A Methodology for Sizing Components in a Dual-Voltage Automotive Electrical System

by

Irene Y. Kuo

Submitted to the Department of Electrical Engineering and Computer Science
in Partial Fulfillment of the Requirements for the Degrees of
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ABSTRACT

Current trends in automotive electrical systems indicate that the existing single-voltage 12V system will not be sufficient in satisfying the power demands of future cars, which will include many more electrical comfort features as well as electrical loads which were previously implemented mechanically. An MIT/Industry Consortium has proposed a dual-voltage system consisting of a high-power alternator delivering current to a 42V bus, which is charged by a 36V battery and connected via a DC/DC converter to a 14V bus, which is charged by a 12V battery. Using the circuit simulation tool Saber, the effects of varying vehicle driving speeds and load events on power flow and energy usage are investigated. Simulation results are used to evaluate power demands and to provide insight into the sizing of key power supply components such as the alternator, batteries, and DC/DC converter.

Thesis Supervisor: Prof. Bernard C. Lesieutre
Title: Associate Professor of Electrical Engineering and Computer Science

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Most importantly, of course, is the love and support I've received from my family throughout the years. They, more than anyone else, have put up with my complaints, my worries, and my tears. Thanks to: my mom, who brought me home-cooked food and fruit, even when I insisted I didn't need it; my dad, who still found time in his busy and around-the-world schedule to encourage me and comfort my fears; Elaine and Peter, who show me regularly that those things most treasured in life are indeed not material.

Above all, I give thanks and praise to my Lord and Father in Heaven. By His strength and through faith in Him have I accomplished anything, and may any achievements of mine serve only to reflect His wondrous grace. All glory be to God.

Irene Kuo

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Chapter 1

Introduction

1.1 Background

Modern automobile electrical systems are designed with a single 12V lead-acid battery supplying power to an electrical bus regulated at 14V. This bus supports all of the automobile's electrical loads, e.g., the starter, windshield wipers, power windows, climate control, etc.

The power used to supply all the loads is divided between the 12V battery and the alternator. The battery generally is responsible for producing high power for short durations. For example, the battery provides the necessary power to engage the starter and start the engine, a demand of about 3000 W over a duration of about two to three seconds.

Once the engine is running, the car's alternator provides a certain amount of current dependent on the speed of the alternator shaft and the voltage on the 14V bus to which it is connected. The alternator delivers current to the 14V bus and supplies most of the required power. At times, the alternator may not be able to sufficiently supply the loads' current demands; in such cases, the battery will discharge and supply what the alternator cannot. The use of the battery in supplying load demand usually occurs when the car is idling; when the alternator shaft is rotating at idling speed, the alternator can produce only minimal current for distribution on the 14V bus.

Such discharging of the battery will result in a decrease in the battery's state of charge, a measure of its available stored energy. The battery, however, needs to be charged sufficiently such that it will start the engine on the subsequent drive. Thus, if the battery's state of charge decreases, it must be restored to an adequate state of charge by the time the engine is turned off. The recharging of the battery occurs when, while the car is running, the alternator is producing more current than is demanded by the loads; the excess current flows into the battery and increases the battery's state of charge. Battery charging usually occurs when the vehicle is traveling at high speeds; when the alternator's shaft is rotating quickly, the alternator can provide a significant amount of current which is often more than is demanded by the loads.

1.2 Motivation

The existing 14V electrical system described above adequately supplies the loads with which average modern automobiles are equipped. When one considers expensive high-end automobiles, however, one immediately sees the need for an increase in the power capacity of automotive electrical systems. High-end luxury vehicles, which have more power-hungry electrical loads than the average car, represent the future of automobile comfort; electrical accessories found only on modern luxury cars today are likely candidates for additional features on the standard car of the future.

To see the need for a more powerful automotive electrical system to satisfy high-power vehicles, one can consider the electrical requirements of the average limousine. Oftentimes, a limousine will idle for long periods of time, with elaborate lighting, entertainment, and climate control loads turned on. These periods may be followed by short drives at relatively low speeds. In such cases, not only can an average alternator not produce the power demanded by all the loads, but the battery is not given the opportunity to be adequately recharged [6]. To satisfy the demands of such scenarios, limousines are often equipped with extra batteries and heavy-duty alternators, which are designed for much higher current output than average alternators.

Although the average car of the future probably will not include all the luxuries of a limousine, the average driver of the future will desire an increasing number of comfort features in his automobile. In addition, improving technology will allow many existing mechanical loads to be made electrical, in order to improve efficiency. Electromechanical valve engines, for example, are likely to be introduced within the next couple years. Furthermore, future cars may include "an electrically heated windshield, electric water pump, electric engine-cooling fan, electric steering and possibly an electric-pump-driven active suspension system" [7]. Consequently, future cars will not only have a greater number of loads, but additional loads will likely require significantly more electrical power than existing loads.

Because of the foreseeable need for a new, more powerful automotive electrical system, a dual-voltage system has been proposed by the MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems. This dual-voltage system consists of the familiar 14V bus along with an additional 42V bus. 42V was chosen as the nominal voltage of the additional bus because of a number of factors, including safety specifications and affordable semiconductor device voltage limitations [5]. In the proposed dual-voltage system, high-power demanding loads, such as the starter and heaters, are placed on the 42V bus, while smaller loads, such as driver electronics, are placed on the 14V bus. The alternator supplies current directly to the 42V bus, and the two buses are connected by a DC/DC converter.

1.3 Project Overview

This section describes the administrative structure within which the research was conducted. It also describes the purpose and goals of the research.

1.3.1 The MIT/Industry Consortium

This project was developed as part of the MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems, a research group within the Laboratory for Electromagnetic and Electronic Systems (LEES) at MIT. The work conducted by the Consortium is divided into the research units listed below in Table 1.1.

Table 1.1: Research Units of the Consortium

Research Unit Number	Title	Description
1	DC/DC Converters for Dual-Voltage Electrical Systems	Investigate the design of DC/DC converters for dual-voltage systems and develop fundamental technologies which facilitate their use in this application
2	High Power Generation and Starting	Determine the benefits and limitations of high-power alternator and combined starter/alternator designs to meet the requirements of the proposed 42/14V system
3	MAESTrO 3.5 Development	Develop a knowledge based software tool for the design, analysis, and evaluation of automotive electrical systems
4	Electrical System Transient Investigation	Investigate the generation and control of high-power electrical transients in dual/higher-voltage power supply architectures
5	Comparative Power Supply Architecture Evaluation	Develop comparative evaluations of candidate dual/higher-voltage power supply architectures to provide insight into their desirability for different vehicle applications
6	Load-Flow Study of the Dual-Voltage System	Evaluate power and energy flow in dual-voltage electrical systems during vehicle drivecycles in order to provide insights into the sizing of key power supply components
7	Dual-Voltage System Protection and Fusing	Investigate alternative strategies, configurations, and components to provide fault protection in dual-voltage systems
8	42V PowerNet System Management Using Multiplexed Remote Switching	Explore techniques for using multiplexed remote switching in dual-voltage systems to perform bus energy management and other useful system functions
9	EMI/EMC in Dual-Voltage Electrical Systems	Investigate EMI/EMC issues and suppression techniques associated with the introduction of higher voltages and increased accessory power levels
10	Economic Analysis of Dual-Voltage Automobile Electrical System	System-level economic analysis of the dual-voltage automobile electrical system, including manufacturing costs of critical new components and the process of transition

The work described in this paper was conducted under Research Unit #6, the Load-Flow Study of the Dual-Voltage System. Research included collaborative efforts with Research Units #1, #4, and #8, as will be described throughout this thesis.

As summarized in Table 1.1, the research presented in this paper seeks to provide insight into the sizing of the key power supply components. Through software simulations of the dual-voltage system, combined with knowledge of existing methods for sizing the battery and alternator in single-voltage systems, this research also aims to provide basic guidelines by which dual-voltage sizing can be accomplished.

1.3.2 Definition of Terms

Presently there is no industry standard regarding the sizing of the alternator and the battery in the existing 14V automotive system; each automobile manufacturer uses its own internal guidelines to size the power supply components. The term "sizing" refers to the process of determining how certain parameters need to be specified in order for all system power demands to be satisfied.

The alternator, for example, is characterized by the amount of current that can be produced at given shaftspeeds. "Sizing" the alternator, then, refers to how much current the alternator needs to output in order to satisfy system requirements. Usually alternators are referred to by the amount of current that can be output at idle alternator shaftspeed (about 1800 rpm) and at high alternator shaftspeed (about 6000 rpm). For example, a 60-120A alternator can supply about 60 A when the engine is idling and about 120 A when the alternator shaftspeed is rotating at high speed.

Batteries, on the other hand, are sized according to their Ampere-hour (Ah) capacity, a measure of the amount of charge stored in the battery. 1 Ah is equivalent to 3600 Coulombs; a 100 Ah battery, for example, can deliver 5 A over 20 hours.

The DC/DC converter, according to the design used in this dual-voltage system, can be sized according to the maximum amount of current that is allowed to be drawn through it onto the 14V bus.

In the design of the new dual-voltage system, key power supply components, in particular, the alternator, the batteries, and the DC/DC converter, need to be sized appropriately. In the absence of even a standard method for sizing components in a single-voltage system, a methodology for sizing components in the dual-voltage system needs to be developed.

1.3.3 Overview of Research Methods

Insights into the sizing of key power supply components were developed through software simulations of the dual-voltage system. The circuit simulation tool Saber was used. Saber has a graphical user interface with which one can model the circuit being simulated. Using MAST, the Saber programming language, Saber models were developed for all components used in the dual-voltage system, e.g., the alternator, batteries, DC/DC converter, and loads. By connecting the individual components as specified in a dual-voltage architecture, a complete design of the dual-voltage system was made. One could then run a DC analysis to find the DC operating point of the system, followed by a transient analysis. By simulating the system over time, the flow of power through the system was monitored as the power supply and demand changed with vehicle speed changes and load on-off transitions. The simulation results, and in particular, the final battery state of charge at the end of each transient analysis, were then used to make judgments regarding the sizing of the power supply components.

Chapter 2

Simulation Data

2.1 Drivecycles

To evaluate the power flow in the dual-voltage system, the system's supply and demand of power under typical driving conditions needed to be simulated. This required the use of two types of data: drivecycles and loadcycles.

Drivecycles are data files that specify the car's speed in kilometers per hour in one second time increments, and the gear of the car at each moment in time. Drivecycles used in the simulations were specified as `.dat` (data) files. Each file has two or three columns: time in seconds in the first column, vehicle speed in kilometers per hour in the second, and gear in the third, if specified. Figure 2.1 below shows a typical drivecycle, the vehicle's speed in kilometers per hour plotted against time in seconds.

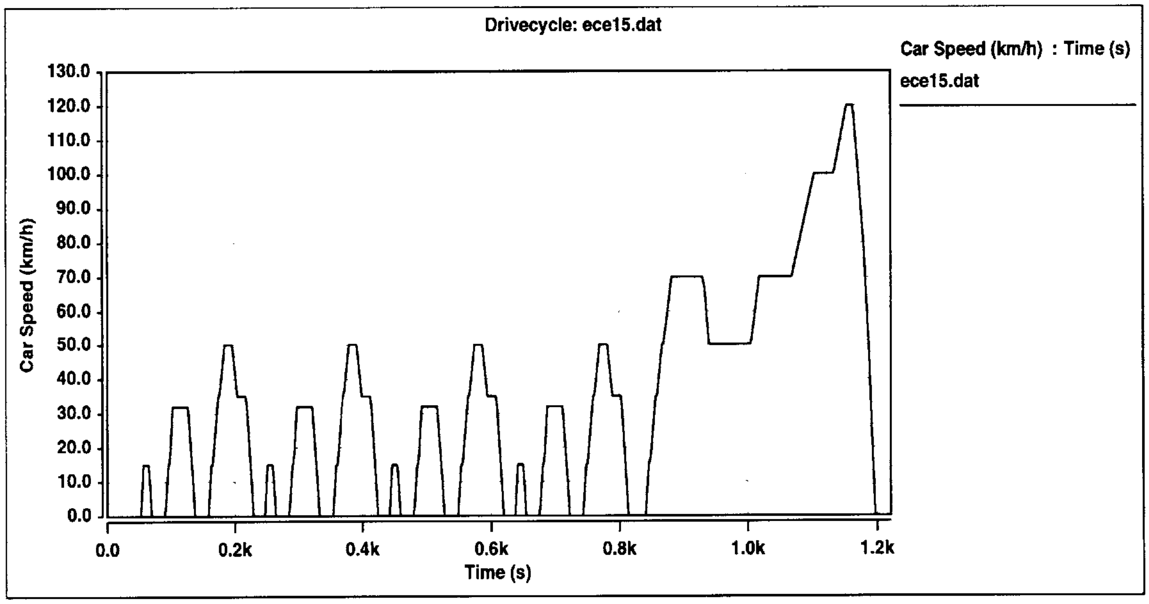

Figure 2.1: European Combined City and Highway Drivecycle

This particular drivecycle, called `ece15.dat`, represents a European combined city and highway driving profile; about the first 800 seconds of the data represent stop-and-go driving similar to what one would expect in city driving, and the last 400 seconds have the car travelling at faster speeds, as if driving on a highway.

These data are used to determine the alternator shaftspeed in revolutions per minute at corresponding time units. In turn, that data, when input into an alternator model, can be used to determine the amount of current being supplied to the electrical system during the vehicle's drive.

Realistic drivecycles are important in verifying that any information derived from simulations are indicative of real-life driving situations. Drivecycles are specified in varying lengths and intensities. Those which consist predominantly of low-speed driving and which last for maybe ten or twenty minutes may be representative of quick, run-to-the-store type drives. Longer drivecycles which are on the order of thirty minutes to an hour and which include periods of high-speed highway driving may be used to simulate commutes to and from work. Even longer drivecycles are on the order of hours; those which consist mainly of low-speed stop-and-go driving may represent city driving such as a taxi might experience, while those which have constant high-speed driving can represent a country drive.

There exists a number of standard and non-standard drivecycles which are used in the industry. Table 2.1 lists each drivecycle used in this study and a brief description of each.

Table 2.1: Drivecycles Used in Simulations

Drivecycle Filename	Description
idle.dat	Vehicle is idling
summer_const.dat	Vehicle is involved in continuous high-speed driving
ece15_city.dat	Vehicle is involved in continuous city (stop-and-go) driving

2.2 Loadcycles

Besides specifying the car's speed, which determines the amount of power that can be supplied to the system by the alternator, it is also necessary to specify the sequence of load events which will demand power from the electrical system.

A loadcycle is a data file which specifies when each load is turned on and off. To incorporate loadcycles into the simulations, loadcycles are specified in `.scs` (Saber command script) files; before running a simulation, the script is run, specifying exactly when in the simulation each load will be turned on and off. Sections 3.2 and 4.1.1 describe in more detail the format and use of the loadcycle files.

Loadcycles are dependent on a number of factors, including environmental conditions. For example, the weather will determine whether or not such loads as the heater, air conditioning, and front windshield wipers will be turned on, and the time of day will influence the use of headlights. Other loads, however, are entirely dependent on the driver's preferences. For example, when and for how long the radio or CD player is used can not be figured deterministically, but must be approximated according to driving experience.

Because there is no industry standard for loadcycles, one major task necessary for the success of this project was the development of realistic loadcycles. This required first specifying the conditions under which each simulation would be run, such that each loadcycle could be catered to a particular scenario. In addition, because the driving profile directly affects some loads, such as the brakes and turn signals, each loadcycle is also designed to correspond with specific drivecycles. In order to help ensure that the dual-voltage system would be evaluated under all plausible real-world conditions, most loadcycles used in the study were worst-case scenarios with particularly high power demand. Table 2.2 lists each loadcycle used, its corresponding drivecycle, and the conditions which describe the profile.

Table 2.2: Loadcycles Used in Simulations

Loadcycle Filename	Corresponding Drivecycle	Conditions
idle.scs	idle.dat	Worst-case summer: hot, raining, night-time
summer_worst_const.scs	summer_const.dat	Worst-case summer: hot, raining, night-time
winter_worst_ece15.scs	ece15_city.dat	Worst-case winter: cold, snowing, night-time

Appendix A shows all the above loadcycles in both time-sequential and Saber command script format.

Chapter 3

Implementing the Dual-Voltage Design in Saber

3.1 The Dual-Voltage Architecture Used in the Saber Design

In order to simulate the dual-voltage system, the entire system, including all subcomponents, needed to be modeled in Saber. The basic dual-voltage design consists of two buses; one supplied by the existing standard 12V battery and regulated at 14V, and the other supplied by a 36V battery and regulated at 42V. The higher-voltage bus is connected directly to the output of the 42V alternator. All high-power loads (e.g., the starter, front windshield wipers, and electromechanical engine valves for future cars) are located on the 42V bus. The 14V bus is connected to the higher bus via a DC/DC converter. All low-power loads (e.g., driver electronics and lamps) are placed on the 14V bus. Figure 3.1 below shows the design as it appears in Saber.

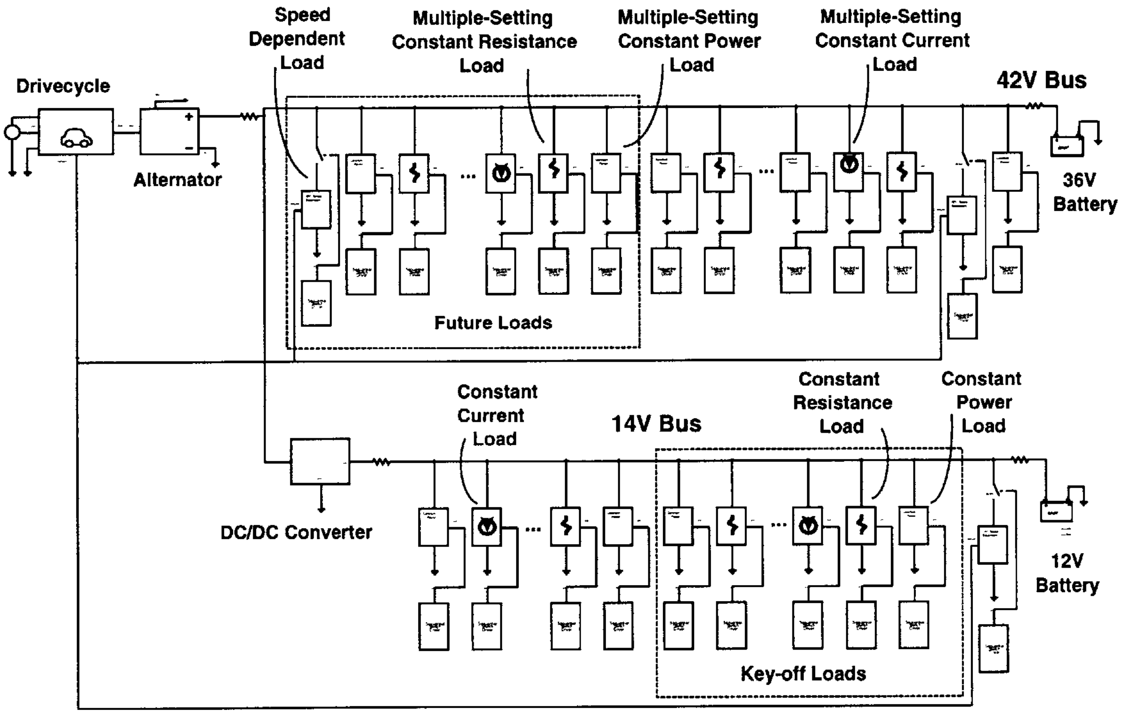

Figure 3.1: Saber Design of Dual-Voltage Automotive Electrical System

Future loads are loads which do not currently exist in vehicles but which are expected to be added in the near future. Examples of future loads include electromechanical engine valves and rear seat heaters. Key-off loads are loads that draw current even when the car is off. The vehicle's clock and anti-theft warning system are examples of key-off loads.

As seen in Figure 3.1, simulation of the dual-voltage system required the development of a number of Saber models, including models of the alternator, the DC/DC converter, the lead-acid batteries, and the loads. Figure 3.1 further shows the various possible power consumption methods used in the modeling of the many electrical loads. Each of the models developed for use in the Saber design of the dual-voltage system will be discussed individually in the following sections.

3.2 Modeling the Loads

The vehicle loadlist lists all electrical loads on a car, including each load's nominal power consumption. Typical power consumption during idling and high-speed driving are also specified if those values are different from the nominal values. The loadlist used for this study includes future loads and specifies to which bus each load should be designated under the dual-voltage system. Loads were divided according to their nominal power consumption; as mentioned in the previous section, high-power loads are placed on the 42V bus, and low-power loads are situated on the 14V bus. Appendix B Section B.1 includes two tables, one listing all 42V loads included in the Saber design, and the other all 14V loads.

The power consumption of each load can be modeled in several ways. All loads are assumed to have a constant consumption method; for the duration of the simulation, the method by which a particular load draws current stays the same. The amount of current drawn under a given power consumption method, however, might change if, for example, the load is speed-dependent; the faster the vehicle drives, the more power a speed-dependent load demands.

Three possible methods of power consumption were used: constant resistance, constant current, and constant power. Lamps and other loads whose power might fluctuate with the bus voltage were modeled as constant resistance loads. Logic and computer-type loads, such as the navigation aid, are likely to be connected to the bus through linear regulators, and thus were modeled as constant current loads. Motors, such as the starter, were approximated as constant power consumers.

In addition, some loads, such as the front windshield wipers and the heaters, have multiple settings and cannot be modeled simply by their nominal power consumption. For such loads, the Saber model accounted for three settings: low, medium, and high.

Appendix B Section B.2 categorizes all loads used in the design by power consumption method.

Regardless of the type of power consumption, all Saber load models are designed to be turned on and off by a switch (Saber component `sw_1pno`), which is controlled by a switch driver (Saber component `sdr_prsq`), as seen in Figure 3.2 below.

