THE BICYCLE-POWERED SMARTPHONE CHARGER

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by

Chris Arntzen

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COMMITTEE MEMBERSHIP

TITLE:	The Bicycle-Powered Smartphone Charger
AUTHOR:	Chris Arntzen
DATE SUBMITTED:	June, 2013
COMMITTEE CHAIR:	Dr. Lynne Slivovsky, Associate Professor Electrical Engineering Department
COMMITTEE MEMBER:	Dr. Bryan Mealy, Associate Professor Electrical Engineering Department
COMMITTEE MEMBER:	Dr. Taufik, Professor Electrical Engineering Department

ABSTRACT

The Bicycle-Powered Smartphone Charger

Chris Arntzen

This thesis entails the design and fabrication of a smartphone charger that is powered by a bicycle dynamo hub. In addition to the design and validation of the charger prototype, this thesis involves the testing and characterization of the dynamo hub power source, the design and construction of specialized test equipment, and the design and prototyping of a handlebar-mounted case for the smartphone and charging electronics. With the intention of making the device a commercial product, price, aesthetics, and marketability are of importance to the design. An appropriate description of the charger circuit is a microcontroller-based energy management system, tailored to meet strict power demands of current smartphones. The system incorporates a switched-mode power supply, lithium polymer battery, microcontroller, and specialized protection circuitry. Prototype testing confirms that the circuit meets the charging requirements of the smartphone at bicycle speeds ranging from 7 miles per hour to as high as 55 miles per hour.

Keywords: DC Converter, Switched Mode Power Supply, Bicycle, Dynamo Hub, Energy Harvesting, Energy Management

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TABLE OF CONTENTS

	Page
List of Tables	ix
List of Figures	x
Chapter	
1. Introduction	1
1.1 Scope of the Project	1
1.1.1 Problem Statement	1
1.1.2 Price Point	2
1.1.3 Ergonomics	2
1.1.4 Speed Considerations	3
1.1.5 Case Design	3
1.2 Background	7
1.2.1 Hub Background	7
1.2.2 Cycling Power Considerations	8
2. Design Requirements	11
2.1 Initial Testing	11
2.1.1 Preliminary Test Fixture	11
2.1.2 Types of Hubs and Wheels	12
2.1.3 Preliminary Test Results	12
2.2 Design Equations and Considerations	15
3. Product Design	20
3.1 Circuit Design	20
3.1.1 System Level Design	20
3.1.2 Input Section	20
3.1.3 DC/DC Converter Topology Selection	26
3.1.4 Microcontroller Selection	32

3.1.5	Voltage, Current, and Temperature Sensing.....	34
3.1.6	Battery and iPhone Cable Selection.....	35
3.2	PCB Design.....	36
3.2.1	Size, shape, and layer considerations.....	36
3.2.2	Layout Considerations	38
3.3	Firmware Design.....	39
3.4	Final Testing	40
3.5	Prototype Revisions	43
3.5.1	Topology Revisions	43
3.5.2	Input Protection Revisions.....	44
3.5.3	Other System Revisions.....	47
4.	Results.....	50
4.1	Simulation Results	50
4.1.1	SEPIC Simulation Results	50
4.1.2	Component Rating Simulation Results.....	54
4.2	Standard Test Bench Results	54
4.2.1	SEPIC Performance	54
4.2.2	System Functionality	58
4.3	Custom Test Fixture Results.....	59
5.	Conclusion	62
5.1	Meeting the Design Requirements.....	62
5.1.1	Description of Criteria Met.....	62
5.1.2	Cost Analysis	62
5.2	Future Improvements	63
5.2.1	Hardware Improvements.....	63
5.2.2	Compatibility	64
5.2.3	Extended Testing	64
5.2.4	Firmware.....	65
5.3	Future Opportunities	66
5.3.1	Patenting	66

5.3.2 Other Smartphones.....	66
5.3.3 Future Applications.....	67
Works Cited	68
Appendices.....	69
Appendix A Hub Test Data.....	70
Appendix B Cycling Power Assessment Procedure	72
Appendix C MATLAB Code.....	77
Appendix D C Test Code for Microcontroller	79
Appendix E SEPIC Test Data.....	82
Appendix F Bill of Materials	84
Appendix G Case Engineering Drawings	86
Appendix H Case Cost Analysis.....	90
Appendix I Digital Potentiometer Settings and Output Voltage Range	91

LIST OF TABLES

Table	Page
1.1: Road Cycling Power Parameters	9
1.2: Bicycling Power Scenarios.	9
2.1: Input Parameter Range.....	16
2.2: Design Parameters.	18
2.3: System Input and Output Parameters.....	19
3.1: Duty Cycle Range	28
3.2: Component Selection.....	30
3.3: Design Tradeoffs – Inductor and Capacitor Values to Switching Frequency	30
A1: Shimano DH-3D72 Constant 500mA Test	70
A2: Additional Shimano DH-3D72 Tests.....	70
A3: SON Delux Constant 500mA Test.....	71
A4: Sanyo H27 Constant 400mA Test	71
B1: Hub Drag Tabulated Data	74
B2: Tabulated Values for Power Parameters.....	75
B3: Example Bicycling Power Calculation	76
E1: SEPIC Test Data with 5.5V Output Voltage	82
E2: SEPIC Test Data with 4.2 Output Voltage	82
E3: SEPIC Test Data with 3.6V Output Voltage	83
F1: Electronic Components Bill of Materials	84
F2: Case Bill of Materials	85
H1: Case Cost Analysis	90
I1: Digital Potentiometer Settings and Output Voltage Range	91

LIST OF FIGURES

Figure	Page
1.1: CAD screenshot of case	5
1.2: Case to handlebar mount.....	6
1.3: Case prototype	6
1.4: Case prototype mounted on bicycle handlebars	7
2.1: Preliminary Test Fixture	11
2.2: Hub Output Power Dependence on Wheel Speed and Load	13
2.3: Hub Electrical Frequency Dependence on Wheel Speed	13
2.4: Hub Output Voltage Dependence on Wheel Speed.....	14
2.5: Hub Output Power Dependence on Wheel Speed	14
2.6: iPhone5 Warning Message	17
3.1: Charger System Level Diagram.....	20
3.2: Input Capacitor Sizing in MATLAB	22
3.3: Input Capacitor Peak Repetitive Current in MATLAB	23
3.4: Input Section Schematic	25
3.5: SEPIC Topology Schematic	27
3.6: DC/DC Converter Section Schematic.....	31
3.7: Microcontroller Section Schematic	33
3.8: PCB Layout Top Layer.....	37
3.9: PCB Layout Bottom Layer	37
3.10: Fully Populated Rev.C PCB	38
3.11: New Test Fixture	41
3.12: DAQ, Motor Controller, and Motor Power Supply	42
3.13: LabVIEW Front Panel User Interface	43
3.14: Large Inductive Voltage Spike	46
3.15: Smaller Inductive Voltage Spike	46

3.16: No Inductive Voltage Spike.....	47
3.17: Circuit and Layout Changes	49
4.1: LTSpice Simulation Circuit with 7 MPH Hub Input.....	51
4.2: LTSpice Simulation Results with 7MPH Hub Input	51
4.3: LTSpice Simulation Circuit with 20MPH Hub Input.....	52
4.4: LTSpice Simulation Results with 20MPH Hub Input	52
4.5: LTSpice Simulation Circuit with Battery Input.....	53
4.6: LTSpice Simulation Results with Battery Input	53
4.7: Test bench SEPIC efficiency with output set to 5.5V	56
4.8: Test bench SEPIC efficiency with output set to 4.2V	56
4.9: Test bench SEPIC efficiency with output set to 3.6V	57
B1: Hub Drag Data	73
B2: Hub Drag Equation Fitting to Data.....	75
G1: Case Bottom Drawing.....	86
G2: Case Top Drawing	87
G3: Clamp Arm Drawing	88
G4: Case Liner Drawing	89

CHAPTER 1

Introduction

1.1 Scope of the Project

1.1.1 Problem Statement

The aim of this thesis project is to present a working prototype of a smartphone charger whose power source is a standard front wheel bicycle dynamo hub. The demographic for this product is the touring cyclist, who may spend weeks to months bicycling on the road, with potentially no access to electricity. Other demographics of bicycle riders, such as commuting cyclists, may have use for this product but the design is tailored to the touring cyclist. Current smartphones offer a variety of utilities to cyclists, including GPS, maps, bicycling apps which display speedometer, odometer, etc., phone, camera and video; these utilities are of value to the cyclist, but of course only if the phone remains charged. Since this project must result in an actual consumer product and not just a proof of concept, certain design considerations as well as ergonomic and economic factors play important roles in the development of the smartphone charger.

A few products are currently on the market and are designed to power portable electronic devices, smartphones included; however they all exhibit certain limitations, which this design overcomes. The existing products are bulky, they have an excessive amount of cables, and some of them cannot charge devices at speeds under 10 MPH. The overall theme for this design is a product which is ergonomic and simple to use, is able to charge the smartphone at speeds under 10 MPH, and is priced comparably with the existing products on the market. The design consists of a weather-proof case which houses the smartphone and charging electronics, with a single cable that connects to the

dynamo hub. The case mounts to the handlebars of the bicycle, giving the user easy access to the visual display and touchscreen, headphone jack, and cameras. Since the dimensions and charging requirements of smartphones vary from model to model, this project is designed specifically for the Apple iPhone5 due to its popularity; all other smartphone models are outside the scope of this project.

1.1.2 Price Point

There are three products currently on the market that are comparable to this design. They are the BioLogic ReeCharge, which totals \$185 for the weather-proof iPhone5 case (\$55), power pack (\$100) and dynamo kit (\$30), the PedalPower Super-i-Cable, at \$168 not including a phone case, and the Busch & Müller USB-Werk, at \$144 also not including a phone case. With these prices in mind, the price of this design should fall in the \$150 to \$200 range considering it will provide all the charging electronics and a weather-proof case for the iPhone5. Compared to standard AC wall chargers and car chargers, this price range is relatively high; however compared to other high-end specialty bicycle products, such as headlamps, panniers, etc., this price range is similar. Since this product is unique to the road cycling application and provides functionality that no other product can provide, it is reasonable to consider it a high-end specialty bicycle product, and therefore the \$150 to \$200 price range is also reasonable.

1.1.3 Ergonomics

Manufacturers of smartphones have certain design constraints to meet in order to make a product that has market appeal. Ergonomics is an important factor, and just as it

is important to the smartphone itself, it is also important to the case. In order to house the iPhone5 and charging electronics while maintaining an ergonomic appeal, the case design accommodates the length and width of the iPhone5, with the depth of the case accommodating the height of the iPhone5 plus the height of the charging electronics. Considering the height of typical surface mount components, the goal is to design the charging electronics to a height roughly equal to that of the iPhone5 itself, which is 0.3 inches (7.6 mm).

1.1.4 Speed Considerations

With the touring cyclist in mind, speed plays an important role in the design of this product. Weight, road grade, and headwind are important factors that contribute to the rider speed. Section 1.2.2 discusses them in greater detail. Depending on these factors and practically speaking, the touring cyclist may be going as slow as 5 MPH, which is a quick walking speed, or as fast as 55 MPH, which is a fast downhill pace. These numbers come from practical experience and observations, and are the boundaries of the scope of this project. A critical portion of this spectrum is at slow speeds, 5 to 10 MPH. In the context of bicycle touring, it is possible to be travelling at speeds less than 10 MPH for hours or even days; this makes charging in this speed range critical.

1.1.5 Case Design

The main design goals for the case are that it be ergonomic, weather-proof, durable, and able to accommodate the iPhone5 and charging electronics. Additionally, the case needs to mount easily to bicycle handlebars, pivot for portrait and landscape

orientation, and provide usability of the touch screen, main button, cameras, and headphone jack. Being weatherproof and durable is necessary since the case mounts to the handlebars and can be subject to rain, sweat, dust, vibration, shock, and drop.

Since the case design is outside of the realm of Electrical Engineering, a Cal Poly Industrial Manufacturing Engineering (IME) student was recruited to complete the case design as a senior project. The deliverables for the senior project and this thesis are a functional prototype, CAD drawings, specifications, and a cost analysis. This project involved direction of the IME student, as well as collaboration and brainstorming on the case design. Figure 1.1 shows each section of the case. From top to bottom, the components are: case top, the iPhone5, silicone liner (to absorb shock and vibration), circuit board, and case bottom. On the right-hand side is the clamp arm which locks the top of the case to the bottom of the case, forming a seal on the silicone liner to keep out water and dust.

Figure 1.1: CAD screenshot of case

Figure 1.2 shows the case to handlebar mount, which has a ball-and-socket joint to allow portrait and landscape orientation of the iPhone5. This component is a standard off-the-shelf part. Figures 1.3 and 1.4 show the actual prototyped case. The prototype was made by a 3-D printer.

Figure 1.2: Case to handlebar mount

Figure 1.3: Case prototype

Figure 1.4: Case prototype mounted on bicycle handlebars

1.2 Background

1.2.1 Hub Background

The power source for the smartphone charger is a front wheel AC dynamo hub, nominally rated at 6 Volts, 3 Watts. These dynamo hubs cost anywhere from \$50 to about \$200 and are intended to power bicycle headlights and taillights [1]. Sidewall bottle type dynamos could also work as a power source; however they have several drawbacks. They suffer from significant losses at the wheel/generator interface and they are unreliable in wet weather because the generator wheel slips [1]. These dynamos are outside of the scope of this project and are not considered.

1.2.2 Cycling Power Considerations

The touring cyclist may be concerned with bicycle performance, efficiency, and the amount of power necessary to ride the bicycle. Many bicycle manufacturers design lighter frames and lower friction components to meet the performance needs of touring cyclists, so it is of value to investigate the effects of using a dynamo hub to provide power for charging a smartphone. In 1998 a research paper was published titled “Validation of a Mathematical Model for Road Cycling Power” and presents the equation for road cycling power [2]:

$$\mathbf{P} = \left[V_a^2 V_G \frac{1}{2} \rho (C_D A + F_W) + V_G C_{RR} m_{TG} \cos(\tan^{-1}(G_R)) + V_G (91 + 8.7 V_G) 10^{-3} + V_G m_{TG} \sin(\tan^{-1}(G_R)) + \frac{1}{2} \left(m_T + \frac{I}{r^2} \right) \left[\frac{(V_{Gf}^2 - V_{Gi}^2)}{(t_i - t_f)} \right] \right] / E_C$$

Equation 1.1: Road Cycling Power

The five terms inside the brackets represent the following quantities:

- 1st term: total aerodynamic power
- 2nd term: power to overcome rolling resistance
- 3rd term: power loss in the wheel bearings
- 4th term: change in potential energy
- 5th term: change in kinetic energy

This sum is then divided by the chain efficiency, E_C , to yield the total power required to move the bicycle. Table 1.1 shows the equation parameters, which either have constant numerical values that are taken from the research paper, or values that are dependent on

the riding conditions. Table 1.2 shows a few investigated scenarios which quantitatively and qualitatively describe the effects of using a dynamo hub on road cycling power.

