ASHESI

ASHESI UNIVERSITY

HYDRAULIC HYBRID REGENERATIVE BRAKING

CAPSTONE PROJECT

B.Sc. Mechanical Engineering

Joel Nana Yaw Ofori-Teiko

2020

ASHESI UNIVERSITY

HYDRAULIC HYBRID REGENERATIVE BRAKING.

CAPSTONE PROJECT

Capstone Project submitted to the Department of Engineering, Ashesi University in partial fulfilment of the requirements for the award of Bachelor of Science degree in Mechanical Engineering.

JOEL OFORI-TEIKO

2020

DECLARATION

I hereby declare that this capstone is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature:

……………………………………………………………………………………………

Candidate's Name:

Joel Ofori-Teiko

……………………………………………………………………………………………

Date: 29/05/2020 ……………………………………………………………………………………………

I hereby declare that preparation and presentation of this capstone were supervised in accordance with the guidelines on supervision of capstone laid down by Ashesi University College.

Supervisor's Signature:

……………………………………………………………………………………………

Supervisor's Name:

……………………………………………………………………………………………

Date: ……………………………………………………………………………………………

ACKNOWLEDGEMENTS

To my supervisor, Dr Kenobi Morris whose encouragement and academic advice helped me undertake this project. Without his continuous support and corrections, this project would never have been completed.

To my dad, Mr. Ofori-Teiko whose financial backing facilitated the purchase of all materials that were employed in completing this project. Without him, the acquisition of all the materials would have been impossible leading to the premature termination of this project.

To my friends, Esi Sagua, Melinawo, Elisheva and Frederick. Without their encouragement, this project would never have been taken to completion.

EXECUTIVE SUMMARY

Traditional friction brakes are wasteful in their method of slowing down a moving vehicle. They typically slow down a moving vehicle by converting the kinetic energy of the car into other forms of energy like friction energy and heat energy. To reduce the wastage of energy, regenerative braking, a method for capturing some of the energy that would have otherwise been lost has been devised. This stored energy is reused by the vehicle when next the accelerator pedal is depressed. Regenerative braking has commercially taken a form that captures energy in the form of electricity stored in battery packs. Because of this, cars that employ the technology either use hybrid electric vehicles or fully electric of vehicles.

In trying to improve the consumers' choices regarding regenerative braking, this project seeks to test the concept of regenerative braking using hydraulics. This form of regenerative braking comes in two forms: parallel hydraulic hybrid regenerative braking and series hydraulic hybrid braking. The Parallel hydraulic hybrid regenerative braking system is chosen as the focus for this study for reasons discussed in subsequent session of the report (1.7).

In testing the Parallel hydraulic hybrid regenerative system, fatigue tests were conducted on the pressure tanks since they were the most prone component to failure. Again, fatigue tests were conducted on the pressure tanks. The weight of the entire system was evaluated as was the system's effect on braking distance. The amount of energy the system stored at peak was also estimated using simple assumptions. The results from this study prompted a very simple conclusion. Parallel hybrid hydraulics are a capable replacement than the widely employed electric hybrid regenerative system. However, a key component of the Hydraulic Hybrid Vehicles (HHV), its pump/motor, is scarce and not a lot of research has gone into it. Thus, it would be a difficult feat to commercialize the HHV. The conclusion of this project is that, HHVs

can replace electric hybrid regenerative braking systems but not until enough research has gone into the pump/motor.

TABLE OF CONTENTS

TABLE OF FIGURES

1 CHAPTER 1: INTRODUCTION

1.1 Introduction

One of the most basic laws of physics is the Law of Conservation of Energy; energy is neither created nor destroyed. At best, it can only be converted from one form to another [1]. In keeping with this law, the kinetic energy a vehicle possesses must be transformed into another form of energy to get that vehicle to stop. Traditional brakes execute this task by converting a vehicle's kinetic energy into friction energy and heat energy [2]. Aside that, traditional friction brakes have the tendency to heat up aggressively leading to a reduction in their ability to effectively slow down a vehicle [3], [4]. While there are certainly positive aspects to using traditional friction brakes, extensive work has gone into trying to improve the overall efficiency of brakes on vehicles. One of the areas that has been heavily focused on is the wastage of kinetic energy the vehicle possesses. Regenerative braking is the technology that has been devised to combat this problem. What this technology does is that it converts the kinetic energy that would have otherwise been wasted into a more useful form of energy that is used to propel the car the next time the accelerator is pressed [5].

In recent times, regenerative braking has taken on the form that allows it to only be fitted commercially to electric cars and hybrid electric vehicles. This works in electric vehicles and hybrid vehicles because the electric motors these vehicles have are set in reverse mode when the brakes are pressed. This means instead of spending energy (motor), they produce energy (generator) which is transferred to the vehicle batteries for storage [5].The energy that is recuperated from braking is converted to electric energy and is used to charge the battery packs in the vehicles.

1.2 Problem

Traditional friction brakes stop vehicles by converting kinetic energy into friction and heat energy. This leads to frequent wear on the brakes of the vehicle and reduce efficiency of the brakes. Again, having to use the combustion engine to get the car moving after coming to a stop uses a substantial amount of fuel that could have otherwise been saved. This project seeks to capture the energy that would have otherwise been lost to the atmosphere in a more useful form which can be used to power the vehicle the next time it needs to accelerate. To achieve this, basic mechanical concepts like hydraulics and pressure differences will be employed for the development of this system. These concepts were chosen for reasons that are discussed extensively in 3.3.1. Aside the reasons discussed, it was important that knowledge that had been amassed during the four (4) year training period in Ashesi University as a Mechanical engineer would be put to use.

1.3 Objectives

- Finding an alternative means of capturing the energy from braking that is not electric.
- Developing a system to test the feasibility of the means discovered as part of the first objective

1.4 Motivation

Consumers should be given more than one option as a solution regardless of the problem. In this scenario, the problem is more efficient cars and the only solution that consumers have been presented with is hybrid electric cars and electric vehicles. If there was a way to give consumers more options in this case, it could be beneficial to automakers and consumers alike. In lieu of the electrical hybrid regenerative system, a more mechanical system can be presented to customers.

1.5 Scope of Research

The scope of this research will focus on developing a mechanical system to recover the energy lost from braking. This will include a literary review on what currently exists in the market and conducting a 3D model of the system. Depending on how quickly the first two objectives are dispatched, a scaled down version of the system may be built. This project in no way seeks to build a 1:1 model of the system.

1.6 Expected Outcome

At the end of the stipulated time for completion of the capstone project, these are the objectives that should have been met.

1. Discover an alternative to electric hybrid regenerative braking
2. Design a system that conclusively answers this question.
    a. Determine amount of energy the real-world model can store
    b. Do a pressure and fatigue analysis on the tanks
3. Build a scaled down version of this [designed] system.
4. Test out this [designed] system.

1.7 Current Market Situation

The Internal Combustion Engine has a stranglehold on the current market for vehicles. Because of this, traditional friction brakes dominate the market. According to findings from a Bloomberg report, as of 2019, upwards of 80% of all vehicles sold were powered by internal combustion engines [6]. Because vehicles powered by internal combustion engine alone are incapable of using the regenerative braking system, this has allowed traditional friction brakes to dominate the market. The current market for regenerative braking is dominated by hybrid electric vehicles and pure electric vehicles; their purpose is to convert the kinetic energy to electric energy and store that energy in battery packs. Another form of regenerative braking is Hydraulic Launch Assist which is a system developed by Eaton Corporation and later taken over by Parker Corporation. This system is **only** fitted to heavy duty vehicles (vehicles over 11.79 metric tons). Eaton discontinued production in 2013, leaving Parker Corporation with a huge stranglehold on the market [7]. Typically, the average person regard this [electric regenerative hybrid] as the default method for recouping energy. This may be attributed to the Hydraulic Hybrid only being fitted to heavy duty vehicles. The delivery service industry in the United States have become the highest consumers of vehicles fitted with Hydraulic Hybrids. Between 2014 and 2017, companies like Between 2014 and 2017, companies like Peapod, Kiessling Transport and UPS have purchased about ninety (90) trucks fitted with the system [hydraulic hybrid].