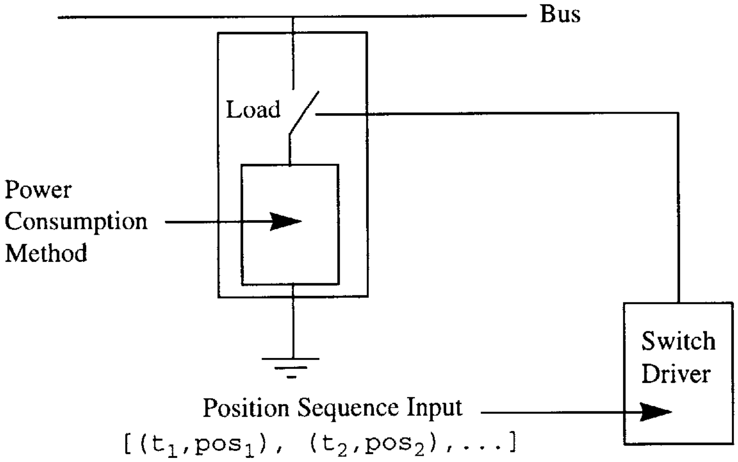

Figure 3.2: Control Circuitry for Any Type of Load

The switch driver receives an input called the position sequence, which indicates the times in seconds (`t`$_i$) at which the switch position changes and the corresponding position to which the switch is being transitioned (`pos`$_i$). For example, a position sequence might be the following: `[(0,1), (10,2), (60,1)]`. This sequence specifies that at time 0, the switch is in `pos`$_1$. After 10 seconds the switch transitions to `pos`$_2$, and after another 50 seconds, the switch returns to `pos`$_1$. In most cases, the switch has two possible positions: `pos`$_1$ corresponds to the switch open state (i.e., the load is off) and `pos`$_2$ corresponds to the switch closed state (i.e., the load is on). The switch positions are slightly different for multiple-setting loads, as will be explained in Section 3.2.5.

3.2.1 Constant Resistance Loads

The power consumed by some loads may be expected to vary somewhat with the bus voltage to which the load is connected. For example, if the bus voltage is low, a lamp might provide a weaker light than it would if the bus voltage was at its maximum. For this reason, all lamps in the design are modeled as constant resistance loads. In addition, the passenger compartment blower is modeled with constant resistance, and therefore any load which circulates air with it (i.e., the vent, air conditioning, and heater) are also modeled with constant resistances. Constant resistance loads are modeled simply with a single resistor whose value is the nominal resistance of the load. Figure 3.3 shows the schematic for the constant resistance load.

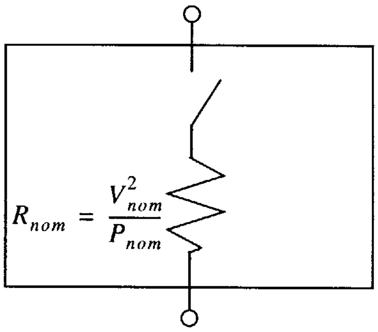

Figure 3.3: Constant Resistance Load

3.2.2 Constant Current Loads

Many loads are categorized as driver electronics, loads which help to make the driving experience more convenient and comfortable. Power windows and power locks already have been available for quite some time, but future cars promise to make available such conveniences as navigation aids. Computer-type loads are likely to be connected to the buses through linear regulators, to ensure that the current being supplied to the load is constant. Thus, all driver electronics are modeled as constant current loads.

A constant current load can be modeled as a simple constant current source with a value equivalent to the nominal power of the load divided by the nominal voltage of the bus (14V or 42V). If, however, the switch that controls the load is open, the constant current source needs a closed path in which current can flow. Figure 3.4 shows the schematic of the constant current load.

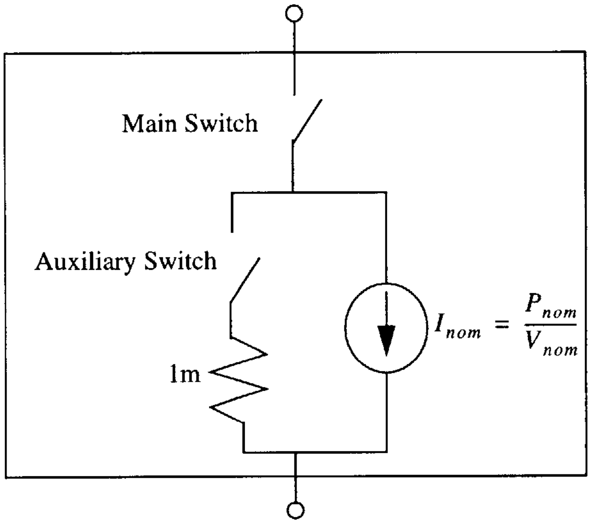

Figure 3.4: Constant Current Load

When the load is turned on, the main switch closes and the auxiliary switch opens, causing I_{nom} A to be drawn from the bus to which the load is connected. When the load is off, the main switch is open, disconnecting the load from the bus, and the auxiliary switch is closed, providing a closed path for the current flow.

3.2.3 Constant Power Loads

Some loads, such as the starter, are motor-based loads. All motors are approximated as constant power loads, utilizing the Saber constant power load component `pload`. This load, however, requires a source at all times. In order for the load to be functional even when the main switch is open, an extra source was connected to the overall load design in such a way that the source is only connected to the `pload` when the load is off. The main switch and the auxiliary switch are controlled in the same manner as described in the previous section. Figure 3.5 shows the schematic for the constant power load.

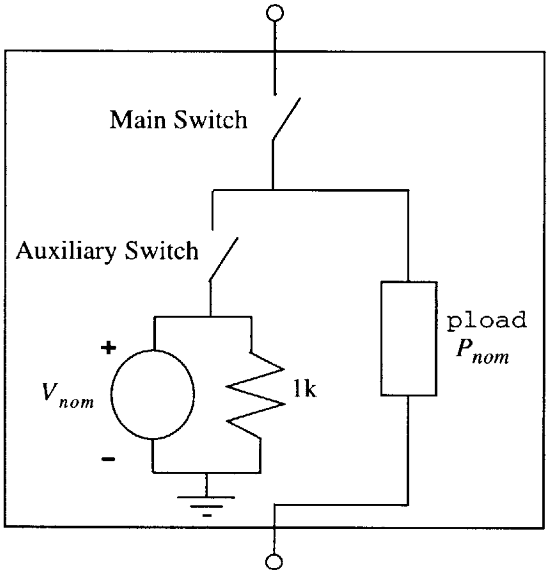

Figure 3.5: Constant Power Load

3.2.4 Speed-Dependent Resistance Loads

Some loads in the dual-voltage system are speed-dependent; the amount of power they consume is dependent on the speed at which the car is driving. If the amount of power consumed by a load is different when the car is idling and when the car is driving at high speeds, that information is specified in the loadlist. In modeling such loads, the speed dependence was assumed to be linear, such that the amount of power demanded by the load increased linearly with increasing vehicle speed. In addition, all speed-dependent loads are assumed to have resistive power consumption. The MAST code for speed-dependent loads can be found in Appendix C.

3.2.5 Multiple-Setting Constant Resistance Loads

Some loads, such as the heater, the air conditioning, and the windshield wipers, have multiple settings, each drawing different amounts of power. Since the amount of power drawn under each setting varies significantly, load settings were incorporated into some load models. This required the use of a four-position switch (Saber component `sw_1p4t`), in place of `sw_1pno`, such that one position represents the load-off state, and the other three represent three possible setting levels. $\mathtt{pos}_1$ remains the load-off state, and $\mathtt{pos}_2$, $\mathtt{pos}_3$, and $\mathtt{pos}_4$ correspond to settings of low, medium, and high, respectively. In each individual case, the nominal values used for each setting were derived from the loadlist.

Figure 3.6 shows the schematic for the multiple-setting constant resistance load, used for loads such as the vent and air conditioning.

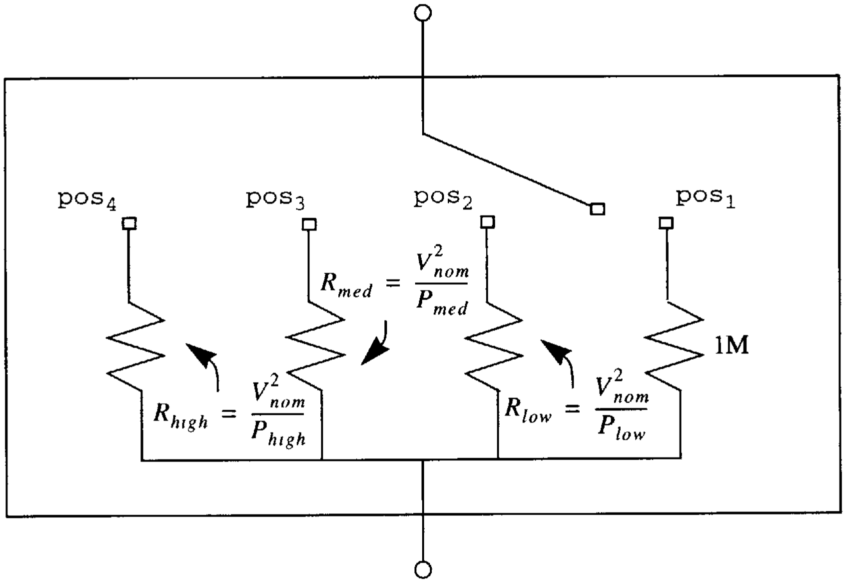

Figure 3.6: Multiple-Setting Constant Resistance Load

3.2.6 Multiple-Setting Constant Current Loads

As mentioned in Section 3.2.2, constant current source loads require a closed path in which current can flow in the case that the load is turned off. In the multiple-setting case, each current source needs a closed path whenever it is not connected to the bus. Figure 3.7 shows how the multiple-setting constant current load was implemented.

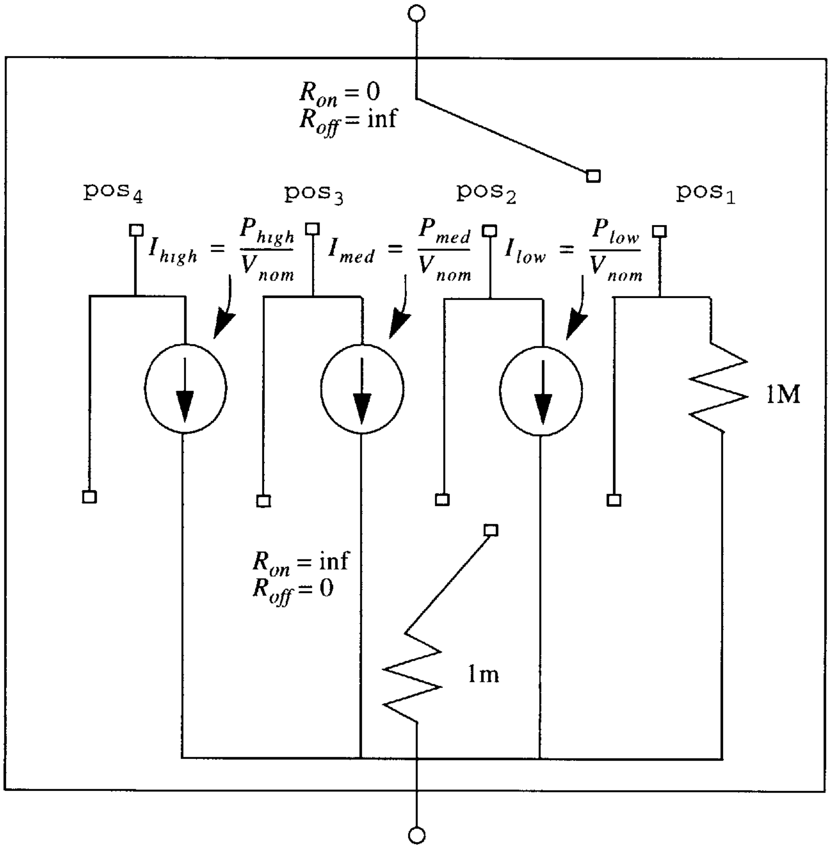

Figure 3.7: Multiple-Setting Constant Current Load

R_{on} is the switch's on-resistance, and R_{off} is the switch's off-resistance. If the load is set to low (pos$_2$), both switches will connect to pos$_2$. R_{on} and R_{off} of the top switch are set such that the load will draw I_{low} A from the bus when the switch is in pos$_2$. At the same time, R_{on} and R_{off} of the bottom switch are set such that when the switch is in pos$_2$, the I_{high} and I_{med} current sources are provided with a closed loop.

3.2.7 Multiple-Setting Constant Power Loads

The multiple-setting constant power load, like the single-setting constant power load described in Section 3.2.3, requires a source for each `pload` when the `pload` is not connected to the bus. Figure 3.8 shows the schematic for implementing this type of load.

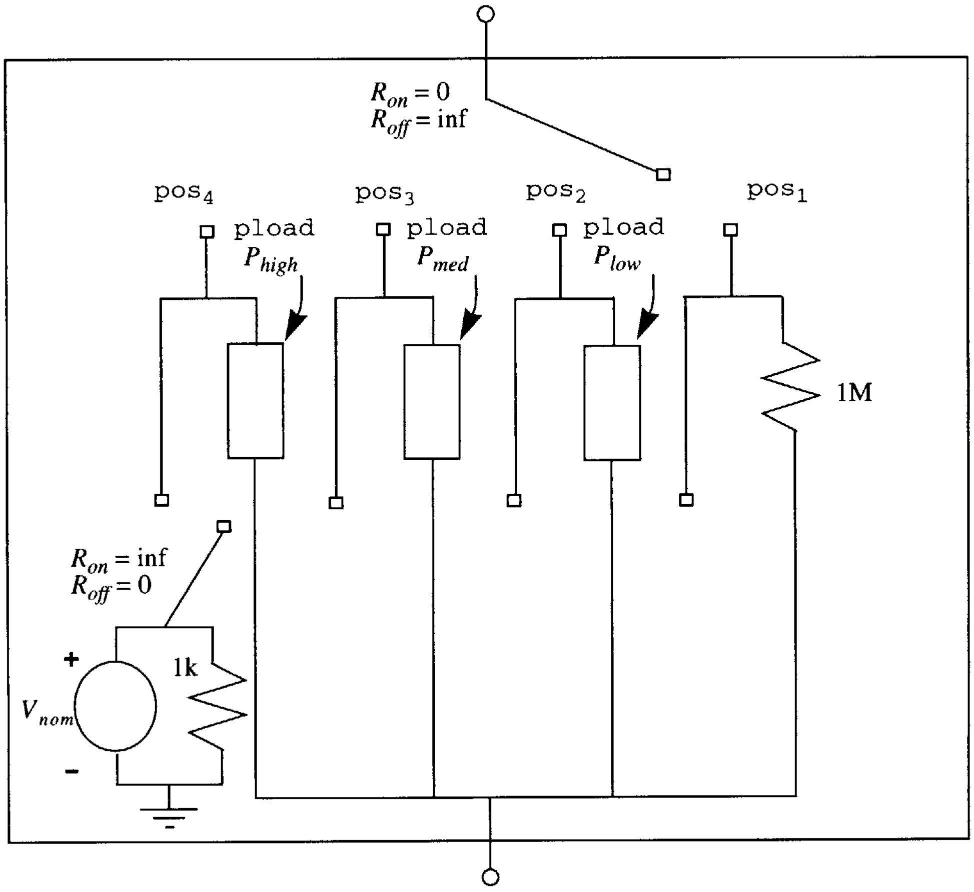

Figure 3.8: Multiple-Setting Constant Power Load

The multiple-setting constant power load was implemented much like the multiple-setting constant current load described in the previous section. The R_{on} and R_{off} values of the two switches are set such that when one `pload` is connected to the bus, the other two are disconnected from the bus and provided with a source.

3.3 Modeling the Alternator

This section explains alternator characteristic curves and describes the alternator model used in the Saber design.

3.3.1 Alternator Characteristic Curves

As mentioned in Section 1.3.2, an alternator regulated at a specific voltage can be characterized by the amount of current it can produce at specific alternator shaftspeeds. Specifically, alternators are commonly referred to by the voltage at which they are regulated, and the maximum amount of current they are capable of producing at idling alternator shaftspeed (1800 rpm) and high alternator shaftspeed (6000 rpm). For example, a 14V 60-120A alternator may have the characteristic curve shown in Figure 3.9.

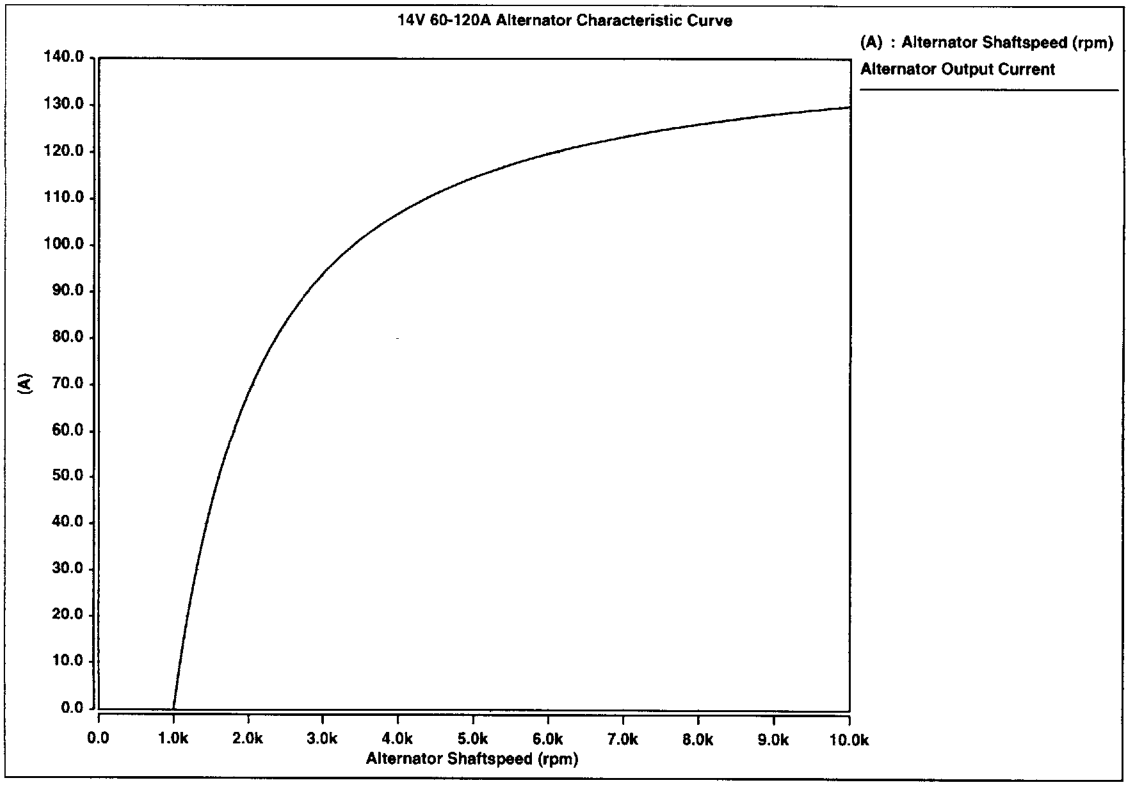

Figure 3.9: Characteristic Curve of a 14V 60-120A Alternator

3.3.2 The Alternator Circuit

The Saber alternator model used in the dual-voltage design was developed under Research Unit #4, Electrical System Transient Investigation. It is an averaged model, suitable for simulation on the order of minutes and hours. For a detailed description of the alternator, please see *Modeling and Simulation of a Claw-Pole Alternator: Detailed and Averaged Models* [4], a relevant excerpt of which is included in Appendix D.

3.3.3 Using Maple to Solve for Parameters

The alternator model, as seen by the MAST code given in Appendix D, Section D.1.2, requires the following parameters:

Table 3.1: Parameters Used in Alternator Model

Parameter	Description
k	Constant
R_s	Stator Resistance
L_s	Stator Inductance
R_f	Field Resistance
L_f	Field Inductance
p	Number of Pole Pairs
k_p	Alternator Regulator Proportional Gain
V_d	Diode Drop in Rectifier
R_{ref}	Alternator Reference Voltage
$V_{reg,min}$	Minimum Value of Regulation Voltage

Most alternator parameters are given, but k, R_s, L_s, and R_f may vary according to the alternator size. As mentioned, each size alternator can be characterized by data specifying output current versus alternator shaftspeed. From this data, the parameters k, R_s, L_s, and R_f can be derived.

From the information provided in *Modeling and Simulation of a Claw-Pole Alternator: Detailed and Averaged Models* [4], a simplified diagram of the alternator can be drawn, as seen in Figure 3.10 on the following page.

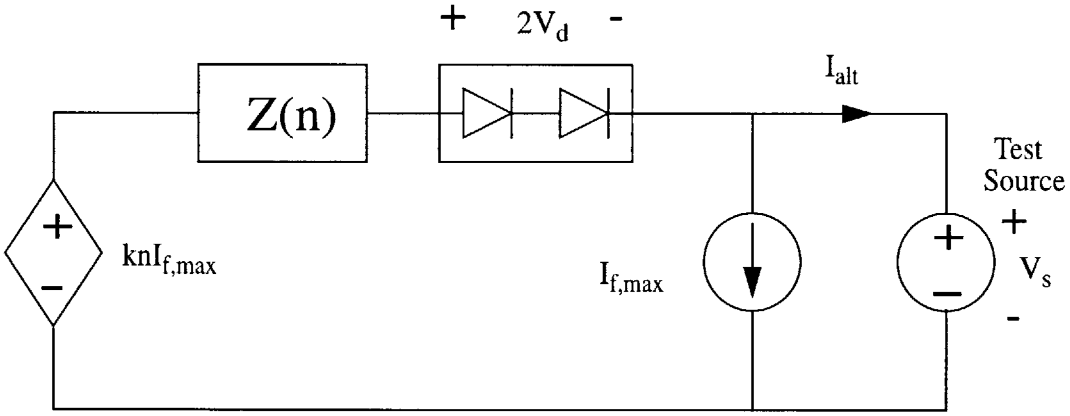

Figure 3.10: Simplified Diagram of the Averaged Alternator Model

In the above diagram, *Z(n)* is given by the following expression:

$$Z(n) = \sqrt{R_s^2 + \left(\frac{\pi}{30}L_s np\right)^2} \quad . \tag{3.1}$$

The variables used above are summarized in Table 3.2 below.

