Micro Urban Electric Vehicle
Phase II – Modeling

Functional Requirements
&
Performance Specifications

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I. Introduction

A significant movement occurring in society is a push for environmental awareness and conservation of energy. Alternative energy sources and enhanced energy efficiency are among the leading technical challenges in implementing this emerging ideal. The Electrical and Computer Engineering Department at Bradley University has decided to participate in meeting these challenges and launched a multi-year project that aims to develop a low carbon footprint electric vehicle for urban commuting that is commercially viable. This requires an ultra compact and lightweight vehicle that is also street legal. It will be capable of holding up to two passengers, traveling up to 55 mph, and traversing up to 50 miles in all weather conditions, making it ideal for a daily commute for the average user [1].

In the first phase of this project, the group performed research in order to design and implement a prototype test platform for a low carbon footprint, single passenger electric urban vehicle. It is currently capable of a maximum speed of 40mph and has a theoretical maximum range of 25 miles. In order to accomplish this, the team researched available battery technology, motors, electronics, and design concepts for regenerative braking (which will be implemented in a later version). While some of the issues surrounding mechanical design were addressed by the previous group, the detailed design of all the vehicle subsystems, particularly regenerative braking and optimized battery sizing, is the next major step in development. In order for this to be implemented, detailed models for vehicle subsystems must be developed.

II. Functional Description

A. Introduction

In the 2009-2010 academic year, the project enters its second phase. Using the research, design, and test platform developed by the previous year's team, this year's team will create a Simulink© system block diagram model that incorporates all parts of the platform. The initial goal, which is necessary in order to begin modeling, is to acquire the necessary experimental data to not only develop the Simulink© blocks, but to also test their validity. Using this data, the team will develop each individual Simulink© block of the platform in order to test the outputs given by the simulation against the experimental results. Ultimately, by continuing to refine the model, this project will provide the future design teams with an accurate and flexible Simulink© model for vehicle design.

B. Goals

- Modeling
  - Battery
  - DC Motor
  - Controller
  - Vehicle Dynamics
  - Loads
    - A/C
    - Lighting
    - Heat
- Verify and Optimize Model
  - Perform data acquisition and compare with experimental results of current platforms
  - Adjust model until desired performance is achieved.
  - Compare experimental and simulated outputs of subsystems and modify Simulink© blocks as necessary
  - Optimize Simulink© blocks