Value (Units)	Variable	Parameter
(m/s)	V_a	Air velocity tangent to the direction of travel
(m/s)	V_G	Ground velocity
1.2234 (kg/m ³)	ρ	Air density
0.2565 (m ²)	C_D	Coefficient of drag
	A	Frontal area
0.0044 (m ²)	F_W	Drag area of the spokes
0.0032	C_{RR}	Coefficient of rolling resistance
(kg)	m_T	Total mass of bike and rider
9.81 (m/s ²)	g	Acceleration of gravity
	G_R	Road gradient (rise/run)
0.14 (kg*m ²)	I	Moment of inertia of the two wheels
0.311 (m)	r	Outside radius of the tire
(m/s)	V_{Gf}	Final ground velocity
(m/s)	V_{Gi}	Initial ground velocity
(s)	t_i	Initial time
(s)	t_f	Final time
0.97698	E_C	Chain Efficiency

Table 1.1: Road Cycling Power Parameters

Slow Speed Scenario 1		Moderate Speed Scenario 1		High Speed Scenario 1	
Speed (MPH)	10	Speed (MPH)	15	Speed (MPH)	25
Headwind (MPH)	0	Headwind (MPH)	0	Headwind (MPH)	0
Combined Weight (lbs)	200	Combined Weight (lbs)	200	Combined Weight (lbs)	200
Gradient (%)	3	Gradient (%)	3	Gradient (%)	3
Bicycle Power (W)	150.13	Bicycle Power (W)	252.62	Bicycle Power (W)	567.19
Hub Drag (W)	1.2	Hub Drag (W)	1.93	Hub Drag (W)	3.48
Hub Electrical Power (W)	4.7	Hub Electrical Power (W)	7.24	Hub Electrical Power (W)	12.33
Total Power (W)	156.03	Total Power (W)	261.79	Total Power (W)	583
Gradient Increase (%)	0.145	Gradient Increase (%)	0.150	Gradient Increase (%)	0.155

Slow Speed Scenario 2		Moderate Speed Scenario 2		High Speed Scenario 2	
Speed (MPH)	10	Speed (MPH)	15	Speed (MPH)	25
Headwind (MPH)	2	Headwind (MPH)	2	Headwind (MPH)	2
Combined Weight (lbs)	200	Combined Weight (lbs)	200	Combined Weight (lbs)	200
Gradient (%)	0	Gradient (%)	0	Gradient (%)	0
Bicycle Power (W)	34.35	Bicycle Power (W)	83.34	Bicycle Power (W)	299.65
Hub Drag (W)	1.2	Hub Drag (W)	1.93	Hub Drag (W)	3.48
Hub Electrical Power (W)	4.7	Hub Electrical Power (W)	7.24	Hub Electrical Power (W)	12.33
Total Power (W)	40.25	Total Power (W)	92.51	Total Power (W)	315.46
Headwind Increase (MPH)	1.6	Headwind Increase (MPH)	1.2	Headwind Increase (MPH)	0.8

Table 1.2: Bicycling Power Scenarios

In Scenario 1, the rider is going up a 3% road gradient with no headwind. The effect of using the dynamo hub is equivalent to a 0.145% to 0.155% increase in road gradient. This may be somewhat noticeable to the rider, but is effectively negligible. Another way to picture the impact of the dynamo hub on performance is in Scenario 2. In this scenario, the rider is cycling on the flats (no gradient) and there is a 2 mile per hour headwind. The effect of using the dynamo hub is equivalent to a 0.8 to 1.6 mile per hour increase in the headwind. Again, this may be somewhat noticeable to the rider, but is effectively negligible. Appendix B details the procedure for arriving at these scenario conclusions.

CHAPTER 2

Design Requirements

2.1 Initial Testing

2.1.1 Preliminary Test Fixture

To design the smartphone charger, it is first necessary to become familiar with the power source. To facilitate dynamo hub testing, a test fixture spins the bicycle wheel on a stationary mount in the lab. This enables controlled testing conditions and close proximity of the wheel to the lab equipment. Figure 2.1 shows the test fixture which facilitated all of the preliminary data collection for this thesis. This test fixture also helped determine the electrical limitations of the existing products in Section 1.1.1.

Figure 2.1: Preliminary Test Fixture

The test fixture consists of a wooden base affixed to four concrete pier blocks, an electric motor connected to a shaft with various sized pulley wheels, two metal brackets which simulate the bicycle front fork, a hall-effect sensor speedometer, and a ceiling fan speed control knob for varying the speed of the electric motor. This test fixture is controlled manually by the user by adjusting the motor speed control knob until the desired wheel speed is achieved.

2.1.2 Types of Hubs and Wheels

The scope of testing included three different hub/wheel combinations. The first is a Shimano DH-3D72 (~\$100) on a 27-inch wheel, the second a Sanyo H27 (~\$50) on a 27-inch wheel, and the third a SON delux (~\$200) on a 20-inch wheel. These combinations show how price range and wheel size effect the hub electrical power; they are also the options that fit within the budget for this thesis.

2.1.3 Preliminary Test Results

After testing all three hubs under different speeds and loads, the three variables found relevant to characterizing the hub as a power source were electrical frequency, voltage, and power. Electrical frequency is dependent on the wheel speed, number of dynamo pole pairs, and wheel diameter, as described by Equation 2.4. For each hub/wheel combination, the number of pole pairs and wheel diameter remain constant, so the only changing variable is the wheel speed. Both the voltage and power output of the hub are dependent on the type of load that is connected. Figures 2.2 to 2.5 show the results of the hub testing.

Figure 2.2: Hub Output Power Dependence on Wheel Speed and Load.
CV: Constant Voltage, CR: Constant Resistance, CC: Constant Current

Figure 2.3: Hub Electrical Frequency Dependence on Wheel Speed.
(constant 500mA for the Shimano & SON, 400mA for the Sanyo to a resistive load)

Figure 2.4: Hub Output Voltage Dependence on Wheel Speed.
(constant 500mA to a resistive load)

Figure 2.5: Hub Output Power Dependence on Wheel Speed.
(constant 500mA to a resistive load)

One note on Figure 2.3 is that the Sanyo hub had a constant 400mA load instead of a constant 500mA load. This was due to the fact that the hub sourced more power at 400mA than at 500mA, suggesting that the hub is optimized for a 400mA load.

2.2 Design Equations and Considerations

The Shimano DH-3D72 is the chosen representative for the dynamo hub as a power source, for deriving design equations and designing the circuit for the smartphone charger. Shimano hubs are moderately priced [1] and the mechanical drag of the Shimano DH-3D72 is between that of the low-cost Sanyo hub and high-end SON hub. The following design equations fit linear approximations to the raw data collected from Figures 2.2 to 2.4 on the Shimano DH-3D72 delivering 500mA constant current to a resistive load.

$$f_e = 2.8758(s) + 0.2862$$

Equation 2.1: Hub Electrical Frequency,
 $f_e \equiv$ electrical frequency (Hertz), $s \equiv$ wheel speed (miles per hour)

$$V_s = \sqrt{2}(1.0172(s) - 2.7785) - 2(0.8)$$

Equation 2.2: Hub Output Voltage, $V_s \equiv$ source voltage (Volts), peak value after full-wave rectification with a 0.8 volt diode drop, $s \equiv$ wheel speed (miles per hour)

$$P = 0.5086(s) - 1.3893$$

Equation 2.3: Hub Output Power, $P \equiv$ real power (Watts),
 $s \equiv$ wheel speed (miles per hour)

From these equations and considering the speed range applicable to the design, as mentioned in Section 1.1.4, the design must accommodate the ranges in electrical frequency, voltage, and power in Table 2.1.

	5 MPH	55 MPH
Electrical Frequency (Hz)	14.67	158.46
Peak Voltage, 500mA load (V)	1.66	73.59
Peak Voltage, open circuit (V)	11	144
Available Power	1.15	26.58

Table 2.1: Input Parameter Range

Equation 2.4 relates the wheel diameter (d) in inches, number of dynamo pole pairs (#p), and bicycle speed (v) in MPH to the hub's electrical frequency (F_e) in Hertz. In the experimental case, the wheel diameter is roughly 27.25 inches and the number of pole pairs is 14. Equation 2.1 is validated since the values obtained from it reasonably fit the theoretical values from Equation 2.4.

$$F_e = (17.6) \frac{\#pv}{\pi d}$$

Equation 2.4: Theoretical Hub Electrical Frequency

The iPhone5 is charged with the Apple Lightning cable, which is normally connected to a USB port on a computer, AC wall charger, or car charger. These sources provide 5V DC, and the iPhone5 expects anywhere from 500mA to 1A of charging current. If the current supplied falls below 500mA, the iPhone5 displays the warning

message in Figure 2.5. This message comes up when using a current limiting power supply connected to the Lightning cable and lowering the current limit from 1A to zero.

Figure 2.6: iPhone5 Warning Message

This warning message should be avoided considering that this charger will be an iPhone5 compatible consumer product.

Table 2.2 shows the range of design parameters to be accommodated. The efficiency of 75% from input power to output power arises considering that the converter design will be a PWM switching type DC/DC converter, and efficiency between 70% and

85% is expected from a PWM Switching Regulator [3]. With the output power requirements set forth, the ranges in input parameters raise some concerns regarding the charger circuit design.

Speed (MPH)	Freq. (Hz)	Vin Peak (V)	Current in (mA)	Power In (W)	Efficiency (%)	Power Out (W)	Vout (V)	Iout max (mA)	
5	14.7	1.66	500	1.15	75	0.87	4.2	206	
7	20.4	4.54	500	2.17	75	1.63	4.2	388	
9	26.2	7.42	500	3.19	75	2.39	5.0	478	
10	29.0	8.86	500	3.70	75	2.77	5.0	555	
15	43.4	16.05	500	6.24	75	4.68	5.0	936	
20	57.8	23.24	500	8.78	75	6.59	5.0	1000	
25	72.2	30.43	500	11.33	75	8.49	5.0	1000	
30	86.6	37.63	500	13.87	75	10.40	5.0	1000	
35	100.9	44.82	500	16.41	75	12.31	5.0	1000	
40	115.3	52.01	500	18.95	75	14.22	5.0	1000	
45	129.7	59.20	500	21.50	75	16.12	5.0	1000	
50	144.1	66.40	500	24.04	75	18.03	5.0	1000	
55	158.5	73.59	500	26.58	75	19.94	5.0	1000	
Battery	DC	3.05	1400	4.27	75	3.20	5.0	641	*Discharged at 2C
Battery	DC	3.05	1050	3.20	75	2.40	5.0	480	*Discharged at 1.5C

Table 2.2: Design Parameters

With regard to the electrical frequency, the low end of the range at 5 MPH is important for input capacitor sizing since lower input frequencies result in larger capacitances. With regard to the peak voltage, a buck/boost type converter must be used to lower the voltages at high speeds and raise the voltages at low speeds to achieve a 5V output. Additionally, the 1.66V minimum peak voltage may not be able to power certain devices, such as integrated circuits, and the 73.59V maximum peak voltage may be excessive and damage components such as capacitors and MOSFETs.

The available power from the hub is also a concern since the output power to the iPhone5 needs to be between 2.5W (5V at 500mA) and 5W (5V at 1A). The 26.58W of available power at 55 MPH is more than enough to charge the iPhone5, but the 1.15W at 5 MPH is not enough. If the rider is going slowly and the 2.5W of output power is not

reached, then the iPhone5 will not charge, or it will charge and display the warning message in Figure 2.6. The proposed scheme to circumvent this issue is to charge a small Lithium Polymer battery and cycle it back to the input of the charger once it is fully charged.

Table 2.3 shows the range of input and output parameters to give a sense of what the overall system must accommodate. The minimum bicycle speed increased from 5 MPH to 7 MPH during the input capacitor sizing in Section 3.2.1.

Input Parameters			Unit
Bicycle Speed	7 - 55		MPH
Frequency	20.4 - 158.5		Hz
Voltage Under Load	6.14 - 75.19		Vpp
Open Circuit Voltage	38 - 288		Vpp
Current	500		mA
Potential Power	2.17 - 26.58		W

Output Parameters			Unit
Voltage	5		V DC
Current	500 - 1000		mA
Power	2.5 - 5		W

Table 2.3: System Input and Output Parameters

CHAPTER 3

Product Design

3.1 Circuit Design

3.1.1 System Level Design

Figure 3.1 shows the system level design of the charger. The flow of power is from the hub on the left to the phone on the right. The power may be cycled through the battery, but ultimately it is delivered to the phone. The microcontroller uses the sensing inputs to make decisions and control the flow of power.

Figure 3.1: Charger System Level Diagram

3.1.2 Input Section

The input section of the circuit converts the AC voltage of the hub to DC, provides protection to the circuit, and reduces the voltage ripple. Figure 3.2 shows the different components in the input protection section. The AC hub input is first rectified to DC for the DC/DC converter. A bridge rectifier composed of four SBR diodes

accomplishes this. The SBR diodes are chosen due to their high reliability and low forward voltage drop, similar to that of a Schottky [4]. The low forward voltage drop is desired since the peak input voltage should be maximized to accommodate slower speeds. Table 2.1 shows that the peak input voltage can be as high as 144V. The reverse breakdown voltage must be higher than at least twice this value, so 400V rated SBRs are chosen. Figure 3.3 shows how MATLAB helped determine the peak repetitive current of the diode for the chosen input capacitance value. The chosen SBRs have an average forward current rating of 1A and a peak rating of 40A, so they should be able to handle a peak repetitive current of 1.963A (1.463A peak capacitor current + 0.5A input current).