Table 3.2: Variables Used in Alternator Model

Variable	Description
k	Constant
n	Alternator Shaftspeed
$I_{f,max}$	Maximum Field Current
p	Number of Pole Pairs
R_s	Stator Resistance
L_s	Stator Inductance
V_d	Voltage Drop Across Diode
I_{alt}	Alternator Output Current
V_s	Test Source

Using the diagram in Figure 3.10 an equation expressing the alternator output current, I_{alt}, as a function of the alternator shaftspeed, n, can be written:

$$I_{alt} = \frac{knI_{f,max} - (V_s + 2V_d)}{\sqrt{R_s^2 + \left(\frac{\pi}{30}L_s np\right)^2}} - I_{f,max} \quad . \tag{3.2}$$

Available data from which an alternator's characteristic curve can be drawn specify I_{alt} for various values of n. All other variables in Equation 3.2 have known values except k, R_s, and L_s. Thus, for a given alternator size, these three variable values need to be specified in order to model that particular size alternator with the Saber model.

In order to solve for k, R_s, and L_s, Maple, a mathematics application, and the alternator data were used. For each alternator, I_{alt} was specified at 100 rpm intervals. Taking three points on the curve given by the data, three independent equations could be written of the form:

$$(I_{alt,0} + I_{f,max})\sqrt{R_s^2 + \left(\frac{\pi}{30}L_s n_0 p\right)^2} = kn_0 I_{f,max} - (V_s - 2V_d) \quad , \tag{3.3}$$

$$(I_{alt,1} + I_{f,max})\sqrt{R_s^2 + \left(\frac{\pi}{30}L_s n_1 p\right)^2} = kn_1 I_{f,max} - (V_s - 2V_d) \quad , \tag{3.4}$$

$$(I_{alt,2} + I_{f,max})\sqrt{R_s^2 + \left(\frac{\pi}{30}L_s n_2 p\right)^2} = kn_2 I_{f,max} - (V_s - 2V_d) \quad . \tag{3.5}$$

Using Maple, these three equations can be solved for the three unknowns, k, R_s, and L_s. Appendix D includes the Maple commands used.

In the absence of any 42V alternator data, the alternator data used characterized only 14V alternators. The dual-voltage design, however, requires the modeling of a 42V alternator. In order to obtain model parameters for 42V alternators, two options were used to convert the 14V data to 42V data. Both options assume that 42V alternators have the same characteristic curve shape as 14V alternators. The first method used 14V data directly for 42V characteristics; 14V 60-120A I_{alt} and n data were used in Maple to solve for parameters for a 42V 60-120A alternator. The resulting curve had the characteristic curve of a 60-120A alternator, but the Saber model parameters were specific for a 42V alternator. Figure 3.11 shows actual 14V 60-120A data and the Saber model curve fit for a 42V 60-120A alternator using parameter values obtained with Maple.

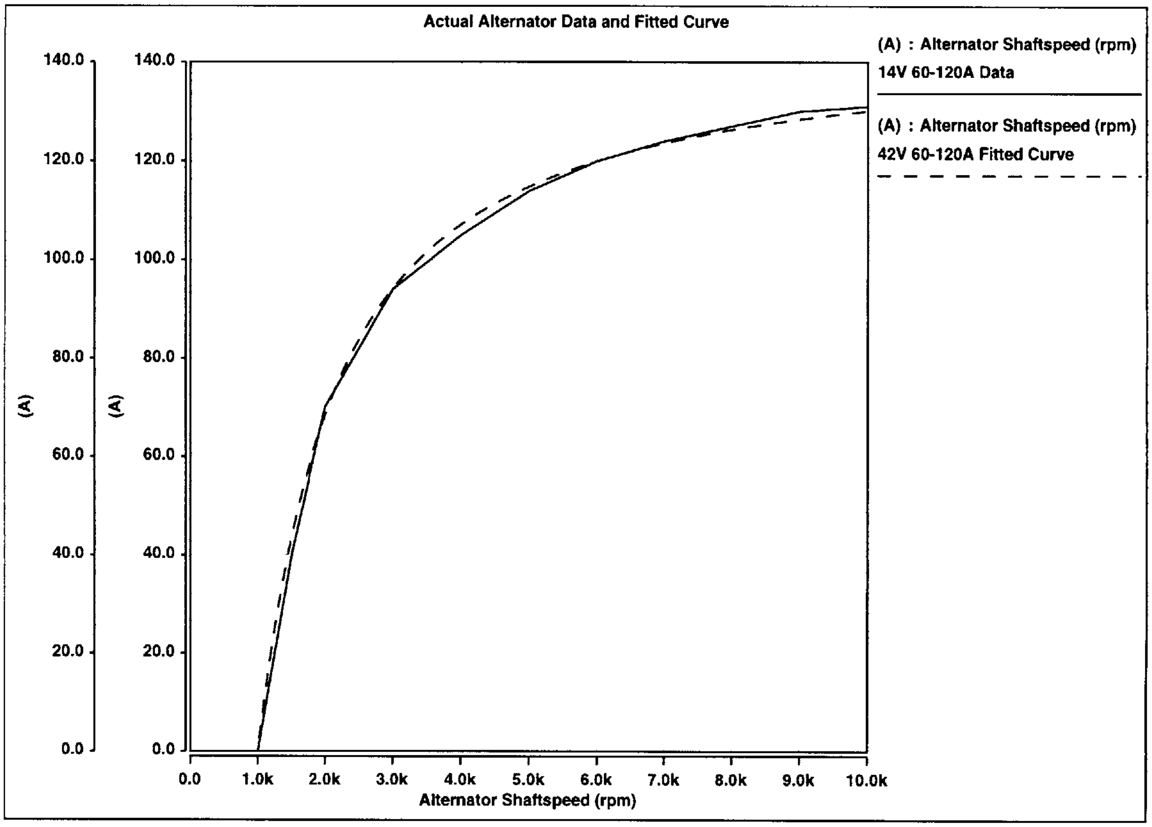

Figure 3.11: Actual 14V Alternator Data and Fitted 42V Alternator Curve

The other option for obtaining 42V alternator data was to map the 14V data to other sizes; all I_{alt} values were divided by a constant. For example, by scaling all 14V 60-120A I_{alt} values by $\frac{1}{3}$, 42V 20-40A alternator data could be obtained. Figure 3.12 shows 14V 60-120A I_{alt} data scaled by $\frac{1}{3}$, and the Saber model curve fit for a 42V 20-40A alternator using parameter values obtained with Maple.

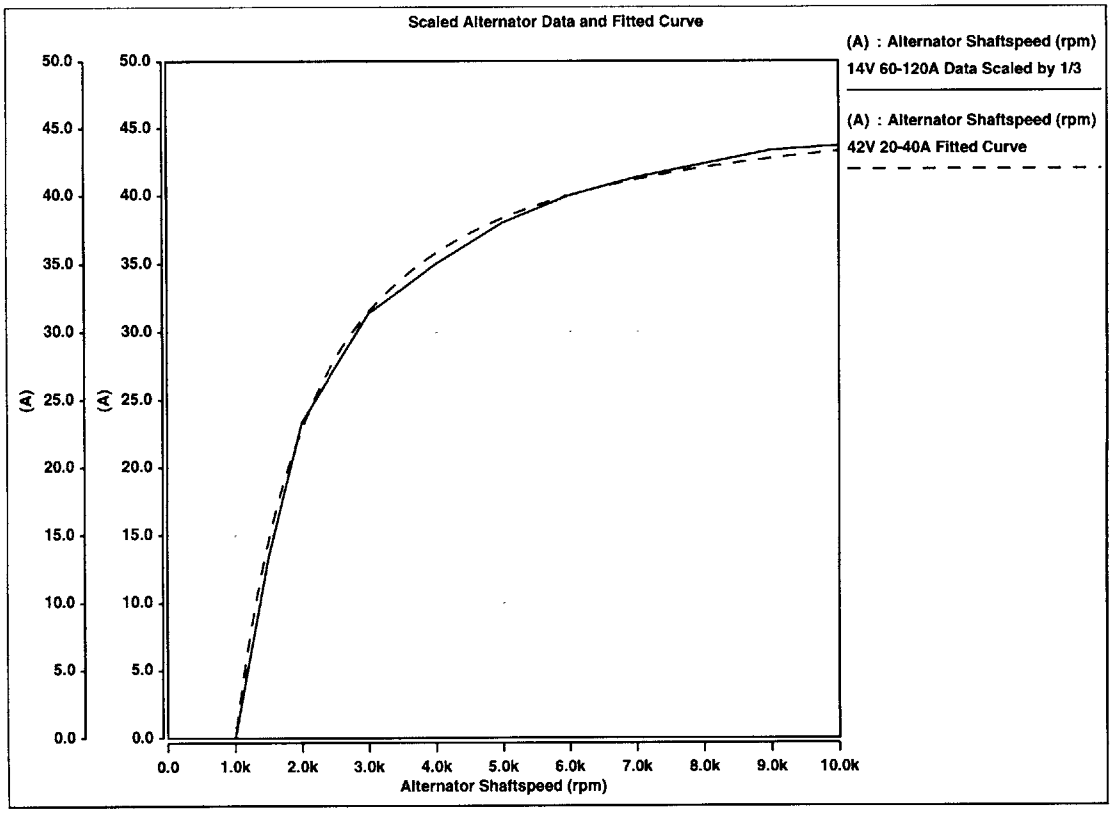

Figure 3.12: Scaled 14V Alternator Data and Fitted 42V Alternator Curve

It may be important to note that the parameters calculated for a 42V 20-40A alternator are not simply the same parameters calculated for a 14V 60-120A alternator; the three independent equations used to solve for the 42V 20-40A parameters are not scaled versions of the three equations used to solve for the 14V 60-120A parameters. Table D.1 in Appendix D lists the values of k, R_s, and L_s obtained for various sizes of 42V alternators that were used in this study.

3.4 Modeling the DC/DC Converter

The DC/DC converter used in the dual-voltage system was designed under Research Unit #1, DC/DC Converters for Dual-Voltage Electrical Systems. Though Research Unit #4 developed a detailed Saber model for the converter, the only important characteristic of the DC/DC converter desired in the simulations run under this project was the amount of current drawn by the converter as a function of the output voltage. Thus, the converter was treated as a black box with the i-v characteristic plotted in Figure 3.13.

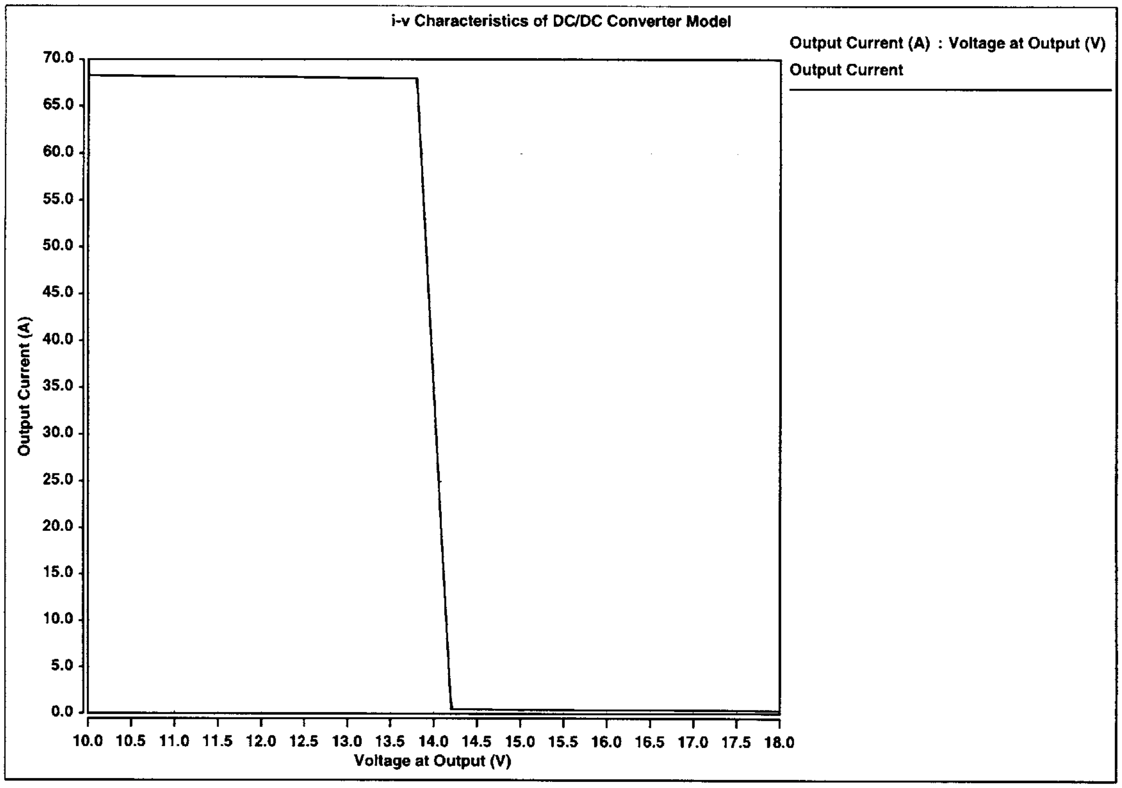

Figure 3.13: i-v Characteristics of DC/DC Converter Model

The amount of current that is drawn through the converter is a function of the voltage on the 14V bus, at the output of the converter. When the 14V bus is at a voltage greater than 14.2 V, the converter will not supply additional current to the bus. When the voltage of the 14V bus is less than 13.8 V, the converter will provide the maximum amount of current possible to the 14V bus. In between 13.8 V and 14.2 V, the amount of current drawn by the converter changes linearly between its maximum value and 0 A.

The MAST code used to implement the model can be found in Appendix E. The parameters used in the converter model are summarized in Table 3.3 below.

Table 3.3: Parameters Used in DC/DC Converter Model

Parameter	Description
eta	Converter Efficiency
imax	Maximum Output Current of Converter
vmax	Maximum Regulation Voltage of Converter
vmin	Converter Voltage at Full Load Current

The values for `eta`, `vmax`, and `vmin` are defined in the design of the actual physical converter. The `imax` value, however, can be varied. In practice, the converter may want to draw varying amounts of current at various times. For example, some speed-dependent loads may dictate that at low speeds, less current will be demanded by the 14V bus than during moderate driving speeds. In such cases, it may be desirable to decrease `imax` to avoid overcharging the 14V battery at the expense of the 42V battery. A key aspect of the utility of the DC/DC converter is the energy management algorithm which controls the value of `imax`. Though some issues of energy management are explored in some simulations, as will be discussed in Section 4.4.3, the actual research aimed at developing an energy management algorithm is conducted by Research Unit #8, 42V PowerNet System Management Using Multiplexed Remote Switching.

3.5 Modeling the Lead-Acid Battery

In the absence of any reliable software lead-acid battery models, the simulations used in this project utilized a beta version of a lead-acid battery model provided by Saber (Saber component `batt_pb_1`). The actual method by which the battery is modeled, however, is encrypted by Saber.

For the purposes of this study, the most important aspects of the battery model are its state of charge measurements and the manner by which it discharges. The discharging of the battery has been studied, and appears acceptable. It is important to note that the purpose of the simulations described in this thesis are to provide the methodology by which component sizing can be accomplished, not to provide the raw data from which component sizes will actually be determined. Thus, as long as the state of charge measurements obtained from the Saber model do not mislead the evaluation of guidelines to favor one sizing criteria over another, the Saber model is sufficient for this study.

Chapter 4

Developing Sizing Criteria

4.1 Running Simulations

The purpose of the research presented in this thesis is to use Saber simulations to provide insight into the sizing of the alternator, the batteries, and the DC/DC converter. This section will describe the method by which simulations were run.

The following sections will describe the three simulation profiles which were considered. The idle case was used to investigate the performance of the alternator and batteries at low alternator shaftspeed. The high-speed scenario was used to investigate the components' performance at high alternator shaftspeed. Finally, a city profile was used to study the variable-speed performance of the components.

The final section of this chapter will discuss the sizing requirements imposed by key-off loads.

4.1.1 The Simulation Process

Running a simulation required the input of drivecycles and loadcycles into the design described in Section 3.1. As mentioned in Section 2.1, the drivecycle is formatted into two or three columns: time in seconds in the first column, car speed in kilometers per hour in the second, and the gear in the third column, if specified. The data is read by a component which outputs the car speed and optional gear data into a black box, which converts the car speed to alternator shaftspeed. The MAST code for the conversion can be found in Appendix F. The conversion is achieved by the following relation:

$$v \cdot \left(\frac{10}{36}\right) \cdot \left(\frac{60}{\pi d}\right) \cdot g_d \cdot g_t \cdot g_{e,a} = shaft \quad . \tag{4.1}$$

The definitions of the variables used in Equation 4.1 are summarized in Table 4.1 below. The ratio $\frac{10}{36}$ converts the car speed from units of kilometers per hour into units of meters per second. The rotational velocity of the tire is determined by multiplying the car speed in meters per second by $\frac{60}{\pi d}$. Finally, through a series of gear ratios, the alternator shaftspeed is calculated.

Table 4.1: Variables Used in Drivecycle-to-Alternator Conversion

Variable	Description
v	Vehicle Driving Speed [km/hr]
d	Diameter of Vehicle's Tires [m]
g_d	Differential Gear Ratio
g_t	Transmission Gear Ratio - Neutral - 1st Gear - 2nd Gear - 3rd Gear - 4th Gear - 5th Gear
$g_{e,a}$	Engine-Alternator Gear Ratio
shaft	Alternator Shaftspeed [rpm]

Figure 4.1 on the following page shows drivecycle `ece15.dat` and its corresponding alternator shaftspeed in revolutions per minute.

The alternator shaftspeed is input into the alternator model, which outputs current to the 42V bus according to the characteristic curve of the particular sized alternator being used, as explained in Section 3.3 and Appendix D.

In order to incorporate a loadcycle into the system, the position sequence of the switch driver controlling each load being transitioned on or off needs to be specified. This task is accomplished by running a Saber command script, as described in Sections 2.2 and 3.2. Each line of the script uses the Saber `alter` command to specify the position sequence of each switch driver in the design. As time progresses in the simulation, the loads are turned

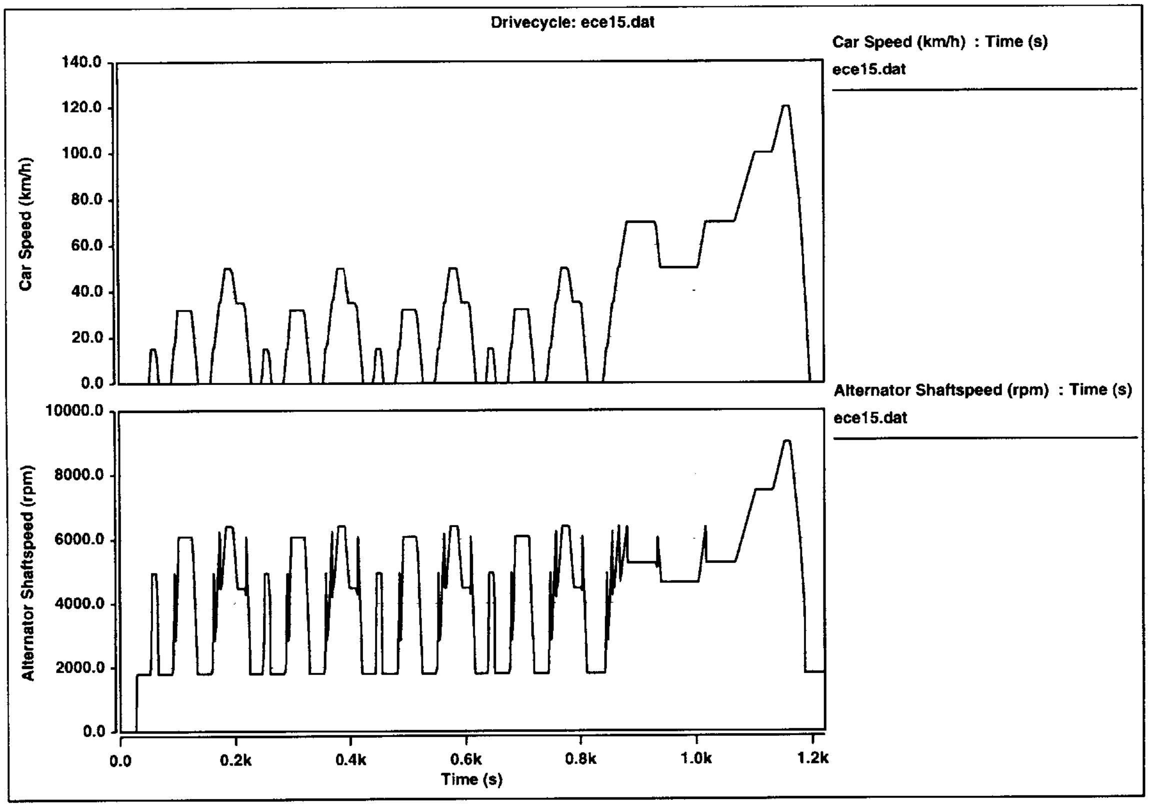

Figure 4.1: A Drivecycle and Its Corresponding Alternator Shaftspeed

on and off accordingly. Appendix B includes examples of loadcycles in Saber command script format.

4.1.2 Simulation Profiles

Each simulation is characterized by a number of contributing factors. For each simulation run, a Profile Sheet kept track of the parameters listed in Table 4.2 on the following page.

