PROJECT PROPOSAL

# DESIGN AND SIMULATION OF A SINGLE-LEVER BICYCLE BRAKE WITH HYDRAULIC PRESSURE PROPORTIONING TO MINIMIZE STOPPING DISTANCE

[redacted] | San Jose State University | May 23, 2021

## 1. BACKGROUND AND SIGNIFICANCE

### 1.1 Background

Since the invention of bicycle braking systems around the early 1900s, there has been an individual brake lever for decelerating each wheel, while on cars, there has been a single control to brake multiple wheels. To perform an emergency stop on a bicycle, the rider must proportion hand pressure on each brake lever and simultaneously vary hand pressure throughout the duration of the maneuver [1]. Even the most experienced bicycle riders do not achieve the minimum stopping distance performance of their bicycle, whereas a driver in a car, can achieve the minimum stopping distance of their vehicle simply by pressing firmly on the brake pedal.

### 1.2 Literature

#### *1.2.1 How users currently proportion each brake lever*

A study involving six participants riding electronically assisted bicycles for a total of 32.5 hours in a natural setting analyzed 1566 braking events. On average, for routine braking, both levers were used during 11.7% of the braking events and that figure increased to 43.5% for unexpected braking events with four out of six of the riders preferring to use the rear brake only. The peak deceleration rates, averaged over all six participants was $1.56 \pm 0.69$ m/s$^2$. This is much below that of the maximum deceleration at pitch over which was calculated to be in the range of 5.4 m/s$^2$ to 7.0 m/s$^2$ [2]. A separate study by the same authors also showed that when riding an electronic bicycle versus a non-assisted bicycle, users rode 2.9 km/h to 5.0 km/h faster and were 1.72 times more likely to have an unexpected braking event [3]. To compound issues, bicycle laws vary by country, for example, England requires the front brake lever to be on the right side of the handlebar whereas the United States requires the front brake lever to be on the left [4]. A rider proportioning the wrong lever could be severely injured.

### *1.2.2 Numerical simulation of longitudinal bicycle braking dynamics*

A bicycle with a 40/60 front to rear weight distribution, 1.067 m wheelbase and 1.143 m center of gravity height, decelerating at 4.91 m/s$^2$ can only apply 10% of the total braking force at the rear wheel before lockup occurs. More than twice the braking distance is required with rear-only braking when compared with front only braking, further magnifying the issues with rear-only braking [1]. Closed-form solutions exist to predict the stopping distance for different brake balances which account for friction coefficients, road gradients, bicycle parameters, rider parameters, inertia, aerodynamic drag and reaction times [5]. These two studies approximated the bicycle and rider as a rigid body. In contrast, a multibody simulation provides a more complete, although more complicated, solution by treating the bicycle and rider as a series of rigid bodies and joints with the potential of adding springs and dampers at the joints. An extensive bicycle multibody simulation with 28 separate bodies and 31 joints was conducted in Simscape (Simulink Simscape, The MathWorks, Inc., Natick, Massachusetts, USA). Results for three separate tests were compared to field experiments which specifically targeted strong braking maneuvers, tip-over motion (where the rider is pitched over the front wheel due to excessive front wheel deceleration), and front wheel lockup [6]. A multibody simulation using the same software, but with only five bodies and three revolute joints, was used to evaluate the effectiveness of preventing tip-over through seat post actuation, fork anti-dive control and front brake pressure control [7]. From these studies it is clear that a multibody simulation is advantageous when investigating the specific mechanism of tip-over, but the extra level of complexity may be unnecessary when tip-over is not a concern.