Ford Motor company tried for the first time in 2004 to try to commercialize the hydraulic hybrid by putting it in their Ford Tonka Truck concept car. Pushing the envelope even more, Ford tested out the technology in a passenger **SUV**; 1999 Lincoln Navigator with a 4.0 Litre V8 engine [8]. Several tests were conducted and the results from the tests form part of the basis for this paper. For reasons not yet discovered at the time of writing, Ford Motor company has still not commercialized the hydraulic hybrids. However, the company frequently teases the public with news that point to the revival of this technology. As recently as 2017, Ford Motor Company announced that it was expanding its Advanced Fuel Qualified Vehicle Modifier program to include companies that develop and install hybrid hydraulic systems on its vehicles [9]. What this means is that Ford will offer you the same warranties and guarantees when you purchase a vehicle fitted with the Hydraulic Hybrid system as it would if you purchased a conventionally powered vehicle.

2 CHAPTER 2: LITERATURE REVIEW

2.1 Traditional Friction Brakes

Traditional friction brakes come in two forms: Drum brakes and Disc brakes. Drum brakes also use friction but in a slightly different way. Drum brakes consist of a brake drum and brake shoes. The hollow drum turns with the wheel. It works by lining up the brake shoes by the action of a hydraulic cylinder against the inner surface of the brake drum when the brake pedal is pressed This creates friction and thus, slows down the wheel. Disc brakes comprise a brake disc, a brake caliper, and a brake pad. Disc brakes use hydraulic fluid to cause the brake caliper to squeeze the brake pad against the brake disc. The action of the brake pad on the brake disc creates friction; it is this friction that stops the car. It [the friction] coverts the kinetic energy to heat thereby slowing down the car [10]

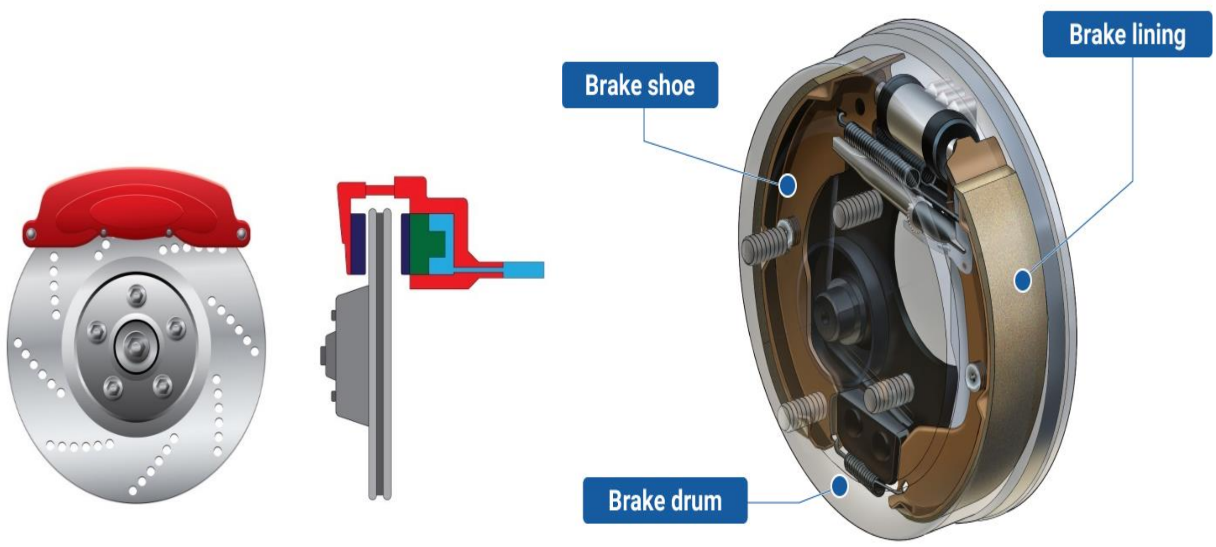

Figure 1: Traditional disc brakes (left) and Traditional drum brakes (right) [10]

2.2 Regenerative Braking

Regenerative braking is a form of braking in hybrid vehicles in which the loss of kinetic energy from braking is stored and then fed back later to provide power to the vehicle [11].

2.2.1 Electric Regenerative Braking

Electric regenerative braking is a phenomenon that is unique to electric vehicles and electric hybrids only. Some of the kinetic energy that would have otherwise been lost as heat energy is converted to a more useful form of energy. For electric hybrids, the kinetic energy is converted to electricity and stored in the battery packs of the electric vehicle or hybrid. The battery supplies electric energy to operate the motor. The motor supplies energy to rotate the vehicle wheels producing kinetic energy. The motor can operate in reverse. When a motor operates in reverse it acts as a generator. When the vehicle slows down, the generator converts the kinetic energy into electrical energy to charge the vehicle's battery [12].

2.2.2 Hydraulic Hybrid Braking

Hydraulic hybrid regenerative braking is a form of regenerative braking much similar to electric regenerative braking in that some of the kinetic energy that would have otherwise been lost as frictional energy and heat energy is converted into a more usable form of energy. That is where the similarities end. 'In a Hydraulic Hybrid Vehicle, energy from regenerative braking is stored in a hydropneumatics accumulator' [8]. The conversion from mechanical energy (rotation of the wheels) to hydraulic energy (hydropneumatics accumulator) is primarily achieved by the action of a pump/motor which has variable pressure and is comfortable working under high pressure [8-eight].

2.2.2.1.1 Series Hydraulic Hybrid Braking

In a series HHV, the engine is not directly connected to the wheels. Instead a pump/motor, acting as a motor, uses high pressure fluid from an accumulator to propel the vehicle. It functions much like the electric hybrid regenerative braking as it can shut of the engine when it is not in use. This ability to shut of the engine is mostly used when the driver depresses the accelerator pedal lightly or during short cruising, when the power demands of the vehicle are very low [13].

2.2.2.1.2 Parallel Hydraulic Hybrid Braking

In a parallel hydraulic hybrid vehicle (HHV), the engine still provides power to the wheels through a standard transmission. The hydraulic components are attached to the driveshaft and assist in stopping and accelerating the vehicle. Because the hydraulic components are not attached separately from the rest of the standard transmission, this form of regenerative braking is unable to propel the vehicle in the absence of power from the engine [13]. Where the parallel hydraulic hybrid shines is in heavy acceleration; both the hydraulic components and the engine provide power to the driven wheels at the same time adding a boost of power [5].

3 CHAPTER 3: DESIGN SELECTION

3.1 USER AND TECHNICAL REQUIREMENTS

Table 1: Level 1: Project Requirements

ID/SHORT NAME	PROJECT LEVEL REQUIREMENT	STAKEHOLDER ADDRESSED
Proj_Req_01 Fuel Efficiency	Significant increase in fuel efficiency	• Automobile drivers • Supervisor • Lecturers
Proj_Req_02 Weight	Should not increase the overall kerb weight significantly	○ Automobile drivers ○ Supervisor ○ Lecturers
Proj_Req_03 Stopping Power	Should not feel significantly different than traditional friction brakes	• Automobile Drivers • Lecturers
Proj_Req_04 Cost	Should not exceed the budget cap for prototype development	○ Ashesi University
Proj_Req_05 Brake life extension	Should significantly increase brake pad life	• Automobile drivers

Table 2: Level 2: Technical Requirements

ID	PARENT REQUIREMENT	SYSTEM LEVEL REQUIREMENT	STAKEHOLDER ADDRESSED
Sys_Req_01	Proj_Req_01 Proj_Req_02	The system should provide an increase in fuel efficiency > 10%	• Automobile Driver • Project Manager • Supervisor
Sys_Req_02	Proj_Req_01 Proj_Req_02	The system should not weigh more than 200 kg	○ Automobile Driver ○ Lecturers ○ Project manager ○ Supervisor
Sys_Req_03	Proj_Req_03	The regenerative brakes should stop the car in ± 5 m as traditional friction brakes	• Automobile Driver • Lecturers • Project manager • Supervisor

