



## Regenerative Braking System on a Conventional Bike

**Dr. Bala Maheswaran, Northeastern University**

Bala Maheswaran, PhD Northeastern University 367 Snell Engineering Center Boston, MA 02115

**Mr. Nicolas Berna Tedori**

**Mr. Eamon J. Whitmore, Northeastern University**

Current sophomore in the Civil Engineering program of Northeastern University's College of Engineering with a small background in physical mechanics from working with racing karts.

**Miss Bailey L. Ritchie**

**Mr. Logan Gross, Northeastern University**

Second year Mechanical Engineering student at Northeastern University. Passion for entrepreneurship, finance, and the culinary arts.

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Logan Gross, Bailey Ritchie, Nicolas Tedori, Eamon Whitmore, and Bala Maheswaran  
College of Engineering  
Northeastern University

## Abstract

As the world's supply of natural resources diminishes, the quest for renewable energy solutions is becoming more and more critical. To help curb the use of non-renewable energy sources, scientist and engineers are tasked with the challenge of finding alternative energies. One of these alternative sources is recovering energy lost to mechanical systems, which could counteract the world's energy shortage. Regenerative braking has already been implemented in hybrid and electric vehicles; however, this paper introduces a regenerative braking system specifically for the conventional, every-day bike. The RE-Brake system recaptures energy that would normally be lost to friction by replacing a conventional caliper brake with a rotating disk that runs along a bike tire's metallic rim, spinning an electric generator. This recovered energy could be used to power a mobile electronic device. Since hundreds of thousands of people rely on bicycles as their primary method of transportation, RE-Brake, a cheap and user-friendly replacement to caliper brakes, could be used to recover a vast amount of energy and serve as an approach to offset the global energy crisis, but provides society with a cheap and user-friendly product is unprecedented. The skills learned from this project were invaluable, as research, design, trial and error, as well as technical writing are all important experiences within engineering. This brake not only provides scientists and researchers with more valuable information about alternative energy, but is also capable of educating the everyday person about the basics of engineering as well as the importance of renewable resources.

## Introduction

This paper shares a sample project illustrating a new teaching approach via innovation. One of the objectives of the Experiential Engineering Education<sup>1-4</sup> and this paper is to reform engineering education by moving away from the boundaries of traditional classroom-based approaches to project- concept- and team-based, and skill- and knowledge-integrated approaches using real world situations. This new teaching approach can improve the effectiveness of engineering education.

We develop an innovative teaching approach for the newly designed eight credit hour cornerstone course for the first year engineering students. This method is very effective and well-suited to educate our students. Rather than just studying for exams to gain good grades, this skill- and knowledge-integrated approaches help highly motivated students to interact with other students and faculties from various institutions and take further strides towards real world situations.

References 5-8 represent four team papers (which includes sixteen students) published in peer reviewed conference proceedings<sup>5-8</sup>. Briefly, these papers outline this theme based teaching approach, in which each team needs to identify an energy system and innovate it. Each team has about four members, and worked on the experiential learning project for about 10-12 weeks. This paper describes the Regenerative Braking System on a Conventional Bike. We hope that the benefits of this teaching approach shown using this sample project-based learning could serve as a model for other educators.

As the world shifts from its use of natural resources to renewable energy, the need for renewable energy solutions has increased rapidly<sup>9</sup>. The Hybrid and Electric vehicles market has greatly expanded allowing more consumers to use both petroleum energy as well as electricity in their daily lives. For example, Tesla's Roadster model currently uses regenerative braking, where regenerative braking energy<sup>10</sup> is defined as "the conversion of the vehicle's kinetic energy into chemical energy stored in the battery". Within most of these vehicles is a system known as regenerative braking, where energy that would normally be lost to friction is converted into electricity by the motor. As the regenerative brake is being applied, the forward movement of the car is slowed and the motor essentially begins acting like a generator. In other words, the energy from the acceleration of the vehicle is absorbed into the reverse direction, which in turn, slows the car down at a constant steady speed. Although this process is much different to that of a bike the same methodology can be applied to recover frictional energy losses from riding a bike. Since 2000, bicycle commuting has grown immensely across the United States proving that the number of people who would benefit from regenerative braking is increasing every year (The League of American Bicyclists, 2013)<sup>11</sup>.