### *1.2.3 Numerical simulation of hydraulic bicycle brake systems*

Research demonstrates that multidomain physical simulation software can also be used to simulate hydraulic brake systems and run test bench hardware with hydraulic pressure sensors to collect results. As shown in figure 1, the interdependence

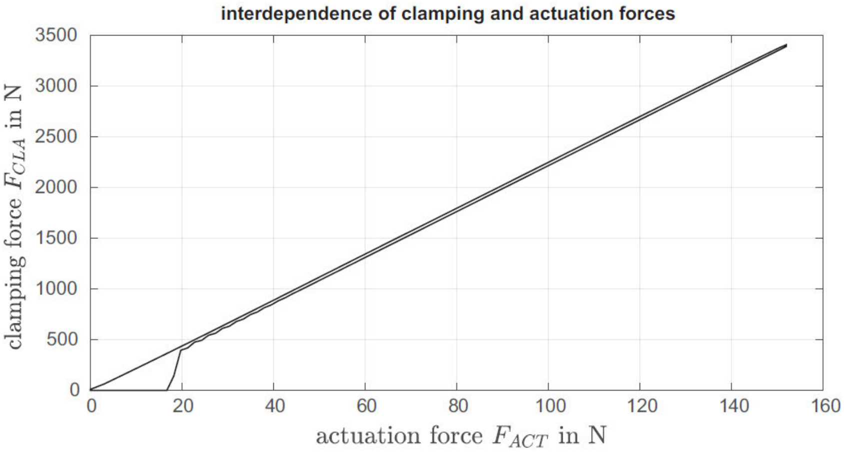


*Figure 1. Hysteresis loop between brake lever actuation force and brake caliper clamping force due to the caliper air gap and system expansion [8].*

between lever and caliper force demonstrates how the air gap between the pads and system volume expansion must be considered [8]. Additionally, a bicycle can be instrumented with brake pressure, wheel speed, longitudinal acceleration and vertical position sensors, then ridden in a natural environment. The numerical information gathered from these sensors can be used in the development of a braking control algorithm [9]. Having an accurate simulation of the braking system is essential in modeling the entire braking process, from lever to tire.

### *1.2.4 Using haptic feedback to regulate brake lever force*

Brake pressure modulation and proportioning can be achieved by providing haptic feedback for the rider in the form of an oscillating offset weight on the brake lever which vibrates when the rider reaches a preset deceleration rate. Results from testing with haptic feedback set at 3 $m/s^2$ up to 6 $m/s^2$ show that a rider sensing the vibration can accurately modulate their deceleration rates which decreases their time spent in the tip-over deceleration region for all tests [10]. A patent filed by the authors two years earlier details the sensors, vibratory actuators and control software needed to communicate the braking limit to the rider [10]. When properly used by experienced riders, this system could decrease stopping distances. This system could also be used to train novice riders on the proper proportioning ratio of front to rear brake application force.

### *1.2.5 Braking torque applied during bicycle battery regeneration*

It is important to quantify the braking torque provided by regenerative braking when developing front and rear proportioning for electrically assisted bikes (e-bikes). Testing on brushless DC motors shows a max regenerative torque of 13 N•m at 50 r/min (100% load) resulting in 11 W of braking power. This provides a correlation of torque and angular velocity down to 0% load [11]. Another study provides a closed-form solution for stopping power based on specific voltage and current measurements, but also outlines a control algorithm where regeneration power is based on a rider's desired braking torque [12].

## 1.3 Related patents

### *1.3.1 Single-lever bicycle brake patents*

A patent from 1969 describes a single hydraulic brake lever actuating two rim brakes with a reservoir that provides a fail-safe in the event that one of the lines becomes damaged. This does not include an option to proportion each brake individually [13]. A

