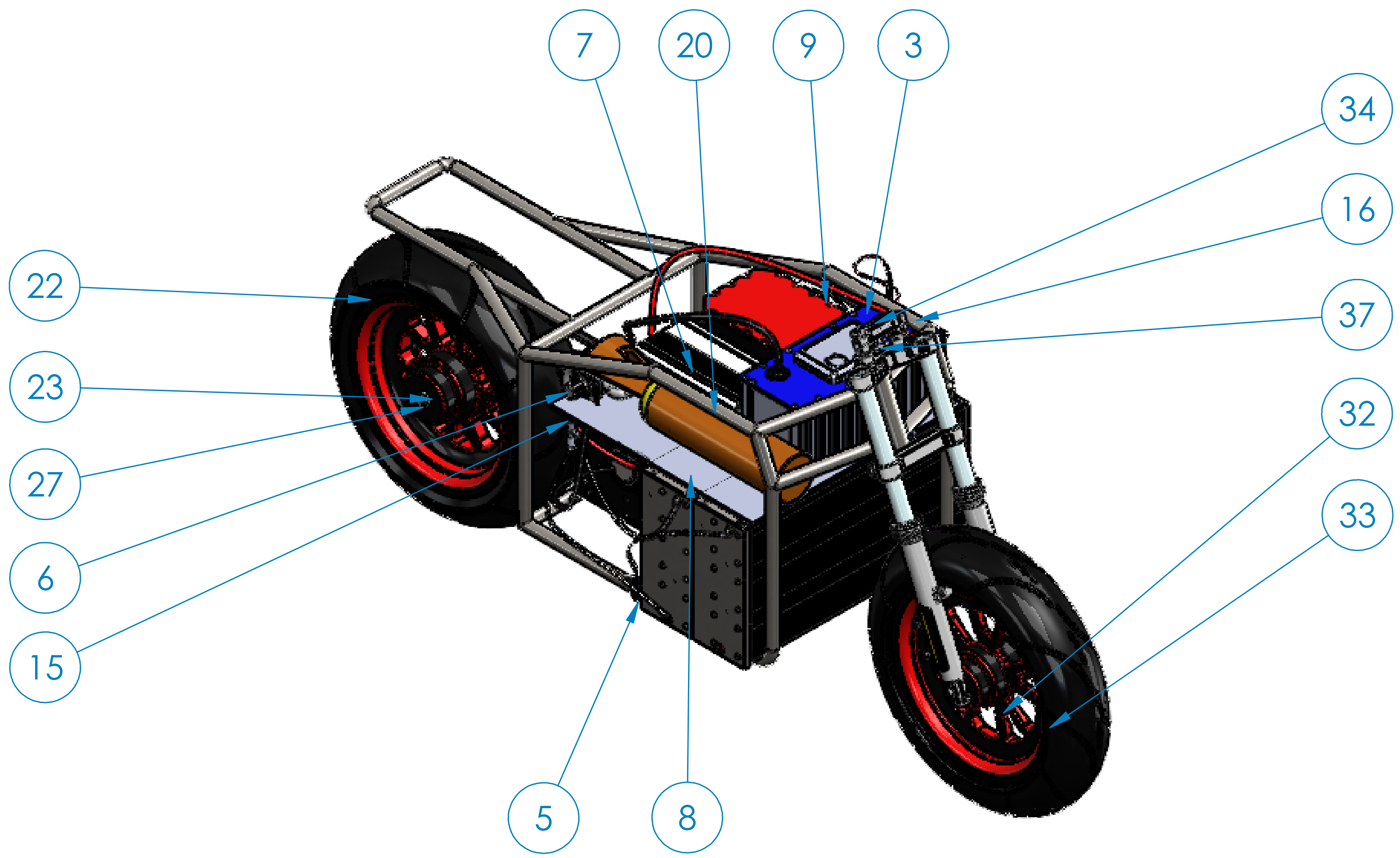
TITLE: Rear Pulley (Tooth profiles and Body dimensions)