A general understanding of brakes need to be attained before continuing further with this issue. Our research on hybrid and electric vehicles, as well as brakes themselves, helped us formulate a clear goal for our project. Brakes on a bicycle work in a similar manner to those of a car, in that, pads are used to generate friction, for a bike this would be the tire rim, and for cars friction would be applied on the brake disk. However, the problem with trying to apply regenerative braking to a bicycle is that no motor exists that is capable of driving the bike in the forward direction as well as the backwards. In other words, an external motor would need to be implemented in order to collect energy from the bike. The emergence of smartphones<sup>12</sup> and mobile technology has also impacted our world greatly. With these new technologies we are able to send and receive information at an unforeseen rate, but our reliance on these devices has grown tremendously. As smartphones become more and more of a necessity to the average college student and employee (MacKay, 2009)<sup>13</sup>, there exists a greater need to keep these devices constantly charged.

We sought to solve both these dilemmas. We needed to apply a motor to the braking system to act similarly to the way the electric motor works in a hybrid cars, thus began the invention of the RE-Brake. The RE-Brake is a braking system that attaches to the front of most conventional bikes, and with a bit of assembly and rearranging, the frictional brake is transformed into an energy-harvesting brake that can be used to charge your USB device.

## **Method and Approach**

The engineering design process was used to identify a need for RE-Brake as well as the course of action to build such a device. We knew that a large amount of energy was being lost through friction, and given the large portion of Americans that ride bicycles today, implementing a regenerative brake could recover a large amount of energy that would otherwise have been lost to the surroundings. However, the real problem was finding a way we could effectively apply a regenerative brake to various types of conventional bikes. The feasibility of a brake had to be analyzed as well to ensure that the brake would be able to safely stop a person on their bike. Would

the brake even be able to generate sufficient energy to power a mobile device? With this question in mind, we needed to calculate and theorize the energy received from our device.

This analyzation was done through extensive research into the physics and implementation of both conventional and regenerative brake systems on both cars and bikes. Before the initial design (Figure 1) of the RE-Brake system was considered, calculations were made based on biking statistics and other energy data to determine how much energy could be gained from such a device. These calculations were done using a few pieces of information, primarily the energy lost when a 73-kg person is riding a 10-kg bike at 4.4 m/s. The calculation was done using,

$$E = \frac{1}{2}mv^2$$

where the mass would be the total of mass of the rider and the bike. The energy of this system was found to be about 803 joules, if the rider has a velocity of 4.4 m/s (MacKay, 2009)<sup>13</sup>. This is significant because depending on how many times the rider brakes; enough energy could be recaptured to charge a phone or external battery. For example, an average hypothesized that not only the spokes, but the gear would not be able to withstand the force of braking for too long without damage. Additionally, the thermoelectric generators would have needed a system to place them in contact with the wheel after braking to reclaim some of the energy lost to heat; it would have been an expensive and time consuming process to create such a system, so the entire design was altered.