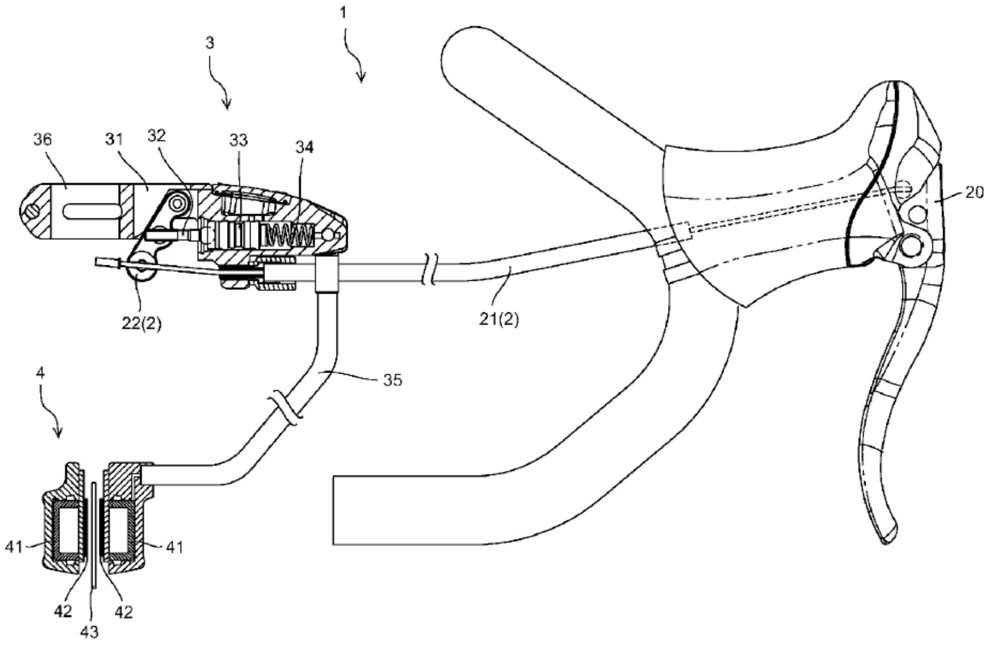


*Figure 2. A patent of a cable actuated master cylinder demonstrates the possibility of combining the master cylinder with the proportioning device [15].*

single lever with a cable-actuated bicycle brake and a proportioning system actively adjusted by the force applied on the rear brake caliper was patented in 1978, but it does not work with disc brakes [14]. Another single-lever cable actuated design works with hydraulic disc brakes by separating the master cylinder from the brake lever thus allowing for a single lever to actuate both brakes, but no mention of front and rear bias proportioning is made in the patent (figure 2) [15].

### *1.3.2 Bicycle brake proportioning patents*

A patent issued in February of 2021 describes a hydraulic braking system with a passive binary proportioning system in which hydraulic pressure to the front brake is only supplied when there is braking force on the rear wheel. This prevents tip-over by inhibiting brake pressure on the front wheel when the rear wheel loses ground contact [16]. This might result in shorter stopping distances on high friction surfaces without a need for rider proportioning, but it does not prevent rear wheel locking and requires two brake levers. Two surprisingly similar patents from 2001 and 2003, describe a hydraulic brake system that proportions the pressure between both brake levers using a hydraulic pressure balancing reservoir between the levers and calipers. These systems deliver the same pressure to both

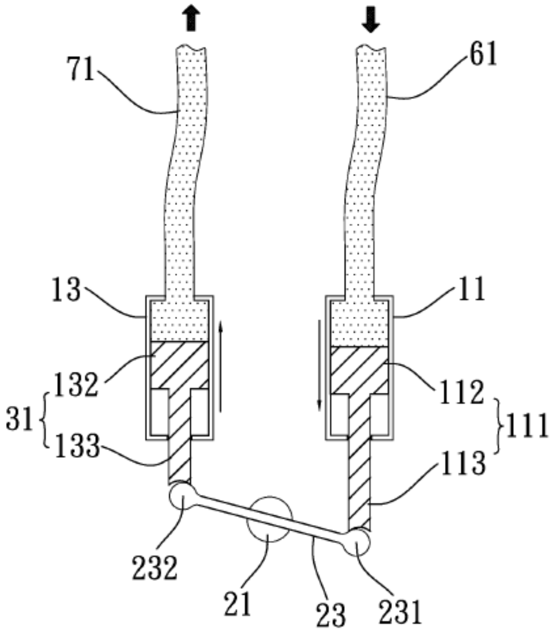


*Figure 3. A patent from 2017 illustrates a proportioning device with an adjustable pivot arm [19].*

front and rear brakes regardless of the pressure distribution at the levers [17,18]. This likely would provide protection from tip-over, but it would cause stopping distances to increase and includes two brake levers. A similar invention, described in a patent issued in 2017, improves upon the proportioning designs from 2001 and 2003 by incorporating a lever arm [19]. Moving the pivot location of this lever arm would allow changes in the proportioning balance between the front and wheels.