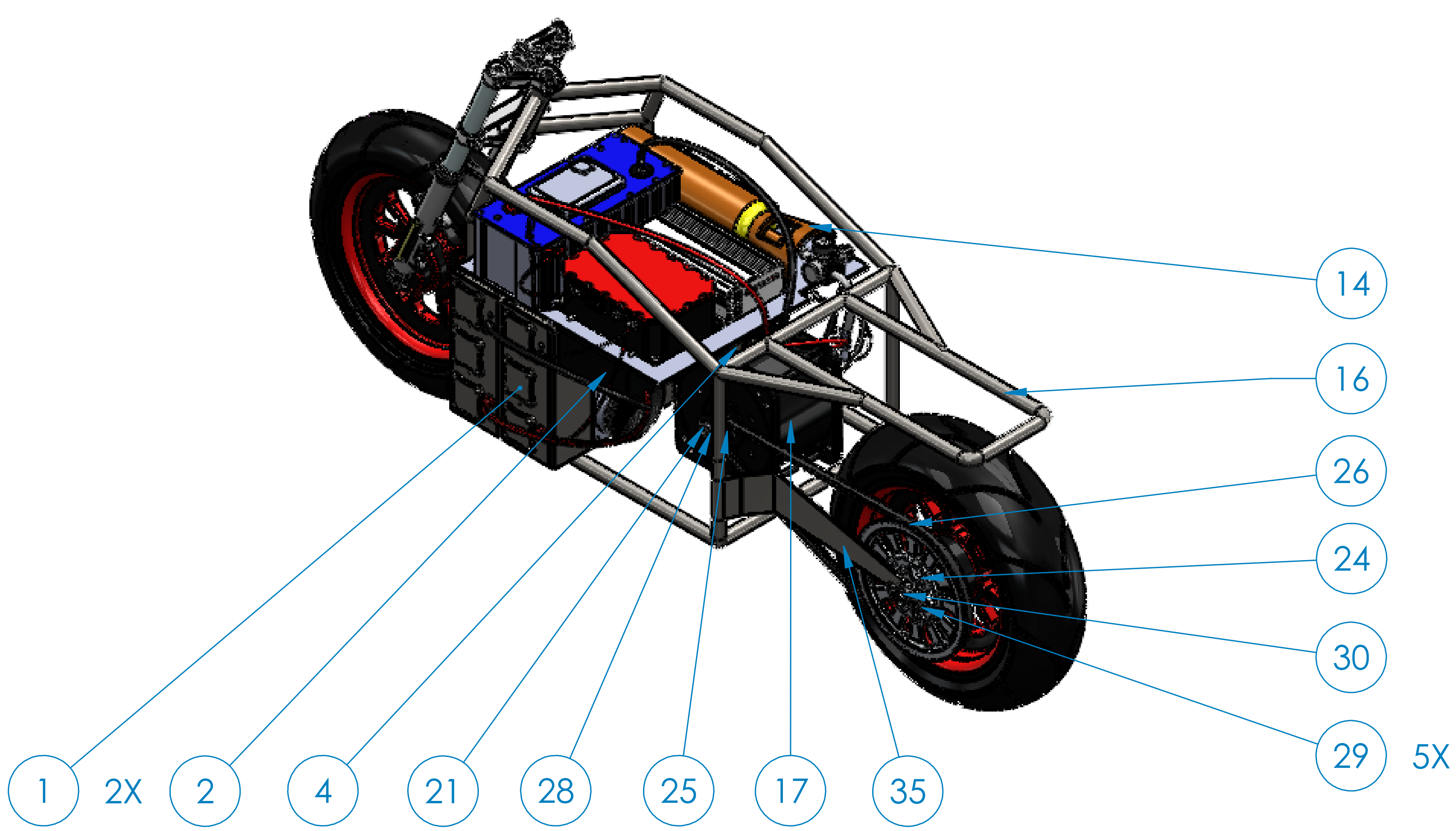
SIZE	Assignment Number	REV
B	**DESIGN PROJECT**	