The input capacitor value is 2200 μ F and rated at 35V. Figure 3.2 shows how MATLAB helped determine an appropriate value for this capacitor. A continuous load current of 500mA is assumed. The Index scale represents the amount of voltage ripple on the capacitor, with the largest ripple at the lowest Index value and vice versa. Although the smallest capacitor value is chosen at the largest allowable ripple, where the minimum voltage is 2V, the Index scale shows how the amount of ripple influences the minimum capacitance value. The 2V minimum value came about by a process of recursion in the circuit design, which is detailed in Section 3.1.3. Ultimately, it is less than the 4.5V maximum at 7 MPH, and higher than the 1.6V lower limit of the LT3759 DC/DC converter controller operating voltage.

The speed range narrowed to between 6.5 and 15 MPH after a few simulations. Ideally, the input capacitance should be large enough to accommodate speeds down to 5 MPH, however simulated speeds less than 6.5 MPH resulted in impractically large capacitance values. The 2200 μ F capacitance value at 7.5 MPH arises since 22 100 μ F,

35V electrolytic capacitors fit nicely on the PCB and at lower load currents, lower speeds can be utilized with the 2200 μ F capacitance value.

Figure 3.2: Input Capacitor Sizing in MATLAB

Figure 3.3: Input Capacitor Peak Repetitive Current in MATLAB

Since the input capacitor is the tallest component on the PCB, 22 100 μ F, 35V electrolytic capacitors are connected in parallel to meet the ergonomic criteria set forth in Section 1.1.3; this minimizes the height of the circuit to 7.7 mm. Higher voltage ratings for the same value of capacitance result in taller and more expensive capacitors, qualities which are undesirable. Since the capacitors are only rated to 35V and the peak input can reach 73.59V at 500mA and 55 MPH, input protection circuitry is necessary to limit the input voltage. To accomplish this, an N-Channel MOSFET connects in series with the input path and turns off when the input voltage gets too high. The MOSFET used is an Infineon IPD320N20N3, which has a V_{DS} rating of 200V, a forward current rating of 34A and an R_{DS-on} of 32m Ω . The V_{DS} rating exceeds the open circuit 144V peak input at 55 MPH, and the low R_{DS-on} is desirable to minimize conduction losses.

An LM311 comparator monitors the input voltage and turns off the MOSFET when the input reaches a pre-determined threshold. This threshold is set at 19V in the final revision of the circuit. A Fairchild FAN73611 high-side gate driver drives the gate of the MOSFET. The input range of the FAN73611 is 10 to 20V, so a Maxim MAX1822 charge pump IC boosts the battery voltage, which ranges from 3.6V to 4.2V, by 11V to achieve a 14.6V to 15.2V input for the FAN73611. The MOSFET gate needs to be driven above the maximum gate-source threshold, which ranges from 4V at an input of zero volts to 27V at an input of 23V. 27.5V is the maximum output of the MAX1822, so 23V was initially chosen as the maximum allowable input voltage. Much time was spent in searching for simpler and less expensive parts that could achieve this functionality, but the FAN73611 and MAX1822 were the only viable options. The maximum recommended input voltage to the MAX1822 is 16.5V, so a 15V zener regulator clamps the input voltage. Two diodes perform an OR function on the input voltage to the gate-driving MAX1822 so that the battery provides the MAX1822 input voltage at first, and then the hub input voltage takes over when it is higher than the battery voltage. A resistor, capacitor, diode circuit is implemented at the gate of the MOSFET to slow the rate of turn-off. This is elaborated in Section 3.5.2. Lastly, an AND gate allows the microcontroller to shut the input off.

Figure 3.4: Input Section Schematic
(Bridge Rectifier, Input Protection, and Input Capacitor blocks in Figure 3.1)

3.1.3 DC/DC Converter Topology Selection

After the input stage, the power must be converted from a rectified and smoothed varying DC level to a regulated 5V or 3.6 – 4.2V output for phone charging or battery charging, respectively. There are several options for voltage regulation, however, since the input voltage can be higher or lower than the output voltage, a converter with buck-boost functionality must be employed. Options that provide this functionality are the Buck-Boost, 4-Switch Buck-Boost, CUK, SEPIC, and the Flyback topologies. The original design (Revision A) used the buck-boost topology since it has a low parts count and since isolation and input to output voltage inversion were originally not of importance. After troubleshooting Revision A, it was evident that the voltage inversion of the Buck-Boost topology is a problem since it made input voltage sensing and input protection circuit design exceedingly difficult. This is elaborated upon in Section 3.5.1.

The Flyback topology was considered since it does not output an inverted voltage and a step-down transformer could eliminate the need for input protection against the high input voltages. The two main caveats of this option are that a step-down transformer would also lower the low voltages at slow speeds, which limits the low-speed range of the design. Additionally, rectification and input capacitor smoothing happen before the transformer stage, so the input capacitors would have to be rated at 200V; this would result in relatively large and expensive input capacitors. For these two reasons the Flyback topology was abandoned.

The 4-Switch Buck-Boost topology was also considered since it does not output an inverted voltage and it has a low parts count and relatively high efficiency. This topology was not selected because the available controllers for the 4-Switch Buck-Boost

topology did not have an input voltage range compatible with the circuits input range of 2V – 23V.

Finally, the Single-Ended Primary Inductor Converter (SEPIC) topology was selected since it does not invert the output voltage and the LT3759 controller works with the SEPIC topology at an input range of 1.6 – 42V. The main drawback to the SEPIC topology is that it has a relatively high parts count, and these extra parts result in extra power dissipation (through the ESR of the DC coupling capacitor and series resistance of the second inductor). This of course results in inherently lower efficiency, but the SEPIC was the only viable option for this application. Figure 3.5 shows the SEPIC topology.

Figure 3.5: SEPIC Topology Schematic

The Applications Information section of the LT3759 datasheet dictated the SEPIC design. The design equations and process are followed here. The first step calculates the maximum duty cycle ($D_{\max}$) that the converter will encounter.

$$D_{\max} = \frac{V_{\text{out}} + V_d}{V_{\text{in}(\min)} + V_{\text{out}} + V_d}$$

From the Diodes Inc. B260 datasheet, at 1A of forward current, the diode forward voltage drop is approximately 0.52V. The minimum input voltage to the converter is 2V and the maximum input voltage is 23V. Substituting $V_{in(max)}$ for $V_{in(min)}$ yields the minimum duty cycle, which is of interest to ensure that the duty cycle stays within the typical range of 10% – 90%.

$V_{out} = 5V$	$D_{max} = 73.4\%$
$V_{out} = 5V$	$D_{min} = 19.6\%$
$V_{out} = 3.6V$	$D_{max} = 67.3\%$
$V_{out} = 3.6V$	$D_{min} = 15.2\%$

Table 3.1: Duty Cycle Range

As seen in Table 3.1, the maximum duty cycle encountered is 73.4%. Next, inductor and switch currents are calculated.

$$I_{L2(max)} = I_{out(max)} = 1A$$

$$I_{L1(max)} = I_{in(max)} = I_{out(max)} \cdot \frac{D_{max}}{1 - D_{max}}$$

$$I_{L1(max)} = 2.76A$$

$$I_{SW(max)} = I_{L1(max)} + I_{L2(max)} = 3.76A$$

$$I_{SW(peak)} = \left(1 + \frac{\chi}{2}\right) \cdot I_{out(max)} \cdot \frac{1}{1 - D_{max}} = 4.32A$$

χ represents the percentage peak-to-peak current ripple relative to $I_{SW(max)}$, and the datasheet suggests that $0.2 \leq \chi \leq 0.4$, so χ is chosen to be 0.3.

$$\Delta I_{SW} = \chi \cdot I_{SW(max)} = 1.128A$$

$$L1 = L2 = \frac{V_{in(min)}}{\Delta I_{SW} \cdot f_{osc}} \cdot D_{max} = 6.5\mu H$$

The closest available inductor value is chosen at 6.8 μ H. The switching frequency, f_{osc} , is chosen at 200kHz as a design trade-off. Switching losses and conduction losses constitute the major contributors in overall power loss, hence efficiency, in power converters, and the contribution from switching losses is linearly proportional to switching frequency [5]; therefore the switching frequency should be kept small. This is especially significant since the SEPIC already has inherently lower efficiency compared to the Buck-Boost and 4-Switch Buck-Boost. On the other hand, higher switching frequencies result in lower inductor and output capacitor values, as seen in Table 3.1. This reduces system size and cost, which is also an important factor in this design. Next, the switch current sensing resistor is calculated.

$$R_{sense} = \frac{40mV}{I_{SW(peak)}} = 9.3m\Omega$$

The closest available resistor value is chosen at 9m Ω . The resistor power rating is determined from the LTSpice circuit simulation under maximum duty cycle conditions. The maximum average power dissipation of the resistor is about 40mW under these conditions, so a resistor rated at double (80mW) is adequate. Next, the MOSFET voltage is rated by:

$$V_{SW} = V_{out(max)} + V_{in(max)} + 10V = 38V$$

The 10V is a safety margin recommended by the LT3759 datasheet. The diode is rated by:

$$I_{d(peak)} = \left(1 + \frac{X}{2}\right) \cdot I_{out(max)} \cdot \frac{1}{1 - D_{max}} = 4.32A$$

$$V_{rrm} = V_{out(max)} + V_{in(max)} + 10V = 38V$$

The DC coupling capacitor is rated by:

$$VC_{dc} \geq V_{in(max)}, \text{ and } V_{in(max)} = 23V, \text{ so choose } VC_{dc} = 50V$$

And finally, the output capacitor is sized by:

$$C_{out} \geq \frac{I_{out(max)}}{0.01 \cdot V_{out(min)} \cdot f_{osc}} = 139\mu F$$

The output capacitor is set to 200 μ F and rated at 10V, which is twice the highest output voltage. The 0.01 in the C_{out} equation represents 1% output voltage ripple. Low ESR tantalum capacitors are used to minimize output voltage ripple. Table 3.2 summarizes the converter components values and ratings.

Calculated Components			Selected Components		
Component	Value	Rating	Part Number	Value	Rating
Inductor	6.5 μ H	2.76A	SRF1260-6R8Y*	6.8 μ H	4.63A
MOSFET	-	38V, 4.32A	DMN4009LK3-13	-	40V, 18A
Sense Resistor	9.3m Ω	80mW	PMR10EZPFU9L00	9m Ω	0.5W
Diode	-	38V, 1A avg	B260-13-F	-	60V, 2A avg
DC Capacitor	4.7 μ F	23V	CL21A475KBQNNNE*	4.7 μ F	50V
Output Capacitor	139 μ F	10V	T520D107M010ATE018*	100 μ F	10V

*Two of each of these components are used

Table 3.2: Component Selection

Fs (kHz)	L (μ H)	Cout (μ F)
100	13.0	278
200	6.5	139
300	4.3	93
400	3.3	69
500	2.6	56

Table 3.3: Design Tradeoffs – Inductor and Capacitor Values to Switching Frequency

Figure 3.6: DC/DC Converter Section Schematic
(DC/DC Converter, Output, and Battery blocks in Figure 3.1)

3.1.4 Microcontroller Selection

There are several features of concern for microcontroller selection. The first is analog to digital conversion (ADC) for monitoring input voltage and current, output voltage and current, and the temperature and voltage of the battery. A digital potentiometer is used in the feedback voltage path of the converter. Serial peripheral interfacing (SPI) programs the value of the digital potentiometer to adjust the output voltage of the converter. Next, at least six general purpose input/ output pins (GPIO) are needed for enabling/ disabling the input, enabling/ disabling the battery as a load, enabling/ disabling the phone as a load, disabling the converter, and two pins for a red/ green debug LED. The remaining qualities are that it be inexpensive and relatively small.

The ATmega328P has SPI, a 10-bit ADC, a sufficient amount of GPIOs, and can run up to 20MHz, which is ample for this application. There exists a great deal of information on it since it is the microcontroller used on the Arduino Uno, which is a popular development board. This made troubleshooting and implementing this microcontroller relatively easy. Figure 3.7 shows the microcontroller section schematic with the ATmega328P and a handful of peripheral components. The header is used to program the microcontroller and the tact switches are intended for debugging purposes. A 2.5V shunt precision voltage reference is used for more accurate ADC values.

Figure 3.7: Microcontroller Section Schematic
(Microcontroller block in Figure 3.1)

3.1.5 Voltage, Current, and Temperature Sensing

The circuit must monitor the input voltage and current as well as the output voltage and current and battery voltage. The output current and battery voltage are of importance in charging the battery. The conventional charging procedure of lithium ion batteries occurs in two steps, the battery is charged at a constant current until the battery voltage reaches the predefined upper voltage limit (4.1 or 4.2V) followed by a constant voltage charging until the current reaches a predetermined small value [6]. The battery temperature is also of importance in charging the battery since it is a main parameter, not only for safe operation of the battery but also to extend battery lifetime [7]. The input voltage is monitored to disable the input in an under-voltage lockout (UVLO) condition. This condition arises at slow bicycle speeds when the hub voltage fluctuates around the UVLO threshold of the converter. In this condition, the input is disabled and the battery is used as the input source to the converter. Input current sensing can facilitate maximum power point tracking algorithms in the microcontroller since the maximum power output of the hub occurs at 500mA current draw.

Resistor dividers achieve voltage levels compatible with the ADC inputs of the microcontroller for voltage sensing. Low impedance current sensing resistors allow for current sensing in the input current path and output current path. Two Fairchild FAN4010 current sensing ICs convert the voltage drop across the current sensing resistors to a voltage level compatible with the ADC inputs of the microcontroller. Figure 3.6 shows the implementation of these current sensing ICs.

3.1.6 Battery and iPhone Cable Selection

The main parameters for battery selection are size, cost and charge/ discharge rate. A 700mAh lithium polymer battery was selected, with dimensions that work within the PCB and case dimensions. The battery is placed on top of the temperature sensing IC so that the battery temperature can be monitored. Despite this stacking of components, the overall height of the temperature sensing IC and the battery is still less than that of the input capacitors (7.7mm) and the low profile of the circuit is maintained. The battery tabs are soldered to the PCB and the battery itself is glued to the PCB with silicone. A dab of thermal paste is placed between the temperature sensing IC and battery to improve thermal conductivity. The battery is rated at 1C charge rate and 2C discharge rate, which correspond to 700mA and 1400mA. Table 2.2 shows that the discharge rate of 2C meets the iPhone5 current requirement of 500mA to 1A, after being fed back to the converter input. Keeping the minimum battery voltage at 3.6V ensures that it does not fully discharge. Since the operation of the circuit is dependent on power supplied from the battery, it is important to keep some charge in the battery at all times.