## 1.4 Significance

In 2019, the Centers for Disease Control and Prevention estimated that 329,000 Americans were injured in cycling related incidents [20]. If a system that simplifies the braking process and decreases stopping distances can prevent a small fraction of these injuries, then a large impact on bicycle safety can be made. Bicycle sales have been growing exponentially since 2006, with the quantity of e-bikes outpacing traditional bikes [21]. Due to the higher speed and mass of e-bikes, the required stopping distances can greatly increase, leading to more injuries. However, e-bikes are particularly suited for brake proportioning technologies because not only are they faster and heavier, they also have a lower center of mass, hydraulic disc brakes, regenerative braking and integrated electronic control systems.

# 2. OBJECTIVES

## 2.1 Objective statement

The objective of this project is to simulate and prototype a hydraulic, single-lever bicycle brake system integrating front and rear brake proportioning which minimizes stopping distance compared to dual-lever simulations. The simulated stopping distance will be corroborated with independent, external field test results. The simulated front and rear brake caliper force as a function of lever force will be validated with sensor data from the stand-alone prototype.

### *2.1.1 Design specifications*

The prototype shall exceed all Consumer Product Safety Commission requirements as defined in the Code of Federal Regulations section 16 CFR 1512.5(b). These requirements include a minimum 445 N lever force, 4.57 m stopping distance and a 44.5 N minimum lever operating force [4]. The complete prototype braking system shall not weight more than two kilograms.

## 2.2 Evaluation metrics

The two design related evaluation metrics are the shortest simulated stopping distance for the prototype single-lever hydraulic brake system with proportioning and the lightest total brake system weight for the physical prototype.

# 3. METHODOLOGY

## 3.1 Approach

The initial step will be to develop the bicycle braking simulation in Simulink. The next step will be to ensure that there is corroboration between the simulation and the derived equations of motion. This will be further corroborated by comparison to external, independent test results of a bicycle performing a decelerating maneuver. Concurrently, a simulation of the hydraulic proportioning device in Simscape Hydraulics will be used to identify the physical parameters which maximize the ratio of caliper to lever force. This will be corroborated against static fluid calculations. Once both simulations have been corroborated they can be combined into a single Simulink model and the proportioning parameters can be further refined with the objective to minimize stopping distances. These parameters will then be transferred to a CAD model of the prototype proportioning device in SOLIDWORKS (Dassault Systémes, Vélizy-Villacoublay, France). During the