Table 4.3, also shown on the following page, lists the variables that were plotted versus time for each simulation. The Profile Sheet used for recording simulations and a table of Saber variables corresponding to the plots recorded can be found in Appendix G.

Table 4.2: Simulation Parameters

Design Component	Parameters
Input	Drivecycle Loadcycle
Alternator	Current Output at Idle Alternator Shaftspeed (1800 rpm) Current Output at High Alternator Shaftspeed (6000 rpm)
42V Battery	Ah Capacity Initial State of Charge Temperature
14V Battery	Ah Capacity Initial State of Charge Temperature
DC/DC Converter	Maximum Current Through Converter (`imax`)

Table 4.3: Plots Recorded for Each Simulation

Variables	Graphs Plotted	Variables	Graphs Plotted
Drivecycle	Drivecycle Alternator Shaftspeed	42V Bus: Current	Current into all 42V Loads Current on 42V Bus from Alternator Current into 42V Battery
Alternator	Output Current Output Power Voltage at Output	42V Bus: Voltage	Voltage on 42 Bus Voltage at Battery Positive Terminal
Battery State of Charge	42V Battery s.o.c. 14V Battery s.o.c.	42V Bus: Power	Power Consumed by 42V Loads Power on 42V Bus from Alternator Power at Battery Positive Terminal
DC/DC Converter: Current	Input Current Output Current	14V Bus: Current	Current into all 14V Loads Current on 14V Bus from Converter Current into 14V Battery
DC/DC Converter: Voltage	Input Voltage Output Voltage	14V Bus: Voltage	Voltage on 14V Bus Voltage at Battery Positive Terminal
DC/DC Converter: Power	Input Power Output Power	14V Bus: Power	Power Consumed by all 14V Loads Power on 14V Bus from Converter Power at Battery Positive Terminal

By monitoring the variables listed in Table 4.3, and in particular the battery states of charge, one can evaluate the adequacy of various sized alternators and batteries in the dual-voltage design. In general, the components need to be sized efficiently in order to ensure starting capability of the 36V battery, and to ensure that the 12V battery can support key-off loads for approximately 5 to 6 weeks, as when a car may be left at an airport for an extended period of time. Each of the different simulations described in the next few sections imposes various possible guidelines on component sizing.

4.1.3 Simulations Run

The following table shows the profiles for which simulations were run.

Table 4.4: Simulation Profiles

Profile	Drivecycle	Loadcycle	Conditions
Idle	idle.dat	idle.scs	Worst-case Summer
High-Speed	summer_const.dat	summer_worst_const.dat	Worst-case Summer
City Driving	ece15_city.dat	winter_worst_ece15.scs	Worst-case Winter

Each simulation profile carries a unique significance and was evaluated under profile-specific guidelines, as will be explained in the following sections.

4.2 Idle Simulations

One of the main conditions under which sizing can be performed is summer idling. It is not unreasonable to suppose a taxi idling for a significant amount of time while waiting for a passenger on a hot, rainy, summer day.

This section describes the parameters used when simulating an idling vehicle, the results obtained from Saber simulations, and the guidelines used to evaluate the results.

4.2.1 Assumptions

In sizing the power supply components, a number of assumption needed to be made. Because the batteries are expected to discharge while the vehicle is idling, the initial state of charge of the battery is 1.0.

Each battery is characterized by its Ah capacity. Because the two batteries can have different capacities, there exists some ratio between the Ah capacities of the batteries; in the criteria discussed here, the ratio was assumed to be 1. Different ratio values could be used in the simulations if desired.

One must consider that, during the course of idle simulations, if the converter is drawing too much current, then the state of charge of the 12V battery may increase at the expense of the 36V battery. If such is the case, the 36V battery will discharge into the 12V battery, and the 42V bus load demands will not be satisfied, while the 12V battery will be charged unnecessarily. To avoid this problem, in all idle simulations, the maximum amount of current which can be drawn through the converter was set to a fixed value such that both batteries discharged at a similar rate and thus had approximately the same final state of charge.

In addition, since the loadcycle used is a worst-case summer profile, the temperature used for the battery model is 40^{o}C.

4.2.2 Idling Conditions

Each simulation simulated two hours of idle time. For each simulation, the `idle.dat` drivecycle and `idle.scs` loadcycle were used. `idle.dat` is a drivecycle in which, after start-up, the vehicle is continuously idling for two hours. `idle.scs` is a worst-case summer loadcycle (hot, raining, and night-time), as can be seen in Table A.1 in Appendix A.

4.2.3 Analysis of Idle Simulation Results

Based on the sums seen in Table A.1, a rough estimate of the amount of current needed on each bus can be estimated. Using this estimation, simulations which provide approximately the expected desired amount can be run, and the results analyzed. Table 4.5 summarizes the parameters used in the simulations that were run, and the final state of charge of the batteries after two hours of simulated time. Note that since the vehicle is idling for the entire duration of the simulation, only the idle output of the alternator is important (the high-speed output is not).

Table 4.5: Idle Simulation Results

Alternator Output Current at Idle [A]	Battery Capacity [Ah each]	Maximum Current Through Converter [A]	12V Battery: Final SOC	36V Battery: Final SOC
15	100	8.5	0.738	0.703
15	85	8.25	0.688	0.654
15	70	7.75	0.61	0.59
15	50	7.5	0.458	0.432
15	30	6	0.132	0.124
15	15	5.75	0.112	0.122
20	100	10	0.78	0.79
20	85	10	0.726	0.741
20	70	10	0.67	0.68
20	50	10	0.55	0.56
20	30	10	0.278	0.276
20	15	10	0.18	0.13
26	100	15	0.86	0.89
26	85	16	0.855	0.86
26	70	15	0.8	0.84
26	50	16	0.76	0.76
26	30	16	0.6	0.6
26	15	15.5	0.23	0.21
31	100	20	0.95	0.93
31	85	20	0.942	0.92
31	70	20	0.93	0.91
31	50	20	0.9	0.87
31	30	19	0.78	0.81
31	15	19	0.584	0.595
34	100	21.5	0.98	0.99
34	85	21.5	0.976	0.986

Table 4.5: Idle Simulation Results

Alternator Output Current at Idle [A]	Battery Capacity [Ah each]	Maximum Current Through Converter [A]	12V Battery: Final SOC	36V Battery: Final SOC
34	70	21.5	0.971	0.982
34	50	21.5	0.96	0.97
34	30	21.8	0.95	0.94
34	15	22.165	0.94	0.84
40	100	40	overcharged	overcharged
40	70	40	overcharged	overcharged

One can take two viewpoints when considering the sizing of components during idle simulations. The first is to expect the batteries to drain after a certain amount of time. The second is to aim to keep the batteries charged indefinitely. One can expect, however, that the latter method might result in oversizing the batteries, and might be too conservative of a method.

If one chooses to examine the batteries' discharge, the final battery states of charge after 2 hours of idling would be important numbers to consider. The final state of charge that is acceptable for the starting battery might vary according to each car manufacturer's sizing guidelines. In some cases, a state of charge of 0.6 might be considered the lowest state of charge that will guarantee start-up on a subsequent drive; a lower state of charge may or may not be sufficient, depending on environmental and loadcycle conditions of the subsequent drive. Perhaps, however, a state of charge of 0.25 could be considered the lowest state of charge below which vehicle start-up is not possible. Each manufacturer might prefer to determine their own state of charge values of interest.

Figure 4.2 on the following page plots, for various battery Ah capacities, the final battery states of charge for each alternator used in the idle simulations.

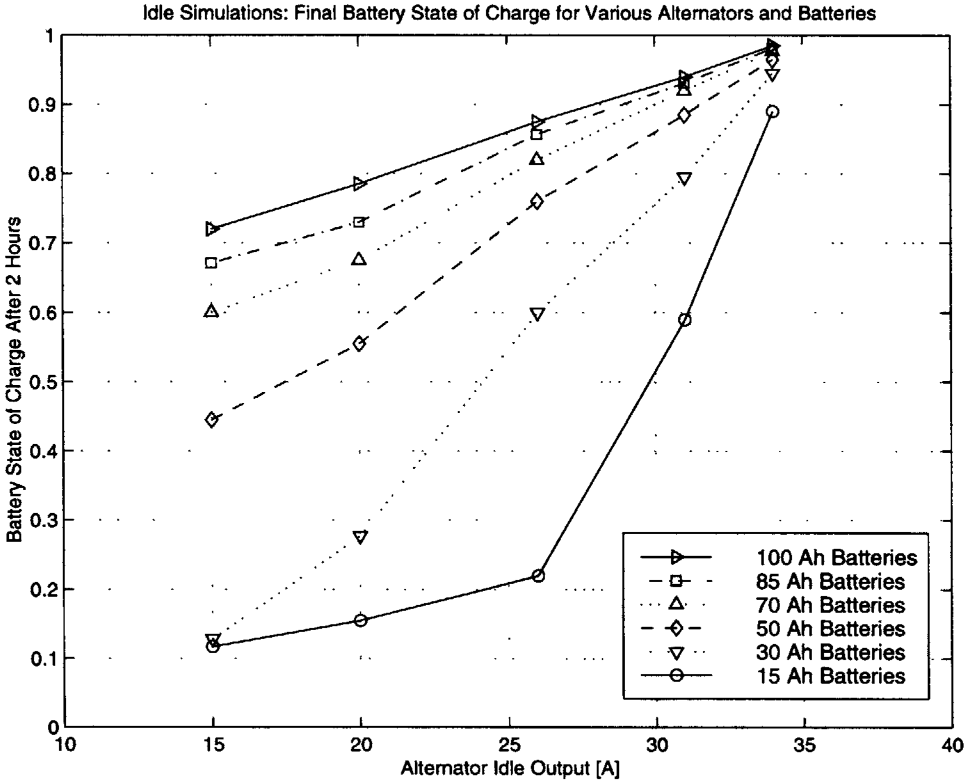

Figure 4.2: Idle Simulations: Final Battery SOC for Each Alternator Size

Figure 4.2 shows the trade-off involved in sizing the alternator and the batteries. If a large enough alternator is used, a smaller-sized battery would suffice. However, if a smaller alternator is used, a larger battery would be needed. For example, if 0.6 is considered the borderline acceptable final state of charge, a 31A-at-idle alternator and 15Ah batteries would suffice. If, however, a 15A-at-idle alternator is used, 70 Ah batteries would be needed to achieve the same final states of charge.

On the following page, Figure 4.3 shows the space of alternators and batteries used in the idle simulations. If the two state of charge values discussed above are considered the borderline points of interest, the alternator-battery combinations simulated could be categorized as shown in the figure. Though the simulations identify points in the alternator-battery space, the important features are the regions defined by the points.

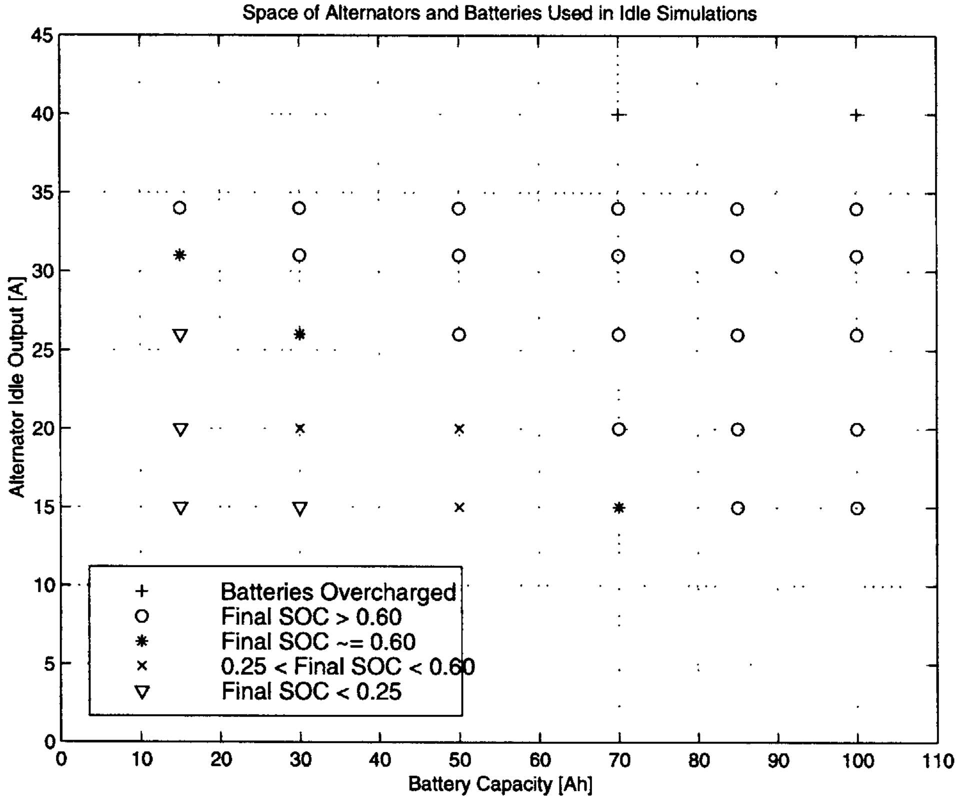

Figure 4.3: Idle Simulations: Space of Alternators and Batteries Used

The plus signs show that if the alternator outputs 40 A at idle, all the load demands are met regardless of the battery sizes, because the batteries are always being charged when the alternator produces more current than is demanded. A horizontal line estimated to be somewhere between 35A-at-idle and 40A-at-idle would define the region above the boundary line to be an "over-sized alternator" region. It is important to note that this boundary could have been identified without simulations and simply from the estimated alternator output calculation made from the idle loadcycle. Table A.1 indicates that the alternator needs to provide about 36 A in order to satisfy all the loads; if the alternator produces more then 36 A at idle, the batteries will charge.

If a state of charge of 0.6 is identified as a borderline point of interest, as suggested earlier, a second line can be drawn connecting the star-marks, indicating another boundary. The region defined by the circles, then, can be considered a "sufficient alternator and battery region," where the alternator-battery combinations are sufficient in guaranteeing vehicle start-up on a subsequent drive.

Since none of the alternator-battery combinations tested resulted in a final state of charge of exactly 0.25, a second boundary line can be estimated, dividing the remaining region into a "grey area: possibly sufficient alternator and battery region," defined by the cross-marks, and an "insufficient alternator and battery region," defined by the upside-down triangles.

4.3 High-Speed Driving Simulations

While the idle simulations are important in evaluating the system's ability to satisfy all power demands at one extreme, when the alternator shaft is rotating at idle speed, the high-speed simulations are used in evaluating the system's capabilities at the other extreme, when the alternator shaft is rotating at high speed.

This section describes the parameters used when simulating high-speed driving, the results obtained from the simulations, and the guidelines used to evaluate the results.

4.3.1 Assumptions

Since the alternator shaft is outputting close to its maximum amount of current possible, it is expected that the batteries will charge under high-speed driving conditions. To account for possible battery charging, the initial state of charge of both batteries is 0.9.

As in the idle profile, the ratio between the Ah capacities of the two batteries is assumed to be 1.

One condition by which one may evaluate the high-speed driving profile is to not allow either battery to discharge indefinitely while the car is driving. In light of this possible guideline, the maximum amount of current that can be drawn through the DC/DC converter is set to a fixed value such that the goal is to not allow either battery to discharge.

Since a worst-case summer loadcycle is used, the battery temperature is assumed to be 40°C.

4.3.2 High-Speed Driving Conditions

Table A.2 in Appendix A shows the loadcycle, `summer_worst_const.scs`, with which high-speed driving simulations were run. `summer_worst_const.scs` is a worst-case summer profile (hot, raining, and night-time) customized for the `summer_const.dat` drivecycle, in which the car is driving at a steady speed of 80 km/hr after start-up. Using the conversion described in Section 4.1.1, 80 km/hr corresponds to an alternator shaftspeed of approximately 6030 rpm.

4.3.3 Analysis of High-Speed Driving Simulation Results

From Table A.2, one can see that the alternator would need to produce about 96 A in order to satisfy all the loads sufficiently. It is important to note that it is the high-power speed-dependent future loads that are responsible for this high power requirement. The electromechanical engine valves alone require up to 2500 W at high speeds, or almost 60 A from the 42V alternator.

As mentioned above, in evaluating the adequacy of components under this profile, one possible guideline might require the alternator and battery to supply all load power demands indefinitely. Table 4.6 on the follow page shows the simulations that were run, and the long-term trend of the state of charge of both batteries.

As expected, when the alternator produces more than the necessary 96 A, as when a 100A-at-high-speed alternator is used, the batteries are charged, causing the battery states of charge to increase. If, however, a 90A-at-high-speed alternator is used, not enough current is being supplied to the loads by the alternator, and the batteries discharge, causing the states of charge to decrease.

Table 4.6: High-Speed Driving Simulation Results

42V Alternator High-Speed Output [A at 6000rpm] --> Battery Capacity [Ah each]	100 A	90 A
100 Ah	36V soc: increases 12V soc: increases	36V soc: decreases 12V soc: decreases
70 Ah	36V soc: increases 12V soc: increases	36V soc: decreases 12V soc: decreases
50 Ah	36V soc: increases 12V soc: increases	36V soc: decreases 12V soc: decreases
30 Ah	36V soc: increases 12V soc: increases	36V soc: decreases 12V soc: decreases

As with the idle simulations, when the profile includes steady-state conditions such as a constant driving speed, simulations may not be necessary for a complete evaluation of the profile. When looking to see simply whether or not all the load demands are satisfied, as in the example guideline presented for the high-speed driving profile, the power and current estimates made by summing the values in the loadcycle are sufficient in making that judgment.

4.4 City Simulations

In sizing the power supply components, it is important to consider the stop-and-go city driving profile. When the car spends a significant amount of time idling (possibly at street lights or in traffic), and then engages only in low-speed driving between stops, it may be difficult for the alternator to produce enough current to meet the demands of all the loads, particularly if heavy loads such as the heater or air conditioning are on.

This section describes the parameters used when simulating a vehicle engaged in city driving, the results obtained from Saber simulations, and the guidelines used to evaluate the results.

4.4.1 Assumptions

City driving profiles usually consist of alternating idle times and low-speed driving. Idle times may account for 20% to 50% of the total drive time. In the city driving profile used here, `ece15_city.dat`, idle time accounts for 33% of the total drivecycle. In addition, `ece15_city.dat` includes speeds no higher than 50 km/hr.

Because the driving portions of the drivecycle allow the alternator to produce enough current to possibly charge the battery, the initial state of charge of both batteries is 0.9, allowing room for charging.

As previously mentioned, the existing Saber dual-voltage design allows for control of the DC/DC converter only in the setting of `imax` to a fixed value for the duration of the simulation. Though this method seemed reasonable in the steady-state conditions discussed in the previous sections, it is not as suitable for the dynamic nature of city simulations. In the absence of a more advanced method to control the converter, the maximum amount of current that can be drawn through the converter was set such that the long-term goal was for both batteries to either charge or discharge, and to avoid the case where one battery charges while the other battery discharges.

Furthermore, since the loadcycle used for the city simulations is a worst-case winter profile, the temperature used for the battery model is 0^{o}C.

4.4.2 City Conditions

All simulations use the drivecycle `ece15_city.dat`, which alternates between idle and low-speed driving. `winter_worst_ece15.scs` is the worst-case winter loadcycle which is used, and it is shown in Table A.3 in Appendix A.

In addition to the usual loads, the turn signals and any brake-related loads are also turned on and off according to the driving speeds in `ece15_city.dat`. The last four row entries of Table A.3 take into consideration the power and current demand of the turn lights and the brakes.

4.4.3 Analysis of City Simulation Results

Some automobile manufacturers might size the battery expecting it to discharge completely after many hours of city driving, while others may place restrictions only on the first couple hours, perhaps requiring that the battery does not go below the initial state of charge after one or two hours of city driving. Assuming the former criterion, one might allow, perhaps, 10 hours of city driving before the batteries may discharge completely. Three hours of city driving were simulated, and the results were used to extrapolate the state of the batteries after 10 hours. Table 4.7 below shows the simulations that were run, and the expected state of the batteries after 10 hours.

Table 4.7: City Simulation Results

42V Alternator Output [A at 1800 rpm - A at 6000 rpm] --> **Battery Capacity [Ah each]**	**60-120 A**	**54-108 A**	**50-100 A**
100 Ah	36V soc: ok, not yet discharged 12V soc: ok, not yet discharged	36V soc: ok, not yet discharged 12V soc: ok, not yet discharged	36V soc: completely discharged 12V soc: completely discharged
70 Ah	36V soc: ok, not yet discharged 12V soc: ok, not yet discharged	36V soc: ok, not yet discharged 12V soc: ok, not yet discharged	36V soc: completely discharged 12V soc: completely discharged
50 Ah	36V soc: ok, not yet discharged 12V soc: ok, not yet discharged	36V soc: completely discharged 12V soc: completely discharged	36V soc: completely discharged 12V soc: completely discharged

Table A.3 shows that the alternator needs to supply about 70 A on average in order to supply all the load demands. The entries in Table 4.7 which are labeled "ok, not yet discharged" represent those alternator-battery combinations which meet the sizing criteria outlined above. According to the results, a 42V 54-108A alternator would suffice as long as the batteries had at least approximately 70 Ah capacity.

Table 4.7 further shows that one can not easily choose an alternator-battery combination which would result in the desired average power supply needed. Whereas the steady-state estimates in the idle and high-speed loadcycles were sufficient in determining the alternator size which would supply all demands, the loadcycle estimate alone is not enough to determine the alternator-battery combination which would satisfy all city driving demands. Intermittent loads such as the turn signals and brakes, combined with the effects of varying car speed on speed-dependent load consumption and alternator output, make it difficult to specify an exact power requirement for city conditions. Consequently, simulations are indeed useful in studying the system requirements when varying conditions are involved, and when a steady-state estimate will not suffice.

