

Modeling, Design, and Testing of Electric Bicycles

by

Richard Vernon Stackhouse

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Dr. Zuomin Dong, Supervisor (Department of Mechanical Engineering)



Dr. George X. Wang, Supervisor (Innovation Center, National Research Council)



Dr. P. Agathoklis, Outside Member (Department of Electrical and Computer Engineering)



Dr. Peter F. Driessen, External Examiner (Department of Electrical and Computer Engineering)

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University of Victoria

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Supervisors: Dr. Zuomin Dong and Dr. George X. Wang

ABSTRACT

Battery powered electric bicycles and scooters, replacing the heavily polluting scooters with 2-cycle internal combustion engines, provide zero-emission transportation for many parts of the world (mainly Asia). Over 500,000 battery powered electric bicycles were sold worldwide in 1999 alone. Worldwide cumulative sales of electric bicycles are estimated to reach 6,000,000 by the year 2003. However, these battery powered electric bicycles suffer from a long recharge time (3-8 hours) and a low range (~32 km average), which hinders even greater application of this clean transportation technology.

The Proton Exchange Membrane (PEM) fuel cell system provides an alternative power plant for the electric bicycle. A fuel cell electric bicycle or scooter can be refueled quickly and provide a range of over 100 km. To facilitate the development of new electric bicycles, a computerized electric bicycle testing facility has been created at UVic in this study. Electric bicycle standardized testing cycles have also been developed. In addition, a new Adaptable Electric Bicycle Power System (AEBPS) is designed and constructed. The AEBPS configuration is designed to transform any bicycle (including bicycles with both front and rear suspension) into an electric bicycle in under ten minutes. The AEBPS can also be removed from the bicycle in less than five minutes.

This thesis covers available electric bicycles, government imposed regulations, prototype fuel cell powered electric bicycles, electric bicycle modeling, the design and construction of the AEBPS, the developed electric bicycle testing methods, and the electric bicycle testing facility. Electric bicycle testing results using the developed testing facility and test methods are also presented.

Examiners:

[Redacted]

Dr. Zuomin Dong, Supervisor (Department of Mechanical Engineering)

[Redacted]

Dr. George X. Wang, Supervisor (National Research Council Innovation Center, Control and Diagnostics Group)

[Redacted]

Dr. P. Agathoklis, Outside Member (Department of Electrical and Computer Engineering)

[Redacted]

Dr. Peter F. Driessen, External Examiner (Department of Electrical and Computer Engineering)

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CHAPTER 1 INTRODUCTION

1.1. The Significance of Zero Emission Vehicles

Worldwide pollution, mainly due to gasoline powered vehicular carbon monoxide, hydrocarbon, and particulate matter emissions, is of great concern today. The gasoline-powered automobile is an essential part of most people's daily lives. Unfortunately, this reliance on the gasoline-powered automobile has caused a very large increase in environmental pollution. The pollution level in some major cities is so severe that air filter masks are required for bicyclists and pedestrians to prevent sickness. These pollutants emitted from fossil fuel burning internal combustion (IC) engines have been linked to severe human illnesses such as leukemia, lung poisoning, lung cancer, and respiratory disease. Vehicle pollutants are also believed to be causing global warming due to the "greenhouse effect." In order to eliminate the unnecessary human illness and other severe problems associated with current vehicle emissions, new, clean electric power systems are being developed. These electrical systems replace the IC engine with an electric motor, and a battery or hydrogen fuel cell system. These systems produce much lower emissions than the IC engine. However, battery powered electric vehicles have not done well in the consumer market mainly due to their limited range. The range of a battery powered electric vehicle is defined as the distance traveled per full charge. The fuel cell powered electric vehicle is currently the choice of many auto manufacturers to solve the range problem of battery powered electric vehicles. The main obstacle for fuel cell powered vehicles to overcome is a large reduction in cost so that commercialization can be achieved.

Concern over the excessive pollution caused mainly by gasoline-powered automobiles is increasing dramatically, resulting in new methods of solving the problem. One main solution has been implemented by the state of California; in 1990, the state of California implemented a plan to reduce vehicle emissions by gradually introducing zero emission

vehicles (ZEVs). California's ZEV program is designed to improve the state's air quality in the long term. The plan was to eventually reduce vehicle emissions to zero within a set amount of years. The California Air Resources Board mandated that at least 2 percent in 1998, 5 percent in 2001, and 10 percent of new cars sold in 2003 be zero emission vehicles. Recently California has modified the original mandate to gradually increase the ZEV percentage requirement from 10 percent in 2003-2008 to 16 percent in 2018 [1].

The severe pollution problem in many highly populated countries, especially in Asia, is causing a great concern. The governments of a number of Asian countries are currently creating new legislations to eliminate the highly polluting scooters powered by two-stroke IC engines. Particulate matter emitted by two-stroke scooter engines has been found to be almost identical as that emitted from a heavy diesel truck per kilometer driven. Even worse, the hydrocarbons and carbon monoxide emitted from these small vehicles is triple that of a large diesel truck per kilometer driven (Figure 1) [2].

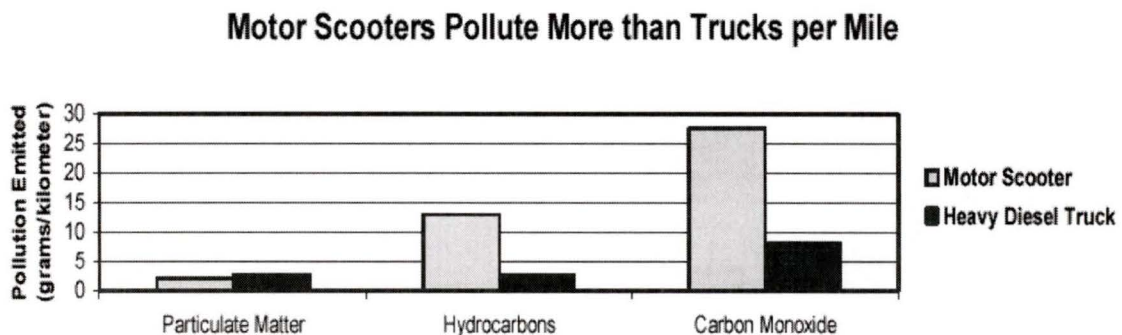


Figure 1: Two-Stroke Scooter Pollution [2]

The enormous level of pollution causes a great problem in Asia, where the scooter form of transportation is very popular. In Indonesia and Taiwan, scooters account for approximately 75% of the entire vehicle fleet (Figure 2) [2].

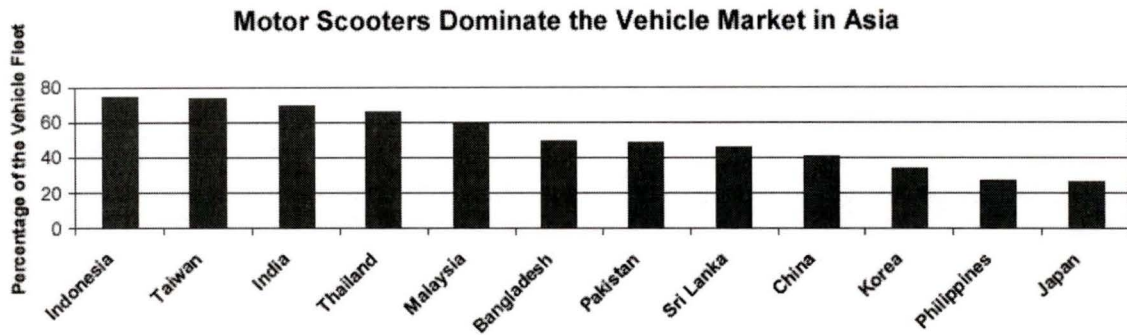


Figure 2: Scooter Fleet in Asia [2]

Due to the high pollution levels, the local governments of most countries in Asia are encouraging the use of electrically powered vehicles due to their many environmental benefits.

1.2. Electric Bicycle and Electric Scooter Definition

Electric bicycles and electric scooters are sometimes classified as the same type vehicle. In this thesis, electric bicycles are defined as a normal pedal bicycle with an electric motor and power supply (Figure 3). The maximum motor power for an electric bicycle is between 200 W and 1 kW. The electric scooter is defined as a sit-down vehicle with a maximum motor power between 3 kW and 6 kW (Figure 4). The electric scooter does not have pedals. In this thesis emphasis is placed on electric bicycles rather than the higher powered electric scooters.



Figure 3: Electric Bicycle



Figure 4: Electric Scooter

1.3. Battery Powered Electric Bicycle and Electric Scooter Advantages and Disadvantages

Electric bicycles and scooters have proven to be a very effective means of transportation in densely populated countries such as China; the small size is desirable for storage and reducing traffic congestion in cities such as Shanghai and Beijing. The electric bicycle and scooter are also environmentally friendly compared to the highly polluting two-stroke gasoline engine. The electric bicycle and scooter are also cheaper to purchase and operate than an automobile. The use of electric bicycles and scooters are being encouraged by the Chinese government, for example, the city of Shanghai imposed a ban on any further two-stroke gasoline powered scooter licenses as of July 1996 [3]. The battery powered electric vehicle has a greater efficiency than an internal combustion engine (~70% vs. 20% from tank to drive wheels). An electrical power system is also more robust and requires less maintenance than an IC engine due to much fewer moving parts. In addition, the electric bicycle requires no special license or insurance to operate. Also, the electric bicycle is permitted to use designated bicycle routes, allowing the commuter to avoid heavy traffic congestion on major city roads. A major advantage of electric vehicles is the considerable reduction in noise pollution, especially in densely populated cities.

There are however some disadvantages to the present battery powered electric bicycle and scooter. The main problem is the limited range; this is the distance that the vehicle is able to travel between battery charges. This problem results in an average electric bicycle range of approximately 32 km (which includes some light pedaling from the rider). The presence of a battery pack results in a lengthy recharge time. Electric bicycles take between three to eight hours to recharge depending on the battery and charger used; this recharge time is inconvenient for most users. It is also difficult to determine the range capability of a partially charged battery; this is frustrating for the user, and reduces electric bicycle user confidence. The batteries used in electric bicycles and scooters also have limited lifetimes of approximately 300 cycles, which means that the battery pack needs to be replaced approximately every year. Since most electric bicycles and scooters use sealed lead-acid batteries due to their low cost, there is an environmental concern associated with these vehicles since the toxic materials in the battery need to be disposed of properly at a recycling facility when the battery can no longer be recharged. In addition, the lead-acid battery performance is also affected by the environmental temperature. Most batteries work well in warm temperatures, but drastically lose performance in cold weather. Lead acid battery power continuously declines during use; therefore, performance in the morning commute may be different than performance in the afternoon.

1.4. Why Fuel Cell Powered Electric Bicycles and Scooters?

The fuel cell powered electric bicycle and fuel cell powered electric scooter have the potential to overcome the limitations associated with the battery powered electric bicycle and scooter. These fuel cell powered electric vehicles are predicted to have much higher range than battery power. The range can be approximately five times greater for a fuel cell powered electric bicycle using one full hydrogen fuel canister, than when using lead-acid battery power. When the hydrogen canister is empty, it can be replaced with a full canister in a couple minutes. A battery pack can take at least three hours to recharge; most standard battery chargers take about 8 hours to charge the battery. The total fuel cell system mass is expected to be less than with battery power. Also, the initial fuel cell system and lifetime operating costs are expected to be lower than with batteries. Since

hydrogen is used as a fuel to the fuel cell stack, the vehicle should have consistent performance at all times of the day.

1.5. Objectives and Scope of the Study

The two main objectives of this research include a feasibility study of fuel cell powered electric bicycles and the development of standard electric bicycle performance tests, so that various electrically powered bicycles can be effectively developed and compared.

This thesis investigates the main aspects of electric bicycle design, including current worldwide regulations and various battery powered electric bicycle specifics. Prototype fuel cell powered electric bicycles are also investigated. Also covered in this research are some of the initial design considerations needed to construct a fuel cell powered electric bicycle. This study describes the design of the Adaptable Electric Bicycle Power System (AEBPS), which can be quickly adapted to almost any bicycle frame.

When a powered vehicle is developed, it is crucial to be able to evaluate the performance of the vehicle through standard tests, to put its performance in the context of other powered vehicles. The performance tests require two major components. First, a dynamometer needs to be utilized that can simulate various road conditions, loads, and obtain vehicle performance data. Second, a number of standard test cycles need to be developed that can be used as benchmark tests to assess the performance of the vehicle for different applications or different markets.

Although the dynamometer and standard test cycle techniques have been well developed and standardized for various IC automobiles and scooters, standard testing techniques for electric bicycles, either powered by a battery or fuel cells, remain non-existent at present, due to the short history of electric bicycle development.

One of the main purposes of this research is to develop effective, universal, and standard electric bicycle testing procedures, test cycles, and testing apparatus system to assist

electric bicycle development. In order to accomplish this objective, it is important to analyze the current electric bicycle technology and government imposed restrictions, as well as various standard test cycles used for IC vehicle applications.

In this work, a dynamometer for testing electrical bicycles is developed using a control system built on a Basic Stamp 2 microcontroller and the commercially available RacerMate Computrainer computerized bicycle trainer. A number of standard electric bicycle testing cycles have been introduced based on the standard test cycles for automobiles and scooters with IC engines. These electric bicycle testing cycles are: the European Elementary Urban Electric Bicycle Testing Cycle (EEUEBTC), the Taipei Electric Bicycle Testing Cycle (TEBTC), and the New York Electric Bicycle Testing Cycle (NYEBTC). A special Electric Bicycle Grade Testing Cycle (EBGTC) is also introduced so that any electric bicycle, no matter what top speed or acceleration capability, can be quickly tested and compared with other electric bicycles. This study also explains the Electric Bicycle Road Acceleration Testing Method (EBRATM) using inexpensive measurement components.

The work forms the foundation for electrical bicycle testing. Furthermore, the developed testing system can be easily modified to test higher-powered electric vehicles, such as electric scooters.

1.6. Thesis Organization

Chapter 1 introduces the research subject. In this chapter the need for zero emission vehicles is explained. Also explained are the advantages and disadvantages of battery powered electric bicycles and electric scooters. The concept of a fuel cell powered bicycle and scooter is also presented.

In Chapter 2, the currently available electric bicycle technology is covered. Worldwide government imposed electric bicycle regulations are also analyzed.

Chapter 3 deals with the analysis of five types of fuel cells to determine their ability to power an electric bicycle. The five types are: proton exchange membrane fuel cells, alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and solid oxide fuel cells. Fuel cell systems that are currently used to power the two main prototype fuel cell powered electric bicycles, the Manhattan Scientifics / Aprilia fuel cell bicycle, and the Palcan fuel cell bicycle are presented. One of the world's most developed prototype fuel cell powered scooters; the ZES IV Fuel Cell Scooter is also presented with full specifics listed.

Chapter 4 covers fuel cell power characteristics, including the polarization curve. Static modeling is performed on an original front wheel motorized fuel cell powered electric bicycle. This modeling reveals the power required from the electric motor at various road grades. The front tire resistive force is also presented for comparison purposes; this data is used to determine the likelihood of the front tire losing traction. The power required for various speeds on a flat road is also modeled. An on-road and an off-road analysis are performed.

Chapter 5 presents the Adaptable Electric Bicycle Power System (AEBPS) concept. Static modeling is then performed on an AEBPS equipped Rocky Mountain RM6 full suspension bicycle model. This modeling reveals the power required from the electric motor at various road grades. The front tire resistive force is also presented and compared with the fuel cell powered electric bicycle model. The power required for various speeds on a flat road is also modeled. An on-road and an off-road analysis are also performed on the AEBPS Rocky Mountain RM6 bicycle model. Construction of the prototype AEBPS is described in detail. This prototype uses a 24V battery pack, a 400-Watt (Maximum power) Heinzmann electric hub motor, and an electrical system that can handle 20A continuously (80A for 1 minute). The AEBPS also features a remote security system that prevents power from reaching the electric motor until the remote is pressed.

Chapter 6 introduces the three tests developed to test electric bicycles: the Electric Bicycle Velocity Testing Cycles (EBVTC), the Electric Bicycle Grade Testing Cycle (EBGTC), and the Electric Bicycle Road Acceleration Test Method (EBRATM). The background of each of the three electric bicycle tests is described in detail. This chapter describes the major components and functions of the developed electric bicycle testing facility. The electric bicycles that are tested are also described. Initial electric bicycle testing is presented, which observes the differences between the indoor electric bicycle testing facility and the outdoor EBRATM.

Chapter 7 describes the three types of electric bicycle standard test cycles in detail. Chapter 7 also presents the EBVTC and EBGTC test results of the Currie Cycles and Suzhou Small Antelope electric bicycles. EBRATM test results for the Currie, Suzhou Small Antelope, and the prototype AEBPS electric bicycles are also included in this chapter.

Chapter 8 draws the conclusions of the project, original research contributions, and future work.

CHAPTER 2 TECHNICAL BACKGROUND ON ELECTRIC BICYCLES

2.1. Commercially Available Electric Bicycles

The battery powered electric bicycle is the main competition for the fuel cell powered bicycle. The current advances in fuel cell technology provide the possibility of an ideal power plant for electric bicycles. However, the fuel cell powered electric bicycle needs to be competitive with the performance, reliability, and price of the battery powered electric bicycles, while providing much greater range. The main goal of the fuel cell powered bicycle is to have a range of more than 100 km, a “recharging” time of less than 10 minutes, and a cost comparable to that of a high quality battery powered electric bicycle. The presently available electric bicycle operates based on an electric motor, a battery pack, an electronic motor controller, and a speed control throttle (usually a potentiometer). There are many different electric bicycles available and most of the sales are in Asia. A large selection of popular commercially available battery powered electric bicycles is presented in Table 1. It has been found that the average peak power of battery-powered bicycles is 386.3 Watts (Table 1); this translates to approximately 200 Watts continuous power. The electric bicycles that have a peak power output in the 200W–250W range (such as the Suzhou Small Antelope, the Panasonic E-Hybrid, and the Yamaha XPC 26) are mainly designed for use by light riders in the Asian market. Almost all the electric bicycles designed for the American market feature motors with ~ 400 Watts peak power, except for the Currie / US Prodrive electric bicycle which features a 900 Watt peak output motor (400 Watt continuous) [4], and the Lafree Standard electric bicycle with a peak power output of 1000W (400W continuous). Table 1 also shows the average mass of the selection of commercially available electric bicycles is 29.8 kilograms (65.7 lbm). The average range of these bikes is found to be 32.2 kilometers (20 miles), which takes into account some light pedaling power from the rider. It can be observed that the Suzhou Small Antelope has a claimed range of up to 60 km; this value has a notable effect on the

average range, increasing the average by 1.3 km. The average battery powered bicycle would have a range approximately 20% less if no pedaling is exerted by the rider. The average top speed of the battery-powered electric bicycles is 26.3 km/h (16.3 mph). Electric bicycles with a top speed of over 25 km/h and a maximum power output of 400 Watts cannot handle a very high grade; these electric bicycles are designed strictly for road use (they are not recommended for any type of off-road riding). A bike that could handle large grades would most likely travel at a much lower top speed, but have a larger amount of hill climbing torque (for the same available power). Table 1 also shows that most electric bicycles operate on a 24V direct current system (78%), however, the number of 36V electric bicycles is increasing. It is also very important to note that the recharging time for these bicycles varies depending on the type of charger used. A regular charger (1A) will charge a 24V (12 Ah) battery system in approximately eight hours, while a quick charger that supplies current at 3 amps will charge the battery in about three hours.

Table 1: Battery Powered Electric Bicycle Statistics

(This table contains a selection of popular electric bicycles sold worldwide; these specifics are the manufacturers claimed values unless noted by an *, which indicates a UVic lab measured value. Note: The - indicates that there is no data currently available or applicable to this category) [5]

EBike	Bike Cost (USD)	Power System Cost (USD)	Power max (Watts)	Motor Description	Bike Mass (kg)	Power System Mass (kg)	Range (km)	Top Speed (km/h)
BIKIT Addon	-	399	360	24V DC Friction	-	10.4	29.0	24.1
Charger Bicycles	700	-	375	24V DC	29.5	14.1	32.2	32.2
Condor	700	-	-	24V DC	34.9	-	24.1	24.1
Currie / US ProDrive / Schwinn	899	595	900	24 V Brushless DC Chain	28.1	12.2	32.2	29.0
Elebike	500	400	200	48V DC Hub	-	-	32.2	24.9
Electransport Co.	600	-	250	24V DC Friction	29.5	12.7	19.3	25.7
Elite Electric Vehicles Co.	877	500	-	36V DC Hub	37.6	-	40.2	20.1

EBike	Bike Cost (USD)	Power System Cost (USD)	Power max (Watts)	Motor Description	Bike Mass (kg)	Power System Mass (kg)	Range (km)	Top Speed (km/h)
Estelle Comfort EXPORT	1798	-	400	36V DC Hub	27.5	-	40.2	28.0
EV Carradale	1656	-	400	24V DC Hub	20.9	-	40.2	-
EV Global 24V standard	995	-	400	24V Brushed DC Hub	32.2	10.4	32.2	22.5
EV Global 36V SX	1895	-	-	36V DC Hub	-	-	32.2	29.0
Heinzmann 24V Retrofit Kits	-	850	400	24V DC Hub	-	9.1	24.1	24.1
Lafree Standard Electric Bike	1000	-	1000	24V DC Brushed BB Drive	31.8	-	32.2	32.2
Merida Touring	1299	-	-	24V DC Brushed, Belt Drive	23.6	-	40.2	19.3
Panasonic E-Hybrid	1395	-	240	24V DC Brushless	20.9	-	40.2	24.1
Suzhou Small Antelope	300	-	230*	36V DC	34.9	-	60.0	20.9*
Think Mobility (Ford) Thinkbike Fun	595	-	400	24V DC Brushed	35.4	-	35.4	32.2
Think Mobility (Ford) Thinkbike Traveler	595	-	400	24V DC Brushed	30.4	-	25.7	29.0
Wello Electric Bicycle	-	-	250	24V DC Friction	34.9	-	32.2	32.2
Yamaha XPC 26	987	-	235	24V DC	28.1	-	40.2	24.1

EBike	Bike Cost (USD)	Power System Cost (USD)	Power max (Watts)	Motor Description	Bike Mass (kg)	Power System Mass (kg)	Range (km)	Top Speed (km/h)
Zap Powerbike	499	-	300	24V DC	26.8	-	19.3	25.7
Zap Retrofit Kit DX	-	450	400	24V DC Friction	-	10.0	12.9	32.2
Zap Retrofit Kit SX	-	360	200	24V DC Friction	-	9.1	24.1	22.5
AVERAGE	\$961	\$508	386.3	78% 24V DC	29.8	11.0	32.2	26.3

2.2. Types of Electric Bicycles

Electric bicycles can be grouped into two main types: the electrically assisted bicycle (EAB), and the electrically propelled bicycle (EPB).

2.2.1. Electrically Assisted Bicycles (EABs)

The EAB is also known as a “Pedelec”. This bicycle needs to be pedaled by a human operator in order for the motor to engage and provide assistance. When the start switch is pressed, the motor will be activated, but power will only be supplied from the battery in response to pedaling; the rider’s muscular strength is then combined with the motor power. These types of electric bicycles usually have a sensor located on the bicycle crank arm to detect if the bicycle is being pedaled. If motion is detected, the motor adds assist; if the rider does not pedal, the motor assist will be disabled. The motor will automatically turn off when the rider stops pedaling or applies the brakes.

2.2.2. Electrically Propelled Bicycles (EPBs)

The EPB is also known as an “E-bike”. This bicycle does not need to be pedaled in order to receive full power from the electric motor. These electric bicycles have a thumb or twist grip throttle that controls the amount of power delivered to the motor. Some countries do not classify EPBs as electric bicycles; they are classified as mopeds, and are subjected to the same licensing legislation as mopeds.

2.3. Main Electric Bicycle Restrictions and Regulations

The main design limitations of electric bicycles are the result of government imposed regulations to insure safety. Most countries have basically the same regulations that limit the bicycle's top speed (while the motor is in operation), and the motor power.

2.3.1. Canada

In Canada, legislation has provided the following regulations for electric bicycles sold (April 2001) [6]:

“Power-assisted bicycle” means a vehicle that:

- (a) has steering handlebars and is equipped with pedals,
- (b) is designed to travel on not more than three wheels in contact with the ground,
- (c) is capable of being propelled by muscular power,
- (d) has an electric motor only, which has the following characteristics, namely:
 - (i) it has a continuous power output rating, measured at the shaft of the motor, of 500 W or less,
 - (ii) if it is engaged by the use of muscular power, power assistance immediately ceases when the muscular power ceases,
 - (iii) if it is engaged by the use of an accelerator controller, power assistance immediately ceases when the brakes are applied, and
 - (iv) it is incapable of providing further assistance when the bicycle attains a speed of 32 km/h on level ground,
- (e) bears a label that is permanently affixed by the manufacturer and appears in a conspicuous location stating, in both official languages [English and French], that the vehicle is a power-assisted bicycle as defined in this subsection, and
- (f) has one of the following safety features,
 - (i) an enabling mechanism to turn the electric motor on and off that is separate from the accelerator controller and fitted in such a manner that it is operable by the driver,
 - or

(ii) a mechanism that prevents the motor from being engaged before the bicycle attains a speed of 3 km/h.

The Canadian government determined that an EPB is just as safe or safer than an EAB, therefore, EPBs will be allowed to be sold in Canada [7].

2.3.2. United States of America (USA)

A bill, H.R. 727 (passed on March 6, 2001) is presently being considered as the new regulatory bill for electric bicycles sold in the United States. The bill places electrically powered bicycles under the control of the Consumer Product Safety Commission (CPSC), rather than the National Highway Traffic Safety Commission (NHTSC). The bill applies to bicycles and tricycles with a mass less than 45 kg (100 lbm) that are not capable of more than 32 km/h (20 mph) using electric motor power. The mass is limited to 45 kg (100 lbm) to ensure that the rider has full control over the electric bicycle. The motor must have a maximum power output of 750 Watts or less. This bill is also only in effect for bicycles and tricycles with functional pedals. If this bill is passed, electric bicycles will not be subjected to strict regulations currently applicable to motor vehicles [8], [9].

2.3.3. Japan

Only EABs are classified as an electric bicycle in Japan. EPBs are subjected to licensing and insurance. The Pedelecs sold in Japan are required to have a varying amount of assistance as the bicycle speed increases from 15 km/h (Figure 5).

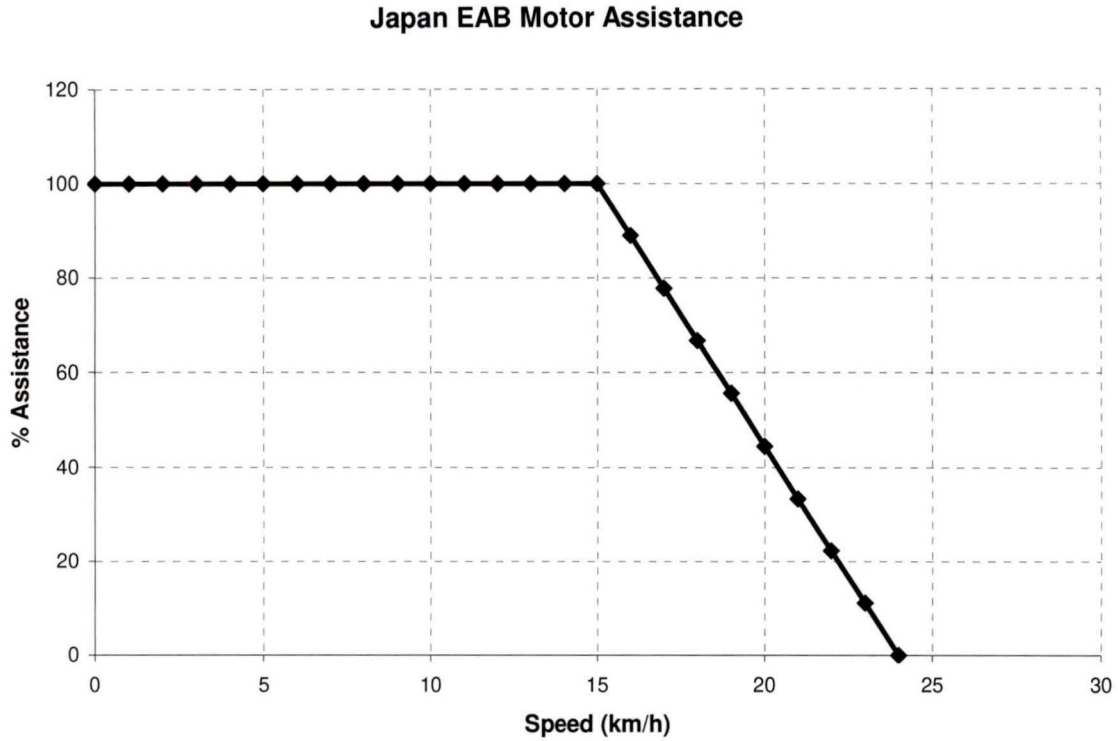


Figure 5: Japanese EAB Motor Assistance

100% motor assistance is permitted from 0 to 15 km/h, and then a linear relationship between % assistance and electric bicycle speed is imposed through the motor controller from 15 km/h to 24 km/h [10]. The linear relationship is shown in Equation 1 [10].

$$\%Assist = \left(1 - \frac{speed^{(km/h)} - 15}{9}\right) \times 100 \quad (1)$$

No motor assistance is permitted after 24 km/h. There are no legal standards regarding motor outputs in Japan.

2.3.4. European Union

The European Union consists of fifteen countries. These countries have varying electric bicycle regulations at the current time, but are working to develop a standard regulation for electric bicycles in the European Union. Table 2 shows the current electric bicycle regulations.

Table 2: European Union Electric Bicycle Regulations [11]

Country	Speed Limit (km/h)	Continuous Motor Output (Watts)	Age Limit
Austria	25	N/A	no
Belgium	no	300	no
Denmark	25	250	no
Finland	25	250	no
France	25	500	no
Germany	24	250	no
Greece	N/A	N/A	N/A
Holland	25	250	no
Ireland	N/A	N/A	N/A
Italy	no	no	no
Luxemburg	no	no	no
Portugal	N/A	N/A	N/A
Spain	25	500	no
Sweden	30	no	15
UK	24	200	14
AVERAGE	25.3	312.5	N/A

The European Union is mainly concerned with Pedelecs (EABs) rather than EPBs. In most countries in the European Union the EPB is classified as a moped, and is subjected to the same licensing and insurance as a moped. It can be seen in Table 2 that the average speed limit is ~25 km/h, and the average continuous motor output is ~313W. Most of the countries have a speed limit of 25 km/h, and a continuous motor output of 250W. It is also apparent that Italy and Luxemburg have not yet imposed any regulations regarding electric bicycles, this is sure to change when the European Union imposes a universal set of electric bicycle regulations in the near future. No data is available for Ireland, Greece, and Portugal.

United Kingdom (UK)

In the UK, electric bicycle rules are based on the 1983 Electrically Assisted Pedal Cycle Regulations [12]:

The regulations state that Electrically Assisted Pedal Cycles (EAPC), including those fitted with auxiliary electric motors, are exempt from all registration and licensing requirements provided that the following conditions are met:

In the case of a bicycle, its curbside weight must not exceed 40 kg, or in case of a tricycle it must not exceed 60 kg (including batteries).

Both bicycles and tricycles must be fitted with pedals by means of which they can be propelled.

The output of the electric motor fitted must not exceed 200W [continuous power] in the case of a bicycle and 250W [continuous power] for tricycles, and it cannot propel the vehicle when it is traveling at more than 15 mph (24 km/h).

There must be a switch that cuts the power to the motor when released by the rider.

If the rider conforms to these regulations an electric bike can be operated on roads without needing a license, tax disc, insurance, etc. If the bike exceeds these regulations it needs to be registered as a moped.

It is important to note that the motor power specified by the UK regulations is for continuous power not maximum power. Also, the mass of the electric bicycle is limited to 40 kg (88 lbm) to ensure that the rider always has full control over the vehicle.

2.3.5. China

Electric bicycles operated in China cannot have a maximum speed higher than 20 km/h. Electric bicycles made for the Chinese market are electrically propelled bicycles (EPBs); there is no need for the rider to pedal to receive motor assistance.

2.3.6. Summary of Worldwide Regulations

It is interesting to note that the majority of regulations for electric bicycles limit the continuous motor output power, while the electric bicycle manufacturers almost always only specify their products with the maximum motor output power; the manufacturers likely do this for marketing purposes. Table 3 summarizes the worldwide electric bicycle regulations. Table 3 shows that the average top speed allowed varies from 20 km/h to 32 km/h, while the continuous motor output power allowed varies from 200W to 500W. The USA is the only country that is considering limiting the maximum motor output, rather than the continuous output power. Canada, France, and Spain are allowing the highest-powered motors to be equipped on electric bicycles (500W continuous power); this would translate to approximately 1000W maximum output power. The only countries limiting the mass of the electric bicycle are the UK and USA. The mass is limited to ensure that the rider has full control over the electric bicycle.

Table 3: Worldwide Electric Bicycle Regulations

(Note: The - indicates that there is no regulation currently applicable to this category)

Country	Top Speed with Motor (km/h)	Continuous Motor Output (Watts)	Maximum Motor Output (Watts)	Maximum Mass (kg)
Austria	25	-	-	-
Belgium	-	300	-	-
Canada	32	500	-	-
China	20	-	-	-
Denmark	25	250	-	-
Finland	25	250	-	-
France	25	500	-	-
Germany	24	250	-	-
Holland	25	250	-	-
Japan	24	-	-	-
Spain	25	500	-	-
Sweden	30	-	-	-
USA	32	-	750	45
UK	24	200	-	40
<i>MINIMUM</i>	20	200	750	40
<i>MAXIMUM</i>	32	500	750	45
<i>AVERAGE</i>	25.8	333.3	750	42.5

2.4. Marketable Electric Bicycle Design

From the electric bicycle regulations and designs analyzed, designs in this thesis have a motor power of 200W continuous (400W maximum). A high torque motor capable of a maximum speed less than 20 km/h is chosen for modeling. The entire electric bicycle mass is also kept below the UK maximum of 40 kg. With these specifications the electric bicycle could be sold in all countries.

CHAPTER 3 FUEL CELLS FOR ELECTRIC VEHICLES

3.1. Hydrogen Fuel Cells

It is important to understand the characteristics of the type of fuel cell that could be used to power an electric bicycle. There are many varieties of fuel cells being produced presently, and not all are suitable for small power applications, such as in an electric bicycle. The fuel cell varieties are investigated in this section to determine the best fuel cell for the electric bicycle power plant.

Five main types of fuel cells are being developed today; these fuel cells are named based on their electrolyte. The five types are: proton exchange membrane fuel cells, alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and solid oxide fuel cells. The most promising portable power plant among these five fuel cell types is the proton exchange membrane fuel cell (PEMFC), due to its high power density, low operating temperature, and quick warm up time.

A very good reference on general fuel cell information can be obtained from the Los Alamos National Laboratory. The paper covers basic fuel cell operation, comparison of various fuel cell types, fuel for fuel cells, hydrogen and more [13].

3.1.1. Proton Exchange Membrane Fuel Cell (PEMFC)

The proton exchange membrane fuel cell (Figure 6) has an electrolyte consisting of a perfluorosulfonic acid polymer. This polymer is basically a Teflon[®] chain with SO₃H side chains. The PEMFC operates at a low temperature range of 60 – 100 °C.

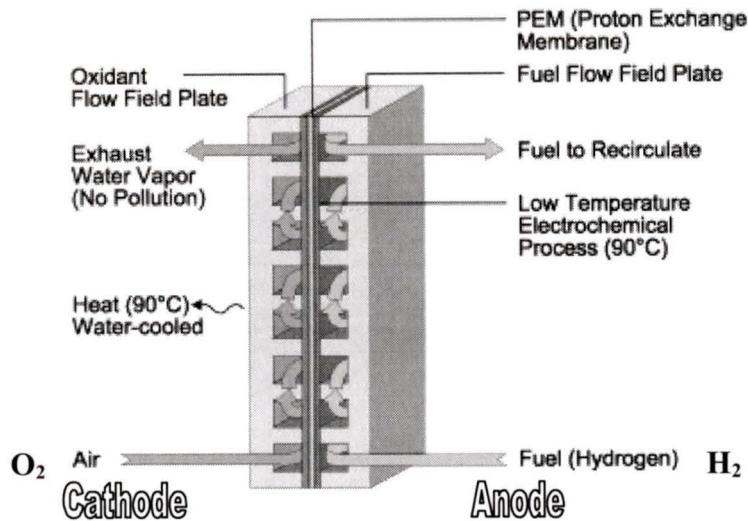


Figure 6: PEMFC Operation [14]

The main equation for a PEMFC is, $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$. The anode reaction is, $\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$, and the cathode reaction is, $\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$.

The PEMFC has many advantages. The membrane in the PEMFC is very thin (less than 50 micrometers); this helps provide low ohmic resistance losses and a very high power density (W/cm^3). The membrane is a solid rather than liquid, this allows a reduction in the complexity of the sealing processes. Since the PEMFC has a low operating temperature, it only takes a small time to start-up the power source; this is particularly useful for vehicular applications. The PEMFC is also capable of dealing with varying current draws and variable operating conditions, also essential for vehicular applications. The PEMFC can also achieve very high current densities.

The PEMFC also has some disadvantages and operation challenges. The PEMFC requires a delicate balance of membrane hydration; if the membrane has too much hydration, flooding will result which will block the flow field channels, blocking the fuel and oxygen delivery to the cell, drastically reducing the cell performance. If the PEMFC membrane becomes too dry, the voltage will drop significantly (as ohmic losses increase dramatically), and the membrane can develop cracks, causing a potentially dangerous

mixing of the fuel and oxygen. Due to the low temperature operation of the PEMFC, an expensive platinum catalyst is used at the anode and cathode to break the H₂ bonds at the anode, and the O₂ bonds at the cathode (approximately 0.2 mg/cm² at the anode, and 0.4 mg/cm² at the cathode). The PEMFC can also be contaminated by impure hydrogen. Impurities attach themselves to the catalysts, blocking the catalyst sites, resulting in a reduction of the fuel oxidation, significantly reducing performance. Also, since the PEMFC operates at such a low temperature, the heat generated cannot be used for additional power utilization, for example powering a turbine or cogeneration. All fuel cells produce heat and electricity as part of the electrochemical reaction; cogeneration is defined as the utilization of both products.

The PEMFC has many desirable qualities, and some notable disadvantages. The PEMFC has a very high power density, and quick start-up time. These are very important characteristics for use in a low power vehicle such as an electric bicycle.

3.1.2. Alkaline Fuel Cell (AFC)

The alkaline fuel cell has a liquid electrolyte that is usually potassium hydroxide (KOH) contained in an asbestos matrix. This fuel cell operates at a low temperature range of 90 – 100 °C. The AFC uses cheap catalysts such as Nickel. The AFC has a high power density, but still not as high as the PEMFC.

The main equation for an AFC is, $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$. The anode reaction is, $H_2 + 2(OH)^- \rightarrow 2H_2O + 2e^-$, and the cathode reaction is, $\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$.

The AFC has some major disadvantages. The AFC cannot withstand high levels of CO₂ at the cathode (50 ppm is the limit). Due to this characteristic, the AFC requires a carbon dioxide scrubber to reduce the CO₂ levels in the air to under 50 ppm. The other main disadvantage is the expensive membrane.

The AFC needs a CO₂ scrubber that adds complexity and weight to the fuel cell system; this is undesirable for a low mass vehicle. The expensive cost of the AFC is also undesirable for an electric bicycle.

3.1.3. Phosphoric Acid Fuel Cell (PAFC)

The PAFC has an electrolyte consisting of liquid phosphoric acid in a silicon carbide matrix. The operating temperature of this fuel cell is in the 50 – 220 °C range. The PAFC is highly efficient if cogeneration is used. Another major advantage of the PAFC is that it can use impure hydrogen as fuel without any adverse effects.

The main equation for a PAFC is, $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$. The anode reaction is, $\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$, and the cathode reaction is, $\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$.

The PAFC has many disadvantages. The PAFC requires a large electrolyte thickness (approximately 0.1mm compared with 50µm for the PEMFC); this results in a large fuel cell stack size. The large stack size contributes to a low power density (approximately 1/3 the performance of a PEMFC). The PAFC also requires an expensive platinum catalyst due to its low temperature operation (~0.2 mg/cm² at the anode, and ~0.4 mg/cm² at the cathode). Another disadvantage is the requirement that the temperature of the cell not drop below 45°C at any time; if the temperature drops below this temperature the phosphoric acid will solidify and expand, damaging the cell.

The PAFC has a power density too low for use in a low mass vehicle where weight is of utmost importance. It is not practical to have the fuel cell warmed when not in use. The large size is also undesirable due to space limitations in a small lightweight electric bicycle.

3.1.4. Molten Carbonate Fuel Cell (MCFC)

The molten carbonate fuel cell has an electrolyte that consists of molten ionic salts (e.g. Li₂CO₃, K₂CO₃). The MCFC operates in the 600 – 700 °C temperature range. The MCFC has many advantages. Due to its high temperature operation, it does not require expensive

platinum catalysts. The MCFC is very efficient when its generated heat is used to drive a turbine for use in cogeneration. The MCFC can operate efficiently with CO₂ enriched fuels. Carbon monoxide can also be used as a fuel.

The main equation for a MCFC is, $H_2 + \frac{1}{2}O_2 + CO_2 \rightarrow H_2O + CO_2$. The anode reaction is, $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$, and the cathode reaction is, $\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$. The disadvantages of the MCFC consist of a very low power density, and also a very large mass. The large mass is due to the requirement of stainless steel for the cell hardware material. Due to the MCFC's operation at high temperatures, corrosion effects are increased and the overall lifetime of cell is lowered. The MCFC also requires a source of CO₂ at the cathode.

The MCFC operates at much too high of a temperature for it to be used in a vehicular application, increasing the startup time immensely. The MCFC is very heavy and has a low power density; these characteristics are very undesirable for an electric bicycle.

3.1.5. Solid Oxide Fuel Cell (SOFC)

The solid oxide fuel cell (SOFC) has many of the same characteristics as the MCFC. The main difference is that the SOFC has a solid electrolyte and no requirement for CO₂ at the cathode. The SOFC has a ceramic oxide electrolyte; it operates within the 650 – 1000 °C range. The SOFC requires an inexpensive catalyst due to its high temperature operation. Like the MCFC, the SOFC operates at high efficiency when its generated heat is used for cogeneration. The solid electrolyte is also advantageous over the MCFC since no flooding occurs due to no liquid being present. The SOFC can also use CO as a fuel. The cell is made of ceramic that reduces corrosion.

The main equation for a SOFC is, $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$. The anode reaction is, $H_2 + O^{2-} \rightarrow H_2O + 2e^-$, and the cathode reaction is, $\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$.

The disadvantages of the SOFC include a low power density, difficult fabrication processes due to the ceramic parts, and many thermal expansion problems that affect the seals.

The high temperature operation of the SOFC is reserved for stationary power plants where its high temperature operation can be fully utilized. Also, the start-up time would be too long for a vehicle due to the high temperature operation.

3.2. Fuel Cells for Transportation Applications

3.2.1. Fuel Cell Selection Table

The fuel cell types analyzed in Section 3.1 are summarized in Table A1, presented in Appendix A. The advantages and disadvantages are listed to display that a compromise has to be made in selecting the best cell for quick startup, long operational life, low mass, and adequate power for an electric bicycle power plant.

It is determined through the analysis that the PEMFC is the best overall choice for a small vehicular application; this is confirmed with the majority of current fuel cell vehicle development.

3.2.2. Current Fuel Cell Vehicle Development

Many major automotive manufacturers are involved with fuel cell vehicle development. Some of these manufacturers include DaimlerChrysler, the Ford Motor Corporation, General Motors, BMW, Fiat, Peugeot/Citroen, Renault, Volkswagen/Volvo, Honda, Hyundai, Mazda, Mitsubishi, Nissan, Suzuki, and Toyota. Among these, Honda and Toyota, plan to have production fuel cell hybrid powered vehicles for sale in 2003.

Honda FCX-V3

The Honda fuel cell hybrid automobile, the FCX-V3 (Figure 7) combines a 70 kW (94 hp) PEMFC stack and a Honda developed ultra capacitor. The FCX-V3 has a very quick startup time of 10 seconds. The capacitor allows for regenerative braking and provides

extra power for quick acceleration. The permanent magnet AC electric motor has a maximum power output of 60 kW (80 hp). The hydrogen for the PEMFC is stored at 250 atm (3675 psi) in a 100-liter tank [15]. The FCX-V3 has a range of 112 miles (180 km), and a top speed of 81 mph (130 km/h) [16].



Figure 7: Honda FCX-V3 Fuel Cell Hybrid Vehicle

Toyota FCHV-4

The Toyota fuel cell hybrid vehicle (FCHV), the FCHV-4 (Figure 8), combines a 90 kW (121 hp) PEMFC stack and a nickel metal hydride battery pack. The FCHV-4 nickel metal hydride battery pack allows for regenerative braking. The FCHV-4 uses a permanent magnet electric motor rated at 80 kW (107 hp) maximum output. The FCHV-4 has a range of over 250 km, and a maximum speed of over 150 km/h [17].



Figure 8: Toyota FCHV-4 Fuel Cell Hybrid Vehicle

DaimlerChrysler NECAR 5

Ballard Power Systems Ltd., an international leading developer of PEM fuel cells for transportation use, has been actively working with many automotive manufacturers to demonstrate, test, and commercialize the PEM fuel cell technology. Ballard fuel cells are featured in the DaimlerChrysler NECAR 5 (Figure 9). The NECAR 5 is powered mainly with a 75 kW (101 hp) PEMFC stack. This fuel cell vehicle can achieve a top speed of over 150 km/h. The NECAR 5 uses a Ballard Mark 900 stack; this stack uses 400 cells supplying 250 Volts to the vehicle at full load. The efficiency of the power system from fuel tank to drive wheels is claimed to be over 45%, which is very high compared to a maximum efficiency of 20% for an IC power system (from fuel tank to drive wheel). The NECAR 5 also utilizes an auxiliary battery, which enables regenerative braking. The NECAR 5 is fueled by liquid methanol; a reformer system generates the hydrogen from the methanol [18].



Figure 9: DaimlerChrysler NECAR 5

3.3. Background of Hydrogen Fuel Cell Systems as a Power Plant for Electric Bicycle and Scooter Propulsion

This section describes known prototype fuel cell powered electric bicycles and their fuel cell systems. These electric bicycles use a proton exchange membrane (PEM) fuel cell system to power their electric motors. The most developed fuel cell powered electric scooter is also presented in this section.

3.3.1. Manhattan Scientifics NovArs Fuel Cell System

One of the most advanced portable fuel cell stacks today is built by NovArs, a German mid-range fuel cell development company, now owned by Manhattan Scientifics (Manhattan, New York, USA). The 670 Watt (0.9 hp) PEM fuel cell stack (Figure 10) uses many proprietary innovations to provide a stack that has a very high power to weight ratio, simple design, and high efficiency. The cylindrical NovArs stack only weighs 780 grams (1.72 lbm) using many carbon composite materials [19]. The stack also uses proprietary sealing techniques that eliminate the need for gaskets and fasteners. Hydration for the stack is done using proprietary techniques that keep adequate amounts of water in the membrane without blocking the flow channels. The stack also operates at ambient pressure, and uses no pumps to pressurize the fuel and oxidant (air). The fuel cell stack does not require any cooling fans.

The fuel for the stack is pure hydrogen and is contained in an aluminum pressure vessel that is reinforced with carbon fiber. This hydrogen container can be refueled very quickly. The entire fuel cell system can achieve a specific power of 205 Watts/kilogram and a power density of 115 Watts/Liter [19]. When compared to a conventional battery powered electric bicycle power system, the Manhattan Scientifics NovArs fuel cell system has approximately seven times more power density than lead acid batteries, which generally have a specific power of 30 Watts/kilogram. The NovArs fuel cell system does not use a sophisticated control system.

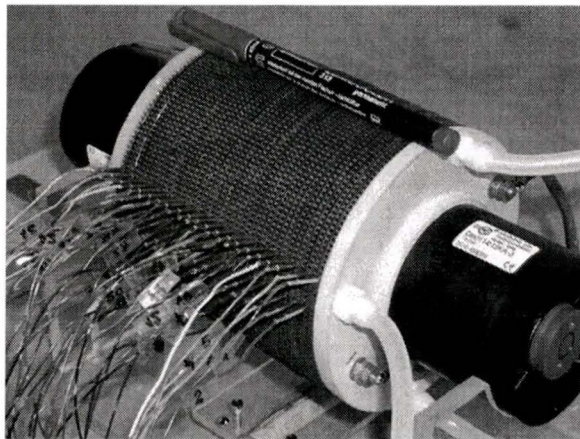


Figure 10: Manhattan Scientifics NovArs PEM Fuel Cell Stack [19]

Manhattan Scientifics / Aprilia Fuel Cell Bicycle

The NovArs PEM fuel cell system is used for powering the most advanced fuel cell bicycle prototypes. The NovArs system was first used to power the Manhattan Scientifics fuel cell powered electric bicycle, named the Hydrocycle™ (Figure 11). This full suspension electric bicycle features a rear hub motor and compressed hydrogen fuel storage. The two liter compressed hydrogen container is located above the rear wheel. Since the hub motor is located at the center of the rear wheel, the bicycle mass remains symmetrical, which is not the case with other electric bicycles that have the motor located on one side of the bicycle. Mass symmetry is desirable for electric bicycle stability. The fuel cell stack is located at the front of the bicycle, and is attached near the handlebars. The Hydrocycle™ has a range of 112 km (70 miles) if ridden on a flat surface without human assistance, compared to approximately 32 km for an average battery powered electric bicycle with some pedaling required. The top speed of the Hydrocycle™ is approximately 30 km/h (19 mph) [20].