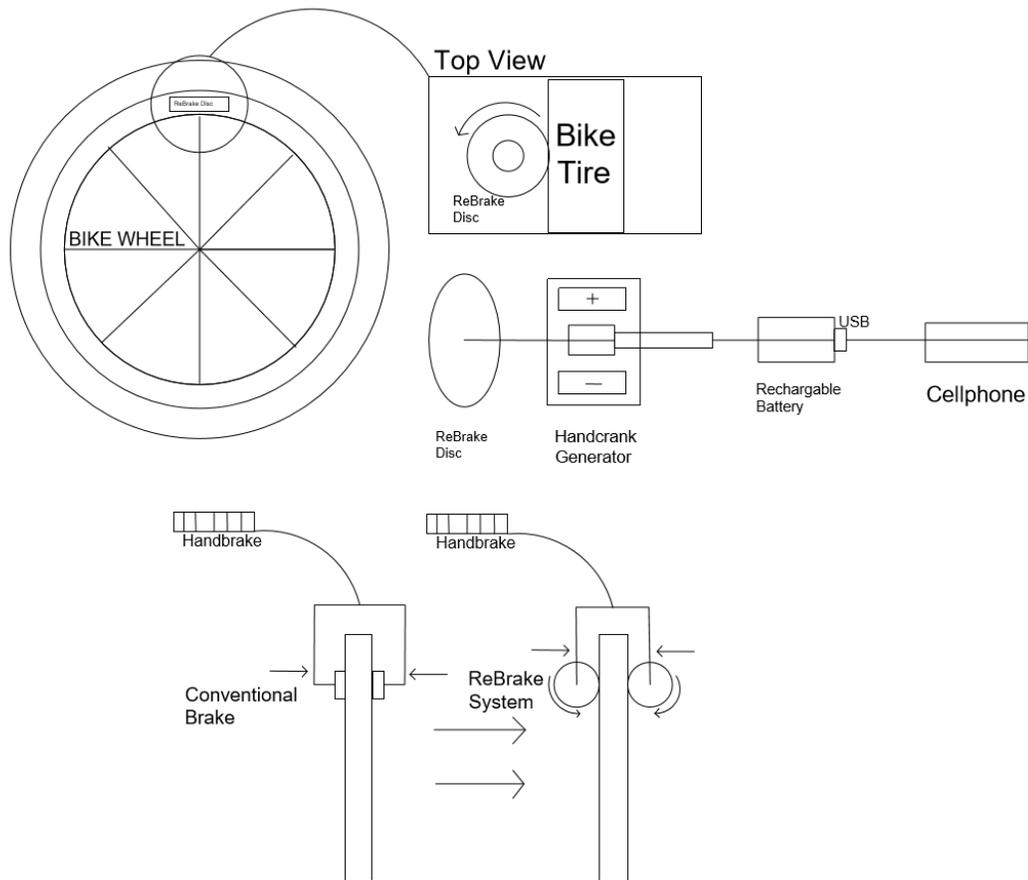


Figure 1 – Initial Design diagram

One of the biggest alterations made was the use of the blades from a plastic desk fan against a bike tire to turn an electric motor. This design failed as well due to the weakness of the plastic of the blades. Although, the choice to use fan blades was changed, the next design used the idea of running a smaller wheel against the tire. This next design planned to run a gear against the tire of the bike, without the thermoelectric generators. This was a much safer idea since the pieces would be running against the tire instead of the delicate spokes. However, this design was still not without its flaws. To increase friction and traction between the wheel of the generator and the tire, the generator wheel would have required teeth, which would have worn out the tire faster than normal due to the increased damages done by the frictional forces between the gear and the tire. Over time, RE-Brake's design evolved, and final changes and adjustments were made for the final design.

### **Design Details**

We struggled with trying to find a material for our device for a long time, once considering applying a rubber coating to plastic, or even finding a wooden material strong enough to withstand the force of braking.

The rotating disk was the most crucial piece to RE-Brake's design. It needed to be strong enough to not shatter, especially when a biker needed to slow down from a high velocity, but also provide the right amount of resistance to stop a biker and spin in conjunction with a generator. The hand-crank, acting as the generator for RE-Brake, was externally resourced from the Internet but was reliable and proved well for our project. It consistently maintained high speeds and provided sufficient resistance within the gears. Fortunately, after many attempted designs, we finally found a wheel that fulfilled our project's high goals and standards. The wheel was originally intended for use on a motorized robot but happened to be the right size, shape and maintained a considerable amount of durability. Consequently, we shifted our focus to plastic materials and went with the resources that our engineering program provided and 3D printed our rotating wheel. We made measurements and tried to fit all our pieces together. The wheel needed to be able to fit a very small metallic rod within its center, which would give it torque and a greater ability to rotate; this would be fit into to the hand crank. However, the hand crank would need to be connected externally through a link, which was fitted with numerous holes in order to screw into the brake holder. The distances to and from each connecting point of our system needed to be carefully measured, and then a plastic link was created within SolidWorks. However, we needed to physically model our device, and thus made wooden cutouts of our pieces, as examples of what would later be 3D printed. This helped us identify exactly how everything would eventually fit together.

RE-Brake needed to be able to recapture energy effectively, but it also needed to be able to store the energy recovered from braking throughout the day. We implemented a dual charging battery, meaning the battery itself could be charged, while the battery was giving charge to another device. A USB would connect the battery to a mobile device, while two spliced input and output wires were connected to the hand-crank. Our final design also consisted of a 3D printed battery case that would fit on the handlebars of a bike and ensure the safety of the battery and the wiring that protruded from it (See Figure 2a-d).