The iPhone5 uses a proprietary charging cable, the Lightning cable, which integrates a small authentication IC. When the iPhone5 first came out, consumers were forced to buy the Apple Lightning cable, which had a retail cost of \$20. After a few months, functioning knock-off cables were available. The cable used on this design comes from a Chinese manufacturer and costs \$3.50 on eBay. With the wiring removed from the Lightning plug, a Molex Flatflex ribbon cable connects to the plug and is wrapped with heat shrink as pictured in Figure 3.10.

3.2 PCB Design

3.2.1 Size, shape, and layer considerations

The size of the PCB is kept to roughly that of the iPhone5 and within the dimensions of the case. The length of the PCB is limited to four inches since Eagle PCB Light Edition design software was used and has a four inch maximum on board length. This is not an issue since there is sufficient surface area for the circuit. The notch in the lower left-hand corner in Figure 3.8 allows use of the camera on the iPhone5 and the LED is mounted at this location so that it can shine through the camera window. This allows the LED to provide information to the user. For example, the LED could flash red if there is a problem in the circuit and the device should be sent back to the manufacturer for repair.

The PCB is kept to a two layer design to reduce cost in PCB fabrication and since the Eagle PCB Light Edition design software is limited to two layers. A four layer design would cost more, but would have made PCB layout easier and could have benefits to the functionality of the circuit. For example, analog and digital lines could be more directly routed; ground and power planes could be more accessible to the ICs.

Figure 3.8: PCB Layout Top Layer

Figure 3.9: PCB Layout Bottom Layer

Figure 3.10: Fully Populated Rev.C PCB

3.2.2 Layout Considerations

There are several aspects of the PCB layout that are important to the operation of the circuit and to the overall product design. In general, the components of each section of the circuit (input protection, microcontroller, and converter) are grouped closely together so that trace lengths are kept short. Shorter trace lengths result in lower trace resistance and lower exposure to unwanted noise. The analog lines are kept away from digital lines and switching nodes to reduce the amount of noise on the signals and improve the ADC readings. The switching node in the converter is kept small to reduce generated electromagnetic interference. The high-power and fast edges of the converter MOSFET switching can easily lead to significant interference if this is not done. Likewise, the switching node at the input protection MOSFET is kept small and placed away from other components.

The layout considerations in manufacturer datasheets were followed to ensure optimum circuit performance on all of the IC components. The LT3759 converter and ATmega328P microcontroller datasheets had many suggestions which were carried out in the PCB layout. One of the most common suggestions is to place the input voltage bypass capacitors as close to the input voltage pins of the ICs; this was done on every IC to reduce noise on the inputs.

3.3 Firmware Design

The firmware performs the functions of voltage, current, and temperature monitoring, battery charging, and making decisions whether to charge the battery or the phone. The microcontroller has the ability to turn the converter off, which could be employed as a safety measure. It also has the ability to shut the input off, which can be used to prevent the hub input from influencing the converter input when the battery is used as the input to the converter. There are many possibilities to what the firmware can do to control the system as a whole.

The code in Appendix D facilitated the development and testing of the charger. This code is executed as follows: first, the data direction registers are set for the GPIOs, ADC channels, and SPI; this defines which pins are outputs and which are inputs. Next, the ADC registers are set to select the ADC channel, select the 2.5V voltage reference, select the ADC mode, and start the conversion. A few variables are declared and the main loop begins. The phone is enabled as the output load and the delay function executes, allowing the charge pumps time to charge. Next, a serial transmission is sent to program the digital potentiometer. The input is enabled and the converter regulates the

voltage to the phone. The main loop cycles infinitely, the ADC reads the selected channel and the green/red LED indicates whether the ADC value is above, below, or between certain values. This code merely provides simple functions for the purpose of testing.

3.4 Final Testing

After testing on the initial test fixture, it was desired to have a more compact and easier to operate test fixture for future testing. The new test fixture meets these goals and incorporates a National Instruments myDAQ Data Acquisition Unit in conjunction with LabVIEW. The test fixture is pictured in Figures 3.11 and 3.12, and the LabVIEW virtual instrument front panel is pictured in Figure 3.13.

The test fixture uses an electric scooter motor and belt to turn the dynamo hub without the wheel. As far as the electrical output of the hub is concerned, it makes no difference whether the rest of the wheel is attached to the hub or not. An optical sensor system reads the speed of the hub. It is composed of an LED and phototransistor positioned on either side of the spoke holes in the hub. Each time a spoke hole passes between the LED and phototransistor, the phototransistor outputs a voltage, which is then read by the analog input of the DAQ. The frequency of the voltage peaks is converted to the hub speed by Equation 3.1.

$$\text{Speed} = \text{Frequency} \cdot \pi \cdot \left(\frac{545}{6336} \right)$$

Equation 3.1: Phototransistor frequency to hub speed

The fraction in the equation comes from the 18 spoke holes per revolution and 27.25 inch wheel diameter, along with several other conversion factors. The mounted motor and hub are enclosed in an ammo can to reduce the audible noise and block the phototransistor from ambient light.

Figure 3.11: New Test Fixture

Figure 3.12: DAQ, Motor Controller, and Motor Power Supply

The DAQ outputs a PWM signal to a motor controller which controls the speed of the motor. LabVIEW controls the PWM signal with a PI controller and provides a user interface on the front panel. The speed of the motor can be controlled manually by the “Low Speed” and “High Speed” knobs or by a data file composed of speed values. The data file can run the hub through a speed profile for simulation of an actual bicycle trip.

Figure 3.13: LabVIEW Front Panel User Interface

3.5 Prototype Revisions

3.5.1 Topology Revisions

The circuit went through three revisions to achieve the current working version. Revision A was based on a Buck-Boost topology, which seemed appropriate at first. The

input to output voltage inversion of the topology wouldn't affect the performance of the power conversion since the input and output can have different ground references. The trouble arises during implementation of the sensing circuitry and input protection circuitry since the ground reference is different for input and output stages. The Buck-Boost topology was therefore abandoned and a SEPIC design based on the LT3759 Controller was implemented on revisions B and C. This topology does not invert the input to output voltage, so every part of the circuit can be referenced to the same ground. The circuit proved to be reliable and stable under all operating ranges, as described in Chapter 4.

3.5.2 Input Protection Revisions

Revision B implemented the MOSFET switching input protection circuitry which disconnects the input from the circuit whenever the input voltage gets too high. This circuit worked fine during testing, however once the hub reached a high enough speed and the MOSFET started switching on and off, an audible clicking was heard from the hub. Probing with an oscilloscope from the MOSFET drain to ground revealed that each time the input was switched off a large voltage spike coincided, as shown in Figure 3.14. This voltage spiking was believed to be related to the audible noise coming from the dynamo hub. The cause of this large voltage spike is the inductive nature of the dynamo hub. The spike arises from the inductor equation $V_L = L di/dt$. Since the MOSFET switches very fast, di/dt becomes very large and consequentially V_L becomes very large.

The solution to this problem was the addition of a resistor, capacitor, diode circuit at the gate of the MOSFET, as shown in Figure 3.2. The MOSFET switching is slowed

by the RC time constant of the gate to source capacitance and series resistance. During turn-on, the input current bypasses the resistor through the diode and charges the gate to source capacitance. During turn-off, the capacitor discharges through the series resistance since it cannot flow back through the diode. This resistor increases the time constant and slows the turn-off of the MOSFET, thereby reducing di/dt and V_L . The values of R and C were determined empirically to eliminate the voltage spike and the audible noise from the hub. It is better to keep C small so that the MOSFET gate driver is not overloaded and can turn the MOSFET on effectively. The R value can be reasonably large since it has no effect other than slowing the discharge of the gate to source capacitance. The final values of R and C are 422k Ω and 470nF respectively. The voltage spike elimination process is shown in Figures 3.14 through 3.16. In each figure, the top trace indicates the output voltage of the AND gate, the middle trace indicates the voltage of the MOSFET gate, and the bottom trace indicates the input voltage at the MOSFET drain. In Figure 3.16, the small hump in the bottom trace is the normal rectified hub voltage which exceeds the input threshold, not an inductive voltage spike.

Figure 3.14: Large Inductive Voltage Spike.
 $C_{gs} = 0.4\mu F$ $R = 12k\Omega$, audible noise, at about 18MPH

Figure 3.15: Smaller Inductive Voltage Spike.
 $C_{gs} = 0.4\mu F$ $R = 112k\Omega$, audible noise, at about 18MPH

Figure 3.16: No Inductive Voltage Spike.
 $C_{gs} = 0.5\mu F$ $R = 112k\Omega$, NO audible noise, at about 18MPH

3.5.3 Other System Revisions

A few other revisions occurred throughout the development process to improve the functionality and performance of the circuit. At testing with the hub at high speeds and with no load, the input voltage reached approximately 25V, which is higher than the expected 23V. Additionally, the input protection zener regulator voltage reached about 17V, which is the maximum input voltage for the MAX1822 charge pumps. To lower the zener voltage, a 13.8V zener diode replaced the previously sized 15V zener diode. The voltage rise on the zener is due to the fact that the zener clamping voltage is dependent upon temperature and temperature is dependent upon the power dissipated in the device. As the input voltage rises, so does the power dissipated in the zener diode. After testing, the 13.8V zener regulator had a maximum of 15V at the highest hub speed

of 55 MPH, so the 13.8V zener is an adequate substitution. One explanation for the input exceeding the expected 23V is that the slower input MOSFET switching and no load condition allows a higher voltage to actually pass through the MOSFET even though the comparator is switched off. A solution to this problem is to adjust the resistor divider at the LM311 comparator so that the input MOSFET switches off at around 19V instead of 23V. After implementing this change and testing, the input did not exceed 23V at 55 MPH at no load, thus the resistor divider change is an adequate solution.

Another issue was with the battery voltage influencing the operation of the converter. The battery voltage induced on the converter output was sensed by the resistor divider feedback node and caused the converter to behave erratically. After testing and troubleshooting Revision C, the placement of a diode between the converter output and the battery, as seen in Figure 3.17, eliminated this problem.

A less crucial revision was in the current sensing circuitry. Revision B used differential amplifier circuits to measure the input and output currents. Each of these circuits requires a current sensing resistor, an op-amp and four biasing resistors. The FAN4010 current sensing ICs implemented in Revision C made current sensing easier, lowered the parts count, and reduced cost. These ICs require an external current sensing resistor and only one output resistor. The resulting circuit is less expensive and easier to implement than its differential amplifier predecessor.

During initial SEPIC performance testing on Revision C, the output voltage ripple at full load with V_{out} set to 4.2V nominal was over 7%, which is higher than the 2% typical tolerance of DC/DC converter design. To alleviate this high ripple, the location of the ceramic output capacitor was changed from after the tantalum capacitors to

immediately after the diode, as seen in Figure 3.17. This change improved the output voltage ripple to under 5% for the same input and output conditions.

Figure 3.17: Circuit and Layout Changes

CHAPTER 4

Results

4.1 Simulation Results

4.1.1 SEPIC Simulation Results

The SEPIC design based on the LT3759 was simulated in LTSpice under a variety of input and output conditions. Since the input to the SEPIC can vary widely with the battery and the dynamo hub ranging from low to high speeds, many scenarios were simulated. Figures 4.1 to 4.3 show three of the most important scenarios. These simulations were carried out at the beginning of the Revision B design, before the phone and battery output diodes were added to the circuit and when the input voltage limit was set to 23V. The output voltages in the simulations are 0.55V (the output diode drop) lower than they actually are in the final design. The input and output parameters i.e. voltage and current are taken from Table 2.2.

The first scenario has the hub as input to the SEPIC and the battery as output. This scenario tests the lowest input voltage, when the bicycle speed is 7 MPH. The input varies from 4.5V maximum to 2V minimum and the output is 4.2V for charging the battery. The simulation results show that the SEPIC operates as expected.

Figure 4.1: LTSpice Simulation Circuit with 7 MPH Hub Input

Figure 4.2: LTSpice Simulation Results with 7MPH Hub Input

The next scenario is again with the hub as input to the SEPIC and the battery as output. The highest input voltage is tested, simulating a bicycle speed of 20 MPH. The input has a peak value of 23V and there should be some ripple on the input when a load

current is drawn. The exact amount of ripple is not known, but a 1V peak-to-peak is used as an estimation. The output is 5V for charging the phone. The simulation results again show that the SEPIC operates as expected.

Figure 4.3: LTSpice Simulation Circuit with 20MPH Hub Input

Figure 4.4: LTSpice Simulation Results with 20MPH Hub Input

The last simulation scenario depicted has the battery as input to the SEPIC and the iPhone5 as output. The input is at the lowest battery voltage of 3.6V minus the 0.55V drop of the input diode, so the input to the converter is 3.05V. The simulation results show that the SEPIC operates as expected.

Figure 4.5: LTSpice Simulation Circuit with Battery Input

Figure 4.6: LTSpice Simulation Results with Battery Input

4.1.2 Component Rating Simulation Results

The LTSpice SEPIC simulation also verified that the component ratings were adequate. The most important ratings are listed in Table 3.2. The exact values measured in the simulation are not of particular interest, so they are omitted from this paper. The important point is that the values measured in the simulation did not exceed any of the component ratings.

No portions of the circuit other than the SEPIC were simulated since there was either no practical way to simulate them, or it did not seem necessary to simulate them. One exception is the MATLAB simulation for input capacitor sizing and peak repetitive diode current carried out in Section 3.1.2. In all other cases, the ratings and operation of components and circuit sections were verified by hand calculation.

4.2 Standard Test Bench Results

4.2.1 SEPIC Performance

The SEPIC was tested using standard test equipment to characterize its performance. The test equipment included one DC power supply for the input to the SEPIC, another DC power supply for the rest of the circuit, a DC electronic load, and an oscilloscope. The performance characteristics are line regulation, load regulation, efficiency, and output voltage ripple. The raw data from the tests is in Appendix E. Three tests were performed, one at 5.5V output for the phone after the output diode, another at 4.2V output for the maximum battery charging voltage, and the last at 3.6V for the minimum battery charging voltage. These last two scenarios were tested before the battery output diode was added to the circuit. In each test, four different input voltages

were tested (22V, 16V, 7.3V and 4.5V), and the load was incremented by 100mA from no load to the full load of 1A. The maximum input voltage to the circuit is 22V (this was after a design revision to lower the 23V input limit to 22V). The other input voltages come from Table 2.2. A 16V input occurs when the output current is roughly the 1A maximum output current. A 7.3V input occurs when the output current is roughly the 500mA minimum current needed by the iPhone5 to charge. Lastly, 4.5V is the minimum peak input to the circuit at a speed of 7 MPH. These input voltages give a general sense of the SEPIC performance over the range of conditions in Table 2.2.