C. Physical Model

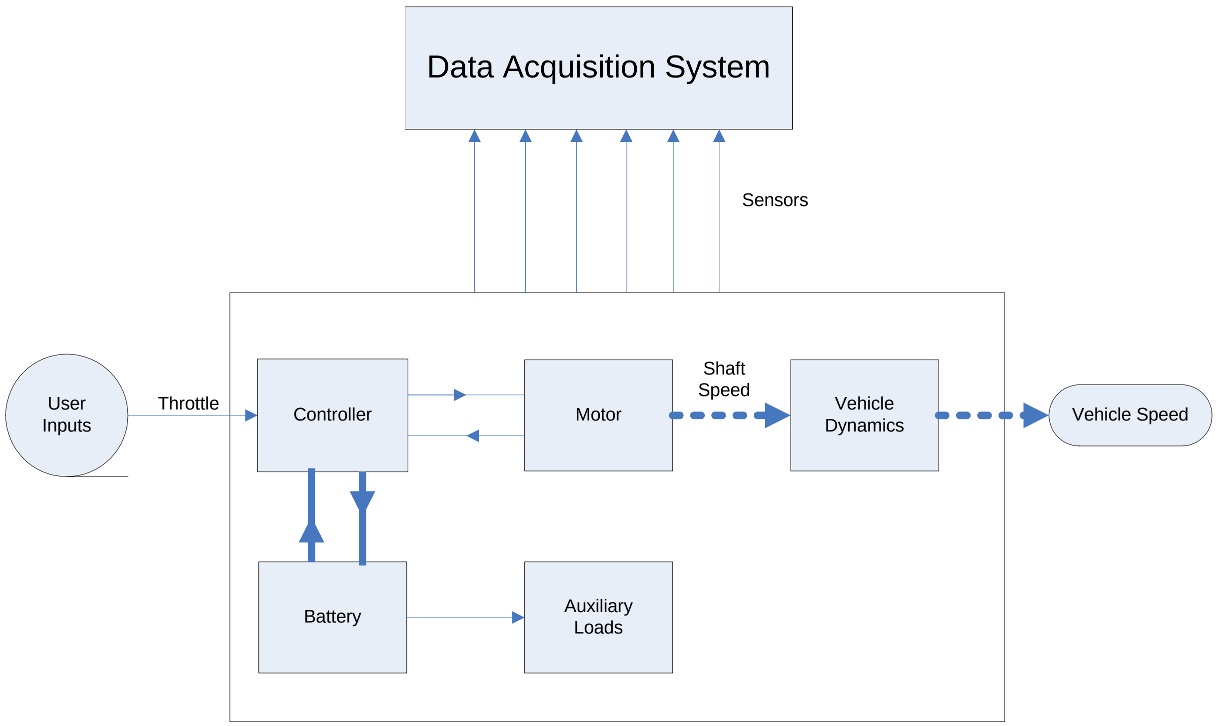

Figure 1: High Level Block Diagram of Experimental Platform

Figure 1 is the high-level block diagram of the physical experimental platform. The user (driver) controls a throttle and a brake, the mechanical actuation of which are transformed into electric inputs to the controller. Based on these inputs, the controller develops two PWM signals from the battery terminal voltage. These signals are applied to the field windings and armature windings of the motor with duty cycles adjusted for desired motor speed and torque. When the shaft torque is applied to the rear axle, vehicle dynamics (speed and acceleration) will change depending on vehicle properties such as vehicle mass, wheel friction, and wheel inertia. Sensors located on the vehicle measure the quantities listed in Table 1. The sensor outputs connect to a data acquisition system. The information provided by the data acquisition system is important for supplying inputs for the Simulink© block diagram model

Table 1: Sensors

Measurements	Type	Accuracy
Battery Current	Analog	3%
Battery Voltage	Analog	3%
Battery Temperature	Analog	3%
Motor Temperature	Analog	3%
Controller Temperature	Analog	3%
Wheel RPM	Digital	3%
Vehicle Acceleration	Unknown	3%
Throttle Position	Analog	3%
Brake Position	Analog	3%
Armature Current	Analog	3%
Armature Voltage	Analog	3%
Field Current	Analog	3%
Field Voltage	Analog	3%

D. Simulink© Model

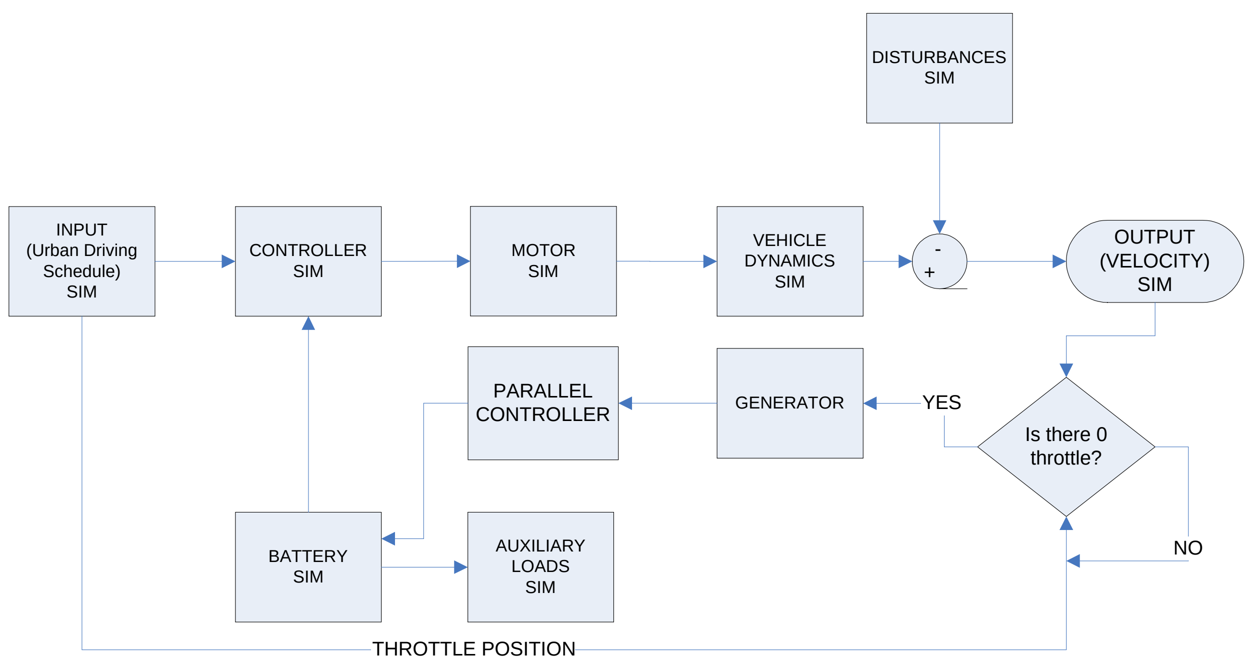

Figure 2: Simulink© High Level Block Diagram

Figure 2 is the high-level overview of the Simulink© block diagram model for the current physical platform. The inputs are throttle and brake, which are derived from measured driving data obtained from the data acquisition system on the physical platform. Figure 3 represents an example of a city driving schedule from the EPA [2] for which the MUEV will be configured and optimized. The input data is fed into the Simulink© block diagram model. The signal flow from block to block is as follows.