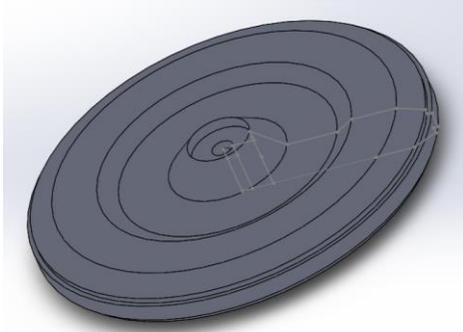


Figure 2a: 3D model of the generator disk

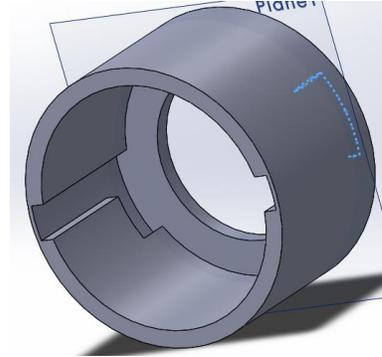


Figure 2c: 3D models of the battery

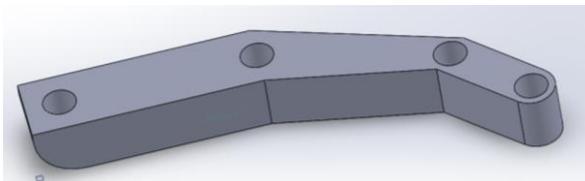


Figure 2b: 3D model of the hand-crank

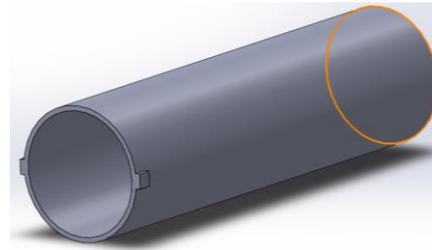


Figure 2d: 3D models of the battery link

through another round of 3D printing, as the holes on the link were too small. Other problems arose, as the metal brake holder would not stay in place and needed to be fitted to the metallic front of the bike. We addressed these problems mostly using zip-ties; often double-looping zip-ties in order to hold everything in place. However, through much persistence, our design could maintain the structural integrity that we desired so that a person can safely ride our bike and brake using RE-Brake.

Although we accomplished most of our goals as we progressed further into our project, upon further examination we realized that RE-Brake could be greatly improved. Although our RE-Brake system worked for us, it lacked portability and was not interchangeable between bikes. We designed RE-Brake specifically for our bike and all the measurements that we took matched our design and layout, however, our next goal would be to make RE-Brake more modular and to have it easily fit on various bikes and models.

Once the RE-Brake system was attached to the bike [Figure 2a-b], three different tests were run. The first test was simply using a light bulb to see if there was any current flowing through the system – if the light bulb did not light up, then a mistake was made. The next test was the initial battery-charging test. This was to determine if the electric motor could be used to charge a battery. The final test was a series of several tests performed using MATLAB and a Sparkfun RedBoard (Figure 3 and Appendix 1). These were used to collect voltage and time data for the system.



Figure 2a: RE-Brake attached to bike



Figure 2b: RE-Brake on a bike

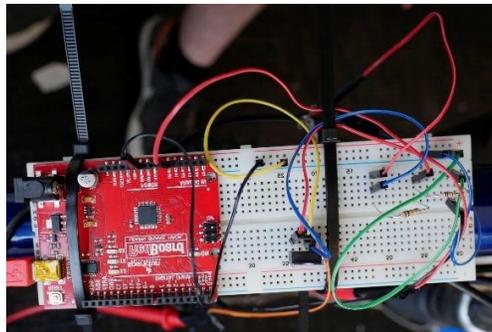


Figure 3: RedBoard Voltmeter

## Results

The first test done using the RE-Brake system was with a 5-volt voltage regulator. This was done primarily to see if the output of the system could be controlled to stay within a usable range that is safe for most small rechargeable electronic devices. The test was performed with the bike moving at a fluctuating velocity, ranging between 0 m/s and 1 m/s [Figure 4a].