Figures 4.7 to 4.9 show how the SEPIC efficiency varies with load current for each of the three output voltage settings. Efficiency is defined by Equation 4.1.

$$\text{Efficiency} = \frac{\text{Output Power}}{\text{Input Power}} \times 100\%$$

Equation 4.1: Efficiency

The highest efficiency of the SEPIC was 83.55% and occurred at 4.5V input, 5.5V output, 500mA load. Generally, the SEPIC has an efficiency between 70% and 85%, which matches the estimated efficiency of 75% in Table 2.2.

Figure 4.7: Test bench SEPIC efficiency with output set to 5.5V

Figure 4.8: Test bench SEPIC efficiency with output set to 4.2V

Figure 4.9: Test bench SEPIC efficiency with output set to 3.6V

The highest line regulation encountered over all tests was 0.92%, and the highest load regulation encountered over all tests was 2.51%. Both of these figures are acceptable. Line regulation is calculated at full load and is defined by Equation 4.2.

$$\text{Line Regulation} = \frac{V_{\text{out}(\text{high input})} - V_{\text{out}(\text{low input})}}{V_{\text{out}(\text{nominal})}} \times 100\%$$

Equation 4.2: Line Regulation

Load regulation is calculated for each input voltage tested and is defined by Equation 4.3.

$$\text{Load Regulation} = \frac{V_{\text{out}(10\% \text{ load})} - V_{\text{out}(90\% \text{ load})}}{V_{\text{out}(90\% \text{ load})}} \times 100\%$$

Equation 4.3: Load Regulation

The one performance parameter that was outside of normal tolerance was the output voltage ripple. The highest ripple encountered over all tests was 6.83%, which is well over the 2% typical tolerance of DC/DC converter design. Voltage ripple is defined by Equation 4.4.

$$\text{Voltage Ripple} = \frac{\Delta V_{\text{out}}}{V_{\text{out(average)}}} \times 100\%$$

Equation 4.4: Voltage Ripple

This deficiency is not an issue since voltage ripple should not significantly affect battery charging and later testing showed no problems charging the iPhone5.

4.2.2 System Functionality

Aside from testing the performance of the SEPIC, the functionality of the rest of the circuit was verified. The input protection did switch the MOSFET off once the input voltage reached the pre-determined threshold. The input protection functioned as expected, with the only noticeable issue being that the zener regulator resistors became hot to the touch during high speed hub testing; this may be an issue to address in the future.

The microcontroller and its peripherals also proved to function correctly. The digital potentiometer was successfully programmed via SPI and allowed for the performance testing of the SEPIC. The ADC was verified with the test code found in Appendix D. Temperature sensor functionality was verified by setting a threshold slightly above ambient room temperature and turning the green LED on below this threshold and the red LED on above this threshold. As the temperature of the sensor was increased by breathing on it, the LED changed from green to red and then back to green once the sensor returned to ambient temperature. The current sensing circuits were tested using the DC electronic load to vary current. The same threshold and LED technique was used to verify the current sensing circuits and voltage sensing. These tests simply verified that the peripherals functioned. No testing was carried out to determine the exact accuracy of the ADC readings; however the test results using the threshold and LED method made sense and seemed reasonable.

The functionality of the tact switches was not verified; however these were never needed for debugging. Enabling and disabling the phone, battery, and input were all verified and used during SEPIC testing, battery charging, and phone charging.

4.3 Custom Test Fixture Results

The following test results validate the fact that the circuit can charge the iPhone5 at speeds ranging from 7 MPH to 55 MPH. The first test verifies that the battery charges at 7 MPH. The second test verifies that the battery can be cycled back to the input of the SEPIC to charge the iPhone5. The last three tests verify that the iPhone5 can be charged directly from the hub at speeds ranging from approximately 15 MPH to 55 MPH. The

battery powered the circuit during these tests, which verifies that the circuit can operate as a stand-alone system, without an external power source.

Test 1: Hub input to battery output

Initial Battery Voltage: 3.8000V
Final Battery Voltage: 3.8370V
Output Voltage¹: 4.193V
Hub Speed: 7 MPH
Elapsed Time: 12 minutes

Test 2: Battery input to iPhone5 output

Initial Charge²: 76%
Final Charge²: 77%
Output Voltage¹: 5.112V
Elapsed Time: 20 minutes
Icon switches between charging and charged

Test 3: Hub input to iPhone5 output, ~15 MPH

Initial Charge²: 74%
Final Charge²: 75%
Output Voltage¹: 5.122V
Hub Speed: 14 to 15 MPH
Elapsed Time: 5 Minutes
Icon switches between charging and charged

Test 4: Hub input to iPhone5 output, 23 MPH

Initial Charge²: 75%
Final Charge²: 78%
Output Voltage¹: 5.122V
Hub Speed: 23 MPH
Elapsed Time: 4 Minutes
Icon indicates charging

Test 5: Hub input to iPhone5 output, 55 MPH

Initial Charge²: 75%
Final Charge²: 75%
Output Voltage¹: 5.122V
Hub Speed: 55 MPH
Elapsed Time³: 1 Minute
Icon indicates charging

Notes:

1. Output Voltage is measured at no load after the output diode
2. Charge is measured using the iBattery Pro Application for iPhone5
3. Testing was stopped at 1 minute due to heating of the input protection zener regulator resistors

During testing with the iPhone5 as output, the output voltage dropped from the nominal 5.112V and fluctuated between 4.8 and 4.9 volts. This did not seem to adversely affect charging. The iPhone5 never displayed the warning message “Charging is not supported with this accessory” during testing. Another important observation is that during tests 2 and 3 the battery icon on the iPhone5 would switch between indicating that it was charging and then indicating that it was charged. This may be an issue to address in the future. An additional test was performed with the hub input to iPhone5 output at 7 miles per hour to see how the iPhone5 would react. The phone vibrated, indicating that it was plugged in, and the battery icon indicated that it was charged. Although this scenario would not normally be encountered, it is good to know that the warning message was not displayed.

CHAPTER 5

Conclusion

5.1 Meeting the Design Requirements

5.1.1 Description of Criteria Met

The charger meets the iPhone5 charging requirements at speeds ranging from 7 MPH to 55 MPH. After troubleshooting and three revisions, all aspects of the circuit have been verified to function properly. Once firmware is finalized, the device can be used in its intended environment. The circuit meets the mechanical dimensions required by the case design and the case meets the ergonomic goals set forth in Section 1.1.3. The case is roughly the size of the BioLogic iPhone case, yet also houses the charging electronics inside, meeting the design goal of a compact and user-friendly product. There is just one cable that connects to the dynamo hub. The user must simply plug in their iPhone5 and start riding for a plug-and-play experience.

5.1.2 Cost Analysis

The overall cost analysis is compiled from the case cost analysis in Appendix H, the Bill of Materials for the electronic components in Appendix F, a PCB fabrication quote from Sunstone Circuits and a PCB assembly quote from Sierra Circuits. The case cost analysis provides two options: an injection molded case and a CNC machined case. The case cost decreases with increasing quantity for both options, but at 1000 pieces, the injection molded case is the better value. Since this charger will be a mass-produced product, the injection molded case option is chosen. Other components for the charger are also priced at the 1000 piece order quantity. Sunstone Circuits quotes 1000 2.5" x 4"

RoHS compatible 2-Layer PCBs with no silkscreen and a 5 week turnaround for \$2539.15. Sierra Circuits quotes a \$34.20 assembly cost per board for a quantity of 1000 pieces and a 15 day turnaround. Each of these quotes was for the lowest cost per board.

The cost per case is \$37.72, the cost of the electrical components is \$35.80, the cost per PCB is \$2.54, and the cost of assembly per PCB is \$34.20. This totals at \$110.26 for the charger at an order quantity of 1000 pieces. This price can be marked up by 50% for a retail cost of \$165.39, which falls in the \$150 - \$200 price range set forth in Section 1.1.2. An established company may have access to less expensive materials and labor, so the profit margin could be increased while maintaining the \$150 - \$200 price range.

5.2 Future Improvements

5.2.1 Hardware Improvements

This thesis has proven the ability to charge a smartphone with a bicycle dynamo hub and provides a foundation for future designs and applications. The device can also be improved by making several hardware changes. First, there are two necessary PCB layout revisions: the layout must accommodate the battery output diode and the ceramic output capacitor footprint must be moved from after the tantalum output capacitors to immediately after the converter diode, as shown in Figure 3.17. A few changes in the layout of the SEPIC could improve the output voltage ripple as well. The switching node can be made smaller and other components can be moved further away from the converter; these changes should reduce switching noise coupled onto other signal paths.

One important issue to address is that the input protection circuitry requires power from the battery to operate, so the battery must maintain a charge at all times. If not, the

circuit will not function at all. If the charger is used on a frequent basis, this should not be an issue; however if the charger is left unused for an extended period, it will not turn on and accept hub power. The quiescent current of the circuit is 12.45mA, and given a fully charged battery, this current would drain the battery completely in about 56 hours. Future revisions should address this issue.

5.2.2 Compatibility

All consumer electronics must meet certain compatibility requirements in order to be marketed and sold. These requirements vary depending on the country in which the product will be sold, but a few of them are: Electromagnetic Compatibility (EMC), Restriction of Hazardous Substances (RoHS), Underwriters Laboratories (UL), and Federal Communication Commission (FCC) compatibility. In the design of this product, the only compatibility that is known is the RoHS status of the PCB and the components listed in the Bill of Materials shown in Appendix F. The product must undergo testing to meet some of the other compatibilities; however this is outside of the scope of this thesis and will be carried out at a later time.

5.2.3 Extended Testing

With the resource of the new test fixture, many different test scenarios can be carried out. The product should be tested over all conceivable operating ranges and should be tested on a bicycle. In addition to testing on the new test fixture, the product should be subjected to mechanical vibration testing, due to the nature of bicycle riding, thermal testing over all conceivable temperatures that the product will be subjected to,

and splash testing to verify that the case is indeed weatherproof. Once the actual end product is made, it should undergo Alpha and Beta testing by actual users to confirm that the device functions properly and meets the needs of the consumer.

5.2.4 Firmware

The development of firmware is necessary to realize the full potential of this device. The current firmware used for testing proves that the potential for a fully functioning product exists. It is the basis for the operation of the system, and will be restructured for a more efficient and logical control flow. For example, SPI and ADC will be executed within functions that are called when needed. Although the entirety of the firmware and its functionality will be realized as it is developed, the general control flow is outlined here.

The battery voltage is measured and the digital potentiometer is set to deliver current to the battery. The battery is enabled as the load and the input is enabled. If sufficient output current is measured (at least 500mA), the battery is disabled as a load, the digital potentiometer is set to 5.5V, and the phone is enabled as the load. The phone charges as long as there is sufficient current to do so. If the output current drops below 500mA, output switches from the phone to the battery. The digital potentiometer is set to a voltage above the open circuit voltage of the battery so that current flows from the output of the converter to the battery. During battery charging, the battery voltage, output current, and battery temperature are monitored. If the temperature rises above the safe operating range of the battery, charging pauses until the temperature returns to the safe operating range. As the battery charges, the output current will decrease as the

internal voltage of the battery increases. Once the output current is below a certain threshold, the digital potentiometer is adjusted to increment the output voltage of the converter, thus increasing the output current to the battery. This accomplishes a stepped version of a constant current charging scheme. Although this encompasses the necessary duties of the firmware, there are future firmware possibilities, such as maximum power point tracking, to exploit the maximum power of the dynamo hub.

5.3 Future Opportunities

5.3.1 Patenting

To bring this product to consumers, a patent must be obtained so that the design can be leased or sold to a company which will manufacture, market and sell the product. Patenting the design is outside of the scope of this thesis, but should be carried out in the near future.

5.3.2 Other Smartphones

This design was intended to meet the electrical and mechanical needs of the iPhone5; however it is conceivable that it could be modified to accommodate other smartphones. The two main aspects to change are the case dimensions and the phone connector. Smartphones can be charged using the USB interface, so the charging electronics would not need modification unless the smartphone draws more than 1A of current to charge.

5.3.3 Future Applications

This design could also be modified to meet the needs of other applications. For example, a low-cost version could be designed for consumers in developing nations. This could be particularly beneficial to people who have bicycles and smartphones, but no access to conventional grid electricity. There are components in this design which could be omitted or replaced with lower-cost components to achieve the same or similar functionality. For example the SEPIC tantalum output capacitors could be replaced with cheaper electrolytic capacitors.