As mentioned, the city simulation results show the difficulty involved in sizing the alternator when changing vehicle speeds cause the alternator output to vary. The characteristic curve of typical alternators, as seen in Figure 3.9 in Section 3.3.1, shows the dependency of alternator output current on alternator shaftspeed, and thus on vehicle speed. As already noted, choosing an alternator whose average output satisfies a given requirement is not a straightforward calculation. This difficulty leads to the possibility that an alternator whose characteristic curve shows more constant power output capabilities over the ranges of common car speeds might be beneficial; it would be simpler to size such an alternator for profiles involving varying car speeds. Research Unit #2, High Power

Generation and Starting, investigates such benefits and limitations related to high-power alternators.

Further analysis of the city simulations centers on the control of the DC/DC converter current. As stated in the assumptions, the `imax` value for the DC/DC converter was set such that the long-term trend for both batteries would be the same: either both batteries charged or both batteries discharged. Though this long-term trend was attainable in the simulations, occasionally, for short periods of time, one battery could be charging while the other was discharging. Figure 4.4 below shows a portion of a typical plot, obtained from city simulations, of the battery states of charge versus time.

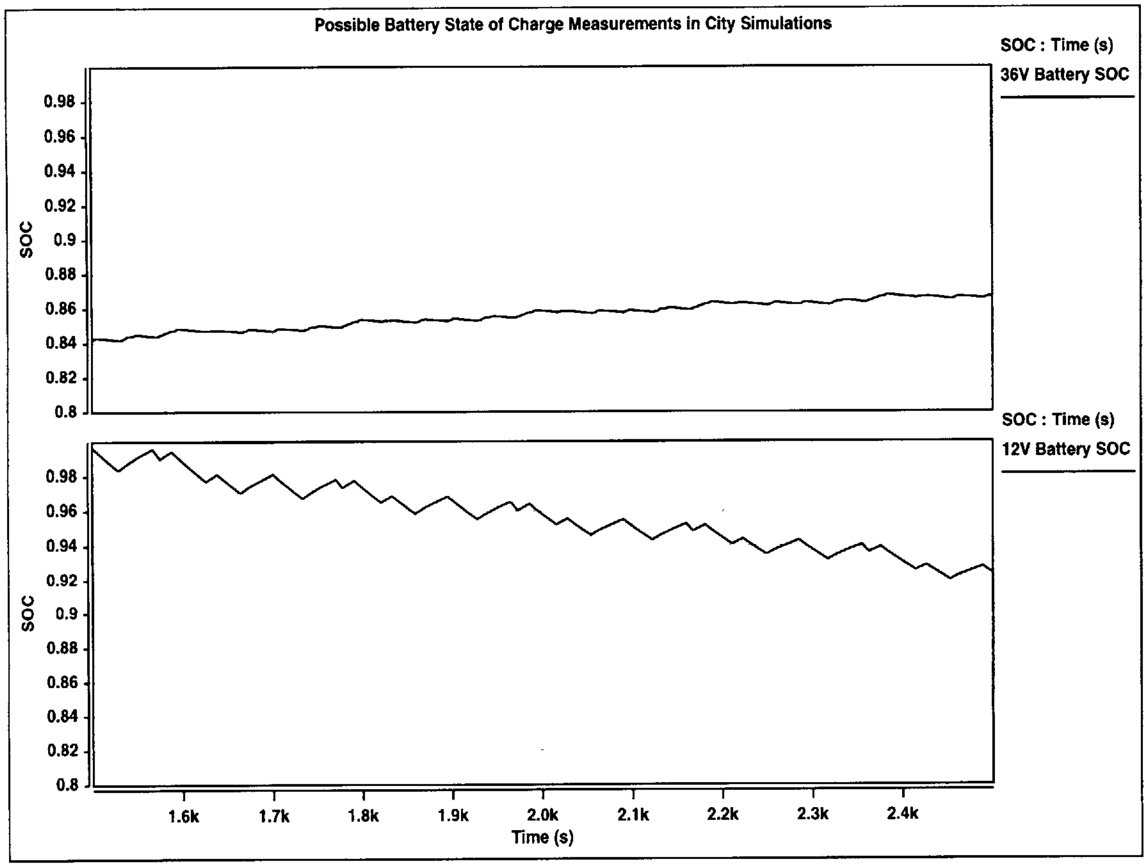

Figure 4.4: Portion of Possible Battery State of Charge Plot from City Simulations

As seen in Figure 4.4, with a fixed `imax`, it is possible for one battery to charge at the expense of the other. Such results are not surprising considering the dynamic nature of the city profile; varying speeds not only affect the amount of current that the alternator delivers to the dual-voltage system, but they also affect the power demanded by speed-dependent loads.

One could observe, however, that if the 12V battery were discharging, and the 36V battery were charging, as in the case presented in Figure 4.4, it might be beneficial for both buses if the maximum converter current could be increased. Ideally, if possible, just enough current would be drawn onto the 14V bus such that neither battery would be discharging. This desire for more dynamic control of the DC/DC converter current confirms the need for an energy management algorithm to control the converter current. The study of the implications and impact of energy management is conducted under Research Unit #8, 42V PowerNet System Management Using Multiplexed Remote Switching.

4.5 Key-Off Energy Requirements

Recall that key-off loads are those loads, such as the clock and the alarm system, which are on even when the vehicle is off. When considering the existing single-voltage automotive electrical system, sizing the battery to be sufficient for key-off and starting requirements can be achieved through simple calculations. The following equation, taken from *A Methodology for the Design and Evaluation of Advanced Automotive Electrical Power Systems* [1], solves for the energy capacity of the battery, E_b, in Joules:

$$E_b = \frac{P_q t_q + P_{st} t_{st}}{1 - f_c - R_d t_q} \quad . \tag{4.2}$$

The following table explains the significance of each variable, with values as specified in *A Methodology for the Design and Evaluation of Advanced Automotive Electrical Power Systems* [1] and in the vehicle loadlist shown in Appendix B.

Table 4.8: Variables Used to Solve for Single-Voltage Battery Capacity

Variable	Description	Typical Value
E_b	Energy capacity of the battery [J]	-
P_q	Total power demand of key-off loads [W]	0.2 to 0.8 W
t_q	Time period during which vehicle is inactive, but key-off loads are on [sec]	5 to 6 weeks, or 3.024×10^6 to 3.63×10^6 sec
P_{st}	Load power requirement during starting process [W]	3150 W
t_{st}	Time required to start the vehicle [sec]	2 to 3 sec
f_c	Fraction under which battery state of charge is not allowed to drop	0.25
R_d	Self-discharge rate, expressed as a fraction of the battery's energy capacity per unit time [sec^{-1}]	0.15% per day, or 1.74×10^{-8} sec^{-1}

In the dual-voltage system, the only key-off loads are located on the 14V bus. The energy capacity needed to supply the key-off loads for a significant amount of time can be calculated for the 12V battery independent of start-up power demands, which are satisfied by the 36V battery on the 42V bus. Consequently, applying Equation 4.2 to the dual-voltage system to solve for the energy capacity of the 12V battery means that the $P_{st}t_{st}$ term can be disregarded. Referring to the loadlists in Appendix B, one can set P_q equal to 0.2 W (demanded by the anti-theft warning device). t_q can be arbitrarily chosen to be 5 weeks, or 3.024×10^6 seconds, and f_c can be arbitrarily chosen to equal 0.25 (Note that there is no requirement for the 12V battery to be capable of start-up.). Using the value of R_d specified in Table 4.8, E_b is calculated to be 0.87×10^6 J, which is about the energy stored in a 20 Ah 12V battery.

Assuming worst-case conditions, however, E_b can be calculated using P_q equal to 0.8W, t_q equal to 3.63×10^6 seconds, and all other values as specified above. In this case,

E_b is equal to 4.22×10^6 J, which can be satisfied by a 100 Ah 12V battery. Note that in present-day vehicles, 100 Ah 12V batteries are used, but even without being concerned with starting capacity, in order to satisfy the highest possible demand from key-off loads for a period of 6 weeks, a 100 Ah battery would still be needed.

As can be seen, if the key-off loads demand a low 0.2 W of power, and if a 5-week key-off criterion is imposed, the 12V battery could possibly be sized according to the lowest possible Ah capacity that will satisfy all demands set by the simulation scenarios described above, rather than by key-off requirements. If, however, key-off loads demand a high 0.8 W of power, the 12V battery would need to be at least 100 Ah in order to meet the key-off requirements alone, perhaps making the key-off requirement the limiting factor in sizing the 12V battery.

Chapter 5

Conclusion

5.1 Discussion of Results

The goal of this thesis has been to provide a methodology by which power supply components in the dual-voltage system can be sized. The work presented in this paper aims to provide a manner by which various criteria can be evaluated under the dual-voltage system. The profiles developed for the simulations serve as the basis on which various guidelines can be imposed.

As presented above, each automobile manufacturer may wish to impose their own internal sizing guidelines, and the criteria set by different manufacturers may not necessarily be compatible with each other. The challenge in sizing the power supply components in the dual-voltage system will be in determining which guidelines should be used as the limiting case, which will likely vary from manufacturer to manufacturer. The key-off load requirement, discussed in Section 4.5, might be the limiting case in sizing the 12V battery if key-off load demands are substantial. If the key-off load demands are low, however, the high-speed driving profile or the city driving profile might instead be the limiting cases by which the 12V battery should be sized.

As mentioned in Sections 4.2.3 and 4.3.3, steady-state profiles such as the idle and country drive profiles may not require simulations. If the guidelines specify that all load demands must be met, as in the example guideline provided for high-speed driving simulations, then the amount of current that the alternator needs to provide can be estimated using nominal values obtained from the vehicle loadlist. Speed-dependent loads, however, should be accounted for as well; speed-dependent loads in the idle loadcycle will demand less power than the nominal values, and those in the high-speed driving loadcycle will demand more. As discussed in Section 4.4.3, however, simulations are necessary for the city profile in order to adequately evaluate the varying requirements which are imposed by the changing car speed.

When developing sizing guidelines, one must consider all simulation results together. As seen in Figure 4.3, the idle simulations defines a space of alternators and batteries which will meet all idle power demands. The idle profile, then, under the guidelines presented in Section 4.2.3, defines as sufficient an alternator that produces at least 36 A at idle shaftspeed.

Considering next the high-speed simulations, however, one sees that at high-speeds, the power demanded by the loads increases greatly, mainly because the speed-dependent electromechanical engine valves account for more than half the total power demand in the high-speed loadcycle. According to the criteria set forth under this profile, then, in order to be sufficient, an alternator needs to supply approximately 100 A when the alternator shaftspeed is spinning at 6000 rpm. For the alternators used in this study, the alternator idle current capability was typically half the high shaftspeed current capability. Consequently, one can observe that a 100 A alternator, which is needed to satisfy the high-speed driving conditions, might supply about 50 A at idle shaftspeed, and thus will almost certainly satisfy the idle condition as well, regardless of the battery size. In this case, the high-speed driving profile provides more critical information for sizing the alternator.

Next, the city simulations need to be considered. In the case of the guidelines presented in Section 4.3.3, the city simulation results provide even more limiting information. Though the high-speed profile requires a 100A-at-high-speed alternator, the city simulations show that 100 A at high speed is not enough to satisfy the city conditions. Furthermore, if a 42V 54-108A alternator were used, batteries with 50 Ah capacity or lower would not be sufficient.

Finally, the key-off load requirements are considered. The loadlist used for the loadcycles presented in this thesis include only 0.2 W of key-off load demand. As calculated in Section 4.5, this key-off requirement can be satisfied by a 20 Ah 12V battery. Since the city simulations have already imposed tighter constraints on the sizing of the 12V battery, the key-off load requirements, in this case, are not the limiting criteria.

5.2 Further Study

In Section 3.5, it was mentioned that the battery model used in the Saber design of the dual-voltage system is a beta version of a model provided by Saber. Since the code underlying the model is encrypted, it is not known exactly how the lead-acid battery is modeled. The Saber battery model should be tested against actual battery performance, or another, well-tested battery model should be used in the design. Further work on this project would benefit from an in-depth study of lead-acid battery models.

As discussed in Section 4.4.3, it is difficult, if not impossible, to evaluate the capabilities of the dual-voltage system under city driving conditions without an energy management algorithm. The only method by which to control current through the DC/DC converter in the existing dual-voltage Saber design is to set the maximum amount of current allowable to a fixed value. Though this method might be acceptable for the steady-state simulations of the idle and country drive profiles, it does not adequately respond to the dynamics of the stop-and-go city drivecycle. Future work should include the implementation of the energy management algorithm developed under Research Unit #8, 42V PowerNet System Management Using Multiplexed Remote Switching, and an evaluation of city simulation results obtained using the algorithm.

The city simulations, together with the idle and high-speed driving profiles, provide a basis on which guidelines for sizing components can be imposed. Component sizing, however, is not limited to these three profiles, which represent, respectively, the extreme cases of continuous worst-case stop-and-go driving, continuous low alternator shaftspeed, and continuous high alternator shaftspeed. Further study should investigate other possible scenarios which might provide insight into the power demands of the dual-voltage system. For example, a drivecycle including both city and high-speed driving might be useful in studying the power requirements involved in replenishing a battery which has been discharging since vehicle start-up.

Lastly, in the sizing criteria discussed in this paper, battery state of charge was used as the central measure of system capability. When considering various Ah capacities, however, it is important to recognize that two batteries of different Ah capacity will have different amounts of stored energy at the same state of charge. Recalling that 1 Ah is equivalent to 3600 Coulombs, a fully charged 30 Ah 12V battery stores about 1.3×10^6 J of energy, while a fully charged 100 Ah 12V battery stores about 4.3×10^6 J of energy. Furthermore, consider a 36V battery, and the amount of stored energy is three times the amount stored in a 12V battery of the same Ah capacity. Further study should explore the effect of various drivecycles and loadcycles on the available stored energy in the batteries, and investigate its connection to the battery state of charge.

Appendix A

Loadcycles

A.1 Loadcycle: `idle`

`idle.scs` is a worst-case summer (hot, raining, night-time) loadcycle customized for the `idle.dat` (continuous idling) drivecycle, both of which are used in the idle simulations. Note that in most cases, the power and current values listed are nominal values; when speed-dependent loads are involved, the values listed are those expected at idle alternator shaftspeed (1800 rpm).

A.1.1 Time-Sequential Format

Table A.1: Loadcycle idle.scs

Time (s)	Event	Power at Idle (W)	Current at Idle (A)	14V Bus	42V Bus
0	Anti-theft warning device on (Always on)	0.2	0.014	X	
1	Power door locks on (Unlock doors)	248	17.7	X	
2	Power door locks off			X	
3	Driver door open	27	1.93	X	
6	Driver door closed			X	
8	Power door locks on (Lock doors)	248	17.7	X	
9	Power door locks off			X	
11	All parking lights on	94.2	6.73	X	
12	Starter on (Turn ignition key)	3150	75		X
14	Starter off				X
	42V Base loads on	92	2.19		X
	42V Speed-dependent base loads on	211.2	5.03		X
	Emissions air pump on	150	3.57		X
	Electromechanical Valve Engine on	500	11.9		X
	14V Base loads on	187.8	13.41	X	
	14V Speed-dependent base loads on	24.37	1.74	X	
16	Front windshield wipers on low	30	0.71		X
20	Radio on	40	0.95		X
	Antenna lift on (Antenna goes up)	45	3.21	X	
	CD changer on	13	0.93	X	

Table A.1: Loadcycle idle.scs

Time (s)	Event	Power at Idle (W)	Current at Idle (A)	14V Bus	42V Bus
24	Antenna lift off			X	
33	Air conditioning on low	150	3.57		X
45	Automatic climate control on	25	1.79	X	
	42V Bus Total (Long-term)	*1173.2*	*27.92*		*X*
	14V Bus Total (Long-term)	*344.57*	*24.61*	*X*	
	Total (Long-term)	*1517.77*	*52.53*		
	14V Bus Total Translated through Converter (Conservation of Power, but 85% efficiency)	*405.37*	*8.2*		*X*
	Approximate Alternator Output Needed (Long-term)	***1578.57***	***36.12***		*X*

A.1.2 `idle.scs`: Saber Command Script Format

```
####################################################
###                                              ###
### Loadcycle: idle.scs                          ###
###                                              ###
### Conditions: hot, raining, night-time         ###
###             Customized for idle.dat          ###
###                                              ###
### Irene Kuo, MIT                               ###
### E-mail: ikuo@mit.edu                         ###
###                                              ###
### posseq = position sequence for related switch ###
### Format: [(t1, pos1), (t2, pos2)]             ###
### Load off = Switch open = position 1          ###
### Load on = Switch closed = position 2          ###
### For loads with 3 settings:                   ###
###   Load off = position 1                      ###
###   Low = position 2                           ###
###   Medium = position 3                        ###
###   High = position 4                          ###
###                                              ###
####################################################

# DC/DC Converter
# Always on when engine is on
alter /sdr_prsq.sdr_converter/posseq = [(0,1), (14,2)]
```

```
# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #
# Loads on 42V bus

# Base Loads: Resistance, 92 W, 2.19 A
# Always on when engine is on
alter /sdr_prsq.sdr_base_loads_42V/posseq = [(0,1), (14,2)]

# Speed-Dependent Base Loads: Speed-Dependent Resistance, 250.6W, 5.97A
# Always on when engine is on
alter /sdr_prsq.sdr_speed_loads_42V/posseq = [(0,1), (14,2)]

# Emissions Air Pump: Power, 150 W, 3.57 A
# Always on when engine is on
alter /sdr_prsq.sdr_emissions/posseq = [(0,1), (14,2)]

# Starter: Power, 3150 W, 75 A
alter /sdr_prsq.sdr_starter/posseq = [(0,1), (12,2), (14,1)]

# Seat Heaters: Resistance, 220 W, 5.24 A
alter /sdr_prsq.sdr_seat_htrs/posseq = [(0,1)]

# Heated Windshield: Resistance, 700 W, 16.67 A
alter /sdr_prsq.sdr_windshield/posseq = [(0,1)]

# Heated Rear Window: Resistance, 280W, 6.67 A
alter /sdr_prsq.sdr_defog/posseq = [(0,1)]

# Windshield Wipers, Front: Current w/ Settings, 30 W, .71 A
alter /sdr_prsq.sdr_wipers/posseq = [(0,1), (16,2)]

# Radio/Subwoofer: Power, 40 W, .95 A
alter /sdr_prsq.sdr_radio/posseq = [(0,1), (20,2)]

# Heater: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_heater/posseq = [(0,1)]

# All Air Conditioning Related Loads: Resistance w/ Settings, 245W, 5.83A
alter /sdr_prsq.sdr_air_cond/posseq = [(0,1), (33,2)]

# Vent: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_ps_cmp_blwr/posseq = [(0,1)]

# Sun Roof: Power, 190 W, 4.52 A
alter /sdr_prsq.sdr_sunroof/posseq = [(0,1)]

# Power Windows: Power, 270 W, 6.43 A
alter /sdr_prsq.sdr_windows/posseq = [(0,1)]
```

```
### Future 42V Loads

# A/C Compressor Pump: Power w/ Settings, 3000 W, 71.43 A
alter /sdr_prsq.sdr_ac_compressor/posseq = [(0,1)]

# Rear Seat Heaters: Resistance w/ Settings, 180 W, 4.29 A
alter /sdr_prsq.sdr_rear_seat_htrs/posseq = [(0,1)]

# All Weather Night Vision: Current, 100 W, 2.38 A
alter /sdr_prsq.sdr_night_vision/posseq = [(0,1)]

# Active Suspension: Resistance, 1000 W, 23.81 A
alter /sdr_prsq.sdr_act_suspension/posseq = [(0,1)]

# Active Engine Mount: Resistance 70 W, 1.67 A
alter /sdr_prsq.sdr_act_eng_mount/posseq = [(0,1)]

# Water Pump: Resistance, 300 W, 7.14 A
alter /sdr_prsq.sdr_water_pump/posseq = [(0,1)]

# Electromechanical Valve Engine (8 cylinder):
# Speed-Dependent Resistance, 1000 W, 23.81 A
alter /sdr_prsq.sdr_electromag_valve_eng/posseq = [(0,1), (14,2)]

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

# Loads on 14V bus

# Base Loads: Resistance, 187.8 W, 13.41 A
# Always on when engine is on
alter /sdr_prsq.sdr_base_loads_14V/posseq = [(0,1), (14,2)]

# Speed-Dependent Base Loads: Speed-Dependent Resistance, 68.78W, 4.91A
# Always on when engine is on
alter /sdr_prsq.sdr_speed_loads_14V/posseq =[(0,1), (14,2)]

# High Beam Headlamps: Reistance, 130 W, 9.29 A
alter /sdr_prsq.sdr_highbeams/posseq = [(0,1)]

# Turn Lights: Resistance, 110.8 W, 7.91 A
alter /sdr_prsq.sdr_turn/posseq = [(0,1)]

# All Brake Related Loads: Resistance, 470.6 W, 33.61 A
alter /sdr_prsq.sdr_brakes/posseq = [(0,1)]

# Power Mirror Heaters: Resistance, 30 W, 2.14 A
alter /sdr_prsq.sdr_mirrors/posseq = [(0,1)]

# Telephone: Current, 5 W, .36 A
alter /sdr_prsq.sdr_phone/posseq = [(0,1)]
```

```
# CD Changer: Current, 13 W, .93 A
alter /sdr_prsq.sdr_cd/posseq = [(0,1), (20,2)]

# Navigation Aid: Current, 50 W, 3.57 A
alter /sdr_prsq.sdr_nav_aid/posseq = [(0,1)]

# Cruise Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_cruise/posseq = [(0,1)]

# Automatic Climate Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_climate/posseq = [(0,1), (45,2)]

# Antenna Lift: Power, 45 W, 3.21 A
# On when radio turns on
alter /sdr_prsq.sdr_antenna/posseq = [(0,1), (20,2), (24,1)]

# Automatic Tire Pump: Power, 100 W, 7.14 A
alter /sdr_prsq.sdr_tire_pump/posseq = [(0,1)]

# ABS/TC (Anti-Lock Brake System & Traction Control) Related Loads:
# Power, 324 W, 23.14 A
alter /sdr_prsq.sdr_abs_tc/posseq = [(0,1)]

### Key-off Loads (Can be on even when ignition is off)

# Anti-Theft Warning Device: Current, .2 W, .014 A
# Always on: switch driver set to [(0,2)]

# All Parking Lights and Lowbeams: Resistance, 204.2 W, 14.59 A
alter /sdr_prsq.sdr_parking_and_lowbeams/posseq = [(0,1)]

# All Parking Lights: Resistance, 94.2 W, 6.73 A
alter /sdr_prsq.sdr_parking_lights/posseq = [(0,1), (11,2)]

# Power Door Locks: Power, 248 W, 17.7 A
alter /sdr_prsq.sdr_locks/posseq = [(0,1), (1,2), (2,1), (8,2), (9,1)]

# Power Trunk Opener: Power, 242 W, 17.29 A
alter /sdr_prsq.sdr_trunk_open/posseq = [(0,1)]

# Trunk Compartment Lamp: Resistance, 10 W, .71 A
alter /sdr_prsq.sdr_trunk_lamp/posseq = [(0,1)]

# Power Trunk Pull-down: Power, 22 W, 1.57 A
alter /sdr_prsq.sdr_trunk_close/posseq = [(0,1)]

# Driver Door Open: Resistance, 27 W, 1.93 A
alter /sdr_prsq.sdr_driver/posseq = [(0,1), (3,2), (6,1)]
```

```
# Seat Adjustments: Power, 73 W, 5.21 A
alter /sdr_prsq.sdr_seat_adjust/posseq = [(0,1)]
```

A.2 Loadcycle: `summer_worst_const`

`summer_worst_const.scs` is a worst-case summer (hot, raining, night-time) loadcycle customized for the `summer_const.dat` (continuous high-speed driving) drivecycle, both of which are used in the high-speed driving simulations. Note that most power and current values shown are nominal values; in the case of speed-dependent loads, however, the values listed are those expected at high alternator shaftspeed (6000 rpm).