Figure 11: HYDROCYCLE™, Manhattan Scientifics Fuel Cell Powered Concept Bicycle [21]

The Aprilia ENJOY fuel cell powered bicycle (Figure 12) is a product of collaboration between Aprilia (Noale, Italy), Manhattan Scientifics, and NovArs. Fuel for the Aprilia ENJOY fuel cell bicycle is contained in an aluminum pressure vessel lined with carbon fiber at a high pressure of 30 MPa (4351 psi). The Aprilia ENJOY fuel cell bicycle uses the same NovArs PEMFC stack used with the Hydrocycle™. The total mass of the

Aprilia fuel cell bicycle is 24 kg (53 lbm) [22], which is very light compared to an average battery powered electric bicycle (30 kg (66 lbm)) [See Table 1].



Figure 12: Aprilia ENJOY Fuel Cell Powered Electric Bicycle Prototype with Manhattan Scientifics NovArs PEM Fuel Cell Power System [19]

3.3.2. Palcan Fuel Cells Ltd. Fuel Cell Systems

The fuel cell system being designed by Palcan Fuel Cells Ltd. (Burnaby, BC, CANADA) for light vehicle propulsion is presently in the prototype stages of development. The Palcan fuel cell systems use PEMFC stacks with a power output ranging from 250 – 450 Watts. The present stack is designed to operate at ambient pressure and is air-cooled. The reactant air is supplied through the use of a small blower. The Palcan portable fuel cell system uses a metal hydride hydrogen storage canister to supply hydrogen fuel. Metal hydride hydrogen containment uses a metal alloy powder that hydrogen bonds to, forming a metal hydride. Metal hydride hydrogen containment occurs at low pressures up to 2 bar (29 psi) [23]. Figure 13 shows the relative sizes of the various methods of powering an electric bicycle.



Figure 13: Palcan Metal Hydride Hydrogen Containment Shown in Middle (Compressed Hydrogen Container on Left and 24 V Sealed Lead Acid Battery Pack on Right)

Palcan Fuel Cell Bicycle

The recent Palcan fuel cell powered electric bicycle prototype is built using a regular Giant brand bicycle, the electric drive of a Currie Cycles electric bicycle, and Palcan's PEM fuel cells, as shown in Figure 14. The bicycle power system uses a metal hydride canister to provide fuel for about 5 hours (125 km @ 25km/h) of operation. The metal hydride hydrogen canister can be quickly replaced when empty. The electrically propelled bicycle (EPB) is controlled with a thumb throttle on the right grip. The total mass of the Palcan prototype fuel cell bicycle is approximately 35 kg (77 lbm). Palcan is currently developing a computerized control system for the fuel cell system that will monitor and optimize the operation of the entire power system. The control system is expected to increase performance and range of the bicycle.

Palcan has signed a Memorandum of Understanding (MOU) with the Chuang Yuan Group Co. Ltd (China), the parent company of the Suzhou Small Antelope Bicycle Company (October 2001). The MOU defines joint development of a fuel cell powered bicycle based on the popular Suzhou Small Antelope electric bike design. The planned fuel cell powered bicycle will use Palcan's portable fuel cell power system, which Palcan

has been testing on their latest demonstration fuel cell powered electric bicycle (Figure 14) [24].



Figure 14: Palcan Fuel Cell Powered Electric Bicycle

3.3.3. Fuel Cell Scooters

PEM fuel cells are also being adapted to power large electric scooters. These vehicles require a much higher-powered fuel cell stack than an electric bicycle; a fuel cell scooter needs a stack capable of providing approximately 3 – 6 kW of power to the electric motor.

The ZES IV Fuel Cell demonstration scooter has been developed through collaboration with Asia Pacific Fuel Cell Technologies Ltd. (USA), Kwang Yang Motor Co., Ltd. (Taiwan), the Taiwan Institute of Economic Research (Taiwan), and the W. Alton Jones Foundation (USA) (Figure 15).



Figure 15: ZES IV Fuel Cell Scooter [25]

The PEM fuel cell stack used to power the electric motor is rated at 6 kW (8HP). It has a power density of 0.9 kW/L, a specific power of 1.0 kW/Kg, operates at atmospheric pressure at a temperature of 60 degrees Celsius, and uses pure hydrogen as fuel. The fuel cell engine produces 5.1 kW (6.8 HP) of traction power, is water-cooled, uses metal hydride fuel storage, and has a fuel capacity of 2400 liters of hydrogen.

The ZES IV scooter has a mass of 95 kg, a driving range of 160 km, a refueling time of 2 minutes, and can achieve a maximum speed of 75 km/h. The scooter uses a DC brushless electric motor, and can climb grades of 18° [25].

CHAPTER 4 DESIGN OF PEM FUEL CELL SYSTEMS FOR ELECTRIC BICYCLES AND SCOOTERS

4.1. PEM Fuel Cell Power Characteristics

4.1.1. Fuel Cell Electrochemical Reaction and Model

The Proton Exchange Membrane (PEM) fuel cell is a promising power plant for electric bicycles and scooters due to its low operating temperature for quick start-up. The PEM fuel cell also features a high volumetric power density, which results in a small size that can fit into the limited space of a compact vehicle. Their electrochemical characteristics and advantages have been discussed previously in Section 3.1.1.

4.1.2. PEM Fuel Cell Polarization Curve

The polarization curve of a PEM fuel cell defines the cell performance characteristics. The polarization curve is a plot of the cell voltage versus the operating current. The current generating capability of a fuel cell is commonly expressed as the current density, i.e. the current divided by the active membrane area (Amps/cm^2). The inefficiencies observed in a fuel cell during operation are due to three main losses: activation losses, ohmic losses, and concentration losses.

The overall cell voltage reflected by the polarization curve of a fuel cell is given in Equation 2.

$$V_c = E_r - (i + i_n)r - A \ln \left(\frac{i + i_n}{i_o} \right) + B \ln \left(1 - \frac{i + i_n}{i_l} \right) \quad (2)$$

where, E_r is the reversible (ideal) cell voltage, $E_r = 1.23$ V, $(i + i_n)r$ are the ohmic losses,

$A \ln\left(\frac{i + i_n}{i_o}\right)$ are the activation losses, and $B \ln\left(1 - \frac{i + i_n}{i_l}\right)$ are the concentration losses.

The other parameters are [26]:

i_l - limiting current density (~ 0.9 A/cm²),

i_n - internal and fuel crossover equivalent current density (~ 0.002 A/cm²),

i_o - exchange current density at cathode ($\sim 6.7 \cdot 10^{-5}$ A/cm²),

A - constant used in determination of activation losses (~ 0.06 V),

B - constant used in determination of mass transport losses (~ 0.05 V), and,

R - cell resistance per unit area (~ 0.03 Ω/cm²).

A theoretical polarization curve, generated using Equation 2, is shown in Figure 16.

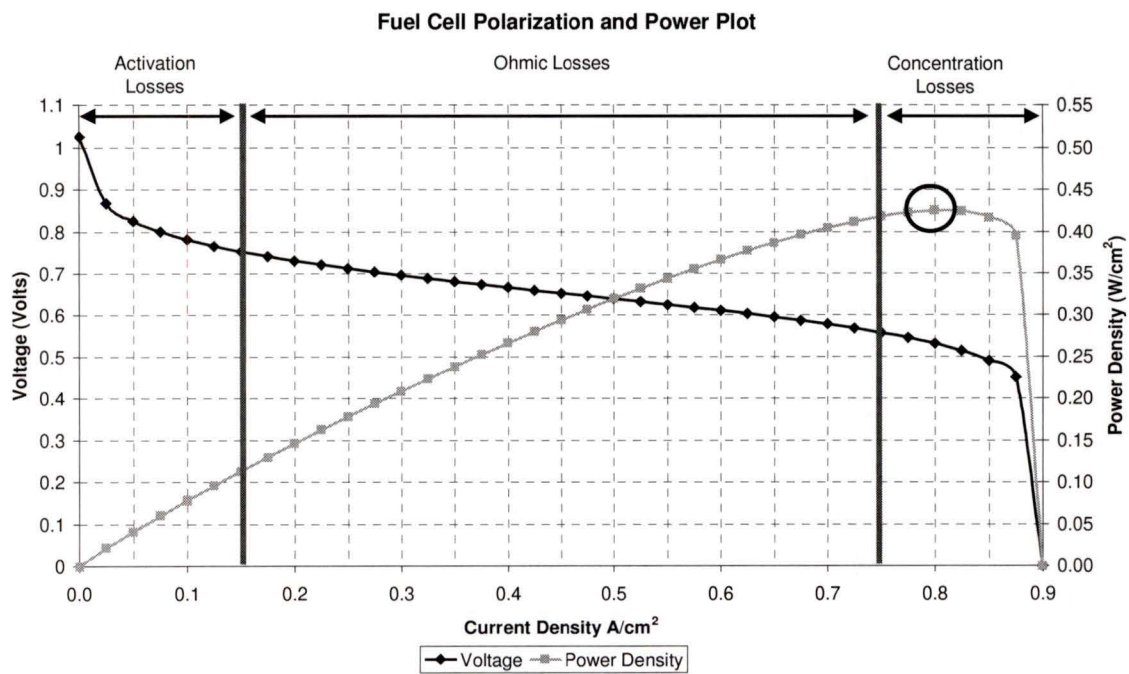


Figure 16: Fuel Cell Polarization Curve and Power Plot

From the original open circuit voltage of 1.03 Volts at 0 A/cm², a sharp decline in the cell voltage occurs due to the activation losses from 0 A/cm² to approximately 0.15 A/cm².

These losses are generated from the energy needed to start the fuel cell reaction. Even with a high platinum catalyst loading, activation losses are very significant. The ohmic losses determine the middle portion of the polarization curve. The ohmic losses are usually linear, based on $V=IR$ (Voltage = Current \times Resistance). As the current is increased, the concentration losses (also known as mass transport losses) occur, this is usually around 0.75 A/cm^2 . These losses are caused by the depletion of the concentration of the reactants at the fuel cell electrodes.

Another useful curve used in fuel cell development is the power density curve (Watts/cm²). The main issue regarding the fuel cell power density curve is the maximum power density (marked with a circle in Figure 16). It can be seen from Figure 16 that the maximum power density (0.425 W/cm^2) occurs at 0.8 A/cm^2 . The maximum power also occurs at a voltage of 0.532 Volts . Any fuel cell operation to the right of the maximum power density results in excessive inefficiencies, which cause a high amount of heat generation in the cell. The less efficient the fuel cell is, the more heat the fuel cell generates. As the inefficiencies become excessive, the fuel cell will become unstable with a high risk of overheating damage. For this reason, a fuel cell like the one in Figure 16 would be operated up to a maximum current density of $\sim 0.75 \text{ A/cm}^2$ (@ 0.56V).

4.1.3. Fuel Cell System Design Considerations

Fuel cell systems can have many different configurations. Some have air-cooled stacks, others have liquid cooling. Some fuel cell stacks operate at a high pressure, while others operate at ambient pressure. The optimization of a fuel cell system is a balance of output performance and input power. Fuel cell stacks can get an increase in power output if higher gas pressures are used, but this results in the need for a gas pressurization system (compressor or blower), which adds cost, size, power consumption, and complexity to the system. Since the fuel cell stack is usually used to power a compressor when high-pressure gasses are used, the output to the electric motor is lessened.

4.2. Power Supply and Demand of an Electric Bicycle

4.2.1. Battery Powered Electric Bicycles

All of the commercially available electric bicycles currently use battery power. There are three main battery types used, the sealed lead acid battery (SLA), the Nickel Cadmium battery (NiCad), the Nickel Metal Hydride battery (NiMH), and the Lithium-Ion battery (Li-ion) (Table 4).

Sealed Lead Acid Battery (SLA)

The sealed lead acid battery is the most common battery currently used to power electric bicycles, mainly due to its low cost; the SLA battery gives the most watt-hours for a given amount of money than the other battery types. The SLA battery is also very robust and durable when used properly. Also of importance is the low self-discharge rate of the SLA battery, only losing ~5% of its charge per month if not used [27]. The SLA battery also does not have a memory effect like the NiCad battery. Problems surrounding the SLA battery are high mass, and environmental unfriendliness, where the lead electrodes and electrolyte can cause environmental harm if not disposed of properly at a recycling facility.

Nickel Cadmium Battery (NiCad)

The NiCad battery is not used a lot for electric vehicles due to its memory effect, and toxic materials (Cadmium is a poison). There are however advantages to the NiCad battery. It has good low temperature performance, a low cost per cycle, long shelf life (in any charge state), and a large amount of charge/discharge cycles when properly used.

Nickel Metal Hydride Battery (NiMH)

The NiMH battery is used almost exclusively to power electric automobiles. The NiMH battery has a low volume for a given capacity than a sealed lead acid battery (can be less than half the volume of a SLA battery with the same capacity). The NiMH battery can have up to four times the energy density (Wh/kg) of a SLA battery. The NiMH is also superior to the NiCad battery in energy density (~40% higher capacity than the NiCad battery for a given mass). The NiMH battery is also relatively environmentally friendly, as

it contains very mild toxic materials that can be easily recycled. The main problem with the NiMH battery pack is the higher price over a SLA battery pack. It is also more difficult to charge than a SLA or NiCad battery, as it generates a large amount of heat when charging. It is also more difficult to determine when the NiMH battery is peak charged than with a SLA or NiCad battery, resulting in the need for more complicated and expensive chargers.

Lithium Ion Battery (Li-ion)

The Lithium Ion (Li-ion) battery is also a competitor in the electric vehicle power market. The Li-ion currently has a very high cost which has severely limited its use in electric vehicles.

The newer Li-ion Polymer battery and Rechargeable Alkaline battery are also shown in Table 4.

Table 4: Battery Comparison [27]

	NiCd	NiMH	Lead Acid	Li-ion	Li-ion polymer	Reusable Alkaline
Gravimetric Energy Density (Wh/kg)	45-80	60-120	30-50	110-160	100-130	80 (initial)
Internal Resistance (includes peripheral circuits) in mW	100 to 200 ¹ 6V pack	200 to 300 ¹ 6V pack	<100 ¹ 12V pack	150 to 250 ¹ 7.2V pack	200 to 300 ¹ 7.2V pack	200 to 2000 ¹ 6V pack
Cycle Life (to 80% of initial capacity)	1500 ²	300 to 500 ^{2,3}	200 to 300 ²	500 to 1000 ³	300 to 500	50 ³ (to 50%)
Fast Charge Time	1h typical	2-4h	8-16h	2-4h	2-4h	2-3h
Overcharge Tolerance	moderate	low	high	very low	low	moderate
Self-discharge / Month (room temperature)	20% ⁴	30% ⁴	5%	10% ⁵	~10% ⁵	0.3%
Cell Voltage (nominal)	1.25V ⁶	1.25V ⁶	2V	3.6V	3.6V	1.5V
Load Current - peak - best result	20C 1C	5C 0.5C or lower	5C ⁷ 0.2C	>2C 1C or lower	>2C 1C or lower	0.5C 0.2C or lower
Operating Temperature (discharge only)	-40 to 60°C	-20 to 60°C	-20 to 60°C	-20 to 60°C	0 to 60°C	0 to 65°C
Maintenance Requirement	30 to 60 days	60 to 90 days	3 to 6 months ⁹	not req.	not req.	not req.
Typical Battery Cost (US\$, reference only)	\$50 (7.2V)	\$60 (7.2V)	\$25 (6V)	\$100 (7.2V)	\$100 (7.2V)	\$5 (9V)
Cost per Cycle (US\$) ¹¹	\$0.04	\$0.12	\$0.10	\$0.14	\$0.29	\$0.10-0.50
Commercial use since	1950	1990	1970	1991	1999	1992

Comments associated with

Table 4 [27]:

1. The internal resistance of a battery pack varies with the cell rating, type of protection circuit, and number of cells. The protection circuit of Li-ion and Li-polymer adds about 100mW.

2. The cycle life is based on the battery receiving regular maintenance; failing to apply periodic full discharge cycles may reduce the cycle life by a factor of three
3. The battery cycle life is based on the depth of discharge. Shallow discharges provide more cycles than deep discharges.
4. The discharge is highest immediately after charge, and then tapers off. The NiCad capacity decreases 10% in the first 24h, then declines to about 10% every 30 days thereafter. Self-discharge increases with higher temperature.
5. Internal protection circuits typically consume 3% of the stored energy per month.
6. 1.25V is the open cell voltage. 1.2V is the commonly used value. There is no difference between the cells; it is simply a method of rating.
7. Capable of high current pulses.
8. Applies to discharge only; the charge temperature range is more confined.
9. Maintenance may be in the form of 'equalizing' or 'topping' charge.
10. The cost of the battery for commercially available portable devices.
11. Derived from the battery price divided by cycle life. Does not include the cost of electricity and chargers.

Battery Discharge Curve

The battery discharge curve displays the characteristics of the battery over its complete discharge cycle (voltage vs. time). The discharge cycle is usually performed at a constant temperature and load. The voltage vs. time, or voltage vs. % discharge is then plotted. For a vehicular application it is preferred that the battery discharge curve be flat rather than sloping downward for consistent vehicle performance. Figure 17 shows the SLA, NiCad, and NiMH batteries during their discharge cycles [28]. It can be seen that the SLA battery has a very sloped curve compared to the much flatter NiCad and NiMH battery curves. It can be seen that a NiCad or NiMH battery pack would be better for consistent electric vehicle performance.

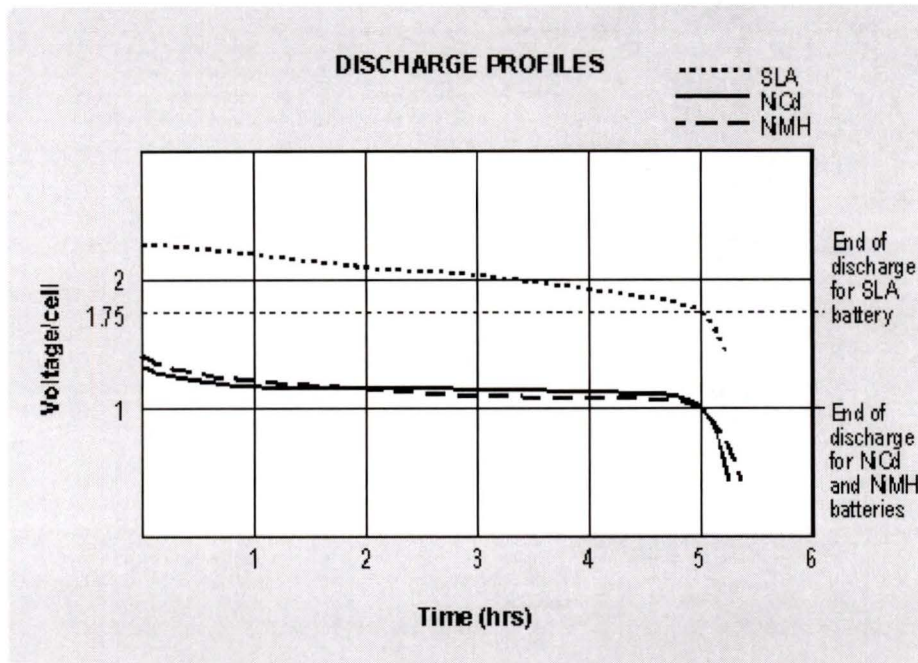


Figure 17: Battery Discharge Curves [28]

Power System Inefficiencies

The inefficiencies of the drive train can be incorporated after the initial power needed is obtained. The efficiency of the electric hub motor plus the electronic speed control is estimated to be approximately 70%; this is based on a hub motor efficiency of 78% and an electronic speed control efficiency of 90%. This estimate is close to what has been used in other small electric vehicle modeling. LaVen calculates for an electric scooter motor, the maximum efficiency to be 76%, while the electronic motor controller is found to have a maximum efficiency of 88% [29]. When these two values are multiplied together the maximum efficiency of the electrical system is found to be 66.88%, which is very close to the estimate of 70%.

It has been determined by DaimlerChrysler that the PEM fuel cell has more than 60% average efficiency associated with the conversion of chemical energy into electrical energy [30]. The maximum efficiency of a gasoline engine power system from fuel tank to drive wheels is 20% [31]. DaimlerChrysler estimates that the NECAR 5 has a fuel tank to drive wheel efficiency of over 45%, which is over 25% higher than an IC power system.

This data is only used to determine the main power needed (battery or fuel cell). The motor rating is the actual maximum and continuous output power available to the rider.

4.2.2. Fuel Cell Powered Electric Bicycles

Fuel cell powered electric bicycles have a much more complex power system than the battery powered electric bicycle as discussed in Section 4.1.3. Since a fuel cell stack is used, the voltage fluctuates much more than a battery during operation, usually needing a voltage regulator.

Fuel Cell Power Output Curve

The fuel cell power output curve is obtained from the polarization curve (Section 4.1.2). As discussed, the fuel cell must not be operated beyond its maximum power due to unnecessary losses, which result in possible damage to the stack, due to overheating. In order for adequate power to be sent to the electric motor of the bicycle, the fuel cell stack needs to be designed to provide the maximum power rating of the motor. Due to the inefficiencies present, this results in the fuel cell stack producing a higher amount of power than the maximum rated electric motor power.

4.2.3. The Need for an Electric Bicycle Power Requirement Model and Systematic Testing Method

It is useful to model the electric bicycle to simulate the performance (power required) at various operating speeds and grades. Modeling can be used to determine the sizing of the motor and fuel cell stack. For this project the model is mainly used to determine if the selected motor (400W maximum, 200 W continuous) is adequate for realistic electric bicycle operating conditions.

Electric bicycle standard tests also need to be developed to aid in electric bicycle development. Research and development teams can make performance improvements, and then observe the improvements quantitatively. The necessity of a standard electric bicycle testing system is even more important for fuel cell powered electric bicycles to

observe performance and functionality at various operating conditions before a product is released to the public.

4.3. Static Modeling of an Original Fuel Cell Powered Electric Bicycle

The modeling determines the power necessary to propel the bicycle and rider given a variety of riding conditions, including off-road riding. This section demonstrates how a static analysis of the bicycle and rider with the main components of the fuel cell system attached can determine the theoretical power required to move the unit at an adequate velocity.

4.3.1. Bicycle Used in Modeling

The Rocky Mountain RM6 (Figure 18) is classified as a “free-ride” bike; this means that it has the ability to be ridden in most road and off-road conditions. Due to this designation, the RM6 is designed with very strong parts and an extremely strong frame. The high strength of the RM6 adds mass; the total mass of the entire bicycle is approximately 15.28 kg (33.68 lbs), and the frame is approximately 3.63 kg (8 lbs). The RM6 has six inches of rear wheel suspension travel, and five inches of front wheel suspension travel. The front axle of the Marzocchi Z1 QR20 suspension fork is 20mm rather than a standard 9mm axle.



Figure 18: Rocky Mountain RM6 Full Suspension Bicycle [32]

4.3.2. Fuel Cell Electric Bicycle Power System Design Objectives

The main objective for the fuel cell powered electric bicycle power system is the ability for it to be put on almost any bicycle. The main aspect of this feature is the front mounted hub motor (Figure 19). By having a hub motor located on the front axle of the bicycle, the bicycle's regular front wheel can be exchanged easily for the hub motor equipped wheel. The front motorized drive also effectively creates a two wheel drive bicycle. The front wheel can be driven by the electric motor, while the rear wheel can be driven in the usual manner, by human power. Having the fuel cell located at the front of the bicycle is investigated with this model to observe the traction advantage of having more mass over the drive wheel, creating more traction, than having it located at a different position on the bicycle. Since the power system is designed to be removed quickly from the bicycle, the fuel cell would be located in a front quick release basket, and the metal hydride hydrogen container would fit into the water bottle cage.

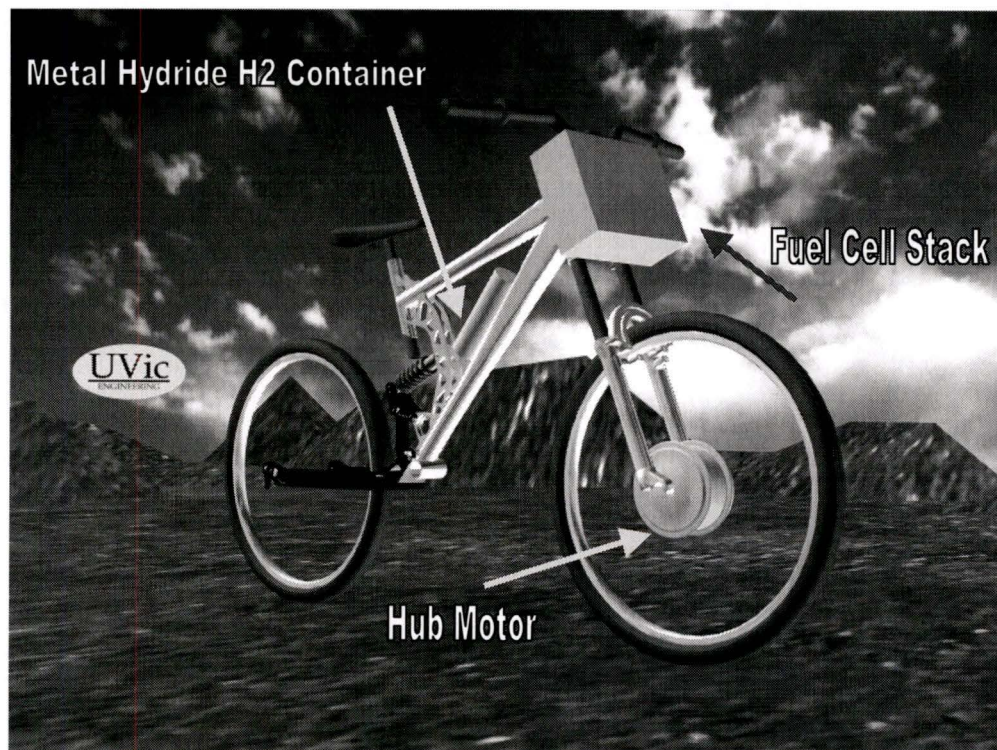


Figure 19: RM6 with Main Components of Fuel Cell System

Determination of Rider Mass

The rider mass used in the electric bicycle modeling and testing is determined by using a percentile mass chart (Figure 20) [33]. It should be noted that any rider mass could be used for modeling purposes. This chart has been created by Dr. S. B. Halls M.D., using data from the NHANES III (National Health and Nutrition Examination Survey). This survey was conducted in the United States of America during 1988 to 1994. The NHANES III included approximately forty thousand people selected from households in 81 counties across the United States. The NHANES III is the same survey data used by the CDC (Center for Disease Control) to construct their standard pediatric growth charts [33].

The percentile mass chart is used to approximate the 50th percentile mass of the author. The curved lines on the Men's Weight Chart (Figure 20) show the percentiles of the adult population surveyed. The thick middle line represents the 50th percentile of adult white males. The 50th percentile shows that 50% of the survey population of adult white males have a mass larger than the line, and the mass of 50% of the adult white males surveyed have a mass smaller. The 95th percentile line indicates the mass where 95% of the adult white male population is smaller (and 5% is larger).

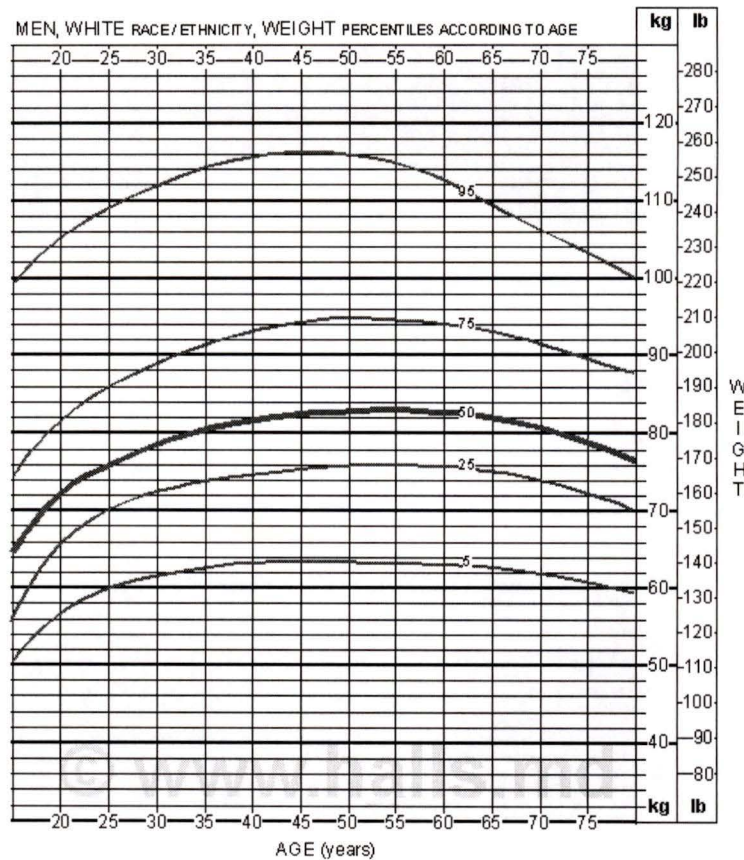


Figure 20: Men's Mass Chart

Using the 50th percentile line from Figure 20, the mass for a 24 year old male is ~165 lbm (74.84 kg). Adding approximately 2 lbm to this mass for light clothing the final mass is 167 lbm (75.75 kg). It can be seen from this chart that the 50th percentile line does increase up until approximately age 55, when it begins to curve back downwards. It is determined that using this value is better for modeling, rather than using the author's actual mass (which is in the 25th percentile compared with others of the same age). The mass of 167 lbm could also be regarded as a 150 lbm rider plus 2 lbm clothing, and a 15 lbm backpack.

4.3.3. Assumptions for Static Modeling

For the initial bicycle modeling, many assumptions are necessary. The following table includes the main assumptions used in the modeling (Table 5). These assumptions are estimated to be within 10 percent of the actual values. The center of gravity of the rider, the hydrogen container, the fuel cell stack, the hub motor, and the additional power

system components is estimated; this is done to develop a free body diagram used to determine the front tire resistive force.

Table 5: Fuel Cell Bicycle Modeling Assumptions

Assumption	Value
Rider Mass	75.7507 kg (167 lbm)
Hydrogen Containment Unit Mass	2 kg (4.4092 lbm)
Hub Motor Mass	3.6288 kg (8 lbm)
400W PEM Fuel Cell Stack Mass	4.0824 kg (9 lbm)
System Components Mass (Pumps, fans, piping, etc)	3.8967 kg (8.5906 lbm)
RM6 Bicycle Mass	15.2771 kg (33.68 lbm)
Total Power System Mass	13.6079 kg (30 lbm)
Drag Coefficient [34]	1.2 (flat plate)
Frontal Area [34], [35], [36]	0.5 m ²
Air Density	1.2 kg/m ³
Headwind Speed	0 km/h
Gravity	9.81 m/s ²
Rocky Mountain RM6 bicycle CG (Horizontal)	560 mm from rear tire ground contact point
Hydrogen Container CG (Horizontal)	660 mm from rear tire ground contact point
Fuel Cell CG (Horizontal)	1120 mm from rear tire ground contact point
First ½ System Components CG (Horizontal)	660 mm from rear tire ground contact point
Second ½ System Components CG (Horizontal)	1120 mm from rear tire ground contact point
Hub Motor CG (Horizontal)	1120 mm from rear tire ground contact point
Rider CG (Horizontal)	250 mm from rear tire ground contact point
Frontal Area CG (Vertical) for aerodynamic drag	1689 mm from ground
Maximum Speed (km/h)	18 km/h

Figure 21 shows the location of the rear tire contact point; this is the point where the rear tire is in contact with the ground. The approximate locations of the power system components are also shown. The arrows indicate the forces acting on the bicycle due to the masses of the power system and rider. The fuel cell components are placed at the front of the bicycle in order to prevent the front tire from slipping due to a low normal force at the front tire during steep hill climbing.

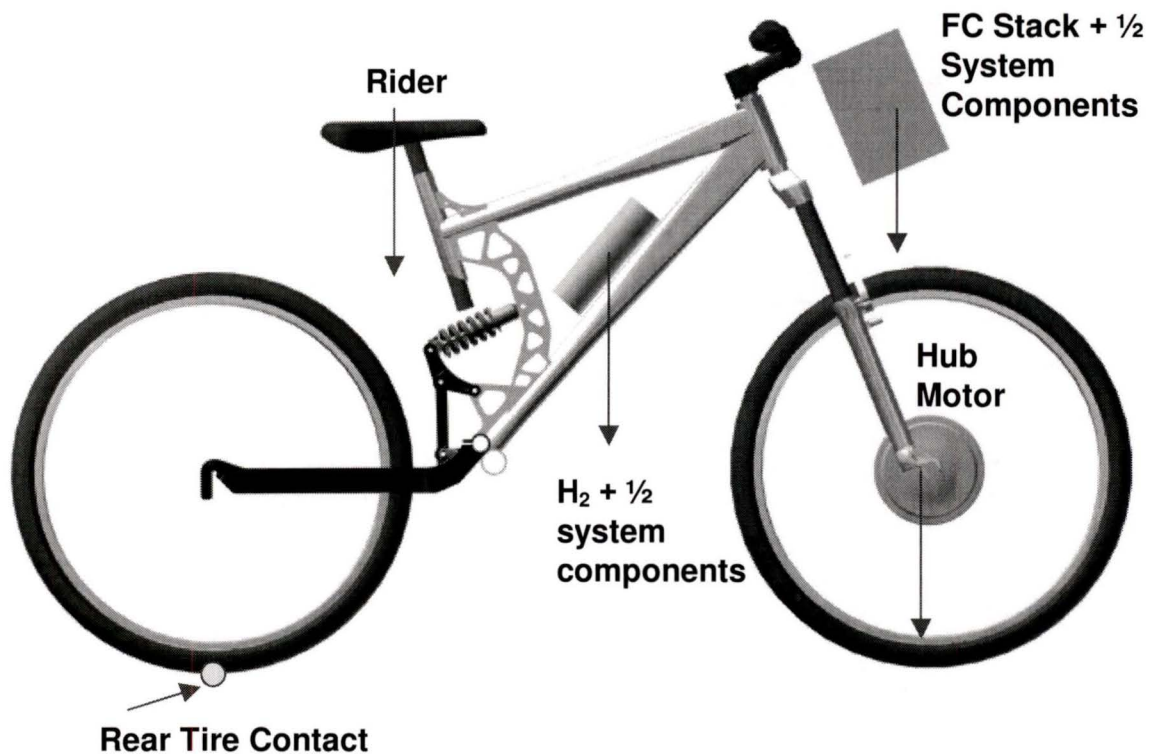


Figure 21: Fuel Cell Bicycle Model

4.3.4. Power Determination

The total power needed for the bicycle and passenger to travel up a hill, with acceleration, incline, rolling resistance, and air resistance (drag) forces opposing its forward travel needs to be defined. The power needed (Watts) is the sum of these forces acting opposite to the direction of travel multiplied by the velocity of the bicycle (Equation 3).

$$\begin{aligned}
 Power &= \sum Forces \times v = (F_{acceleration} + F_{incline} + F_{rr} + F_{drag}) \times v \\
 &= (ma + mg \sin \theta + mgC_{rr} \cos \theta + \frac{1}{2} \rho_{air} C_D A_F v_{aero}^2) \times v
 \end{aligned} \tag{3}$$

where:

m - total mass of the bicycle system including passenger, bicycle, and fuel cell system (kg),

a - the acceleration of the vehicle (m/s^2),

v - velocity of the vehicle (m/s),

v_{aero} - velocity of the vehicle plus headwind (m/s),

g - acceleration due to gravity (m/s^2),

θ - angle of inclination ($^\circ$),

C_{rr} - coefficient of rolling resistance,

ρ_{air} - density of air (kg/m^3),

C_D - air drag coefficient, and

A_F - frontal area of the vehicle and rider (m^2).

The forces are defined in the following sections.

(Note: A quick power calculator for bicycles can be found at the Exporatorium Web Site [37]. It will give an approximate power requirement that does not incorporate as many variables as the method used in the modeling contained in this thesis, but gives a close value.)

Acceleration Force

The acceleration force is based on the mass of the system multiplied by the acceleration desired. If the bicycle system is accelerating, the value will be positive, and if the value is negative, the vehicle is decelerating. An acceleration force of 0 is adequate for any type of hill climbing modeling, this means that no acceleration is taking place, but the vehicle is

constantly traveling at velocity, v , up the incline. The acceleration force in the direction opposite to the vehicle motion is defined in Equation 4.

$$F_{acceleration} = ma \quad (4)$$

The acceleration force can be very large if a large amount of acceleration is required, resulting in a high contributor to the power required. For any large hills, it is assumed that the vehicle has been brought up to the required speed, v , before the incline begins, resulting in $F_{acceleration} = 0$ for all modeling in this thesis.

Force due to incline

The force due to incline is based on the total mass of the passenger, bike, and fuel cell system. The force opposing the direction of travel as the bicycle goes up an incline is shown in Equation 5.

$$F_{incline} = m \times g \times \sin \theta \quad (5)$$

The force due to incline contributes a very large portion of the total power needed even at small inclines. The vehicle should be kept as light as possible due to this. Note: the modeling uses % grade as the measure of incline. The % grade is defined in Equation 6.

$$\%Grade = \frac{Rise(Vertically)}{Run(Horizontally)} \times 100\% \quad (6)$$

Therefore, a 10% grade would define an incline that is 1 meter high (vertically) and 10 meters long (horizontally). To find the angle of a 10% grade, the arctan of 0.10 is calculated, resulting in an angle of 5.71 degrees.

Force Due to Rolling Resistance

The force due to rolling resistance is determined by multiplying the normal force of the vehicle by a rolling resistance coefficient, C_{RR} . The rolling resistance coefficient is difficult to determine since different terrain and tire tread combinations will result in different values. For the vehicle modeling, the value of 0.06 is used for off-road conditions [38], while a value of 0.008 is used for smooth on-road riding conditions [38], [39]. The force due to rolling resistance acts in the opposite direction of vehicle travel for this model, and is defined as Equation 7.

$$F_{rr} = mgC_{rr} \cos \theta \quad (7)$$

The rolling resistance of the tires does not contribute much to the power requirement on smooth pavement, but on a rough off-road surface the contribution is significant.

Force Due to Aerodynamic Drag

The force due to aerodynamic drag is important to include in the power determination since it increases with the square of the vehicle's relative velocity, v_{aero} (vehicle speed plus headwind). A headwind would be added to the model to simulate non-ideal conditions for design engineering of the power system; for the model presented in this thesis, an ideal aerodynamic load is applied which does not include a headwind. By not including a headwind the ideal performance of the electric bicycle can be observed. The force due to aerodynamic drag is represented by Equation 8.

$$F_{drag} = \frac{1}{2} \rho_{air} C_D A_F v_{aero}^2 \quad (8)$$

This force acts in the opposite direction to the vehicle's motion. F_{drag} incorporates a drag coefficient, C_D , which is estimated to be 1.2 for a rider in an upright position. This is a very conservative value, assuming the upright rider is simulated by a flat plate, but is probably justified since the rider is usually wearing loose clothing that catches the air like a

parachute. The drag coefficient becomes less as the rider moves into a more aerodynamic shape, wears skintight clothing, and wears an aerodynamic helmet. The frontal area, A_F , is also taken into account for determining the drag force. This area is taken as a frontal projection of the vehicle and rider, then measuring the shadow projected on to the wall. The frontal area value is approximately 0.5 m^2 for an upright rider position [34], [35]. For bicyclists in skintight racing cloths the drag coefficient, C_D , has been determined to be ~ 0.9 , and the frontal area, A_F , to be 0.33 m^2 [40].

The force due to aerodynamic drag is a relatively small contributor to the total power required even at moderate electric bicycle velocities (15 km/h).

Front Tire Resistive Force

The calculation of front tire resistive force is a measure of the ability of the front drive tire to resist losing traction. Since the electrically powered bicycles designed in this thesis feature front wheel motorized drive, this is a critical calculation as most of the rider's mass is over the rear tire on a bicycle.

The calculation is based on an assumed coefficient of friction (static), μ_s , for both on-road and off-road use (Figure 22). For dry paved roads the coefficient of friction is assumed to be 0.8 [41], while for off-road use the coefficient of friction is assumed to be 0.4 (this estimation is based on the value for rubber tires on dry pavement being ~ 0.8 and the value for rubber tires on ice being 0.1[41]). A static analysis is performed on the bicycle model to first find the normal force, F_N , acting at the front tire contact point. This force is then multiplied by the static coefficient of friction, μ_s , to obtain the friction force, F_f (which is also known as the front tire resistive force). This force can then be compared with different models to reduce the probability of front tire traction loss.



Figure 22: Front Tire Resistive Force

Human Power

Since the prototype electric bicycles designed in this thesis are capable of being operated using human and motor power simultaneously due to the front motorized drive, and the rear human powered drive, it is important to determine the maximum and continuous power output of a human being. This value can be added to the motor power, and compared with the power required from the modeling calculations.

Estimates of human power output (in horsepower) can be obtained using Equations 9 a–d [42]:

Short Term Output (10–120 seconds, where t is in seconds):

$$\text{Strong, healthy males: } hp = 2.5t^{-0.40} \quad (9a)$$

$$\text{World Class Athletes: } hp = 0.25 + 2.5t^{-0.40} \quad (9b)$$

Long Term Output (2–200 minutes, where t is in minutes):

$$\text{Strong, healthy, males: } hp = 0.50 - 0.13 \log t \quad (9c)$$

World Class Athletes: $hp=0.65-0.13\log t$

(9d)

From the above equations it can be determined that a strong healthy male can output 0.486 hp (363 Watts) for one minute, but only 0.269 hp (200 Watts) for a continuous hour.

It is assumed that an average healthy human can output ~200 Watts of peak power continuously for approximately a minute on a bicycle. This adds to the maximum output rating of the motor of 400W, for a total of 600 Watts available to power the bicycle under extreme conditions. Continuous available power for the motor is 200 Watts, and assuming an average human can achieve 100 Watts of continuous power on a bicycle, this adds to a total of 300W continuous available power.

4.3.5. On Road Analysis

This model analyzes the capabilities of the fuel cell bicycle model when used only on the road. Using the assumptions discussed in Section 4.3.3, the power required under certain circumstances can be attained. The power required vs. percent grade is graphed (Figure 23) (Note: 0.05 equals a 5% grade etc.). For this analysis there is no acceleration force considered; the power required is at a constant velocity of 18 km/h. The coefficient of static friction used in the model is 0.8; the coefficient of rolling friction is taken to be 0.008.

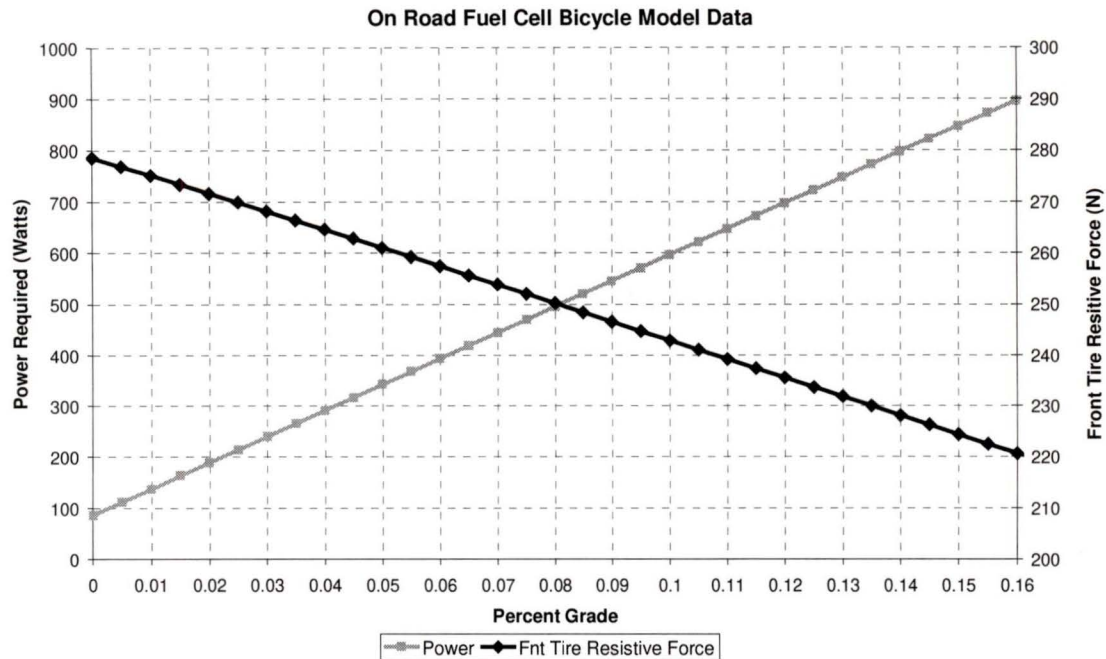


Figure 23: On Road Power Requirements vs. Grade @ 18km/h

From Figure 23 it can be seen that without any human exertion, the bicycle should be able to climb a 6.1% grade at a constant 18 km/h for a limited amount of time using the motor's maximum output power (400W). Using the continuous motor power (200W), a grade of only 2.2% can be climbed (Table 6). Table 6 also shows that when the maximum human and maximum motor powers are combined (600W), a 10.1% grade can be climbed at 18 km/h. When the continuous human and continuous motor powers are combined (300W), a 4.2% grade can be climbed at 18 km/h.

The resistive force at the front drive tire is plotted as a comparison with another front wheel motorized drive bicycle analyzed in the next section. The motor needs to exceed the listed resistive force for the front tire to lose traction and "spin out." It should be noted that the maximum torque of the motor would not occur at the bicycle's top speed of 18 km/h. Maximum torque for electric motors occurs at low speeds during acceleration, and then declines as a constant velocity is attained. With any front wheel drive bicycle, it

will be necessary for the operator to accelerate carefully in order to avoid losing front wheel traction, since the majority of the rider's mass is concentrated over the rear tire.

Table 6: On Road Model Grade Performance at Maximum Speed

Power Description	Power Output (Watts)	Grade	Front Tire Resistive Force (N)
Maximum Motor Power	400	6.13 %	257.0
Continuous Motor Power	200	2.22 %	270.9
Combined Max. Motor and Max. Human Power	600	10.07 %	242.7
Combined Cont. Motor and Cont. Human Power	300	4.17 %	264.0

Figure 24 shows that the fuel cell electric bicycle should be able to easily achieve the top speed of 18 km/h on a flat road (0% grade). There is no acceleration force involved with this plot. The power required at 18 km/h is 86.1 Watts. Table 7 shows a selection of data points from Figure 24.

On Road Fuel Cell Bicycle Model Power vs. Speed (0% Grade)

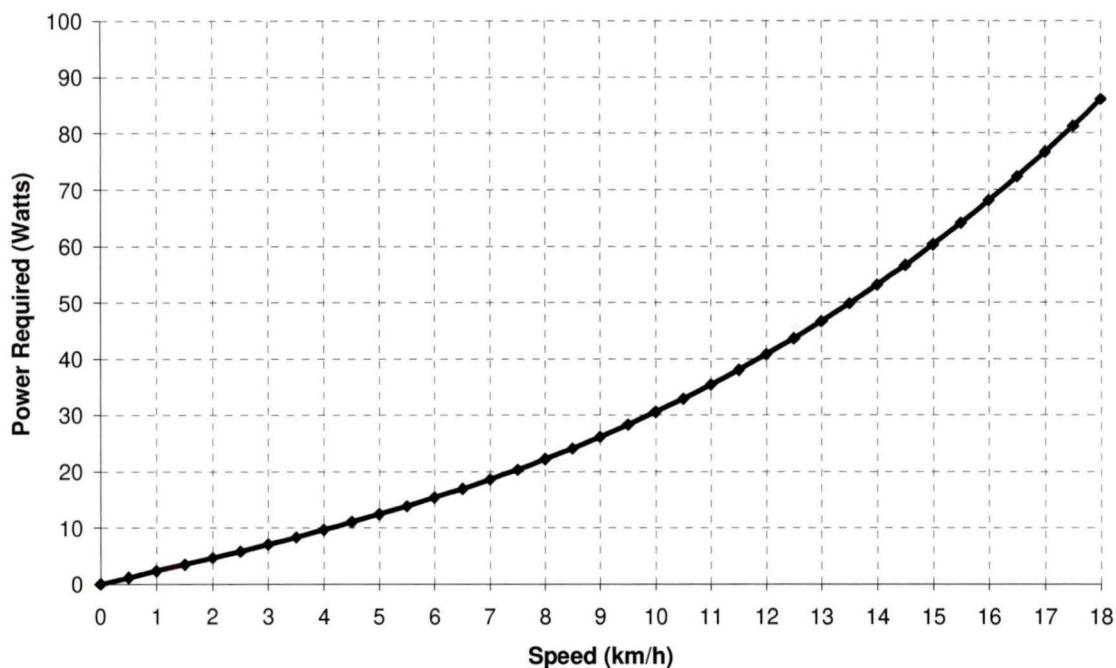


Figure 24: On Road Power vs. Speed Plot (0% Grade)

Table 7: On Road Power vs. Speed (0% Grade)

Speed (km/h)	Power (Watts)
5	12.4
10	30.5
15	60.3
18	86.1

4.3.6. Off Road Analysis

The off road analysis simply assumes a higher rolling resistance and a lower coefficient of friction. The purpose of this analysis is to display the attainable grades while riding through relatively harsh off road riding conditions. Figure 25 shows the results of the off road analysis. For this analysis there is no acceleration force considered; the power required is at a constant velocity of 18 km/h. The coefficient of static friction used in the off road model is 0.4; the coefficient of rolling friction is taken to be 0.06.