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Appendices

- A. Hub Test Data
- B. Cycling Power Assessment Procedure
- C. MATLAB Code
- D. C Test Code for Microcontroller
- E. SEPIC Test Data
- F. Bill of Materials
- G. Case Engineering Drawings
- H. Case Cost Analysis
- I. Digital Potentiometer Settings and Output Voltage Range

APPENDIX A

Hub Test Data

Speed (MPH)	Voltage (V)	Current (mA)	Power (W)	Frequency (Hz)
3.0	0.215	499	0.107	8.80
5.0	2.163	500	1.082	13.89
6.8	3.974	500	1.987	20.16
10.0	7.290	500	3.645	29.41
15.2	12.770	500	6.385	43.86
20.0	17.870	500	8.935	58.82
25.1	22.890	500	11.445	72.46
30.0	27.930	500	13.965	86.21
35.0	33.050	500	16.525	100.80
40.0	37.790	500	18.895	114.70
45.1	42.980	500	21.490	130.20
47.6	45.400	500	22.700	137.40

Table A1: Shimano DH-3D72 Constant 500mA Test

Speed (MPH)	Voltage (V)	Current (mA)	Power (W)
Constant Current 400 mA			
9.5	9.50	400.0	3.800
15.3	16.59	401.0	6.653
19.7	21.92	400.0	8.768
24.5	27.64	400.0	11.056
34.5	39.60	400.0	15.840
Constant Current 550 mA			
15.5	6.75	551.2	3.721
20.6	10.54	549.9	5.796
25.2	13.53	550.6	7.450
35.0	20.41	550.1	11.228
45.5	27.47	550.2	15.114
Constant Voltage 6V			
5.2	6.01	214.0	1.286
7.0	6.00	436.0	2.616
10.0	6.00	518.0	3.108
13.0	6.03	544.0	3.280
13.7	6.00	547.0	3.282

Speed (MPH)	Voltage (V)	Current (mA)	Power (W)
Constant 20.11 ohm Resistance			
3.0	3.60	179.0	0.644
4.8	5.30	263.6	1.397
6.5	6.90	343.1	2.367
8.4	8.25	410.2	3.385
10.1	9.16	455.5	4.172
14.1	10.29	511.7	5.265
16.9	10.69	531.6	5.683
20.3	10.98	546.0	5.995
22.9	11.12	553.0	6.149
26.8	11.27	560.4	6.316
31.4	11.39	566.4	6.451
34.9	11.45	569.4	6.519
38.3	11.50	571.9	6.576
42.8	11.55	574.3	6.634

Table A2: Additional Shimano DH-3D72 Tests

Speed (MPH)	Voltage (V)	Current (mA)	Power (W)	Frequency (Hz)
3.6	1.51	500.0	0.755	13.0
4.8	2.77	500.0	1.385	18.9
6.8	4.46	501.0	2.234	24.0
10.3	7.51	499.2	3.749	37.9
14.9	11.14	500.1	5.571	56.8
20.1	14.92	501.7	7.485	76.9
25.1	18.50	501.5	9.278	92.6
30.1	21.88	500.0	10.940	111.1
35.1	24.99	500.0	12.495	131.6
40.6	28.57	499.0	14.256	150.6
45.1	31.09	500.0	15.545	168.9
48.6	32.50	500.0	16.250	181.2

Table A3: SON Delux Constant 500mA Test

Speed (MPH)	Voltage (V)	Current (mA)	Power (W)	Frequency (Hz)
2.9	1.36	392	0.533	7.7
5.0	3.36	400	1.344	16.9
7.2	5.59	400	2.236	22.9
10.4	8.50	400	3.400	32.0
15.3	12.59	398	5.011	45.5
19.8	15.47	401	6.203	58.8
24.7	18.33	401	7.350	71.4
30.0	21.00	400	8.400	87.7
35.0	23.50	399	9.377	101.6
40.2	25.50	401	10.226	117.9
45.1	27.47	400	10.988	130.2
51.8	29.88	400	11.952	150.6

Table A4: Sanyo H27 Constant 400mA Test

*Note: All voltages and currents from the hub tests are AC RMS values. The load used for testing was a decade load resistor in series with a rheostat.

APPENDIX B

Cycling Power Assessment Procedure

1. Figure B1 was examined to obtain hub drag values.
2. The hub drag values were tabulated and averaged in Table B1.
3. Equations were fitted to the hub drag values in Figure B2.
4. The hub electrical power output was derived from Equation 2.3 for speeds of interest i.e. 5 MPH, 10 MPH, etc.
5. Hub electrical power and drag were tabulated in Table B2. The HB NX32 was grouped with the Sanyo H27 and labeled as “Low-End Hub”. The DH Average was grouped with the Shimano DH-3D72 and labeled as “Middle-Of-The-Road Hub”. The SON Average was grouped with the SON Delux and labeled as “High-End Hub”.
6. Equation 1.1: Road Cycling Power and the data for the “Middle-Of-The-Road Hub” is used in the Excel spreadsheet pictured in Table B3 to determine the power needed to ride the bicycle with no front dynamo hub. The Power Loss in Wheel Bearings is divided by two since the front wheel bearing is replaced by the dynamo hub.
7. The Total Power is calculated as the sum of the Bicycle Power, Hub Drag, and Hub Electrical Power.
8. In Scenario 1 the Gradient is increased until the Bicycle Power approximately equals the previous Total Power value. The Gradient Increase is the old Gradient value subtracted from the new Gradient value. The same procedure is done for Scenario 2, but with Headwind instead of Gradient.

*Note: This procedure does not take into account the power loss in the conversion of mechanical energy to electrical energy in the hub. There was no practical way to measure this and no data providing this information could be found. Since this procedure is implemented only to get a general sense of the impact of the dynamo hub on bicycling performance, and it is reasonable to assume high electrical generator efficiency, it is also reasonable to neglect this power loss.

Figure B1: Hub Drag Data [1]

Hub	Speed (km/hr)	Speed (MPH)	Drag (W)
HB NX32	10	6.21	1.4
	20	12.43	4
	30	18.64	7
	50	31.07	14.8

	Speed (km/hr)	Speed (MPH)	Drag (W)
HB NX32	10	6.21	1.4
	20	12.43	4
	30	18.64	7
	50	31.07	14.8

Hub	Speed (km/hr)	Speed (MPH)	Drag (W)
DH 3N30	10	6.21	0.8
	20	12.43	1.8
	30	18.64	3
	50	31.07	5

	Speed (km/hr)	Speed (MPH)	Drag (W)
DH Average	10	6.21	0.7
	20	12.43	1.5
	30	18.64	2.5
	50	31.07	4.5

Hub	Speed (km/hr)	Speed (MPH)	Drag (W)
DH 3N70	10	6.21	0.5
	20	12.43	1.2
	30	18.64	2
	50	31.07	3.8

	Speed (km/hr)	Speed (MPH)	Drag (W)
SON Average	10	6.21	0.3
	20	12.43	0.8
	30	18.64	1.4
	50	31.07	2.9

Hub	Speed (km/hr)	Speed (MPH)	Drag (W)
DH 3N71	10	6.21	0.7
	20	12.43	1.6
	30	18.64	2.5
	50	31.07	4.6

Hub	Speed (km/hr)	Speed (MPH)	Drag (W)
SON28	10	6.21	0.3
	20	12.43	0.9
	30	18.64	1.6
	50	31.07	3.3

Hub	Speed (km/hr)	Speed (MPH)	Drag (W)
SON20	10	6.21	0.2
	20	12.43	0.7
	30	18.64	1.2
	50	31.07	2.5

Table B1: Hub Drag Tabulated Data

Figure B2: Hub Drag Equation Fitting to Data

Pedaling Power		Low-End Hub			Middle-Of-The-Road Hub			High-End Hub		
Speed (MPH)	Power (W)	Electrical (W)	Hub Drag (W)	Efficiency (%)	Electrical (W)	Hub Drag (W)	Efficiency (%)	Electrical (W)	Hub Drag (W)	Efficiency (%)
5	8.47	2.08	0.98	47.12	2.15	0.49	43.65	2.49	0.16	69.76
10	27.93	3.78	2.90	47.07	4.70	1.20	62.71	4.63	0.57	76.73
15	69.33	5.34	5.15	44.77	7.24	1.93	68.03	6.69	1.04	78.30
20	143.60	6.75	7.76	42.10	9.78	2.69	70.41	8.66	1.56	78.48
25	261.71	8.01	10.71	39.38	12.33	3.48	71.68	10.54	2.14	78.10
30	434.58	9.13	14.00	36.70	14.87	4.28	72.41	12.33	2.77	77.43
35	673.17	10.10	17.64	34.11	17.41	5.12	72.84	14.03	3.45	76.58
40	988.42	10.93	21.62	31.61	19.95	5.98	73.09	15.64	4.20	75.62
45	1391.28	11.62	25.95	29.22	22.50	6.86	73.22	17.16	4.99	74.57
50	1892.69	12.16	30.63	26.92	25.04	7.77	73.27	18.59	5.84	73.46
55	2503.59	12.55	35.65	24.71	27.58	8.70	73.26	19.93	6.75	72.30

Table B2: Tabulated Values for Power Parameters

Parameter	Variable	Value	Unit
Air velocity	V_a	12.43	m/s
Ground velocity	V_G	11.18	m/s
Air density	ρ	1.2234	kg/m ³
Coefficient of drag	C_D		
Frontal area	A	0.2565	m ²
Drag area of the spokes	F_W	0.0044	m ²
Coefficient of rolling resistance	C_{RR}	0.0032	
Total mass of bike and rider	m_T	90.79	kg
Acceleration of gravity	g	9.81	m/s ²
Road gradient (rise/run)	G_R	0	
Moment of inertia of the two wheels	I	0.14	kg*m ²
Outside radius of the tire	r	0.311	m
Final ground velocity	V_{Gf}	0	m/s
Initial ground velocity	V_{Gi}	0	m/s
Initial time	t_i	0	s
Final time	t_f	0	s
Chain Efficiency	E_C	0.97698	

Speed in MPH
25
Headwind in MPH
2.8
Weight in Pounds
200
Gradient (%)
0

Total Aerodynamic Power	275.47
Power to overcome Rolling Resistance	31.85
Power loss in Wheel Bearings	1.05
Change in Potential Energy	0.00
Change in Kinetic Energy	0.00
Total Power	315.64

Table B3: Example Bicycling Power Calculation

APPENDIX C

MATLAB Code

```
%Input Capacitor Sizing
%Chris Arntzen
%Master Thesis
%Advisor: Prof. Slivovsky
%Cal Poly, SLO

clc
clear all

%150 data points results in a speed increment of 0.1 MPH from 0 - 15
MPH
speed = zeros(150,1); %Bicycle Speed
C = zeros(150,2); %Capacitance
Ipk = zeros(150,2); %Peak Current
Vmin = zeros(150,1); %Minimum voltage, greatest capacitor ripple
t1 = zeros(150,1); %Time at which capacitor reaches minimum
voltage
dvdt = zeros(150,1); %Voltage waveform derivative
Iin = 0.5; %Input current is 500mA constant

%Increment speed from 0 to 15 MPH
for m = 1:150

    speed(m) = m*0.1;
    %Neglect speeds less than 6.5 MPH since they result in huge
    capacitor values
    if speed(m) <= 6.5
        speed(m) = 6.5;
    end
    %Hub frequency calculation
    Fhub = 2.8758*speed(m) + 0.2862;
    %Source voltage calculation
    Vs = (1.0172*speed(m) - 2.7785)*sqrt(2) - 1.6;
    %Input voltage limited to 22V
    if Vs > 22
        Vs = 22;
    end
    %2V is the lower limit for the input to the converter
    if Vs <= 2
        Vs = 2;
    end
    t2 = 1/(4*Fhub); %t2 is at the peak of the voltage waveform

    %For each speed, calculate the capacitance as minimum voltage is
    %incremented from 2 to Vs
    for n = 1:150
        %Vmin ranges from 2V to a maximum of Vs
        Vmin(n) = ((n-1)*(Vs-2)/150) + 2;
```



```

        %Calculate t1
        t1(n) = (asin(Vmin(n)/Vs))/(2*pi*Fhub);
        %Calculate the capacitance
        C(n,m) = (Iin*(t2 + t1(n)))/(Vs - Vmin(n));
        %Calculate the derivative of the voltage waveform
        dvdt(n) = Vs*2*pi*Fhub*cos(2*pi*Fhub*t1(n));
        %Calculate the repetative peak current for diode rating
        Ipk(n,m) = C(n,m)*dvdt(n);
    end

end

Y = 1:1:150;
[ speed, Y] = meshgrid(speed, Y);

%Plot Peak Current
surf(speed, Y, Ipk);
xlabel('Speed (MPH) '); ylabel('Index'); zlabel('Peak Current (A) ');

%Plot Capacitance
surf(speed, Y, C);
xlabel('Speed (MPH) '); ylabel('Index'); zlabel('Capacitance (F) ');

```

APPENDIX D

C Test Code for Microcontroller

```
//Smartphone Charger Testing Code
//Chris Arntzen
//Master Thesis
//Advisor: Prof. Slivovsky
//Cal Poly, SLO

#include <avr/io.h>
#include <util/delay.h>    // software delay functions

int main(void){

    // set Data Direction for GPIO
    DDRD |= (1<<PD0);      // PORTD0 = output (input_enable)
    DDRD |= (0<<PD1);      // PORTD1 = input (switch1)
    DDRD |= (0<<PD2);      // PORTD2 = input (switch2)
    DDRD |= (1<<PD3);      // PORTD3 = output (greenLED)
    DDRD |= (1<<PD4);      // PORTD4 = output (redLED)
    DDRD |= (1<<PD5);      // PORTD5 = output (battery_enable)
    DDRD |= (1<<PD6);      // PORTD6 = output (phone_enable)
    DDRD |= (1<<PD7);      // PORTD7 = output (converter_disable)

    // set Data Direction for ADC Analog Inputs
    DDRC |= (0<<PC0);      // analog pin0/PORTC0 = input (Batt_VSense)
    DDRC |= (0<<PC1);      // analog pin1/PORTC1 = input (Out_ISense)
    DDRC |= (0<<PC2);      // analog pin2/PORTC2 = input (VOut_VSense)
    DDRC |= (0<<PC3);      // analog pin3/PORTC3 = input (In_ISense)
    DDRC |= (0<<PC4);      // analog pin4/PORTC4 = input (VIn_VSense)
    DDRC |= (0<<PC5);      // analog pin5/PORTC5 = input (Temp_Sense)

    // set Data Direction for SPI
    DDRB |= (1<<PB2);      // PORTB2 = output (/cs)
    DDRB |= (1<<PB3);      // PORTB3 = output (MOSI)
    DDRB |= (1<<PB5);      // PORTB4 = output (SCK)

    // set ADC registers
    ADCSRA |= ((1<<ADPS2)|(1<<ADPS1)|(1<<ADPS0));
    ADMUX |= (1<<MUX0);
    ADMUX |= (1<<MUX1);
    ADMUX |= (0<<MUX2);
    ADMUX &= ~(1<<REFS0);
    ADMUX &= ~(1<<REFS1);    //Vref as voltage reference
    ADCSRB &= ~( (1<<ADTS2)|(1<<ADTS1)|(1<<ADTS0));    //Free-running mode
    ADCSRA |= (1<<ADATE);    //Enable auto-triggering
    ADCSRA |= (1<<ADEN);      //Enable the ADC
    ADCSRA |= (1<<ADSC);      //Start conversion

    // initialize variables
```

```

int adc_value;
int twohundred_mA = 193;
int onehundred_mA = 96;
int n = 0;
char cData = 0;

//***** MAIN LOOP *****
//*****

for(;;){

if(n == 0){

PORTD |= (1<<PD6);          //enable phone

_delay_ms(600);              // Wait for MAX1822 charge pumps to charge

//***** SPI WRITE *****
//*****

PORTB |= (1<<PB2);           // Disable CS

/* Enable SPI, Master, set clock rate fck/16 */
SPCR = (1<<SPE) | (1<<MSTR) | (1<<SPR0);
//5.5V = 0x01  5V = 0x03  4.2V = 0x0A  3.6V = 0x10
cData = 0x02;
//Start transmission
PORTB &= ~(1<<PB2);          // Enable CS
SPDR = cData;

/* Wait for transmission complete */
while(!(SPSR & (1<<SPIF)))
;
PORTB |= (1<<PB2);           // Disable CS

PORTD |= (1<<PD0);           //enable input
}

n = 1;

//***** ADC READ *****
//*****

adc_value = ADCW;            //Read the ADC value

if((adc_value >= onehundred_mA) && (adc_value <= twohundred_mA)){
    PORTD |= (1<<PD3);
    PORTD |= (1<<PD4);        //Turn both LEDs on
}else
if(adc_value < onehundred_mA){
    PORTD |= (1<<PD3);        //If ADC value is above turn green led on
}
}