A.2.1 Time-Sequential Format

Table A.2: Loadcycle summer_worst_const.scs

Time (s)	Event	Power (W)	Current (A)	14V Bus	42V Bus
0	Anti-theft warning device on (Always on)	0.2	0.014	X	
1	Power trunk opener on (Open trunk)	242	17.29	X	
2	Trunk lamp on Power trunk opener off	10	0.71	X X	
10	Power trunk pull-down on (Close trunk) Trunk lamp off	22	1.57	X X	
11	Power door locks on (Unlock doors)	248	17.7	X	
12	Power door locks off			X	
13	Power trunk pull-down off Driver door open	 27	 1.93	X	
16	Driver door closed			X	
17	Seat adjustments on	73	5.21	X	
20	Seat adjustments off			X	
22	Power door locks on (Lock doors)	248	17.7	X	
23	Power door locks off			X	
25	All parking lights and lowbeams on	204.2	14.59	X	
26	Starter on (Turn ignition key)	3150	75		X

Table A.2: Loadcycle summer_worst_const.scs

Time (s)	Event	Power (W)	Current (A)	14V Bus	42V Bus
28	Starter off				X
	Heated Catalytic Converter on	3000	71.43		X
	42V Base loads on	92	2.19		X
	42V Speed-dependent base loads on	250.6	5.97		X
	Emissions air pump on	150	3.57		X
	Electromechanical Valve Engine on	2500	59.5		X
	14V Base loads on	187.8	13.41	X	
	14V Speed-dependent base loads on	68.78	4.91	X	
30	Air conditioning on high	350	8.33		X
32	Power windows on (Open windows)	270	6.43		X
36	Power windows off				X
37	Radio on	40	0.95		X
	Antenna lift on (Antenna goes up)	45	3.21	X	
	CD changer on	13	0.93	X	
40	Antenna lift off			X	
	All-weather night vision on	100	2.38		X
42	Navigation aid on	50	3.57	X	
53	Heated Catalytic Converter off				
120	Cruise control on	25	1.79	X	
330	Front windshield wipers on high	150	3.57		X
332	Power windows on (Close windows)	270	6.43		X
336	Power windows off				X
750	Front windshield wipers on medium	90	2.14		X
930	Air conditioning on medium	245	5.83		X
1000	Automatic climate control on	25	1.79	X	
	42V Bus Total (Long-term)	*3467.6*	*82.53*		*X*
	14V Bus Total (Long-term)	*573.98*	*41.004*	*X*	
	Total (Long-term)	*4041.58*	*123.534*		
	14V Bus Total Translated through Converter (Conservation of Power, but 85% Efficiency)	*675.27*	*13.668*		*X*
	Approximate Alternator Output Needed (Long-term)	***4142.87***	***96.198***		*X*

A.2.2 `summer_worst_const.scs`: Saber Command Script Format

```
#####################################################
###                                               ###
### Loadcycle: summer_worst_const.scs             ###
###                                               ###
### Conditions: hot, rain, night-time,            ###
###             Customized for summer_const.dat   ###
###                                               ###
### Note: starts raining after windows closed     ###
###                                               ###
### Irene Kuo, MIT                                ###
### E-mail: ikuo@mit.edu                          ###
###                                               ###
### posseq = position sequence for related switch ###
### Format: [(t1, pos1), (t2, pos2)]              ###
### Load off = Switch open = position 1           ###
### Load on = Switch closed = position 2           ###
### For loads with 3 settings:                    ###
###   Load off = position 1                       ###
###   Low = position 2                            ###
###   Medium = position 3                         ###
###   High = position 4                           ###
###                                               ###
#####################################################

# DC/DC Converter
# Always on when engine is on
alter /sdr_prsq.sdr_converter/posseq = [(0,1), (28,2)]

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

# Loads on 42V bus

# Base Loads: Resistance, 92 W, 2.19 A
# Always on when engine is on
alter /sdr_prsq.sdr_base_loads_42V/posseq = [(0,1), (28,2)]

# Speed-Dependent Base Loads: Speed-Dependent Resistance, 250.6W, 5.97A
# Always on when engine is on
alter /sdr_prsq.sdr_speed_loads_42V/posseq = [(0,1), (28,2)]

# Emissions Air Pump: Power, 150 W, 3.57 A
# Always on when engine is on
alter /sdr_prsq.sdr_emissions/posseq = [(0,1), (28,2)]

# Starter: Power, 3150 W, 75 A
alter /sdr_prsq.sdr_starter/posseq = [(0,1), (26,2), (28,1)]
```

```
# Seat Heaters: Resistance, 220 W, 5.24 A
alter /sdr_prsq.sdr_seat_htrs/posseq = [(0,1)]

# Heated Windshield: Resistance, 700 W, 16.67 A
alter /sdr_prsq.sdr_windshield/posseq = [(0,1)]

# Heated Rear Window: Resistance, 280W, 6.67 A
alter /sdr_prsq.sdr_defog/posseq = [(0,1)]

# Windshield Wipers, Front: Current w/ Settings, 30 W, .71 A
alter /sdr_prsq.sdr_wipers/posseq = [(0,1), (330,4), (750,3)]

# Radio/Subwoofer: Power, 40 W, .95 A
alter /sdr_prsq.sdr_radio/posseq = [(0,1), (37,2)]

# Heater: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_heater/posseq = [(0,1)]

# All Air Conditioning Related Loads: Resistance w/ Settings, 245W, 5.83A
alter /sdr_prsq.sdr_air_cond/posseq = [(0,1), (30,4), (930,3)]

# Vent: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_ps_cmp_blwr/posseq = [(0,1)]

# Sun Roof: Power, 190 W, 4.52 A
alter /sdr_prsq.sdr_sunroof/posseq = [(0,1)]

# Power Windows: Power, 270 W, 6.43 A
alter  /sdr_prsq.sdr_windows/posseq  =  [(0,1),  (32,2),  (36,1),  (332,2),
(336,1)]

### Future 42V Loads

# A/C Compressor Pump: Power w/ Settings, 3000 W, 71.43 A
alter /sdr_prsq.sdr_ac_compressor/posseq = [(0,1)]

# Rear Seat Heaters: Resistance w/ Settings, 180 W, 4.29 A
alter /sdr_prsq.sdr_rear_seat_htrs/posseq = [(0,1)]

# All Weather Night Vision: Current, 100 W, 2.38 A
alter /sdr_prsq.sdr_night_vision/posseq = [(0,1), (40,2)]

# Active Suspension: Resistance, 1000 W, 23.81 A
alter /sdr_prsq.sdr_act_suspension/posseq = [(0,1)]

# Active Engine Mount: Resistance 70 W, 1.67 A
alter /sdr_prsq.sdr_act_eng_mount/posseq = [(0,1)]

# Water Pump: Resistance, 300 W, 7.14 A
alter /sdr_prsq.sdr_water_pump/posseq = [(0,1)]
```

```
# Heated Catalytic Converter, 3000 W, 71.43 A
alter /sdr_prsq.sdr_catalytic/posseq = [(0,1), (28,2), (53,1)]

# Electromechanical Valve Engine (8 cylinder):
# Speed-Dependent Resistance, 1000 W, 23.81 A
# Always on when engine is on!
alter /sdr_prsq.sdr_electromag_valve_eng/posseq = [(0,1), (28,2)]

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

# Loads on 14V bus

# Base Loads: Resistance, 187.8 W, 13.41 A
# Always on when engine is on
alter /sdr_prsq.sdr_base_loads_14V/posseq = [(0,1), (28,2)]

# Speed-Dependent Base Loads: Speed-Dependent Resistance, 68.78W, 4.91A
# Always on when engine is on
alter /sdr_prsq.sdr_speed_loads_14V/posseq =[(0,1), (28,2)]

# High Beam Headlamps: Resistance, 130 W, 9.29 A
alter /sdr_prsq.sdr_highbeams/posseq = [(0,1)]

# Turn Lights: Resistance, 110.8 W, 7.91 A
alter /sdr_prsq.sdr_turn/posseq = [(0,1)]

# All Brake Related Loads: Resistance, 470.6 W, 33.61 A
alter /sdr_prsq.sdr_brakes/posseq = [(0,1)]

# Power Mirror Heaters: Resistance, 30 W, 2.14 A
alter /sdr_prsq.sdr_mirrors/posseq = [(0,1)]

# Telephone: Current, 5 W, .36 A
alter /sdr_prsq.sdr_phone/posseq = [(0,1)]

# CD Changer: Current, 13 W, .93 A
alter /sdr_prsq.sdr_cd/posseq = [(0,1), (37,2)]

# Navigation Aid: Current, 50 W, 3.57 A
alter /sdr_prsq.sdr_nav_aid/posseq = [(0,1), (42,2)]

# Cruise Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_cruise/posseq = [(0,1), (120,2)]

# Automatic Climate Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_climate/posseq = [(0,1), (1000,2)]
```

```
# Antenna Lift: Power, 45 W, 3.21 A
# On when radio turns on
alter /sdr_prsq.sdr_antenna/posseq = [(0,1), (37,2), (40,1)]


# Automatic Tire Pump: Power, 100 W, 7.14 A
alter /sdr_prsq.sdr_tire_pump/posseq = [(0,1)]

# ABS/TC (Anti-Lock Brake System & Traction Control) Related Loads:
# Power, 324 W, 23.14 A
alter /sdr_prsq.sdr_abs_tc/posseq = [(0,1)]

### Key-off Loads (Can be on even when ignition is off)

# Anti-Theft Warning Device: Current, .2 W, .014 A
# Always on: switch driver set to [(0,2)]

# All Parking Lights and Lowbeams: Resistance, 204.2 W, 14.59 A
alter /sdr_prsq.sdr_parking_and_lowbeams/posseq = [(0,1), (25,2)]

# All Parking Lights: Resistance, 94.2 W, 6.73 A
alter /sdr_prsq.sdr_parking_lights/posseq = [(0,1)]

# Power Door Locks: Power, 248 W, 17.7 A
alter /sdr_prsq.sdr_locks/posseq = [(0,1), (11,2), (12,1), (22,2),
(23,1)]

# Power Trunk Opener: Power, 242 W, 17.29 A
alter /sdr_prsq.sdr_trunk_open/posseq = [(0,1), (1,2), (2,1)]

# Trunk Compartment Lamp: Resistance, 10 W, .71 A
alter /sdr_prsq.sdr_trunk_lamp/posseq = [(0,1), (2,2), (10,1)]

# Power Trunk Pull-down: Power, 22 W, 1.57 A
alter /sdr_prsq.sdr_trunk_close/posseq = [(0,1), (10,2), (13,1)]

# Driver Door Open: Resistance, 27 W, 1.93 A
alter /sdr_prsq.sdr_driver/posseq = [(0,1), (13,2), (16,1)]

# Seat Adjustments: Power, 73 W, 5.21 A
alter /sdr_prsq.sdr_seat_adjust/posseq = [(0,1), (17,2), (20,1)]
```

A.3 Loadcycle: `winter_worst_ece15`

`winter_worst_ece15.scs` is a worst-case winter (cold, snowing, night-time) loadcycle customized for the `ece15_city.dat` (continuous city driving) drivecycle, both of which are used in the city simulations. All power and current values listed are nominal values.

A.3.1 Time-Sequential Format

Table A.3: Loadcycle winter_worst_ece15.scs

Time (s)	Event	Power (W)	Current (A)	14V Bus	42V Bus
0	Anti-theft warning device on (Always on)	0.2	0.014	X	
1	Power trunk opener on (Open trunk)	242	17.29	X	
2	Trunk lamp on	10	0.71	X	
	Power trunk opener off			X	
10	Power trunk pull-down on (Close trunk)	22	1.57	X	
	Trunk lamp off			X	
11	Power door locks on (Unlock doors)	248	17.7	X	
12	Power door locks off			X	
13	Power trunk pull-down off			X	
	Driver door open	27	1.93		
16	Driver door closed			X	
17	Seat adjustments on	73	5.21	X	
20	Seat adjustments off			X	
22	Power door locks on (Lock doors)	248	17.7	X	
23	Power door locks off			X	
25	All parking lights and lowbeams on	204.2	14.59	X	
26	Starter on (Turn ignition key)	3150	75		X
28	Starter off				X
	Heated Catalytic Converter on	3000	71.43		X
	42V Base loads on	92	2.19		X
	42V Speed-dependent base loads on	250.6	5.97		X
	Emissions air pump on	150	3.57		X
	Electromechanical Valve Engine on	1000	23.81		X
	14V Base loads on	187.8	13.41	X	
	14V Speed-dependent base loads on	68.78	4.91	X	
30	Heater on high	300	7.14		X
31	Heated rear window on (Rear defog on)	280	6.67		X
32	Heated windshield on	700	16.67		X
33	Seat heaters on	220	5.24		X
	Rear seat heaters on high	250	5.95		X

Table A.3: Loadcycle winter_worst_ece15.scs

Time (s)	Event	Power (W)	Current (A)	14V Bus	42V Bus
35	Front windshield wipers on low	30	0.71		X
37	Radio on	40	0.95		X
	Antenna lift on (Antenna goes up)	45	3.21	X	
	CD changer on	13	0.93	X	
40	Antenna lift off			X	
	All-weather night vision on	100	2.38		X
42	Navigation aid on	50	3.57	X	
45	Automatic climate control on	25	1.79	X	
53	Heated Catalytic Converter off				X
300	Front windshield wipers on medium	90	2.14		X
332	Heated windshield off				X
480	Front windshield wipers on high	150	3.57		X
631	Heated rear window off				X
633	Rear seat heaters on low	110	2.62		X
750	Front windshield wipers on medium	90	2.14		X
930	Heater on medium	195	4.64		X
	42V Bus Total (Long-term)	*2247.6*	*53.13*		*X*
	14V Bus Total (Long-term)	*344.78*	*24.63*	*X*	
	Total (Long-term)	*2592.38*	*77.76*		
	14V Bus Total Translated through Converter (Conversation of Power, but 85% Efficiency)	*405.62*	*8.21*		*X*
	Approximate Alternator Output Needed (Long-term)	***2653.22***	***61.34***		*X*
	14V Bus Total (Long-term, with Brakes and Turn Lights)	*926.18*	*66.15*	*X*	
	Total (Long-term, with Brakes and Turn Lights)	*3173.18*	*119.28*		
	14V Bus Total Translated through Converter (Conservation of Power, but 85% Efficiency)	*1089.62*	*22.05*		*X*
	Approximate Alternator Output Needed (Long-term, with Brakes and Turn Lights)	***3337.22***	***75.18***		*X*