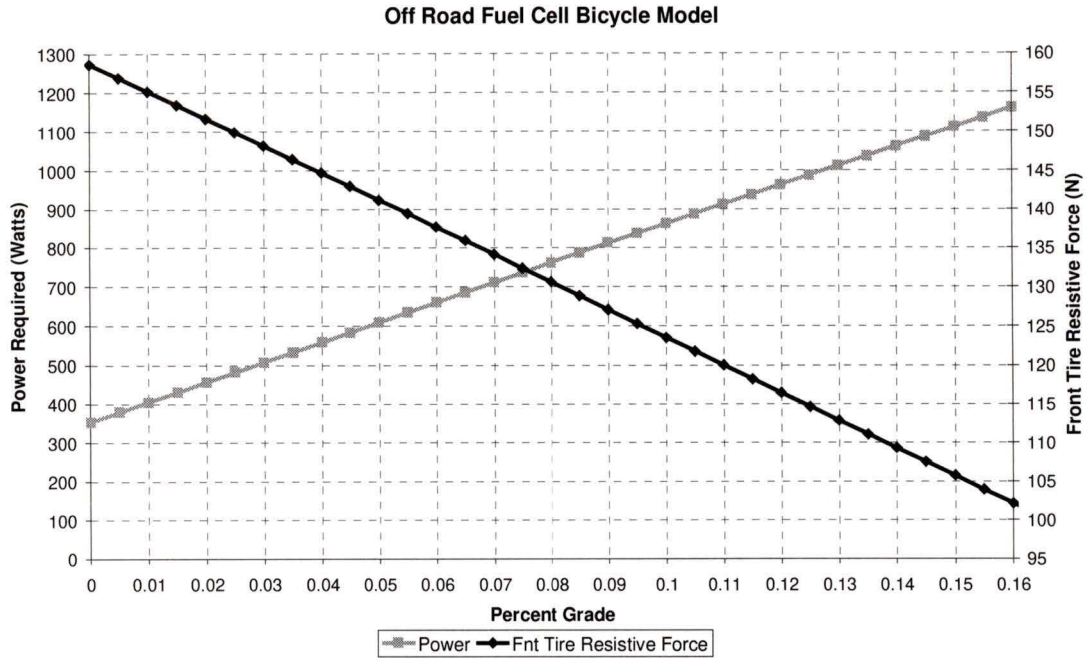


Figure 25: Off-Road Data Chart

It can be seen in Figure 25 that the power required to travel up a 6.1% grade is approximately 666 Watts, compared with 400 Watts for the on-road analysis for constant travel at 18 km/h. A full 600 Watts would be necessary to climb a grade of ~ 4.8% at 18 km/h; while a grade of only 0.92% can be climbed using the motor's peak amount of power (400W). The off-road analysis results are summarized in Table 8.

Table 8: Off Road Grade Performance at 18 km/h

Power Description	Power Output (Watts)	Grade	Front Tire Resistive Force (N)
Maximum Motor Power	400	0.92 %	155.4
Continuous Motor Power	200	N/A	N/A
Combined Max. Motor and Max. Human Power	600	4.83 %	141.8
Combined Cont. Motor and Cont. Human Power	300	N/A	N/A

From Table 8 it can be observed that the off road electric bicycle will be able to climb only very small grades using maximum power when traveling off road at full speed (18 km/h).

From this analysis it is useful to observe the power required versus speed (Figure 26). The plot of the electric bicycle operating on a 0% grade shows that 353 Watts are required to attain the top speed of 18 km/h. At the motor's continuous power rating (200W), only a speed of 11.08 km/h is achievable. If a combination of human continuous power and motor continuous power is modeled (300W), then the bicycle could attain a speed of 15.77 km/h. It can be seen that the off road power versus speed plot (Figure 26) is much more linear than the on road model (Figure 24); this is due the much higher rolling resistance experienced during off road conditions (loose gravel). The rolling resistance force is a linear force; this force overpowers the exponential nature of the force due to aerodynamic drag, resulting in a more linear power curve. Table 9 shows a selection of data points from Figure 26.

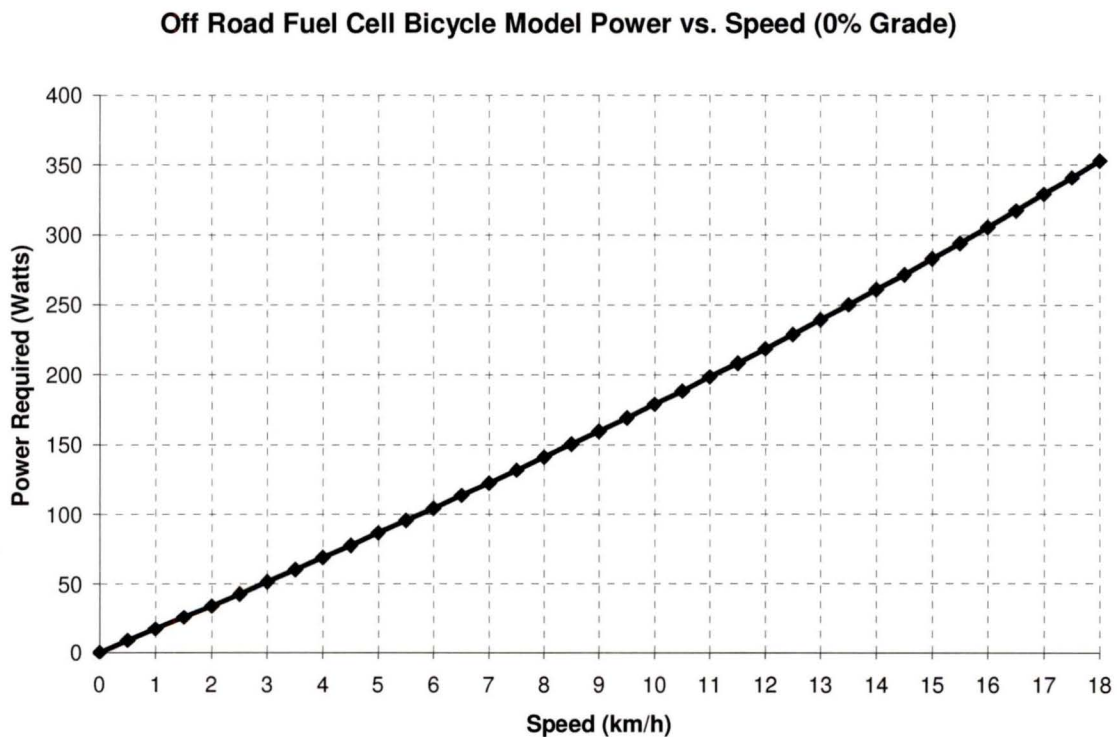


Figure 26: Off Road Power vs. Speed Plot (0% Grade)

Table 9: Off Road Power vs. Speed (0% Grade)

Speed (km/h)	Power (Watts)
5	86.5
10	178.8
15	282.7
18	352.9

4.3.7. Fuel Cell Bicycle Model On Road / Off Road Comparison

The differences between the on road modeling and the off road modeling are shown in Table 10. From this table it can be seen that the off road model has a very large reduction in grade climbing ability. The front tire resistive force of the off road model is found to be ~ 40% less than the on road model. Using the maximum motor power (400W), the on road model can climb a 6.13 % grade, while the off road model can only climb a grade of 0.92 %.

Table 11 compares the power required to maintain a specific speed at a 0% grade for the on road and off road model. It can be seen that the power required off road is much more than if the electric bicycle is ridden on road.

Table 10: Fuel Cell Bicycle Modeling Grade Comparison (@ 18 km/h)

Power Description	Power Output (Watts)	On Road Grade	Off Road Grade	On Road Front Tire Resistive Force (N)	Off Road Front Tire Resistive Force (N)
Maximum Motor Power	400	6.13 %	0.92 %	257.0	155.4
Continuous Motor Power	200	2.22 %	N/A	270.9	N/A
Combined Max. Motor and Max. Human Power	600	10.07 %	4.83 %	242.7	141.8
Combined Cont. Motor and Cont. Human Power	300	4.17 %	N/A	264.0	N/A

Table 11: Fuel Cell Bicycle Power vs. Speed (0% Grade)

Speed (km/h)	On Road Power (Watts)	Off Road Power (Watts)
5	12.4	86.5
10	30.5	178.8
15	60.3	282.7
18	86.1	352.9

CHAPTER 5 DESIGN AND CONSTRUCTION OF AN ADAPTABLE ELECTRIC BICYCLE POWER SYSTEM (AEBPS)

5.1. Adaptable Electric Bicycle Power System (AEBPS) Development

The main goal of the adaptable electric bicycle power system (AEBPS) for a bicycle is versatility. The adaptable system allows almost any bicycle to be turned into an electric bicycle in under ten minutes. The power system can be taken off the bicycle in less than five minutes. This allows a rider to use a bicycle that they already have purchased and are comfortable riding. If desired, the rider can put the power system on the bicycle for commutes during the week, and then easily and quickly remove it for weekend biking excursions. This system is designed to fit onto almost any bike, from a low cost department store bicycle to a \$6000 full suspension downhill mountain bike. By designing a fully adaptable electric bicycle power system, the consumer is able to choose the type of bike they would like to ride, rather than the common electric bike manufacturer trend of permanently attaching an electric power system to a bicycle with low quality parts.

The front wheel is driven by the electric power; the rear wheel is driven by the rider if additional power is needed, similar to the fuel cell electric bicycle model described in Section 4.3.2. The main difference between the adaptable electric bicycle power system and the fuel cell bicycle model of Section 4.3 is that this design uses battery power and the main system mass is located at the rear of the bicycle rather than near the front as with the fuel cell electric bicycle model. The AEBPS could easily be converted to fuel cell power in the future, keeping the same unique quick release design. The battery pack would be replaced by a proton exchange membrane fuel cell (PEMFC) system.

5.1.1. Adaptable Electric Bicycle Power System Initial Design Considerations

The initial design for the AEBPS involves testing the ability for a bicycle to safely carry loads on the front handlebars, like on the fuel cell bicycle model (Figure 19). Testing using a front (handlebar) mountable basket reveals a high amount of instability created when a mass of ~12 lbm (5.5 kg) is placed on the handlebars. Mass attached to the handlebars makes the bicycle steer very slowly, and results in an unsafe riding situation. It is determined through this testing that no more than 1 kg (2.2 lbm) should be carried on the front handlebars for safety reasons. Due to these limitations, the location for the 9.75 kg (21.5 lbm) battery is found at the rear of the bicycle on a quick release beam rack.

5.1.2. Adaptable Electric Bicycle Power System Modeling

After determining the general layout of the various components, modeling takes place to determine the power required to ride different grades, and the front tire resistive force. Since this design has the battery located at the rear of the bicycle, rather than at the front, the weight distribution will make the bicycle even more likely to lose front tire traction than with the fuel cell electric bicycle model. The modeling of the AEBPS is also used to compare the difference in front drive wheel traction of the fuel cell and AEBPS electric bicycle models.

The AEBPS bicycle uses the same high torque front hub motor used in the analysis of the fuel cell bicycle in Section 4.3, therefore, an analysis of on road and off road performance is completed. The AEBPS is also modeled on the Rocky Mountain RM6 full suspension bicycle as with the fuel cell electric bicycle modeling example.

AEBPS Bicycle Modeling Assumptions

For the initial bicycle modeling many assumptions are made. Table 12 includes the main assumptions used in the AEBPS bicycle modeling. Figure 27 shows a side view of the AEBPS. The battery, electronic motor controller, and quick release beam rack are located at the rear of the bicycle. The hub motor is mounted in the front wheel of the bicycle. The thumb throttle is mounted on the handlebar.

Table 12: AEBPS Modeling Assumptions

Assumption	Value
Rider Mass	75.7507 kg (167 lbm)
Hub Motor Mass	3.6288 kg (8 lbm)
Battery Pack Mass	9.7523 kg (21.5 lbm)
Electrical System Components Mass	0.9072 kg (2 lbm)
Beam Rack Mass	0.6237 kg (1.375 lbm)
RM6 Bicycle Mass	15.2771 kg (33.68 lbm)
Total Power System Mass	14.912 kg (32.875 lbm)
Drag Coefficient [34]	1.2 (flat plate)
Frontal Area [34], [35], [36]	0.5 m ²
Air Density	1.2 kg/m ³
Headwind Speed	0 km/h
Gravity	9.81 m/s ²
Rocky Mountain RM6 Bicycle CG (Horizontal)	560 mm from rear tire ground contact point
Battery CG (Horizontal)	0 mm from rear tire ground contact point
Electrical System CG (Horizontal)	0 mm from rear tire ground contact point
Hub Motor CG (Horizontal)	1120 mm from rear tire ground contact point
Beam Rack CG (Horizontal)	0 mm from rear tire ground contact point
Frontal Area CG (Vertical) for Aerodynamic Drag	1689 mm from ground
Rider CG (Horizontal)	250 mm from rear tire ground contact point
Maximum Speed (km/h)	18 km/h



Figure 27: AEBPS Components (Side View)

Figure 28 shows a rendered three-dimensional model of the AEBPS mounted on the Rocky Mountain RM6 full suspension bicycle.

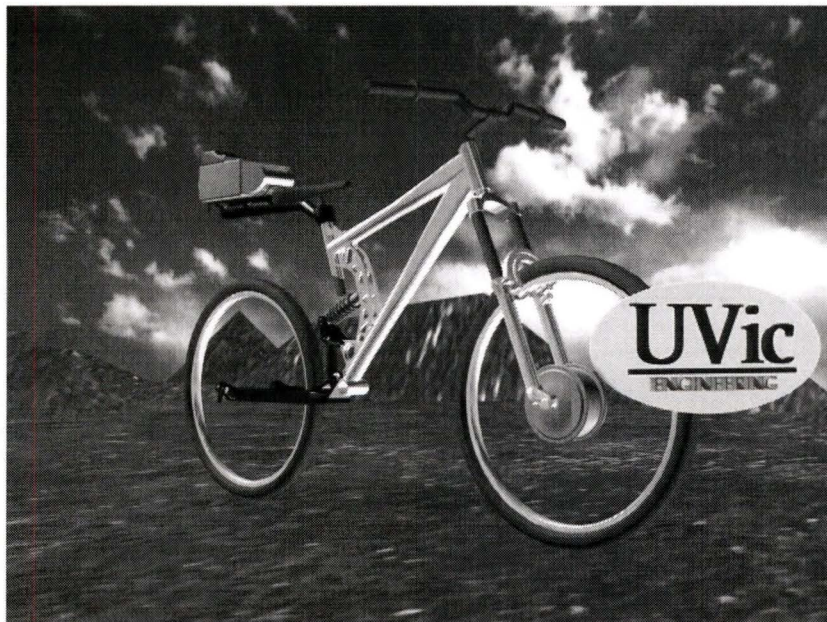


Figure 28: AEBPS 3D Solid Model

On Road Analysis Comparison

This model analyzes the capabilities of the AEBPS attached to the Rocky Mountain RM6 bicycle when used only on the road. Using the assumptions discussed above (*AEBPS Bicycle Modeling Assumptions*), the power required under certain circumstances can be attained. The power required vs. percent grade is graphed for both the AEBPS and the fuel cell bicycle models in Figure 29 (Note: 0.05 equals a 5% grade etc.). For this analysis there is no acceleration force considered; the power required is at a constant velocity of 18 km/h. The coefficient of static friction used in the model is 0.8; the coefficient of rolling friction is taken to be 0.008.

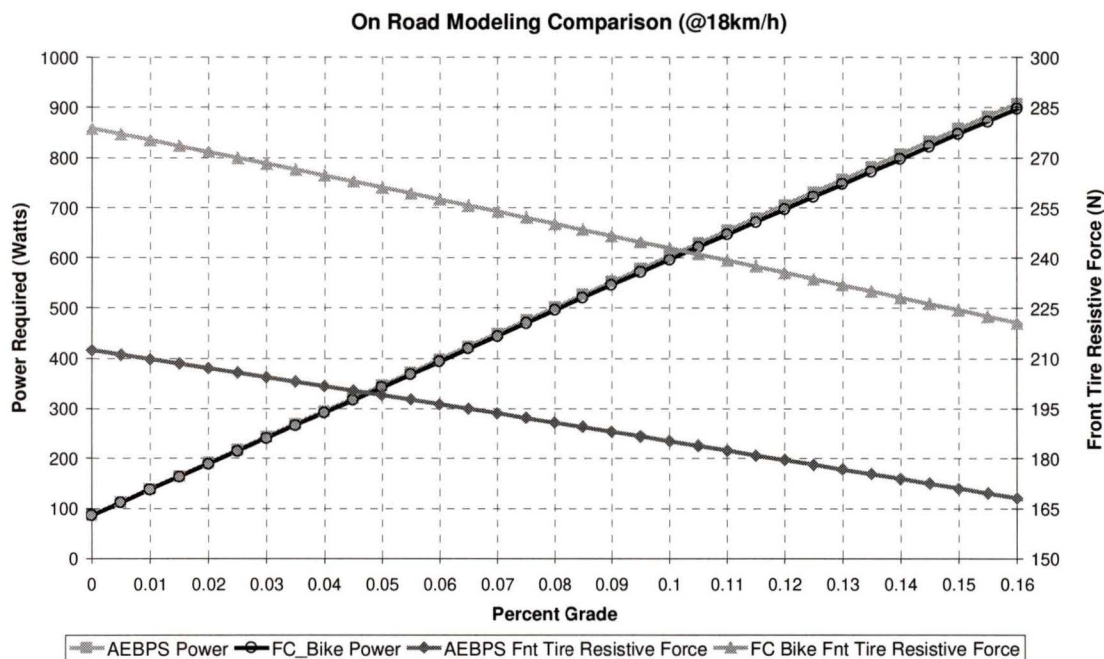


Figure 29: On Road Power Requirements vs. Grade Comparison

From this information it can be seen that without any human exertion, the AEBPS bicycle should be able to climb a 6.0% grade at a constant 18 km/h using full motor power (400W). This is assuming the use of a high torque hub motor that has a maximum rpm of 145, giving the electric bicycle with 26 inch diameter tires a top speed of 18 km/h. The resistive force at the front drive tire is plotted, and it is obvious that the AEBPS design will make the bicycle have a greater tendency to lose front wheel traction. At the 6.0%

grade level the front tire resistive force for the AEBPS equipped bicycle is 196.2 N while the resistive force of the fuel cell electric bicycle model (FCEBM) is 257.5 N, a difference of 61.3 N, which is significant. When considering front tire resistive force, the AEBPS model is always 76.223% of the FCEBM at the same grade level, for example if the FCEBM has a front wheel resistive force of 242.9 N at a 10% grade, the AEBPS model will have a value of 185.1 N at a 10% grade. The difference in front tire resistive force is due to the difference in static friction and the positioning of the masses between the two models. It can also be easily seen in Figure 29 that the power requirement for a given grade is almost identical to the FCEBM since the masses of both models are virtually the same; the AEBPS plus RM6 and 167 lb rider is 105.94 kg, while the FCEBM bicycle with 167 lbm rider is 104.64 kg, a difference of only 1.3 kg. Table 13 shows the data from Figure 29 at each of the main power output levels. The front tire resistive force values are measured at the respective grade levels attainable at each power output level for each electric bicycle model.

Table 13: On Road Modeling Grade Performance Comparison

Power Description	Power Output (Watts)	Fuel Cell Model Grade	AEBPS Model Grade	Fuel Cell Model Front Tire Resistive Force (N)	AEBPS Model Front Tire Resistive Force (N)
Maximum Motor Power	400	6.13 %	6.04 %	257.0	196.1
Continuous Motor Power	200	2.22 %	2.18 %	270.9	206.6
Combined Max. Motor and Max. Human Power	600	10.07 %	9.93 %	242.7	185.3
Combined Cont. Motor and Cont. Human Power	300	4.17 %	4.11 %	264.0	201.4

The Power vs. Speed plot for the AEBPS (Figure 30) is very similar to the fuel cell electric bicycle model; this is due to the similar masses.

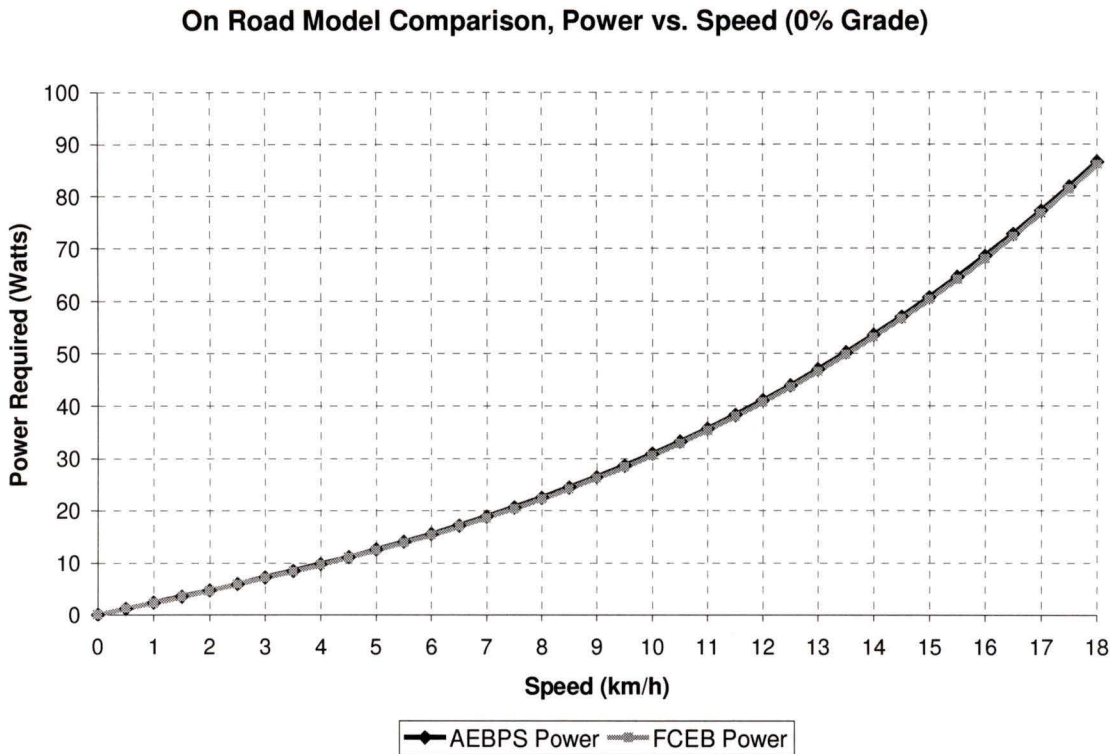


Figure 30: On Road Power vs. Speed Comparison (0% Grade)

Off Road Analysis Comparison

The off road analysis simply assumes a higher rolling resistance and a much lower coefficient of friction than the fuel cell electric bicycle model. The purpose of this analysis is to display the attainable grades while riding through relatively harsh off road riding conditions. Figure 31 shows the off road data for the AEBPS and the fuel cell bicycle model. Table 14 shows the data from Figure 31 at each of the main power output levels. The front tire resistive force values are measured at the respective grade levels attainable at each power output level for each electric bicycle model. For this analysis there is no acceleration force considered; the power required is at a constant velocity of 18 km/h. The coefficient of static friction used in the off road model is 0.4; the coefficient of rolling friction is taken to be 0.06.

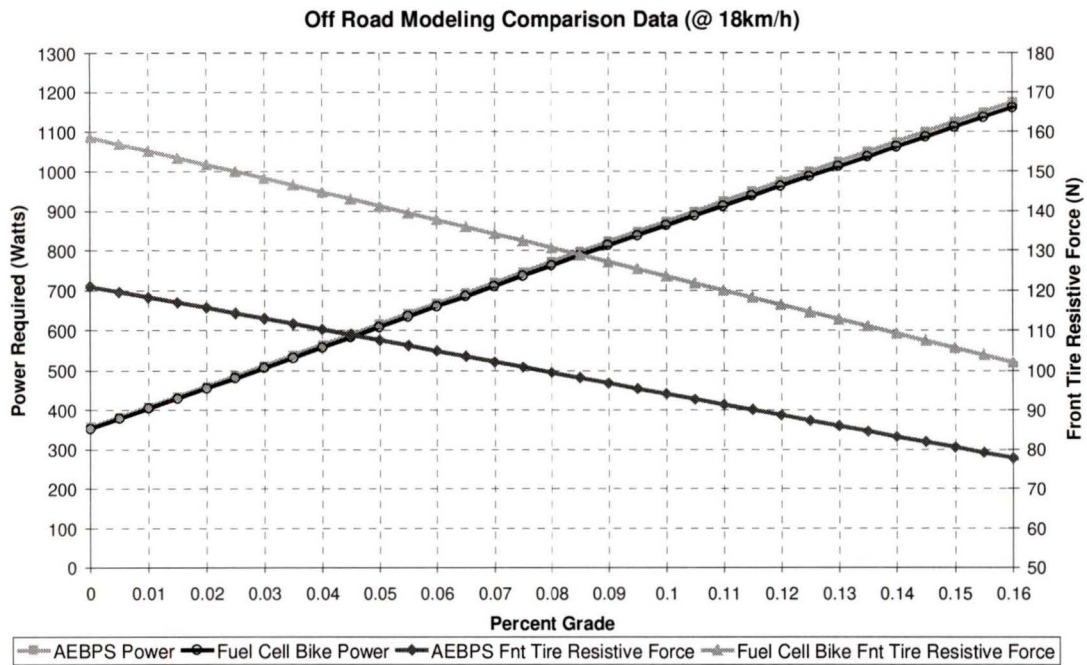


Figure 31: Off-Road Data Comparison

Table 14: Off Road Modeling Grade Performance Comparison

Power Description	Power Output (Watts)	Fuel Cell Model Grade	AEBPS Model Grade	Fuel Cell Model Front Tire Resistive Force (N)	AEBPS Model Front Tire Resistive Force (N)
Maximum Motor Power	400	0.92 %	0.83 %	155.4	118.7
Continuous Motor Power	200	-	-	-	-
Combined Max. Motor and Max. Human Power	600	4.83 %	4.69 %	141.8	108.5
Combined Cont. Motor and Cont. Human Power	300	-	-	-	-

The resistive force at the front drive tire is plotted, and it is obvious that the AEBPS design will make the bicycle have a greater tendency to lose front wheel traction than with the fuel cell electric bicycle model. Figure 31 shows that at the maximum motor output (400W), the AEBPS bicycle can climb a 0.83% grade at 18 km/h during off road conditions. At the 0.83 % grade level the front tire resistive force for the AEBPS equipped bicycle is 118.72 N while the resistive force of the fuel cell electric bicycle model (FCEBM) is 155.75 N, a difference of 37.0 N, which is significant, but 24.2 N less than the difference between the two models during the on road analysis. This is due to the effect of a higher front wheel friction force during on-road conditions; the on road model has a greater difference in total resistive force than the off road model. When considering front tire resistive force, the AEBPS model is always 76.223% of the FCEBM at the same grade level, for example if the FCEBM has a front wheel resistive force of 123.5 N at a 10% grade, the AEBPS model will have a value of 94.1 N at a 10% grade.

It can also be easily seen in Figure 32 that the power requirement for a given grade for the AEBPS model is almost identical to the FCEBM since the masses of both models are virtually the same; the AEBPS plus RM6 and 167 lb rider is 105.94 kg, while the FCEBS bicycle with 167 lbm rider is 104.64 kg.

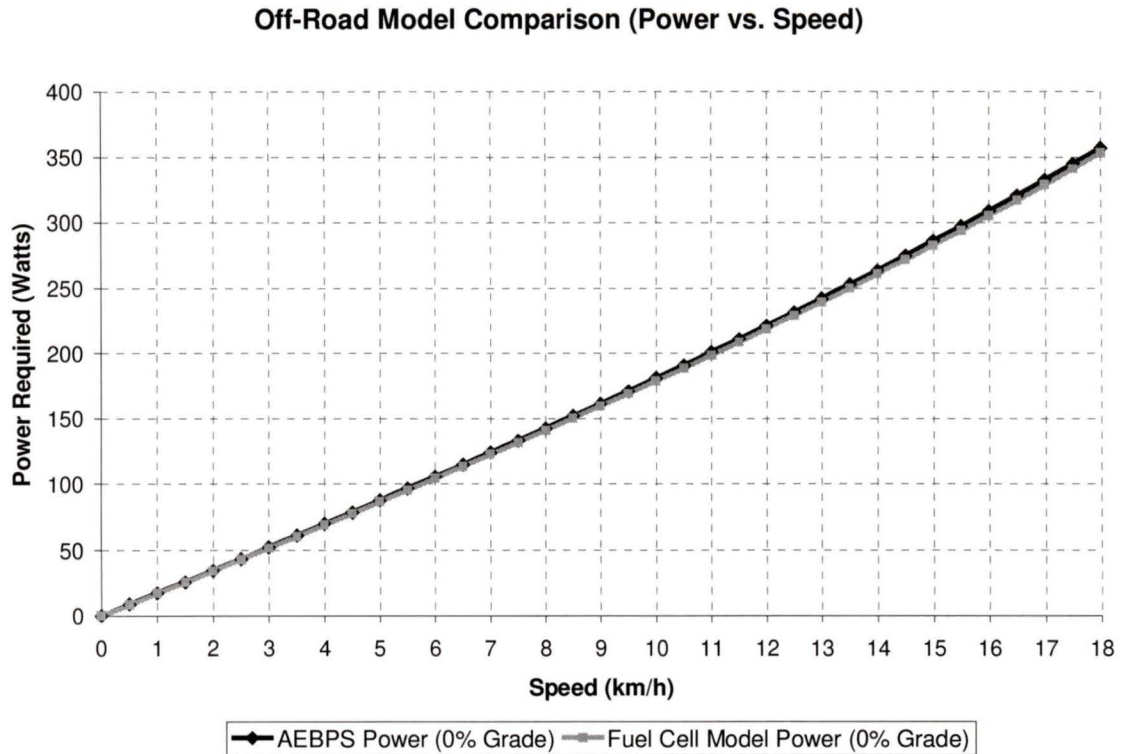


Figure 32: Off Road Power vs. Speed (0% Grade)

5.2. Adaptable Electric Bicycle Power System Construction

To verify the AEBPS concept, a full prototype is constructed. The parts used in the construction are described in detail in this section.

5.2.1. Rocky Mountain Bicycles RM6

This bicycle is described in Section 4.3.1; it is capable of on-road and off-road riding. Due to the large amount of suspension travel, and 20mm front axle, the RM6 basically presents a worst-case scenario for the adaptability of the AEBPS. This particular bicycle was very desirable for this project to display that the AEBPS can be truly used to power any type of bicycle.

5.2.2. Quick Release Beam Rack

A quick release beam rack is necessary to carry items at the rear of a full suspension mountain bike. The Topeak quick release beam rack (Figure 33) attaches to the seat post of the bicycle easily and quickly [43].

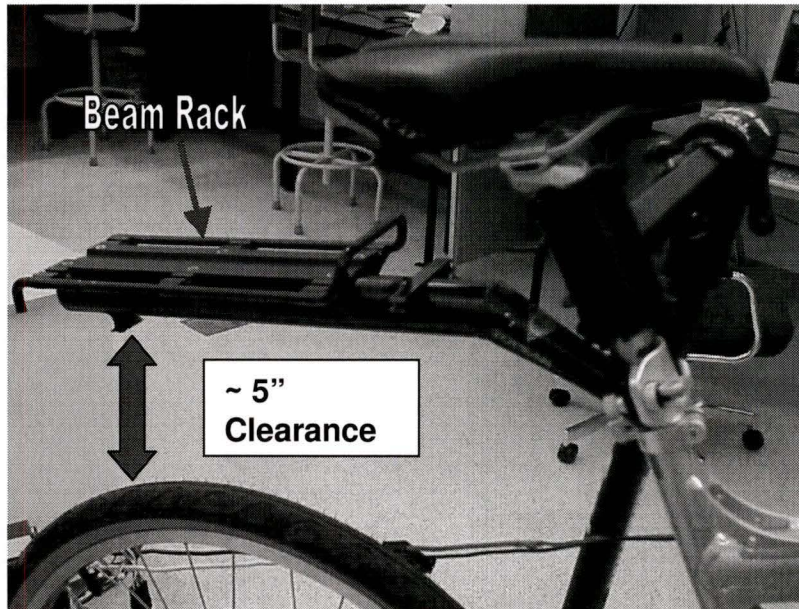


Figure 33: Topeak Quick Release Beam Rack Type A

The quick release beam rack is perfect for this application since it can be removed from the bicycle in under 30 seconds, and can withstand a load of 25 lbm (11.4 kg). The “Type A” version of the QR beam rack is designed for small bicycle frames, but is desirable for a universally fitting power system since it gives ~ 5 inches of clearance above most rear tires; this is very desirable for long travel full suspension mountain bikes. The Topeak QR Beam rack is made of 6061-T6 aluminum and has a mass of ~625 grams, adding very little mass to the overall power system mass. The Topeak quick release beam rack used with the AEBPS can be obtained from Cycles Lambert Inc. in Canada [44]. This company is a distributor for bicycle stores; therefore, it is advisable to obtain the QR beam rack from a bicycle store rather than dealing directly with Cycles Lambert Inc. This rack retails for \$45 USD (~\$72 CDN).

5.2.3. EVS-1 Electric Vehicle Electrical System

The EVS-1 electric vehicle system is purchased from Diverse Electronic Services in Nanticoke PA USA [45], and is originally the electrical system for an electric bicycle called the EV Warrior. This 24 volt electrical system is a complete electric bicycle system consisting of a Curtis 1505 motor controller, a 24 to 12 volt DC-DC converter so that 12V accessories can be operated (horn, lights etc.), a radio controlled anti theft system, a throttle, a voltage and current indicator, a signal and horn switch, and all wiring. The EVS-1 system purchased from Diverse Electronic Services was an affordable \$100 USD, but better prices (\$75 USD (\$120 CDN)) were available later from Industrial Liquidators in San Diego [46].

EV Warrior Electric Bicycle and Electrical System

The EV Warrior (Figure 34) was a product from the now bankrupt Electric Bicycle Company started by entrepreneur Malcolm Bricklin. Malcolm Bricklin is most noted for bringing the cheap Yugo automobile to North America and building the Bricklin automobile equipped with gull-wing doors. The EV Warrior was sold from 1995 to 1997 until the company went bankrupt in September 1997; the company's huge inventory was then liquidated, and there are still huge amounts of electric bicycle parts available for a very low price. The motors from the EV Warrior are used a lot in the building of fighting robots for Robot Wars [47] and Battlebots [48].



Figure 34: EV Warrior Electric Bicycle

The complete electrical system from the EV Warrior (“Harness Assembly with Extras”) can be obtained from Industrial Liquidators in San Diego CA [49]. This system is supplied with additional items not in the EVS-1 system from Diverse Electronic Services, such as a right side mirror with turn signal, left side mirror with turn signal, a dual lamp headlight, and a taillight for \$25 USD less than the EVS-1 system from Diverse Electronic Services. It has been stated by the owner of Diverse Electronic Services that the entire EVS-1 system is no longer available; only certain parts of the system are now available from Diverse Electronic Services [50]. This reinforces the necessity to purchase the EV Warrior electric bicycle electrical system from Industrial Liquidators.

Curtis PMC Electronic Motor Speed Controller

The Curtis 1505 electronic speed control (Figure 35, Figure 36) is a small motor controller designed specifically for electric bicycles, mopeds, and other small electric motor designs. The 1505 operates at a very low sound level and provides smooth power delivery to the electric bicycle motor. The 1505 has the following features [51]:

1. Power MOSFET design for silent, high frequency, and high efficiency operation resulting in low temperature operation, and low battery and motor losses.
2. Current limited to protect the electronics.
3. 3 wire 5k Ω potentiometer throttle input.
4. Open wire pot fault turns off controller if any throttle wire becomes a short circuit.
5. Under voltage cutback reduces output current as battery voltage drops below a preset level (18V).
6. Keyswitch input to turn on the controller.
7. On board main safety relay with capacitor precharge.
8. Inhibit input disables controller during battery charging, for example.
9. Simple to install, with no adjustments to make.
10. Plug in connector for control wiring.

11. Quick connect battery and motor terminals.
12. Optional battery current measurement and output to drive a display module.

The Curtis 1505 model operates at 24 volts, has a continuous current rating of 20A, and a one minute rating of 80A. The 1505 needs a minimum motor resistance of 0.130 ohms, and a typical voltage drop at 20A is 0.40 volts. The 1505 has an under voltage of 18V, which means that the controller will shut down power to the electric bicycle at any voltage below 18 volts, this is implemented to protect the battery. The 1505 has a compact size, it measures 113mm × 65mm × 40mm (L × W × H).

It is important to note that a 24V fuel cell power system varies its voltage as different currents are drawn (polarization curve, Section 4.1.2). For this reason a DC-DC converter (or other voltage regulator) may be needed to provide a constant voltage to the motor controller if a PEMFC was to be adapted. Another option would be to custom design a motor controller that does not have an under voltage cutoff, designed specifically for fuel cell electric bicycle power systems.

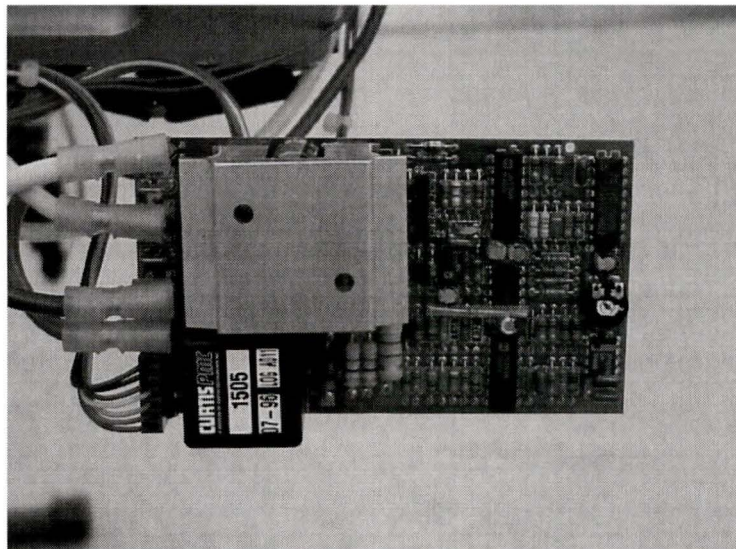


Figure 35: EVS-1 Curtis 1505 Motor Controller

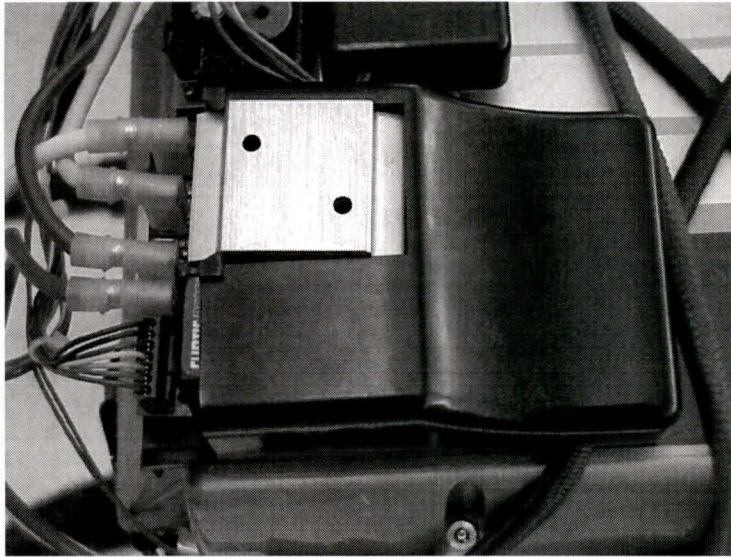


Figure 36: EVS-1 Curtis 1505 Motor Controller with Cover

24-12 V DC-DC Converter

The 24-12 volt DC-to-DC converter (Figure 37) is a very small unit that enables the use of common 12V components with the electric bicycle. The converter is used to power a horn, and can be used for providing power to a common 12V motorcycle headlight.

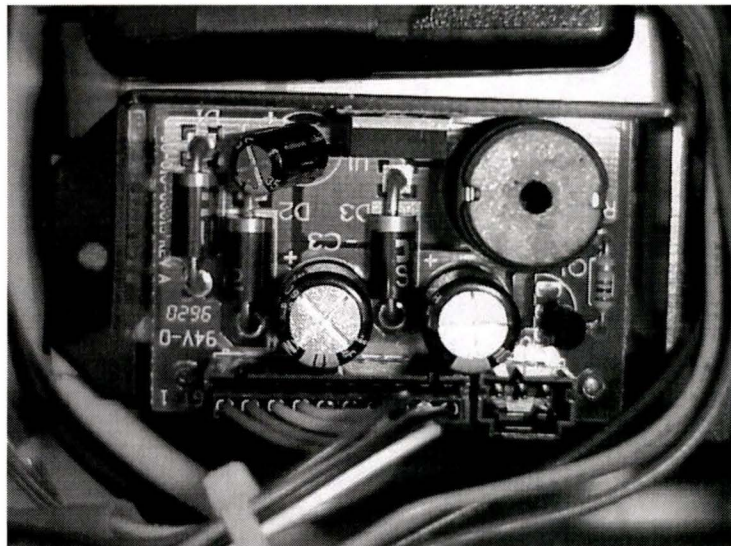


Figure 37: EVS-1 24V-12V DC-DC Converter

Anti Theft System

The ability to stop the theft of an expensive electric bicycle is a concern of many potential consumers as described in Canada's Electric Bike 2000 Project Report [52]. The anti-theft system provided with the EVS-1 system disables the electric bicycle until it receives a signal from a transmitter carried by the owner (Figure 38).

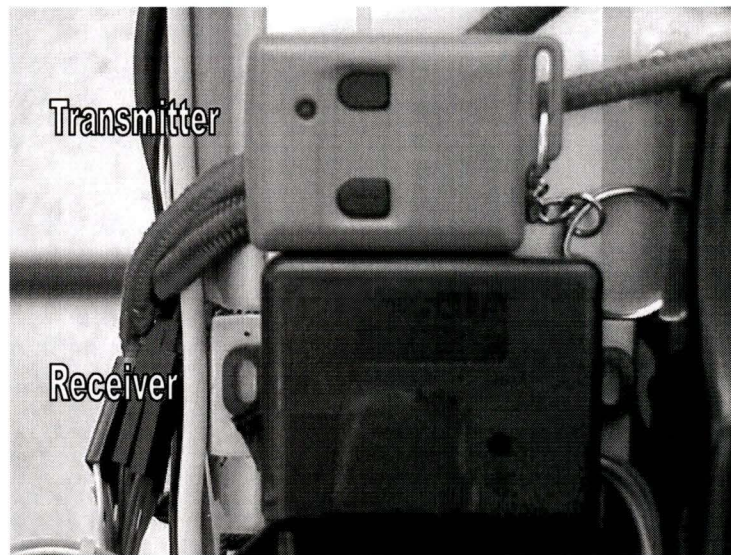


Figure 38: EVS-1 Antitheft System

The anti-theft system uses a common automobile security system transmitter to provide the enable signal. This signal is sent to the small black receiver. This anti-theft system prevents the throttle from becoming usable until it is deactivated. When the main power to the electric bicycle is turned off, the anti-theft system automatically activates. If someone tries to start the electric bicycle by turning the power on, the throttle will not operate until the deactivate button on the transmitter is pressed. When the button is pressed, a beep is sounded to notify the owner that the throttle is now active and the electric bicycle can be operated. The security system can also be bypassed if the user wishes so.

Throttle

The throttle provided is operated by the users right hand thumb. It is a 5 k Ω potentiometer encased in a handlebar mount (Figure 39). The throttle also features an on/off switch. The throttle is spring loaded so that the electric bicycle always starts at 0% speed, and stops the motor if the rider falls off the bicycle.



Figure 39: EVS-1 Throttle

Current and Voltage Meter

The current and voltage meters are located on a printed circuit board (Figure 40). The meters show the voltage and current draw through the use of a LED array. The voltage meter varies approximately from 18V to 24V, and the current meter varies from 0A to approximately 20A.

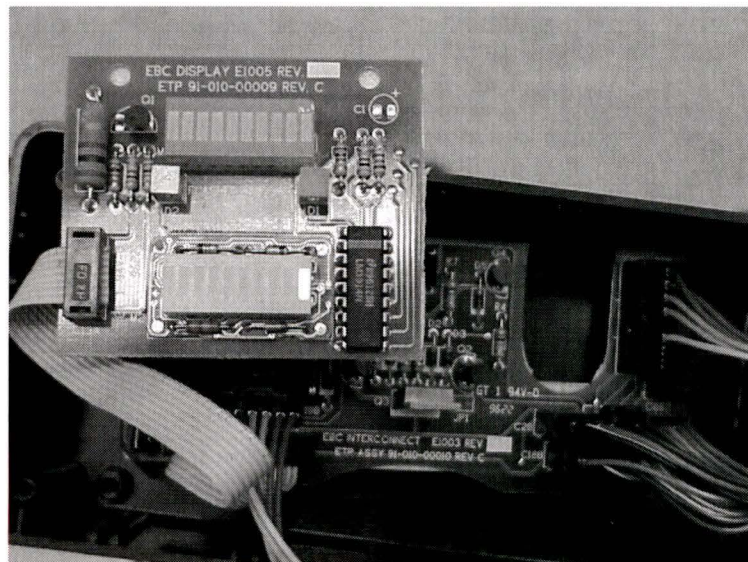


Figure 40: EVS-1 Voltage / Current Meter

The printed circuit board is placed in a plastic electronics project box to insure electrical system safety and durability (Figure 41).

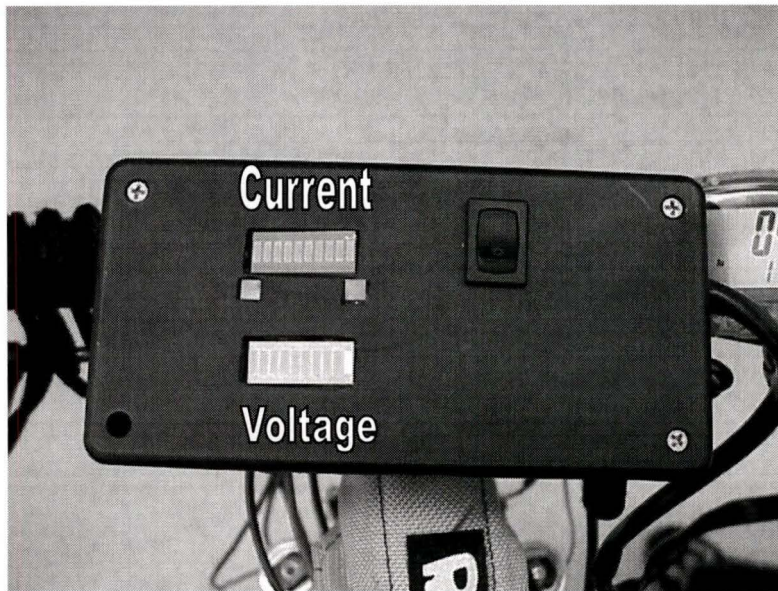


Figure 41: EVS-1 Current and Voltage Meter in Project Box

Headlight, Horn, and Turn Signal Switch

The EVS-1 system is provided with a horn, headlight, and turn signal switch (Figure 42). This unit attaches to the left side of the handlebars, and it is operated with the rider's left thumb. The headlight switch is located at the top of the unit, the turn signal in the middle, and the horn at the bottom. The turn signals are operated by pushing the control switch to the left or right, and then pressing the middle yellow unlock button when turning is completed. The headlight, horn, and side mirrors with integrated turn signals are all included with the "Harness Assembly with Extras" from Industrial Liquidators [49].



Figure 42: EVS-1 Horn, Turn Signal, Headlight Switch

5.2.4. Battery Pack

The AEBPS uses a 24V 12Ah (288Wh) sealed lead acid battery pack from a Currie Cycles electric bicycle (Figure 43). The battery pack has a mass of 9.75 kg (21.5 lbm). The battery pack has following dimensions, 295mm × 101mm × 177mm (Length × Width × Height) for a total volume of $5.27 \times 10^6 \text{ mm}^3$. This particular battery pack can be purchased from Currie Technologies for \$155 USD (\$248 CDN); but much cheaper battery packs are available. The Currie battery pack comes with an on/off switch, a light that indicates the battery pack is turn on, and a plastic casing. These 24-volt battery packs have two, 12 volt, 12 Amp-Hour sealed lead acid batteries contained in the plastic package. This battery has the capacity to deliver 12 Amps of current for one hour (12 Ah). If no pedaling is exerted by the rider (and incorporating 70% electrical system efficiency) the AEBPS electric bicycle is estimated to have a range of 24 km, and if it is assumed that this is at a continuous speed of 18 km/h on a flat road, the AEBPS electric bicycle should be able to travel for 80 minutes. The continuous current draw from the motor would then be 9 Amps. It should be noted that this is a low capacity deep cycle sealed lead acid battery. This battery pack can be charged in ~ 8 hours with a low cost 1A charger, but can be quick charged in ~ 3 hours with a 3A charger.