Sys_Req_04	Proj_Req_04	The prototype development should not cost more than $50.00	○ Ashesi University ○ Project Manager
Sys_Reg_05	Proj_Req_05	The system should increase brake life by at least 20%	• Project Manager • Automobile Drivers

3.2 Assessing Different Solutions

Table 3: Pugh Matrix for assessing different solutions

		BASELINE	ALTERNATIVE SOLUTIONS	
CRITERIA	WEIGHT	SERIES HYBRID	PARALLEL HYDRAULIC HYBRID	ELECTRIC HYBRID
FUEL EFFICIENCY GAINS [4]	5	4	3	2
OVERALL EFFICIENCY OF SYSTEM	4	3	3	2
COST	4	2	2	3
EASE OF USE	4	3	3	3
EASE OF MANUFACTURING	3	1	3	3
TOTAL	20	13	14	13

3.3 Notes on The Evaluation Criteria

FUEL EFFICIENCY GAINS: This refers to the fuel efficiency gains of a vehicle fitted with any of these systems compared to a car without any of the systems. It compares the systems using data from the EPA in stringent test conditions. These test conditions include City tests, Highway tests, High Speed tests, Air-Conditioning use, and Cold Temperature use. Because consumers are most concerned with how much fuel they can save as a result of these systems, it was awarded the highest weighting [14].

OVERALL EFFICIENCY OF SYSTEM: This refers to how efficient the systems are at transforming kinetic energy that would have been otherwise lost as friction energy into a more useful form of energy. It was awarded a weight of 4 because although the amount of kinetic energy recaptured, it is not as important as the returns the driver would obtain.

COST: This refers to how much it would cost to manufacture the components needed to set-up the systems. It takes into consideration the sum of the prices of all the individual components that the systems comprise. For any engineering project, the cost of the system is critical and thus, it was awarded a weighting of 4.

EASE OF USE: This refers to how comfortable each of the three systems is to use. It takes into account factors like noise, size among other things. For a user driven system, new technology should not feel drastically different standard and thus, this category was awarded a weight of 4.

EASE OF MANUFACTURING: This refers to how easy the manufacturing process is for the components that make up the systems. Ease of manufacturing carries a weighting of 3 because the users would not worry much about how easy it is to make a system; availability and cost of system is more important to them.

3.3.1 Justification for Parallel Hybrid

The Series Hydraulic Hybrid has fuel efficiency gains of 60-70% (OTAQ, 2011) compared to 40% [13] for the Parallel Hydraulic Hybrids and 23% for the Electric Regenerative Braking [5].

Both Series and Parallel Hydraulic Hybrids have an overall efficiency of 70-80% compared to 55% for Electric Hybrids [13].

Series and Parallel Hydraulic Hybrids have their cost of production higher than the Electric Regen Braking. This is because during the research phase carbon fiber was used and costed about $150 per pound. However, this value has dropped to $10 a pound which could improve the cost effectiveness of hydraulic hybrids [14]. Again, series hybrids have an extra electronic component known as the hybrid controller that controls the engine. This part costs extra to design and thus increases the cost of production significantly compared to parallel hybrids [13].

Parallel and Series Hydraulic Hybrids were slightly noisier compared to Electric Regenerative Braking because Flat Format hydraulic motors were used. However, there have been developments like the Floating Cup motors whose noise outputs are comparable to electric motors [15].

In conclusion, Series and Parallel hybrids are both better solutions than electric regenerative braking from the end user's perspective. However, between Series and Parallel Hybrids, the better option is parallel hybrids because it comes with almost all the benefits of the Series Hybrids without the extra cost of the hybrid controller.

4 CHAPTER 4: METHODOLOGY

4.1 Overview and Scaling Considerations

One of the objectives of this project is to build a scaled down version of the system that is chosen as per the system requirements. The system chosen was the parallel hybrid hydraulic system. The system comprises two pressure accumulator tanks, a pump and a motor which are connected to the drive shaft.

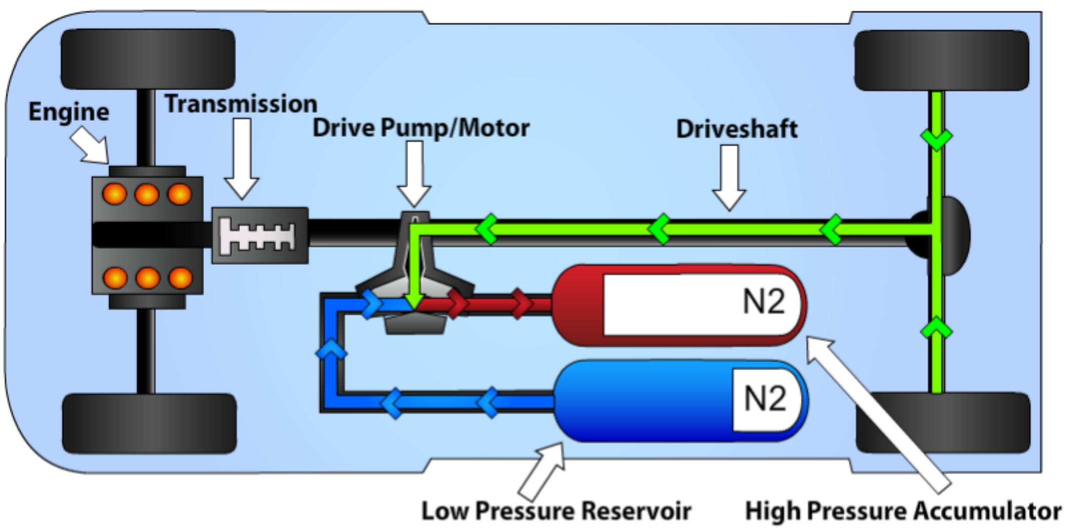

Figure 2: diagram of a parallel hydraulic hybrid [13]

The system is analogous to an electrical circuit with each individual component acting as a member of the circuit. For figure 1, the circuit comprises an engine, a transmission, two pressure accumulators, a drive pump and a drive shaft. For this project, the circuit was split into two parts. The first part of the circuit recovers energy that would have been lost by braking. The second part of the circuit expends the energy recovered from braking to rotate the driven wheels.

To build a scaled down version of an entire system, one has to understand the concept of similitude. Cambridge dictionary defines similitude as the state of being similar or having similar features

[16]. Pertaining to science however, similitude is expressed as the relationship between smaller sized models and structures considered human sized [17]. In achieving similitude, three conditions ought to be met: dynamic similarity, geometric similarity and kinematic similarity [18]. “Geometric similarity requires similarity in shape; all length dimensions in the model are ‘x’ times shorter than of its real-world prototype. Kinematic similarity implies geometric similarity and in addition indicates a similarity of motion between model and prototype particles. It requires constant ratios of time, velocity, acceleration and discharge in the model and its prototype at all times. Dynamic similarity requires in addition to geometric and kinematic similarities that all force ratios in the two systems are identical” [18].

If these three conditions are not met, scale effect, the deviation in characteristics of a scaled down model and its real-world prototype occurs. In models that involve hydraulics, there will always be scale effect since it is impossible to model all force ratios [18]. While scale effect creates these deviations, the models produced still allow the researcher to understand some aspects of how the real-world model will work.

For this project, the pressure accumulators were the main area of study. This is because achieving adequate pressure in the high-pressure accumulator will be paramount in getting the wheels of the vehicle to spin. Thus, the concepts of similarity were mainly applied to these components. Out of the three types of similarity, geometric similarity was most focused on since the other two included force analysis that are impossible to predict for hydraulic models. The human sized prototype had a volume of 54.5 liters while the scaled down model had a volume of a thousand (1000) g. The real-world model employed two cylinders, each with a shell, a gas charging port, a fluid port and a gas bladder.

For this project, two different cylinders were used, each for a different purpose. The high-pressure cylinder was modelled using a refrigerant bottle of refrigerant R-134a. It had an operating pressure threshold of 931 to 2379 kPa. This part of the model represented the part of the life-sized system that aided the combustion engine to provide power to the driven wheels. The outward appearance of the refrigerant was like the life-sized model and thus, a conclusion was drawn that geometric similitude was achieved. Thus, area, volume and the characteristic length of the model was 54.5 times smaller than the life-sized model.