SCALE: 1:3 | Mass: 2841.75 g | SHEET 1 OF 2



MEC E 460 Instructor: **Dr. Tetsu Nakashima** Comments:	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH µm 0.6 DO NOT SCALE DRAWING	DRAWN BY: **Hydro Motors** Lab Day SM By **Hydro Motors** TA Initials danie December 5, 2022 2:54:27 PM November 29, 2022 12:04:13 AM	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: Rear Pulley (Additional body details)
MATERIAL:			SIZE **B** Assignment Number **DESIGN PROJECT** REV
FILE NAME: NEWwheelpully			SCALE: 1:5 Mass: SHEET 2 OF 2





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.	Author
1	FuelCell	Hydrogen Fuel Cells With Integrated Fans	2	Hydro Motors
2	Battery	24v 22Ah Ebike Battery Pack	1	Hydro Motors
3	Super Capacitor	10 kW Super Capacitor	1	Hydro Motors
4	Motor Controller	10 kW Motor Controller	1	Hydro Motors
5	Purge Valve	Purge Valve	1	Ravindrasai Arangi
6	Pressure Regulator	Pressure Regulator	1	Anil Reddy
7	FC Controller	Fuel Cell Controller	1	Hydro Motors
8	Plate	Plate to Hold Components	1	Hydro Motors
9	Dc-Dc Converter	10kW - 800V Converter	1	Hydro Motors
10	Aux Power Board	Aux Power Board	1	Hydro Motors
11	FC Power Board	Fc Power Board	1	Hydro Motors
12	H2 Sensor Board	H2 Sensor Board	1	Hydro Motors
13	Relay Board	Relay Board	1	Hydro Motors
14	HydrogenTank	Metal Hydride Hydrogen Tank	1	Hydro Motors
15	Venturi Meter	Venturi Meter	1	Christopher Tarczewski Novais
16	Chassis	Chassis	1	Hydro Motors
17	Motor	20kW Golden Motors Motor	1	Hydro Motors
18	Motor_Key	Motor Key	1	Hydro Motors
19	96505A129	Steel Oversized Washer	1	MacMaster
20	97654A201	18-8 Stainless Steel Flanged Button Head Screw	1	MacMaster
21	98363A114	Steel Oversized Washer	1	MacMaster
22	Rim 17x6inch Rear Wheel	Rear Wheel Rim	1	Hydro Motors
23	Tyre 17x6in	Rear Wheel Tire	1	Hydro Motors
24	NEWwheelpully	Rear Pulley	1	Hydro Motors
25	S8Mpulley_small	Motor Pulley	1	Hydro Motors
26	Belt1-1^BeltPulleyAssembly	S8M 21mm Belt	1	Hydro Motors
27	Bolt	Bolt	1	Hydro Motors
28	Motor Shaft	Motor Shaft	1	Hydro Motors
29	90759A810	High-Torque 12-Point Flange Nut	5	MacMaster
30	93760A119	Steel Locknut for Use with Cotter Pins	1	MacMaster
31	98350A250	Cotter Pin	1	MacMaster
32	Rim 17x3.5inch Front Wheel	Front Wheel Rim	1	Hydro Motors
33	Tyre 17x3.5in	Front Wheel Tire	1	Hydro Motors
34	XL120R Sportster1200 Fork	Front Fork/Control Arm	1	Andrey Jasiukaitis
35	Back Control Arm	Rear Control Arm	1	Hydro Motors

MecE 460

Instructor:
Dr. Tetsu Nakashima
Win 2022

Comments:

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025

SURFACE FINISH µm 0.6

DO NOT SCALE DRAWING

DRAWN BY: **Hydro Motors**

Lab Day

SM By Hydro Motors

TA Initials

Amos Liu
December 7, 2022 5:03:15 PM
December 5, 2022 2:42:35 PM

MATERIAL:
Variety of Materials

FILE NAME:
Final Assembly V2

The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

TITLE:
Hydrogen Fuel Cell Motorcycle Isometric View

SIZE **B** | Assignment Number: Design Project | REV 1

SCALE: 1:15 | Mass: 195.3kg | SHEET 1 OF 1

Appendix R: Design Compliance Matrix Discussion

The final cost of the vehicle came to $58,052.56, which exceeds the initially defined $10,00.00 budget, but complies with the redefinition of the project as an exploratory project to create a concept design which removed budget limitations.

The design dimensions were 1036mm in height and 650mm in width, which is less than the estimated 1100mm high and 715mm wide. The overall estimated mass of the vehicle was 195.3 kg however proper custom chassis design and further development of aspects out of scope may change this mass estimate, which also less than the estimated 235kg.

The final design complies with the vehicle specification that the client had set. The motorcycle can achieve a top speed of 140km/h, which is higher than the 120km/h that the client had requested. The motorcycle also has a range of 342km, which is also higher than the 300km that the client requested to get from Edmonton to Calgary. Both are achieved based on the power system that is in place. The fuel cell provides 10kW of power while the supercapacitor provides 10kW, combined complies with the motor requirements of 20kW and its 4100 rpm.

The final design also complies the safety and lifetime requirements; of the 10,000 hours lifecycle the client requested. With FEA of the drivetrain showing that the driven and drive pulleys do not yield and each of the pullies and the knowledge that fuel cells degradation is 0.4-0.5% per 1000 hours, the design complies with the client. [1] The protective layer implemented into the motorcycle will separate the rider and any internal components of the vehicle to protect the rider from any shock hazards and burns.

Assembly of the motorcycle will be compiled of sourced parts, aside from the rear pulley. To reduce the complications of the manufacturing process. The rear pulley is created in a method that is designed for manufacturing.

Investigations into the braking system as well as the vehicle lights were not completed due to the time constraints of the project.

The complete accuracy of this project cannot be fully determined at this point due to the development of the control not yet completed, the chassis has not been custom developed, and implementation of regenerative braking was not done, as all were out of scope.

Appendix S: Quotes

Driven Pulley Material and Manufacturing Cost

HUBS
A PROTOLABS COMPANY

3D Hubs Manufacturing LLC
228 East 45th Street Suite 9E
10017, New York, NY

Quote: 2BV1NWJ6J-V1

Bill to

652372 - University Of Alberta
Natalia Brezovan
141 Lalor Dr
Red Deer, AB T4R 0R5
Canada
nbrezova@ualberta.ca
+1 403-304-7605

Ship to

652372 - University Of Alberta
Natalia Brezovan
141 Lalor Dr
Red Deer, AB T4R 0R5
Canada
nbrezova@ualberta.ca
+1 403-304-7605

Quote Details

Quote #	2BV1NWJ6J-V1
Lead Time	20 Business Days
Hubs Qc & Customs	0 Business Days
Quote Date	2022-12-01
Expiry Date	2022-12-31

Secure Payment Link Powered by stripe
https://www.hubs.com/manufacture/payment/quote/b166c648-bc2f-460c-a31d-f1a8725f5815?quote_access_token=90816d8b-9d66-449d-98e4-d3af10a9e4f1

Description			Qty	Unit Price	Price
1	 NEWwheelpully.STEP 37.5x309.9x309.9 mm	CNC machining / Aluminum 6061-T6 | AlMg1SiCu / As machined (Ra 3.2µm / Ra 126µin)	1	$643.88	$643.88
	- General tolerance: ISO 2768 medium - Tighter tolerances: Not required - No features intended for fits - Does not contain part markings - Manufactured with 2mm radii - No threads				
Shipping		Standard / 3 – 5 business days			$0.00

Parts	$643.88
Subtotal	$643.88
Sales tax	$0.00
Total	USD $643.88

Signature:

Natalia Brezovan
By signing or submitting a payment, customer agrees to specifications of the quote (#2BV1NWJ6J-V1) and the attached Terms & Conditions.
This quote isn't legally binding on Hubs until the order has been confirmed by email.