Figure 43: Currie Cycles 12AH Battery Pack

There are other battery types available with much greater capacities such as nickel metal hydride (NiMH), but at a higher cost. Nickel metal hydride electric bicycle battery packs are available from NEXcell Battery Co., LTD (Figure 44). This company produces a 24V battery pack with a capacity of 13 Ah (312 Wh) and a mass of only 5 kg (11 lbm) [53]. The cost of a single 24V-13Ah battery pack is \$212 USD, which makes it \$57 USD more than the Currie battery pack. This NiMH battery pack can be charged in 5 hours with a 3A NiMH charger available from NEXcell [54]. The nickel metal hydride battery pack has a length of 331mm, a width of 66mm, and a height of 91mm for a total volume of $1.99 \times 10^6 \text{ mm}^3$. The volume is 265% less than the Currie lead-acid battery pack. The NEXcell battery pack has just over double the capacity to mass ratio of the Currie 12 Ah battery pack; this shows that a NEXcell nickel metal hydride battery pack that had the same mass of the Currie pack would have over double the capacity, resulting in over double the range. The deep cycle sealed lead acid is still the most common rechargeable battery used in electric bicycles; this is due to the low cost, and robust performance (As discussed in Section 4.2.1).

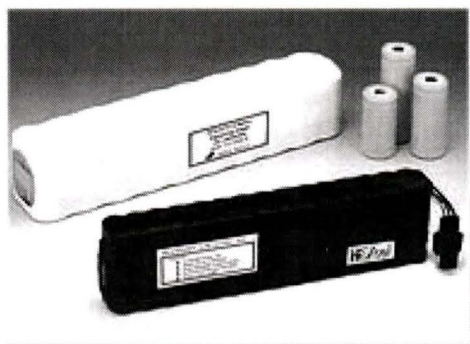


Figure 44: NEXcell Nickel Metal Hydride Electric Bicycle Battery

5.2.5. Hub Motor

The motor used with the AEBPS is a Heinzmann high torque hub motor. This hub motor is made in Germany. One of the most popular and effective drive systems for electric bicycles are hub motors. Hub motors are particularly suited for direct drives; they do not require any additional gearing, as they are connected directly to the driving axle (Figure 45).

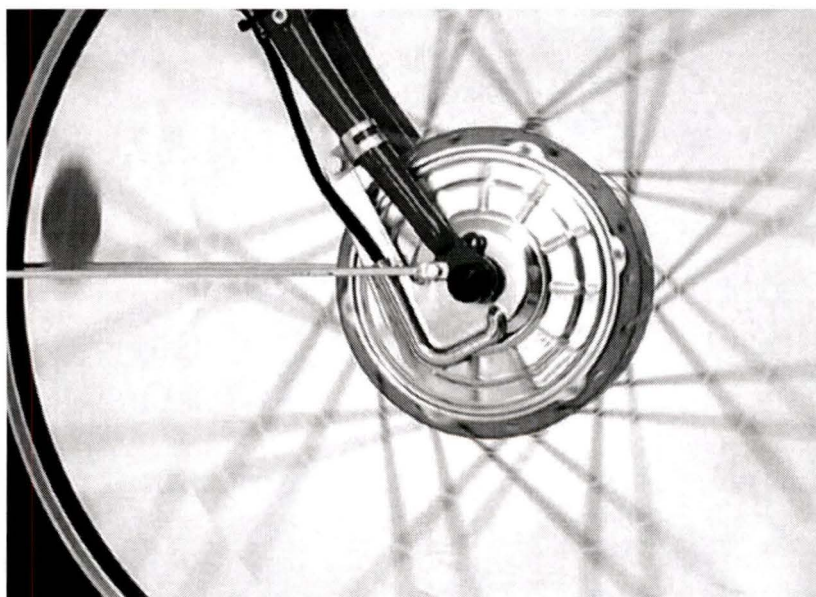


Figure 45: Heinzmann Hub Motor [55]

Hub motors feature a compact package design. Hub motors are practically noiseless, maintenance-free, and environment-friendly; the hub motor does not need lubricants or gear grease that has to be disposed of. One of the main benefits of the high efficiency of hub motors is a greater traveling range.

For a front mounted hub motor, it is possible that the front tire will lose traction on wet roads or loose surfaces if the throttle is applied too fast. With the front wheel motorized drive, and human power going to the rear, a two wheel drive electric bicycle is constructed. The two wheel drive characteristics allow the bicycle to perform well in off-road conditions.

It has been stated that the Heinzmann hub motor is the best choice available for hub motors [56]. There are low quality, low powered hub motors available from China. The Heinzmann hub motor features exceptional quality, and design. Heinzmann offers many different varieties of their 24V front wheel hub motors (Figure 46); they can be ordered directly from Heinzmann at their electric bicycle website order form by selecting “Single Components” [57]. Heinzmann also offers a variety of front and rear wheel hub motors with a 36 Volt capacity. The AEBPS Heinzmann hub motor cost is \$192.50 USD plus \$71 USD shipping (Total \$422 CND) directly from Heinzmann. The hub motor used for the AEBPS is item # 870-00-101-0108 (Figure 46). This motor is rated at 400 Watts maximum power, maximum grade of 12%, maximum speed of 18 km/h, and maximum current draw of 30A. Due to this low geared motor, the AEBPS is currently designed for hill climbing rather than a high top speed. The AEBPS could also come with a higher geared motor such as item # 870-00-101-0408 for a top speed of ~25 km/h, but with a lower maximum grade climbing ability of 8%; this might be a better choice for some users since the potential for front tire slippage is less due to a lower torque output for this motor.

The hub motor is built into a 26" bicycle wheel at a bicycle store that specializes in electric bicycles. The total cost for the rim, spokes, and wheel build labour is \$116 CND (including tax).

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ORDER

You can also purchase the components of the retrofit kits separately.
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FRONT WHEEL MOTORS 24 V















Wheel	Speed on level roads (1)	Maximum slope (2)	Maximum output	Rated Operation Time (3)	Max. motor current (4)	Gearing	Price incl. 16% VAT		Item No.	
inch	k.p.h.	%	Watts	min	Amps	S or K	DM	USD		
	26	9	16	220	22,3	17	S	537,08	268,54	870-00-101-2904
	26	14	15	250	unlimited	27	S	537,08	268,54	870-00-101-2106
	26	18	12	400	21	30	S	537,08	268,54	870-00-101-0108
	26	18	12	250	unlimited	30	S	537,08	268,54	870-00-101-0106
	26	25	8	400	18,1	30	S	537,08	268,54	870-00-101-0408
	26	25	8	250	unlimited	30	S	537,08	268,54	870-00-101-0406
	26	29	6	250	unlimited	30	K	537,08	268,54	870-00-101-1806
	26	29	6	400	19,3	30	K	537,08	268,54	870-00-101-1808
	26	39	2	400	16	30	K	537,08	268,54	870-00-101-3008
	26	22	9	200	unlimited	30	K	537,08	268,54	870-00-101-1902
	26	22	9	400	20,9	30	S	537,08	268,54	870-00-101-0508
	26	22	9	250	unlimited	30	S	537,08	268,54	870-00-101-0506
	26	23	9	400	15,7	30	K	537,08	268,54	870-00-101-1908
	26	23	9	250	unlimited	30	K	537,08	268,54	870-00-101-1906

Figure 46: Heinzmann 24V Front Wheel Motor Models [57]

5.2.6. QR20 Front Fork Dropout Adaptors

To adapt the Heinzmann hub motor to the Rocky Mountain RM6 bicycle front suspension forks, an adaptor needs to be designed since the Heinzmann hub motor comes with a 10mm axle, while the suspension forks on the RM6 bicycle require a 20mm axle. The adaptors designed feature quick releases so that the front wheel can be removed quickly (less than 10 seconds). The adaptors are designed using the 3D modeling package Pro/ENGINEER for design accuracy (See Appendix B for the prototype drawings). The adaptors are designed so that the axles of the hub motor do not need to be cut; this results in no modifications needed at all to the stock Heinzmann hub motor. The only problem with this adaptor design is that they make the front axle too wide to fit into the

Computrainer rear mount stand (Figure 56). For this reason the AEBPS is only road tested. This should be adequate since the AEBPS is only designed for proof of concept, rather than a consumer ready product. The adaptors can be redesigned to fit into the electric bicycle testing apparatus at a later date.

There are two different inner adaptors, a universal outer adaptor, and a universal quick release (Figure 47). Since the motor fits into the area between the fork legs asymmetrically, the inner adaptors have a different flange thickness. The main purpose of the inner adaptors is to change the motor's 10mm axle to a 20mm axle that fits in to the fork dropouts. The outer adaptors are designed to hold the motor in the fork dropouts, and the quick releases are included to install and remove the front wheel quickly. A small quick release spring is placed in between the inner and outer adaptors to automatically push the outer adaptor away from the fork dropouts as the quick release is unscrewed. The actual adaptors used on the AEBPS equipped bicycle are shown in Figure 48 and Figure 49.

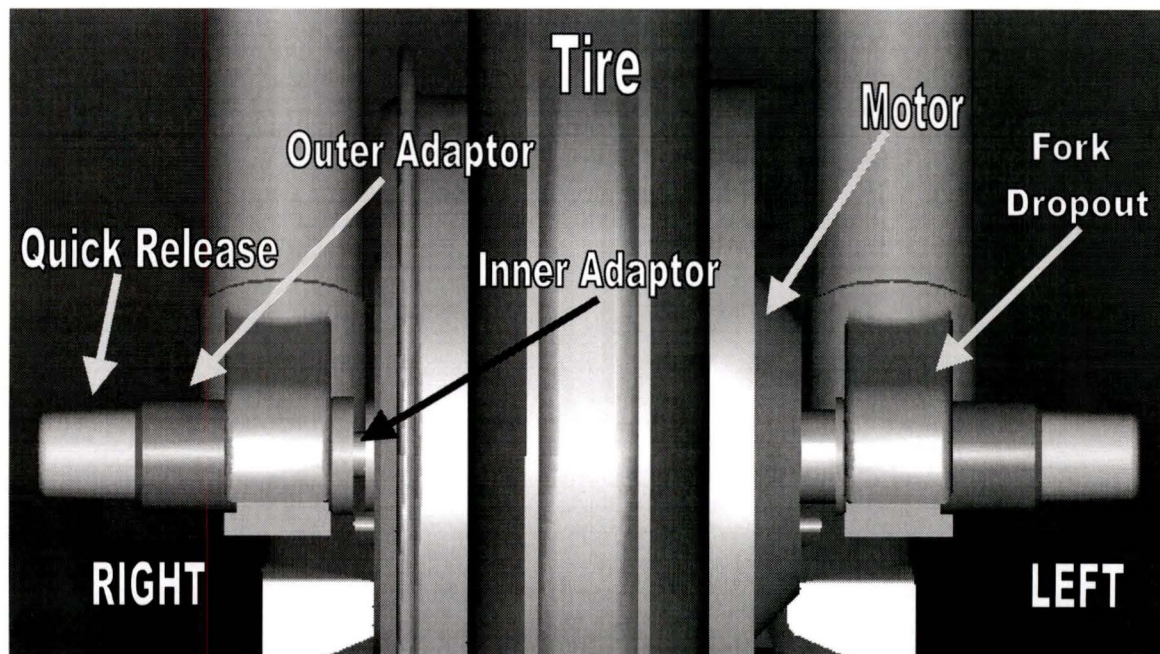


Figure 47: Pro/ENGINEER 3-D Model of Axle Adaptors

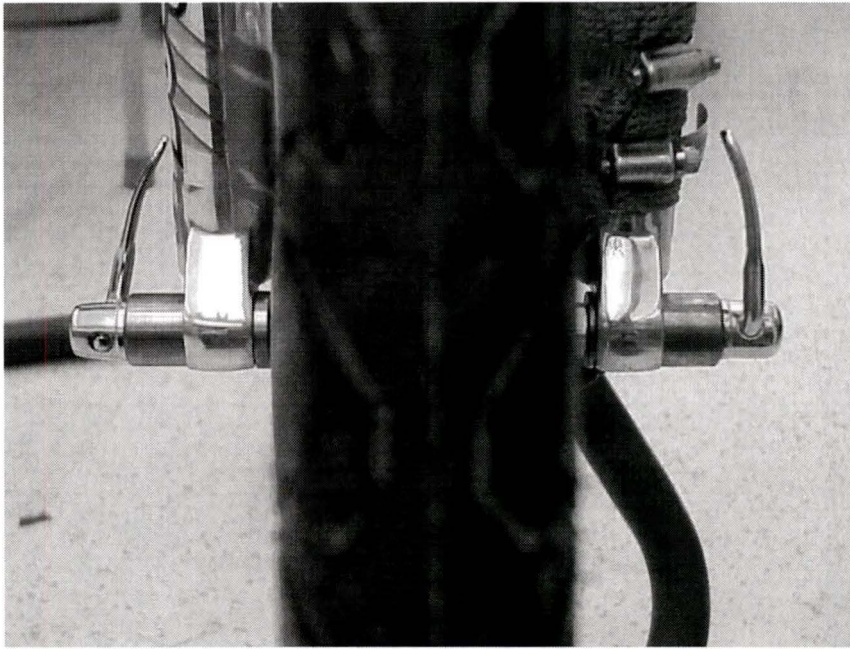


Figure 48: QR20 Hub Motor Adaptors

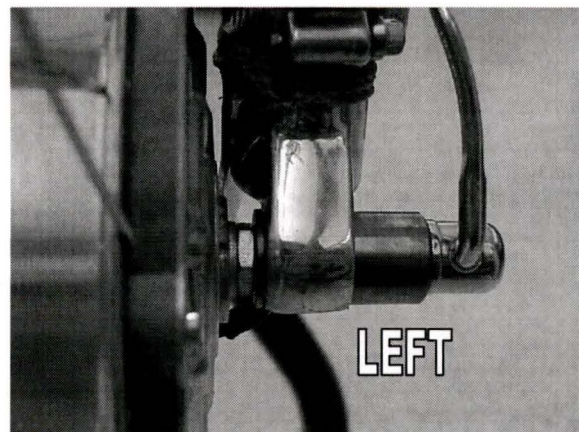
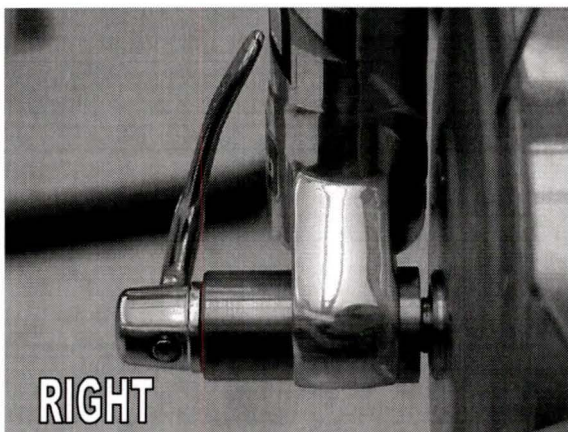


Figure 49: QR20 Hub Motor Adaptors (Close Up View)

5.2.7. Quick Release Fasteners

A very simple and effective method of holding the power cables, and the current and voltage (C/V) meter project box to the bicycle is using Gardner Bender GRIP STRIP (hook and loop) straps (Figure 50). These particular straps have a slot cut in them so that the strap loops through the slot and holds the cables and box very tightly in place. They can be purchased from any Radio Shack store, and are very inexpensive (~\$1 CND each).

The straps allow the power cables and C/V box to be removed from the bicycle very quickly.



Figure 50: Gardner Bender GRIP STRIP Fastening Strips

5.3. Final Adaptable Electric Bicycle Power System

Figure 51 a–h show the completed AEBPS mounted on the Rocky Mountain RM6 full suspension bicycle. On-road and off-road tests of the AEBPS prove it to be very successful (see Section 7.3.3 for the road acceleration test results). The Rocky Mountain RM6 equipped with the AEBPS has no problem climbing large on-road and off-road grades. The AEBPS RM6 bicycle is tested to have a top speed of 18.5 km/h.

As the AEBPS modeling suggests, the front tire does have a tendency to lose traction during acceleration from a standstill. The rider simply needs to be easy on the throttle during acceleration from a stop.



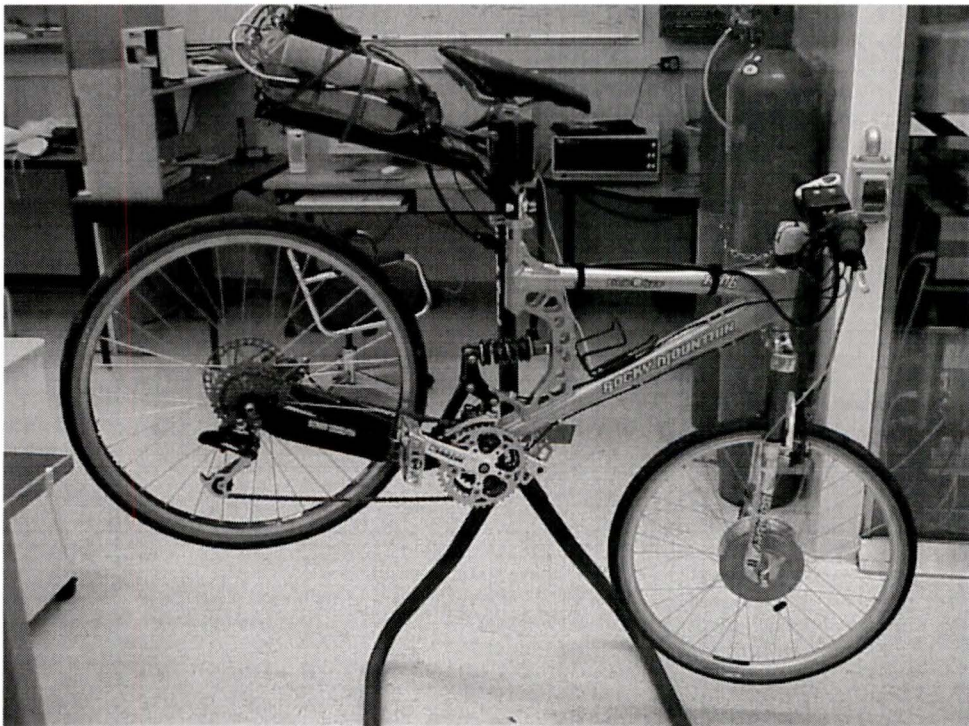
(a)



(b)



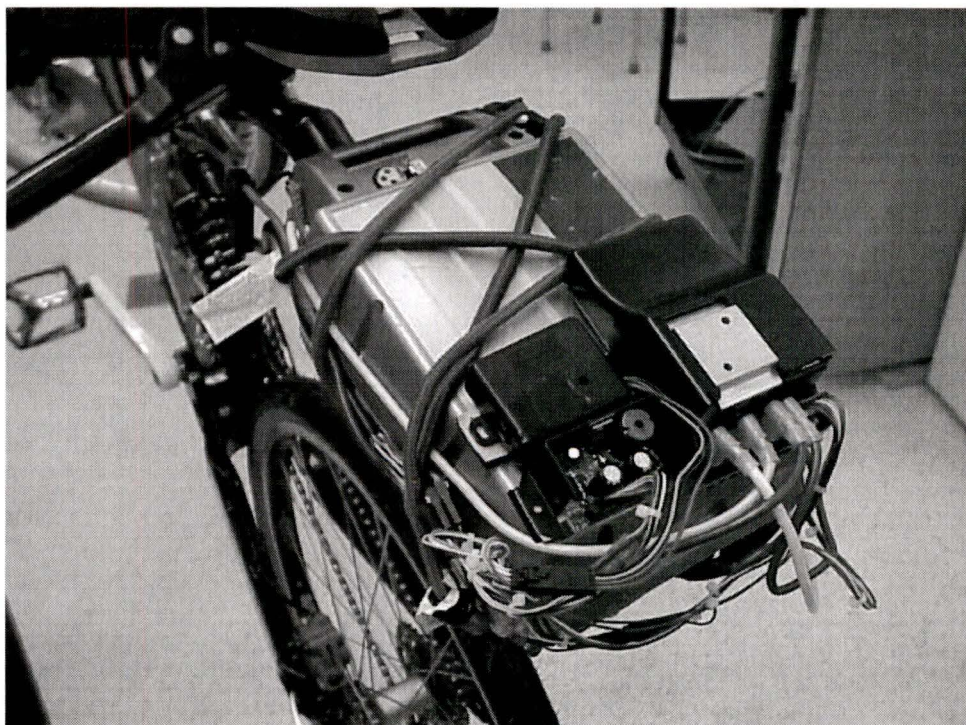
(c)



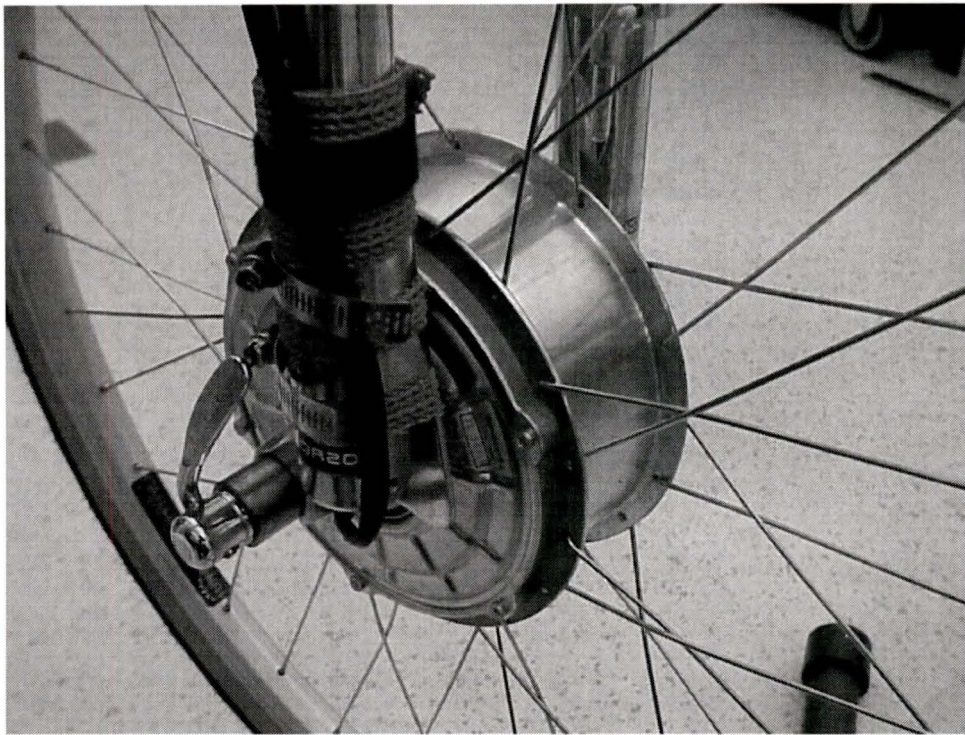
(d)



(e)



(f)



(g)



(h)

Figure 51: AEBPS Mounted on Rocky Mountain RM6

5.4. AEBPS Specifics

Table 15 shows the final specific values of the constructed prototype AEBPS.

Table 15: AEBPS Specifics

Prototype Cost	~\$1000 CDN (\$625 USD) including tax & shipping costs
Electrical System	24 Volt EV Warrior System
Motor Controller	Curtis 1505 (20A Continuous, 80A (1 Minute Rating))
Battery Pack	Currie Cycles 24V Sealed Lead Acid 12Ah
Motor Power Output	400 Watts (Maximum) 200 Watts (Continuous)
Maximum Motor Torque	37 Nm
Maximum Bicycle Speed	18.5 km/h (Mounted on RM6 with 167 lbm rider)
Throttle	Fully Variable Speed (Thumb Operated)
Total AEBPS Mass	14.9 kg (32.9 lbm)
Hub Motor Mass	3.6 kg (8 lbm)
Battery Pack Mass	9.8 kg (21.5 lbm)
Electrical System Mass	0.9 kg (2 lbm)
Topeak Beam Rack Mass	0.6 kg (1.4 lbm)

5.5. Present AEBPS Limitations

The AEBPS is able to fit on almost any production bicycle, but the present design with the Heinzmann hub motor and thumb throttle do present a few limitations to the adaptability of the AEBPS.

1. The bicycle fork needs to have at least 95 mm of clearance between the legs so that the front hub motor can fit. Other hub motors are available that may be thinner than the Heinzmann, but presently the Heinzmann is the best hub motor available.
2. The EV Warrior (EVS-1) electrical system uses a handlebar mounted thumb throttle, therefore, it is difficult to use if the bicycle does not use a Grip Shift rear gear (dérailleur) shifter. Having a Grip Shift shifter allows the throttle to be positioned properly for the rider. A solution to this problem can be achieved by replacing the thumb throttle with a commercially available electric bicycle twist throttle.

3. The present Heinzmann hub motors do not have a disk mount for disk brakes, therefore, a cantilever brake or V-brake needs to be used that brakes on the rim of the wheel. There has been confirmation that a disk mount is being developed for Heinzmann hub motors at EV Select (Scotland UK) to solve this problem [58].

5.6. Results from AEBPS Modeling and Development

The fuel cell bicycle model provides a higher amount of front tire traction due to the fuel cell stack being located in a basket attached to the front handlebars. However, it is found through testing that unless the fuel cell stack has a mass less than 1 kg, the bicycle will steer too slowly to be safely ridden on public roads. It should also be noted that a small mass of 1 kg located at the handlebars would not increase the motorized drive wheel traction force significantly. It is then recommended that the fuel cell bicycle model be altered to follow the design of the adaptable electric bicycle system (AEBPS), locating the fuel cell stack at the rear of the bicycle on a quick release beam rack.

The Heinzmann electric hub motor is found to be the best electric bicycle motor on the market today. It is presently used on many commercial electric bikes including Lee Iacocca's Ebike. The Heinzmann motor features exceptional quality and reliability; this is proven during testing of the AEBPS RM6 bicycle.

The AEBPS configuration is proven to work excellent during on-road and off-road testing.

CHAPTER 6 ELECTRIC BICYCLE TESTING EQUIPEMENT AND TEST PROCEDURE DEVELOPMENT

6.1. Types of Tests Developed

Three types of electric bicycle tests are developed during this study. These are: the Electric Bicycle Velocity Testing Cycles (EBVTC), the Electric Bicycle Grade Testing Cycle (EBGTC), and the Electric Bicycle Road Acceleration Testing Method (EBRATM). The EBRATM is quite simple, using low cost instruments for measuring electrical bicycle acceleration and top speed. The EBVTC and EBGTC are more complex, utilizing a computerized bicycle dynamometer, the RacerMate Computrainer. In addition to the Computrainer dynamometer, the EBVTC use a microcontroller.

Two electric bicycles are tested on the EBGTC, the Currie Cycles electric bicycle, and the Suzhou Small Antelope electric bicycle so that the performance differences can be observed. Only the Currie electric bicycle is tested on the EBVTC for proof of concept purposes. All electric bicycles are road tested, including the AEBPS equipped Rocky Mountain RM6.

6.2. Test Bicycles Specifics

The electric bicycles tested are all EPBs; they do not have to be pedaled in order for full power to be delivered.

6.2.1. Currie Cycles Electric Bicycle

The Currie electric bicycle (Figure 52) is designed mainly for the American market rather than for Asia, due to its high power output (Americans prefer vehicles with high power output even though range is reduced). It features one of the highest powered motors available on an electric bicycle (900W peak, 400W continuous). This electric bicycle is

geared quite high to achieve a manufacturer's claimed top speed of 29.0 km/h (18 mph); this is also one of the highest top speeds available for an electric bicycle, although some available electric bicycles have top speeds of 32.2 km/h (20 mph). This electric bicycle has a 12 Ah battery pack that has a mass of 9.75 kg (21.5 lbm). The entire bicycle has a mass of 28.1 kg (62 lbm), which makes it one of the lightest electric bicycles on the market today. The complete Currie electric bicycle costs ~\$899 USD (\$1438 CDN) for the complete bicycle, and an add-on kit costs ~\$595 USD (\$952 CND). The add-on kit consists of the electric motor, battery, throttle, and rear wheel adaptor. The Currie electric bicycle features a range of 32.2 km with some light pedaling required. Additional specifics are listed in Appendix C.



Figure 52: Currie Cycles Electric Bicycle

Theoretical Range (No Pedaling)

If no pedaling is exerted by the rider the Currie electric bicycle is estimated to have a range of 25.8 km (80% of 32.2 km), and if it is assumed that this is at full speed (~29 km/h) on a flat road (including inefficiencies), the electric bicycle should be able to travel for 53.4 minutes using the 12 Ah battery pack. The continuous current draw from the motor would then be 13.5 Amps.

6.2.2. Suzhou Small Antelope Electromobile Electric Bicycle

The Small Antelope electric bicycle (Figure 53) is made by Suzhou Small Antelope Electromobile. The company is located in the Jiangsu province of China. The Suzhou Small Antelope company was established in 1997. The electric bicycles are built in a large 5,000 square meter plant. The company has capital of \$10 million USD. As of October 2000, Suzhou Small Antelope Electromobile had 280 employees, which includes 45 research and development personnel. 90% of all electric bicycle sales are to the Chinese domestic market. Suzhou Small Antelope Electromobile sold 3,400 electric bicycles in 1998, generating an income of \$9.4 million USD. In 1999, electric bicycle sales grew to 25,000 units achieving \$63.8 million USD in sales. Following the purchase by Elebike in 2000, the Suzhou Small Antelope Electromobile company maintains an output of approximately 6,000 electric bicycles per month. The total annual electric bicycle production will reach up to 70,000 units at Suzhou Small Antelope Electromobile [59]. Most of the electric bicycles sold by Small Antelope Electromobile are low powered, with motor peak power rated at 150 – 250 Watts.

The Small Antelope test bicycle is has a total mass of 35 kg (77.2 lbm). The 36 volt battery pack has a mass of 12.5 kg (27.5 lbm). The mass of the Small Antelope is quite high compared to the other electric bicycles listed in Table 1. The Small Antelope has a top speed of ~21 km/h, and a maximum motor power output of ~230 Watts. The high mass and low power output of the Small Antelope results in a relatively slow electric bicycle compared to the light and powerful Currie electric bicycle.



Figure 53: Suzhou Small Antelope Electric Bicycle (China)

6.2.3. AEBPS RM6 bicycle

As discussed in Section 5.2. This electric bicycle is only road tested.

6.3. Computrainer Bicycle Dynamometer Description

The Computrainer is made by RacerMate Inc. in Seattle, Washington. The computerized trainer is designed mainly for professional road bicyclists. The main components of the Computrainer system consists of an electronic load generator assembly, a handlebar control module, a rear mount trainer stand, and computer software.

The Computrainer can create resistance loads from 50 to 1500 Watts. The Computrainer software takes data points every 30ms (33.3 Hz), resulting in precise output plots.

6.3.1. Load Generator Assembly

The Computrainer electronic load generator assembly, shown in Figure 54, consists of an eddy current brake that generates up to 1500 Watt loads; this allows the ability to simulate road grades up to 15%. The load generator assembly is very quiet, and utilizes a dynamically balanced, vibration free flywheel. The load generator used in the electric

bicycle testing is six-point calibrated on a RacerMate laboratory bicycle dynamometer for load accuracy. The load generator assembly features a hard-anodized aluminum friction roller. The load generator assembly also consists of a rear adjusting knob; this knob is used to press the friction roller on to the bicycle tire.

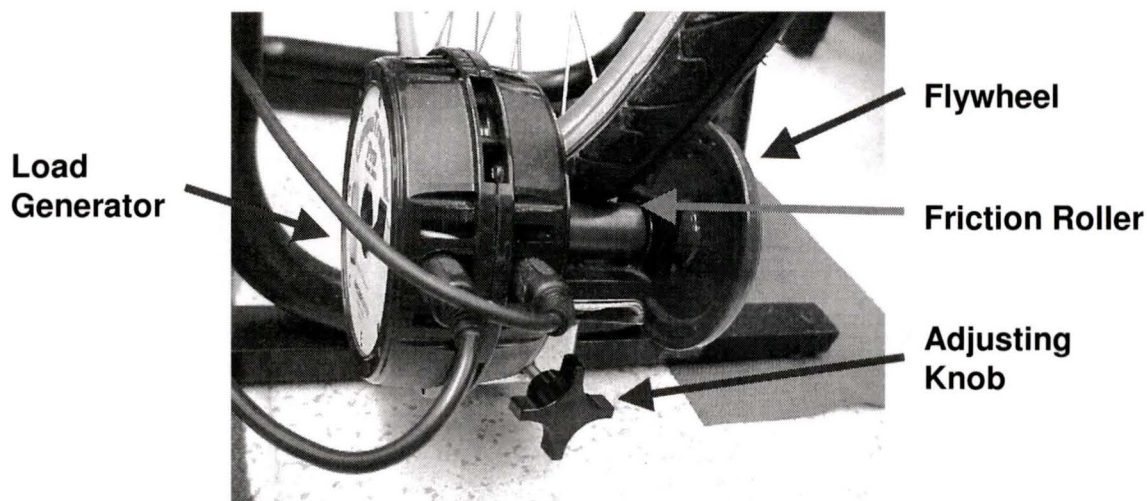


Figure 54: Computrainer Load Generator Assembly

6.3.2. Control Module

The handlebar control module (Figure 55) is used to connect the Computrainer load generator to the computer. If no computer is used, the handlebar control module is used to select loads. The handlebar control module also displays the bicycle speed, distance, elapsed time, and watts when a computer is not used.

The main use of the handlebar control module when using a computer is the tire rolling resistance calibration. This calibration is critical for accurate load determination. The rolling resistance calibration allows for the same load to be applied even when different bicycle tires with different pressures, and tread patterns are used. The rolling resistance calibration is described in detail in Section 6.4.2.

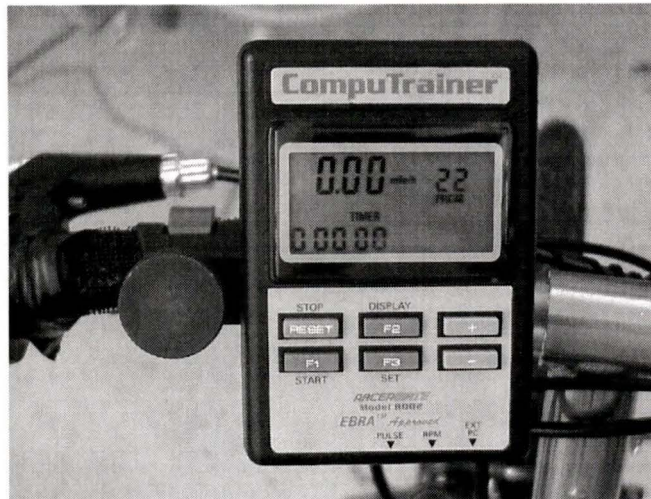


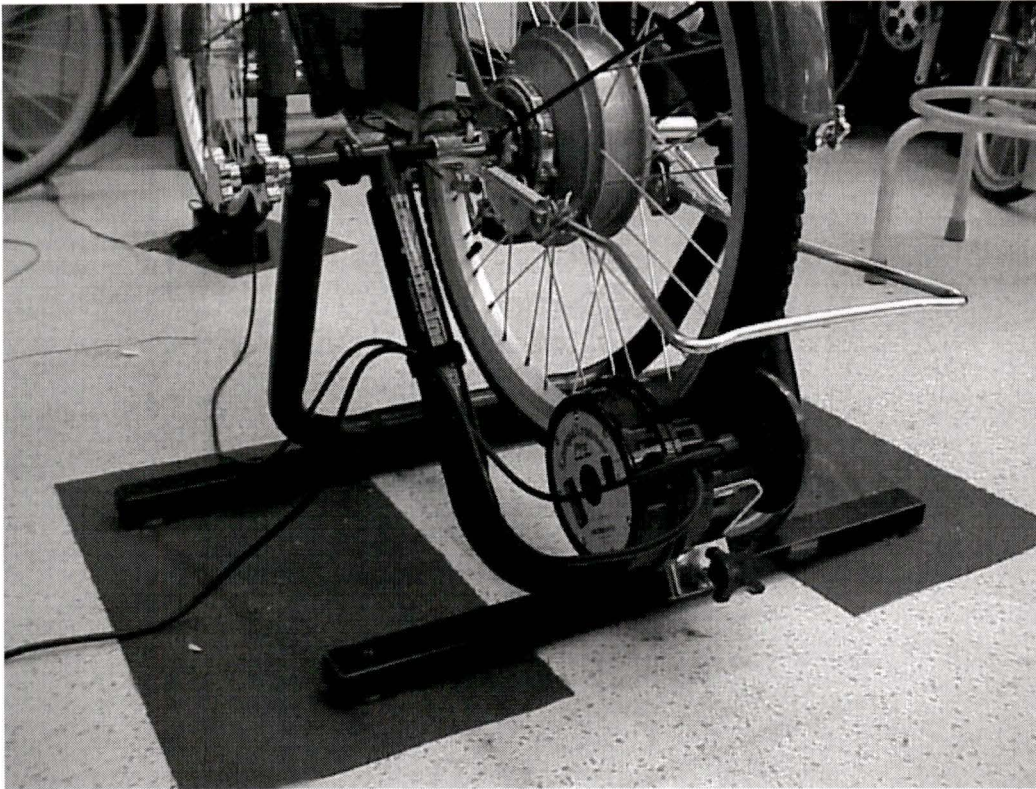
Figure 55: CompuTrainer Handlebar Control Module

6.3.3. Rear Mount Stand

The CompuTrainer rear mount stand is built strong to minimize deflection. The stand also has a very large footprint for stability. Figure 56a displays the adjustment knobs. Figure 56b shows the Suzhou Small Antelope mounted in the stand.



(a)



(b)

Figure 56: Computrainer Rear Mount Stand

6.3.4. Computrainer Software

For testing of the electric bicycles, two types of computer software are used, the PC1 software and the Coaching Software; both are products from RacerMate. The PC1 software is used to record the data from the load generator (Watts, Distance, Speed, Time), and the Coaching Software is used to export the data to a spreadsheet.

Pro PC1 Software

The main software used is the Pro PC1 interactive software. The software displays a graphic image of the rider and bicycle on the computer screen. The PC1 software also displays the speed, distance, and Watts in real time during testing (Figure 57). The PC1 software allows for custom courses to be programmed. A custom course can contain up to 1000 sections, with a minimum section length of 10 meters. The data can also be

displayed in Metric or English units. The PC1 software records data points approximately every 30 milliseconds (33.3 points per second).

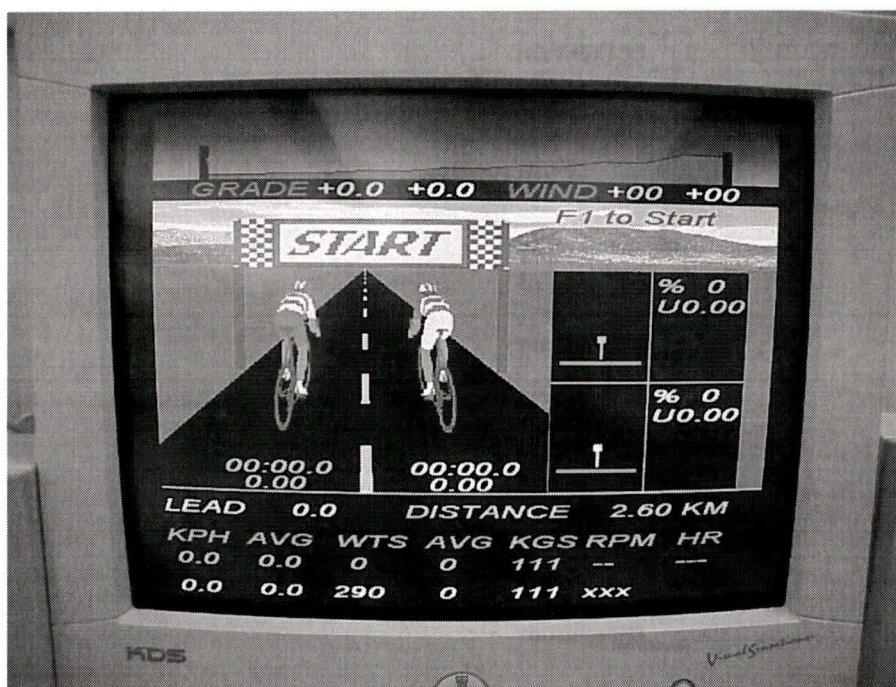


Figure 57: Computrainer PC1 Software

Computrainer Coaching Software

The main use of the coaching software is to export the performance data obtained from the PC1 software as ASCII text files to a spreadsheet, such as Microsoft Excel etc (Figure 58). The coaching software is essential for analysis of the electric bicycle performance. The coaching software can also be used to display the performance of the electric bicycle test before the data is exported (Figure 59). The coaching software exports the data in English units even if the test is completed in Metric; the data simply needs to be converted in a spreadsheet once it is imported.

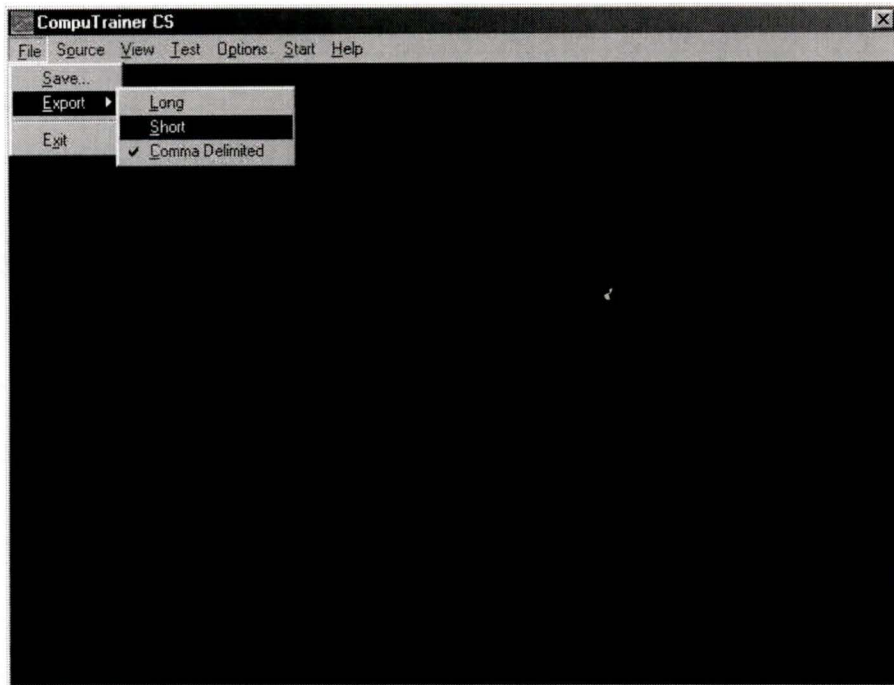


Figure 58: Computrainer Coaching Software Export Data

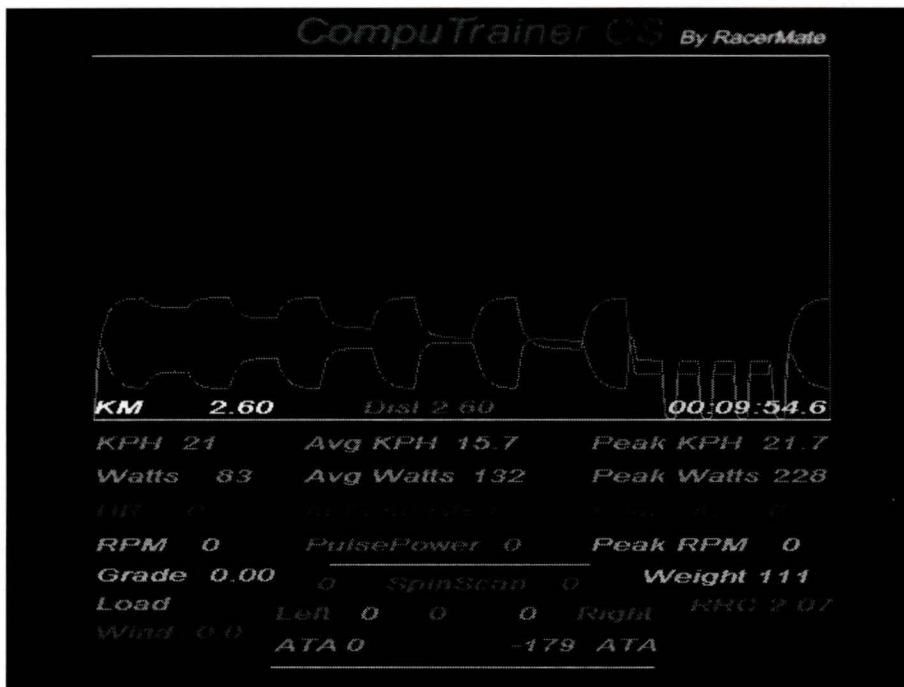


Figure 59: Computrainer Coaching Software

6.4. Computrainer Testing Procedure

The following section describes the critical steps involved in testing an electric bicycle on the RacerMate Computrainer. The Computrainer tests all occur at a room temperature of approximately 70.5°F (21.4°C).

6.4.1. Test Tire Set-up

The tires on the bicycle being tested on the Computrainer should be quite thin (~1.25” to 2” wide), and have little tread so that there is a lot of contact between the tire and friction roller. Smooth tires are the preferred tire choice for use with the Computrainer [60]. A tire that is popular for road use is the Tioga City Slicker (Figure 60). This tire has a smooth outer profile, but also features rain grooves to provide traction on wet pavement. The recommended tire pressure is between 35 to 90 psi. This tire is also very affordable at \$19.00 CDN from Mountain Equipment Co-op [61]. This tire is used for testing the electric bicycles with standard tires not compatible with the Computrainer due to an oversized width or poor quality. This tire is inflated to 60 psi during testing on the road and on the Computrainer.



Figure 60: Tioga City Slicker Tire

Tire Cleaning Procedure

It is recommended that the test tire be cleaned before each test with Isopropyl Alcohol (Rubbing Alcohol) [60]. This procedure is important since the isopropyl alcohol will

remove any remaining mold release on the tire, or any oils or dirt from road use. The tire should also be thoroughly inspected for small rocks in the tire tread that could damage the Computrainer friction roller.

Tire Press On Force

The tire press on force is completed using the rear adjusting knob on the Computrainer load generator assembly. Once the electric bicycle is mounted in the trainer stand the roller is pressed against the tire using the adjusting knob. The roller should be pressed against the tire so that there is no possibility of slippage. The roller first needs to be brought up so it just touches the tire. It is determined through testing that a 26" × 1.5" Tioga City Slicker tire inflated to 60 psi should then have the knob turned an additional ~1½ times creating a strong press on force. It is also found that a 24" tire inflated to 40 psi should have the knob turned ~2⅝ times to achieve the same press on force.

6.4.2. Rolling Resistance Calibration

An important feature of the Computrainer system is the rolling resistance calibration. This calibration inputs the current tire rolling resistance into the Computrainer software so that the same loads can be properly applied no matter what temperature, press on force, or tire pressure is present during the test [62]. This calibration ensures a high level of repeatability from one electric bicycle test to another. The procedure for calibration requires the rider to ride the electric bicycle to 40 km/h (25 mph) then jump from the bicycle seat, removing his/her mass from the bicycle, and allowing the bicycle to coast to a stop. As the electric bicycle coasts down to 0 km/h the rolling resistance of the tire is measured. The reason for the rider to remove his/her weight from the bicycle is because the rider's mass will increase the rolling resistance due to a slight deflection of the rear mount stand, and since the electric bicycle testing is more comfortably executed without a rider sitting on the bike, the rider needs to calibrate the bicycle with only the electric bicycle mass on the trainer.

The rolling resistance of the tire will be reduced as the tire warms up during riding. For this reason, the bicycle is ridden and the calibration procedure repeated until the rolling

resistance becomes constant. To warm up the tire, the bicycle is first ridden for three minutes with a 120 Watt load, and then calibration is started. A rolling resistance of approximately 2.08 is recommended to avoid tire slippage on the friction roller; rolling resistances higher than 2.08 are not necessary, but can be used.

6.4.3. Mass Input

In order for the Computrainer to produce an accurate and realistic load, the mass of the rider plus the bicycle needs to be entered into the Computrainer software; this data is entered by creating a rider data file using the Pro PC1 software [63]. This file tells the Computrainer software what total mass to use for its load calculations. Basically, a lighter mass makes it easier for the electric bicycle to get up a hill, while a larger mass makes it more difficult for the electric bicycle to climb a hill. For all testing, a rider mass of 167 lbm is used plus the electric bicycle mass.

6.4.4. Exporting Data Using Computrainer Coaching Software

One of the most powerful aspects of the Computrainer is the ability to analyze and export data using the Computrainer Coaching Software (CS). The coaching software also can display the power and velocity of the electric bicycle during a test cycle. The CS also exports the data taken during a Pro PC1 test to a file; this file can then be opened in a spreadsheet program such as Microsoft Excel. In order to view the data of a particular Pro PC1 test using the CS, the Pro PC1 test first needs to be saved as a “saved race file” (*.SRF). This file can then be opened in the CS program. Exporting of the data is simple; the user chooses File, then Export. The export is then selected; it is found that exporting using “Short Format” works the best. The short format allows only one blank space between data columns and is best suited for import into a spreadsheet program [64]. It also recommended to select “Comma Delimited” to easily import the file into a spreadsheet (Figure 58). The CS exports the saved race file as a text file (*.TXT).

Toss Amount

The CS toss amount is the amount of data that is not included in the export file. The toss amount lets the program know how many lines of data should be removed from the file.