A.3.2 `winter_worst_ece15.scs`: Saber Command Script Format

```
#####################################################
###                                               ###
### Loadcycle: winter_worst_ece15.scs             ###
###                                               ###
### Conditions: cold, snow, night-time,           ###
###             Customized for ece15_city.dat     ###
###                                               ###
### Irene Kuo, MIT                                ###
### E-mail: ikuo@mit.edu                          ###
###                                               ###
### posseq = position sequence for related switch ###
### Format: [(t1, pos1), (t2, pos2)]              ###
### Load off = Switch open = position 1           ###
### Load on = Switch closed = position 2           ###
### For loads with 3 settings:                    ###
###   Load off = position 1                       ###
###   Low = position 2                            ###
###   Medium = position 3                         ###
###   High = position 4                           ###
###                                               ###
#####################################################

# DC/DC Converter
# Always on when engine is on
alter /sdr_prsq.sdr_converter/posseq = [(0,1), (28,2)]

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

# Loads on 42V bus

# Base Loads: Resistance, 92 W, 2.19 A
# Always on when engine is on
alter /sdr_prsq.sdr_base_loads_42V/posseq = [(0,1), (28,2)]

# Speed-Dependent Base Loads: Speed-Dependent Resistance, 250.6W, 5.97A
# Always on when engine is on
alter /sdr_prsq.sdr_speed_loads_42V/posseq = [(0,1), (28,2)]

# Emissions Air Pump: Power, 150 W, 3.57 A
# Always on when engine is on
alter /sdr_prsq.sdr_emissions/posseq = [(0,1), (28,2)]

# Starter: Power, 3150 W, 75 A
alter /sdr_prsq.sdr_starter/posseq = [(0,1), (26,2), (28,1)]

# Seat Heaters: Resistance, 220 W, 5.24 A
alter /sdr_prsq.sdr_seat_htrs/posseq = [(0,1), (33,2)]
```

```
# Heated Windshield: Resistance, 700 W, 16.67 A
alter /sdr_prsq.sdr_windshield/posseq = [(0,1), (32,2), (332,1)]

# Heated Rear Window: Resistance, 280W, 6.67 A
alter /sdr_prsq.sdr_defog/posseq = [(0,1), (31,2), (631,1)]

# Windshield Wipers, Front: Current w/ Settings, 30 W, .71 A
alter /sdr_prsq.sdr_wipers/posseq = [(0,1), (35,2), (300,3), (480,4),
(750,3)]

# Radio/Subwoofer: Power, 40 W, .95 A
alter /sdr_prsq.sdr_radio/posseq = [(0,1), (37,2)]

# Heater: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_heater/posseq = [(0,1), (30,4), (930,3)]

# All Air Conditioning Related Loads: Resistance w/ Settings, 245W, 5.83A
alter /sdr_prsq.sdr_air_cond/posseq = [(0,1)]

# Vent: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_ps_cmp_blwr/posseq = [(0,1)]

# Sun Roof: Power, 190 W, 4.52 A
alter /sdr_prsq.sdr_sunroof/posseq = [(0,1)]

# Power Windows: Power, 270 W, 6.43 A
alter /sdr_prsq.sdr_windows/posseq = [(0,1)]

### Future 42V Loads

# A/C Compressor Pump: Power w/ Settings, 3000 W, 71.43 A
alter /sdr_prsq.sdr_ac_compressor/posseq = [(0,1)]

# Rear Seat Heaters: Resistance w/ Settings, 180 W, 4.29 A
alter /sdr_prsq.sdr_rear_seat_htrs/posseq = [(0,1), (33,4), (633,2)]

# All Weather Night Vision: Current, 100 W, 2.38 A
alter /sdr_prsq.sdr_night_vision/posseq = [(0,1), (40,2)]

# Active Suspension: Resistance, 1000 W, 23.81 A
alter /sdr_prsq.sdr_act_suspension/posseq = [(0,1)]

# Active Engine Mount: Resistance 70 W, 1.67 A
alter /sdr_prsq.sdr_act_eng_mount/posseq = [(0,1)]

# Water Pump: Resistance, 300 W, 7.14 A
alter /sdr_prsq.sdr_water_pump/posseq = [(0,1)]
```

```
# Heated Catalytic Converter, 3000 W, 71.43 A
alter /sdr_prsq.sdr_catalytic/posseq = [(0,1), (28,2), (53,1)]

# Electromechanical Valve Engine (8 cylinder):
# Speed-Dependent Resistance, 1000 W, 23.81 A
# Always on when engine is on!
alter /sdr_prsq.sdr_electromag_valve_eng/posseq = [(0,1), (28,2)]

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

# Loads on 14V bus

# Base Loads: Resistance, 187.8 W, 13.41 A
# Always on when engine is on
alter /sdr_prsq.sdr_base_loads_14V/posseq = [(0,1), (28,2)]

# Speed-Dependent Base Loads: Speed-Dependent Resistance, 68.78W, 4.91A
# Always on when engine is on
alter /sdr_prsq.sdr_speed_loads_14V/posseq =[(0,1), (28,2)]

# High Beam Headlamps: Reistance, 130 W, 9.29 A
alter /sdr_prsq.sdr_highbeams/posseq = [(0,1)]

# Turn Lights: Resistance, 110.8 W, 7.91 A
alter  /sdr_prsq.sdr_turn/posseq  =  [(0,1),  (196,2),  (204,1),  (391,2),
(399,1), (586,2), (594,1), (781,2), (789,1), (985,2), (993,1), (1177,2),
(1185,1),  (1372,2),  (1380,1),  (1567,2),  (1575,1),  (1770,2),  (1778,1),
(1965,2),  (1973,1),  (2160,2),  (2168,1),  (2355,2),  (2363,1),  (2559,2),
(2567,1),  (2751,2),  (2759,1),  (2946,2),  (2954,1),  (3141,2),  (3149,1),
(3351,2),  (3359,1),  (3546,2),  (3554,1),  (3741,2),  (3749,1),  (3936,2),
(3944,1),  (4140,2),  (4148,1),  (4332,2),  (4340,1),  (4527,2),  (4535,1),
(4722,2),  (4730,1),  (4925,2),  (4933,1),  (5120,2),  (5128,1),  (5315,2),
(5323,1),  (5510,2),  (5518,1),  (5713,2),  (5722,1),  (5905,2),  (5914,1),
(6101,2),  (6110,1),  (6296,2),  (6304,1),  (6516,2),  (6524,1),  (6711,2),
(6719,1),  (6906,2),  (6914,1),  (7101,2),  (7109,1),  (7305,2),  (7313,1),
(7497,2),  (7505,1),  (7692,2),  (7700,1),  (7887,2),  (7895,1),  (8090,2),
(8098,1),  (8285,2),  (8293,1),  (8480,2),  (8488,1),  (8675,2),  (8683,1),
(8879,2),  (8887,1),  (9071,2),  (9078,1),  (9266,2),  (9274,1),  (9461,2),
(9469,1), (9662,2), (9670,1), (9857,2), (9865,1), (10052,2), (10060,1),
(10247,2),   (10256,1),   (10451,2),   (10459,1),   (10642,2),   (10650,1),
(10838,2),   (10846,1),   (11033,2),   (11041,1),   (11236,2),   (11244,1),
(11431,2),   (11439,1),   (11626,2),   (11634,1),   (11821,2),   (11829,1),
(12024,2),   (12033,1),   (12217,2),   (12225,1),   (12412,2),   (12420,1),
(12607,2), (12615,1)]

# All Brake Related Loads: Resistance, 470.6 W, 33.61 A
alter  /sdr_prsq.sdr_brakes/posseq  =  [(0,1),  (64,2),  (90,1),  (126,2),
(158,1), (196,2), (204,1), (217,2), (247,1), (259,2), (285,1), (321,2),
(353,1), (391,2), (399,1), (412,2), (442,1), (454,2), (480,1), (516,2),
(548,1), (586,2), (594,1), (607,2), (637,1), (649,2), (675,1), (711,2),
(743,1), (781,2), (789,1), (802,2), (841,1), (853,2), (879,1), (915,2),
```

```
(947,1),  (985,2),  (993,1),  (1004,2),  (1033,1),  (1045,2),  (1071,1),
(1107,2), (1139,1), (1177,2), (1185,1), (1198,2), (1228,1), (1240,2),
(1266,1), (1302,2), (1334,1), (1372,2), (1380,1), (1393,2), (1423,1),
(1435,2), (1461,1), (1497,2), (1529,1), (1567,2), (1575,1), (1588,2),
(1626,1), (1638,2), (1664,1), (1700,2), (1733,1), (1770,2), (1777,1),
(1791,2), (1821,1), (1833,2), (1859,1), (1895,2), (1928,1), (1965,2),
(1973,1), (1986,2), (2016,1), (2028,2), (2054,1), (2090,2), (2122,1),
(2160,2), (2167,1), (2181,2), (2211,1), (2223,2), (2249,1), (2285,2),
(2317,1), (2355,2), (2363,1), (2376,2), (2415,1), (2427,2), (2453,1),
(2489,2), (2521,1), (2559,2), (2567,1), (2578,2), (2607,1), (2619,2),
(2645,1), (2681,2), (2713,1), (2751,2), (2759,1), (2772,2), (2802,1),
(2814,2), (2840,1), (2876,2), (2908,1), (2946,2), (2954,1), (2967,2),
(2997,1), (3009,2), (3035,1), (3071,2), (3103,1), (3141,2), (3149,1),
(3162,2), (3207,1), (3219,2), (3245,1), (3281,2), (3313,1), (3351,2),
(3359,1), (3372,2), (3402,1), (3414,2), (3440,1), (3476,2), (3508,1),
(3546,2), (3554,1), (3567,2), (3597,1), (3609,2), (3635,1), (3671,2),
(3703,1), (3741,2), (3749,1), (3762,2), (3792,1), (3804,2), (3830,1),
(3866,2), (3898,1), (3936,2), (3944,1), (3957,2), (3996,1), (4008,2),
(4034,1), (4070,2), (4102,1), (4140,2), (4148,1), (4159,2), (4188,1),
(4200,2), (4226,1), (4262,2), (4294,1), (4332,2), (4340,1), (4353,2),
(4383,1), (4395,2), (4421,1), (4457,2), (4489,1), (4527,2), (4535,1),
(4548,2), (4578,1), (4590,2), (4616,1), (4652,2), (4684,1), (4722,2),
(4730,1), (4743,2), (4781,1), (4793,2), (4819,1), (4854,2), (4887,1),
(4925,2), (4933,1), (4946,2), (4976,1), (4988,2), (5014,1), (5050,2),
(5082,1), (5120,2), (5128,1), (5141,2), (5171,1), (5183,2), (5209,1),
(5245,2), (5277,1), (5315,2), (5323,1), (5336,2), (5366,1), (5378,2),
(5404,1), (5440,2), (5472,1), (5510,2), (5518,1), (5531,2), (5570,1),
(5582,2), (5608,1), (5644,2), (5676,1), (5714,2), (5722,1), (5733,2),
(5762,1), (5774,2), (5800,1), (5836,2), (5868,1), (5906,2), (5914,1),
(5927,2), (5957,1), (5969,2), (5995,1), (6031,2), (6063,1), (6101,2),
(6109,1), (6122,2), (6152,1), (6164,2), (6190,1), (6226,2), (6258,1),
(6296,2), (6304,1), (6317,2), (6372,1), (6384,2), (6410,1), (6446,2),
(6478,1), (6516,2), (6524,1), (6537,2), (6567,1), (6579,2), (6605,1),
(6641,2), (6673,1), (6711,2), (6719,1), (6732,2), (6762,1), (6774,2),
(6800,1), (6836,2), (6868,1), (6906,2), (6914,1), (6927,2), (6957,1),
(6969,2), (6995,1), (7031,2), (7063,1), (7101,2), (7109,1), (7122,2),
(7161,1), (7173,2), (7199,1), (7235,2), (7267,1), (7305,2), (7313,1),
(7324,2), (7353,1), (7365,2), (7391,1), (7427,2), (7459,1), (7497,2),
(7505,1), (7518,2), (7548,1), (7560,2), (7586,1), (7622,2), (7654,1),
(7692,2), (7700,1), (7713,2), (7743,1), (7755,2), (7781,1), (7817,2),
(7849,1), (7887,2), (7895,1), (7908,2), (7946,1), (7958,2), (7984,1),
(8020,2), (8052,1), (8090,2), (8098,1), (8111,2), (8141,1), (8153,2),
(8179,1), (8214,2), (8247,1), (8285,2), (8293,1), (8306,2), (8336,1),
(8348,2), (8374,1), (8410,2), (8442,1), (8480,2), (8488,1), (8501,2),
(8531,1), (8543,2), (8569,1), (8605,2), (8637,1), (8675,2), (8683,1),
(8696,2), (8735,1), (8747,2), (8773,1), (8809,2), (8841,1), (8879,2),
(8887,1), (8898,2), (8927,1), (8939,2), (8965,1), (9001,2), (9033,1),
(9071,2), (9079,1), (9092,2), (9122,1), (9134,2), (9160,1), (9196,2),
(9228,1), (9266,2), (9274,1), (9287,2), (9317,1), (9329,2), (9355,1),
(9391,2), (9423,1), (9461,2), (9469,1), (9482,2), (9518,1), (9530,2),
(9556,1), (9592,2), (9624,1), (9662,2), (9670,1), (9683,2), (9713,1),
(9725,2), (9751,1), (9787,2), (9819,1), (9857,2), (9865,1), (9878,2),
(9908,1), (9920,2), (9946,1), (9982,2), (10014,1), (10052,2), (10060,1),
(10073,2),  (10103,1),  (10115,2),  (10141,1),  (10177,2),  (10209,1),
```

```
(10246,2), (10255,1), (10268,2), (10307,1), (10319,2), (10345,1)]

# Power Mirror Heaters: Resistance, 30 W, 2.14 A
alter /sdr_prsq.sdr_mirrors/posseq = [(0,1)]

# Telephone: Current, 5 W, .36 A
alter /sdr_prsq.sdr_phone/posseq = [(0,1)]

# CD Changer: Current, 13 W, .93 A
alter /sdr_prsq.sdr_cd/posseq = [(0,1), (37,2)]

# Navigation Aid: Current, 50 W, 3.57 A
alter /sdr_prsq.sdr_nav_aid/posseq = [(0,1), (42,2)]

# Cruise Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_cruise/posseq = [(0,1)]

# Automatic Climate Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_climate/posseq = [(0,1), (45,2)]

# Antenna Lift: Power, 45 W, 3.21 A
# On when radio turns on
alter /sdr_prsq.sdr_antenna/posseq = [(0,1), (37,2), (40,1)]

# Automatic Tire Pump: Power, 100 W, 7.14 A
alter /sdr_prsq.sdr_tire_pump/posseq = [(0,1)]

# ABS/TC (Anti-Lock Brake System & Traction Control) Related Loads:
# Power, 324 W, 23.14 A
# Assume to be on when brakes are on
alter /sdr_prsq.sdr_abs_tc/posseq = [(0,1)]

### Key-off Loads (Can be on even when ignition is off)

# Anti-Theft Warning Device: Current, .2 W, .014 A
# Always on: switch driver set to [(0,2)]
# alter /sdr_prsq.sdr_alarm/posseq = [(0,2)]

# All Parking Lights and Lowbeams: Resistance, 204.2 W, 14.59 A
alter /sdr_prsq.sdr_parking_and_lowbeams/posseq = [(0,1), (25,2)]

# All Parking Lights: Resistance, 94.2 W, 6.73 A
alter /sdr_prsq.sdr_parking_lights/posseq = [(0,1)]

# Power Door Locks: Power, 248 W, 17.7 A
alter  /sdr_prsq.sdr_locks/posseq  =  [(0,1),  (11,2),  (12,1),  (22,2),
(23,1)]

# Power Trunk Opener: Power, 242 W, 17.29 A
alter /sdr_prsq.sdr_trunk_open/posseq = [(0,1), (1,2), (2,1)]
```

```
# Trunk Compartment Lamp: Resistance, 10 W, .71 A
alter /sdr_prsq.sdr_trunk_lamp/posseq = [(0,1), (2,2), (10,1)]

# Power Trunk Pull-down: Power, 22 W, 1.57 A
alter /sdr_prsq.sdr_trunk_close/posseq = [(0,1), (10,2), (13,1)]

# Driver Door Open: Resistance, 27 W, 1.93 A
alter /sdr_prsq.sdr_driver/posseq = [(0,1), (13,2), (16,1)]

# Seat Adjustments: Power, 73 W, 5.21 A
alter /sdr_prsq.sdr_seat_adjust/posseq = [(0,1), (17,2), (20,1)]
```

Appendix B

Loadlists

B.1 Loads Included in the Saber Design

Table B.1 lists all loads designated for placement on the 42V bus, along with each load's nominal power and current. Occasionally, several loads are combined and modeled as one load; in such cases, the individual sub-loads are italicized. For speed-dependent loads, the expected power at idling alternator shaftspeed (1800 rpm) and high alternator shaftspeed (6000 rpm) are also given. For multiple-setting loads, the amount of power and current estimated for low, medium, and high settings are shown. Future loads are marked with an asterisk (*).

Table B.1: 42V Loads Used in Saber Design

42V Load	Nominal Power [W]	Nominal Current [A]	Idle Power [W]	High Speed Power [W]
Base Loads	92.0	2.19		
Fuel Pump	*64.0*	*1.52*		
Trans Shift Solenoid 1	*18.0*	*0.43*		
Torque Converter Clutch Enable	*10.0*	*0.24*		
Speed-Dependent Base Loads	248.0	5.90	211.2	250.6
EDIS (Spark Ignition)	*13.0*	*0.31*	*9.1*	*15.6*
Engine Cooling Fans	*235.0*	*5.60*	*202.1*	*235.0*
Vent				
Passenger Compartment Blower	*195.0*	*4.64*		
Low	100.0	2.38		
Medium	195.0	4.64		
High	300.0	7.14		
Heater				
Passenger Compartment Blower	*195.0*	*4.64*		
Low	100.0	2.38		
Medium	195.0	4.64		
High	300.0	7.14		
Air Conditioning				
Passenger Compartment Blower	*See Above*	*See Above*		
A/C Clutch [Solenoid]	*50.0*	*1.19*		
Low	150.0	3.57		
Medium	245.0	5.83		
High	350.0	8.33		

Table B.1: 42V Loads Used in Saber Design

42V Load	Nominal Power [W]	Nominal Current [A]	Idle Power [W]	High Speed Power [W]
Front Windshield Wipers				
Low	30.0	0.71		
Medium	90.0	2.14		
High	150.0	3.57		
Starter	3150.0	75.00		
Starter	*3000.0*	*71.43*		
Starter Motor Solenoid	*150.0*	*3.57*		
Heated Rear Window	280.0	6.67		
Front Seat Heaters, Left and Right	220.0	5.24		
Radio/Subwoofer	40.0	0.95		
Power Windows (driver side)	270.0	6.43		
Sun Roof	190.0	4.52		
Emissions Air Pump	150.0	3.57		
Heated Windshield	700.0	16.67		
Active Suspension (all 4 corners)*	1000.0	23.81		
Heated Catalytic Converter*	3000.0	71.43		
Active Engine Mount*	70.0	1.67		
Rear Seat Heaters*				
Low	110.0	2.62		
Medium	180.0	4.29		
High	250.0	5.95		
All Weather Night Vision*	100.0	2.38		
Water Pump*	300.0	7.14		
A/C Compressor Pump* (N/A until post-2005)				
Low	2000.0	47.62		
Medium	3000.0	71.43		
High	4000.0	95.24		
Electromechanical Valve Engine (8 cylinders)*	1000.0	23.81	500.0	2500.0

Table B.2 shows all loads designated to be placed on the 14V bus.

Table B.2: 14V Loads Used in Saber Design

14V Load	Nominal Power [W]	Nominal Current [A]	Idle Power [W]	High Speed Power [W]
Base Loads	187.6	13.40		
Engine Management	*31.0*	*2.21*		
Heated Oxygen Sensor	*36.0*	*2.57*		
ABS/Traction Control	*15.0*	*1.07*		
Steering Control	*7.0*	*0.50*		
Lighting Module	*10.0*	*0.71*		
Active Suspension Control	*13.0*	*0.93*		
Generic Electronic Module	*26.0*	*1.86*		
AIr Bag Control	*1.3*	*0.09*		
Multiplexer	*1.3*	*0.09*		
IP + Interior Illumination	*30.0*	*2.14*		
Vehicle Emergency Management System	*7.0*	*0.50*		
Tire Pressure Monitor	*10.0*	*0.71*		
Anti-Theft Warning System	0.2	0.01		
Speed-Dependent Base Loads	65.7	4.69	24.37	68.78
Trans Shift Solenoid 2	*18.0*	*1.29*	*3.85*	*10.78*
Fuel Injectors (1 through 8)	*7.7*	*0.55*	*9.72*	*18.00*
Vehicle Dynamic Module (Including Vehicle Assist Power Steering)	*40.0*	*2.86*	*10.80*	*40.00*
Power Mirror Heaters, Left and Right	30.0	2.14		
CD Changer	13.0	0.93		
Automatic Climate Control	25.0	1.79		
Telephone	5.0	0.36		
All Parking Lights	94.2	6.73		
Parking Lamps, Left and Right	*15.0*	*1.07*		
Front Sidemarkers, Left and Right	*14.0*	*1.00*		
Rear Sidemarkers, Left and Right	*18.0*	*1.29*		
Tail Lamps, Left and Right	*15.1*	*1.08*		
Applique Tail Lamps, Left and Right	*15.1*	*1.08*		
License Plate Lamps, Left and Right	*10.0*	*0.71*		
Console	*7.0*	*0.50*		
All Parking Lights and Lowbeams	204.2	14.59		
All Parking Lights	*See Above*	*See Above*		
Low Beam Headlamps, Left and Right	*110.0*	*7.86*		
Turn Lights	110.8	7.91		
Stop/Turn, 1 side	*26.9*	*1.92*		
Applique Stop/Turn, 1 side	*28.5*	*2.04*		
Front Turn Lamps, 1 side	*28.5*	*2.04*		
Front Cornering, 1 side	*26.9*	*1.92*		

Table B.2: 14V Loads Used in Saber Design

14V Load	Nominal Power [W]	Nominal Current [A]	Idle Power [W]	High Speed Power [W]
All Brake Related Loads	470.6	33.61		
Stop/Turn, Left and Right	*53.8*	*3.84*		
Applique Stop/Turn, Left and Right	*57.0*	*4.07*		
Rear CHMSL Brake, Left and Right	*35.8*	*2.56*		
ABS/Traction Hydraulic Pump	*256.0*	*18.29*		
ABS/TC Solenoids	*68.0*	*4.86*		
Anti-lock Brake System/Traction Control Related Loads	324.0	23.14		
ABS/Traction Hydraulic Pump	*256.0*	*18.29*		
ABS/TC Solenoids	*68.0*	*4.86*		
Power Locks	248.0	17.70		
Power Door Locks	*235.0*	*16.79*		
Door Module	*13.0*	*0.9*		
Trunk Opening	242.0	17.28		
Power Trunk Pull-down/Opener	*22.0*	*1.57*		
Power Trunk Release	*220.0*	*15.71*		
Trunk Closing	22.0	1.57		
Power Trunk Pull-down/Opener	*22.0*	*1.57*		
Seat Adjustments	73.0	5.20		
Seat Adjustments	*60.0*	*4.3*		
Seat Module	*13.0*	*0.9*		
Antenna Lift	45.0	3.21		
Automatic Tire Pump	100.0	7.14		
High Beam Headlamps	130.0	9.29		
Trunk Compartment Lamp	10.0	0.71		
Driver Door Open Lamps	27.0	1.93		
Driver Door Exit Lamp	*17.0*	*1.21*		
Dome Lamp	*10.0*	*0.71*		
Cruise Control	25.0	1.79		
Navigation Aid*	50.0	3.57		

B.2 Categorization of Load Models by Power Consumption Method

Table B.3 shows all 42V loads included in the design and the method of power consumption which was used to model each load.

Table B.3: Power Consumption Method of 42V Loads

Power Consumption Method	42V Loads
Speed-Dependent	Speed-Dependent Base Loads Electromechanical Valve Engine (8 cylinders)
Constant Resistance	Base Loads Heated Rear Window Front Seat Heaters, Left and Right Heated Windshield Active Suspension (all 4 corners) Active Engine Mount Active Engine Mount
Constant Power	Starter Radio/Subwoofer Power Windows (driver side) Sun Roof Emissions Air Pump Heated Catalytic Converter
Constant Current	All Weather Night Vision
Multiple-Setting Constant Resistance	Vent Heater Air Conditioning Rear Seat Heaters
Multiple-Setting Constant Power	A/C Compressor Pump
Multiple-Setting Constant Current	Front Windshield Wipers

Table B.4 shows all 14V loads included in the design and the method of power consumption which was used to model each load.

Table B.4: Power Consumption Method of 14V Loads

Power Consumption Method	14V Loads
Speed-Dependent	Speed-Dependent Base Loads
Constant Resistance	Base Loads Power Mirror Heaters, Left and Right All Parking Lights All Parking Lights and Lowbeams Turn Lights High Beam Headlamps Trunk Compartment Lamp Driver Door Open Lamps
Constant Power	CD Changer All Brake Related Loads Anti-lock Brake System/Traction Control Related Loads Power Locks Trunk Opening Trunk Closing Seat Adjustments Antenna Lift Automatic Tire Pump
Constant Current	Anti-Theft Warning System Automatic Climate Control Telephone Cruise Control Navigation Aid

Appendix C

MAST Code for Speed-Dependent Loads

C.1 MAST Code for 42V Speed-Dependent Load

```
########################################################################
####  Models a speed-dependent 42V load, given the power            ####
####  dissipated at high speeds and the power dissipated at idle.   ####
####  At each specific speed, load is modeled as constant           ####
####  resistance, assuming a sufficient bus voltage of 42V.         ####
####                                                                ####
####  Irene Kuo,  MIT                                               ####
####  Email: ikuo@mit.edu                                           ####
####  WWW:   http://web.mit.edu/ikuo/www/                           ####
####                                                                ####
########################################################################

element template load_speed_42 shaft_rpm p m = maxpwr, idlepwr

electrical  p,  # Positive electrical terminal
            m   # Negative electrical terminal

ref nu  shaft_rpm       # Alternator shaftspeed (rpm)

number  maxpwr = 2500,  # Power dissipated by load at high speed
        idlepwr = 500   # Power dissipated by load when idling

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

{
val nu slope
val nu pwr
val nu resval
val v  v
val i  i

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

values {
  slope = (maxpwr-idlepwr)/(6000-1800)
  pwr = slope*(shaft_rpm-1800) + idlepwr

  resval = (42*42)/pwr
  v = v(p) - v(m)
  i = v/resval
  }
```

```
# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

equations {
  i(p->m) += i
  }

#######################################################################

}
```

C.2 MAST Code for 14V Speed-Dependent Load

```
#########################################################################
####  Models a speed-dependent 14V load, given the power             ####
####  dissipated at high speeds and the power dissipated at idle.    ####
####  At each specific speed, load is modeled as constant            ####
####  resistance, assuming a sufficient bus voltage of 14V.          ####
####                                                                 ####
####  Irene Kuo,  MIT                                                ####
####  Email: ikuo@mit.edu                                            ####
####  WWW:   http://web.mit.edu/ikuo/www/                            ####
#########################################################################

element template load_speed_14 shaft_rpm p m = maxpwr, idlepwr

electrical  p,  # Positive electrical terminal
            m   # Negative electrical terminal

ref nu  shaft_rpm        # Alternator shaftspeed (rpm)

number  maxpwr = 10.78,  # Power dissipated by load at high speed
        idlepwr = 3.85   # Power dissipated by load when idling

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

{
val nu slope
val nu pwr
val nu resval
val v  v
val i  i

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

values {
  slope = (maxpwr-idlepwr)/(6000-1800)
  pwr = slope*(shaft_rpm-1800) + idlepwr
```

```
  resval = (14*14)/pwr
  v = v(p) - v(m)
  i = v/resval
  }

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

equations {
  i(p->m) += i
  }

#######################################################################

}
```

Appendix D

The Averaged Alternator Model

D.1 The Alternator Model

This section includes supplementary information describing the development of the averaged alternator model.