Payment Details

Secure Payment Link https://www.hubs.com/manufacture/payment/quote/b166c648-bc2f-460c-a31d-f1a8725f5815?quote_access_token=90816d8b-9d66-449d-98e4-d3af10a9e4f1 Powered by stripe

Fuel Cell and Fuel Cell Controller Quote (Email)

UNIVERSITY OF ALBERTA

RE: Request for Quotation
3 messages

Radek Jelinek <radovan@horizoneducational.com>
To: "nbrezova@ualberta.ca" <nbrezova@ualberta.ca>

Dear Natalia,

Here is the pricing for you:

Product	Code	EUR/unit	units	discount %	EUR	
H-5000	FCS-C5000	15 999,00	1	15	13 599,15	
Monitoring SW	CS-MSW	699,00	1	15	594,15	optional
Shipping (DAP) and insurance cost		484,00	1	0	484,00	
TOTAL					14 677,30	

DC/DC Converter Quote

Hydro Motors 10kW 800V
9 messages

Georgi Merdzhanov <gm@zekalabs.com>
To: dgye@ualberta.ca
Thu, Nov 24, 2022 at 12:54 AM

Hello Daniel,

Thank you for the interest to our company!

Can you please tell me the expected voltage ranges on both sides of the converter for your application and also the power requirement, so that I can advise you better.

Thank you!

Best regards,

Georgi Merdzhanov

DC-DC High-Power	N/A
AC-DC High-Power	N/A
DC-DC Isolated	• DC-DC Converter 10kW, 800V
AC-DC Isolated	N/A
Full Cabinet Solution	N/A
Message	Hello, I work at a start up within the University of Alberta and we are looking for a large 10 kW Isolated DC DC converter for a hydrogen fuel cell powered motorcycle. We are interested in the 10 kW 800 V model, and were hoping if you could provide a quote for this component. All the best, Daniel Gye

Daniel Gye <dgye@ualberta.ca> Fri, Nov 25, 2022 at 5:46 PM
To: Georgi Merdzhanov <gm@zekalabs.com>

Hey Georgi,

We have an incoming voltage of 48 V, and we will need it stepped up to 96 V. This is for an electric motorcycle design that will use capacitors as an additional power storage method. I hope this helps clarify things.

Warmest regards,
[Quoted text hidden]

Georgi Merdzhanov <gm@zekalabs.com> Wed, Dec 7, 2022 at 1:30 AM
To: Daniel Gye <dgye@ualberta.ca>

Hello Daniel,

This one costs 6 180 USD.

[Quoted text hidden]

Appendix T: Client Communication

As the project proceeded, there were changes to the budget, battery choice, and scope. The following figures show the communication between Hydro Motors and the Client, which include the approval of the changes.

12/6/22, 3:05 PM University of Alberta Mail - MEC E 460 - Team 14

UNIVERSITY OF ALBERTA

Amos Liu <acliu@ualberta.ca>

MEC E 460 - Team 14

2 messages

Daniel Gye <dgye@ualberta.ca> Wed, Oct 12, 2022 at 2:21 PM
To: Larry Unsworth <lunswort@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, James Donick <donick@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>

Hello Dr. Unsworth,

I am sending this email to obtain written confirmation that we have your permission to exceed the originally established budget of $10000. Please reply at your earliest convenience.

Thank you,

--
Daniel G.