For example, if the toss value is 10, the export function of the CS will include the first line, then remove ten lines, include the twelfth line, then remove ten lines, etc. The size of a file can be enormous in a very short amount of test time since data lines are collected approximately every 30 milliseconds (~33.3 lines per second); it is for this reason that a toss amount is always used during tests that are over two minutes in duration. A two minute test would result in 3996 lines of data recorded.

6.5. Electric Bicycle Velocity Testing Cycles (EBVTC)

One method of electric bicycle testing is by modifying current automobile and scooter velocity dynamometer testing cycles. These tests observe the performance of the vehicles as they are driven during a specific velocity profile. The main problem with current automobile and scooter velocity tests is that the vehicle is usually driven using a human and a computer screen that prompts the driver to obtain the next speed. This creates a significant amount of error, especially for repeatability testing. For this reason, a microcontroller is used with open loop control to ensure that the test bicycle follows the electric bicycle velocity test cycle very closely. Using open loop control requires an iterative process to match the electric bicycle velocity to the test cycle velocity, resulting in a significant setup time for each electric bicycle tested. The total setup time is approximately two hours.

Three electric bicycle specific velocity tests are created, the European Elementary Urban Electric Bicycle Testing Cycle (EEUEBTC), the Taipei Electric Bicycle Testing Cycle (TEBTC), and the New York Electric Bicycle Testing Cycle (NYEBTC). The RacerMate Computrainer is used to obtain the electric bicycle performance data as it is driven during each test cycle.

6.5.1. Open Loop Control

In order to efficiently make the electric bicycle follow the created electric bicycle velocity testing cycles, open loop control is used. A microcontroller is used to obtain extremely precise velocities throughout the velocity test cycles. The use of a microcontroller and

open loop control is much more consistent and repeatable than if a human operator is used to control the throttle during testing.

Microcontroller Background

The microcontroller used in this project is a Basic Stamp 2 (BS2) made by Parallax Inc. This microcontroller is based on the PIC 16C57 (Figure 61).

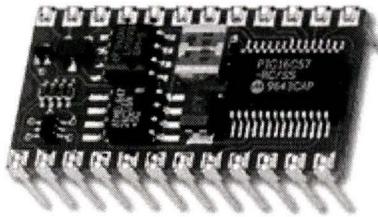


Figure 61: Basic Stamp 2 Microcontroller [65]

The Basic Stamp 2 features a 20MHz clock speed (Table 16), and is programmed using a code very similar to Basic called PBasic.

Table 16: Basic Stamp 2 Microcontroller Specifics [65]

Microcontroller:	PIC16C57 surface mount
Speed:	20 MHz / 4,000 instructions per second
EEPROM:	2K bytes (program and data)
Program Length:	500 lines of PBASIC
RAM (variables):	32 bytes (8 for I/Os and 26 for variables)
Input / Outputs:	16 (up to 17 RS-232 communication ports)
Source / Sink Current:	20 mA / 25 mA
Serial Communication:	300-50K baud I/O
Current Requirements:	7 mA running, 50 uA in sleep
PC Interface:	Serial port
Package:	24 pin DIP module
Size:	1 3/16" L x 5/8" W x 3/8" H
Project Area:	Optional carrier board

The BS2 is very easy to program. The BS2 also features sixteen input/output pins. The Basic Stamp 2 microcontroller is not capable of floating point math; only integer mathematical operations can be performed.

The Basic Stamp 2 can be made to run the programmed software up to twenty times faster by converting the high level PBasic code to low level Assembler code. This is

accomplished by using a Basic compiler program on a PC and a programming adapter; this loads the Assembly language of the Basic code on to the Basic Stamp 2 chip [66]. This is not used in this project, but could be used in the future.

Parallax also offers a much faster Basic Stamp II SX based on a Scenix SX28AC/SS microcontroller (Figure 62).

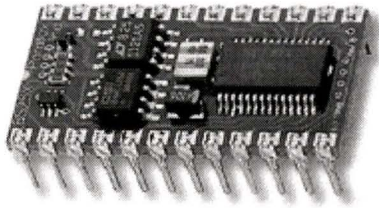


Figure 62: Basic Stamp II SX Microcontroller [65]

The BS2 SX microcontroller has the following features (Table 17),

Table 17: Basic Stamp 2 SX Microcontroller Specifics [65]

Microcontroller:	Scenix SX28AC/SS
Speed:	50 MHz / 10,000 instructions per second
EEPROM:	16K bytes (program and data in 8 x 2K program spaces)
Program Length:	4,000 lines of PBASIC
RAM (variables):	32 bytes (8 for I/Os and 26 for variables) plus 63 bytes "scratch pad RAM" for interprogram sharing
Input / Outputs:	16 (up to 17 RS-232 communication ports)
Source / Sink Current:	30 mA / 30 mA
Serial Communication:	305-115K baud I/O
Current Requirements:	60 mA running, 200 uA in sleep
PC Interface:	Serial port
Package:	24 pin DIP module
Size:	1 3/16" L x 5/8" W x 3/8" H
Project Area:	Optional carrier board

The BS2 SX microcontroller is not used for this project since the BS2 is found to have adequate processing speed. A BS2 SX may be used in future test procedures that require a higher amount of electrically erasable, programmable, read-only memory (EEPROM); the BS2 SX has 16 kb of EEPROM, while the BS2 has only 2 kb. If a BS2 SX is used the

PBasic program length can be up to 4000 lines, while the BS2 can only have a maximum program length of 500 lines.

Board of Education

The Board of Education from Parallax Inc. is used to interface the Basic Stamp 2 microcontroller with various inputs and outputs (Figure 63). It is ideal for prototyping purposes since it is simple to use and includes a built-in breadboard prototyping area.

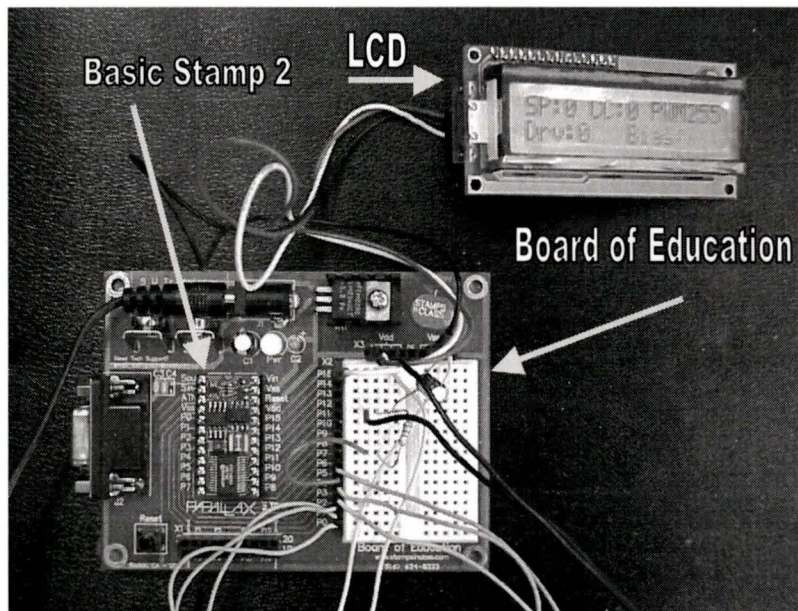


Figure 63: Board of Education

Some of the features of the Board of Education include [67]:

- Mechanically interlocked power supply to prevent dual connection of wall-pack and 9-volt battery.
- Low-insertion force socket for BS2-IC allows removal for other applications.
- DB9 connector for BS2-IC programming and serial communication during run-time.
- P0 - P15 I/O pins, Vdd (5V) and Vss (Ground) connections brought adjacent to 2" x 1 3/8" breadboard area.
- Female 10-pin dual row connector for optional AppModules (more breadboard space).

- Traces on top of the board show connections between BS2-IC and breadboard connections.

6.5.2. Software Development

The software to make the electric bicycle follow the velocity profile through open loop control is by using a program code called PBASIC. This programming language is required by the Basic Stamp 2 microcontroller, and is highly based on the BASIC programming language. See Appendix D for detailed explanations of each developed electric bicycle velocity cycle software.

The software code is divided into a loop for each section of the velocity profile (These sections are linear and shown in Figure 74; there are 15 sections for the velocity profile in Figure 74). The software has a main program that sends the program to the subprogram loops for each section. The sub programs are what drive the motor of the electric bicycle during each section of the velocity cycle.

The software also displays information on an LCD screen that simplifies setting up an electric bicycle velocity test or calibration (electric bicycle calibration is described in Section 6.5.4).

It is important to know that each “debug” statement will add ~17ms to the program execution time when the Basic Stamp 2 microcontroller is used. This very small amount of time is critical if used in the PWM (Pulse Width Modulation) drive loops of a velocity section since the open loop control is based on the time of each PWM loop. The definition of the Basic Stamp 2 PWM command is as follows [68]:

PWM Pin, Duty, Cycles

where,

- ***Pin*** is a variable/constant/expression that specifies the I/O pin to use. This pin is set to output mode initially and then set to input mode when the command finishes. The *Pin* value range is 0 – 15.
- ***Duty*** is a variable/constant/expression that specifies the analog output level (from 0 to ~5V). The value range for *Duty* is 0 – 255. The number 255 can be held in one byte (8 bits) binary. The PWM duty is also known as the PWM drive.
- ***Cycles*** is a variable/constant/expression that specifies the duration of the PWM signal in milliseconds. The value range for *Cycles* is 0 – 255.

It is important to emphasize that the Basic Stamp can not perform floating-point math, therefore only integers can be used in the PWM command.

To adequately and quickly match the velocity cycle profile, equations are developed to determine the amount of pause time during each PWM loop. The PWM command converts a digital value to an analogue output using pulse width modulation. This pause time allows the PWM step to be the correct amount of time for each section of the velocity cycle. The pause time is not ideal since during the pause there is no power going to the motor, resulting in a dip in the linear velocity slope. The electric bicycle motor basically is driven with very noticeable pulses during each pause then PWM drive cycle, this is very undesirable in terms of velocity cycle match and realistic electric bicycle driving operation. To remedy this problem, and reduce the pause time to a minimum, additional loops of the same PWM drive step amount are implemented.

The first step in creating a pause equation is to determine the time duration of one PWM drive loop. For the *PWM pin, duty, 25* command used in the electric bicycle test software, the time for one PWM loop is measured to be 29.66 ms. This value is determined by using the following program loop:

```

Debug "START",cr
for x = 1 to 500
  PWM 5, 50, 25
Next
Debug "STOP",cr

```

This loop is initiated and timed with a stopwatch. The average of five tests is 14.83 seconds; this is for 500 loops, which then equals 29.66 ms/loop (33.715 loops/second).

The original PWM drive loops had large pause times. For example, the original loop for providing PWM increments for a linear slope going from a PWM drive of 0 to 100 in 30 seconds was as follows:

```

't = 30 seconds
one:
for drive = 0 to 100
  PWM 5, drive, 25
  pause 267
next
return

```

Equation 10 shows that the pause time is the total time duration (30000 ms) divided by the number of loops (101), minus the PWM drive time (29.66ms).

$$PauseTime(ms) = \frac{TotalTimeDuration(ms)}{\#PWMLoops} - 29.66 = \frac{30000}{101} - 29.66 = 267.37ms = 267ms \quad (10)$$

Unfortunately, this pause time of 267ms causes a rippling effect in the velocity profile as the motor stops for 267ms during each loop.

The solution to this problem uses a new equation, which includes a double loop PWM increment procedure. Rather than pausing for a long period of time to achieve the desired time duration, the pause is reduced by increasing the amount of PWM drive proportionally using Equation 11.

$$PauseTime(ms) = \frac{TimeDuration(ms)}{\#PWMLoops} - (29.66ms * \#SecondaryLoops) \quad (11)$$

For example, the previous example changes to:

```

't = 30 seconds
one:
for drive = 0 to 100
  for x = 1 to 10
    PWM 5, drive, 25
  next
pause 0
next
return

```

Since,

$$PauseTime(ms) = \frac{30000ms}{101} - (29.66ms \times 10) = 0.429ms = 0ms \quad (12)$$

Equation 12 displays that there now is no pause, of course in different circumstances the pause can reach up to 29.66 ms since one PWM drive loop takes 29.66 ms.

The response of the electric bicycle is now a series of small steps from a PWM drive of 0 to 100, which is much smoother than with large pauses.

6.5.3. Hardware Development

The hardware for electric bicycle velocity testing consists of a Parallax Basic Stamp 2 (BS2) microcontroller, a Parallax Board of Education (BOE) prototyping project board, a potentiometer, an 8-bit analogue to digital (A/D) converter, two pushbuttons, and various resistors and wires (Figure 64). The potentiometer works with the 8 bit analogue to digital converter to provide an input to the BS2 microcontroller from 0 – 255. The A/D converter is connected to pins 0 – 2. This works perfectly with the PWM command since the duty cycle range is 0 – 255. The buttons are set up as inputs to the BS2; they determine which test should be initiated (electric bicycle calibration or electric bicycle

velocity cycle). The velocity test selection button (Yellow) is connected to Pin 3. The calibration select button (White) is an input to Pin 6.

There is also an output control voltage (0 – 5V) supplied to the Currie motor controller via the control voltage wire at Pin 5 of the BOE. More information regarding the pin designations can be found in Appendix D.

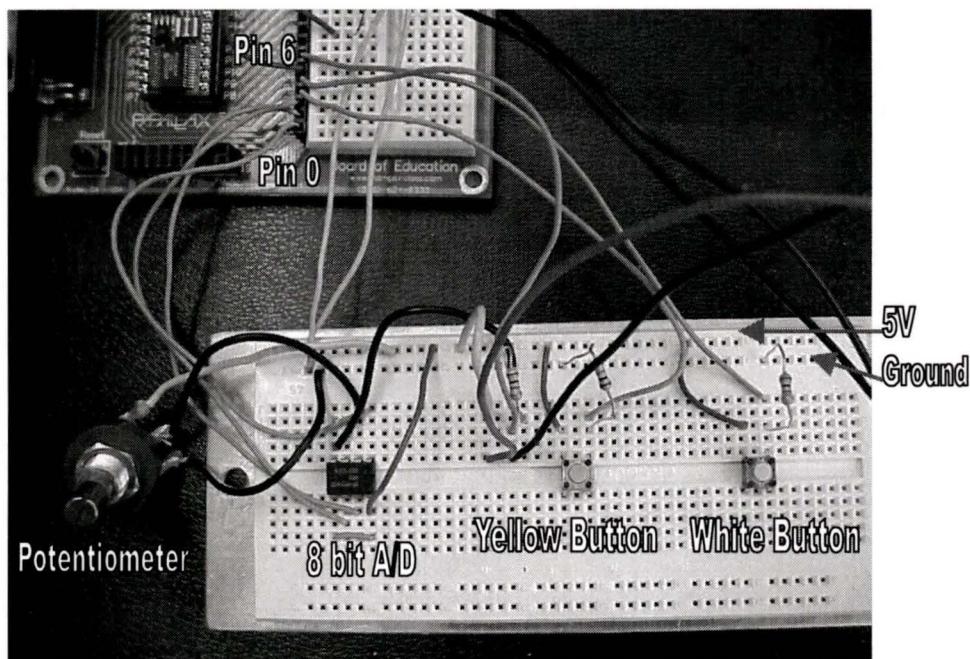


Figure 64: EBVTC Hardware

6.5.4. Electric Bicycle Calibration

Using the hardware and software created (main_calibrate procedure (see Appendix D)), the PWM drive amount (0 – 255) versus the speed of the electric bicycle can be observed (Figure 65). This initial observation is done using the Computrainer PC1 software and manually recording the speed of the electric bicycle in PWM drive increments of 10. This initial chart is used to match the PWM amounts with the required speeds of the velocity test cycle. For example, it can be observed from Figure 65 that a PWM drive amount of ~140 will make the Currie electric bicycle attain a velocity of ~16 km/h.

It is important to note that velocity profiles with sharp peaks (such as the New York Electric Bicycle Testing Cycle (NYEBTC) (Section 7.1.3)), will require more PWM than observed in Figure 65 to achieve the peak velocity. The PWM drive increase needed is due to the lag time of the electric bicycle to attain the desired velocity.

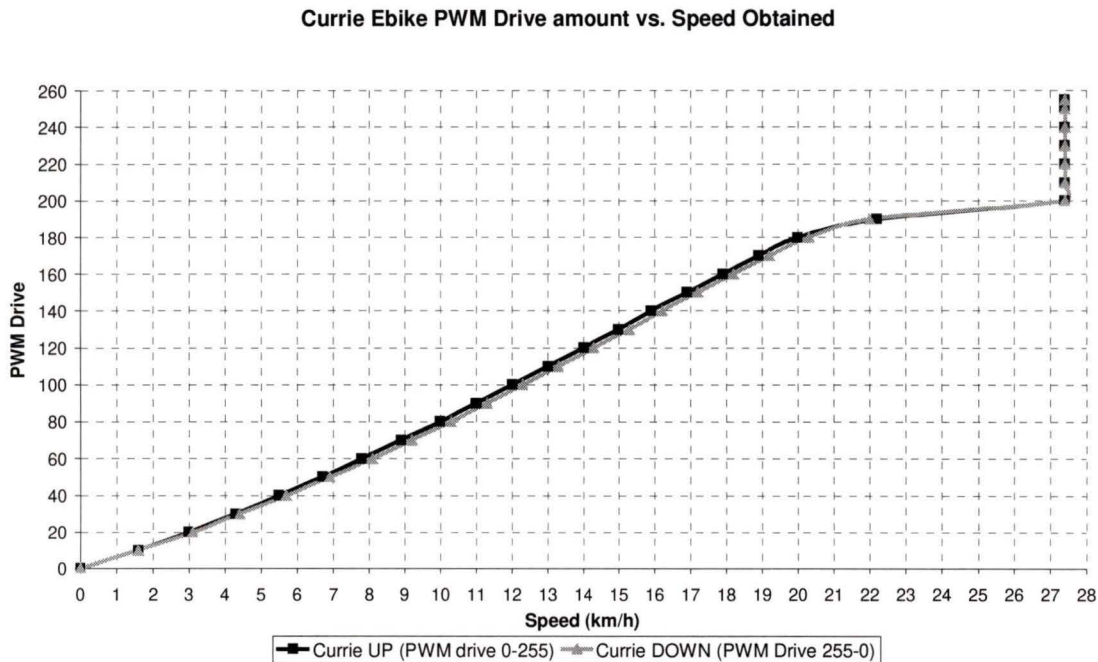


Figure 65: Currie Electric Bicycle PWM Drive vs. Speed

6.6. Electric Bicycle Grade Testing Cycle (EBGTC)

6.6.1. Objectives of Test

This test is designed specifically as a universal test for all electric bicycles. Electric bicycles of all top speeds and power capabilities can be tested using the EBGTC. For EPBs, this test also only requires putting the electric bicycle in the Computrainer and holding the throttle to full power, unlike the EBVTC that requires a significant amount of time to match the velocity profile. The EBVTC also requires the electric bicycle being tested to be capable of reaching all the velocities of the profile limiting its universal use. The EBGTC does not use a Basic Stamp 2 microcontroller; the EBGTC is programmed into the Computrainer by using the required Computrainer Pro PC1 software. EABs can

also be tested, but comparison of results and repeatability are difficult since human powered assistance is needed. Only EPBs are tested during this project.

6.6.2. Grade Test Explanation

The electric bicycle grade test cycle is 2.6 km long and consists of thirteen, 0.2 km segments (Figure 66). The segments alternate between a specific grade section and a flat (0% grade) section (Table 18). The Pro PC1 program to initiate this test profile is very simple (Figure 67). Grades higher than 10% are not tested for fear of damaging the Computrainer due to overheating; it is probable that grades larger than 10% could be tested if a high powered fan is placed on the Computrainer load generator. By having a flat section at the beginning of the test, the acceleration of the electric bicycle can be observed from a standstill. By imposing sections of 0.2 km the bicycle velocity and power output can come to equilibrium before the next section.

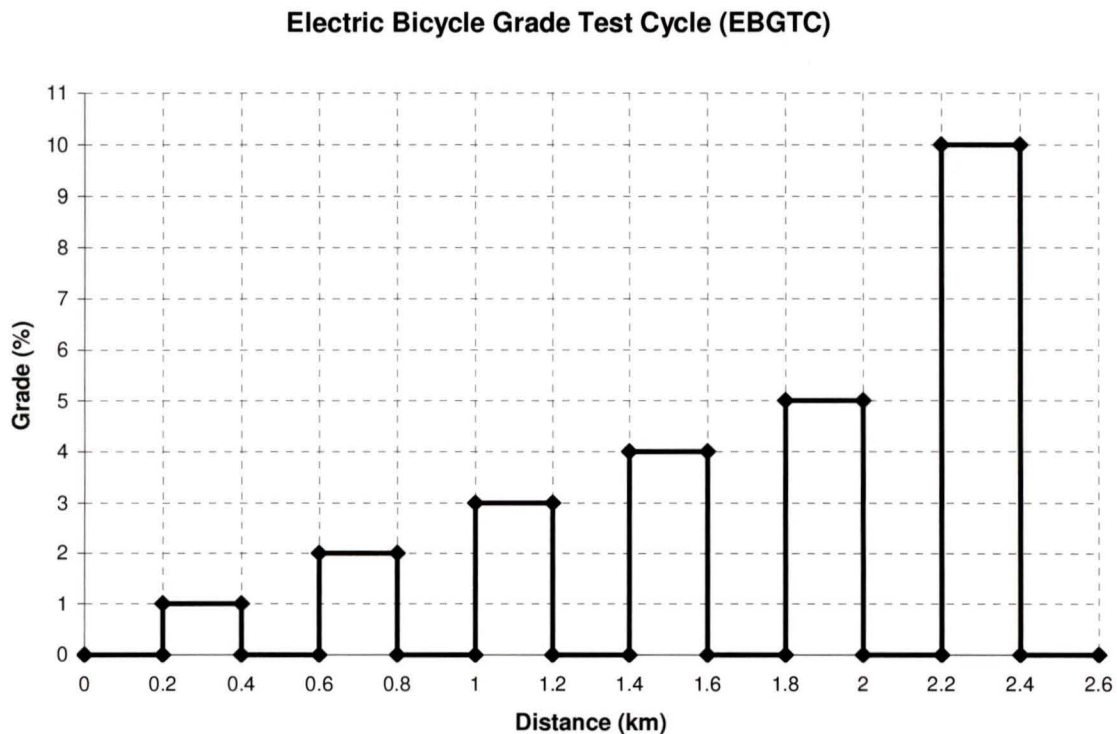


Figure 66: Electric Bicycle Grade Testing Cycle (EBGTC) Profile

Table 18: Electric Bicycle Grade Test Cycle (EBGTC)

Section Number	Grade (%)
1	0
2	1
3	0
4	2
5	0
6	3
7	0
8	4
9	0
10	5
11	0
12	10
13	0

```

EBIKE_PERF_Profile_1.crs - Notepad
File Edit Search Help
[COURSE HEADER]
UNITS = METRIC
DESCRIPTION = ELECTRIC BICYCLE FLAT TEST
FILE NAME = FC_EBIKE_TEST_CYCLE.CRS
;DISTANCE GRADE WIND
; COMMENTS
[END COURSE HEADER]

[COURSE DATA]
0.000 0.00 0
0.200 0.00 0
0.200 1.00 0
0.200 0.00 0
0.200 2.00 0
0.200 0.00 0
0.200 3.00 0
0.200 0.00 0
0.200 4.00 0
0.200 0.00 0
0.200 5.00 0
0.200 0.00 0
0.200 10.00 0
0.200 0.00 0
[END COURSE DATA]

```

Figure 67: Pro PC1 EBGTC Software

6.7. Electric Bicycle Road Acceleration Testing Method (EBRATM)

To determine the true acceleration performance of the electric bicycles tested, road testing is performed. This road testing is performed on a flat (~0% grade) paved area located near the UVic Engineering Lab Wing parking lot. The testing takes place with a 167 lbm test rider. The rider's mass is measured using a digital strain gauge scale before each test to insure a consistent rider mass. Mass is added or removed from the rider's backpack until 167 lbm is measured; this mass includes a helmet, and light clothing. The testing is very simple and does not require expensive sophisticated equipment. The only test equipment is a stopwatch and a bicycle computer. The electric bicycles are all tested on dry pavement, during sunny days. There is very little wind present during testing.

6.7.1. Test Equipment

The main testing equipment consists of a stopwatch and a low cost bicycle computer.

Stopwatch

The stopwatch is attached to the bicycle handlebars so that it can be started and stopped easily with the rider's left hand. The stopwatch is started at the same time the electric bicycle throttle is engaged. The stopwatch is then stopped at a desired speed observed on the bicycle computer. The stopwatch time and speed are then immediately recorded prior to the next test. The large buttons and large spacing make for easy use when testing.



Figure 68: Road Test Stopwatch Mounted on Handlebar

Bicycle Computer

The bicycle computer used for road testing is a Cat Eye Enduro 2 [69] bicycle computer (Figure 69). This bicycle computer can give accurate speed readings for a bicycle by using a magnet mounted on the bicycle wheel and a magnetically activated reed switch attached to the front fork leg (Figure 70). The Cat Eye Enduro 2 computer speed reading is accurate to one decimal place. This bicycle computer can be purchased at any bicycle store for ~\$30 CND. The method of calibrating the Cat Eye bicycle computer is to enter the tire circumference in centimeters. The tires used for road testing of the Currie electric bicycle and the AEBPS bicycle is a 26" Tioga City Slicker (Figure 60). This tire is 1.5 inches wide and is a very popular tire for mountain bike road use. This bicycle tire is measured to have a circumference of 198 cm when fully loaded (167 lbm rider on bicycle). This distance is measured by marking the point on the tire that is initially in contact with the ground, and then riding the bicycle until that point contacts the ground again (one complete revolution); this distance is then measured with a tape measure.



Figure 69: Cat Eye Bicycle Computer

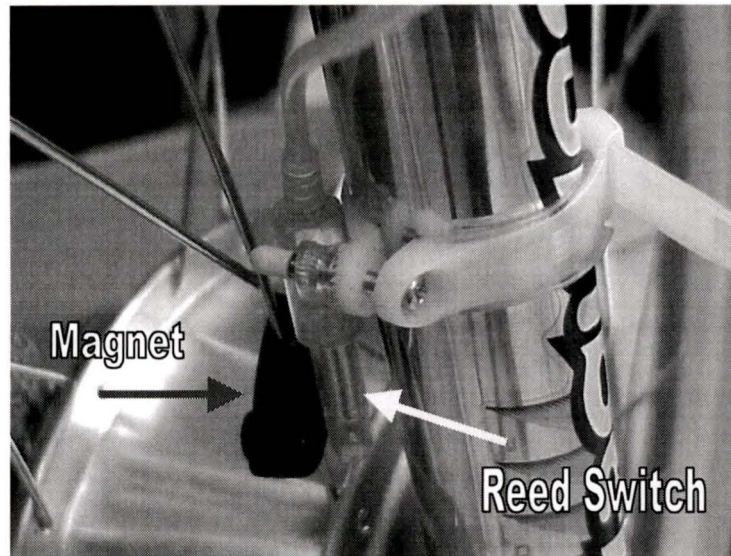


Figure 70: Bicycle Computer Reed Switch and Magnet

6.7.2. Test Method

The bicycle is tested from a stop to a desired velocity (km/h). The velocity is visually captured by the rider from the Cateye bicycle computer at the precise moment that the stopwatch is stopped. The time and the velocity are then recorded prior to the next acceleration test.

Battery Charging

The battery pack of all the bicycles tested is fully peak charged prior to testing.

Tire Conditioning

The tires are warmed up prior to acceleration testing by riding at a constant velocity (~15km/h) for five minutes using human power only. By using human power only, the full battery charge is saved for the testing; this is done in an attempt to achieve a constant tire rolling resistance during testing. The tires are not cleaned with rubbing alcohol prior to road testing.

Tire Pressure

The tire pressure for tests using the 26" Tioga City Slicker tires is 60 psi. Since the Suzhou Small Antelope has 24" diameter tires, the stock tires are used during testing. The

maximum recommended pressure of the Small Antelope's tires of 40 psi is used. These pressures are accurately measured using a Topeak digital tire pressure gauge (Figure 71) [70].



Figure 71: Topeak Digital Pressure Gauge [70]

6.8. Initial Electric Bicycle Acceleration Testing

Initial testing is completed using the Currie battery powered electric bicycle. This initial testing is completed for comparison purposes of road acceleration testing versus Computrainer dynamometer acceleration testing. It can be seen from the Figure 72 that during Computrainer testing at a 0% grade, the Currie electric bicycle can attain a velocity of ~27km/h in ~14 seconds. When road testing on a flat road the Currie electric bicycle does not accelerate as well as with the Computrainer. Note: the top speed is not attained due to a limited length 0% grade runway. The difference in acceleration performance is most likely due to the inertial force required to accelerate a bicycle and rider with a combined mass of over 100 kg, where on the Computrainer only a small roller needs to be rotated during acceleration. It appears that entering the mass of the rider and bicycle into the Pro PC1 software does not have a notable effect on the acceleration performance, only the top speed. Variables such as uneven pavement, small rocks, wind, temperature, and rider balance could also be contributing to these differences. It is for these reasons that the Computrainer acceleration testing results are not taken as being completely realistic, but can provide an excellent standardized comparison of all the electric bicycles tested. It is then determined that road acceleration tests can be performed to compare some actual performance aspects of the various electric bicycles tested, but are not compared to the Computrainer testing results.

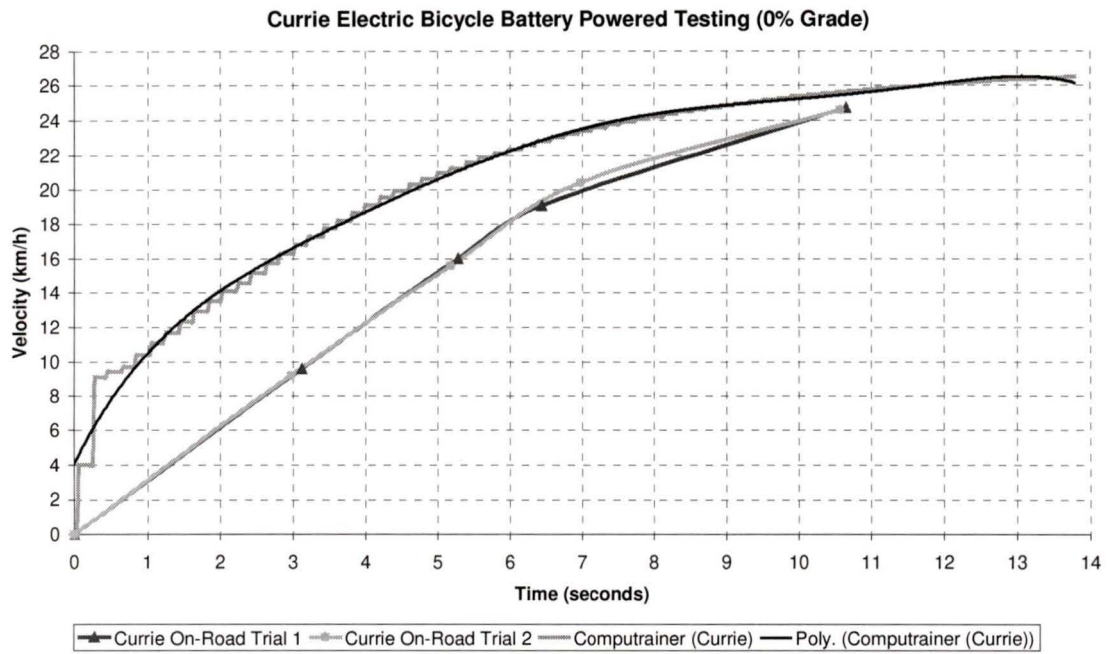


Figure 72: Initial Currie Electric Bicycle Acceleration Testing

CHAPTER 7 ELECTRIC BICYCLE STANDARD TEST CYCLE DEVELOPMENT AND TESTING RESULTS

This section explains the test development and the testing results from the three created types of electric bicycle tests, the Electric Bicycle Velocity Testing Cycles (EBVTC), the Electric Bicycle Grade Testing Cycle, and the Electric Bicycle Road Acceleration Testing Method (EBRATM).

7.1. Electric Bicycle Velocity Testing Cycles (EBVTC)

Three electric bicycle specific velocity tests are created. These tests are tested using the Currie Cycles electric bicycle for proof of concept purposes. The tests are: the European Elementary Urban Electric Bicycle Testing Cycle (EEUEBTC), the Taipei Electric Bicycle Testing Cycle (TEBTC), and the New York Electric Bicycle Testing Cycle (NYEBTC).

7.1.1. European Elementary Urban Electric Bicycle Testing Cycle (EEUEBTC)

The European Elementary Urban Electric Bicycle Testing Cycle (EEUEBTC) is created based on the Elementary Urban Cycle (EUC) for motor vehicles in Europe [71] (Figure 73). The EUC is created by the Economic Commission for Europe Dynamometer Operating Cycles (ECEDOC). This test is very quick, only taking 195 seconds. The EUC test is also very simple, with three gradually increasing velocity requirements.

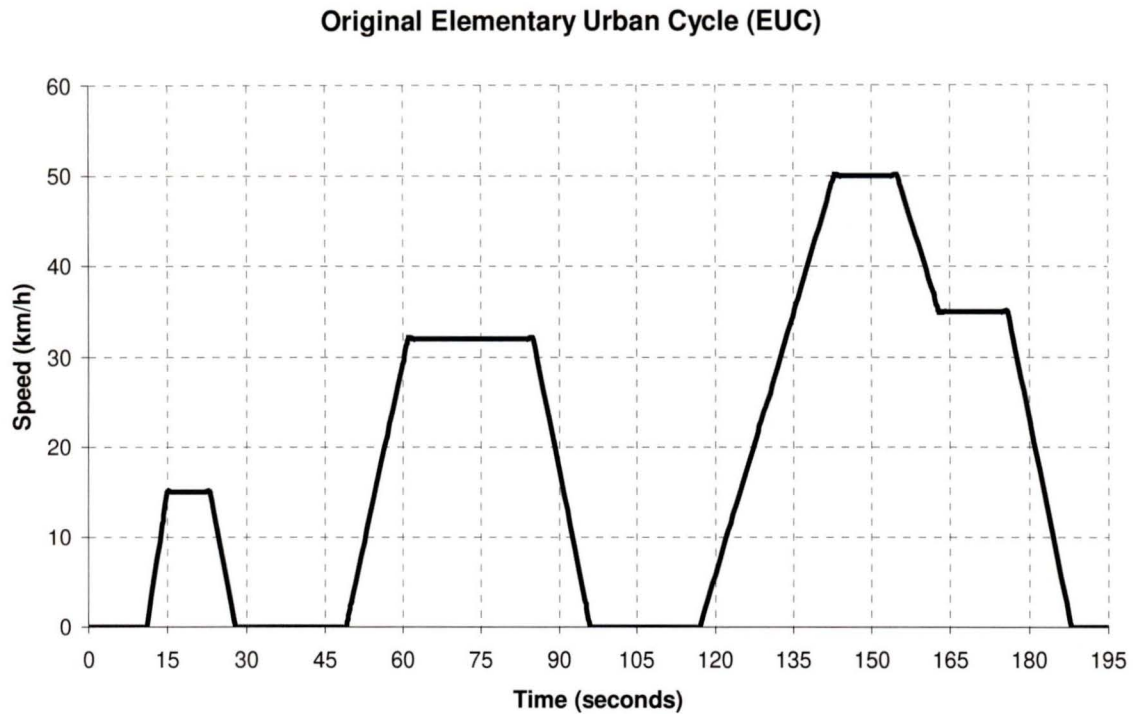


Figure 73: Original Elementary Urban Cycle [71]

The EEUEBTC is approximately half the speed of the original EUC, but keeps the same time duration (Figure 74). The time duration remains the same as the original EUC, assuming the electric bicycle would have to accelerate with traffic. In addition to halving the speed, section 11 is lowered to 22.3 km/h to allow electric bicycles with a lower top speed to be tested; this is done because some electric bicycles cannot reach 25 km/h (half the original EUC). The original EUC average velocity is 18.26 km/h, while the EEUEBTC average speed is 8.94 km/h.

Elementary Urban Cycle Modified for Electric Bicycle Testing

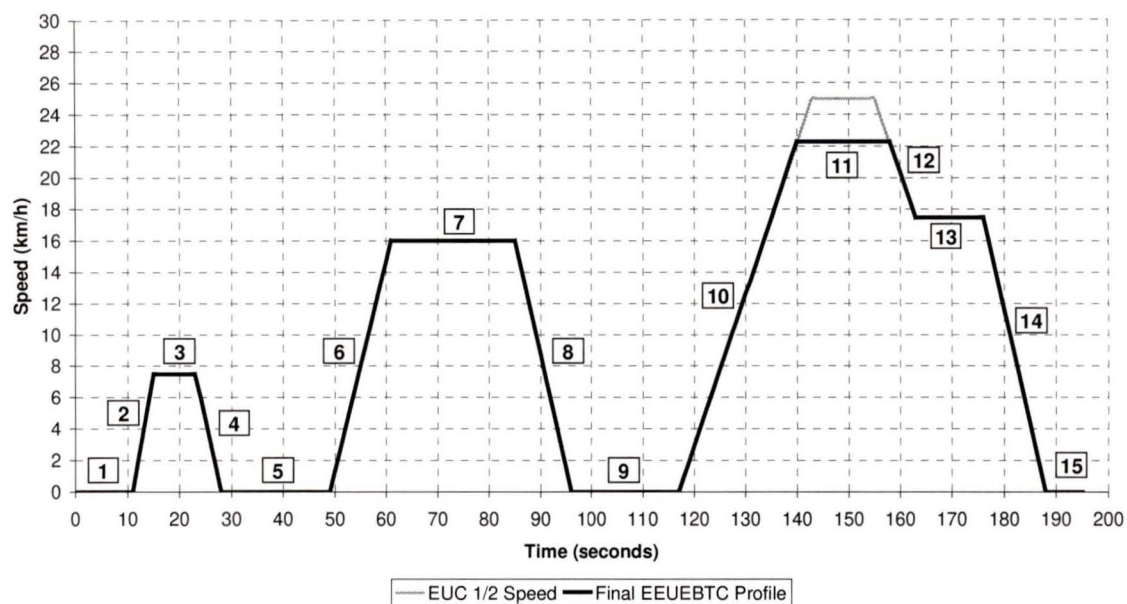


Figure 74: European Elementary Urban Electric Bicycle Testing Cycle (EEUEBTC)

Figure 75 shows the actual test data of the Currie electric bicycle. The velocity match is very good. The average velocity for the Currie electric bicycle is 8.82 km/h, the average power is 39.64 Watts, and the maximum power is found to be 224 Watts. The difference in average velocity between the EEUEBTC profile and the Currie electric bicycle velocity profile is 0.12 km/h.

European Elementary Urban Electric Bicycle Testing Cycle (Currie Test Results)

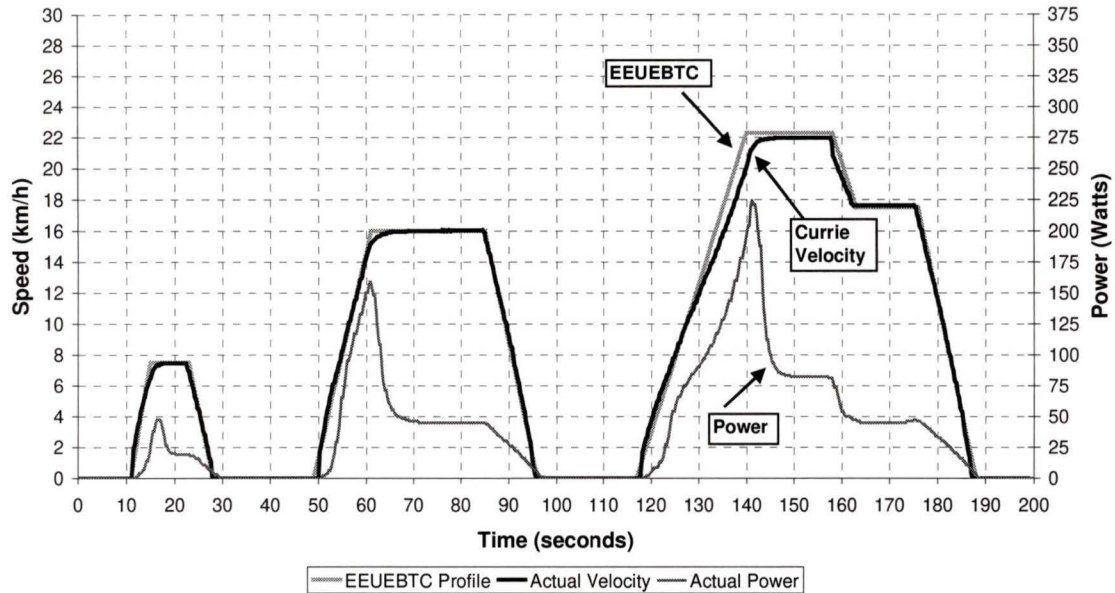


Figure 75: Currie Electric Bicycle EEUEBTC Test Results

7.1.2. Taipei Electric Bicycle Testing Cycle (TEBTC)

The Taipei Motorcycle Driving Cycle (TMDC) originates from the Institute of Traffic and Transportation at the National Chiao Tung University in Taiwan. The velocity profile of the cycle is generated from an instrumented “chase vehicle” that followed a scooter along a specific road route [72]. The Taipei Motorcycle Driving Cycle has an average speed of 19.32 km/h and a duration of 951 seconds (Figure 76).

Taipei Motorcycle Driving Cycle (TMDC)

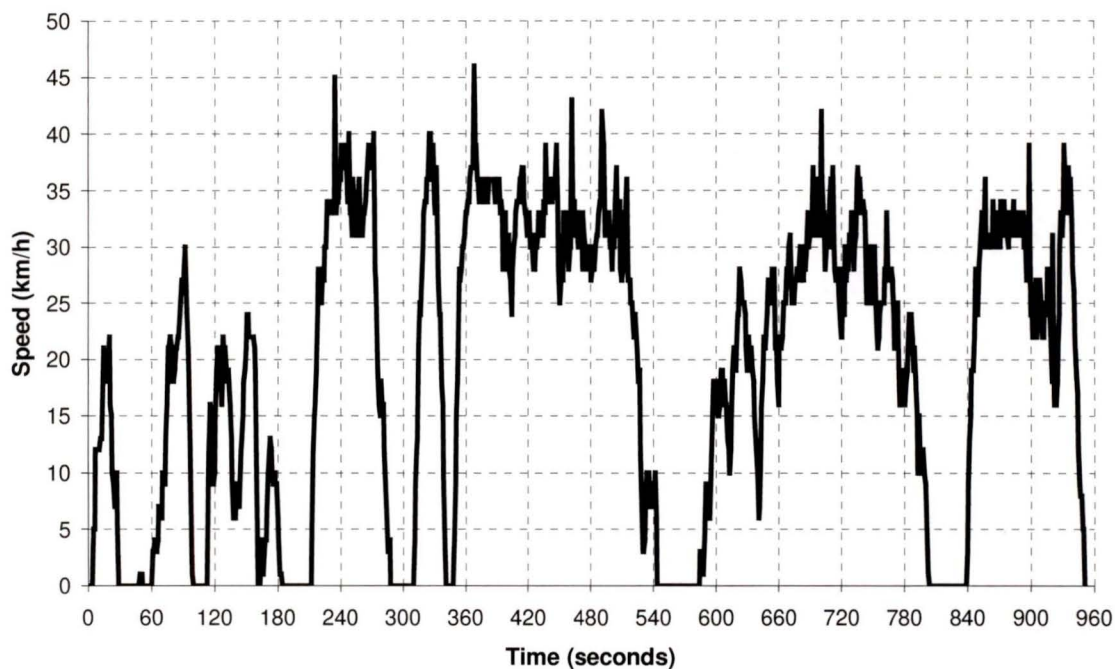


Figure 76: Original Taipei Motorcycle Driving Cycle

The Taipei Electric Bicycle Testing Cycle (TEBTC) is based on the TMDC; it is approximately half the speed of the original cycle, but retains the same time duration. The time duration remains the same as the original TMDC, assuming the electric bicycle would have to accelerate with traffic. Figure 77 shows the electric bicycle test cycle (dark line) as a simplified representation of the half speed TMDC. The exact profile can not be replicated using the limited EEPROM of the BS2 microcontroller, and since this is an original electric bicycle test, it is not necessary to be exactly like the motorcycle test.

The TEBTC has a top speed of 20 km/h, a time duration of 951 seconds, and an average speed of 9.48 km/h. The duration of the TEBTC is quite long (~16 minutes) and displays the characteristics of the electric bicycle during long duration constant velocities, as well as driving conditions that do not require fast acceleration.

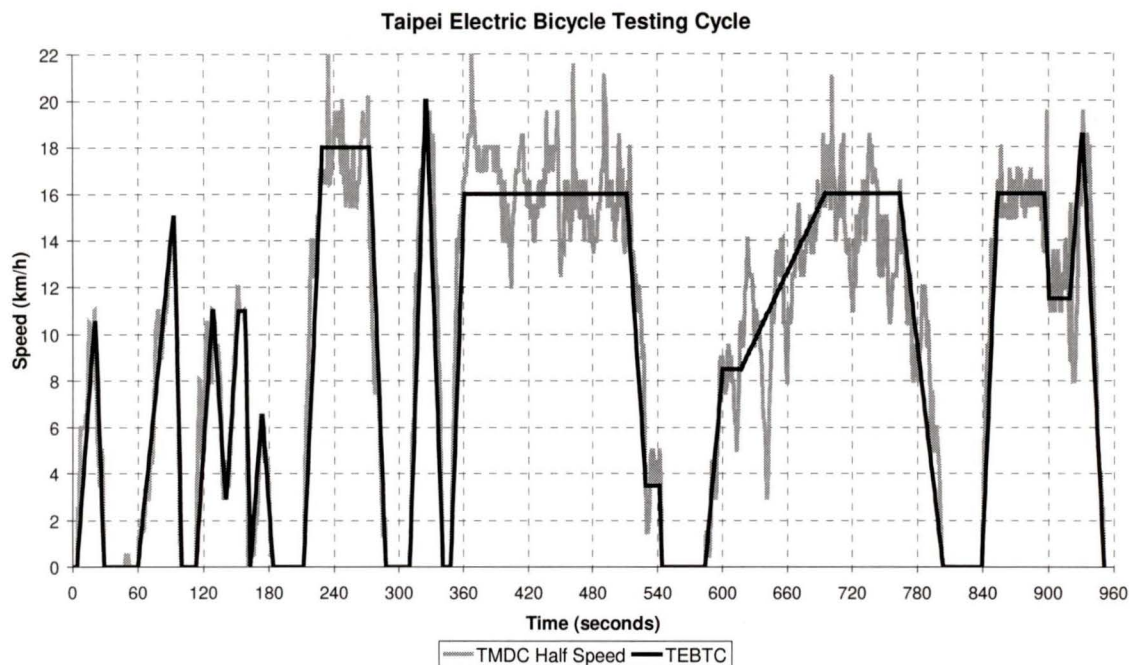


Figure 77: Taipei Electric Bicycle Testing Cycle (TEBTC)

Actual testing with the Currie electric bicycle gives good results. The electric bicycle follows the velocity profile almost exactly (Figure 78). The average speed is found to be 9.64 km/h, the average power to be 34.22 Watts, and the maximum power output is found to be 226 Watts (at the 325 second mark). The difference in average velocities of the Currie electric bicycle test and the TEBTC velocity profile is only 0.15 km/h.

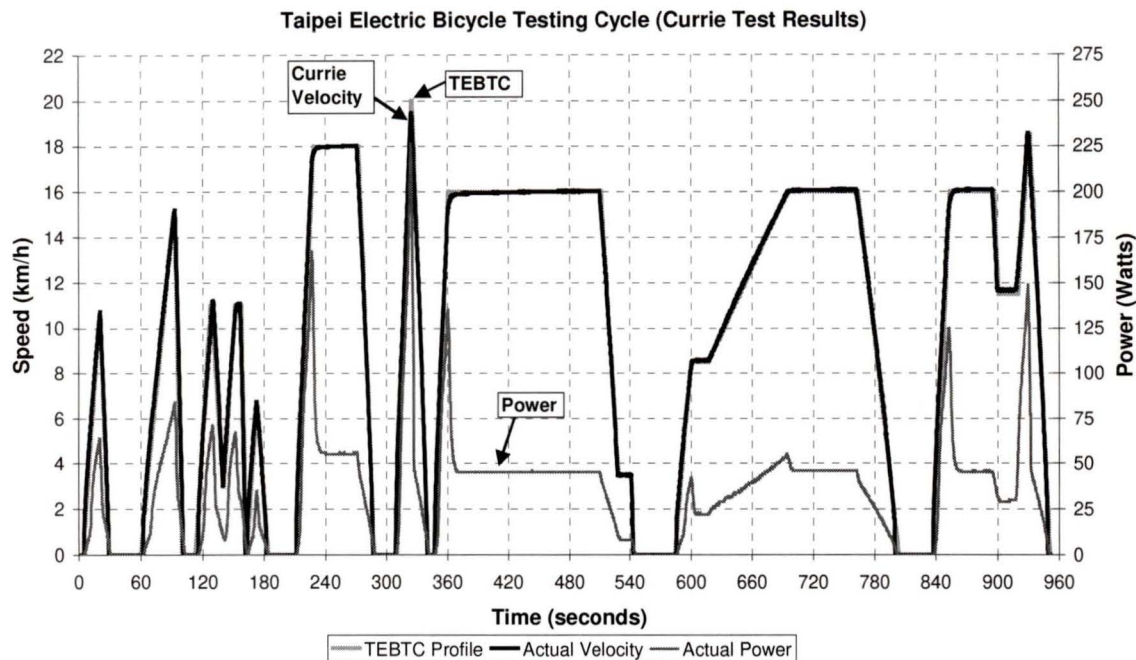


Figure 78: Currie Electric Bicycle TEBTC Results

7.1.3. New York Electric Bicycle Testing Cycle (NYEBTC)

The New York City Cycle (NYCC) (Figure 79) is designed to simulate automobile driving conditions in a large city. The NYCC simulates traffic conditions that require quick acceleration, and very few areas where the vehicle's velocity can remain high for any large amount of time. This test cycle is created by the United States Environmental Protection Agency (USEPA) [71].