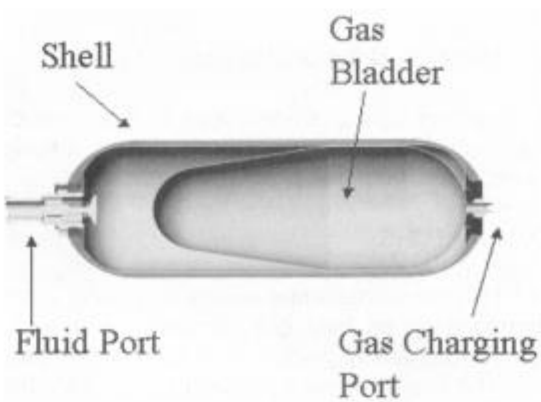

Figure 3: Life sized tank (left), [10] and model tank (right)

4.2 High Pressure Side Overview

The high-pressure side was simulated using the refrigerant bottle to power a toy dump truck that weighed approximately seven hundred (700) g. It should be noted that although this project sought to incorporate the hydraulic hybrid system into a passenger vehicle, a dump truck was picked for the simulation because it was one of the readily available scaled models that could carry a refrigerant bottle without compromising its structural integrity and operation. Before the two components were connected, first, a simple Newtonian test had to conducted. This test was conducted to determine if the thrust from the refrigerant would be enough to propel the dump truck forward based on Newton's third law. This test involved placing the refrigerant bottle on top of the truck and releasing the gas. The results from this test were conclusive. Although the wheels of the toy dump truck were almost frictionless, the weight of the refrigerant bottle (> 1 kg) in addition to the weight of the dump truck (700 g) prevented the truck from moving. This was because the inertia resulting static friction that existed between the truck + refrigerant bottle and the surface were too much to be overcome by the thrust provided by the refrigerant bottle.

Figure 4:Dump truck with 1 kilo refrigerant bottle

The refrigerant bottle was changed from one that weighed in excess of a thousand (1000) g to a bottle that weighed a little over three hundred and ninety (340) g.

Figure 5: a visual comparison between the 1000 g bottle and the 340 g bottle

The simple Newtonian test was reconducted and this time, the thrust provided by the 340-gram bottle was able to overcome the inertia created by the bottle and the truck. The operating pressures of the 390-gram refrigerant bottle was the same as the 1000-gram bottle as was the thrust provided by the bottle. The only significance in changing the refrigerant bottle was positive as the overall weight of the system reduced. Another effect of downsizing the refrigerant bottle was the impact on geometric similitude. The characteristic length of the model of the model was now 140 times less than the characteristic length of the model. However, as already discussed, this would not change the validity of the results that the model would produce. Thus, these results could be used to determine the behavior of the life-sized model.

Even though the refrigerant bottles served as a good approximation of the behavior of the life-sized model, a computer-aided designed model was also developed to better understand and approximate the results of the life-sized pressure tanks. An image of it is depicted below.

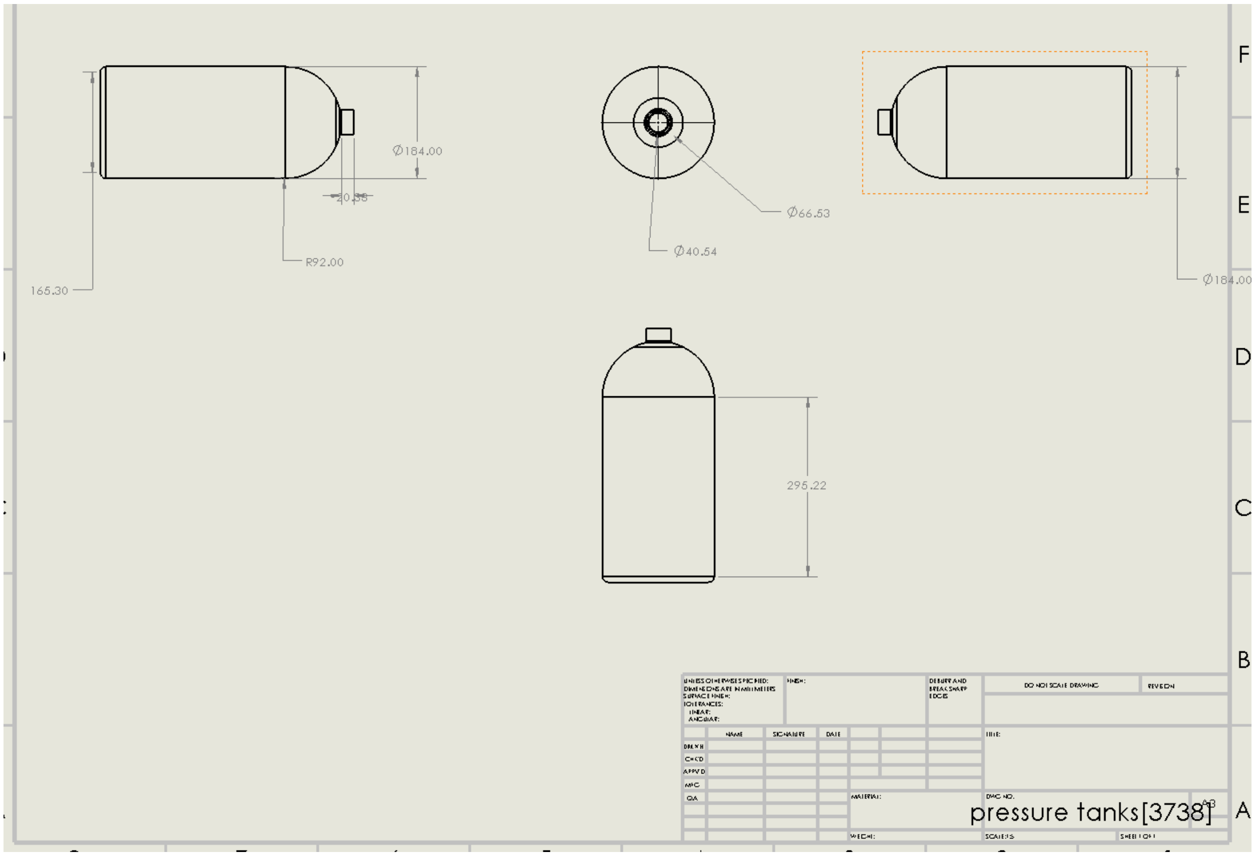

Figure 6: Drawing of pressure tanks

4.2.1 High pressure side development

Once a pressure tank and the vehicle were chosen, it was time to find a way to connect the two components mechanically. Following the example of the system used by the EPA [13] was out of the question. This is because in their system, the working fluid from the pressure tanks went through a pump/motor and that created the driving force to turn the driven wheels of the vehicle. Two different methods were considered: using differentials or working with a friction drive system.

4.2.1.1.1   Using the Differential

This option involved building a differential for the rear wheels of the dump truck and incorporate a section in the differential that would spin because of the thrust provided by the high-pressure tank. Thus, driving all the gears inside the differential and in turn turning the driven wheels. The benefit of this system was that it could send the rotational energy to each wheel on the driven axle independently of each other [19]. This system was mechanically more complex than the other option but provided better output as it curtailed the tendency of the wheels of the dump truck to slip instead of rolling on the surface the truck was on.