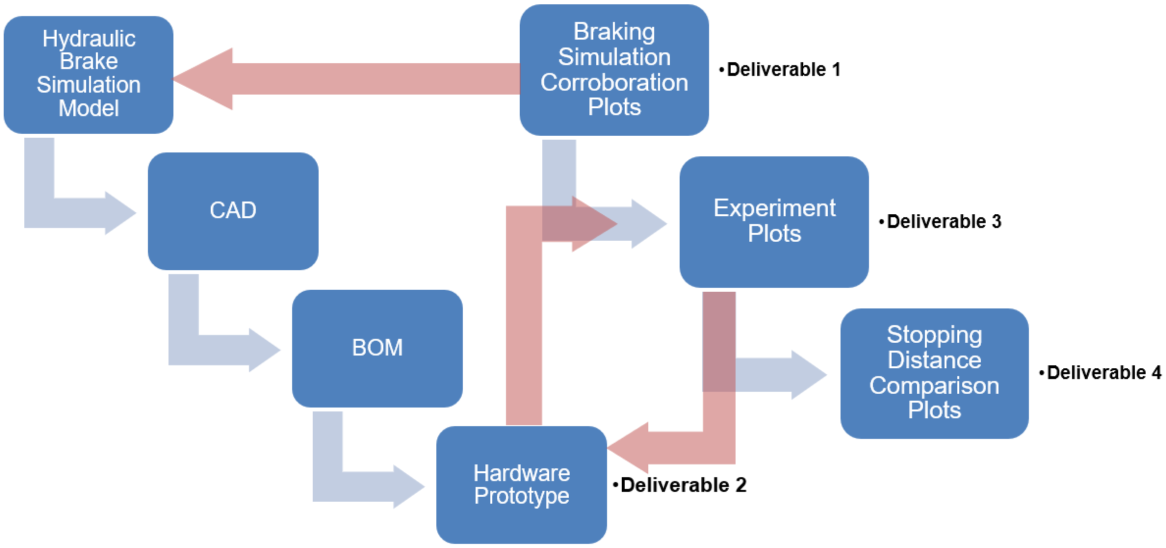


*Figure 4. Outline showing the hardware prototype process flow on the left and simulation process flow on the right with the red arrows indicating interdependencies.*

process of building the CAD model, the necessary parts, such as o-rings, fittings, and machining billet can be selected and ordered. Using drawings created from the CAD model, the prototype will be fabricated at the SJSU Central Machine Shop. The proportioning device will be combined with a consumer brake system and instrumented with both lever force and caliper force measurement devices. Once this is complete, experiments will be run on the fabricated prototype (see experiment plans for additional details). If no further iterations of the prototype are needed, the braking simulation will be updated with the experimental caliper to lever force relationship and the simulated stopping distance for a single-lever bicycle with proportioning and a dual-lever bicycle without proportioning will be compared.

### 3.2 Experiment Plans

The prototype braking system will consist of a brake lever, two brake calipers and a proportioning device. Force sensors will need to measure lever application force and the clamping force of both calipers. The experiment will start by applying and measuring a continuously increasing load to the brake lever. The front and rear caliper clamping force will be measured during the lever load application. The level of pressure proportioning between each caliper will be varied between runs and multiple runs will be conducted for each setting. The wheel and brake rotor are not included in this section of the experiment because the short-term relationship between clamping force and braking torque would not change with varying levels of proportioning. The relationship between lever force and braking torque will be measured by rotating a mass of known inertia (preferably the same as a bike and rider system) and using a rotary encoder to measure the rotational velocity.

By applying a set brake lever force then measuring the change in rotational velocity of the mass, a braking torque can be calculated and the simulation model can be compared and updated.

## 3.3 Resources

The estimated resources needed for this project, along with the dates needed and costs are shown in table 1. The SJSU Central Machine Shop will be a vital resource to machine the proportioning device from the aluminum billet. Depending on the prototype complexity, machine shop priorities, and lead times, a new fabrication resource may need to be procured (see risks and contingencies below). To keep cost and complexity low, a standard consumer available brake system will be used in conjunction with the proportioning device to create a brake system with a single brake lever. This may necessitate a variety of hydraulic fittings, adapters, and hoses to mate with the proportioning device.

*Table 1. Required resources with estimated costs and timeline.*

| **Resource** | **Deadline** | **Cost ($)** |
|---|---|---|
| SJSU Central Machine Shop CNC Mill. | Sep 2021 | 300 |
| Test stand materials. | Sep 2021 | 184 |
| Steel cylindrical billet. | Sep 2021 | 60 |
| Aluminum billet. | Sep 2021 | 82 |
| Measurement devices which fit within a standard bicycle brake caliper. | Nov 2021 | 600 |
| Measurement device which can record lever pull force. | Nov 2021 | 500 |
| Standard consumer hydraulic brake levers, calipers and rotors. | Aug 2021 | 320 |
| Hydraulic fittings, lines, seals, and oil. | Oct 2021 | 80 |
| Arduino UNO, HX711 load cell amplifier and associated hardware. | Nov 2021 | 60 |
|  | **Total** | **2186** |