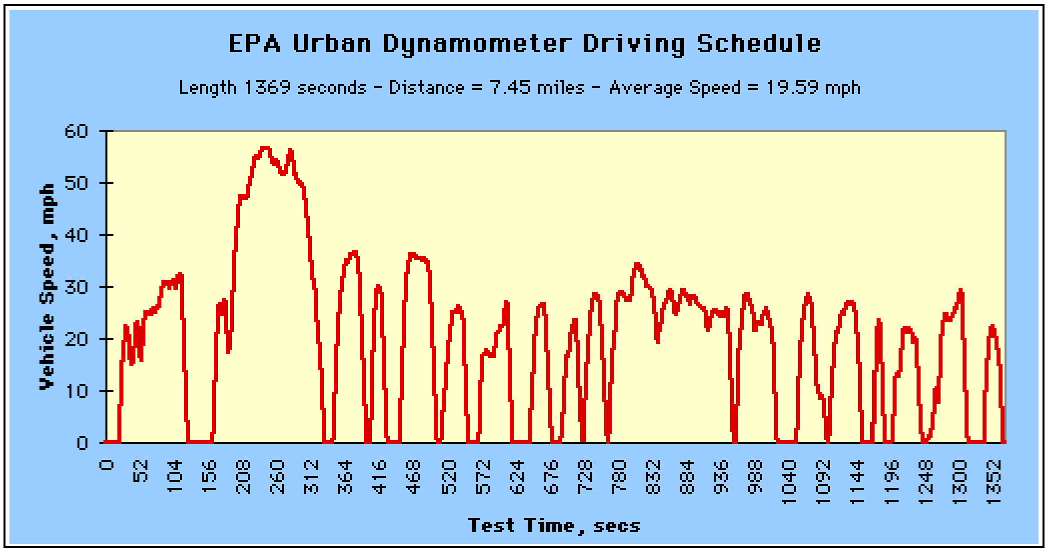

Figure 3: Urban Driving Schedule [2]

The controller block accepts battery terminal voltage from the battery block and throttle and brake signal inputs and generates two PWM signals applied to the motor block. This PWM signal provides the input to the motor block, generating a shaft speed and back EMF. The vehicle block accepts the shaft speed and applies it to the vehicle properties, which include vehicle weight, wheel friction, and wheel inertia, to produce an ideal RPM velocity. The disturbance block, which contains external disturbances such as wind resistances, slopes, and road friction, impacts the ideal RPM to produce the actual RPM of the vehicle. The auxiliary load block consists of heat, A/C, radio, data acquisition, and lights and accepts battery terminal voltage from the battery block whenever in use.

The regenerative braking feature of the MUEV occurs when there is a 0 throttle input or a break input. For either of these inputs, the vehicle speed will be fed back through a parallel path of the motor model, which serves as a generator. This then feeds back to a parallel controller block, which is the same physical controller block but behaves differently for regenerative current. It feeds the generated current into the battery and also limits the maximum amount of current that is being fed into the battery. If this is not done, the battery could be damaged or destroyed.

III. Functional Requirements

A. Data Acquisition Requirements

The data acquisition system (DAS) shall be capable of running two different test modes and will acquire data via the use of sensors and LabVIEW.

- The first mode shall be for long term test runs and shall acquire data at a slower rate.
- The second mode shall be for short term runs and be capable of taking data every 1ms.
- The DAS shall be capable of interfacing a minimum of 20 sensors.
    - Of these 20 sensors, the DAS shall accept five digital and 15 analog inputs.
- All inputs shall be differential in nature, meaning each input will have its own reference terminal.
- All inputs shall have a rate of 1000 samples/second and shall be sampled simultaneously.

B. Simulation Requirements

Each simulation block shall be capable of producing Y% accurate outputs for X% accurate inputs, provided that the user has the proper parameters for that given block within Z% accuracy. These percentage values are largely unknown at this point. Each system block shown in Figure 2 has specific parameters that can be adjusted for a replacement component, which are listed in Table 2 below. Each block shall be ideally capable of producing an output with a % error equal to or less than the % error of the input and the block parameters.