The NYCC has an average speed of 7.09 mph (11.41 km/h), and a maximum speed of 27.7 mph (44.58 km/h). The duration of the NYCC test is 598 seconds.

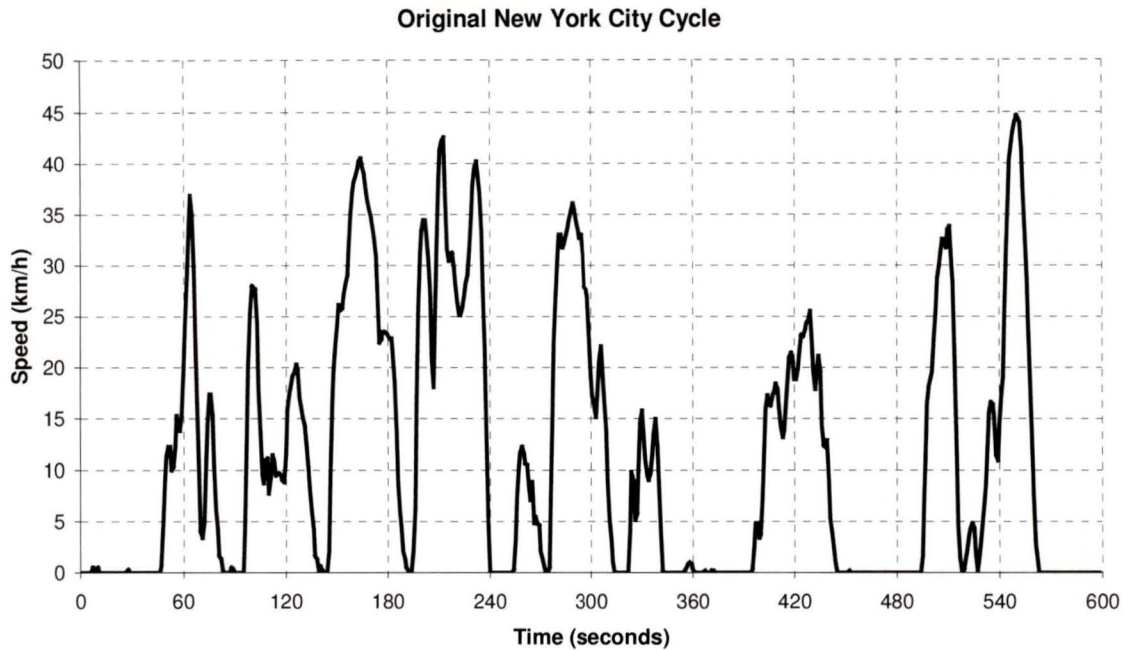


Figure 79: Original New York City Testing Cycle [71]

The New York Electric Bicycle Testing Cycle (NYEBTC) (Figure 80) is based approximately on the NYCC. The NYEBTC is based on a NYCC at half speed, and then the velocity profile is simplified (Figure 80, dark line) so that the PBASIC program can fit into the BS2 microcontroller EEPROM. The average speed of the NYEBTC is 5.66 km/h, and has a maximum velocity of 22.5 km/h. The time duration of the NYEBTC remains the same as the NYCC at 598 seconds. The time duration remains the same as the original NYCC, assuming the electric bicycle would have to accelerate with traffic.

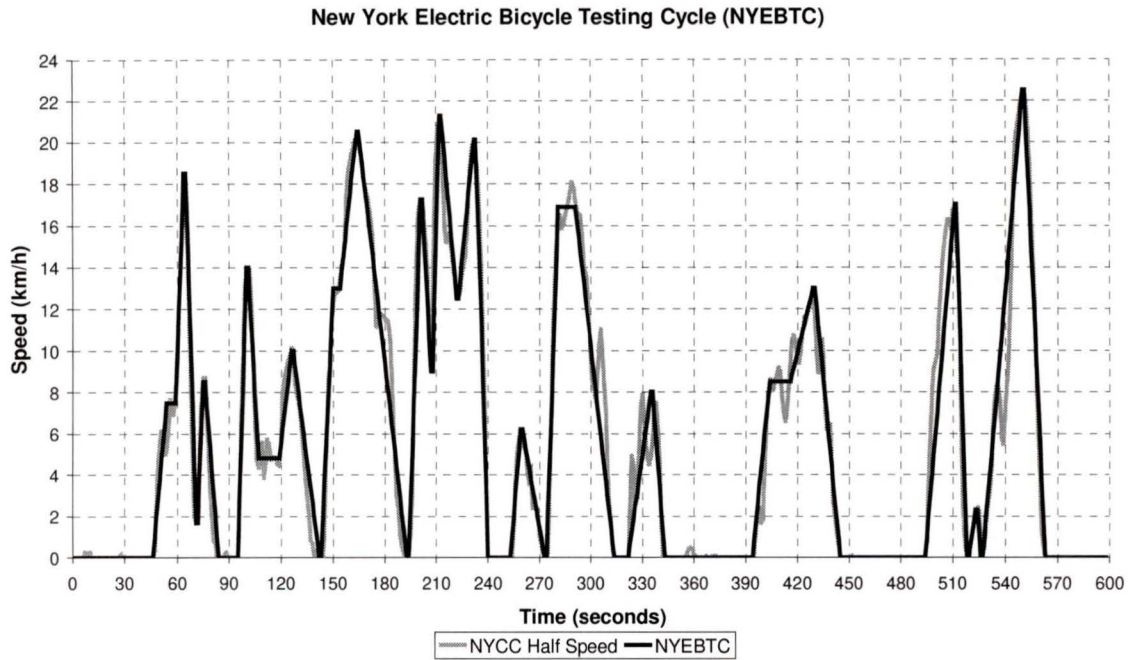


Figure 80: New York Electric Bicycle Testing Cycle (NYEBTC)

Testing the Currie electric bicycle with the NYEBTC (Figure 81) gives an average velocity of 5.63 km/h, an average power of 34.39 Watts, and a maximum power output of 393 Watts (at the 213 second mark). The Currie electric bicycle follows the velocity profile very closely, with a difference in average velocity from the NYEBTC of only 0.07 km/h.

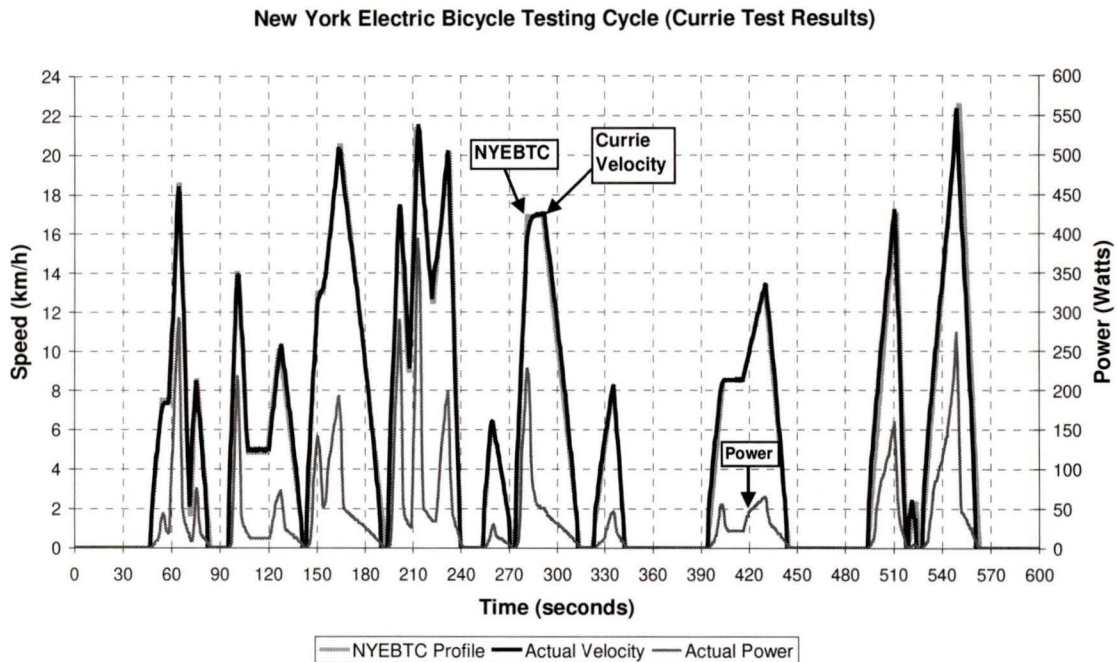


Figure 81: Currie Electric Bicycle NYEBTC Results

7.2. Electric Bicycle Grade Testing Cycle (EBGTC)

The electric bicycle grade test cycle (EBGTC) is performed on two electric bicycles, the Currie Cycles electric bicycle, and the Suzhou Small Antelope electric bicycle for comparison purposes. The EBGTC is found to reveal useful electric bicycle comparison performance data in a small amount of time (less than 30 minutes for a complete test, including set-up).

7.2.1. Currie Electric Bicycle Grade Test

The Currie electric bicycle is one of the most powerful electric bicycles on the market today (400W cont. 900W max.). Figure 82 shows the Currie electric bicycle mounted in the RacerMate Computrainer. The EBGTC applied to the Currie electric bicycle (Figure 83) shows that it can reach a maximum speed of 27.55 km/h when operated on a 0% grade, and that it can handle a large 10% grade. Figure 83 also displays the equilibrium velocity and power at each grade level.



Figure 82: Currie Electric Bicycle Attached To Computrainer

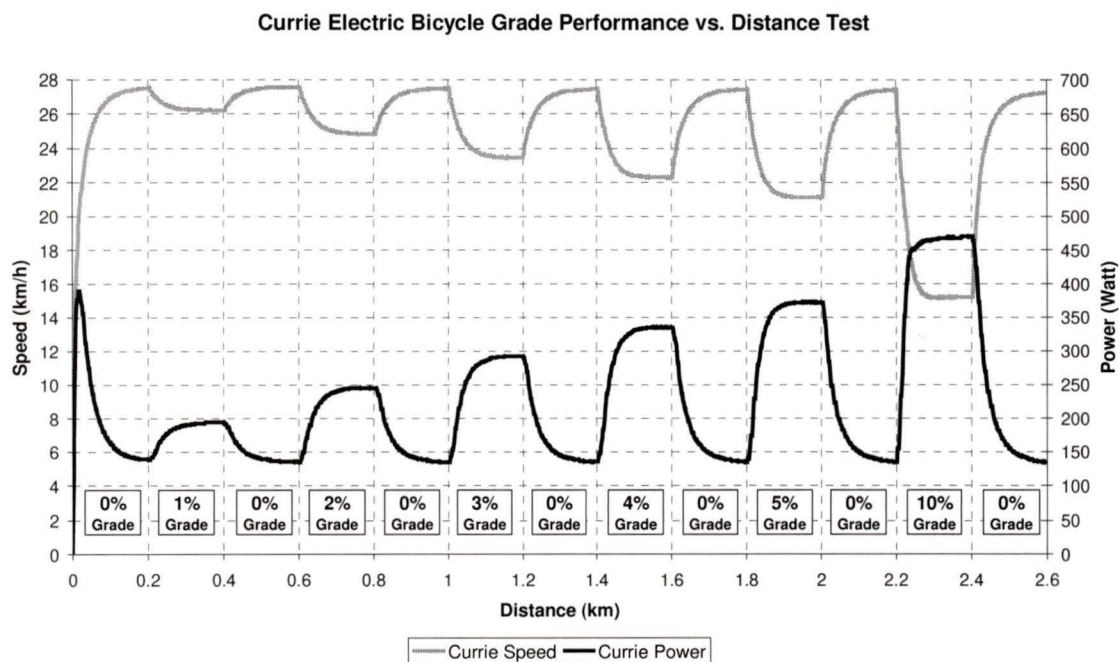


Figure 83: Electric Bicycle Grade Testing Cycle (EBGTC)

The data in Table 19 shows the extreme speed and power at equilibrium (zero acceleration) at each grade level (for example, lowest power at 0% grade, highest speed at 0% grade, highest power at 1% grade, lowest speed at 1% grade). When the electric bicycle is traveling on a flat surface, the maximum speed is found to be 27.55 km/h, with a

constant power output of 135W. The speed at a 10% grade is 15.13 km/h with a power output of 470W. Since this bicycle has a manufacturer's claimed maximum power output of 900W, it should be able to handle grades higher than 10% without overheating the motor controller.

Table 19: Currie Electric Bicycle Performance vs. Grade

Grade (%)	Speed (km/h)	Power (W)
0	27.55	135
1	26.20	194
2	24.78	246
3	23.46	292
4	22.27	336
5	21.08	373
10	15.13	470

Figure 84 shows the performance of the electric bicycle (Speed and Power) versus % Grade. The speed is almost linear, while the shape of the power output is slightly logarithmic. With this graph, the approximate speed and power of intermediate grades can be determined, for example, at a 6% grade the electric bicycle speed would be approximately 20 km/h, and the power output would be ~397W.

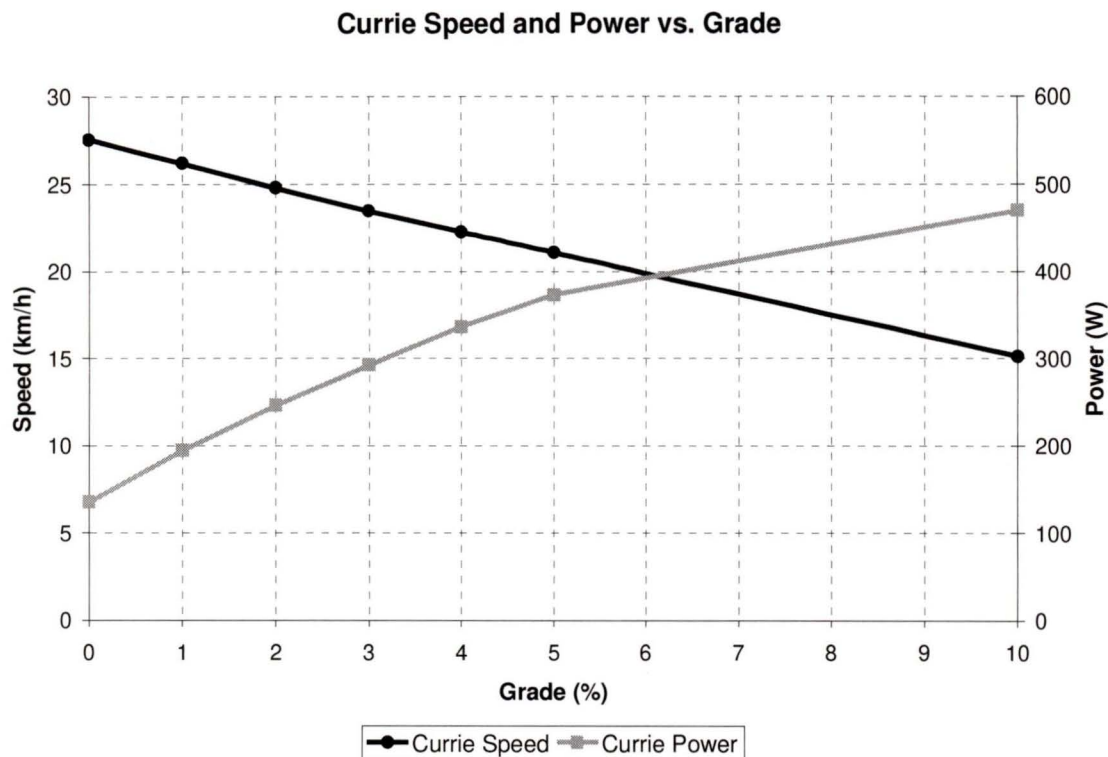


Figure 84: Currie Performance vs. Grade

Theoretical Power Output

Table 20 and Figure 85 show that the Computrainer uses a different drag coefficient, C_D , and frontal area, A_f , than normally assumed for a bicycle and rider as in Section 4.3.3. To match the Computrainer results, a C_D of 0.9 and a frontal area of 0.29 m^2 are used. This coincides very closely with the values given for road cyclists in full skintight clothing and aerodynamic body positioning ($C_D = 0.9$, $A_f = 0.33 \text{ m}^2$) [40]. The observation that the Computrainer is probably using these low values for the aerodynamic loading is not surprising since it is a trainer designed specifically for professional road bicyclists. Figure 85 shows the modified model matches the actual power output vs. % grade data very closely. Note: A mass of 104 kg is used for the total mass during modeling of the Currie electric bicycle plus rider (167 lbm rider + 62 lbm bicycle). Also, all values shown in Table 20 are based on on-road power requirements with a coefficient of rolling resistance, C_{rr} , of 0.008.

Table 20: Currie Electric Bicycle Theoretical Power vs. Grade

Grade (%)	Speed (km/h)	Power (W)	Theoretical Power (W) ($C_d = 1.2 A_f = 0.5$)	Theoretical Power (W) ($C_d = 0.9 A_f = 0.29$)
0	27.55	135	223.85	132.67
1	26.20	194	272.42	194.01
2	24.78	246	314.09	247.72
3	23.46	292	352.26	295.94
4	22.27	336	388.01	339.83
5	21.08	373	418.41	377.56
10	15.13	470	487.44	472.34

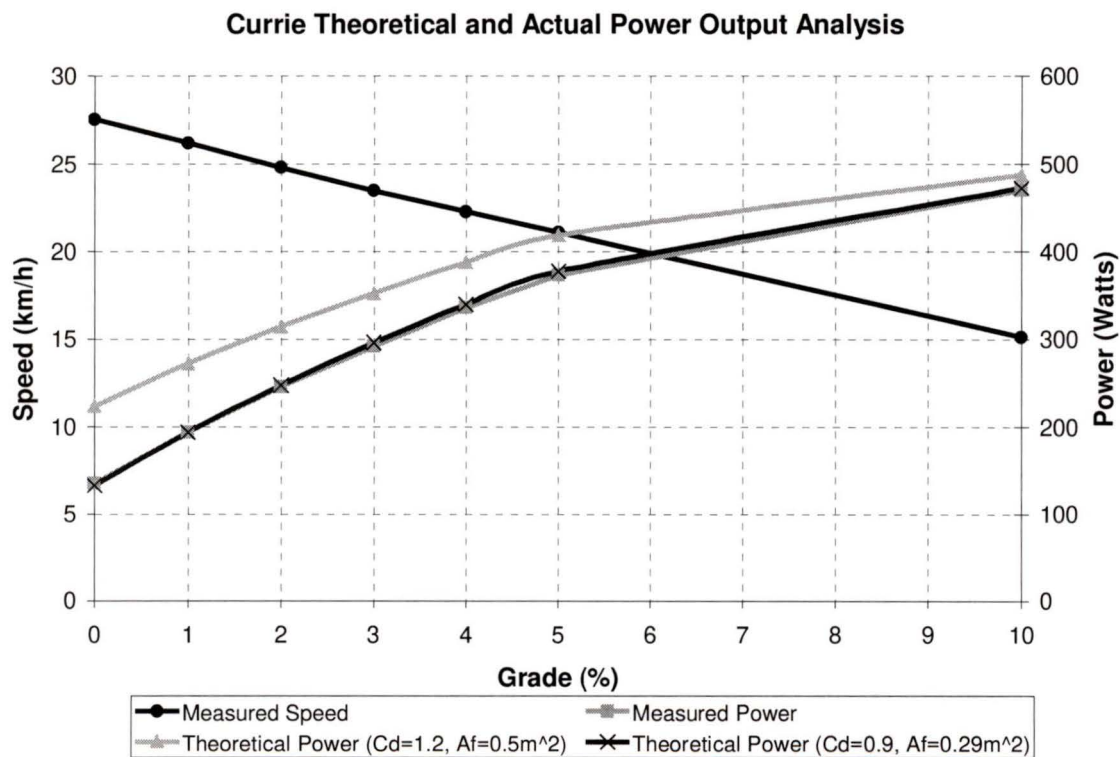
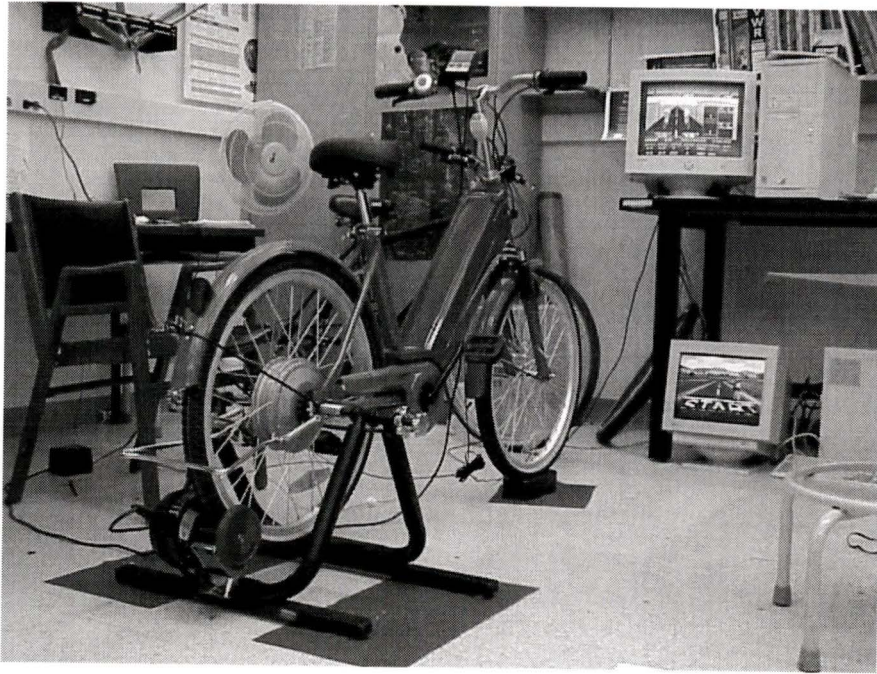


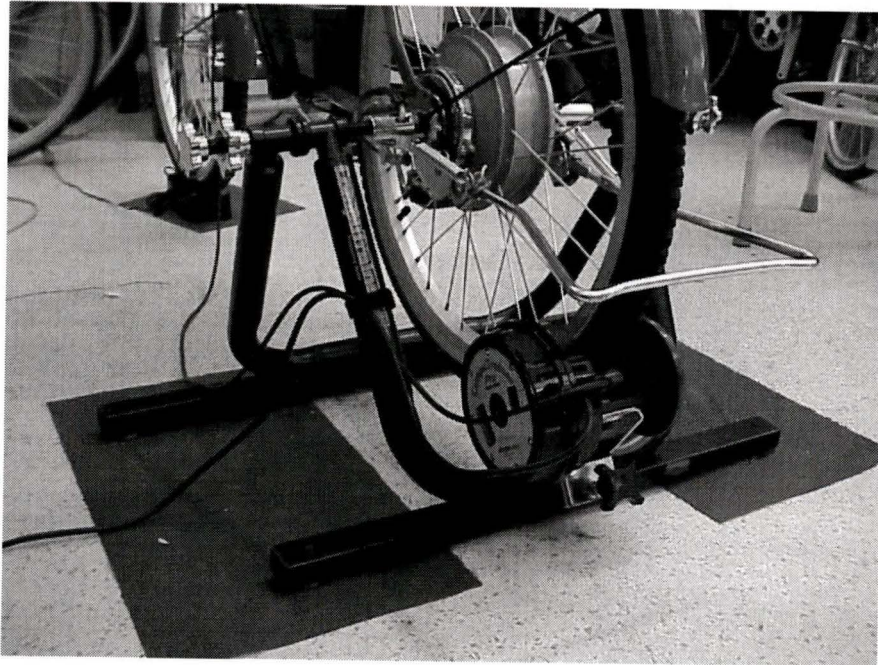
Figure 85: Currie Electric Bicycle Theoretical Power vs. Grade

7.2.2. Suzhou Small Antelope Electric Bicycle

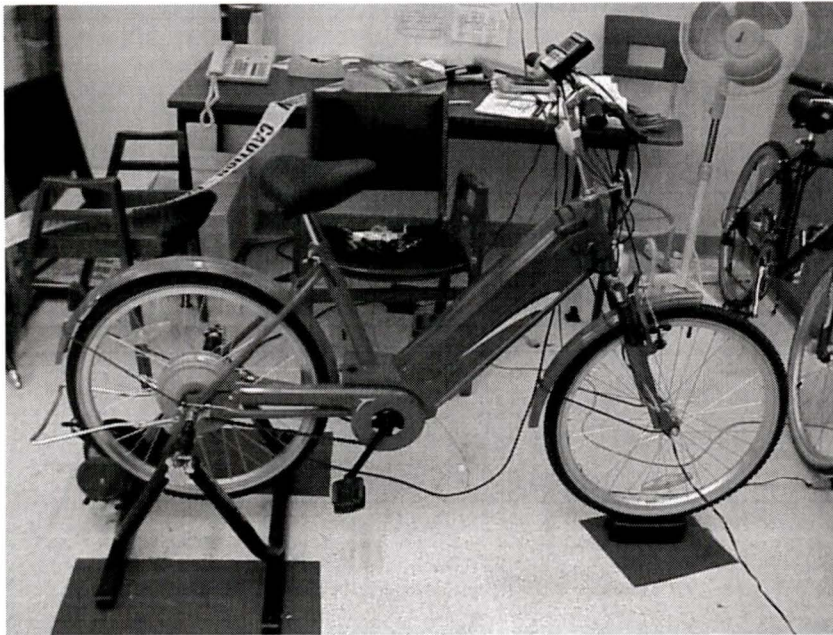
Figure 86 shows the Suzhou Small Antelope during grade testing using the Computrainer.



(a)



(b)



(c)

Figure 86: Suzhou Small Antelope Grade Testing

Figure 87 shows that the Small Antelope is not capable of climbing a 10% grade; the electric bicycle's motor controller shuts down operation multiple times during the 10% grade section.

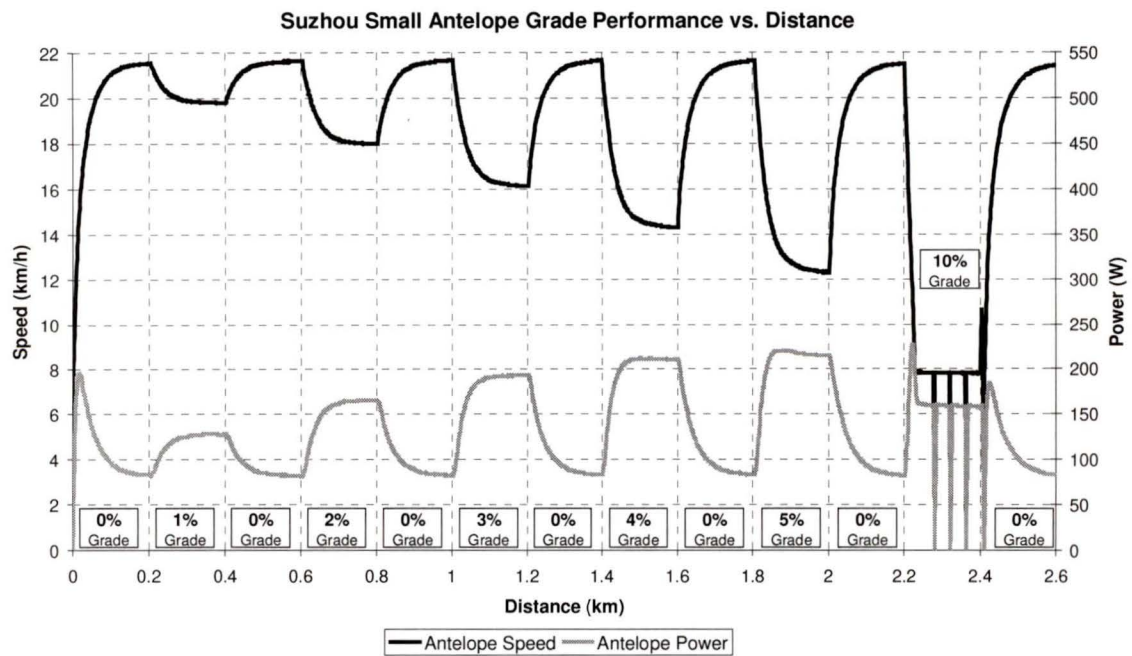


Figure 87: Suzhou Small Antelope Performance vs. Distance

Table 21 shows that the top speed of the Small Antelope at a 0% grade is 21.66 km/h with a power output of 81W. At a 5% grade the speed is 12.30 km/h at a power output of 221W.

Table 21: Suzhou Small Antelope Performance vs. Grade

Grade (%)	Speed (km/h)	Power (Watts)
0	21.66	81
1	19.79	128
2	17.99	165
3	16.16	193
4	14.32	212
5	12.30	221

Figure 88 shows the Small Antelope performance versus the percent grade. The speed is linear, while the power curve is shaped slightly logarithmically.

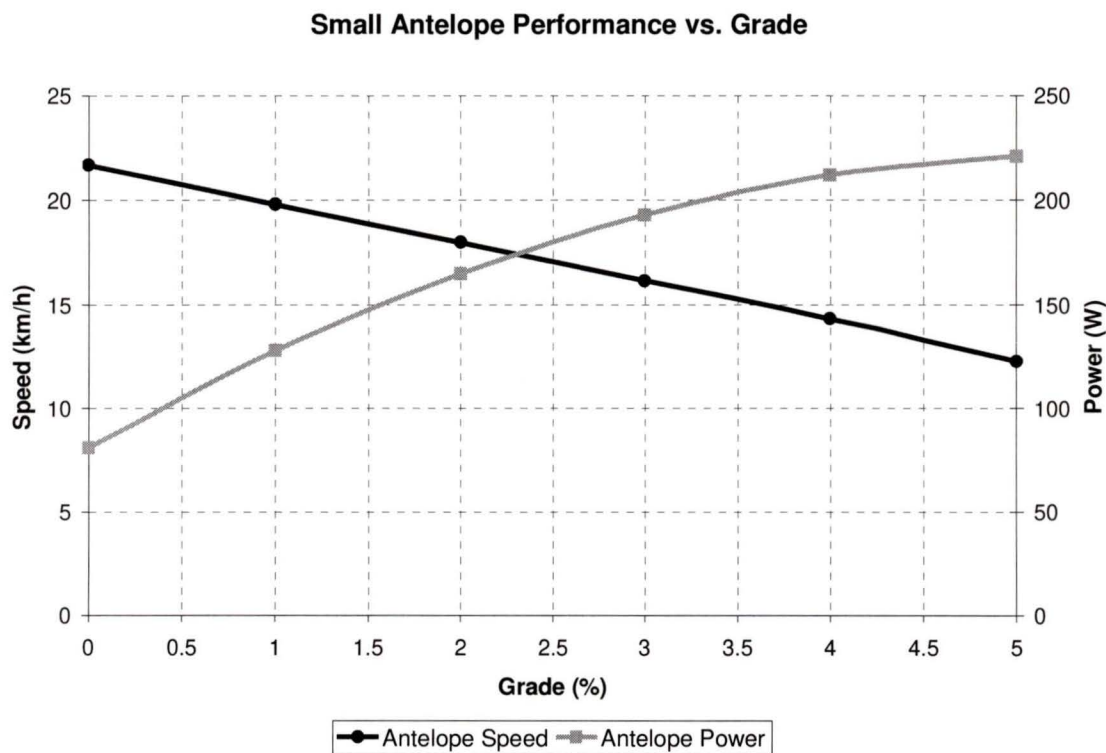


Figure 88: Suzhou Small Antelope Performance vs. Grade

7.2.3. Electric Bicycle Grade Testing Cycle Performance Comparison

The EBGTC allows for easy and quick comparison of the main performance aspects of electric bicycles, including acceleration.

Since the Currie electric bicycle and the Small Antelope electric bicycle are very different in terms of performance output, a comparison is performed to display the differences obtained with the developed EBGTC test.

Figure 89 shows the performance (speed and power) of the Currie electric bicycle and Small Antelope versus time during acceleration from 0 km/h to maximum speed at a 0% grade (This is the first section of the EBGTC). It can be observed in Figure 89 that the Small Antelope has a much lower power consumption than the Currie electric bicycle, indicating that this bicycle could have a very high range as claimed by the manufacturer (60 km). It is also important to note that the maximum power during acceleration occurs at 4.55 seconds and a power output of 390W for the Currie electric bicycle, and at 5.76 seconds and 195 Watts for the Small Antelope electric bicycle.

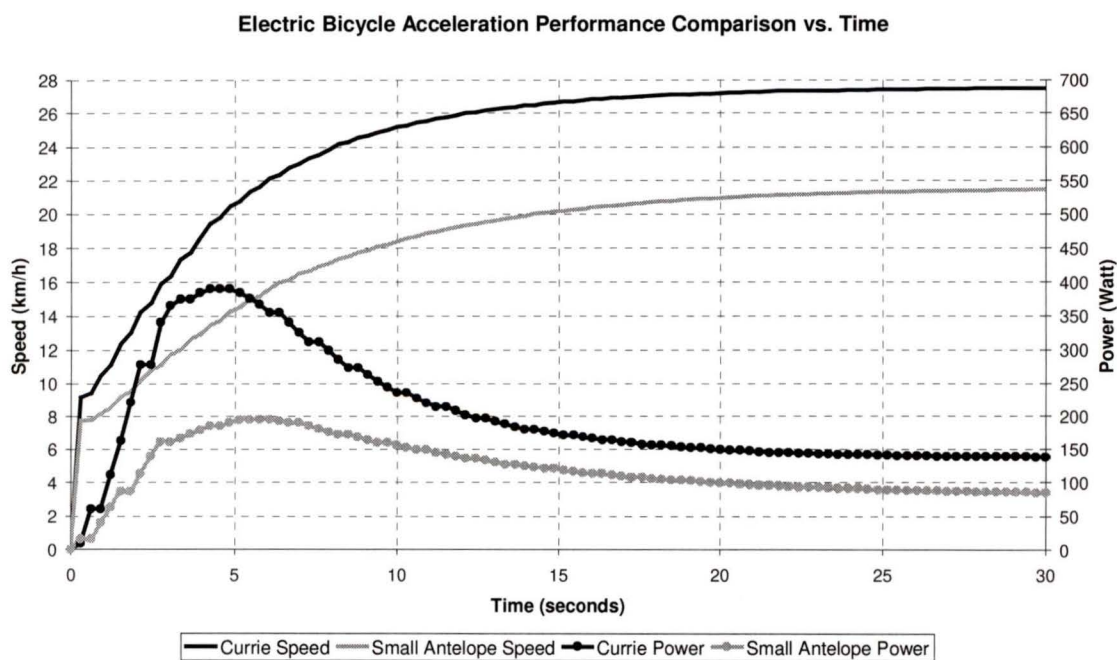


Figure 89: Electric Bicycle Acceleration Speed vs. Time Comparison

It can be seen in Table 22 that the Currie electric bicycle accelerates much faster than the Small Antelope.

Table 22: Electric Bicycle Acceleration Comparison

Acceleration (km/h)	Time (seconds)	
	Currie	Small Antelope
0 – 10	0.776	2.041
0 – 12	1.427	3.291
0 – 14	2.064	4.700
0 – 16	2.797	6.429
0 – 18	3.721	9.272
0 – 20	4.647	14.194

Figure 90 shows the speed of the two electric bicycles versus the distance traveled. The Currie electric bicycle is observed to have a higher amount of velocity compared to the Small Antelope electric bicycle at all grades. Figure 91 shows the power output of the two electric bicycles versus the distance traveled. It can be seen that the Currie electric bicycle has a much greater amount of power output capability compared to the Small Antelope electric bicycle. The Small Antelope electric bicycle is observed to be more suited to small percent grade conditions where range is of utmost importance, since it does not use a large amount of power.

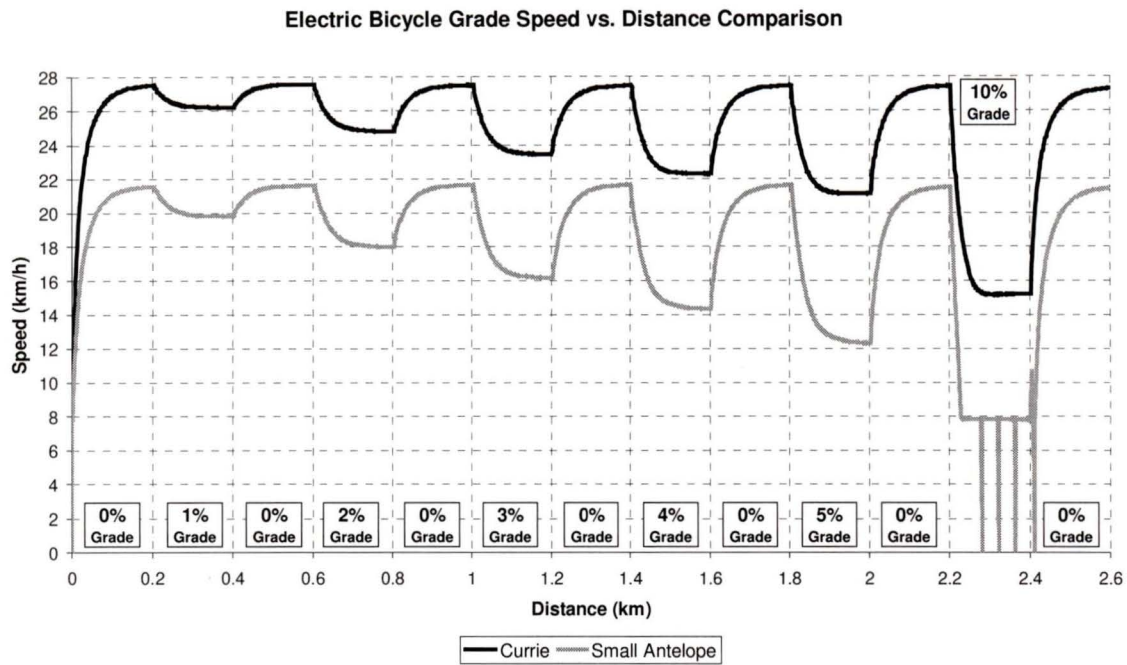


Figure 90: Electric Bicycle Speed vs. Distance Comparison

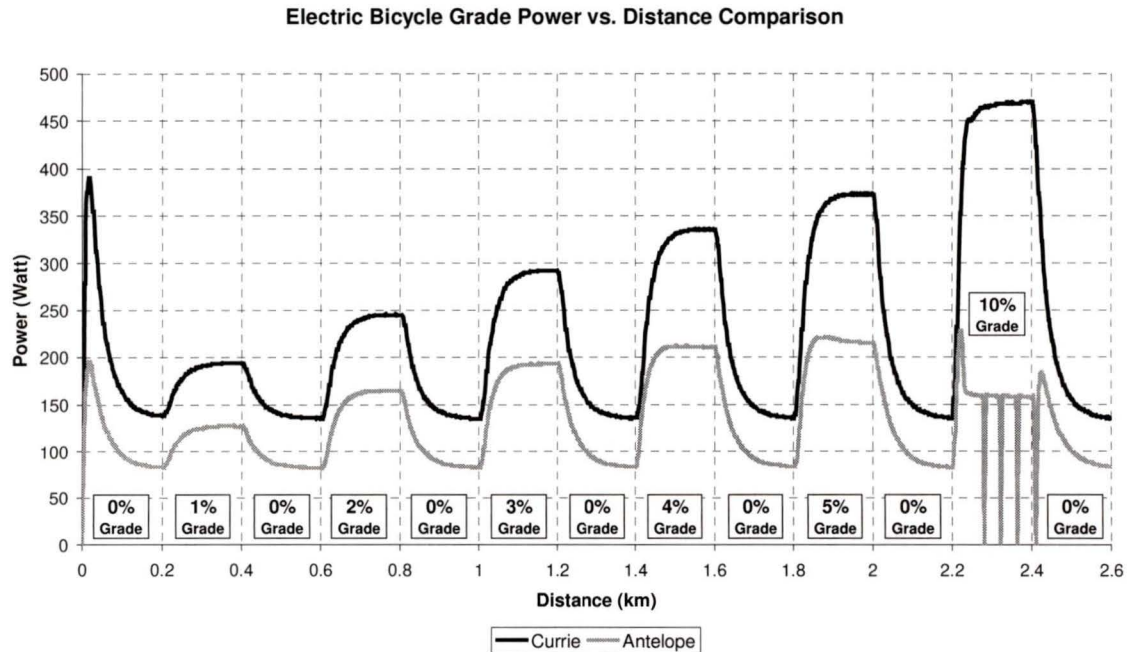


Figure 91: Electric Bicycle Power vs. Distance Comparison

7.2.4. Repeatability

The EBGTC has a very good repeatability. Figure 92 shows the speed versus distance of the Small Antelope electric bicycle on November 18, 2001 and November 7, 2001. Figure 93 shows the power versus distance of the Small Antelope electric bicycle on November 18, 2001 and November 7, 2001. The data for both tests is almost identical, however, it can be observed that on the November 7th test, the Small Antelope shut down at the end of the 5% grade section (at the 2 km mark). The Small Antelope did not shut down until the 10% grade section during the November 18th test. This indicates that a 5% grade is likely the limit of the Small Antelope electric bicycle. It is also likely that the Small Antelope electric bicycle is almost ready to shut down at the end of the 5% grade section during the November 18th test; this can be seen by observing the downward slope of the power curve during the 5% grade section in Figure 93. The downward sloping power curve is obviously a sign that the electric bicycle is struggling to maintain the given load.

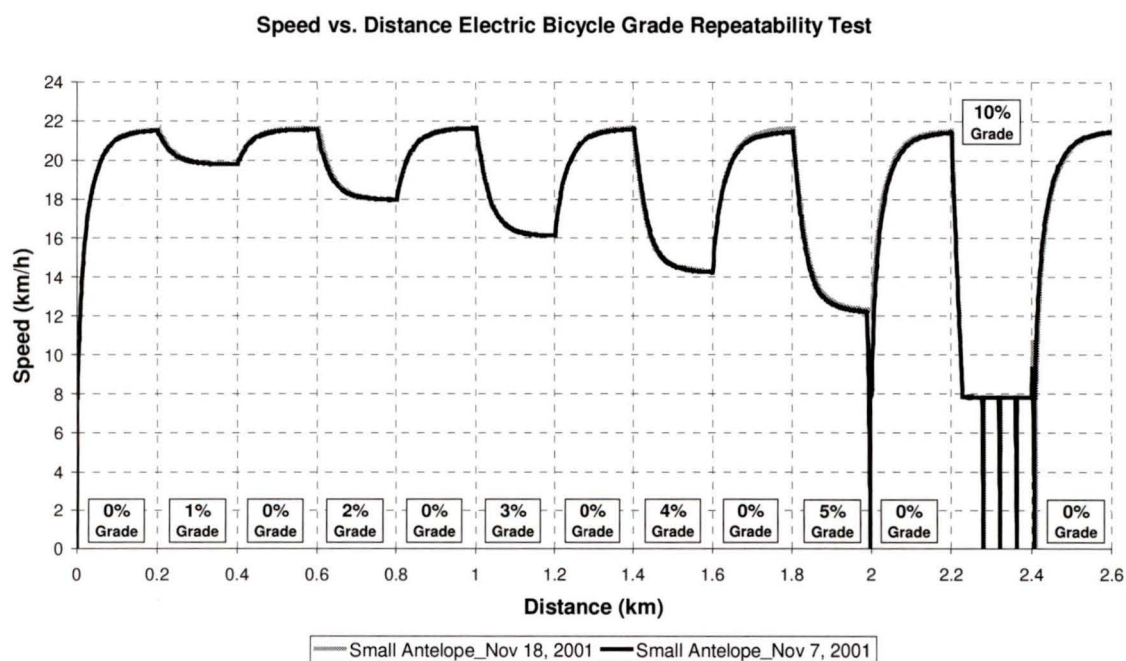


Figure 92: Computrainer Repeatability; Speed vs. Distance

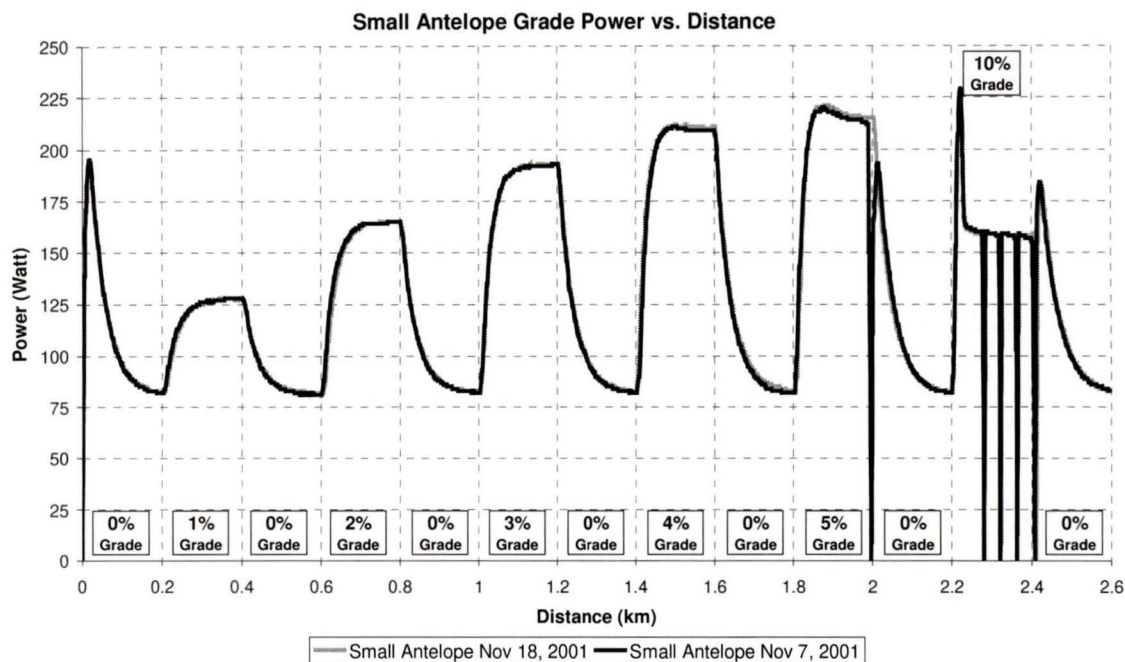


Figure 93: Computrainer Repeatability; Power vs. Distance

7.3. Electric Bicycle Road Acceleration Testing Method (EBRATM)

Results

The electric bicycle road acceleration testing method (EBRATM) takes place with a 167 lbm rider. The road conditions are dry, and at an approximately 0% grade (flat). The road tests are performed on the Currie, Small Antelope, and the prototype AEBPS electric bicycles. The top speed of each electric bicycle is also determined during testing on a flat road (~0% grade).

7.3.1. Currie Electric Bicycle Road Acceleration Testing

The Currie electric bicycle is tested two times to observe the repeatability of the EBRATM (Figure 94). The repeatability of the test is very good with minimal difference between the two tests. The top speed of the Currie electric bicycle is observed to be 25.7 km/h, which is 1.85 km/h less than the top speed observed with the EBGTC (27.55 km/h) at 0% grade. It should be noted that the manufacturer states that the Currie electric

bicycle is capable of a maximum speed of 18 mph (29 km/h). This speed is not observed during any of the testing.

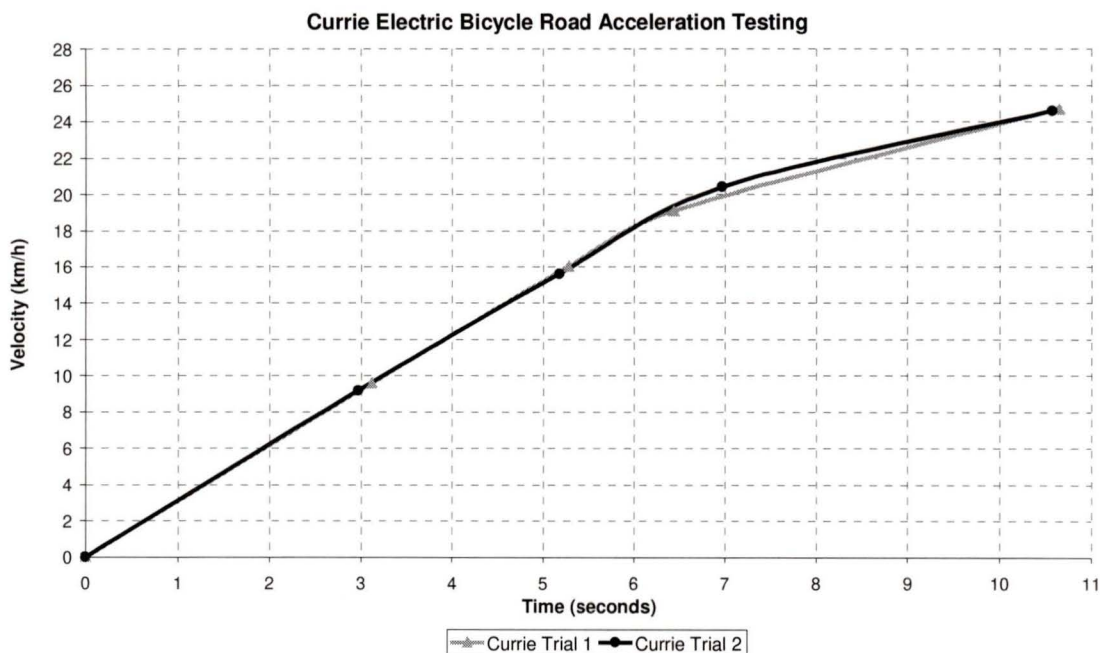


Figure 94: Currie Electric Bicycle Road Test Results

7.3.2. Suzhou Small Antelope Road Acceleration Testing

The Small Antelope electric bicycle has a very low power output, and it is very evident during road acceleration testing. The Small Antelope seems to be designed strictly for flat roads; it experiences a lot of trouble going up any grade. The acceleration is also poor; the Small Antelope accelerates from zero to 10 km/h in 5.25 seconds (Figure 95). The top speed of the Small Antelope electric bicycle is observed to be 20.9 km/h, which is 0.76 km/h less than the top speed observed with the EBGTC (21.66 km/h) at a 0% grade.