## 3.4 Risks and Contingencies

The largest potential risk is machine shop lead time due to the number of tasks dependent on the prototype proportioning device. If the SJSU machine shop lead time poses a risk to the project deadline, then quotes from outside machine shops will be solicited. This may incur additional costs depending on the prototype complexity, however, if the prototype is simple to fabricate, then it may be fabricated at a Makerspace or other do-it-yourself type facility. Inquiring on machine shop availability and ability to fabricate the prototype early in the semester will be essential to mitigating this risk. Using a standard consumer brake lever and caliper for a single-lever design can pose a risk as there may not be enough fluid displacement from a single lever to supply the movement of two separate brake calipers. One possible contingency is to add spacers to the load cell to limit free space movement of the caliper pistons. Another option would be to find a lever with the most fluid displacement and a caliper with the least fluid supply requirements. The proportioning device may also pose fluid displacement concerns, in which case, an additional fluid reservoir can be designed into the device. A consumer hydraulic brake lever and caliper may be difficult to acquire due to the bike component shortage caused by the recent demand surge in bicycles. Finding a salvage bike with functioning used brake components may be a contingency in extreme circumstances. Lastly, there may be time constraints due to my plan of reentering the workforce next semester. My contingency is to only take ME-295 next semester if career schedules become time intensive.

# 4. DELIVERABLES

## 4.1 Plots corroborating the simulated stopping distances against external field test results and simulation results for a dual-lever bicycle with hydraulic disc brakes.

### *4.1.1 Locate independent, external field test results and simulation results*

### *4.1.2 Assemble a simulation model in Simulink*

### *4.1.3 Derive longitudinal equations of motion for a bicycle*

### *4.1.4 Conduct tests, compare results, and interpret discrepancies*

The independent, external field test dataset must include all the information necessary to replicate the results in Simulink. The derived equations of motion will be used to validate the simulation results.

## 4.2 A stand-alone hardware prototype of a hydraulic single-lever bicycle brake system with front and rear brake proportioning including a brake lever, brake calipers and a proportioning device.

### *4.2.1 Assemble hydraulic brake pressure model with proportioning*

### *4.2.2 Build CAD model of the proportioning system*

### *4.2.3 Identify and order parts necessary materials*

### *4.2.4 Fabricate physical prototype*

The CAD model will help in adjusting flow and pressure parameters to minimize stopping distances and maximize the brake caliper to lever force ratio. The selected parameters and desired results can be checked with fluid statics calculations. Prototype manufacturing drawings with geometric dimensioning and tolerancing will be sent to the SJSU Central Machine Shop for fabrication. Iterations on the physical prototype may be necessary therefore communication with the Central Machine Shop will begin as soon as the brake pressure model is started.

## 4.3 Plots showing both caliper force and braking torque as a function of lever force for a single-lever brake system including a prototype proportioning device.

### *4.3.1 Assemble test bench with rotating mass and frame*

### *4.3.2 Specify and order experimental measurement hardware*

### *4.3.3 Conduct caliper force and braking torque tests*

### *4.3.4 Determine if the prototype needs a modification*

Tests of the corresponding front and rear caliper compression force for a given lever actuation force will demonstrate the relationship between front and rear braking force for varying levels of proportioning with the prototype proportioning device. Decelerating a rotating mass of known inertia will provide a lever force to brake torque relationship.