```

```

        PORTD &= ~(1<<PD4);    //If ADC value is above turn red led off
    }else
    if(adc_value > twohundred_mA){
        PORTD |= (1<<PD4);    //If ADC value is above turn red led on
        PORTD &= ~(1<<PD3);    //If ADC value is above turn green led off
    }

}

return 1;
}

```

APPENDIX E

SEPIC Test Data

22V Input (Maximum)							16V Input (15 MPH)						
Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)	Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)
0	5.548				<264		0	5.545				<252	
100	5.537	33	0.726	0.554	<264	76.27	100	5.533	45	0.720	0.553	<252	76.85
200	5.526	64	1.408	1.105	<264	78.49	200	5.523	88	1.408	1.105	<252	78.45
300	5.516	96	2.112	1.655	<264	78.35	300	5.514	132	2.112	1.654	<252	78.32
400	5.505	127	2.794	2.202	<264	78.81	400	5.504	175	2.800	2.202	<252	78.63
500	5.495	159	3.498	2.748	264	78.54	500	5.495	219	3.504	2.748	<252	78.41
600	5.484	190	4.180	3.290	264	78.72	600	5.484	263	4.208	3.290	<252	78.19
700	5.475	222	4.884	3.833	264	78.47	700	5.475	307	4.912	3.833	252	78.02
800	5.464	253	5.566	4.371	264	78.53	800	5.464	351	5.616	4.371	252	77.83
900	5.454	284	6.248	4.909	264	78.56	900	5.455	394	6.304	4.910	252	77.88
1000	5.443	315	6.930	5.443	264	78.54	1000	5.445	437	6.992	5.445	252	77.87
7.3V Input (9 MPH)							4.5V Input (7 MPH)						
Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)	Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)
0	5.538						0	5.537				<328	
100	5.530	96	0.701	0.553	<180	78.91	100	5.531	153	0.689	0.553	<328	80.33
200	5.522	187	1.365	1.104	<180	80.90	200	5.526	299	1.346	1.105	<328	82.14
300	5.515	279	2.037	1.655	<180	81.23	300	5.522	444	1.998	1.657	<328	82.91
400	5.507	371	2.708	2.203	<180	81.34	400	5.516	588	2.646	2.206	<328	83.39
500	5.500	463	3.380	2.750	180	81.36	500	5.512	733	3.299	2.756	<328	83.55
600	5.492	553	4.037	3.295	180	81.63	600	5.506	882	3.969	3.304	328	83.24
700	5.485	643	4.694	3.840	180	81.80	700	5.502	1036	4.662	3.851	328	82.61
800	5.477	734	5.358	4.382	180	81.77	800	5.497	1193	5.369	4.398	328	81.91
900	5.470	826	6.030	4.923	180	81.64	900	5.493	1356	6.102	4.944	328	81.02
1000	5.462	920	6.716	5.462	180	81.33	1000	5.488	1523	6.854	5.488	328	80.08

*NOTE: Digipot set for approximately 5.5Vout with 7.3Vin at no load

Speed (MPH)	Load Regulation (%)
Max	1.52
15	1.43
9	1.10
7	0.69

Line Regulation (%)
0.81

Speed (MPH)	Output Ripple (%)
Max	4.85
15	4.63
9	3.30
7	5.98

Table E1: SEPIC Test Data with 5.5V Output Voltage

22V Input (Maximum)							16V Input (15 MPH)						
Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)	Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)
0	4.174				<252		0	4.171				<236	
100	4.162	26	0.572	0.416	<252	72.76	100	4.159	35	0.560	0.416	<236	74.27
200	4.151	50	1.100	0.830	<252	75.47	200	4.149	68	1.088	0.830	<236	76.27
300	4.141	74	1.628	1.242	<252	76.31	300	4.138	101	1.616	1.241	<236	76.82
400	4.129	98	2.156	1.652	<252	76.60	400	4.128	135	2.160	1.651	<236	76.44
500	4.119	122	2.684	2.060	252	76.73	500	4.118	169	2.704	2.059	<236	76.15
600	4.107	146	3.212	2.464	252	76.72	600	4.106	202	3.232	2.464	236	76.23
700	4.096	171	3.762	2.867	252	76.21	700	4.096	235	3.760	2.867	236	76.26
800	4.084	195	4.290	3.267	252	76.16	800	4.085	269	4.304	3.268	236	75.93
900	4.074	219	4.818	3.667	252	76.10	900	4.075	301	4.816	3.668	236	76.15
1000	4.062	242	5.324	4.062	252	76.30	1000	4.063	333	5.328	4.063	236	76.26
7.3V Input (9 MPH)							4.5V Input (7 MPH)						
Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)	Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)
0	4.167				<188		0	4.167				<208	
100	4.157	73	0.533	0.416	<188	78.01	100	4.159	117	0.527	0.416	<208	78.99
200	4.148	145	1.059	0.830	<188	78.38	200	4.152	228	1.026	0.830	<208	80.94
300	4.141	216	1.577	1.242	<188	78.79	300	4.146	340	1.530	1.244	<208	81.29
400	4.131	288	2.102	1.652	<188	78.60	400	4.139	450	2.025	1.656	208	81.76
500	4.123	359	2.621	2.062	<188	78.66	500	4.133	560	2.520	2.067	208	82.00
600	4.114	428	3.124	2.468	<188	79.00	600	4.125	674	3.033	2.475	208	81.60
700	4.105	498	3.635	2.874	188	79.04	700	4.119	791	3.560	2.883	208	81.00
800	4.095	569	4.154	3.276	188	78.87	800	4.113	911	4.100	3.290	208	80.26
900	4.087	640	4.672	3.678	188	78.73	900	4.106	1034	4.653	3.695	208	79.42
1000	4.078	714	5.212	4.078	188	78.24	1000	4.1	1161	5.225	4.100	208	78.48

*NOTE: Digipot set for approximately 4.2Vout with 7.3Vin at no load

Speed (MPH)	Load Regulation (%)
Max	2.16
15	2.06
9	1.71
7	1.29

Line Regulation (%)
0.91

Speed (MPH)	Output Ripple (%)
Max	6.20
15	5.81
9	4.61
7	5.07

Table E2: SEPIC Test Data with 4.2 Output Voltage

22V Input (Maximum)							16V Input (15 MPH)						
Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)	Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)
0	3.685				<244	57.60	0	3.682				<244	
100	3.675	29	0.638	0.368	<244	66.60	100	3.671	36	0.576	0.367	<244	63.73
200	3.663	50	1.100	0.733	<244	69.17	200	3.66	65	1.040	0.732	<244	70.38
300	3.652	72	1.584	1.096	<244	71.18	300	3.65	95	1.520	1.095	<244	72.04
400	3.641	93	2.046	1.456	<244	71.74	400	3.639	125	2.000	1.456	<244	72.78
500	3.63	115	2.530	1.815	244	72.55	500	3.629	155	2.480	1.815	<244	73.17
600	3.618	136	2.992	2.171	244	72.64	600	3.618	185	2.960	2.171	<244	73.34
700	3.607	158	3.476	2.525	244	73.05	700	3.607	214	3.424	2.525	244	73.74
800	3.596	179	3.938	2.877	244	73.33	800	3.595	243	3.888	2.876	244	73.97
900	3.585	200	4.400	3.227	244	73.18	900	3.585	272	4.352	3.227	244	74.14
1000	3.574	222	4.884	3.574	244		1000	3.574	302	4.832	3.574	244	73.97
7.3V Input (9 MPH)							4.5V Input (7 MPH)						
Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)	Load (mA)	Vout (V)	Iin (mA)	Pin (W)	Pout (W)	Vrip. (mV)	Eff. (%)
0	3.679				<184	73.91	0	3.678				<184	
100	3.669	68	0.496	0.367	<184	76.55	100	3.672	105	0.473	0.367	<184	77.71
200	3.66	131	0.956	0.732	<184	77.05	200	3.665	206	0.927	0.733	<184	79.07
300	3.652	194	1.416	1.096	<184	77.28	300	3.658	307	1.382	1.097	<184	79.44
400	3.642	259	1.891	1.457	<184	78.16	400	3.651	406	1.827	1.460	<184	79.93
500	3.633	322	2.351	1.817	<184	77.90	500	3.644	506	2.277	1.822	184	80.02
600	3.642	383	2.796	2.185	<184	77.77	600	3.636	609	2.741	2.182	184	79.61
700	3.615	445	3.249	2.531	<184	77.51	700	3.629	714	3.213	2.540	184	79.06
800	3.605	508	3.708	2.884	184	77.02	800	3.622	823	3.704	2.898	184	78.24
900	3.596	572	4.176	3.236	184		900	3.616	935	4.208	3.254	184	77.35
1000	3.587	638	4.657	3.587	184		1000	3.608	1051	4.730	3.608	184	76.29