Larry Unsworth <lunswort@ualberta.ca> Wed, Oct 12, 2022 at 2:21 PM
To: Daniel Gye <dgye@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, James Donick <donick@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>

Yes, I approve.
[Quoted text hidden]
--
Best Regards,

Larry

Larry D. Unsworth, Ph.D., P.Eng. (he/him)
Professor, Chemical and Materials Engineering, Faculty of Engineering
Adjunct Professor, Biomedical Engineering, Faculty of Medicine & Dentistry

Canadian Biomaterials Society - Past President
Associate Editor - Frontiers in Biomaterials
Women and Children's Health Research Initiative - Member

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University of Alberta
Edmonton, AB
T6G 2V4
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Fax: 780-492-2881

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https://mail.google.com/mail/u/2/?ik=a3db193ba8&view=pt&search=all&permthid=thread-f%3A1746514556164478636&simpl=msg-f%3A1746514556... 1/1

UNIVERSITY OF ALBERTA

Amos Liu <acliu@ualberta.ca>

MEC E 460 Design Conference

4 messages

Daniel Gye <dgye@ualberta.ca> Mon, Nov 28, 2022 at 8:00 AM
To: Larry Unsworth <lunswort@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>, James Donick <donick@ualberta.ca>

Good morning Dr. Unsworth,

I am excited to announce that this Saturday, December 3rd, we will be presenting our Hydrogen Fuel Cell Motorcycle design at the MEC E 460 Fall Design Conference. Hydro Motors has been incredibly hard at work to source the necessary parts, perform calculations and simulations, and assess the viability of our design, and we are all looking forward to sharing this with you. The conference begins at 10 AM and once we have our specified presentation time slot, I will make sure to update you soon after.

I look forward to seeing you there,

--
Daniel G.

Larry Unsworth <lunswort@ualberta.ca> Mon, Nov 28, 2022 at 8:11 AM
To: Daniel Gye <dgye@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>, James Donick <donick@ualberta.ca>

Sounds great!
[Quoted text hidden]
--
Best Regards,

Larry

Larry D. Unsworth, Ph.D., P.Eng. (he/him)
Professor, Chemical and Materials Engineering, Faculty of Engineering
Adjunct Professor, Biomedical Engineering, Faculty of Medicine & Dentistry

Canadian Biomaterials Society - Past President
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Daniel Gye <dgye@ualberta.ca> Tue, Nov 29, 2022 at 2:18 PM
To: Larry Unsworth <lunswort@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>, James Donick <donick@ualberta.ca>

Good afternoon Dr. Unsworth,

I have just received an update from Professor Nakashima, and the official conference schedule has been released. We will be the very first group to present at **10:00 AM** in **ECERF W2-090**. Before we present, would you like to view and approve our current design ahead of time? If so, please let me know and we would be happy to provide you with our design and specifications. We look forward to hearing from you, and we hope to see you at the conference this coming Saturday.

Warmest wishes,

Daniel
[Quoted text hidden]

MECE460_(2022-09) Design Conference Scedule_FINAL.pdf
90K

Larry Unsworth <lunswort@ualberta.ca> Tue, Nov 29, 2022 at 3:38 PM
To: Daniel Gye <dgye@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>, James Donick <donick@ualberta.ca>

No need,

But please send me the final materials when able.

Otherwise, I'll see you Saturday!
[Quoted text hidden]

UNIVERSITY OF ALBERTA

Amos Liu <acliu@ualberta.ca>

RE: MEC E 460 Team 14 Follow Up Meeting

4 messages

Daniel Gye <dgye@ualberta.ca> Sun, Sep 18, 2022 at 6:18 PM
To: Larry Unsworth <lunswort@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, James Donick <donick@ualberta.ca>

Good Evening Dr. Unsworth,

Last week, we met with our advisor, and our project scope changed due to their suggestions and expertise. As such, our initial intention for this upcoming meeting was to delve into our new scope for the project, discuss its feasibility with you, directly answer questions you may have, and bring up our questions and concerns we had ourselves. However, upon further discussion, we believe that it may potentially be more efficient to directly send you our new proposed scope. Below, we have divided the work for this project into three areas of focus:

Main Focus	Partial Focus	Out of Scope
Powertrain Design • Fuel Cell Selection • Motor Selection • Battery Selection • Free Body Diagrams • Motor Performance Calculations (Speed, acceleration, torque, etc.) • Concept CAD • FEA Analysis of drivetrain components (chains, shafts, gears, etc.) • Design for Manufacture • Drawings	Safety • Hydrogen hazard assessment • HAZOPs Integration • Mounting Materials (Brackets, fasteners, etc.) • Mounting Design and Assembly CAD • Tolerancing and Assembly Drawings	Body Design and Manufacturing Controls and Electronics • Fuel Cell controller • Relay Board • Motor Controller

If you would like to still meet in person to address any concerns or questions regarding the above scope, then we will gladly be available at the previously confirmed time. However, if you feel as if the work above satisfies your desires for the project, please provide your approval and we can cancel the proposed meeting.

Thank you,

Team 14.

Larry Unsworth <lunswort@ualberta.ca> Sun, Sep 18, 2022 at 10:57 PM
To: Daniel Gye <dgye@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, James Donick <donick@ualberta.ca>

Hi all,

See comments below.

I am ok with the changes, they make sense to me.

Recall... the battery should not be li ion based though.

Cheers, Larry
[Quoted text hidden]

Larry Unsworth <lunswort@ualberta.ca> Mon, Sep 19, 2022 at 7:52 AM
To: Daniel Gye <dgye@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, James Donick <donick@ualberta.ca>

Dear Team,

I suppose this means that we will not need to meet today.

So I have cancelled the meeting for us.

Cheers,
Larry
[Quoted text hidden]
--
Best Regards,

Larry

Larry D. Unsworth, Ph.D., P.Eng. (he/him)
Professor, Chemical and Materials Engineering, Faculty of Engineering
Adjunct Professor, Biomedical Engineering, Faculty of Medicine & Dentistry

Canadian Biomaterials Society - Past President
Associate Editor - Frontiers in Biomaterials
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Daniel Gye <dgye@ualberta.ca> Tue, Sep 20, 2022 at 12:46 PM
To: Larry Unsworth <lunswort@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, James Donick <donick@ualberta.ca>

Good Afternoon,

Thank you for letting us know. We look forward to hearing your thoughts on our upcoming phase one report.

All the best,

[Quoted text hidden]

UNIVERSITY OF ALBERTA

Amos Liu <acliu@ualberta.ca>

Lithium Ion Battery Clarification

3 messages

Daniel Gye <dgye@ualberta.ca> Wed, Sep 28, 2022 at 6:31 PM
To: Larry Unsworth <lunswort@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>, James Donick <donick@ualberta.ca>

Good evening Dr. Unsworth,

My group and I have begun exploring the design options for the design of the hydrogen fuel cell motorcycle, and we were just curious as to what exactly you meant by "no lithium ion batteries". Is this an opposition to the inclusion of a battery outright? Or is this just a specific opposition to the lithium ion batteries commonly used in electric vehicles at this time?

Thank you,

--
Daniel G.

Larry Unsworth <lunswort@ualberta.ca> Wed, Sep 28, 2022 at 7:35 PM
To: Daniel Gye <dgye@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>, James Donick <donick@ualberta.ca>

Just saying that a normally used battery is preferred.
[Quoted text hidden]

Daniel Gye <dgye@ualberta.ca> Thu, Sep 29, 2022 at 3:49 PM
To: Larry Unsworth <lunswort@ualberta.ca>
Cc: Natalia Brezovan <nbrezova@ualberta.ca>, Amos Liu <acliu@ualberta.ca>, Anita Petrovic <apetrovi@ualberta.ca>, Bingqing Guo <bguo1@ualberta.ca>, James Donick <donick@ualberta.ca>

Hello,

Understood, thank you for the clarification.

All the best,
[Quoted text hidden]
--
Daniel G.