Table 2: Variable Parameters

Motor Model	Battery Model	Vehicle Properties
Armature Resistance (Ra)	Series Resistance (Rs)	Vehicle Mass
Field Resistance (Rf)	Shorter Time Constant Resistance (Rts)	Wheel Radius
Armature Inductance (La)	Shorter Time Constant Capacitance (Cts)	Equivalent Inertia
Field Inductance (Lf)	Longer Time Constant Resistance (Rtl)	Equivalent Friction
Viscous Friction Coefficient (b)	Longer Time Constant Capacitance (Ctl)	**Disturbances**
Inertia (J)	Overall Capacitance of Battery (Ccap)	Wind Resistances
Inputs	**Controller**	Grade
Driving Schedule (throttle and brake)	TBD	Road Friction

IV. Modeling

A. Motor Model

The MUEV utilizes a separately-excited DC motor that has been modeled in Figure 7-1. The motor accepts two PWM signals from the controller and generates a field and armature current to control the shaft velocity [3]. The field current i_f is described as

$$V_f = R_f i_f + L_f(di_f/dt) \qquad \textbf{Equation 1}$$

The armature current can be found from

$$V_a = R_a i_a + L_a(di_a/dt) + e_g \qquad \textbf{Equation 2}$$

The motor back emf is expressed as

$$E_g = K_v \omega i_f \qquad \textbf{Equation 3}$$

The torque developed by the motor is

$$T_d = K_t * i_f * i_a = J(d\omega/dt) + B*\omega + T_L \qquad \textbf{Equation 4}$$

Where ω = motor speed [rad/s]

B = viscous friction constant [N*m/rad/s]

K_v = voltage constant [V/A * rad/s]

$K_t = K_v$ = torque constant

L_a = armature circuit inductance [H]

L_f = field circuit inductance [H]

R_a = armature circuit resistance [ohms]

R_f = field circuit resistance [ohms]

T_L = load torque [N*m]

Unfortunately, an accurate model requires additional depth than what is provided from the above equations. The torque constant K_t is actually a function of the field armature current i_f and the machine constant, K_m, such that $K_t = K_m i_f$. The machine constant is also variable, being a function of the field current i_f. In order to establish this relationship between K_m and i_f, data points were taken from a motor performance test provided by D&D Motors that allowed K_m to be computed at various field currents. A plot of these values is shown in Figure 4 below.

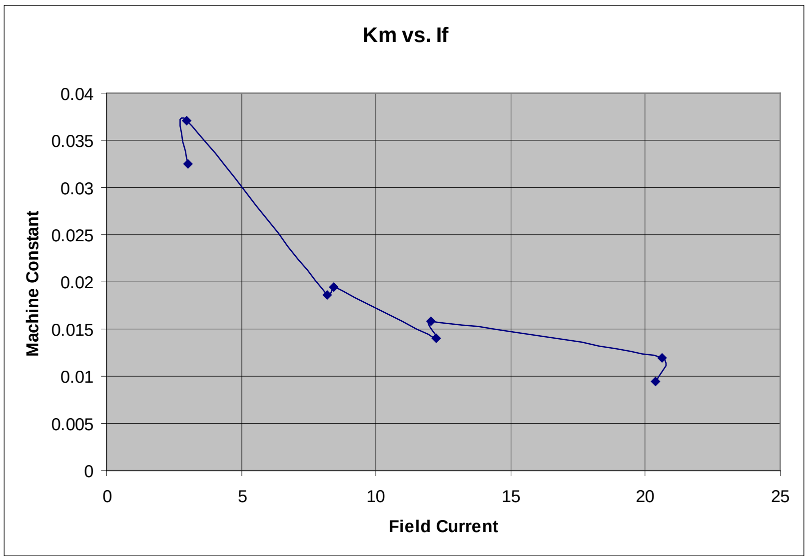

Figure 4: K_m vs. I_f Plot

The two machine constant values within a close proximity to the same field current value corresponds to the maximum and minimum armature current values provided in the performance test for that given field current. By averaging the two values and plotting a curve with that average, a smoother curve was developed and fitted to create the equation for K_m shown below.

$$K_m = (1.16*10^{-4})*(i_f)^2 - .00396*i_f + .0455 \qquad \textbf{Equation 5}$$

With this relationship established, the final form of the model could be created, as shown in Figure 5. Note that the load torques being subtracted from the motor torque are being derived in the vehicle dynamics section of the model and consist of columbic friction torque of the load and the motor, dynamic friction torque of the load and the motor, and acceleration torque of the load. In this case, the load refers to the vehicle itself.