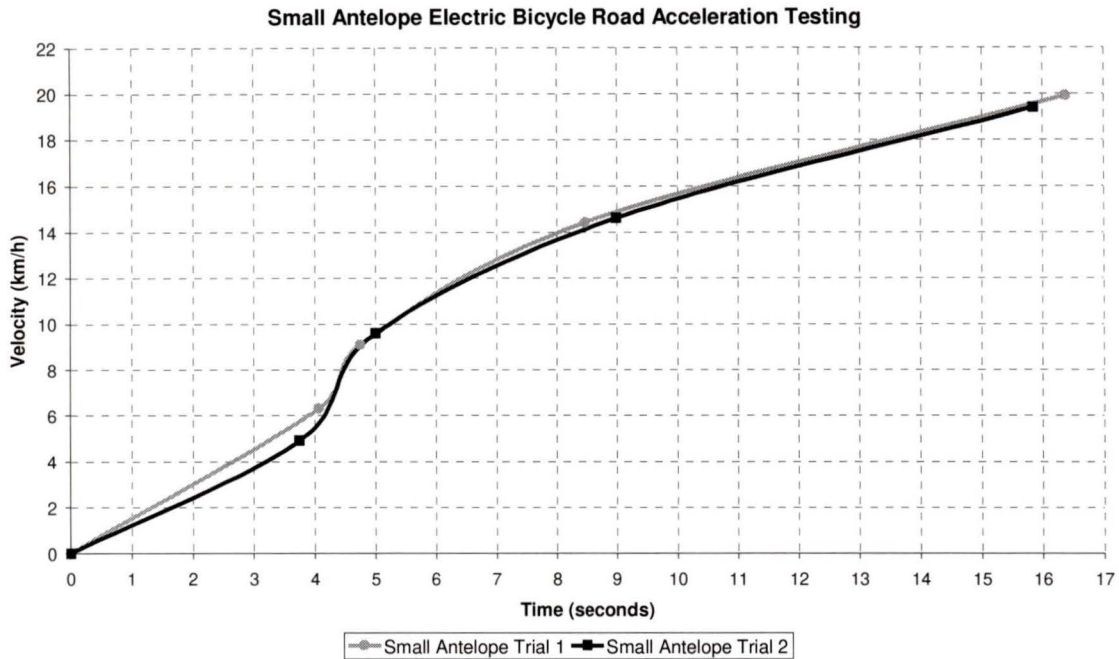


Figure 95: Suzhou Small Antelope Road Test Results

7.3.3. Adaptable Electric Bicycle Power System Road Acceleration Testing

The Rocky Mountain RM6 equipped with the AEBPS is tested two times to observe repeatability. The AEBPS road test plot is shown in Figure 96. It is found that it is difficult to perform an acceleration test on an electric bicycle with a lot of front wheel torque, which explains the differences between the two tests. This high amount of motor torque requires a level of throttle sensitivity in order to prevent the bicycle from losing front wheel traction.

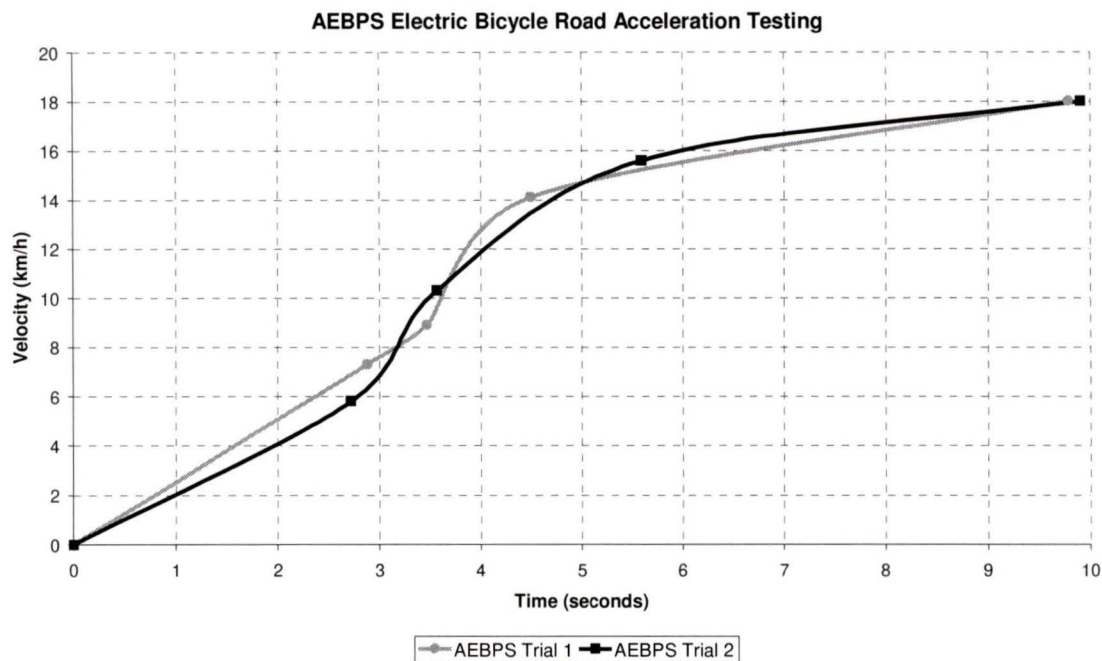


Figure 96: AEBPS Road Test Results

The top speed of the AEBPS equipped electric bicycle is observed to be 18.5 km/h on a ~0% grade.

During off-road testing the AEBPS proves to be extremely successful. The Heinzmann hub motor has more than enough torque to climb most hills; the motor controller could also handle the large loading, and never shut down.

7.3.4. Electric Bicycle Road Test Comparison

Figure 97 shows the different accelerations of each electric bicycle tested. It can be observed that the Currie and AEBPS provide fast acceleration, but the AEBPS has a slower top speed. The AEBPS performance is due to the low-g geared Heinzmann hub motor; other available Heinzmann hub motors offer a higher top speed comparable to the Currie electric bicycle. Since the peak power of the Currie electric bicycle is rated at 900W and the Heinzmann hub motor is 400 Watts, a Heinzmann hub motor with a top speed of 25 km/h would likely have a much slower acceleration than the Currie electric bicycle. The Small Antelope electric bicycle has a much slower acceleration than the other

electric bicycles; this is not surprising since the power output is only 230 Watts peak, which is approximately half the power of the Heinzmann hub motor.

Table 23 shows the acceleration results. Note: the values listed in Table 23 are approximate due to the testing method used, since only 5 data points are obtained for each acceleration test. The values for time are obtained from Figure 97. The best time of the two tests for each electric bicycle is displayed in Table 23. It can be seen in Table 23 that the Currie electric bicycle and the AEBPS bicycle have approximately the same acceleration from 0 km/h to 14 km/h; when the velocity curves in Figure 97 collide at ~14.25 km/h, the higher gearing of the Currie electric bicycle takes it to a greater speed. It can also be observed that the Small Antelope has a very low acceleration capability. The Currie electric bicycle accelerates from 0 km/h to 16 km/h almost twice as fast as the Suzhou Small Antelope.

Table 23: Road Test Acceleration Comparison

ACCELERATION (km/h)	Time (seconds)		
	AEBPS	Currie	Small Antelope
0-10	3.5	3.25	5.25
0-12	3.8	3.9	6.5
0-14	4.5	4.6	8.0
0-16	6.0	5.3	10.5
0-18	9.8	5.9	13.5

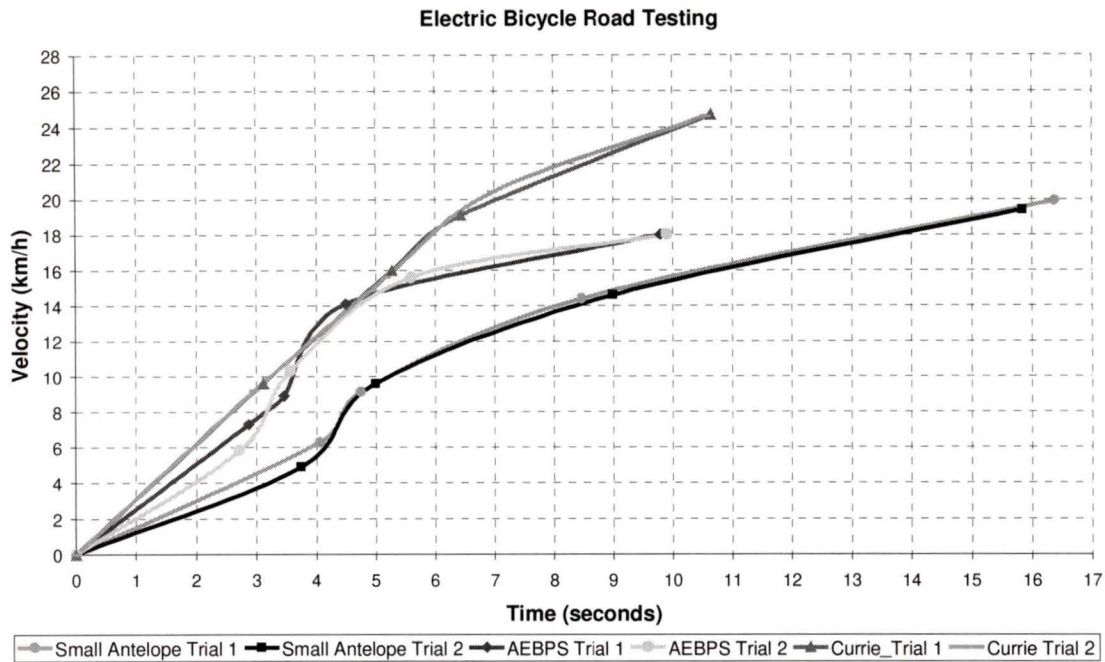


Figure 97: Electric Bicycle Road Test Results Comparison

The road test top speed of the Currie electric bicycle and the Suzhou Small Antelope are compared in

Table 24 with the top speeds observed during EBGTC testing. The Computrainer EBGTC appears to produce a higher top speed at a 0% grade than road testing. The higher top speeds when using the Computrainer is most likely due to the ideal conditions in which the EBGTC takes place; outdoor road testing can incorporate many variables such as light wind, uneven road surfaces, temperature fluctuation, and varying rolling resistance. It is also for these reasons that road testing can produce significantly different results from one similarly executed test to another, which is undesirable when testing electric bicycle design changes that may only have a small increase in performance.

Table 24: Top Speed Comparison

Electric Bicycle	Road Test Top Speed (km/h)	EBGTC Top Speed (km/h)	Difference (km/h)
Currie	25.7	27.55	1.85
Small Antelope	20.9	21.66	0.76

CHAPTER 8 CONCLUSIONS

8.1. Summary

Battery powered electric bicycles and scooters, replacing the heavily polluting scooters with 2-cycle internal combustion engines, provide zero-emission transportation for many parts of the world (mainly Asia). However, these battery powered electric bicycles suffer from a long recharge time (3-8 hours) and a low range (~32 km average), which hinders even greater application of this clean transportation technology.

The Proton Exchange Membrane (PEM) fuel cell system provides an alternative power plant for the electric bicycle. A fuel cell electric bicycle or scooter can be refueled quickly and provide a range of over 100 km. To facilitate the development of new electric bicycles, a computerized electric bicycle testing facility has been created in this study. Electric bicycle standardized testing cycles have also been developed. In addition, a new Adaptable Electric Bicycle Power System (AEBPS) is designed and constructed. The AEBPS configuration is designed to transform any bicycle (including full-suspension) into an electric bicycle in under ten minutes. The AEBPS can also be removed from the bicycle in less than five minutes due to its quick release design.

By analyzing a selection of commercially available electric bicycles and worldwide government electric bicycle regulations, as well as modeling the power required from an electric bicycle, it is found that the motor power for an electric bicycle should be 400W maximum (200W continuous). The 400W maximum (200W continuous) motor is found to provide adequate electric bicycle propulsion, and allows the electric bicycle to be marketed in the maximum amount of countries.

Three different methods for testing electric bicycles have been investigated in this work; these methods are: the Electric Bicycle Velocity Testing Cycles (EBVTC), the Electric Bicycle Grade Testing Cycle (EBGTC), and the outdoor Electric Bicycle Road

Acceleration Testing Method (EBRATM). All three methods are found to provide useful results.

The EBVTC is time consuming to set up for each electric bicycle (approximately two hours) using open loop control to match the velocity profile, but gives a continuous power curve over the specific velocity pattern representing a specific area or city (i.e. New York city). The EBVTC requires a Basic Stamp 2 microcontroller and Board of Education in addition to a RacerMate Computrainer, adding complexity and cost to the testing system.

The EBGTC is simple and effective, giving useful acceleration information, as well as performance values for comparison purposes. The EBGTC takes very little time for a complete test (less than 30 minutes for set-up and testing). The EBGTC method could also be used to determine the grade limit of each electric bicycle. The EBGTC is programmed into the Computrainer by using the Computrainer Pro PC1 software; this is quite a simple task. The EBGTC does not require a Basic Stamp 2 microcontroller, reducing cost and complexity.

The electric bicycle road acceleration testing method (EBRATM) is very quick (under fifteen minutes) to complete an acceleration test for an electric bicycle, but tests, especially those in terms of repeatability can fluctuate due to varying outdoor environmental conditions. It is observed that road testing is very inexpensive, and gives realistic performance values at the time of testing (even though the results will most likely be different if the same test is initiated the next day due to wind, temperature, etc.). The EBRATM also does not presently have the ability to observe the power output of the electric bicycle.

The EBVTC and the EBGTC both require a RacerMate Computrainer and the associated Pro PC1 and Coaching software. The ability to perform these tests require an initial investment of approximately \$1500 USD (\$2400 CND) for the Computrainer and software. The EBVTC also requires ~\$125 USD (\$200 CND) for the Board of Education

and BS2 microcontroller. The ability to test electric bicycles indoors in a small amount of space is beneficial compared to road testing. Since the Computrainer is only used indoors, different standardized environmental conditions can be simulated for more diverse tests (such as testing at precisely freezing (0°C) in the middle of summer). The EBRATM provides more realistic velocity results than the EBVTC or the EBGTC, but introduces much more possible errors such as wind, uneven pavement, outdoor temperature, as well as difficulty obtaining hills that are a constant grade to determine the electric bicycle grade limit. One main disadvantage of the EBRATM is the absence of power output measurement; this could likely be done with some instrumentation, but would increase the cost of this testing method as well as the set-up time.

The Basic Stamp 2 appears to be adequate for the development purposes of this project, but a processor with more EEPROM would allow for more complex velocity tests to be performed with a larger amount of sections.

8.2. Research Contributions

The work in this thesis forms the foundation for electrical bicycle testing. In this study an original electric bicycle computerized test facility is developed. Original methods for testing electric bicycles are also developed. The data obtained from the test facility is very valuable for comparison between different electric bicycles. The test facility also enables precise electric bicycle development work, as improvements to the electric bicycle can be tested at each stage of development.

This thesis also displays a unique adaptable electric bicycle power system (AEBPS) that can turn almost any bicycle into an electric bicycle. The AEBPS is constructed and is tested in outdoor conditions on and off road; it is found to fulfill all expectations.

8.3. Future Work

The methods presented in this thesis form the foundation for electric bicycle modeling, design, and testing. Much more research in this area can be completed in the future.

1. Design and construct a PEMFC version of the AEBPS; this prototype could then be tested and compared with the performance of the AEBPS with battery power.
2. Adapt the electric bicycle test facility to test electric scooters up to 6kW.
3. Develop a test to perform accurate and standardized range testing using the RacerMate Computrainer.
4. Test an electrically assisted bicycle (EAB) to see the performance, and repeatability.
5. Try the same Computrainer tests in different temperature environments (45 degrees C to -10 degrees C) to observe differences in performance.
6. Make grade tests for main cities interested in electric bicycles to show performance of electric bicycle in their area. This can be done with measured grades from the city, or if grade data does not exist, it can be measured quite cheaply with a bicycle computer that has an inclinometer. A bicycle computer that is commercially available with an inclinometer is the Specialized SpeedZone Pro computer (Figure 98), it retails for \$130 USD [73].

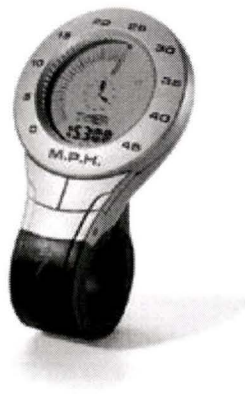


Figure 98: 2002 Specialized Bicycle Computer with Inclinometer [73]

7. Redesign QR20 Adaptors so that the AEBPS bicycle can be tested on the Computrainer.

8. Use EBGTC method to find grade limit of electric bicycles.

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APPENDIX A

Fuel Cell Advantages and Disadvantages

Table A1: Fuel Cell Advantages / Disadvantages

Fuel Cell Type	Electrolyte	Operation Temperature (°Celsius)	Advantages	Disadvantages	Application to 400 Watt Bicycle Power
Proton Exchange Membrane Fuel Cell (PEMFC)	Perfluorosulfonic acid polymer (Teflon chain with SO ₃ H side chains)	60 – 100	<p>Membrane is very thin (less than 50µm), resulting in high power density (low ohmic losses)</p> <p>Solid electrolyte reduces amount of sealing compared with liquid electrolytes</p> <p>Can be started quickly due to the low temperature operation</p> <p>Able to handle varying operational conditions (vehicular use)</p> <p>Can handle very high current densities</p>	<p>Require delicate balance of membrane hydration; too much hydration causes flooding and blocks flow field channels, and too little results in low voltage and membrane destruction</p> <p>Require an expensive Pt catalyst (~ 0.2 mg/cm² on anode, ~ 0.4 mg/cm² cathode)</p> <p>Can be contaminated with impure Hydrogen</p> <p>Rejected heat can not be used for cogeneration or additional power purposes due to the small amount produced</p>	<p>High power density is very desirable</p> <p>Suitable for vehicular use</p> <p>Quick startup time</p>

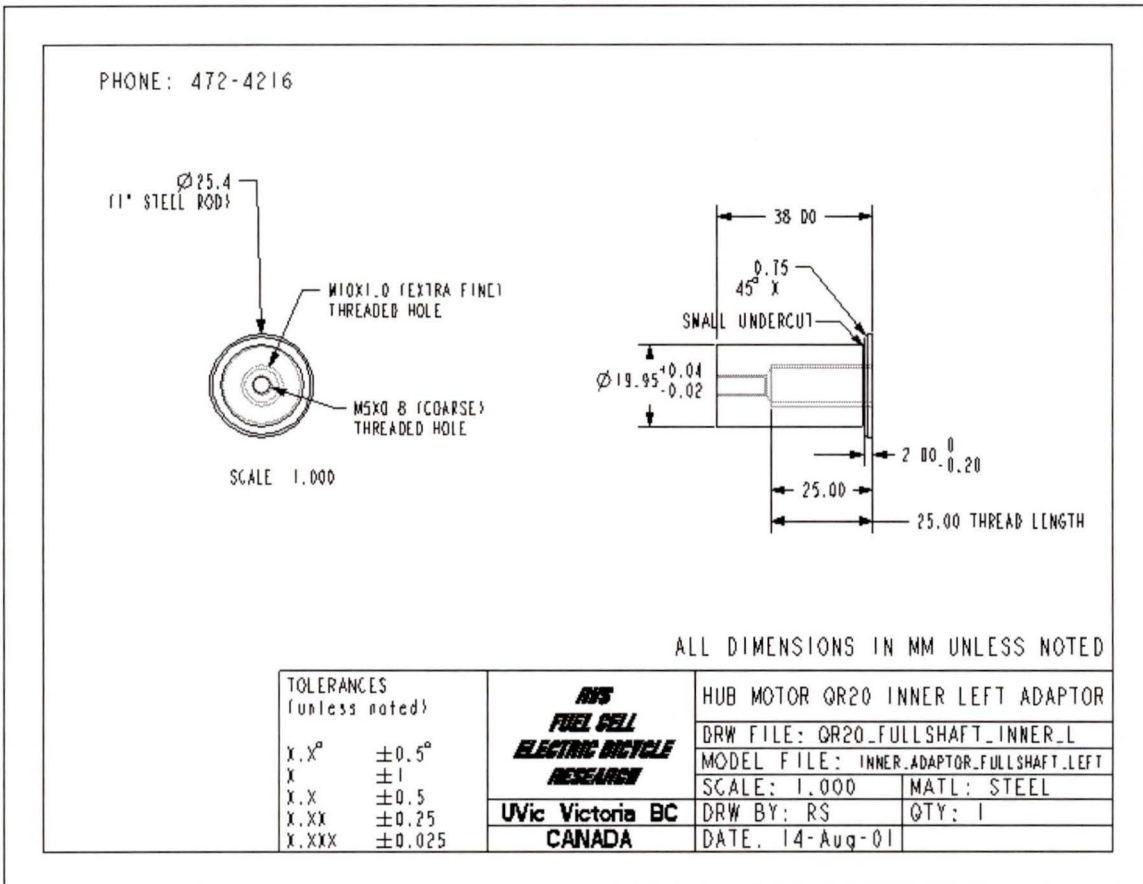
Fuel Cell Type	Electrolyte	Operation Temperature (°Celsius)	Advantages	Disadvantages	Application to 400 Watt Bicycle Power
Alkaline Fuel Cell (AFC)	Usually potassium hydroxide (KOH) in a asbestos matrix	90 – 100	Uses cheap catalysts (Nickel) High power density (but not as high as PEMFC)	Can not withstand CO ₂ at cathode (only withstands up to 50ppm) Requires a CO ₂ scrubber Membrane is very expensive	CO ₂ scrubber adds to the complexity of the FC system, and should be avoided Expensive cost is undesirable
Phosphoric Acid Fuel Cell (PAFC)	Liquid phosphoric acid in a silicon carbide matrix	150 – 220	High efficiency with co-generation of electricity and heat Can use impure hydrogen as fuel (reformate)	High cost Pt catalyst is required (~ 0.2 mg/cm ² on anode, ~ 0.4 mg/cm ² cathode) ~1/3 the performance of PEMFC (Power density W/cm ²) Large electrolyte thickness required (~0.1mm), resulting in a large stack size Temperature needs to be greater than 45°C at all times to stop acid from solidifying and expanding	Power density is too low Difficult to keep temperature at 45°C at all times (not practical while bike is in storage) The large stack size is undesirable

Fuel Cell Type	Electrolyte	Operation Temperature (°Celsius)	Advantages	Disadvantages	Application to 400 Watt Bicycle Power
Molten Carbonate Fuel Cell (MCFC)	Molten ionic salts (e.g. Li_2CO_3 , K_2CO_3)	600 – 700	<p>Inexpensive catalyst due to high temperature operation</p> <p>High efficiency</p> <p>CO is a directly usable fuel</p> <p>Rejected heat is enough to drive a turbine for use in cogeneration</p> <p>Operates efficiently with CO_2 enriched fuels</p>	<p>Operation at high temperatures accelerates corrosion effects and overall lifetime of cell</p> <p>Low power density</p> <p>A source of CO_2 is required at the cathode</p> <p>Stainless steel is required as the cell hardware material, resulting in a heavy stack</p>	<p>Low power density is undesirable</p> <p>Operation temperature is too high (increasing startup time)</p> <p>Start-up time would be too long</p> <p>Stack would be very heavy</p>

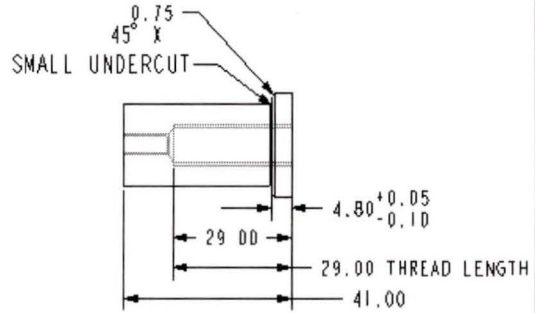
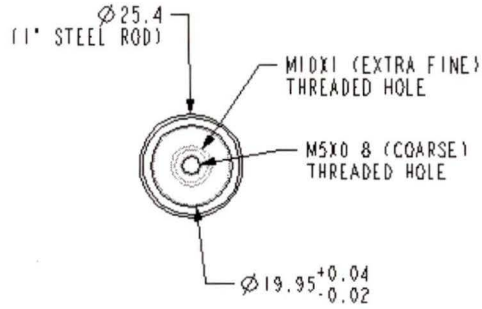
Fuel Cell Type	Electrolyte	Operation Temperature (°Celsius)	Advantages	Disadvantages	Application to 400 Watt Bicycle Power
Solid Oxide Fuel Cell (SOFC)	Ceramic oxide	650 – 1000	<p>Inexpensive catalyst due to high temperature operation</p> <p>High efficiency</p> <p>Solid electrolyte</p> <p>Ceramic cell construction reduces corrosion</p> <p>No flooding occurs in the SOFC due to no liquid present</p> <p>CO is a directly usable fuel</p> <p>No requirement for CO₂ at the cathode as with the MCFC</p>	<p>Low power density</p> <p>Thermal expansion problems affecting seals</p> <p>Difficult fabrication processes</p>	<p>Low power density is undesirable</p> <p>Operation temperature is too high (increasing startup time)</p> <p>Start-up time would be too long</p>

APPENDIX B

QR20 Front Fork Adaptor Drawings



PHONE: 472-4216

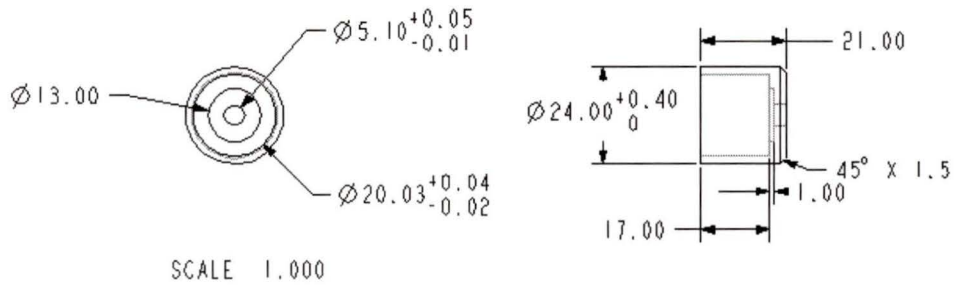


SCALE 1 000

ALL DIMENSIONS IN MM UNLESS NOTED

<p>TOLERANCES (unless noted)</p> <p>X X° ±0.5°</p> <p>X ±1</p> <p>X X ±0.5</p> <p>X XX ±0.25</p> <p>X XXX ±0.025</p>	RYS		HUB MOTOR QR20 INNER RIGHT ADAPTOR	
	FUEL CELL		DRW FILE: QR20_FULLSHAFT_INNER_R	
	ELECTRIC BICYCLE		MODEL FILE: INNER.ADAPTOR.FULLSHAFT_RIGHT	
	RESEARCH		SCALE: 1 000	MATL STEEL
	UVic Victoria BC		DRW BY: RS	QTY: 1
	CANADA		DATE: 15-Aug-01	

PHONE: 472-4216



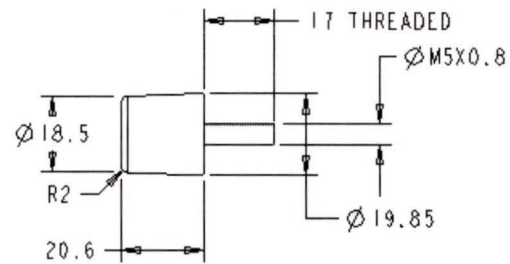
ALL DIMENSIONS IN MM UNLESS NOTED

TOLERANCES (unless noted) X X° ±0.5° X ±1 X.X ±0.5 X.XX ±0.25 X.XXX ±0.025	RYS FUEL CELL ELECTRIC BICYCLE RESEARCH	HUB MOTOR QR20 OUTER ADAPTOR	
		DRW FILE: OUTER_ADAPTOR_FULLSHAFT	
		MODEL FILE: OUTER_ADAPTOR_FULL_SHAFT	
		SCALE: 1.000	MATL: STEEL
		DRW BY: RS	QTY: 2
	UVic Victoria BC CANADA	DATE 15-Aug-01	

THREADED SHAFT LENGTH IN FULLY CLOSED POSITION



SCALE 1.000



ALL DIMENSIONS IN MM UNLESS NOTED

TOLERANCES (unless noted) X.X° ±0.5° X ±1 X.X ±0.5 X.XX ±0.25 X.XXX ±0.025	BVS FUEL CELL ELECTRIC MOTOR RESEARCH UVic Victoria BC CANADA	QR20 ADAPTOR QUICK RELEASE	
		DRW FILE: QUICK_RELEASE	
		MODEL FILE: QUICK_RELEASE_FULLSHAFT	
		SCALE: 1.000	MATL: STEEL
		DRW BY: RS	
		DATE: 15-Aug-01	

APPENDIX C

Currie Technologies Electric Bicycle Specifications

Technical Specifications:

Propulsion System: Patented Electro Drive direct drive with QR mounting plate

Motor: Hi-Torque Electro Drive, 24-volt brushless motor with built-in electronic pulse-width modulated (PWM) controller

Throttle: Handlebar mounted on-demand variable speed thumb throttle.

Power Source: Dual 12-volt, 12-amp hour sealed recyclable lead acid batteries in a lock-on frame mounted case

Colors: Gloss Black, Forest Green. Black Cherry Red

Frame: Pulse TIG welded MTB, with CrMo seat tube, cast vertical dropouts, welded battery pack mounts and propulsion system fittings

Fork: 1 1/8" RST 167 elastomer suspension

Handlebar: Satin finish MTB with 600 mm width & 30 mm rise

Stem: Satin finish MTB with 90 mm rise & 40° rise

Brakes: Alloy V-brakes with 3 finger MTB levers

Saddle: Velo coil spring comfort design

Front Hub: Alloy, 36H, Quick Release

Rear Hub: Alloy, 36H, Quick Release, LH threaded for Electro Drive

Spokes: 13G Stainless with brass nipples

Rims: 26 x 1.5 Alloy 6N style, silver anodized

Tires & Tubes: 26 x 1.95 On-Off road all terrain, Schrader valve

Shifters: SRAM Gripshift MRX-170, 21 speed

Front Derailleur: SR FD-TP05-GXH, top pull

Rear Derailleur: Shimano RD-CT-92GS, 7 speed

Freewheel: 13/28, 7-speed

Chainwheel: SR alloy arm, 48/38/28, silver & black

Pedals: Resin one-piece, black

Extras: 1 amp. Smart-Charger, Kickstand (Optional fast charging 3 & 5 amp chargers available.)

APPENDIX D

Electric Bicycle Testing Basic Stamp Microcontroller Software

European Elementary Urban Electric Bicycle Testing Cycle (EEUEBTC) Software

Program: Ebike_Elementary_Urban_Cycle_1_13_Thesis.bs2

Basic Stamp Program to perform European Elementary Urban Electric Bicycle Testing Cycle Version 13 test for electric bicycles.

This program is designed for testing the Currie electric bicycle. Other electric bicycles tested will need to have some of the subprogram parameters adjusted to achieve the same velocity profile.

Note: the use of a debug statement will take ~17ms of processing time

CONSTANTS

N9600 con \$4054	Used for LCD baudmode-9600 bps inverted
I con 254	LCD Instruction prefix value
CLR con 1	LCD clear screen instruction

***** A/D CONSTANTS *****

CS con 0	0831 A/D chip select active low from BS2 (P0)
CLK con 1	Clock pulse from BS2 (P1) to 0831 A/D chip
D0 con 2	Serial data output from A/D to BS2 (P2)

debug "EEUEBTC Version 13",cr

Wkspc3 var byte	Workspace for BUTTON command for electric bicycle test start button
Wkspc3 = 0	Clear workspace before using BUTTON command

Wkspc4 var byte	Workspace for BUTTON command for electric bicycle calibration start button
Wkspc4 = 0	Clear workspace before using BUTTON command

VARIABLES

```

adcbits var byte          '8 bit A/D variable from potentiometer throttle (value range 0-255)

drive var byte           'Total PWM drive amount variable
drive = 0                 'Initialize drive to value 0

x var word               'Total secondary PWM loops
x=0                       'Initialize as 0

debug "EEUEBTC Version 13",cr

serout 15,n9600,[I,CLR]   'clears the LCD screen in order to update the new data displayed

SELECT_BUTTON:          'loop designed to see if calibration or testing should be initiated

serout 15,n9600,[I,CLR]   'clears the LCD screen in order to update the new data displayed

for x = 0 to 25
serout 15,n9600,[I,128]   'moves LCD cursor to position 128 (leftmost position of top line)
serout 15,n9600,["YELLOW FOR"] 'display "YELLOW FOR" on LCD

serout 15,n9600,[I,192]   'moves cursor to position 192 (leftmost 2nd line)
serout 15,n9600,["EBIKE TEST"] 'display "EBIKE TEST" on LCD
next

serout 15,n9600,[I,CLR]   'clears the screen in order to update the new data displayed

for x = 0 to 25
serout 15,n9600,[I,128]   'clears the screen in order to update the new data displayed
serout 15,n9600,["WHITE FOR"] 'display "WHITE FOR" on LCD

serout 15,n9600,[I,192]   'moves cursor to position 192 (leftmost 2nd line)
serout 15,n9600,["PWM CALIBRATION"] 'display "PMW CALIBRATION" on LCD
next

BUTTON 3,1,255,0,Wkspace3,1,testselect_display 'if the testing button (Yellow) is pressed (Pin 3) the
'program will branch immediately to the subprogram
'testselect_display
BUTTON 6,1,255,0,Wkspace4,1,calselect_display 'if the testing button (White) is pressed (Pin 6) the
'program will branch immediately to the subprogram
'calselect_display

goto SELECT_BUTTON       'repeat

```

```

*****MAIN PWM CALIBRATION PROGRAM*****

```

```

main_calibrate:

```

```

gosub ADCDATA          `Acquire 8 bit data from potentiometer (0-255)

gosub DISPLAY_CAL     `Display potentiometer data on LCD

gosub PWM1           `Send power to motor using PWM command

goto main_calibrate

***** SUB PROGRAMS *****

ADCDATA:              `Acquire data from 0831 8 bit Analogue to digital converter

high CS               `Initially make sure chip select (CS) is high

low CS                `Select the chip by setting the chip select to low

low CLK               `Make the clock line ready by setting the chip select low

pulsout CLK,210       `Send a 210 uS clock pulse to the 0831 A/D

shiftin D0,CLK,msbpost,[adcbits\8] `Shift in the 8 bit data, output variable is D0, the mode is
`msbpost which signifies that the 8031 chip is ready to send
`the output bits after the clock pulse's negative edge. msbpost
`also indicates that the bits are sent in descending order
`starting with the most significant bit (leftmost) first. For
`more info see the Parallax Basic analog to digital student
`guide Experiment #3 from www.stampsinclass.com

return                `return to next command in main_calibrate

-----
      PWM1:           `This subprogram sends pulse width modulation signals to the electric
`bicycle motor controller by sending a voltage from 0 to 5V. The
`PWM command requires a pin to output the voltage to, a duty of 0-
`255, and the charge cycle in milliseconds. This subprogram is only
`used when the electric bicycle test is not used

PWM 5,adcbits,25      `uses value obtained earlier from adcbits to output a control
`voltage between 0V and 5V

return                `return to main program

***** END CALIBRATION *****

START_BUTTON:         `loop designed to see if the testing should be initiated

BUTTON 3,1,255,0,Wkspace3,1,main `if the testing button (Yellow) is pressed (Pin 3) the
`program will branch immediately to the
`subprogram "main"

goto start_button     `loop until electric bicycle testing button is pressed

```

***** MAIN TESTING PROGRAM *****

This program increments through each section of the Elementary European Urban Electric Bicycle Testing Cycle (EEUEBTC).

There are fifteen different sections of the EEUEBTC. The main program sends the program to each subprogram of each section.

main:

```
serout 15,n9600,[I,CLR]      'clears the LCD screen in order to update the new data displayed
serout 15,n9600,[I,128]     'moves LCD cursor to position 128 (leftmost position of top line)
serout 15,n9600,["START !!!"] 'display "START !!!" on LCD

debug "START!!!!",cr       'displays that the test has started in the computer debug window

gosub one                   'goes to section one subprogram
gosub two                   'goes to section two subprogram
gosub three                 'goes to section three subprogram
gosub four                 'goes to section four subprogram
gosub five                 'goes to section five subprogram
gosub six                  'goes to section six subprogram
gosub seven                'goes to section seven subprogram
gosub eight                'goes to section eight subprogram
gosub nine                 'goes to section nine subprogram
gosub ten                  'goes to section ten subprogram
gosub eleven               'goes to section eleven subprogram
gosub twelve               'goes to section twelve subprogram
gosub thirteen             'goes to section thirteen subprogram
gosub fourteen             'goes to section fourteen subprogram
gosub fifteen              'goes to section fifteen subprogram

debug "DONE!!!!!!",cr     'displays that the electric bicycle test is complete in the debug window

goto select_button        'returns to select_button
```

***** SECTION SUBPROGRAMS *****

These subprograms provide the open loop control of the electric bicycle motor. There is one subprogram for each section of the velocity test cycle.

```

t=10s
one:
  pause 10000
return
`holds the electric bicycle at a velocity of 0 km/h for 10 seconds
`ten second pause
`go to next command in "main" program

t=5s
two:
  for drive = 0 to 56
  for x = 1 to 2
    PWM 5,drive,25
  next
  pause 28
  next
return
`linearly increments the electric bicycle velocity from 0km/h to
7.5km/h in 5 seconds
`PWM drive incremented from 0 to 56 in steps of 1
`2 secondary loops of PWM (2* 29.66ms)
`PWM command provides PWM signal at pin 5 for 25ms
`next PWM loop
`calculated pause time to match time duration
`next drive amount
`return to next command in "main" program

t=7s
three:
  for x = 1 to 236
    PWM 5,56,25
  next
return
`keeps electric bicycle at a constant velocity of 7.5km/h for 7 seconds
`236 loops of PWM (7 * 33.715 loops/second)
`PWM drive = 56
`next PWM loop
`return to next command in "main" program

t=6s
four:
  for drive = 56 to 0
  for x = 1 to 3
    PWM 5,drive,25
  next
  pause 16
  next
return
`linearly decrements electric bicycle velocity from 7.5km/h to 0km/h
`PWM drive decremented from 56 to 0 in steps of 1
`3 secondary loops of PWM (3* 29.66ms)
`PWM command provides PWM signal at pin 5 for 25ms
`next PWM loop
`calculated pause time to match time duration
`next drive amount
`return to next command in "main" program

t=21s
five:
  pause 21000
return
`holds the electric bicycle at a velocity of 0 km/h for 21 seconds
`21 second pause
`return to next command in "main" program

t=11s
six:
  for drive = 0 to 138
  for x = 1 to 2
    PWM 5,drive,25
  next
  pause 20
  next
return
`linearly increments the electric bicycle velocity from 0km/h to 16km/h
`in 11 seconds
`PWM drive incremented from 0 to 138 in steps of 1
`2 secondary loops of PWM (2* 29.66ms)
`PWM command provides PWM signal at pin 5 for 25ms
`next PWM loop
`calculated pause time to match time duration
`next drive amount
`return to next command in "main" program

t=24.5s
seven:
  for x = 1 to 826
    PWM 5,138,25
  next
return
`holds the electric bicycle at a constant velocity of 16km/h for 24.5
`seconds
`826 loops of PWM (24.5 * 33.715 loops/second)
`PWM drive = 138

```

next	'next PWM loop
return	'return to next command in "main" program
't=11s	
eight:	'linearly decrements the electric bicycle velocity from 16km/h to 0km/h in 11 seconds
for drive = 138 to 0	'PWM drive decremented from 138 to 0 in steps of 1
for x = 1 to 2	'2 secondary loops of PWM (2* 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 20	'calculated pause time to match time duration
next	'next drive amount
return	'return to next command in "main" program
't=21s	
nine:	'holds the electric bicycle at a velocity of 0 km/h for 21 seconds
pause 21000	'21 second pause
return	'return to next command in "main" program
't=23.75s	
ten:	'linearly increments the electric bicycle velocity from 0km/h to 22.3km/h in 23.75 seconds
for drive = 0 to 187	'PWM drive incremented from 0 to 187 in steps of 1
for x = 1 to 4	'4 secondary loops of PWM (4* 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 8	'calculated pause time to match time duration
next	'next drive amount
return	'return to next command in "main" program
't=17.5s	
eleven:	'keeps electric bicycle at a constant velocity of 22.3km/h for 17.5 seconds.
For x = 1 to 590	'590 loops of PWM (17.5 * 33.715 loops/second)
PWM 5,187,25	'PWM drive = 187
next	'next PWM loop
return	'return to next command in "main" program
't=4.75s	
twelve:	'linearly decrements the electric bicycle velocity from 22.3km/h to 17.5km/h in 4.75 seconds
for drive = 187 to 153	'PWM drive decremented from 187 to 153 in steps of 1
for x = 1 to 4	'4 secondary loops of PWM (4* 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 17	'calculated pause time to match time duration
next	'next drive amount
return	'return to next command in "main" program
't=13s	
thirteen:	'keeps electric bicycle at a constant velocity of 17.5km/h for 13 seconds
For x = 1 to 438	'438 loops of PWM (13 * 33.715 loops/second)
PWM 5,153,25	'PWM drive = 153

```

next                'next PWM loop
return              'return to next command in "main" program

t=12s
fourteen:          'linearly decrements the electric bicycle velocity from 17.5km/h to
                   '0km/h in 5 seconds
for drive = 153 to 0
  for x = 1 to 2   'PWM drive decremented from 153 to 0 in steps of 1
    PWM 5,drive,25 '2 secondary loops of PWM (2* 29.66ms)
    next           'PWM command provides PWM signal at pin 5 for 25ms
  next            'next PWM loop
  pause 19        'calculated pause time to match time duration
  next           'next drive amount
return            'return to next command in "main" program

t=7s
fifteen:           'holds the electric bicycle at a velocity of 0 km/h for 7 seconds
  pause 7000      '7 second pause
return            'return to next command in "main" program

```

***** END SECTION SUBPROGRAMS *****

***** DISPLAY SUBPROGRAMS *****

The following subprograms are used to display important data on an LCD screen. The BPI-216 serial LCD from Scott Edwards Electronics (www.seetron.com) is used. The LCD is connected to Pin 15 on the BS2 and can display 2 lines of data using 16 characters on each line

DISPLAY_CAL:

```

serout 15,n9600,[I,CLR]           'clears the screen in order to update the new data
                                   'displayed
serout 15,n9600,[I,128]          'moves cursor to position 128 on LCD (leftmost
                                   'position first line)
serout 15,n9600,["PWM Drive = ",dec adcbits] 'display the adcbits obtained from the 0831 A/D
                                   'converter (0-255)

return

```

```

Calselect_display:              'lets the user know that the calibration mode has been selected
                                   'on the LCD display

serout 15,n9600,[I,CLR]          'clears the screen in order to update the new data displayed

for x = 0 to 20                  '21 loops
  serout 15,n9600,[I,128]        'moves LCD cursor to position 128 (leftmost position
                                   'of top line)

  serout 15,n9600,["PWM CALIBRATION"]

  serout 15,n9600,[I,192]        'moves cursor to position 192 (leftmost 2nd line)

```

```

serout 15,n9600,["SELECTED"]
next
goto main_calibrate

```

Testselect_display:

```

serout 15,n9600,[I,CLR]           'clears the screen in order to update the new data displayed

```

```

for x = 0 to 20
serout 15,n9600,[I,128]          'moves LCD cursor to position 128 (leftmost position of top
line)

```

```

serout 15,n9600,["EBIKE TEST"]   'display "EBIKE TEST" on LCD

```

```

serout 15,n9600,[I,192]          'moves cursor to position 192 (leftmost 2nd line)

```

```

serout 15,n9600,["SELECTED"]     'display "SELECTED" on LCD

```

```

next

```

```

serout 15,n9600,[I,CLR]           'clears the screen in order to update the new data displayed

```

```

for x = 0 to 40                   '41 loops

```

```

serout 15,n9600,[I,128]          'moves LCD cursor to position 128 (leftmost position of top
line)

```

```

serout 15,n9600,["PRESS YELLOW"] 'display "PRESS YELLOW" on LCD

```

```

serout 15,n9600,[I,192]          'moves cursor to position 192 (leftmost 2nd line)

```

```

serout 15,n9600,["BUTTON"]       'display "BUTTON" on LCD

```

```

next

```

```

goto start_button

```

```

***** END OF EEUEBTC PROGRAM *****

```

Taipei Electric Bicycle Testing Cycle Software

Program: Ebike_Taipei_Cycle_1_5_Thesis.bs2

Basic Stamp Program to perform Taipei Electric Bicycle Testing Cycle (TEBTC) test for electric bicycles

This program is designed for testing the Currie electric bicycle. Other electric bicycles tested will need to have some of the subprogram parameters adjusted to achieve the same velocity profile.

The Taipei Electric Bicycle Testing Cycle (TEBTC) is based on the TMDC (Taipei Motorcycle Driving Cycle); it is approximately half the speed of the original cycle, but retains the same time duration

Note: the use of a debug statement will take ~17ms of processing time

CONSTANTS

N9600 con \$4054	Used for LCD baudmode-9600 bps inverted
I con 254	LCD Instruction prefix value
CLR con 1	LCD clear screen instruction

***** A/D CONSTANTS *****

CS con 0	0831 A/D chip select active low from BS2 (P0)
CLK con 1	Clock pulse from BS2 (P1) to 0831 A/D chip
D0 con 2	Serial data output from A/D to BS2 (P2)

Wkspc3 var byte	Workspace for BUTTON command for electric bicycle test start button
-----------------	---

Wkspc3 = 0	Clear workspace before using BUTTON command
------------	---

Wkspc4 var byte	Workspace for BUTTON command for electric bicycle calibration start button
-----------------	--

Wkspc4 = 0	Clear workspace before using BUTTON command
------------	---

VARIABLES

adcbits var byte	8 bit A/D variable from potentiometer throttle (value range 0-255)
------------------	--

drive var byte	Total PWM drive amount variable
drive = 0	Initialize drive to value 0

x var word	Total secondary PWM loops
x=0	Initialize as 0

debug "TEBTC Version 5",cr

serout 15,n9600,[I,CLR]	clears the screen in order to update the new data displayed
-------------------------	---

```

SELECT_BUTTON:                'loop designed to see if calibration or testing should be initiated

serout 15,n9600,[I,CLR]       'clears the LCD screen in order to update the new data displayed

for x = 0 to 25
serout 15,n9600,[I,128]       'moves LCD cursor to position 128 (leftmost position of top line)
serout 15,n9600,["YELLOW FOR"] 'display "YELLOW FOR" on LCD

serout 15,n9600,[I,192]       'moves cursor to position 192 (leftmost 2nd line)
serout 15,n9600,["EBIKE TEST"] 'display "EBIKE TEST" on LCD
next

serout 15,n9600,[I,CLR]       'clears the screen in order to update the new data displayed

for x = 0 to 25
serout 15,n9600,[I,128]       'clears the screen in order to update the new data displayed
serout 15,n9600,["WHITE FOR"] 'display "WHITE FOR" on LCD

serout 15,n9600,[I,192]       'moves cursor to position 192 (leftmost 2nd line)
serout 15,n9600,["PWM CALIBRATION"] 'display "PWM CALIBRATION" on LCD
next

BUTTON 3,1,255,0,Wkspace3,1,testselect_display    'if the testing button (Yellow) is pressed
                                                    '(Pin 3) the program will branch
                                                    'immediately to the subprogram
                                                    'testselect_display

BUTTON 6,1,255,0,Wkspace4,1,calselect_display     'if the testing button (White) is pressed (Pin
                                                    '6) the program will branch immediately to
                                                    'the subprogram calselect_display

goto SELECT_BUTTON                                'repeat

*****MAIN PWM CALIBRATION PROGRAM*****
main_calibrate:

  gosub ADCDATA                                  'Acquire 8 bit data from potentiometer (0-255)
  gosub DISPLAY_CAL                              'Display potentiometer data on LCD
  gosub PWM1                                     'Send power to motor using PWM command
goto main_calibrate

*****SUBPROGRAMS*****

ADCDATA:                                         'Acquire data from 0831 8 bit analogue to digital converter

high CS                                         'Initially make sure chip select (CS) is high

```

```

low CS                `Select the chip by setting the chip select to low

low CLK              `Make the clock line ready by setting the chip select low

pulsout CLK,210      `Send a 210 uS clock pulse to the 0831 A/D

shiftin D0,CLK,msbpost,[adcbits\8]  `Shift in the 8 bit data, output variable is D0, the mode is
                                        `msbpost which signifies that the 8031 chip is ready to send
                                        `the output bits after the clock pulse's negative edge.  msbpost
                                        `also indicates that the bits are sent in descending order
                                        `starting with the most significant bit (leftmost) first.
                                        `For more info see the Parallax Basic analog to digital student
                                        `guide Experiment #3 from www.stampsinclass.com

return              `return to next command in main_calibrate

```

```

?-----

```

```

PWM1:              This subprogram sends pulse width modulation signals to the electric
                    `bicycle motor controller by sending a voltage from 0 to 5V.  The
                    `PWM command requires a pin to output the voltage to, a duty of 0-
                    `255, and the charge cycle in milliseconds.  This subprogram
                    `is only used when the electric bicycle test is not used

                    PWM 5,adcbits,25  `uses value obtained earlier from adcbits to output a control voltage
                    `between 0V and 5V

return            `return to main program

```

```

***** END CALIBRATION *****

```

```

START_BUTTON:      `loop designed to see if the testing should be initiated

                    BUTTON 3,1,255,0,Wkspace3,1,main  `if the testing button (Yellow) is pressed (Pin 3) the program
                    `will branch immediately to the subprogram "main"

goto start_button  `loop until electric bicycle testing button is pressed

```

```

***** MAIN TESTING PROGRAM *****

```

```

This program increments through each section of the TEBTC.
There are forty different sections of the TEBTC.  The main program sends the program to each
`subprogram of each section.