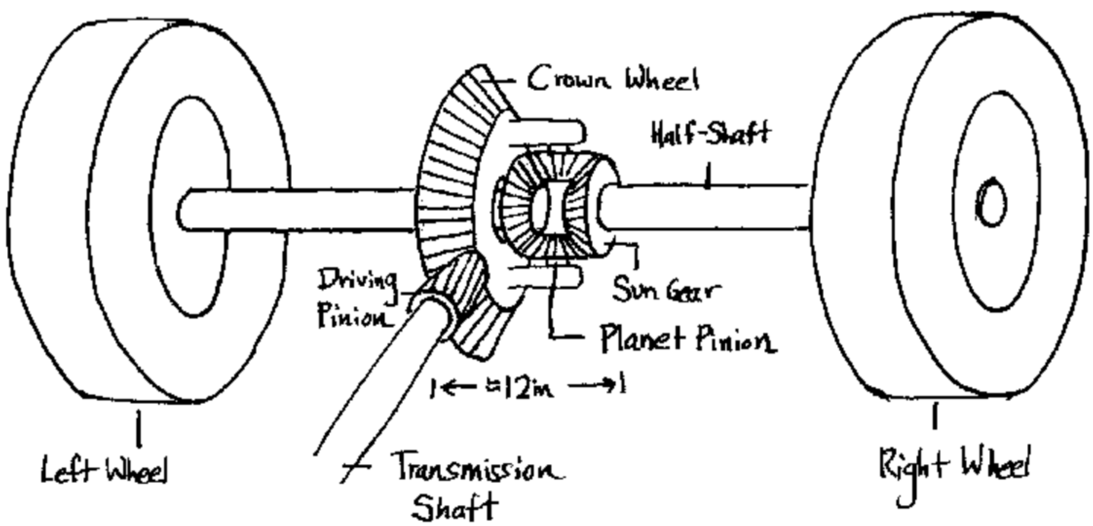

Figure 7: diagram of a differential connected to the driven axle [20]

4.2.1.1.2   Using the Friction Drive

This option was one that involved purchasing another type of toy automobile. Those that were wound up by pulling them backwards and letting go. This type of toy automobile would move for a little while and then come to a stop when the energy stored in the spring was depleted. Compared to building the differential, this option was mechanically simpler and would not provide the same results as the differential. This is because the friction drive only did one thing; it spun the driven wheels without caring much about whether the tires were slipping or rolling. Again, all that had to be altered from the traditional friction drive was to spin the primary gear not by winding the spring up, but rather, by using the thrust from the refrigerant bottle.

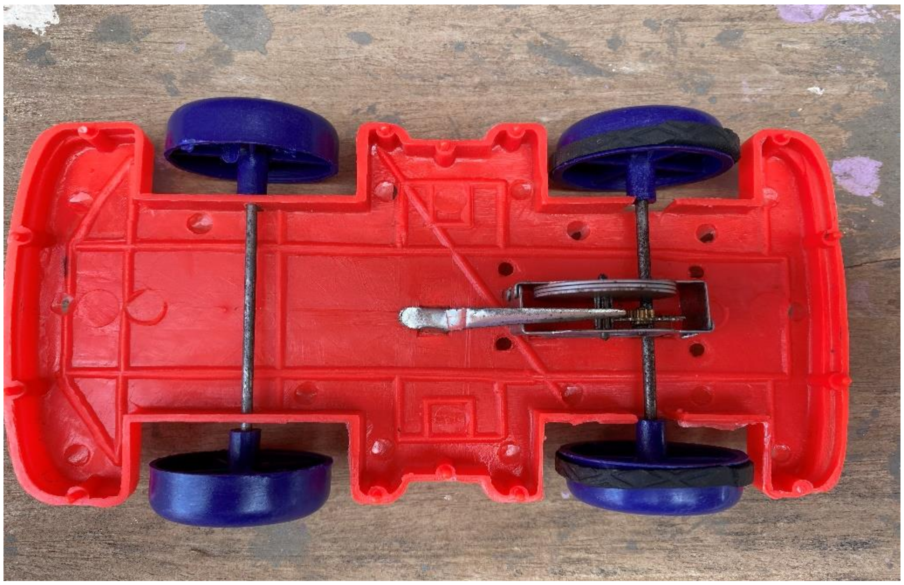

Figure 8: toy automobile with friction drive

4.2.2 High Pressure Side Execution

The initial plan was to go with the differential because the benefits it came with were favorable and the downsides were not of any consequence. This would have involved designing the gears by Computer Aided Design (CAD) and then 3D printing those parts. Once the gears were complete, all that would remain would be to join the completed design of the differential to the driven axle of the dump truck. This would have been done by sawing off a section of the rear axle and then joining it to the differential. However, a series of unfortunate events that led to the closure of the university premises destroyed any chances of printing the gears. Thus, the second and less mechanically complex system was chosen.

Using the friction drive was not an option that was favorable as it allowed the wheels to slip and not only roll. However, under present circumstances, it was the solution that was readily available. Again, the true aim of this project was to determine if hydraulic hybrids were a reasonable replacement for electric hybrids. Thus, all that needed to be proven was that the pressure from the tanks could power the driven wheels of the vehicle if even for a short period of time.

As previously stated, the friction drive did not have to be developed from scratch as it was readily available on many toy vehicles. Thus, one of such vehicles was bought and the friction drive system was lifted from it. The friction drive was coupled to the rear axle of the dump truck by sawing off a section of the rear axle and then joining it to the friction drive through the slots made for the axle. A hole was made in the bed of the dump truck to serve as a passthrough for the tube connecting the refrigerant bottle and the friction drive. The finished system had to be turned on manually as the valve on the refrigerant bottle did not have an electric component. However, this was a non-issue as the aim of the study was to power a vehicle using hydraulics. Thus, when the system was turned on, it could travel a short distance and then the valve on the refrigerant bottle was shut off. If this was not done, the refrigerant bottle would empty its contents after every trial; this was not an efficient or cost-effective way of testing out the final system.

4.3 Low Pressure Side Overview

Low-pressure side as referred to in this project is a misnomer because it does not actually depict the low-pressure side accurately. Rather, the primary aim of the low-pressure side in this project was the demonstration of how the working fluid in the life-sized model would pressurize the fluid. The assumption that the working fluid was an ideal gas is discussed in depth in 5.1. This assumption served as a basis for a theory the low-pressure side in this project. To increase the pressure of any fluid in a container, you can decrease the volume of the fluid in the container by adding air to the volume of the fluid already present in the container. At the beginning of the implementation stage of this project, the low-pressure and high-pressure side were to be made as one complete system. The differential that ought to have been built would have incorporated the low-pressure system to act as the power source to push air into the system. However, the differential alone could not have done the job of the pump/motor of the life-sized model. Research went into finding a suitable replacement for this pump/motor for the scaled down model. This was futile and thus, a new plan had to be quickly devised. This plan involved the separation of the low-and-high-pressure sides. Thus, the two subsystems would be studied independently of each other. This separation of the two systems was deemed to have no effect on the tests to be conducted on the system. The augmenting of the two subsystems is discussed further in 6.1.

4.3.1 Low-Pressure Side Development

The backup plan was to use the same refrigerant bottle used for the high-pressure side prototype. However, the refrigerant bottle used in the high-pressure side was capped by a one-directional valve which prevents backflow (inflow) of fluid into the bottle. In trying to circumvent this issue, the 1000 gram bottle that is discussed in 4.2 was used since it had almost depleted its contents during the Newtonian tests and no longer had a need for the valve. Once a container had been found, the next task was to find a device that would supply the air to reduce the volume of the working fluid inside the refrigerant bottle. A tyre inflator kit, found in many modern cars was the device of choice. It was chosen not because of any innate qualities the tyre inflator kit possessed but rather it is a device that is readily available and would easily do the work required.

5 CHAPTER 5: ANALYSIS AND RESULTS

5.1 Quantifying energy stored in the real-world model

One of the objectives of this project is to analyze the amount of energy that can be stored by the high-pressure accumulator. To do this, some assumptions had to be made to simplify the calculations and yet present a compelling estimate. The first assumption made is that the heat transfer between the system and the environment is negligible. The second assumption made is that the model undergoes an isothermal compression. The final assumption made is that the working fluid obeys the ideal gas laws.

$$PV = constant \tag{1}$$

$$W = \int_{V1}^{V2} PdV \tag{2}$$

$$W = -P1 * V1 * In\left(\frac{V2}{V1}\right) \tag{3}$$

These are the three equations that governed the system. Using these equations, the amount of energy that a 0.34 litre tank would be able to store about 6.210 kW of energy. From this estimate, the real-world model would be able to store 869.49 kW. This value was obtained by multiplying the amount of energy stored in the model tank by the scale factor (140). This value is an overestimation due to the simplification made by the assumptions. In the real system, this value would be much lower due to the following:

a) The system will exchange heat with its surroundings

b) There will be pressure drops along the system

c) There will be residual volume left in the system even after the high pressure system 'empties' its contents

d) The motor that will spin the driven axle is not 100% efficient

However, this value gives us a good estimate of the kind of energy that this system would provide More accurate data can be obtained by fitting the system to a test vehicle and running several experiments on the vehicle

5.2 Pressure Analysis on the Tanks

To pass the project as a success, a pressure analysis was conducted on the pressure tanks. This was necessary as the pressure tanks are the components of the entire system which are subjected to the most forces and are thus most likely to fail.