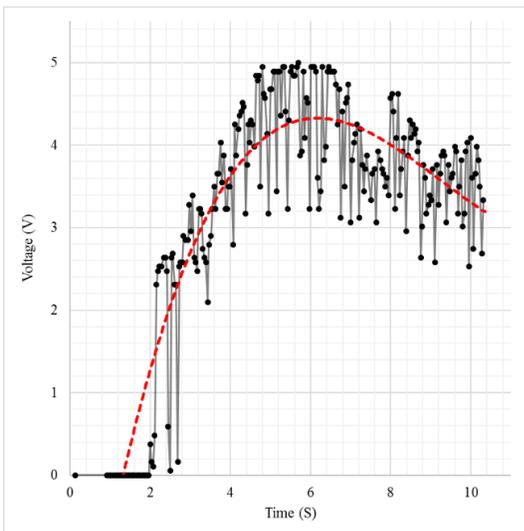


Figure 4a: Voltage of the RE-Brake System with Fluctuating Velocity over a Given Time

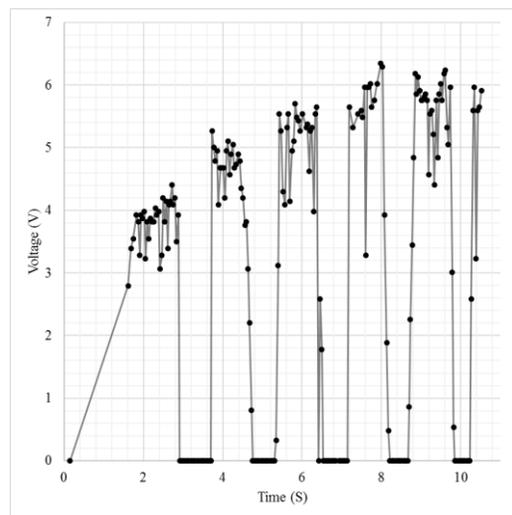


Figure 4b: Voltage of Periodic Braking at 1 m/s

This graph shows that when using a 5-volt voltage regulator, there was a maximum of 5 volts read. In addition to testing with a voltage regulator, two other tests were performed without it. The second test was done over a constant velocity of about 1 m/s with a rider periodically applying the regenerative brake (Figure 4b). Since this was done without a regulator, the maximum voltage obtained was higher. This maximum is about 6.34-volts at about 7.98 seconds. The graph (Figure 4c) shows the voltage received from one complete stop using only the regenerative braking system. This was done with a starting velocity of 2 meters per second.

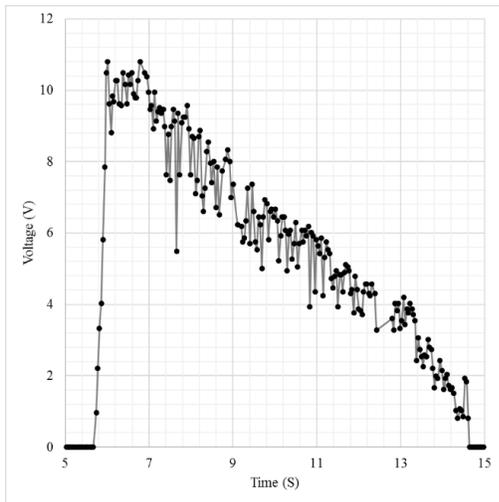


Figure 4c: Voltage of One Complete Stop with  $V_0$  of 2 m/s

|                           |         |
|---------------------------|---------|
| Time braking (s)          | 8.90    |
| Average voltage (V)       | 5.95    |
| Current (A)               | 6.55E-4 |
| Current (mA)              | 0.655   |
| Electrical charge (mAs)   | 5.83    |
| Power (milliwatt-seconds) | 34.66   |
| Energy (J)                | 0.035   |

Table 1 – Values from the complete stop test

Also, the graph Fig. 4c shows that, when unregulated, a maximum voltage of about 10.81 volts can be obtained. This occurs 0.27 seconds after the brake is applied. Additionally, the average voltage of one full stop is about 5.95 volts (Table 1). Given the data from a complete stop, the power can be found. The current, electrical charge, and power can be found using Ohm's Law and the following formulas:

$$I_{avg} = \frac{V_{avg}}{R}$$

$$P = I_{avg} \times V_{avg}$$

$$E = P \times \Delta t$$

This shows that the average voltage is about 5.95 volts for a complete stop when a rider is going 2 m/s (Table 1). Additionally, using the above equations, the electrical current and energy can be found. Given that an average phone battery has a capacity of 1866 mAh (Social Compare, 2017)<sup>14</sup>, it would take approximately  $1.03 \times 10^7$  seconds of continuous braking at 2 m/s to completely charge a phone battery.