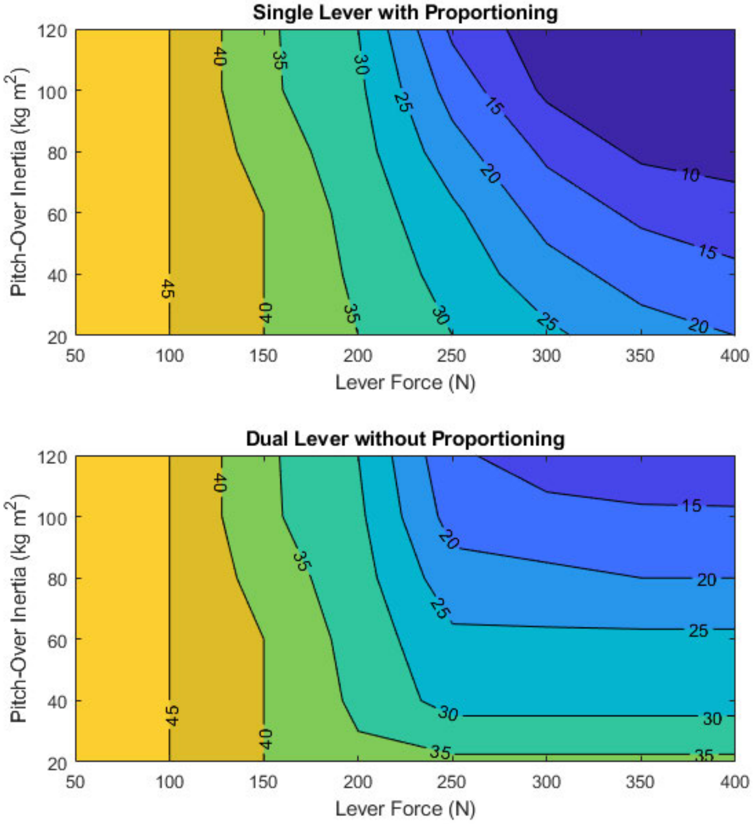
## 4.4 Plots of numerically simulated stopping distance for a given lever force, rider weight, center of mass and coefficient of friction comparing a single-lever brake system with proportioning and a dual-lever brake system without proportioning.

### *4.4.1 Adjust Simulink braking simulation model*

### *4.4.2 Conduct simulation runs*

### *4.4.3 Compare the stopping distance simulations of single and dual lever systems*

The braking simulation model will be updated to include the relationship between caliper and lever force found in task 3.4 for single-lever braking with proportioning. Using this updated model, a batch of simulation runs will be conducted varying rider mass, location of the center of mass, coefficient of friction and lever force for both single-lever and dual-lever systems. Plotted as a contour map, these results will illustrate the advantages and disadvantages of single-lever and dual-lever brake systems for a variety of scenarios.