*NOTE: Digipot set for approximately 3.6Vout with 7.3Vin at no load

Speed (MPH)	Load Regulation (%)
Max	2.51
15	2.40
9	2.03
7	1.55

Line Regulation (%)
0.92

Speed (MPH)	Output Ripple (%)
Max	6.83
15	6.83
9	5.13
7	5.10

Table E3: SEPIC Test Data with 3.6V Output Voltage

APPENDIX F

Bill of Materials

Part	Value	Rating	Manufacturer	Mfg. Part No.	RoHS	Package	Qty	Price Ea.	Ext. Price	1K Price Ea.	1k Ext. Price	
Hi-Side Driver	FAN73611		Fairchild	FAN73611MX	Y	8 SOIC	1	\$ 1.260	\$ 1.26	\$0.54250	\$ 0.54250	
Charge Pump	MAX1822		Maxim	MAX1822ESA+	Y	8 SOIC	2	\$ 5.220	\$ 10.44	\$2.33326	\$ 4.66652	
C1 & C2 (MAX 1)	0.01uF	50V	TDK	C1005X5R1H103K050BB	Y	402	2	\$ 0.100	\$ 0.20	\$0.01500	\$ 0.03000	
C1 & C2 (MAX 2)	47nF	50V	TDK	C1608X5R1H473K080AA	Y	603	2	\$ 0.100	\$ 0.20	\$0.01140	\$ 0.02280	
C3	10uF	35V	Kemet	EEV106M035A9BAA	Y		2	\$ 0.350	\$ 0.70	\$0.10005	\$ 0.20010	
Zener	13.8V	1W	Rohm	KDZTR138	Y	SOD-123F	1	\$ 0.600	\$ 0.60	\$0.16580	\$ 0.16580	
Zener Resistor	30.9	1W	Rohm	MCR100J2HF30R9	Y	2512	2	\$ 0.362	\$ 0.72	\$0.08395	\$ 0.16790	
MAX Supply OR Diode	150mA	100V	Bourns	CD1206-S01575	Y	1206	2	\$ 0.142	\$ 0.28	\$0.02630	\$ 0.05260	
MOSFET Gate Diode	150mA	100V	Bourns	CD1206-S01575	Y	1206	1	\$ 0.142	\$ 0.14	\$0.02630	\$ 0.02630	
MOSFET Gate Resistor	422k	0.1W	Panasonic	P422KHCT-ND	Y	603	1	\$ 0.009	\$ 0.01	\$0.00256	\$ 0.00256	
MOSFET Gate Cap	0.47uF	35V	TDK	C1608X5R1V474M080AB	Y	603	1	\$ 0.240	\$ 0.24	\$0.05875	\$ 0.05875	
Comparator	LM311		TI	LM311DR	Y	8 SOIC	1	\$ 0.320	\$ 0.32	\$0.24920	\$ 0.24920	
AND Gate			TI	SN74AHCI08D8BVR	Y	SOT-23-5	1	\$ 0.240	\$ 0.24	\$0.12700	\$ 0.12700	
Pull-Down Resistor	10k	0.1W	Panasonic	ERJ-3GEYJ103V	Y	603	1	\$ 0.009	\$ 0.01	\$0.00256	\$ 0.00256	
Hysteresis Resistor	1M	0.1W	Panasonic	ERJ-3GEYJ105V	Y	603	1	\$ 0.009	\$ 0.01	\$0.00256	\$ 0.00256	
Comparator Res1	36.5k	0.1W	Panasonic	ERJ-3EF3652V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
Comparator Res2	5.76k	0.1W	Panasonic	ERJ-3EF5761V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
Input Zener	30V	5W	Micro Commercial	SMBJ5363B-TP	Y	DO-214AA	1	\$ 0.900	\$ 0.90	\$0.40000	\$ 0.40000	
Input NMOS	34A	200V	Infineon	IPD32ON20N3 G	Y	D PAK	1	\$ 3.090	\$ 3.09	\$1.41424	\$ 1.41424	
								\$ 19.40		\$ 8.13907		INPUT PROTECTION
Current Sense IC			Fairchild	FAN4010IL6X_F113	Y		2	\$ 0.820	\$ 1.64	\$0.33000	\$ 0.66000	
Rout Resistor	4.7k	1/16W	Susumu	RR0816P-472-D	Y	603	2	\$ 0.093	\$ 0.19	\$0.01575	\$ 0.03150	
I sense Resistor	0.05	0.5W	Ohmite	LVK12R050DER	Y	1206	2	\$ 0.500	\$ 1.00	\$0.32000	\$ 0.64000	
								\$ 2.83		\$ 1.33150		CURRENT SENSING
Rectifier Diode	1A	400V	Diodes Inc	SBR1U400P1-7	Y	POWERDI-123	4	\$ 0.446	\$ 1.78	\$0.15725	\$ 0.62900	
Load Switch	3A	6V	Micrel	MIC94042YFL TR	Y	4-MLF	2	\$ 1.630	\$ 3.26	\$0.66650	\$ 1.33300	
Cin	100 uF	35V	Nichicon	UWT1V101MCL1G5	Y		22	\$ 0.227	\$ 4.98	\$0.16988	\$ 3.73736	
Battery	700 mAh	3.7V	AA Portable Power Corp	PL-503048-2C	?		1	\$ 5.500	\$ 5.50	\$4.95000	\$ 4.95000	
Phone Output Diode	2A	60V	Diodes Inc	B260-13-F	Y	DO-214AA	1	\$ 0.440	\$ 0.44	\$0.12025	\$ 0.12025	
Battery Output Diode	2A	60V	Diodes Inc	B260-13-F	Y	DO-214AA	1	\$ 0.440	\$ 0.44	\$0.12025	\$ 0.12025	
Inductor	6.8uH	3.32A	Bourns	SRF1260-6R8Y	Y		1	\$ 1.080	\$ 1.08	\$0.76950	\$ 0.76950	
Converter Diode	2A	60V	Diodes Inc	B260-13-F	Y	DO-214AA	1	\$ 0.440	\$ 0.44	\$0.12025	\$ 0.12025	
Battery Input Diode	2A	60V	Diodes Inc	B260-13-F	Y	DO-214AA	1	\$ 0.440	\$ 0.44	\$0.12025	\$ 0.12025	
Controller	LT3759		Linear Technology	LT3759EMSE#PBF	Y	12-TSSOP	1	\$ 5.030	\$ 5.03	\$2.85000	\$ 2.85000	
Controller Supply Cap	4.7uF	50V	Samsung	CL21A475KBQNNNE	Y	805	4	\$ 0.099	\$ 0.40	\$0.04202	\$ 0.16808	
Drive Bypass Cap	4.7uF	10V	Yageo	CC0603KRXSR6BB475	Y	603	1	\$ 0.095	\$ 0.09	\$0.04024	\$ 0.04024	
NMOS Switch	18A	40V	Diodes Inc	DMN4009LK3-13	Y	D PAK	1	\$ 0.590	\$ 0.59	\$0.21000	\$ 0.21000	
EN/UVLO R3	422k	0.1W	Panasonic	ERJ-3EFK4223V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
EN/UVLO R4	665k	0.1W	Panasonic	ERJ-3EFK6653V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
Rt Resistor	41.2k	0.1W	Panasonic	ERJ-3EFK4122V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
PGOOD Resistor	100k	0.1W	Panasonic	ERJ-3GEYJ104V	Y	603	1	\$ 0.009	\$ 0.01	\$0.00256	\$ 0.00256	
Comp Resistor	7.5k	0.1W	Panasonic	ERJ-3EFK7501V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
Cdc	4.7uF	50V	Samsung	CL21A475KBQNNNE	Y	805	2	\$ 0.099	\$ 0.20	\$0.04202	\$ 0.08404	
CINTVcc	4.7uF	10V	Yageo	CC0603KRXSR6BB475	Y	603	1	\$ 0.095	\$ 0.09	\$0.04024	\$ 0.04024	
Cout XSR	10uF	10V	Murata	GRM21BR61A106KE19L	Y	805	1	\$ 0.144	\$ 0.14	\$0.04463	\$ 0.04463	
Cout Tant	100uF	10V	Kemet	T520D107M010ATE018	Y	2917	2	\$ 2.130	\$ 4.26	\$1.02120	\$ 2.04240	
I sense Resistor	9m	0.5W	Rohm	PMR10E2PFU9L00	Y	805	1	\$ 0.620	\$ 0.62	\$0.20419	\$ 0.20419	
SS Cap	47nF	50V	TDK	C1608X5R1H473K080AA	Y	603	1	\$ 0.100	\$ 0.10	\$0.01140	\$ 0.01140	
Comp Cap	22nF	100V	TDK	C1608X5R2A223K080AA	Y	603	1	\$ 0.014	\$ 0.01	\$0.01800	\$ 0.01800	
FBX Rbot	4.7k	0.1W	Panasonic	ERJ-3EFK4701V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
FBX Rtop	12.4k	0.1W	Panasonic	ERJ-3EFK1242V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
USB Resistor R1	49.9k	0.1W	Panasonic	ERJ-3EFK4992V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
USB Resistor R2	75k	0.1W	Panasonic	ERJ-3EFK7502V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
USB Resistor R4	28k	0.1W	Panasonic	ERJ-3EFK2802V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
Disable MOSFET	360mA	60V	NXP	2N7002P,215	Y	SOT-23-3	1	\$ 0.140	\$ 0.14	\$0.02781	\$ 0.02781	
DigiPot Supply Cap	10uF	35V	Kemet	EEV106M035A9BAA	Y		1	\$ 0.350	\$ 0.35	\$0.10005	\$ 0.10005	
DigiPot	10k		Analog Devices	AD5201BRMZ10	Y	10-TFSOP	1	\$ 1.400	\$ 1.40	\$0.65250	\$ 0.65250	
								\$ 31.93		\$ 18.43056		CONVERTER
MicroController	-	-	Atmel	ATMEGA328P-MU	Y		1	\$ 3.050	\$ 3.05	\$1.70280	\$ 1.70280	
AVcc Choke	10uH	15mA	Bourns	CV201210-100K	Y	805	1	\$ 0.100	\$ 0.10	\$0.03120	\$ 0.03120	
ADC Bypass Caps	12nF	25V	Kemet	C0603C123J3GACTU	Y	603	6	\$ 0.322	\$ 1.93	\$0.10580	\$ 0.63480	
Resonator	16MHz		Murata	CSTCE16MOV53-R0	Y		1	\$ 0.480	\$ 0.48	\$0.25637	\$ 0.25637	
Resonator Resistor	1M	0.1W	Panasonic	ERJ-3GEYJ105V	Y	603	1	\$ 0.009	\$ 0.01	\$0.00256	\$ 0.00256	
Reset Resistor	10k	0.1W	Panasonic	ERJ-3GEYJ103V	Y	603	1	\$ 0.009	\$ 0.01	\$0.00384	\$ 0.00384	
Reset Diode	150mA	100V	Bourns	CD1206-S01575	Y	1206	1	\$ 0.142	\$ 0.14	\$0.02630	\$ 0.02630	
Debug LED	red/green		Lite-On	LTST-C155KGJRK	Y	1210	1	\$ 0.420	\$ 0.42	\$0.12060	\$ 0.12060	
LED Resistor	150 Ohm		Panasonic	ERJ-3GEYJ151V	Y	603	2	\$ 0.009	\$ 0.02	\$0.00256	\$ 0.00512	
Prec. Voltage Ref.	2.5V	15mA	Analog Devices	ADR5041ARTZ-REEL7	Y	SOT-23-3	1	\$ 0.970	\$ 0.97	\$0.41850	\$ 0.41850	
Ref. Biasing Res.	1k	0.25W	Panasonic	ERJ-8ENF1001V	Y	1206	1	\$ 0.100	\$ 0.10	\$0.01024	\$ 0.01024	
Vsense R1	3.3k	0.1W	Panasonic	ERJ-3EFK3301V	Y	603	2	\$ 0.014	\$ 0.03	\$0.00384	\$ 0.00768	
Vsense R2	4.7k	0.1W	Panasonic	ERJ-3EFK4701V	Y	603	2	\$ 0.014	\$ 0.03	\$0.00384	\$ 0.00768	
Input Vsense R2	71.5k	0.1W	Panasonic	ERJ-3EFK7152V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
Input Vsense R1	4.7k	0.1W	Panasonic	ERJ-3EFK4701V	Y	603	1	\$ 0.014	\$ 0.01	\$0.00384	\$ 0.00384	
Bypass Caps	0.1uF	25V	Taiyo Yuden	TMK107B1J104KA-T	Y	603	8	\$ 0.120	\$ 0.96	\$0.00975	\$ 0.07800	
Temp. Sensor	neg.40 to 125 Cels	2.3 to 5.5V	Microchip Technology	MCP9700T-E/TT	Y	SOT-23-3	1	\$ 0.290	\$ 0.29	\$0.19000	\$ 0.19000	
Prog Header	6-pin		TE Connectivity	5-1775444-6	Y		1	\$ 0.730	\$ 0.73	\$0.45480	\$ 0.45480	
Lightning Cable					?		1	\$ 3.500	\$ 3.50	\$3.50000	\$ 3.50000	
Flatflex to Lightning	5 inch	1.3A	Molex	210390709	Y		0.5	\$ 2.280	\$ 1.14	\$0.88673	\$ 0.44337	
								\$ 13.93		\$ 7.90154		MICROCONTROLLER
								Qty: 1		Qty: 1000		
								TOTAL \$	68.09	\$	35.80	

Table F1: Electronic Components Bill of Materials

Level	Part Number	Description	Quantity	Purchased/Manufactured
0	1001	Bicycle mounted iPhone 5 Case w/ Charging	1	
1	1002	Handlebar Mount	1	Manufactured
2	EC1001	Electrical Contact	1	Purchased
2	W244	Wiring to hub, 3 feet	1	Purchased
1	GH1001	Generator Hub	1	Purchased
1	1003	Case	1	Manufactured
2	CB20012	Circuit Board with components installed	1	Purchased
2	1004	Silicone Liner	1	Manufactured
2	1005	Case Top	1	Manufactured
3	WS555	Front window screen	1	Purchased
2	1007	Clamp Arm	1	Manufactured
3	SR116-3	1/16 steel rod for attaching clamp arm, 3"	1	Purchased
2	1006	Case Bottom	1	Manufactured
3	EC5005	Spring Electrical Contact	2	Purchased
3	SR116-4	1/16 steel rod for attaching top/bottom, 4"	1	Purchased
3	W4455	Rear Camera Window	1	Purchased
3	SC#46	Screws for mounting board	4	Purchased

Table F2: Case Bill of Materials

APPENDIX G

Case Engineering Drawings

Figure G1: Case Bottom Drawing

Figure G2: Case Top Drawing

Figure G3: Clamp Arm Drawing

Figure G4: Case Liner Drawing

APPENDIX H

Case Cost Analysis

Option 1- Injection molded case						
Purchased items		Quantity	Cost	Extended cost		
	Handlebar mount	1	2	2		
	Wiring to hub, 3 ft	1	0.1	0.1		
	Circuit board w/ components	1	10	10		
	Front window screen	1	0.1	0.1		
	1/16 steel rod, 3 in	1	0.08	0.08		
	1/16 steel rod, 4 in	1	0.09	0.09		
	Electrical contacts	2	0.07	0.14		
	Rear camera window	1	0.11	0.11		
	Circuit board mounting screws	4	0.01	0.02		
Manufactured items						
	Injection molding labor, \$45/hr	10 min/part	7.5	7.5		
	Material - plastic	5 in^3	0.25	0.25		
	Material - silicone	1.5 in^3	0.33	0.33		
	Case assembly labor, \$30/hr	8 min/part	4	4		
					24.72	
Mold Costs						
	Mold for case top	1	4000	4000		
	Mold for case bottom	1	5000	5000		
	Mold for clamp arm	1	1500	1500		
	Mold for liner	1	2500	2500	13000	
Option 2- CNC Machined case						
Purchased items		Quantity	Cost	Extended cost		
	Handlebar mount	1	2	2		
	Wiring to hub, 3 ft	1	0.1	0.1		
	Circuit board w/ components	1	10	10		
	Front window screen	1	0.1	0.1		
	1/16 steel rod, 3 in	1	0.08	0.08		
	1/16 steel rod, 4 in	1	0.09	0.09		
	Electrical contacts	2	0.07	0.14		
	Rear camera window	1	0.11	0.11		
	Circuit board mounting screws	4	0.01	0.02		
Manufactured items						
	Machining molding labor, \$60/hr	40 min/part	40	40		
	Injection molding liner labor \$45/hr	3 min/part	2.25	2.25		
	Material - Aluminum	35 in^3	5	5		
	Material - silicone	1.5 in^3	0.33	0.33		
	Case assembly labor, \$30/hr	8 min/part	4	4	64.22	
	Mold for liner	1	2500	2500		
Option 1- Injection Molded case	Quantity	Cost per case		Option 2 - CNC machined case	Quantity	Cost per case
	100	154.72			100	89.22
	200	89.72			200	76.72
	266	73.59			266	73.62
	300	68.05			300	72.55
	1000	37.72			1000	66.72
	Breakeven point: 266 units					

Table H1: Case Cost Analysis

APPENDIX I

Digital Potentiometer Settings and Output Voltage Range

Position	HEX	Nominal	30% up	30% down
32	0x20	2.945	2.717	3.291
31	0x1F	2.974	2.743	3.323
30	0x1E	3.005	2.770	3.356
29	0x1D	3.036	2.799	3.391
28	0x1C	3.070	2.829	3.427
27	0x1B	3.104	2.861	3.464
26	0x1A	3.141	2.894	3.504
25	0x19	3.179	2.930	3.544
24	0x18	3.220	2.967	3.587
23	0x17	3.262	3.006	3.631
22	0x16	3.307	3.048	3.678
21	0x15	3.354	3.092	3.727
20	0x14	3.404	3.139	3.778
19	0x13	3.456	3.189	3.831
18	0x12	3.512	3.243	3.888
17	0x11	3.572	3.300	3.947
16	0x10	3.635	3.361	4.009
15	0x0F	3.702	3.427	4.075
14	0x0E	3.774	3.498	4.144
13	0x0D	3.851	3.575	4.218
12	0x0C	3.934	3.658	4.296
11	0x0B	4.023	3.749	4.378
10	0x0A	4.119	3.848	4.466
9	0x09	4.223	3.956	4.560
8	0x08	4.337	4.075	4.659
7	0x07	4.460	4.208	4.766
6	0x06	4.595	4.355	4.881
5	0x05	4.743	4.519	5.004
4	0x04	4.907	4.705	5.137
3	0x03	5.088	4.916	5.280
2	0x02	5.291	5.157	5.436
1	0x01	5.519	5.437	5.605
0	0x00	5.777	5.764	5.790

Table I1: Digital Potentiometer Settings and Output Voltage Range.
±30% Tolerance Included