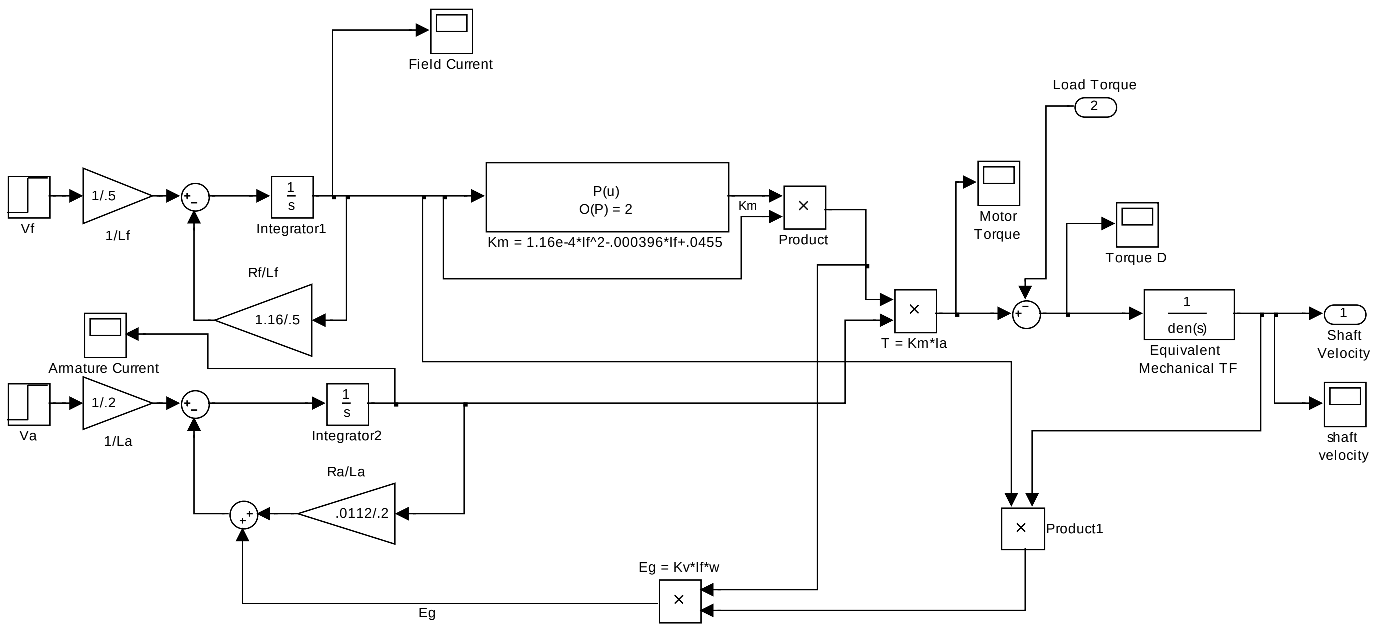

Figure 5: Separately-Excited DC Motor Model

B. Modeling the Battery

The basic model for the MUEV's battery is derived from analyses performed on lithium-ion batteries [4]. This model will be sufficient for applying to the Interstate Lead Acid battery being used in the current vehicle. The concept for the model is derived from the basic battery circuit model shown in Figure 6.

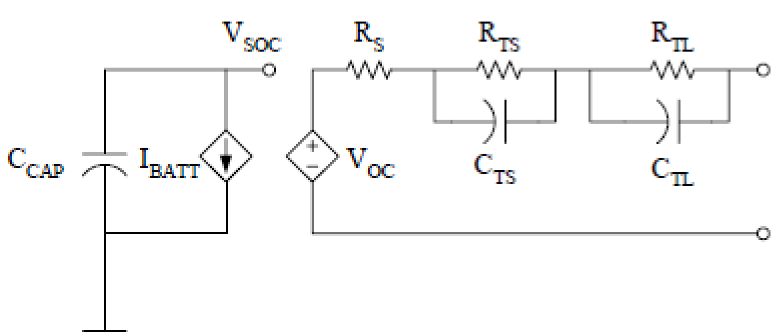

Figure 6: Basic Battery Circuit [4]

The model consists of two separate circuits linked by a voltage controlled voltage source and a current controlled current source. One circuit represents the overall capacity of the battery, while the other circuit models the internal resistance and transient behavior of the battery using a series resistance and two RC circuits. C_{CAP} represents the capacity of the battery. R_S is the series resistance, R_{TS} and C_{TS} refer to resistance and capacitance in the shorter time constant RC circuit, and R_{TL} and C_{TL} refer to the resistance and capacitance in the longer time constant RC circuit. The voltage controlled voltage source linking the two circuits is used to represent the non-linear relationship between the state of charge (S.O.C.) and the open circuit voltage, V_{OC}. This relationship is normalized such that when the voltage across C_{CAP} is 1V, the battery is at 100% (S.O.C.).