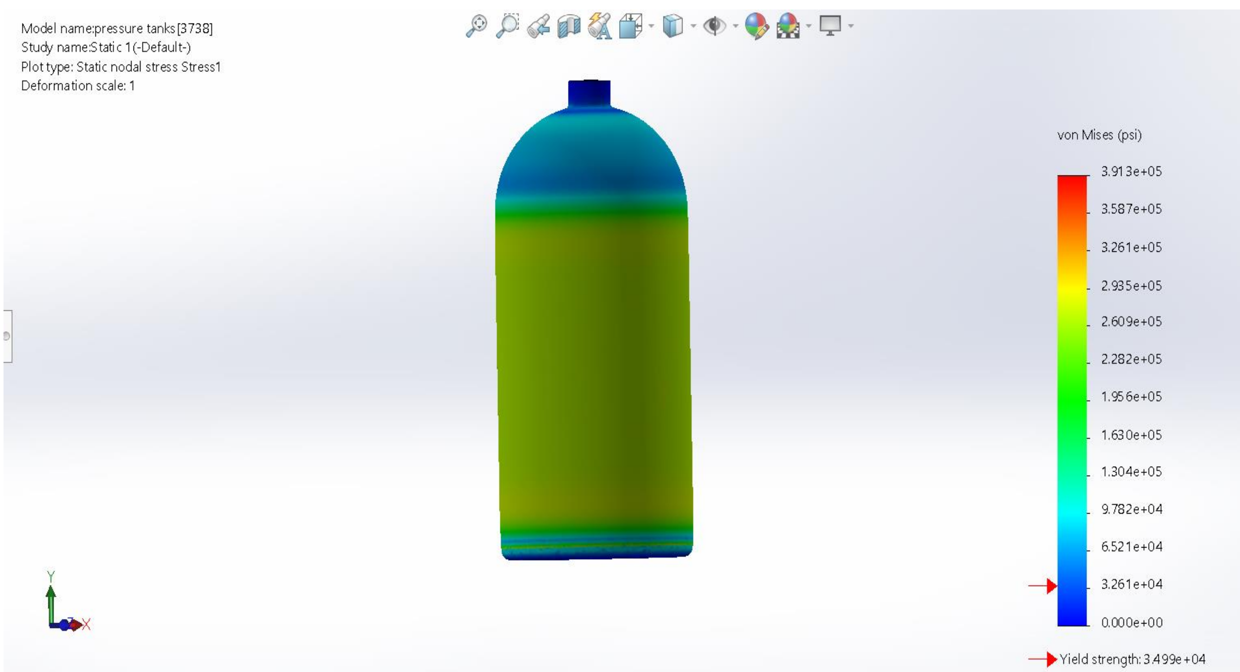

Figure 9: front view of pressure tank subjected to 5000 psi

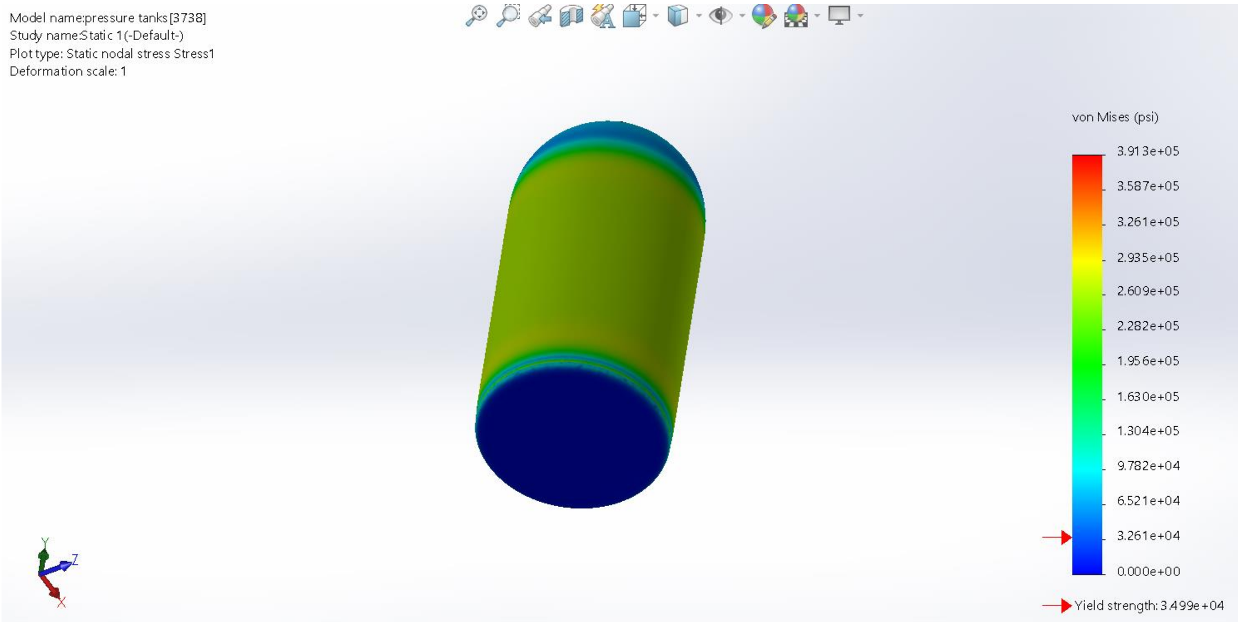

Figure 10: isometric view of pressure tank subjected to 5000 psi

The tank simulated using SolidWorks had the dimensions already stated and was made out of cast alloy steel which has an ultimate tensile strength of 2697.919 (MPa). When operating at 34473.79 kPa, the highest internal and external stresses that the tanks undergo was around 1426.52528 MPa which is about 1272 MPa less than what would cause failure. These high stresses occurred at the surfaces where the pressure tanks changed shape and was expected. However, even then, the factor of safety was calculated to be around 1.89. In most other systems, this would have been an issue since the loading would be varied by the user. Because this system would in reality have a maximum pressure that is fairly constant and in reality less than 34000 kPa due to losses in the system, it can be concluded that a factor of safety of 1.89 is enough to sustain this design. Thus, it was unlikely for the pressure tanks to fail due to the forces they undergo alone.

5.3 Fatigue Analysis on Tanks

While the static analysis paints a fair picture of how the system would handle its maximum pressure, it does not give us any further information. The pressure tanks in this system will not just undergo this form of loading once. Every time a vehicle slows down, the tanks will undergo loading. There are various kinds of scenarios drivers face every day; fast-moving traffic (highways), stop and go traffic and medium to fast-moving traffic (town and country roads). With each of these different scenarios, driver braking habits would vary and thus, it is difficult to get an estimate on average number of times drivers' brake. However, a figure that is readily known is the number of miles brakes can be used before needing replacement. Because one of the claimed benefits of the hydraulic hybrid is the extension of brake life, a test can be run to prove whether the pressure tanks would last as long. To do this, first you would need to find the average brake pad and disc life which generally is given by 80467.2 km [21]. Then making an educated guess of braking 2-3 times per km, this adds up to around 150,000 cycles in a worst-case scenario. Because one of the requirements of the project was to ensure that brake life would be extended by at least 20%, the pressure tanks had to survive at least 180000 cycles before failing. However, because it would cost significantly more to replace pressure tanks compared to replacing just the traditional brakes, the pressure tanks would have to undergo around 360,000 cycle before failing to be considered a success. 360,000 cycles amount to around 193121.28 km which is about 10 times the average distance road users cover in a year [22]. Thus, if the pressure tanks can experience 360,000 cycles before failing, they would need replacement every ten (10) years. In general, people keep their cars for an average maximum of about six (6) to eight (8) years before letting them go [23]. Thus, a life cycle of 360,000 cycles would be very desirable as it leads to two (2) more years of usability compared to the number of years drivers tend to keep their vehicles.