```

```

main:

serout 15,n9600,[I,CLR]  `clears the screen in order to update the new data displayed

serout 15,n9600,[I,128]  `moves LCD cursor to position 128 (leftmost position of top
                        `line)

serout 15,n9600,["START !!!"]  `display "START !!!" on LCD

```

```
debug "START!!!!",cr      'displays that the test has started in the computer debug
                           'window

gosub one                 'goes to section one subprogram
gosub two                 'goes to section two subprogram
gosub three              'goes to section three subprogram
gosub four               'goes to section four subprogram
gosub five               'goes to section five subprogram
gosub six               'goes to section six subprogram
gosub seven             'goes to section seven subprogram
gosub eight             'goes to section eight subprogram
gosub nine              'goes to section nine subprogram
gosub ten               'goes to section ten subprogram
gosub eleven            'goes to section eleven subprogram
gosub twelve            'goes to section twelve subprogram
gosub thirteen          'goes to section thirteen subprogram
gosub fourteen          'goes to section fourteen subprogram
gosub fifteen           'goes to section fifteen subprogram
gosub sixteen           'goes to section sixteen subprogram
gosub seventeen         'goes to section seventeen subprogram
gosub eighteen         'goes to section eighteen subprogram
gosub nineteen          'goes to section nineteen subprogram
gosub twenty            'goes to section twenty subprogram
gosub twentyone        'goes to section twentyone subprogram
gosub twentytwo        'goes to section twentytwo subprogram
gosub twentythree      'goes to section twentythree subprogram
gosub twentyfour       'goes to section twentyfour subprogram
gosub twentyfive       'goes to section twentyfive subprogram
```

gosub twentysix	'goes to section twentysix subprogram
gosub twentyseven	'goes to section twentyseven subprogram
gosub twentyeight	'goes to section twentyeight subprogram
gosub twentynine	'goes to section twentynine subprogram
gosub thirty	'goes to section thirty subprogram
gosub thirtyone	'goes to section thirtyone subprogram
gosub thirtytwo	'goes to section thirtytwo subprogram
gosub thirtythree	'goes to section thirtythree subprogram
gosub thirtyfour	'goes to section thirtyfour subprogram
gosub thirtyfive	'goes to section thirtyfive subprogram
gosub thirtysix	'goes to section thirtysix subprogram
gosub thirtyseven	'goes to section thirtyseven subprogram
gosub thirtyeight	'goes to section thirtyeight subprogram
gosub thirtynine	'goes to section thirtynine subprogram
gosub forty	'goes to section forty subprogram
debug "DONE!!!!!!",cr	'displays that the electric bicycle test is complete in the debug 'window
goto select_button	'returns to select_button

***** MAIN SECTION SUBPROGRAMS *****

These subprograms provide the open loop control of the electric bicycle motor. There is one subprogram for each section of the velocity test cycle.

<pre> t=3s one: pause 3000 return </pre>	<pre> 'holds the electric bicycle at a velocity of 0 km/h for 3 seconds '3 second pause 'go to next command in "main" program </pre>
<pre> t=17s two: for drive = 0 to 90 for x = 1 to 6 PWM 5,drive,25 next </pre>	<pre> 'linearly increments the electric bicycle velocity from 0km/h 'to 10.5km/h in 17 seconds 'PWM drive incremented from 0 to 90 in steps of 1 '6 secondary loops of PWM (6* 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop </pre>

pause 9	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
τ=9s	
three:	'linearly decrements electric bicycle velocity from 10.5km/h
	'to 0km/h in 9 seconds
for drive = 90 to 0	'PWM drive decremented from 90 to 0 in steps of 1
for x = 1 to 3	'3 secondary loops of PWM (3* 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 10	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
τ=31s	
four:	'holds the electric bicycle at a velocity of 0 km/h for 31
	'seconds
pause 31000	'31 second pause
return	'go to next command in "main" program
τ=33s	
five:	'linearly increments the electric bicycle velocity from 0km/h
	'to 15km/h in 33 seconds
for drive = 0 to 136	'PWM drive incremented from 0 to 56 in steps of 1
for x = 1 to 8	'2 secondary loops of PWM (2* 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 4	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
τ=8s	
six:	'linearly decrements electric bicycle velocity from 15km/h to
	'0km/h in 8 seconds
for drive = 136 to 0	'PWM drive decremented from 130 to 0 in steps of 1
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
pause 29	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
τ=13s	
seven:	'holds the electric bicycle at a velocity of 0 km/h for 13
	'seconds
pause 13000	'13 second pause
return	'go to next command in "main" program
τ=16s	
eight:	'linearly increments the electric bicycle velocity from 0km/h
	'to 11km/h in 16 seconds
for drive = 0 to 95	'PWM drive incremented from 0 to 95 in steps of 1
for x = 1 to 5	'5 secondary loops of PWM (5* 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop

pause 18	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
't=10s	
nine:	'linearly decrements electric bicycle velocity from 11km/h to 3km/h in 10 seconds
for drive = 95 to 20	'PWM drive decremented from 95 to 20 in steps of 1
for x = 1 to 4	'4 secondary loops of PWM (4* 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 13	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
't=12s	
ten:	'linearly increments the electric bicycle velocity from 3km/h to 11km/h in 12 seconds
for drive = 20 to 89	'PWM drive incremented from 20 to 89 in steps of 1
for x = 1 to 5	'5 secondary loops of PWM (5* 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 23	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
't=5s	
eleven:	'keeps electric bicycle at a constant velocity of 11km/h for 5 seconds
for x = 1 to 169	'169 loops of PWM (5 * 33.715 loops/second)
PWM 5,89,25	'PWM drive = 89
next	'next PWM loop
return	'go to next command in "main" program
't=5s	
twelve:	'linearly decrements electric bicycle velocity from 11km/h to 0km/h in 5 seconds
for drive = 89 to 0	'PWM drive decremented from 89 to 0 in steps of 1
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
pause 26	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
't=11s	
thirteen:	'linearly increments the electric bicycle velocity from 0km/h to 6.5km/h in 11 seconds
for drive = 0 to 51	'PWM drive incremented from 0 to 51 in steps of 1
for x = 1 to 7	'7 secondary loops of PWM (7 * 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 4	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program

<pre> t=11s fourteen: for drive = 51 to 0 for x = 1 to 7 PWM 5,drive,25 next pause 4 next return </pre>	<pre> 'linearly decrements electric bicycle velocity from 6.5km/h to '0km/h in 11 seconds 'PWM drive decremented from 51 to 0 in steps of 1 '7 secondary loops of PWM (7 * 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program </pre>
<pre> t=27s fifteen: pause 27000 return </pre>	<pre> 'holds the electric bicycle at a velocity of 0 km/h for 27 'seconds '27 second pause 'go to next command in "main" program </pre>
<pre> t=16s sixteen: for drive = 0 to 158 for x = 1 to 3 PWM 5,drive,25 next pause 12 next return </pre>	<pre> 'linearly increments the electric bicycle velocity from 0km/h 'to 18km/h in 16 seconds 'PWM drive incremented from 0 to 158 in steps of 1 '3 secondary loops of PWM (3 * 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program </pre>
<pre> t=45s seventeen: for x = 1 to 1517 PWM 5,158,25 next return </pre>	<pre> 'keeps electric bicycle at a constant velocity of 18km/h for 45 'seconds '1517 loops of PWM (45 * 33.715 loops/second) 'PWM drive = 158 'next PWM loop 'go to next command in "main" program </pre>
<pre> t=16s eighteen: for drive = 158 to 0 for x = 1 to 3 PWM 5,drive,25 next pause 12 next return </pre>	<pre> 'linearly decrements electric bicycle velocity from 18km/h to '0km/h in 16 seconds 'PWM drive decremented from 158 to 0 in steps of 1 '3 secondary loops of PWM (3 * 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program </pre>
<pre> t=21s nineteen: pause 21000 return </pre>	<pre> 'holds the electric bicycle at a velocity of 0 km/h for 21 'seconds '21 second pause 'go to next command in "main" program </pre>
<pre> t=16s </pre>	

twenty:	'linearly increments the electric bicycle velocity from 0km/h 'to 20km/h in 16 seconds 'PWM drive incremented from 0 to 183 in steps of 1 '2 secondary loops of PWM (2* 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program
<pre> for drive = 0 to 183 for x = 1 to 2 PWM 5,drive,25 next pause 28 next return </pre>	
<pre> t=16s twentyone: </pre>	
<pre> for drive = 183 to 0 for x = 1 to 2 PWM 5,drive,25 next pause 28 next return </pre>	'linearly decrements electric bicycle velocity from 20km/h to '0km/h in 16 seconds 'PWM drive incremented from 183 to 0 in steps of 1 '2 secondary loops of PWM (2* 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program
<pre> t=6s twentytwo: </pre>	
<pre> pause 6000 return </pre>	'holds the electric bicycle at a velocity of 0 km/h for 6 seconds '6 second pause 'go to next command in "main" program
<pre> t=14s twentythree: </pre>	
<pre> for drive = 0 to 136 for x = 1 to 3 PWM 5,drive,25 next pause 13 next return </pre>	'linearly increments the electric bicycle velocity from 0km/h 'to 16km/h in 14 seconds 'PWM drive incremented from 0 to 136 in steps of 1 '3 secondary loops of PWM (3* 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program
<pre> t=152s twentyfour: </pre>	
<pre> for x = 1 to 5125 PWM 5,136,25 next return </pre>	'keeps electric bicycle at a constant velocity of 16km/h for 152 'seconds '5125 loops of PWM (152 * 33.715 loops/second) 'PWM drive = 136 'next PWM loop 'go to next command in "main" program
<pre> t=18s twentyfive: </pre>	
<pre> for drive = 136 to 23 for x = 1 to 5 PWM 5,drive,25 next pause 10 next </pre>	'linearly decrements electric bicycle velocity from 16km/h to '3.5km/h in 18 seconds 'PWM drive decremented from 136 to 23 in steps of 1 '5 secondary loops of PWM (5 * 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop 'calculated pause time to match time duration 'next drive amount

return	'go to next command in "main" program
<pre> t=13s twentysix: for x = 1 to 438 PWM 5,23,25 next return </pre>	<pre> 'keeps electric bicycle at a constant velocity of 3.5km/h for 13 'seconds '438 loops of PWM (13 * 33.715 loops/second) 'PWM drive = 23 'next PWM loop 'go to next command in "main" program </pre>
<pre> t=3s twentyseven: for drive = 23 to 0 for x = 1 to 4 PWM 5,drive,25 next pause 6 next return </pre>	<pre> 'linearly decrements electric bicycle velocity from 3.5km/h to '0km/h in 3 seconds 'PWM drive decremented from 23 to 0 in steps of 1 '4 secondary loops of PWM (4 * 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program </pre>
<pre> t=39s twentyeight: pause 39000 return </pre>	<pre> 'holds the electric bicycle at a velocity of 0 km/h for 39 'seconds '39 second pause 'go to next command in "main" program </pre>
<pre> t=17s twentynine: for drive = 0 to 64 for x = 1 to 8 PWM 5,drive,25 next 'debug "Drive= ",dec drive,cr 'gosub display pause 24 next return </pre>	<pre> 'linearly increments the electric bicycle velocity from 0km/h 'to 8.5km/h in 17 seconds 'PWM drive incremented from 0 to 64 in steps of 1 '8 secondary loops of PWM (8 * 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program </pre>
<pre> t=17s thirty: for x = 1 to 573 PWM 5,64,25 next return </pre>	<pre> 'keeps electric bicycle at a constant velocity of 8.5km/h for 17 'seconds '573 loops of PWM (17 * 33.715 loops/second) 'PWM drive = 64 'next PWM loop 'go to next command in "main" program </pre>
<pre> t=79s thirtyone: for drive = 64 to 136 for x = 1 to 36 PWM 5,drive,25 </pre>	<pre> 'linearly increments the electric bicycle velocity from 8.5km/h 'to 16km/h in 79 seconds 'PWM drive incremented from 64 to 136 in steps of 1 '36 secondary loops of PWM (36 * 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms </pre>

next	'next PWM loop
pause 14	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
τ=68s	
thirtytwo:	'keeps electric bicycle at a constant velocity of 16km/h for 68
	'seconds
for x = 1 to 2293	'2293 loops of PWM (68 * 33.715 loops/second)
PWM 5,136,25	'PWM drive = 136
next	'next PWM loop
return	'go to next command in "main" program
τ=41s	
thirtythree:	'linearly decrements electric bicycle velocity from 16km/h to
	'0km/h in 41 seconds
for drive = 136 to 0	'PWM drive decremented from 136 to 0 in steps of 1
for x = 1 to 10	'10 secondary loops of PWM (10 * 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 3	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
τ=34s	
thirtyfour:	'holds the electric bicycle at a velocity of 0 km/h for 34
	'seconds
pause 34000	'34 second pause
return	'go to next command in "main" program
τ=16s	
thirtyfive:	'linearly increments the electric bicycle velocity from 0km/h
	'to 16km/h in 16 seconds
for drive = 0 to 136	'PWM drive incremented from 0 to 136 in steps of 1
for x = 1 to 3	'3 secondary loops of PWM (2* 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 28	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
τ=43s	
thirtysix:	'keeps electric bicycle at a constant velocity of 16km/h for 43
	'seconds
for x = 1 to 1450	'1450 loops of PWM (43 * 33.715 loops/second)
PWM 5,136,25	'PWM drive = 136
next	'next PWM loop
return	'go to next command in "main" program
τ=5s	
thirtyseven:	'linearly decrements electric bicycle velocity from 16km/h to
	'11.5km/h in 5 seconds
for drive = 136 to 91	'PWM drive incremented from 136 to 91 in steps of 1
for x = 1 to 3	'3 secondary loops of PWM (3 * 29.66ms)

```

    PWM 5,drive,25
    next
  pause 20
  next
return

t=18s
thirtyeight:
  for x = 1 to 607
    PWM 5,91,25
    next
  return

t=12s
thirtynine:
  for drive = 91 to 168
    for x = 1 to 5
      PWM 5,drive,25
      next
    pause 6
    next
  return

t=20s
forty:
  for drive = 168 to 0
    for x = 1 to 3
      PWM 5,drive,25
      next
    pause 29
    next
  return

```

PWM command provides PWM signal at pin 5 for 25ms
 'next PWM loop
 'calculated pause time to match time duration
 'next drive amount
 'go to next command in "main" program

'keeps electric bicycle at a constant velocity of 11.5km/h for
 '18 seconds
 '607 loops of PWM (18 * 33.715 loops/second)
 PWM drive = 91
 'next PWM loop
 'go to next command in "main" program

'linearly increments the electric bicycle velocity from 0km/h
 'to 18.5km/h in 12 seconds
 PWM drive incremented from 91 to 168 in steps of 1
 '5 secondary loops of PWM (5 * 29.66ms)
 PWM command provides PWM signal at pin 5 for 25ms
 'next PWM loop
 'calculated pause time to match time duration
 'next drive amount
 'go to next command in "main" program

'linearly decrements electric bicycle velocity from 18.5km/h
 'to 0km/h in 20 seconds
 PWM drive decremented from 0 to 56 in steps of 1
 '3 secondary loops of PWM (2 * 29.66ms)
 PWM command provides PWM signal at pin 5 for 25ms
 'next PWM loop
 'calculated pause time to match time duration
 'next drive amount
 'go to next command in "main" program

***** END SECTION SUBPROGRAMS *****

***** DISPLAY SUBPROGRAMS *****

The following subprograms are used to display important data on an LCD screen. The BPI-216 serial LCD from Scott Edwards Electronics (www.seetron.com) is used. The LCD is connected to Pin 15 'on the BS2 and can display 2 lines of data using 16 characters on each line

DISPLAY_CAL:

'NOT USED DUE TO LIMITED EEPROM

'serout 15,n9600,[I,CLR]

'clears the screen in order to update the new data

'displayed

'serout 15,n9600,[I,128]

'moves cursor to position 128 on LCD (leftmost
'position first line)

```

`serout 15,n9600,["PWM Drive = ",dec adcbits]      `display the adcbits obtained from the 0831 A/D
                                                    `converter (0-255)

return

'-----

Calselect_display:                                `lets the user know that the calibration mode has
been selected                                     `on the LCD display

`serout 15,n9600,[I,CLR]                          `clears the screen in order to update the new data
displayed

`for x = 0 to 20                                    `21 loops
`serout 15,n9600,[I,128]                          `moves LCD cursor to position 128 (leftmost position
                                                    `of top line)

`serout 15,n9600,["PWM CALIBRATION"]

`serout 15,n9600,[I,192]                          `moves cursor to position 192 (leftmost 2nd line)
`serout 15,n9600,["SELECTED"]
`next
goto main_calibrate

'-----

Testselect_display:

serout 15,n9600,[I,CLR]                          `clears the screen in order to update the new data displayed

for x = 0 to 20
serout 15,n9600,[I,128]                          `moves LCD cursor to position 128 (leftmost position of top
line)
serout 15,n9600,["EBIKE TEST"]                   `display "EBIKE TEST" on LCD

serout 15,n9600,[I,192]                          `moves cursor to position 192 (leftmost 2nd line)
serout 15,n9600,["SELECTED"]                     `display "SELECTED" on LCD
next

`serout 15,n9600,[I,CLR]                          `clears the screen in order to update the new data displayed

`for x = 0 to 40                                    `41 loops
`serout 15,n9600,[I,128]                          `moves LCD cursor to position 128 (leftmost position of top
line)
`serout 15,n9600,["PRESS YELLOW"]                 `display "PRESS YELLOW" on LCD

`serout 15,n9600,[I,192]                          `moves cursor to position 192 (leftmost 2nd line)
`serout 15,n9600,["BUTTON"]                       `display "BUTTON" on LCD
`next

goto start_button

***** END OF TEBTC PROGRAM *****

```

New York Electric Bicycle Testing Cycle (NYEBTC) Software

Program Ebike_NewYorkCity_Cycle_1_14_Thesis.bs2

Basic Stamp Program to perform New York Electric Bicycle Testing Cycle (NYEBTC) Version 14 for electric bicycles.

This test is approximately half the speed of the NYCC.

This cycle has so many sections that the calibration choice is eliminated so that the EEPROM does not overflow.

This program is designed for testing the Currie electric bicycle. Other electric bicycles tested will need to have some of the subprogram parameters adjusted to achieve the same velocity profile.

Note: the use of a debug statement will take ~17ms of processing time

-----CONSTANTS-----

N9600 con \$4054	Used for LCD baudmode-9600 bps inverted
I con 254	LCD Instruction prefix value
CLR con 1	LCD clear screen instruction

***** A/D CONSTANTS*****

NOTE: NOT USED

CS con 0	0831 A/D chip select active low from BS2 (P0)
CLK con 1	Clock pulse from BS2 (P1) to 0831 A/D chip
D0 con 2	Serial data output from A/D to BS2 (P2)

Wkspc3 var byte	Workspace for BUTTON command for electric bicycle test start button
Wkspc3 = 0	Clear workspace before using BUTTON command

Wkspc4 var byte	Workspace for BUTTON command for electric bicycle calibration start button
Wkspc4 = 0	Clear workspace before using BUTTON command

VARIABLES

adcbits var byte	8 bit A/D variable from potentiometer throttle (value range 0-255)
------------------	--

drive var byte	Total PWM drive amount variable
drive = 0	Initialize drive to value 0

x var word	Total secondary PWM loops
x=0	Initialize as 0

debug "NYEBTC Version 14",cr

serout 15,n9600,[I,CLR]	clears the screen in order to update the new data displayed
-------------------------	---

```

SELECT_BUTTON:           'loop designed to see if calibration or testing should be initiated

'serout 15,n9600,[I,CLR]      'clears the LCD screen in order to update the new data displayed

for x = 0 to 25
'serout 15,n9600,[I,128]      'moves LCD cursor to position 128 (leftmost position of top line)
'serout 15,n9600,["YELLOW FOR"]  'display "YELLOW FOR" on LCD

'serout 15,n9600,[I,192]      'moves cursor to position 192 (leftmost 2nd line)
'serout 15,n9600,["EBIKE TEST"]  'display "EBIKE TEST" on LCD
next

'serout 15,n9600,[I,CLR]      'clears the screen in order to update the new data displayed

for x = 0 to 25
'serout 15,n9600,[I,128]      'clears the screen in order to update the new data displayed
'serout 15,n9600,["WHITE FOR"]  'display "WHITE FOR" on LCD

'serout 15,n9600,[I,192]      'moves cursor to position 192 (leftmost 2nd line)
'serout 15,n9600,["PWM CALIBRATION"]  'display "PWM CALIBRATION" on LCD
next

BUTTON 3,1,255,0,Wkspace3,1,testselect_display      'if the testing button (Yellow) is pressed
                                                        '(Pin 3) the program will branch
                                                        'immediately to the subprogram
                                                        'testselect_display.

'BUTTON 6,1,255,0,Wkspace4,1,calselect_display      'if the testing button (White) is pressed (Pin
                                                        '6) the program will branch immediately to
                                                        'the subprogram calselect_display

goto SELECT_BUTTON      'repeat

```

```

***** MAIN PWM CALIBRATION PROGRAM *****
NOTE: NOT USED DUE TO LIMITED EEPROM

```

```

main_calibrate:

'gosub ADCDATA      'Acquire 8 bit data from potentiometer (0-255)

'gosub DISPLAY_CAL  'Display potentiometer data on LCD

'gosub PWM1         'Send power to motor using PWM command

'goto main_calibrate

```

```

*****SUB PROGRAMS*****

```

NOT USED DUE TO LIMITED EEPROM

```
'ADCDATA:                                'Acquire data from 0831 8 bit analogue to digital converter

'high CS                                  'Initially make sure chip select (CS) is high

'low CS                                    'Select the chip by setting the chip select to low

'low CLK                                   'Make the clock line ready by setting the chip select low

'pulsout CLK,210                           'Send a 210 uS clock pulse to the 0831 A/D

'shiftin D0,CLK,msbpost,[adcbits\8]       'Shift in the 8 bit data, output variable is D0, the mode is
                                             'msbpost which signifies that the 8031 chip is ready to send
                                             'the output bits after the clock pulse's negative edge.  msbpost
                                             'also indicates that the bits are sent in descending order
                                             'starting with the most significant bit (leftmost) first.  For
                                             'more info see the Parallax Basic analog to digital student
                                             'guide Experiment #3 from www.stampsinclass.com

'return                                     'return to next command in main_calibrate
```

NOT USED!!

```
PWM1:                                     'This subprogram sends pulse width modulation signals to the electric
                                             'bicycle motor controller by sending a voltage from 0 to 5V.  The
                                             'PWM command requires a pin to output the voltage to, a duty of 0-
                                             '255, and the charge cycle in milliseconds.  This subprogram is only
                                             'used when the electric bicycle test is not used

'debug "Line15",cr                          'uses value obtained earlier from adcbits to output a control voltage
PWM 5,adcbits,25                             'between 0V and 5V

'debug "Line16",cr
'debug "PWM ",dec3 adcbits,cr
'return                                       'return to main program
```

***** END CALIBRATION *****

NOT USED

```
'START_BUTTON:                            'loop designed to see if the testing should be initiated

'BUTTON 3,1,255,0,Wkspc3,1,main           'if the testing button (Yellow) is pressed (Pin 3) the
                                             'program will branch immediately to the
                                             'subprogram "main"

'goto start_button                          'loop until electric bicycle testing button is pressed
```

MAIN TESTING PROGRAM

This program increments through each section of the New York Electric Bicycle Testing Cycle (NYEBTC).

There are forty-five different sections of the NYEBTC. The main program sends the program to each subprogram of each section.

main:

serout 15,n9600,[I,CLR]	'clears the screen in order to update the new data displayed
serout 15,n9600,[I,128]	'moves LCD cursor to position 128 (leftmost position of top line)
serout 15,n9600,["START !!!"]	'display "START !!!" on LCD
debug "START!!!!",cr	'displays that the test has started in the computer debug window
gosub one	'goes to section one subprogram
gosub two	'goes to section two subprogram
gosub three	'goes to section three subprogram
gosub four	'goes to section four subprogram
gosub five	'goes to section five subprogram
gosub six	'goes to section six subprogram
gosub seven	'goes to section seven subprogram
gosub eight	'goes to section eight subprogram
gosub nine	'goes to section nine subprogram
gosub ten	'goes to section ten subprogram
gosub eleven	'goes to section eleven subprogram
gosub twelve	'goes to section twelve subprogram
gosub thirteen	'goes to section thirteen subprogram
pause 1000	'one second pause added due to fast velocity loss at bottom of V profile
gosub fourteen	'goes to section fourteen subprogram
gosub fifteen	'goes to section fifteen subprogram
gosub sixteen	'goes to section sixteen subprogram
gosub seventeen	'goes to section seventeen subprogram
pause 3000	'3 second pause added due to fast velocity loss

```
'at bottom of V profile  
gosub eighteen 'goes to section eighteen subprogram  
gosub nineteen 'goes to section nineteen subprogram  
gosub twenty 'goes to section twenty subprogram  
gosub twentyone 'goes to section twentyone subprogram  
gosub twentytwo 'goes to section twentytwo subprogram  
gosub twentythree 'goes to section twentythree subprogram  
gosub twentyfour 'goes to section twentyfour subprogram  
gosub twentyfive 'goes to section twentyfive subprogram  
gosub twentysix 'goes to section twentysix subprogram  
pause 1000 'one second pause added due to fast velocity loss  
'at bottom of V profile  
gosub twentyseven 'goes to section twentyseven subprogram  
gosub twentyeight 'goes to section twentyeight subprogram  
gosub twentynine 'goes to section twentynine subprogram  
gosub thirty 'goes to section thirty subprogram  
gosub thirtyone 'goes to section thirtyone subprogram  
gosub thirtytwo 'goes to section thirtytwo subprogram  
gosub thirtythree 'goes to section thirtythree subprogram  
gosub thirtyfour 'goes to section thirtyfour subprogram  
gosub thirtyfive 'goes to section thirtyfive subprogram  
gosub thirtysix 'goes to section thirtysix subprogram  
gosub thirtyseven 'goes to section thirtyseven subprogram  
gosub thirtyeight 'goes to section thirtyeight subprogram  
gosub thirtynine 'goes to section thirtynine subprogram  
gosub forty 'goes to section forty subprogram  
gosub fortyone 'goes to section fortyone subprogram  
gosub fortytwo 'goes to section fortytwo subprogram
```

```

pause 1000                                'one second pause added due to fast velocity loss
                                           'at bottom of V profile

gosub fortythree                          'goes to section fortythree subprogram

gosub fortyfour                            'goes to section fortyfour subprogram

gosub fortyfive                            'goes to section fortyfive subprogram

debug "DONE!!!!!!",cr                    'displays that the electric bicycle test is complete in the debug window

goto select_button                        'returns to select_button

***** MAIN SUB PROGRAMS *****

t=45s
one:                                       'holds the electric bicycle at a velocity of 0 km/h for 45
                                           'seconds
pause 45000                               '45 second pause
return                                    'go to next command in "main" program

t=8.25s
two:                                       'linearly increments the electric bicycle velocity from 0km/h
                                           'to 7.5km/h in 8.25 seconds
for drive = 0 to 55                       'PWM drive incremented from 0 to 55 in steps of 1
  for x = 1 to 4                           '4 secondary loops of PWM (4* 29.66ms)
    PWM 5,drive,25                         'PWM command provides PWM signal at pin 5 for 25ms
  next                                      'next PWM loop
pause 29                                   'calculated pause time to match time duration
next                                       'next drive amount
return                                    'go to next command in "main" program

t=4s
three:                                    'keeps electric bicycle at a constant velocity of 7.5km/h for 4
                                           'seconds
for x = 1 to 136                           '136 loops of PWM (5 * 33.715 loops/second)
  PWM 5,55,25                              'PWM drive = 55
next                                       'next PWM loop
return                                    'go to next command in "main" program

t=6s
four:                                     'linearly increments the electric bicycle velocity from 7.5km/h
                                           'to 18.5km/h in 6 seconds
for drive = 55 to 178                     'PWM drive incremented from 55 to 178 in steps of 1
  PWM 5,drive,25                           'PWM command provides PWM signal at pin 5 for 25ms
pause 19                                   'calculated pause time to match time duration
next                                       'next drive amount
return                                    'go to next command in "main" program

t=7s

```

<pre>five: for drive = 178 to 12 PWM 5,drive,25 pause 12 next return</pre>	<pre>'linearly decrements electric bicycle velocity from 18.5km/h 'to 1.7km/h in 7s 'PWM drive decremented from 178 to 12 in steps of 1 'PWM command provides PWM signal at pin 5 for 25ms 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program</pre>
<pre>τ=3.8s six: for drive = 12 to 71 for x = 1 to 2 PWM 5,drive,25 next pause 4 next return</pre>	<pre>'linearly increments the electric bicycle velocity from 1.7km/h 'to 8.5km/h in 3.8 seconds 'PWM drive incremented from 12 to 71 in steps of 1 '2 secondary loops of PWM (2 * 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program</pre>
<pre>τ=8.3s seven: for drive = 71 to 0 for x = 1 to 3 PWM 5,drive,25 next pause 26 next return</pre>	<pre>'linearly decrements electric bicycle velocity from 8.5km/h to '0km/h in 8.3s 'PWM drive decremented from 71 to 0 in steps of 1 '6 secondary loops of PWM (3* 29.66ms) 'PWM command provides PWM signal at pin 5 for 25ms 'next PWM loop 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program</pre>
<pre>τ=12s eight: pause 12000 return</pre>	<pre>'holds the electric bicycle at a velocity of 0 km/h for 12 'seconds '12 second pause 'go to next command in "main" program</pre>
<pre>τ=5.5s nine: for drive = 0 to 135 PWM 5,drive,25 pause 11 next return</pre>	<pre>'linearly increments the electric bicycle velocity from 0km/h 'to 14km/h in 5.5 seconds 'PWM drive incremented from 0 to 135 in steps of 1 'PWM command provides PWM signal at pin 5 for 25ms 'calculated pause time to match time duration 'next drive amount 'go to next command in "main" program</pre>
<pre>τ=6.6s ten: for drive = 135 to 35 for x = 1 to 2 PWM 5,drive,25 next pause 6 next</pre>	<pre>'linearly decrements electric bicycle velocity from 14km/h to '4.8km/h in 6.6s 'PWM drive decremented from 135 to 35 in steps of 1 'PWM command provides PWM signal at pin 5 for 25ms 'calculated pause time to match time duration 'next drive amount</pre>

return	'go to next command in "main" program
't=13s eleven:	'keeps electric bicycle at a constant velocity of 4.8km/h for 13 'seconds
for x = 1 to 438	'438 loops of PWM (13 * 33.715 loops/second)
PWM 5,35,25	'PWM drive = 35
next	'next PWM loop
return	'go to next command in "main" program
't=7.3s twelve:	'linearly increments the electric bicycle velocity from 4.8km/h 'to 10km/h in 7.3 seconds
for drive = 35 to 85	'PWM drive incremented from 35 to 85 in steps of 1
for x = 1 to 4	'4 secondary loops of PWM (4 * 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 25	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
't=14.6s thirteen:	'linearly decrements electric bicycle velocity from 10km/h to '0km/h
for drive = 85 to 0	'PWM drive decremented from 85 to 0 in steps of 1
for x = 1 to 5	'5 secondary loops of PWM (5 * 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 21	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
't=7.25s fourteen:	'linearly increments the electric bicycle velocity from 0km/h 'to 13km/h in 7.25 seconds
for drive = 0 to 110	'PWM drive incremented from 0 to 110 in steps of 1
for x = 1 to 2	'2 secondary loops of PWM (2 * 29.66ms)
PWM 5,drive,25	'PWM command provides PWM signal at pin 5 for 25ms
next	'next PWM loop
pause 6	'calculated pause time to match time duration
next	'next drive amount
return	'go to next command in "main" program
't=3.5s fifteen:	'keeps electric bicycle at a constant velocity of 13km/h for 3.5 'seconds
for x = 1 to 118	'118 loops of PWM (3.5 * 33.715 loops/second)
PWM 5,110,25	'PWM drive = 110
next	'next PWM loop
return	'go to next command in "main" program
't=10s sixteen:	'linearly increments the electric bicycle velocity from 13km/h 'to 20.5km/h in 10 seconds

<pre> for drive = 110 to 185 for x = 1 to 4 PWM 5,drive,25 next pause 13 next return </pre>	<pre> PWM drive incremented from 110 to 185 in steps of 1 4 secondary loops of PWM (4 * 29.66ms) PWM command provides PWM signal at pin 5 for 25ms next PWM loop calculated pause time to match time duration next drive amount go to next command in "main" program </pre>
<pre> t=27.5s seventeen: for drive = 185 to 0 for x = 1 to 4 PWM 5,drive,25 next pause 29 next return </pre>	<pre> linearly decrements electric bicycle velocity from 20.5km/h to 0km/h in 27.5s PWM drive decremented from 185 to 0 in steps of 1 4 secondary loops of PWM (4* 29.66ms) PWM command provides PWM signal at pin 5 for 25ms next PWM loop calculated pause time to match time duration next drive amount go to next command in "main" program </pre>
<pre> t=7.5s eighteen: for drive = 0 to 170 PWM 5,drive,25 pause 14 next return </pre>	<pre> linearly increments the electric bicycle velocity from 0km/h to 17.25km/h in 7.5 seconds PWM drive incremented from 0 to 170 in steps of 1 PWM command provides PWM signal at pin 5 for 25ms calculated pause time to match time duration next drive amount go to next command in "main" program </pre>
<pre> t=6.7s nineteen: for drive = 170 to 71 for x = 1 to 2 PWM 5,drive,25 next pause 7 next return </pre>	<pre> linearly decrements electric bicycle velocity from 17.25km/h to 9km/h in 6.7s PWM drive decremented from 170 to 71 in steps of 1 PWM command provides PWM signal at pin 5 for 25ms calculated pause time to match time duration next drive amount go to next command in "main" program </pre>
<pre> t=4.5s twenty: for drive = 71 to 205 PWM 5,drive,25 pause 4 next return </pre>	<pre> linearly increments the electric bicycle velocity from 9km/h to 21.3km/h in 4.5 seconds PWM drive incremented from 71 to 205 in steps of 1 PWM command provides PWM signal at pin 5 for 25ms calculated pause time to match time duration next drive amount go to next command in "main" program </pre>
<pre> t=9.3s twentyone: for drive = 205 to 105 for x = 1 to 3 PWM 5,drive,25 </pre>	<pre> linearly decrements electric bicycle velocity from 21.3km/h to 12.5km/h in 9.3s PWM drive decremented from 205 to 105 in steps of 1 3 secondary loops of PWM (3* 29.66ms) PWM command provides PWM signal at pin 5 for 25ms </pre>

next	`next PWM loop
pause 3	`calculated pause time to match time duration
next	`next drive amount
return	`go to next command in "main" program
τ=10s	
twentytwo:	`linearly increments the electric bicycle velocity from
	`12.5km/h to 20.1km/h in 10 seconds
for drive = 105 to 184	`PWM drive incremented from 105 to 184 in steps of 1
for x = 1 to 4	`4 secondary loops of PWM (4 * 29.66ms)
PWM 5,drive,25	`PWM command provides PWM signal at pin 5 for 25ms
next	`next PWM loop
pause 6	`calculated pause time to match time duration
next	`next drive amount
return	`go to next command in "main" program
τ=7.3s	
twentythree:	`linearly decrements electric bicycle velocity from 20.1km/h
	`to 0km/h in 7.3s
for drive = 184 to 0	`PWM drive decremented from 184 to 0 in steps of 1
PWM 5,drive,25	`PWM command provides PWM signal at pin 5 for 25ms
pause 10	`calculated pause time to match time duration
next	`next drive amount
return	`go to next command in "main" program
τ=13.5s	
twentyfour:	`holds the electric bicycle at a velocity of 0 km/h for 13.5
	`seconds
pause 13500	`13.5 second pause
return	`go to next command in "main" program
τ=6.4s	
twentyfive:	`linearly increments the electric bicycle velocity from 0km/h
	`to 6.2km/h in 6.4 seconds
for drive = 0 to 48	`PWM drive incremented from 0 to 48 in steps of 1
for x = 1 to 4	`4 secondary loops of PWM (4 * 29.66ms)
PWM 5,drive,25	`PWM command provides PWM signal at pin 5 for 25ms
next	`next PWM loop
pause 11	`calculated pause time to match time duration
next	`next drive amount
return	`go to next command in "main" program
τ=13.5s	
twentysix:	`linearly decrements electric bicycle velocity from 6.2km/h to
	`0km/h in 13.5 seconds
for drive = 48 to 0	`PWM drive decremented from 48 to 0 in steps of 1
for x = 1 to 9	`9 secondary loops of PWM (9 * 29.66ms)
PWM 5,drive,25	`PWM command provides PWM signal at pin 5 for 25ms
next	`next PWM loop
pause 9	`calculated pause time to match time duration
next	`next drive amount
return	`go to next command in "main" program
τ=7.5s	

<pre> twentyseven: for drive = 0 to 147 PWM 5,drive,25 pause 21 next return </pre>	<pre> `linearly increments the electric bicycle velocity from 0km/h `to 16.9km/h in 7.5 seconds `PWM drive incremented from 0 to 147 in steps of 1 `PWM command provides PWM signal at pin 5 for 25ms `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>
<pre> `t=11s twentyeight: for x = 1 to 371 PWM 5,147,25 next return </pre>	<pre> `keeps electric bicycle at a constant velocity of 16.9km/h for `11 seconds `371 loops of PWM (11 * 33.715 loops/second) `PWM drive = 147 `next PWM loop `go to next command in "main" program </pre>
<pre> `t=24s twentynine: for drive = 147 to 0 for x = 1 to 5 PWM 5,drive,25 next pause 0 next return </pre>	<pre> `linearly decrements electric bicycle velocity from 16.9km/h `to 0km/h in 24s `PWM drive decremented from 147 to 0 in steps of 1 `5 secondary loops of PWM (5 * 29.66ms) `PWM command provides PWM signal at pin 5 for 25ms `next PWM loop `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>
<pre> `t=8s thirty: pause 8000 return </pre>	<pre> `holds the electric bicycle at a velocity of 0 km/h for 8 seconds `8 second pause `go to next command in "main" program </pre>
<pre> `t=15s thirtyone: for drive = 0 to 64 for x = 1 to 7 PWM 5,drive,25 next pause 3 next return </pre>	<pre> `linearly increments the electric bicycle velocity from 0km/h `to 8km/h in 15 seconds `PWM drive incremented from 0 to 64 in steps of 1 `7 secondary loops of PWM (7 * 29.66ms) `PWM command provides PWM signal at pin 5 for 25ms `next PWM loop `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>
<pre> `t=7.3s thirtytwo: for drive = 64 to 0 for x = 1 to 3 PWM 5,drive,25 next pause 24 next return </pre>	<pre> `linearly decrements electric bicycle velocity from 8km/h to `0km/h in 7.3 seconds `PWM drive decremented from 64 to 0 in steps of 1 `3 secondary loops of PWM (3 * 29.66ms) `PWM command provides PWM signal at pin 5 for 25ms `next PWM loop `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>

<pre> t=50s thirtythree: pause 50000 return </pre>	<pre> `holds the electric bicycle at a velocity of 0 km/h for 50 `seconds `50 second pause `go to next command in "main" program </pre>
<pre> t=9.9s thirtyfour: for drive = 0 to 64 for x = 1 to 5 PWM 5,drive,25 next pause 4 next return </pre>	<pre> `linearly increments the electric bicycle velocity from 0km/h `to 8.5km/h in 9.9 seconds `PWM drive incremented from 0 to 64 in steps of 1 `5 secondary loops of PWM (5 * 29.66ms) `PWM command provides PWM signal at pin 5 for 25ms `next PWM loop `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>
<pre> t=13s thirtyfive: for x = 1 to 438 PWM 5,64,25 next return </pre>	<pre> `keeps electric bicycle at a constant velocity of 8.5km/h for 13 `seconds `438 loops of PWM (13 * 33.715 loops/second) `PWM drive = 64 `next PWM loop `go to next command in "main" program </pre>
<pre> t=14.5s thirtysix: for drive = 64 to 113 for x = 1 to 9 PWM 5,drive,25 next pause 23 next return </pre>	<pre> `linearly increments the electric bicycle velocity from 8.5km/h `to 13km/h in 14.5 seconds `PWM drive incremented from 64 to 113 in steps of 1 `9 secondary loops of PWM (9 * 29.66ms) `PWM command provides PWM signal at pin 5 for 25ms `next PWM loop `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>
<pre> t=14.3s thirtyseven: for drive = 113 to 0 for x = 1 to 4 PWM 5,drive,25 next pause 8 next return </pre>	<pre> `linearly decrements electric bicycle velocity from 13km/h to `0km/h in 14.3s `PWM drive decremented from 13 to 0 in steps of 1 `4 secondary loops of PWM (4 * 29.66ms) `PWM command provides PWM signal at pin 5 for 25ms `next PWM loop `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>
<pre> t=48.5s thirtyeight: pause 48500 return </pre>	<pre> `holds the electric bicycle at a velocity of 0 km/h for 48.5 `seconds in 48.5s `48.5 second pause `go to next command in "main" program </pre>
<pre> t=17.5s </pre>	

<p>thirtynine:</p> <pre> for drive = 0 to 158 for x = 1 to 3 PWM 5,drive,25 next pause 21 next return </pre>	<pre> `linearly increments the electric bicycle velocity from 0km/h `to 17km/h in 17.5 seconds `PWM drive incremented from 0 to 158 in steps of 1 `3 secondary loops of PWM (3 * 29.66ms) `PWM command provides PWM signal at pin 5 for 25ms `next PWM loop `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>
<p>$t=6.5s$ forty:</p> <pre> for drive = 158 to 0 PWM 5,drive,25 pause 11 next return </pre>	<pre> `linearly decrements electric bicycle velocity from 17km/h to `0km/h in 6.5s `PWM drive decremented from 158 to 0 in steps of 1 `PWM command provides PWM signal at pin 5 for 25ms `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>
<p>$t=4.5s$ fortyone:</p> <pre> for drive = 0 to 15 for x = 1 to 9 PWM 5,drive,25 next pause 16 next return </pre>	<pre> `linearly increments the electric bicycle velocity from 0km/h `to 2.3km/h in 4.5 seconds `PWM drive incremented from 0 to 15 in steps of 1 `9 secondary loops of PWM (9 * 29.66ms) `PWM command provides PWM signal at pin 5 for 25ms `next PWM loop `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>
<p>$t=4.5s$ fortytwo:</p> <pre> for drive = 15 to 0 for x = 1 to 9 PWM 5,drive,25 next pause 16 next return </pre>	<pre> `linearly decrements electric bicycle velocity from 2.3km/h to `0km/h in 4.5 s `PWM drive decremented from 15 to 0 in steps of 1 `9 secondary loops of PWM (9 * 29.66ms) `PWM command provides PWM signal at pin 5 for 25ms `next PWM loop `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>
<p>$t=22s$ fortythree:</p> <pre> for drive = 0 to 199 for x = 1 to 3 PWM 5,drive,25 next pause 21 next return </pre>	<pre> `linearly increments the electric bicycle velocity from 0km/h `to 22.5km/h in 22 seconds `PWM drive incremented from 0 to 199 in steps of 1 `3 secondary loops of PWM (3 * 29.66ms) `PWM command provides PWM signal at pin 5 for 25ms `next PWM loop `calculated pause time to match time duration `next drive amount `go to next command in "main" program </pre>
<p>$t=12.3s$</p>	

```

fortyfour:                                'linearly decrements electric bicycle velocity from 22.5km/h
                                           'to 0km/h
for drive = 199 to 0                       'PWM drive decremented from 199 to 0 in steps of 1
PWM 5,drive,25                             'PWM command provides PWM signal at pin 5 for 25ms
pause 32                                   'calculated pause time to match time duration
next                                       'next drive amount
return                                     'go to next command in "main" program

t=35s
fortyfive:                                'holds the electric bicycle at a velocity of 0 km/h for 35
                                           'seconds
pause 35000                               '35 second pause
return                                     'go to next command in "main" program

```

***** END SECTION SUBPROGRAMS *****

***** DISPLAY SUBPROGRAMS **** NOT USED *****

The following subprograms are used to display important data on an LCD screen. The BPI-216 serial LCD from Scott Edwards Electronics (www.seetron.com) is used. The LCD is connected to Pin 15 on the BS2 and can display 2 lines of data using 16 characters on each line

DISPLAY_CAL:

'NOT USED

```

'serout 15,n9600,[I,CLR]                  'clears the screen in order to update the new data
                                           'displayed
'serout 15,n9600,[I,128]                  'moves cursor to position 128 on LCD (leftmost
                                           'position first line)
'serout 15,n9600,["PWM Drive = ",dec adcbits] 'display the adcbits obtained from the 0831 A/D
                                           'converter (0-255)

```

'return

'----- NOT USED -----

```

'calselect_display:                       'lets the user know that the calibration mode has been selected
                                           'on the LCD display

```

```

'serout 15,n9600,[I,CLR]                  'clears the screen in order to update the new data displayed

```

```

'for x = 0 to 20                           '21 loops

```

```

'serout 15,n9600,[I,128]                  'moves LCD cursor to position 128 (leftmost position of top
                                           'line)

```

```

'serout 15,n9600,["PWM CALIBRATION"]

```

```

'serout 15,n9600,[I,192]                  'moves cursor to position 192 (leftmost 2nd line)

```

```

'serout 15,n9600,["SELECTED"]

```

```

'next

```

```

'goto main_calibrate

```

'----- NOT USED -----

'Testselect_display:

'serout 15,n9600,[I,CLR] 'clears the screen in order to update the new data displayed

'for x = 0 to 20

'serout 15,n9600,[I,128] 'moves LCD cursor to position 128 (leftmost position of top line)

'serout 15,n9600,["EBIKE TEST"] 'display "EBIKE TEST" on LCD

'serout 15,n9600,[I,192] 'moves cursor to position 192 (leftmost 2nd line)

'serout 15,n9600,["SELECTED"] 'display "SELECTED" on LCD

'next

'serout 15,n9600,[I,CLR] 'clears the screen in order to update the new data displayed

'for x = 0 to 40

'serout 15,n9600,[I,128] '41 loops
'moves LCD cursor to position 128 (leftmost position of top line)

'serout 15,n9600,["PRESS YELLOW"] 'display "PRESS YELLOW" on LCD

'serout 15,n9600,[I,192] 'moves cursor to position 192 (leftmost 2nd line)

'serout 15,n9600,["BUTTON"] 'display "BUTTON" on LCD

'next

'goto start_button

***** END OF NYEBTC PROGRAM *****

VITA

Surname: Stackhouse Given Names: Richard Vernon

Place of Birth: Mission, British Columbia, Canada

Educational Institutions Attended:

University of Victoria, 1995 to 2002

University College of the Fraser Valley, 1992 to 1995

Degrees Awarded:

M.A.Sc., Department of Mechanical Engineering, University of Victoria, 2002

B.Eng. (Distinction), Department of Mechanical Engineering, University of Victoria, 1999

Honours and Awards:

PTC (Pro/ENGINEER) Student Design Challenge Winner, 2002

University of Victoria Fellowship Award, 2000 to 2001

BC Advanced Systems Institute Award, 2000

NSERC Undergraduate Research Award, 1999

Daniel Lavoie Memorial Scholarship, 1995

Hollister Engineering Award, 1992

Publications:

Canadian Hydrogen Association Paper, "Hydrogen Fuel Cell Power For Electric Bicycles", Stackhouse, Dong, 2001.

Technical Report: "Portable Fuel Cell Power System Design Adequate For Electric Bicycle Propulsion", Stackhouse, 2001.

NRC Technical Report: "An Examination of Wall-pressure-based Boundary-correction Methods with Off-center models in a Closed Wind Tunnel". Cooper, Corber, Stackhouse, Mokry, Hackett. NRC LTR-A-50, 2000.

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Title of Thesis:

Modeling, Design, and Testing of Electric Bicycles

Author



Richard Vernon Stackhouse

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