From the circuit in Figure 6, an ordinary differential equation was found to describe it. The equation appears as follows [4].

$$\dot{\mathbf{x}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -(R_{TS}C_{TS})^{-1} & 0 \\ 0 & 0 & -(R_{TL}C_{TL})^{-1} \end{bmatrix} \mathbf{x} + \begin{bmatrix} -C_{CAP}^{-1} \\ -C_{TS}^{-1} \\ -C_{TL}^{-1} \end{bmatrix} \mathbf{u} \qquad \textbf{Equation 6}$$

$$\mathbf{y} = g(x_1) + x_2 + x_3 + R_S \mathbf{u}$$

Here, g(x) is the non-linear function which maps S.O.C. to V_{OC} and the input **u** is the current entering the battery. The output **y** is the voltage across the battery terminals, while the state vector **x** represents the voltages across C_{CAP}, C_{TS}, and C_{TL}. Thus, the three voltage equations are further broken down into the following form…

$$d\mathbf{x_1}/dt = -C_{CAP}^{-1} * \mathbf{u} \qquad \textbf{Equation 7}$$

$$d\mathbf{x_2}/dt = -(R_{TS} * C_{TS})^{-1} * \mathbf{x_2} - C_{TS}^{-1} * \mathbf{u} \qquad \textbf{Equation 8}$$

$$d\mathbf{x_2}/dt = -(R_{TL} * C_{TL})^{-1} * \mathbf{x_3} - C_{TL}^{-1} * \mathbf{u} \qquad \textbf{Equation 9}$$

$$\text{where } \mathbf{x_1} = V_{CCAP}, \mathbf{x_2} = V_{CTS}, \mathbf{x_3} = V_{CTL}$$

It is from this form that the battery block is envisioned. By integrating each voltage and then summing them with the series voltage of the battery, the final output **y** is achieved. This model is shown in Figure 7 [4].

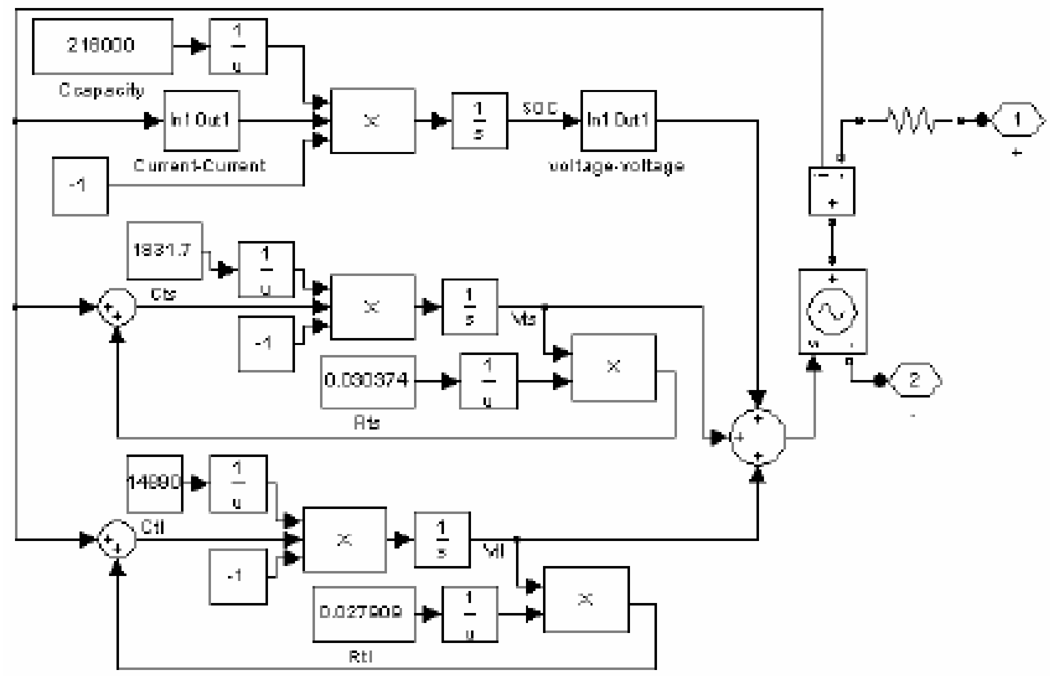

Figure 7: Battery Model [4]

C. Modeling the Controller

Currently, there is not enough information to model the controller. The manufacturer is allegedly providing behavioral curves for the armature and field currents, which will make accurate modeling of the controller possible. Until that information is somehow acquired or directly measured, the controller model is a work in progress.

D. Modeling the Vehicle Dynamics

The model of the vehicle dynamics will convert the motor shaft velocity to the vehicles linear velocity [5]. The angular shaft velocity will first be converted to an axle velocity by multiplying the gear ratio (N_1/N_2). Then it will be multiplied by the radius of the wheel in order to obtain linear vehicle velocity.

$$v = (N_1/N_2)*r*\omega \qquad \textbf{Equation 10}$$

Where ω = shaft velocity [rad/s]

N_n = turns ratio of respective gear

r = wheel radius [m]

With these relationships formed a Simulink© model was formed as shown in Fig. 8.