The results from the simulation are depicted in the diagrams below.

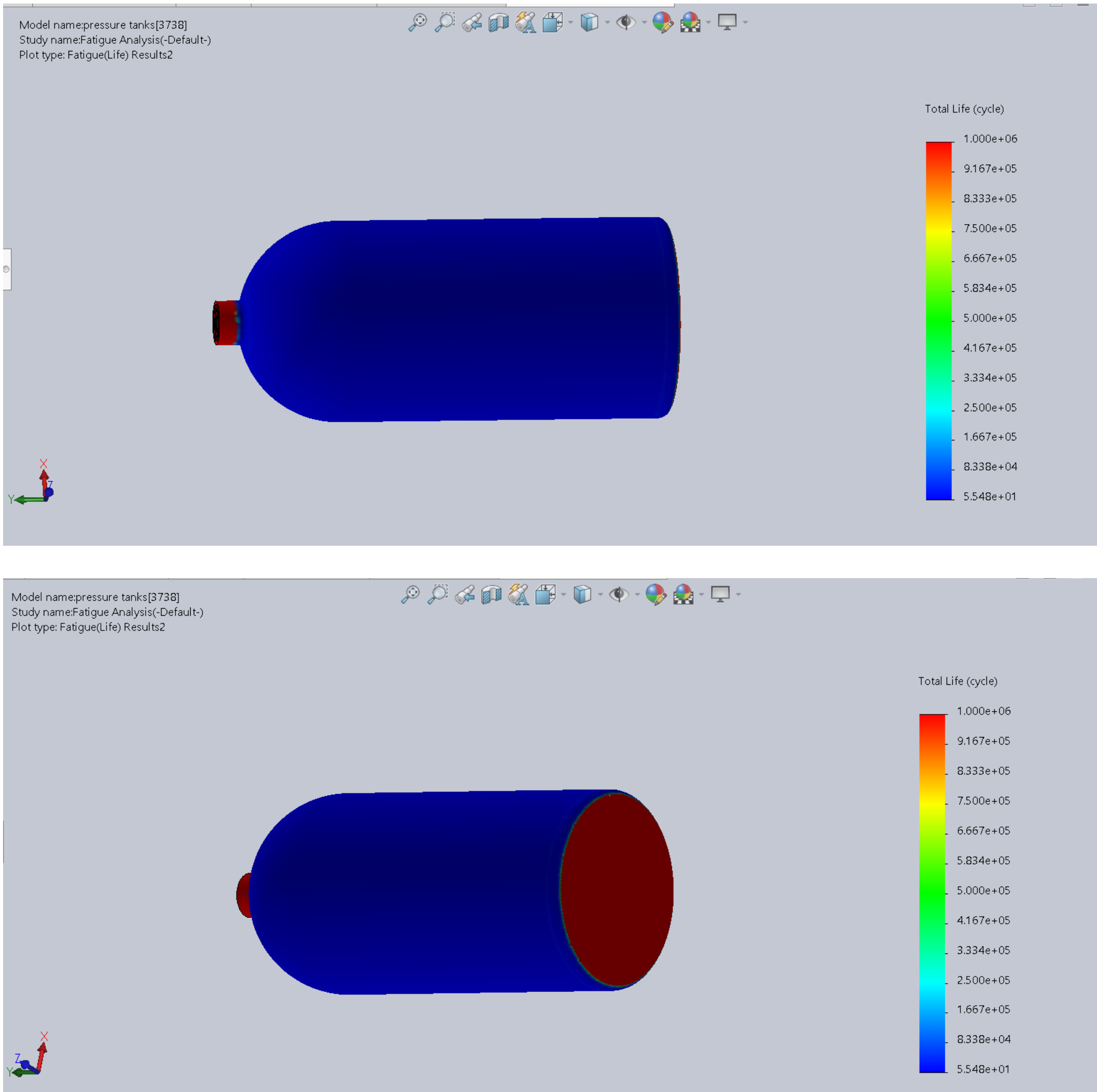

Figure 11:Different views of pressure tanks subjected to 36,000,000 cycles of loading

The results were obtained by testing the pressure tanks against a 3.6 million repeated loading cycles. As visible, most of the surface of the pressure tank remained intact. The surfaces where the shape of the pressure tank changed are the places that failed. Even then, they failed at around a million cyclic loading. This is more almost three times the success criteria stated above. Thus, it was concluded that the pressure tanks would survive longer than the eight (8) year life cycle of vehicles.

5.4 Weight Analysis

One of the criteria for objectifying the project is the weight of the entire system. The weight of the entire system was not to exceed 200 kg. If the system exceeded 200 kg, the heft of the vehicle would negate the fuel efficiency benefits. The pressure tanks which are the heaviest components of the system contain 54. 5 litres of working fluid. This means that, at their heaviest, they would be 54.5 kg ± 20 kg of the actual cylinder weight. This results in a combined total weight of both cylinders of around 150 kg. The weight of the valves and tank heads are negligible in this system. The last part of this system is the motor/pump assembly which weighs around 32 kg [24]. This brings the total weight of the system to around 180 kg. Adding a 10% compensation for any under or over estimations, this brings the total weight of the system to 162 kg for the best-case scenario and 198 kg in the worst-case scenario. In both scenarios, the system is under the 200 kg mark.

5.5 Braking Distance

The braking distance of a vehicle fitted with the hydraulic hybrid system (series and parallel) have no effect on the braking distance of vehicles it is fitted with. From (Figure 2: diagram of a parallel hydraulic hybrid [13]), it is obvious that the braking system of a vehicle is uncompromised. Rather, the braking system is uncompromised and works the same way it would if the hydraulic hybrid system was not connected to it.

5.6 Fuel Efficiency Gains

No experiment was carried out to test the fuel efficiency claims of the hydraulic hybrid system and thus, the project manager cannot state conclusively that the fuel efficiency benefits are at least similar to the values claimed by Ford Motor Company.

6 CHAPTER 6: CONCLUSION

6.1 Future Works

As clear from 4.3, the low-pressure side was not given as much consideration. While this did not compromise the results obtained, it would be prudent to have found a way to test the theory behind the action of the low-pressure side. Thus, further studies will be conducted into refining the prototype to incorporate the low-pressure side. Again, the life-sized model augmented the low-pressure side and high-pressure side of the system while this project built them as separate parts. Though it was stated that the two parts would be built independently of each other, further studies will be carried out to augment to two systems and test them as a unit. Once this test has been concluded, the project will be ramped up into a 1:1 model. This would be to answer the questions this study left unanswered as discussed in 6.3.

6.2 Challenges and Recommendations

6.2.1 Challenges

As with most human endeavors, this project was not without problems. The most prominent of which was procurement of the necessary parts to complete the prototype. This stemmed from the fact that too much time was spent into researching into an alternate form of regenerative braking. The only other challenge that plagued this project was the pandemic that resulted in the closure of the school. This prompted a drastic simplification of the entire project and a restructuring of the scope of the project. This was an unavoidable situation and thus could not have been curbed.

6.2.2 Recommendations

The problem of procurement that plagued this project could easily have been remedied. Using the summer vacation preceding the final year to not just decide on a topic but to start research on the topic of choice and materials needed to complete the project are measures that students currently in their third year could employ.

Secondly, although the closure of the school occurred through no fault of the school, had the project commenced in the vacation preceding the final year, it is more than likely that the implementation of this project would have been completed before the closure of the school.

As stated in 6.1, this project would be carried out with a broader scope even after the stipulated time for this project has elapsed. However, if there are any interested persons who would like to take this project to the next level, the help would gladly be accepted.

6.3 Conclusion

This project sought to find a system that would recoup some of the energy lost through braking. This led to the discovery of two different kinds of systems: electric hybrid regenerative braking and hydraulic hybrid regenerative braking. Hydraulic hybrid regenerative braking was chosen because several studies have been conducted on the electric hybrid regenerative braking. The studies on electric hybrid regenerative braking have been so extensive that the automobile industry has commercialized it. This was one of the reasons that spurred the pursuit of another kind of regenerative braking. The project was meant to come up with another mode of regenerative braking that could compete with the electric hybrid. Several objectives were stated at the beginning including with efficiency, weight and brake life among the most important.