## Discussion

Although this regenerative braking system should be getting approximately 803 joules of energy back, this initial calculation assumes that the only system removing energy is that of the regenerative brake. This is not true since given current standards and technology, most regenerative braking systems are around 40% efficient (Lampton, 2009)<sup>15</sup>. Since this efficiency

number is for precisely machined cars, it can be assumed that the efficiency of RE-Brake is below that. However, RE-Brake's efficiency can be calculated by taking the actual energy output and dividing that by the expected energy output and multiplying by 100. This result was found to be quite small at  $5.45 \times 10^{-5} \%$  (appendix 2)<sup>16</sup> for the RE-Brake system.

However, there are a lot more forces acting on a bike than just the friction between the RE-Brake system and the tire rim. For example, there are the frictional forces between the ground and tire that would be removing energy from bike and the material of the ground would change the amount of friction as well, possibly increasing friction between the tire and ground. Therefore, the efficiency for our current RE-Brake model is not accurate, since the assumption for the initial recovered energy is wrong. Regardless, this shows that our model still needs improvements to, as recapturing more energy is always desired.

The first of these improvements is the motor. Although the use of a preassembled hand-crank reduced the time required to build the system, the system could benefit from a higher quality motor. Specifically, a motor with a higher voltage output, higher torque, and lower revolutions per minute – these changes would increase energy output and decrease the time required to stop.

Another change to the system would be to move the electricity produced straight to an electronic device being charged. Given that the average resistance for a USB cord is about 0.03 ohms (Gough, 2014)<sup>17</sup>, the calculations could be altered using that value (instead of the value for the resistors used in the voltmeter circuit) and the time for when the average voltage is more than or equal to 5 volts. This would greatly change how much power can be obtained from the system; however, this is in part due to the difference of the resistance of both systems. For example, when a rechargeable battery is connected directly to the RE-Brake system, the battery does begin to charge when a rider engages the regenerative brake.

This work focuses on the reduction of energy loss through friction, and requires the use of an external wheel in order to slow down the bike. In the front end of the bike, RE-Brake will be installed, however, for safety reasons, the back end of the bike will only contain a regular friction brake. This needed to be implemented as a backup, in case that the rider sees an obstacle ahead and makes the decision that it is not possible to use RE-Brake. Additionally, if RE-Brake fails at any point, the rider will still have control over their vehicle. The decision to still maintain a back brake was in light of the ethical responsibility that our device needed to uphold. Eliminating the rear friction brake, would possibly mean forgoing the safety and well-being of not only the rider, but their surrounding environment. Although more regenerative energy could be recovered from having two regenerative braking systems, ethical decision making needed to take place in order to safeguard the welfare of the public.

The quality of the materials and their reliability are also vital to the rider and the environment. If the quality of the material was not as high, and broke under great force of pressure, the device is not be reliable and could not keep the rider safe. Although minimizing cost is important, ensuring the safety and well-being of society is the standard that all engineers should strive meet. Furthermore, we took these implications into consideration and withheld the highest standard of safety throughout our entire project.

## Conclusions

Our tests show that the RE-Brake can recover energy, and safely store it in an external battery. However, in order to recover enough energy to truly negate the global energy crisis, the regenerative braking system would have to be deployed in a large scale and most, if not all, bike riders would have to regularly use it. Although there are still points of improvement for the RE-Brake, but we have gained a multitude of valuable experiences that have shaped our view of engineering and educated us on the importance of persistence and collaboration. Our project provided us with a large array of skills from research, design and construction as well as testing and technical writing. Additionally, collaboration was extremely important to this project as we learned how to communicate with different people and engineers as well as discovered how to spend our time the most effectively. According to our data, if the changes were made to the system, as mentioned previously, wide spread implementation of the RE-Brake could be possible. This could lead to future innovations in regenerative braking technology, not only in bikes, but many other forms of transportation.