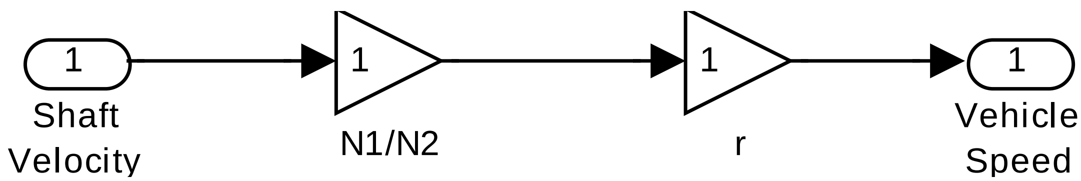

Figure 8: Vehicle Dynamics Model

The acceleration torque can be derived by taking the derivative of vehicle speed to obtain acceleration, then multiplying this acceleration by the mass of the vehicle and the radius of the wheels. This equation is shown below.

$$T_a = (dv/dt)*m*r \quad \textbf{Equation 11}$$

Where T_a = Acceleration Torque [N*m], m = vehicle mass

V. Datasheet

Listed below are datasheet with pertinent information concerning the vehicle platform, the battery, the motor, and the controller.

Vehicle Platform

Model #:	4170
Transmission type:	Torque converter with #420 1/2" Pitch chain
Brakes:	7.5" hydraulic disc with parking brake
Tires (Front):	16"x6"x8"
Tires (Rear):	16"x7"x8"
Dimensions:	72"L x 46"W x 49"H
Wheel Base :	47.5"
Seat to petals:	33" to 37"
Max. Rider weight:	300lbs

Battery x 3

Product ID:	Interstate SLA1161
Type:	Sealed lead acid
Voltage:	12
Termination:	INSERT W/BOLT REPLACES FLAG TY
Chemistry:	SLA OR VRLA VALVE REGULATED S
Color:	FLAME RETARDENT
Weight:	34.8
Width:	6.50
Length:	7.75
Height:	6.69
Capacity:	44 Ah

Controller

Type:	Alltrax DCX-600
Max current (2 min):	600A
Max current (5 min):	350A
Max current (1 hr):	250A
Voltage range:	24-48
Weight:	8lbs
Voltage drop @ 100A:	<0.08V

Motor

Type: D&D Separately Excited 24-48V DC Motor
Model #: ES-10E-33
Max power: 17HP
Max speed: 3000RPM
Weight: 57lbs

VI. Patents

Table 3 lists a number of relevant patents for both phases of the MUEV design [6].

Table 3: Related Patents

Phase I Patents	
Patent number	*Description*
5,291,960	Hybrid electric vehicle regenerative braking energy recovery system
5,585,209	Bipolar lead/acid batteries
5,941,328	Electric vehicle with variable efficiency regenerative braking depending upon battery charge state.
6,037,751	Method and apparatus for charging batteries
6,116,368	Electric vehicle with battery regeneration dependent on battery charge state
6,866,350	Regenerative braking on an electrical vehicle when towed
7,455,133	Electric four-wheel drive vehicle and control unit for same
7,546,536	Electric motor
Phase II Patents	
Patent number	*Description*
5,878,189	Control system for a separately excited DC motor
6,192,745	Method and system for simulating vehicle and roadway interaction
6,885,951	Method and device for determining the state of function of an energy storage battery
7,098,665	Method for prediction of the internal resistance of an energy storage battery, and a monitoring device for energy storage batteries
7,498,772	Method and system of modeling energy flow for vehicle battery diagnostic monitoring

VII. Standards

U.S. Department of Energy – Illinois Electric Laws and Incentives:

Neighborhood Vehicle Access to Roadways

Neighborhood vehicles may only be operated on streets if authorized by the local government and where the posted speed limit is 35 miles per hour (mph) or less. Neighborhood vehicles are allowed to cross a road or street at an intersection where the road or street has a posted speed limit greater than 35 mph. Neighborhood vehicles are defined as self-propelled, electronically powered, four-wheeled motor vehicles (or a self-propelled, gasoline-powered four-wheeled motor vehicle with an engine displacement under 1,200 cubic centimeters) which are capable of attaining in one mile a speed of more than 20 mph, but not more than 25 mph, and which conform to federal regulations under Title 49 of the Code of Federal Regulations, Part 571.500. (Reference 625 Illinois Compiled Statutes 5/11-1426.1)

Underwriters Laboratories:

Standard for Safety, *Electric Vehicle (EV) Charging System Equipment, UL 2202*

This Standard covers conductive and inductive charging system equipment intended to be supplied by a branch circuit of 600 volts or less for recharging the storage batteries in over-the-road EVs. In an inductive charging system, there is no direct metal-to-metal electrical connection between the charger and the vehicle. Instead, electrical power is passed through an electromagnetic field between the primary winding of a transformer, which is usually located off board the vehicle, to the secondary winding of the transformer which is usually located on board the vehicle. Conversely, in a conductive charging system, power is passed from the charger to the vehicle though direct metal-to-metal contact by way of a coupler or a plug and receptacle suitable for EV charging.