To test out the viability of the hydraulic hybrid system, the project was divided into two sections: experimenting on the low-pressure side and then experimenting on the high-pressure side. The high-pressure side took precedence over the low-pressure side since it was the part of the system that powered the wheels. The high-pressure side was tested using a toy dump truck, refrigerant bottles and a friction drive system. These three components were used to represent the real-life model and provided estimates of how the real-world system would behave.

The results from these tests are discussed in extensive detail in 5. From these results, it was concluded that indeed the hydraulic hybrid regenerative system is;

1) Capable of powering a vehicle for a short while
2) Capable of maintaining the same braking distance as vehicles that do not have the system fitted to them
3) Capable of lasting throughout the life cycle of the vehicle itself
4) Under the 200 kg figure and would not increase the weight of the vehicle significantly

The objectives that rendered inconclusive results are as follows.

1) Fuel efficiency gains would exceed 10%
2) The system would increase life of brake pad and brake discs.

From the results obtained from the tests, the conclusion reached was that hydraulic hybrid regenerative braking as an alternative to electric hybrid regenerative braking is possible. It is possible in that; you can use hydraulics and pressure differences to power a vehicle for a short while. In (Justification for Parallel Hybrid), it was claimed that the Parallel hydraulic hybrid regenerative braking system had benefits that far outweighed those of the electric hybrid regenerative braking system. The results of this paper proved some of these to be true while others were inconclusive. However, a very critical component (the pump/motor) of the real-world system was approximated with a very simple model (friction drive). The iField motor that was used in the prototype by Ford Company sold by a specific company and is scarce. This kind of motor has important benefits which include a high power to weight ratio and a high efficiency.

However, as already stated, this kind of motor is scarce. Because it is the component that transmits power between the driven axle and the hydraulic system, its availability is fundamental to the success of commercializing the hydraulic hybrid regenerative braking system. Thus, although hydraulic hybrid regenerative braking systems can replace electric hybrid regenerative braking, it [HHV] is not ready to be commercialized just yet. However, this could easily be remedied as it was when electric hybrids started to be commercialized. The more the industry researches and develops the hydraulic hybrid system, its components will become cheaper and more available as with every other technological components. It should be remembered that it was just nineteen (19) years ago that the GWiz, one of the first commercial electric cars was capable of driving only 50 miles on a single charge [25]. Yet, barely two decades later, we have electric vehicles capable of travelling over 250 miles on a single charge.

In conclusion, hydraulic hybrid regenerative braking systems are indeed a viable alternative to electric hybrid regenerative braking. However, the technology needed to drive the HHV is not ready for a commercial scale yet and thus, it would be an ill-fated move to try to implement the hydraulic hybrid systems in passenger vehicles.

REFERENCES

[1]

"Conservation of Energy." [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/thermo1f.html. [Accessed: 11-Feb-2020].

[2]

P. Filip, "Friction Brakes for Automotive and Aircraft," in *Encyclopedia of Tribology*, Q. J. Wang and Y.-W. Chung, Eds. Boston, MA: Springer US, 2013, pp. 1296–1304.

[3]

M. E. • 2 Y. Ago, "The Advantages and Disadvantages of Disc Brake," *Steemit*, 04-Apr-2018. [Online]. Available: https://steemit.com/engineering/@mujahud/the-advantages-and-disadvantages-of-disc-brake. [Accessed: 11-Feb-2020].

[4]

"The Pros and Cons of cars with drum brakes," *Haynes Publishing*, 12-Jul-2017. [Online]. Available: https://haynes.com/en-gb/tips-tutorials/pros-and-cons-cars-drum-brakes. [Accessed: 11-Feb-2020].

[5]

S. J. Clegg, "A Review of Regenerative Braking Systems," p. 24.

[6]

"Electric Vehicle Outlook 2019," *BloombergNEF*. [Online]. Available: https://about.bnef.com/electric-vehicle-outlook/. [Accessed: 11-Feb-2020].

[7]

J. Park and D. Lockridge, “Eaton Drops Hydraulic Hybrid System.” [Online]. Available: https://www.truckinginfo.com/113384/eaton-drops-hydraulic-hybrid-system. [Accessed: 10-Nov-2019].

[8]

R. P. Kepner, “Hydraulic Power Assist – A Demonstration of Hydraulic Hybrid Vehicle Regenerative Braking in a Road Vehicle Application,” *SAE Transactions*, vol. 111, pp. 826–833, 2002.

[9]

“Ford names Lightning Hybrids, XL Hybrids, Motiv Power its first eQVM upfitters,” *Green Car Congress*. [Online]. Available: https://www.greencarcongress.com/2017/03/20170314-eqvm.html. [Accessed: 10-Feb-2020].

[10]

“How Do Car Brakes Work?” [Online]. Available: https://www.wonderopolis.org/wonder/how-do-car-brakes-work. [Accessed: 10-Nov-2019].

[11]

“Regenerative braking definition and meaning | Collins English Dictionary.” [Online]. Available: https://www.collinsdictionary.com/dictionary/english/regenerative-braking. [Accessed: 10-Nov-2019].

[12]

K. T. Chau, “Pure electric vehicles,” in *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance*, Elsevier, 2014, pp. 655–684.

[13]

“Clean Automotive Technology | Transportation and Air Quality | US EPA.” [Online]. Available: https://archive.epa.gov/otaq/technology/web/html/. [Accessed: 10-Nov-2019].

[14]

“Carbon Composites Are Becoming Competitive And Cost Effective,” p. 12, 2018.

[15]

“HyDrid - Hydraulic Hybrid.” [Online]. Available: https://www.innas.com/hydrid.html. [Accessed: 15-Jan-2020].

[16]

“SIMILITUDE | meaning in the Cambridge English Dictionary.” [Online]. Available: https://dictionary.cambridge.org/dictionary/english/similitude. [Accessed: 22-Feb-2020].

[17]

W. Braga, “Similitude And Theory Of Models,” *EXPERIMENTAL MECHANICS*, p. 6.

[18]

V. Heller, “Scale effects in physical hydraulic engineering models,” *Journal of Hydraulic Research*, vol. 49, no. 3, pp. 293–306, Jun. 2011, doi: 10.1080/00221686.2011.578914.

[19]

“How Differentials Work,” *HowStuffWorks*, Aug. 02, 2000. https://auto.howstuffworks.com/differential.htm (accessed Apr. 18, 2020).

[20]

"2.972 How A Differential Works."

https://web.mit.edu/2.972/www/reports/differential/differential.html (accessed Apr. 18, 2020).

[21]

"How Often Should Brakes Be Replaced? | YourMechanic Advice."

https://www.yourmechanic.com/article/how-often-should-brakes-be-replaced (accessed Apr. 19, 2020).

[22]

"Average Annual Miles per Driver by Age Group."

https://www.fhwa.dot.gov/ohim/onh00/bar8.htm (accessed Apr. 19, 2020).

[23]

"How Long Should a Car Last?," *Autolist*. https://www.autolist.com/guides/how-long-should-car-last (accessed Apr. 19, 2020)

[24]

"32kg V4 Submersible Pump," *indiamart.com*. https://www.indiamart.com/proddetail/32kg-v4-submersible-pump-20574484291.html (accessed Apr. 19, 2020).

[25]

"How the G-Wiz Electric Car Works," *HowStuffWorks*, Feb. 20, 2008.

https://auto.howstuffworks.com/g-wiz-electric-car.htm (accessed Apr. 19, 2020).

APPENDIX A: MATHEMATICAL TERMS

1) W = work = energy
2) P = pressure of fully charged tank
3) V2 = final volume
4) V1 = initial volume
5) ΔV = V initial – V final
6) g = grams
7) kg = kilograms
8) kW = kilowatts
9) kPa = kilopascal
10) MPa = megapascal
11) m = metres
12) km = kilometres