## Acknowledgement

The authors would like to express their sincere thanks to Dr. Donald Goldthwaite and the First year Engineering Learning and Innovation Center and Lab Assistants for their support during this project and making the prototype in the lab.

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## Appendix I

```
clear
clc

a = arduino('COM4', 'uno'); % Replace 'COM4' with what port Arduino is
communicating through (check Arduino IDE)
end_time = 0;
ticker = 1;
user_time = 0;
x = 0;

%% Input from the user.
user_time = input('Enter time to test voltage for (seconds): ');
fprintf('\nRunning, please be patient...')

%% Counts down before reading volatge.
for cDwn = 3:-1:0
    fprintf('\nTest in %0.0f seconds...',cDwn)
    if cDwn == 0
        fprintf('Begin testing!')
    else
        pause(1);
    end
end

%% Start timer to control when the while loop will end.
start = tic;
% Loops until user-defined time.
while end_time <= user_time
    voltage_output = readVoltage(a, 'A0');
    v = voltage_output*10;
    % Arrays for the voltage output and time
    voltage_val(ticker,1) = voltage_output;
    t(ticker,1) = toc(start);
    % This is to draw a graph live.
    figure(1)
    x = [x,v];
    plot(x,'b-')
    title('Voltage - FOR REFERENCE ONLY')
    xlabel('t (20 ms)')
    ylabel('Voltage(v)')
    grid;
    drawnow;
```

```

% Controls the looping of the function
    ticker = ticker + 1;
end_time = round(toc(start));
end

% Converts voltages and outputs to a graph
voltage_val = voltage_val*11; % 10:1 voltage splitter, ergo 10+1 = 11.
figure(2)
plot(t,voltage_val,'r-')
axis([0,max(t),max(voltage_val),6]);
grid;
xlabel('Time(s)'); ylabel('Voltage(V)');
title('Output Voltage from RE-Brake Generator, 1.0');

%% Exports Data to Excel File
% Remember to change name of the file as not to overwrite previously
% written data.
for row = 1:1:length(voltage_val)
    TV(row,2) = voltage_val(row,1);
    TV(row,1) = t(row,1);
end

xlswrite('voltage_time_data_X.xlsx',TV); % MUST REPLACE THE OUTPUT FILE
NAME TO PREVENT THE OVERWRITING OF DATA.

```

## Appendix 2:

### Phone Battery Calculation

Average phone battery capacity = 1866 mAh at 4.2 V (Social Compare, 2017)

$$1.866 \text{ Ah} \times 3600 \text{ s} = 6717.6 \text{ coulombs}$$

$$\frac{1}{2} \times Q \times V = \frac{1}{2} \times 6717.6 \times 4.2 = 14106.96 \text{ joules}$$

### Efficiency Calculation

$$\text{Efficiency} = \frac{\text{Actual output}}{\text{Expected output}} \times 100$$

$$\text{Efficiency} = \frac{4.37 \times 10^{-4}}{806} \times 100 \approx 5.45 \times 10^{-5} \%$$

### USB Cord Calculation

$$P = \frac{V^2}{R_{USB}} \frac{5^2}{0.03} = 833.\overline{33} \text{ watts}$$

$$W_{total} = \# \text{ of bikers} \times P = 882,000 \times 833.\overline{33} = 735 \text{ megawatts}$$

*Assuming a bicyclist brakes 40 times a day and they obtain about 5.41 seconds of usable voltage:*

$$\text{Time braking per year (s)} = 40 \times 365 \times 5.41 = 78986 \text{ seconds per year}$$

$$\text{Seconds in a year} = 31536000$$

$$\text{Ratio of year spent braking} = \frac{78986}{31536000} \approx 0.00250$$

$$\text{Actual power gained from braking} \approx 0.00250 \times 735 \text{ megawatts} \approx 1.841 \text{ megawatts}$$

$$\text{Hours in a month} = 720$$

$$\text{Power consumed by average U.S. home in a month} = 901 \text{ kWh}$$

$$\begin{aligned} \text{Number of homes that could be powered every month} &= \left(\frac{901}{720}\right)^{-1} \times 1841 \text{ kW} \\ &= 1471 \text{ homes} \end{aligned}$$