Standard for Safety, *Personnel Protection Systems for EV Supply Circuits, UL 2231*

This Standard covers devices and systems intended for use in accordance with the *National Electrical Code ® (American National Standards Institute/National Fire Protection Association 70)*, to reduce the risk of electric shock to the user from accessible parts, in grounded or isolated circuits for charging EVs.

Standard for Safety, *Plugs, Receptacles, and Couplers for EVs, UL 2251*

This Standard covers plugs, receptacles, vehicle inlets, and connectors rated up to 800 amperes and up to 600 volts ac or dc, intended for conductive connection systems, for use with EVs in accordance with the *National Electrical Code* ® for either indoor or outdoor nonhazardous locations.

Society of Automotive Engineers [7]:

Standard for Hybrid Electric Vehicle (HEV) & Electric Vehicle (EV) Terminology, SAE J1715_200802

This SAE Information Report contains definitions for electric vehicle terminology. It is intended that this document be a resource for those writing other electric vehicle documents, specifications, standards, or recommended practices. Hybrid electric vehicle terminology will be covered in future revisions of this document or as a separate document.

Vibration Testing of Electric Vehicle Batteries, SAE J2380_200903

This SAE Recommended Practice describes the vibration durability testing of a single battery (test unit) consisting of either an electric vehicle battery module or an electric vehicle battery pack. For statistical purposes, multiple samples would normally be subjected to such testing. Additionally, some test units may be subjected to life cycle testing (either after or during vibration testing) to determine the effects of vibration on battery life. Such life testing is not described in this procedure; SAE J2288 may be used for this purpose as applicable.

Recommended Practice for Performance Rating of Electric Vehicle Battery Modules, SAE J1798_200807

This SAE Recommended Practice provides for common test and verification methods to determine Electric Vehicle battery module performance. The document creates the necessary performance standards to determine (a) what the basic performance of EV battery modules is; and (b) whether battery modules meet minimum performance specification established by vehicle manufacturers or other purchasers. Specific values for these minimum performance specifications are not a part of this document.

Recommended Practice for Packaging of Electric Vehicle Battery Modules, SAE J1797_200806

This SAE Recommended Practice provides for common battery designs through the description of dimensions, termination, retention, venting system, and other features required in an electric vehicle application. The document does not provide for performance standards. Performance will be addressed by SAE J1798. This document does provide for guidelines in proper packaging of battery modules to meet performance criteria detailed in J1766.

U.S. Department of Transportation:

571.500 Standard No. 500; Low-speed Vehicles

571.305 Standard No. 305; Electric-powered vehicles: electrolyte spillage and electrical shock protection.

National Electric Code 2005 Edition:

Article 625 – Electric Vehicle Charging Systems

VIII. Schedule

The schedule of tasks shown in Table 4 is an educated projection of the activities that will be completed during the spring semester based on what has been accomplished in the fall semester.

Table 4: Schedule of Tasks

Date		Brian Kuhn	Steven Komperda	Matt Leuschke
Week 1	**1/26/2010**	Finalize motor model	Finalize vehicle dynamics model	Research controller and finalize data acquisition
Week 2	**2/2/2010**	Test motor and controller for model parameters and verify model		Research controller and finalize data acquisition
Week 3	**2/9/2010**	Test motor and controller for model parameters and verify model		
Week 4	**2/16/2010**	Model controller and model vs. test conditions		
Week 5	**2/23/2010**	Finalize battery model	Test batteries for model parameters	
Week 6	**3/2/2010**	Verify battery model	Perform coast down test on vehicle chassis	
Week 7	**3/9/2010**	Connect model subsystems	Verify vehicle dynamics model	Verify controller model
Week 8	**3/23/2010**	Interface sensors for data acquisition to vehicle		
Week 9	**3/30/2010**	Test data acquisition system		
Week 10	**4/6/2010**	Test driving schedule on vehicle		
Week 11	**4/13/2010**	Test driving schedule on vehicle		
Week 12	**4/20/2010**	Verify complete vehicle model		
Week 13	**4/27/2010**	Update vehicle model to match driving model		
Week 14	**5/4/2010**	Finalize report and presentation		
Week 15	**5/11/2010**	Presentation		

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