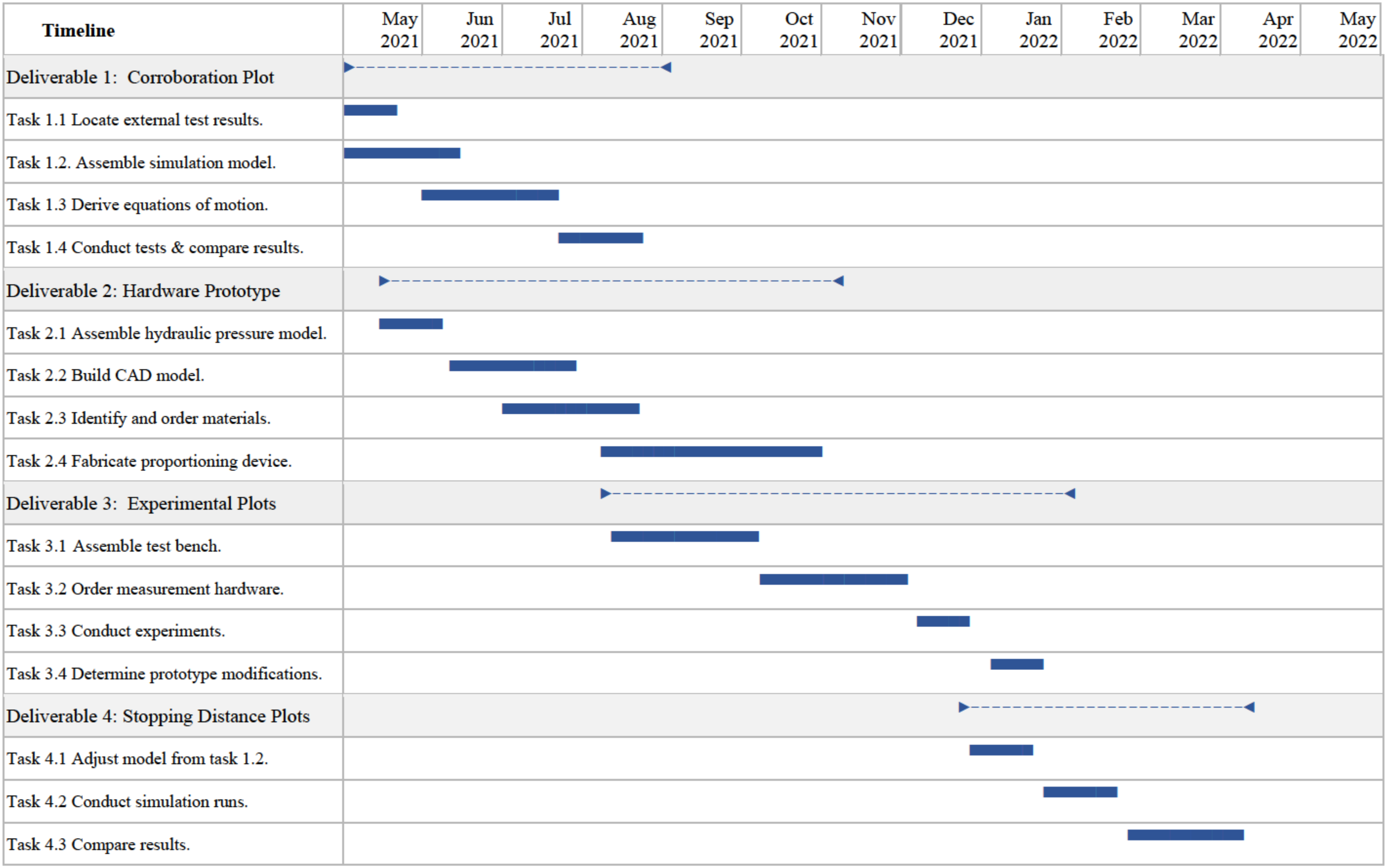

Single Lever with Proportioning

Dual Lever without Proportioning

*Figure 5. These data are not real. Sample plot of the stopping distances as a function of lever force for single and dual-lever brake systems.*

## 5. TIMELINE

The table on the next page shows the anticipated start and completion dates for the four deliverables and the associated tasks. The first two deliverables were started during the preliminary work phase and extra time is given at the end of the timeline for project scope creep and report writing.


Timeline
May 2021
Jun 2021
Jul 2021
Aug 2021
Sep 2021
Oct 2021
Nov 2021
Dec 2021
Jan 2022
Feb 2022
Mar 2022
Apr 2022
May 2022
Deliverable 1: Corroboration Plot
Task 1.1 Locate external test results.
Task 1.2. Assemble simulation model.
Task 1.3 Derive equations of motion.
Task 1.4 Conduct tests & compare results.
Deliverable 2: Hardware Prototype
Task 2.1 Assemble hydraulic pressure model.
Task 2.2 Build CAD model.
Task 2.3 Identify and order materials.
Task 2.4 Fabricate proportioning device.
Deliverable 3: Experimental Plots
Task 3.1 Assemble test bench.
Task 3.2 Order measurement hardware.
Task 3.3 Conduct experiments.
Task 3.4 Determine prototype modifications.
Deliverable 4: Stopping Distance Plots
Task 4.1 Adjust model from task 1.2.
Task 4.2 Conduct simulation runs.
Task 4.3 Compare results.

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