D.1.1 Documentation of the Averaged Alternator Model

The following excerpt is taken from Chapter 3 of *Modeling and Simulation of a Claw-Pole Alternator: Detailed and Averaged Models* [4] and explains the implementation of the averaged alternator model used in this project:

> The models for the subsystems presented in the last section can be used to simulate the time-domain behavior of an alternator based system. However, due to the complexity of the models and the presence of diodes, the simulation time can be rather long depending on the time scale of interest. For instance, in long term simulation of automotive systems, the time scales of interest can be in the order of hours. This requires simulation times which are unreasonable. What is needed are models that give the averaged behavior of the subsystems without sacrificing the accuracy of the simulation. This leads us into the introduction of the averaged alternator model. The schematic which is utilized to model the alternator is shown in Figure [D.1].

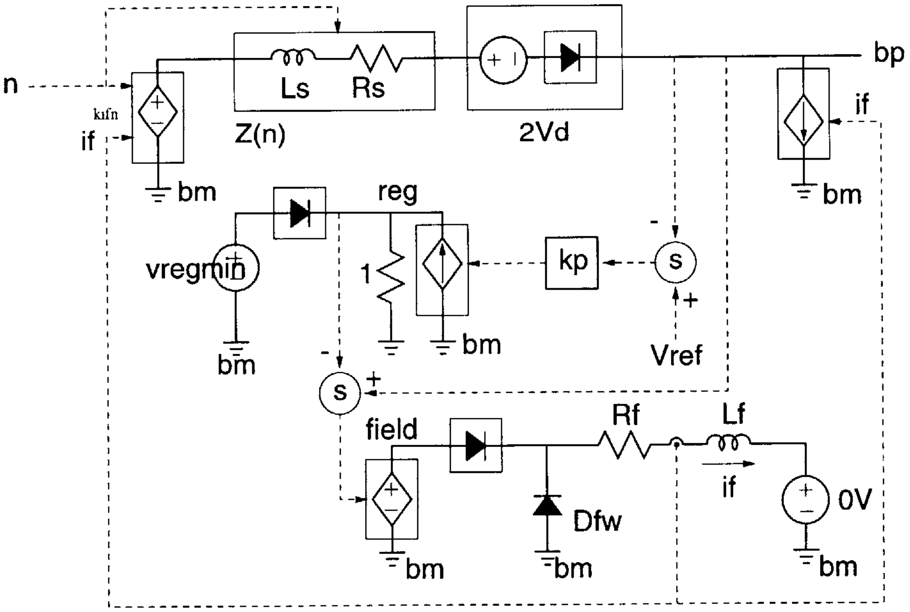

Figure D.1: Averaged Model of an Alternator

The main circuitry appears at the top where a controlled voltage source appears. The value of the controlled voltage is proportional to the alternator speed (n) and the field current (i_f). The impedance of the stator is modeled with a speed dependent resistive drop and is given by

$$Z(n) = \sqrt{R_s^2 + \left(\frac{\pi}{30}(p/2)nL_s\right)^2} \quad . \qquad [D.1]$$

The dc voltage drop in the three phase rectifier is accounted for by the inclusion of a constant voltage drop of $2V_d$, where V_d is the forward drop of a single power diode. In the figure, the use of ideal diodes has been denoted by a boxed diode symbol. Field current is drawn from the positive alternator terminal (`bp`) by the use of a controlled current source. The value of the field current is derived by the use of the other two circuit fragments shown in Figure [D.1]. First an amplified error signal is generated by comparing the alternator output voltage to a reference voltage V_{ref} and multiplying it by the proportional gain kp. The voltage at (`reg`) represents the average value of the voltage that would appear across the transistor switch in an actual regulator and is thus limited to a value no higher than the collector-emitter saturation voltage of the device. To model this, amplified error signal (`reg`) is clamped to a minimum value $V_{reg,min}$ by the use of the diode-voltage source combination. The voltage appearing across the field winding (`bp-reg`) is used to drive the field circuit composed of resistance R_f, inductance L_f and the freewheeling diode D_{fw}. The resulting current i_f in the field inductance L_f is then reported to the controlled sources to complete the model. Model parameters for the three phase alternator such as the stator and rotor inductances/resistances can be used here as well. For some of the other parameters, one has to consult a maximum current versus speed curve provided by the manufacturer. For instance, the constant of proportionality k appearing in the speed voltage ($k\, i_f n$) is given by

$$k = \frac{V_{ref} + 2V_d}{n_0 i_{f,max}} \quad , \qquad [D.2]$$

where n_0 is the speed at the which the alternator produces no current and maximum field current $i_{f,max}$ is given by

$$i_{f,max} = \frac{V_{const} - V_{reg,min}}{R_f} \quad , \qquad [D.3]$$

where V_{const} is the constant voltage value under which the maximum current versus speed curve is generated.

D.1.2 MAST Code for 42V Averaged Alternator Model

Using the design and MAST code given in *Modeling and Simulation of a Claw-Pole Alternator: Detailed and Averaged Models* [4] for a 14V averaged alternator model, a similar model can be derived for the 42V averaged alternator model:

```
########################################################################
####  Alternator Averaged Model - 42 V - Level 0                   ####
####                                                               ####
####  Vahe Caliskan, MIT                                           ####
####  Email: vahe@mit.edu                                          ####
####  WWW:   http://web.mit.edu/vahe/www/home.html                 ####
####  Created: May 28, 1998                                        ####
####  Modified:                                                    ####
####                                                               ####
########################################################################

template alt42v_avg_0 shaft bp bm data = k, rs, ls, rf, lf, p, kp, vd,
                                          vref, vregmin

rotational_vel  shaft   # rotor mechanical angular velocity connection

electrical      bp,     # bp (battery +) terminal
                bm      # negative terminal - ground

ref nu data             # data output (for comparison)

number   k = <input parameter>, # Multiplier for speed voltage
                                # k = (vref+2*vd)/(n0 if)
                                # where if=(vconst-vregmin)/rf
                                # n0 is usually 1000
        rs = <input parameter>, # Stator winding resistance
        ls = <input parameter>, # Stator equivalent self-inductance
        rf = <input parameter>, # Rotor (field) winding resistance
        lf = <input parameter>, # Rotor (field) self-inductance
                                # [not used]
        p  = 12,                # Number of poles
        kp = 20,                # Alternator regulator proportional gain
        vd = 1,                 # diode drop in rectifier
      vref = 14.2*3,            # alternator reference voltage
   vregmin = 0.5                # min value of regulation voltage

{

<consts.sin
```

```
########################################################################
### Speed voltage
element template speedvolt n ifield pos neg = k
electrical      pos, neg
ref nu          n
number          k=1

ref     i       ifield

{
<consts.sin

branch i=i(pos,neg), v=v(pos,neg)
v=k*n*ifield

}
########################################################################
### Stator Impedance
element template zn n pos neg = rs, ls, p
electrical      pos, neg
ref nu          n

number  rs = 33m,
        ls = 177u,
        p  = 12
{
<consts.sin

val nu  z

values  {
        z = sqrt( rs**2 + ( (math_pi/30)*(p/2)*n*ls )**2 )
        }

branch i=i(pos,neg), v=v(pos,neg)
i=v/z

}
########################################################################
#### Netlist
# speed voltage k if n
rot_vel2var.1 shaft 0 n = units=ios
speedvolt.1 n i(l.lf) 1 bm = k=k        # v(1)=k*ifield*n
zn.1 n 1 2 = p=p, ls=ls, rs=rs          # stator impedance
#l.ls 20 2 = l=ls                           # stator inductance (for LD)
v.d2 2 3 = dc = 2*vd                    # two-diode drop
pwld.1 3 bp = von=1m                    # keeps i_stator >0
####cccs.field i(l.lf) bp bm = k=1          # pull ifield out of bp node
cccs.field i(l.lf) 2 bm = k=1           # pull ifield out of 2 node
```

```
v.ref ref bm = dc=vref                  # v(ref) = vref
vsum.1 bp ref kerr = k1=kp, k2=-kp      # kerr = kp*(v(bp)-v(ref))

vccs.reg  kerr bm bm reg = k=1          # i(0->reg)=
                                        #    kp*(v(bp)-v(ref))=kerr
r.reg  reg bm = rnom=1                  # v(reg)=kp*(v(bp)-v(ref)
pwld.clamp clamp reg = von=1m
v.clamp clamp bm = dc=vregmin           # min[v(reg)] = vregmin

vcvs.field bp reg field bm = k=1        # v(field) = (v(4) - v(reg))
r.rf bm1 bm2 = rnom=rf                  # field resistance
l.lf bm2 bm3 = l=lf                     # field self inductance
v.if bm3 bm  = dc=0                     # i(field) = i(v.if)
d.flyback bm bm1                        # flyback diode
#pwld.flyback bm bm1 = von=0.7              # flyback diode - pwl ideal
#d.reg field bm1                            # reg diode - ireg >=0
pwld.reg field bm1 = von=1m             # reg diode - pwl ideal

map1d.1 n data = data=[<include alternator data (rpm, current) here>]
```

D.2 Using Maple to Estimate Alternator Parameters

This section includes information relevant to the use of Maple in determining the value of parameters used in modeling various sizes of alternators.

D.2.1 Maple Commands Used to Estimate *k*, R_s, and L_s

```
> restart;

% Rs = stator resistance
% Ls = stator inductance
% k = constant
> assume(Rs>0); assume(Ls>0); assume(k>0);

% Rf = field resistance
% Vref = reference voltage
% Vregmin = minimum regulator voltage
% kp = constant
% p = number of poles
% Vd = drop across each diode
% va = voltage at output of alternator
> Rf:=<input parameter>: Vref:=13.5*3: Vregmin:=0.5: kp:=20: p:=12:
Vd:=1: va:=Vref:

% Alternator Data
% nx = rpm
% Iax = alternator output current at nx rpm
> <include alternator data here: n0:=<data>: Ia0:=<data>: n1:=<data>:
Ia1:=<data>: n2:=<data>: Ia2:=<data>: >
```

```
% ifield = field current
% Equation used if field current not given.
> ifield:=(Vref-Vregmin)/Rf:

% Equations to solve simultaneously for parametrs k, Rs, and Ls.
>  eq0:=(Ia0+ifield)*(sqrt(Rs^2+((Pi/30)*Ls*n0*(p/2))^2))=k*ifield*n0  -
(Vref+2*Vd):

>  eq1:=(Ia1+ifield)*(sqrt(Rs^2+((Pi/30)*Ls*n1*(p/2))^2))=k*ifield*n1  -
(Vref+2*Vd);

>  eq2:=(Ia2+ifield)*(sqrt(Rs^2+((Pi/30)*Ls*n2*(p/2))^2))=k*ifield*n2  -
(Vref+2*Vd);

% Solve three equations simultaneously for k, Rs, and Ls.
% Solution exists for which all values are positive.
> solve({eq0,eq1,eq6},{k,Rs,Ls}):
```

D.2.2 Table of Estimated Parameters

The following table lists the 42V alternator parameters found using Maple. The data which the alternators model are derived from existing 14V alternators, as explained in Section 3.3.3. It is important to note that the 42V alternators listed below are not models of existing 42V alternators, but rather, are representative of the characteristic curves which 42V alternators might be expected to have.

Table D.1: 42V Alternator Parameters Obtained from Maple

Amps at Idle rpm (1800rpm)	Amps at High rpm (6000rpm)	k	R_s (Ω)	L_s (H)	R_f (Ω)
15	29	0.005258374068	0.9191148456	0.002090956967	3.44
20	43	0.004903885643	0.8011976285	0.001524732359	3.44
26	53	0.004337658154	0.1490143522	0.001060283588	3.44
31	61.5	0.01206561163	0.06121521759	0.0009165426596	10.81
34	68	0.004279093296	0.2064098273	0.0008535845756	3.44
40	77	0.004139458432	0.1408500995	0.0007377329018	3.44
50	90	0.01270466022	0.2830341610	0.0006377554833	11.11
50	100	0.004107402290	0.2719090709	0.0005754574644	3.44

Table D.1: 42V Alternator Parameters Obtained from Maple

Amps at Idle rpm (1800rpm)	Amps at High rpm (6000rpm)	k	R_s (Ω)	L_s (H)	R_f (Ω)
54	108	0.004072187964	0.2499528498	0.0005316093666	3.44
60	120	0.004028596691	0.2229554653	0.0004771075219	3.44

Appendix E

DC/DC Converter Model

E.1 MAST Code for DC/DC Converter Model

```
##############################################################
####  Buck DC/DC Converter Simplified Model              ####
####  Model is intended for long term simulations.       ####
####                                                     ####
####  Vahe Caliskan, MIT                                 ####
####  Email: vahe@mit.edu                                ####
####  WWW:   http://web.mit.edu/vahe/www/home.html       ####
####  Created: October 1, 1998                           ####
####  Modified: October 2, 1998                          ####
####                                                     ####
####  Irene Kuo                                          ####
####  Email: ikuo@mit.edu                                ####
####  Modified: November 9, 1998                         ####
####                                                     ####
##############################################################

template dcdc in out com = eta, imax, vmax, vmin

electrical  in,   # converter input
            out,  # converter output
            com   # common terminal (usually grounded)


number  eta=0.85,     # converter efficiency (0 < eta < 1)
        imax=68,      # maximum current output of converter
        vmax=14.2,    # maximum regulation voltage of converter
                      # this is the no-load (open-circuit) voltage
        vmin=13.8     # converter voltage at full load current

{

# Branch current, voltage relationships
branch iin=i(in->com), vin=v(in,com)
branch iout=i(out->com), vout=v(out,com)

val nu vin1  # Used for providing a slight slope over input voltage
val nu vout1 # Used for providing a slight slope over output voltage
val nu iout1
val nu iin1
```

```
val nu imax2 # Used for providing a slight slope over input voltage
val nu imin
val nu vmax2 # Used for providing a slight slope over output voltage

values {

  imax2 = imax+1
  imin = 0.5
  vmax2 = 28

  vin1 = v(in) - v(com)
  vout1 = v(out) - v(com)

  if (vout1 >= 0.0 & vout1 < vmin)
    iout1 = imax2 + ((imax-imax2)/vmin)*vout1
  else if (vout1 >= vmin & vout1 <=vmax)
    iout1 = imax + ((imin-imax)/(vmax-vmin))*(vout1-vmin)
  else if (vout1 > vmax)  iout1 = imin +
                                  (-imin/(vmax2-vmax))*(vout1-vmax)

  iin1 = vout1*iout1/(eta*vin1 + 1m)

       }

equations {
  iout = - iout1 + vout/1e6
  iin = iin1 - vin/1e6
          }

}
```

Appendix F

Drivecycle-to-Alternator Shaftspeed Conversion

F.1 MAST Code for Conversion without Gear Data

```
##############################################################
####  Drive Cycle -> Alternator RPM --> shaftspeed rad/s  ####
####                                                      ####
####  Vahe Caliskan, Irene Kuo, MIT                       ####
####  Email: vahe@mit.edu, ikuo@mit.edu                   ####
####  WWW:   http://web.mit.edu/vahe/www/home.html        ####
##############################################################

element template drive_speed p m shaft_rpm shaft = cd, ac, rho,
                                                    mass, rr, g, d,
                                                    g1, g2, g3, g4,
                                                    g5, gd, gea, eid

electrical  p,  # Positive electrical terminal
            m   # Negative electrical terminal

ref nu  shaft_rpm       # Alternator shaftspeed (rpm)

rotational_vel  shaft   # Alternator speed (rad/s)

number  cd   = 0.3,                # Coefficient of Air Friction (-)
                                   # [not used]
        ac   = <input parameter>, # Frontal cross-sectional area
                                   # of vehicle (m^2) [not used]
        rho  = 1.29,               # Density of air (kg/m^3)
                                   # [not used]
        mass = <input parameter>, # Mass of vehicle (kg) [not used]
        rr   = 0.012,              # Coefficient of static friction
                                   # of tires (-) [not used]
        g    = 9.81,               # Acceleration due to gravity
                                   # (m/s^2) [not used]
        d    = <input parameter>, # Tire diameter (m)
        g1   = <input parameter>, # First gear ratio (-)
        g2   = <input parameter>, # Second gear ratio (-)
        g3   = <input parameter>, # Third gear ratio (-)
        g4   = <input parameter>, # Fourth gear ratio (-)
        g5   = <input parameter>, # Fifth gear ratio (-)
        gd   = <input parameter>, # Differential gear ratio (-)
        gea  = <input parameter>, # Engine-alternator gear ratio (-)
        eid  = <input parameter>  # Engine idle rpm (rpm: rev/min)
```

```
# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

{

val v   speed   # Voltage -> speed in km/h

val nu  gtval   # Value for gear transmission ratio
var nu  gt      # Gear transmission ratio

val nu  k1val   # Used to ensure alternator is off when starter is on
var nu  k1

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

values {
  speed = v(p) - v(m)   # voltage between p and m -> speed in km/h

  #Calculate transmissions gear ratio 'gt' based on current speed
  if (speed > 0 & speed <= 15) gtval = g1
  else if (speed > 15 & speed <= 33) gtval = g2
  else if (speed > 33 & speed <= 50) gtval = g3
  else if (speed > 50 & speed < 67.5) gtval = g4
  else if (speed >= 67.5) gtval = g5
  else if (speed <= 0) gtval = 0

  # For use in making shaftspeed=0 when key is being turned.
  # Car speed = -1 when key is being turned (in drivecycle).
  if (speed < 0) k1val = 0
  else k1val = 1

  }

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

equations {
  gt : gt = gtval
  k1 : k1 = k1val
  }

######################################################################

# Netlist
# convert voltage input -> speed in km/h
elec2var.1 p m v_kmh

# convert speed in km/h -> speed in m/s
gain.ms v_kmh v_ms = k=(10/36)

# calculate tire rpm from speed in m/s
gain.trpm v_ms t_rpm = k=60/(3.14159*d)
```

```
# Calculate engine rpm based on differential gear ratio 'gd',
# transmission gear ratio 'gt', tire rpm 't_rpm', and
# engine idle rpm 'eid'
gain.erpm1 t_rpm e_rpm1 = k=gd
mult.erpm2 e_rpm1 gt e_rpm2
map1d.1 e_rpm2 e_rpm = data=[(0,eid), (eid,eid), (100000,100000)]

# calculate shaftspeed (rpm)
gain.rpm e_rpm shaft_rpm1 = k=gea

# Make sure the alternator shaftspeed_rpm = 0 when the starter is on
mult.shaft_rpm shaft_rpm1 k1 shaft_rpm

# convert rpm to rad/s
gain.rads shaft_rpm shaft_rads = k=3.14159/30

# Convert output to rotational_vel
var2w_radps.out shaft_rads shaft 0

}
```

F.2 MAST Code for Conversion with Gear Data

```
##############################################################
####  Drive Cycle -> Alternator RPM --> shaftspeed rad/s  ####
####                                                      ####
####  Vahe Caliskan, Irene Kuo, MIT                       ####
####  Email: vahe@mit.edu, ikuo@mit.edu                   ####
####  WWW:   http://web.mit.edu/vahe/www/home.html        ####
##############################################################

element template drive_gear p m shaft_rpm shaft gear = cd, ac,
                                          rho, mass, rr, g, d,
                                          g1, g2, g3, g4, g5,
                                          gd, gea, eid

electrical  p,  # Positive electrical terminal
            m   # Negative electrical terminal

ref nu  gear    # Gear Position

ref nu  shaft_rpm       # Alternator shaftspeed (rpm)

rotational_vel  shaft   # Alternator speed (rad/s)
```

```
number  cd   = 0.3,               # Coefficient of Air Friction (-)
                                  # [not used]
        ac   = <input parameter>, # Frontal cross-sectional area
                                  # of vehicle (m^2) [not used]
        rho  = 1.29,              # Density of air (kg/m^3)
                                  # [not used]
        mass = <input parameter>, # Mass of vehicle (kg) [not used]
        rr   = 0.012,             # Coefficient of static friction
                                  # of tires (-) [not used]
        g    = 9.81,              # Acceleration due to gravity
                                  # (m/s^2) [not used]
        d    = <input parameter>, # Tire diameter (m)
        g1   = <input parameter>, # First gear ratio (-)
        g2   = <input parameter>, # Second gear ratio (-)
        g3   = <input parameter>, # Third gear ratio (-)
        g4   = <input parameter>, # Fourth gear ratio (-)
        g5   = <input parameter>, # Fifth gear ratio (-)
        gd   = <input parameter>, # Differential gear ratio (-)
        gea  = <input parameter>, # Engine-alternator gear ratio (-)
        eid  = <input parameter>  # Engine idle rpm (rpm: rev/min)

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

{

val v   speed   # Voltage -> speed in km/h

val nu  gtval   # Value for gear transmission ratio
var nu  gt      # Gear transmission ratio

val nu  k1val   # Used to ensure alternator is off when starter is on
var nu  k1

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

values {
  speed = v(p) - v(m)   # voltage between p and m -> speed in km/h

  #...Calculate transmission gear ratio 'gt' based on current speed
  if (gear <= .5) gtval = 0
  else if (gear > .5 & gear <= 1.5) gtval = g1
  else if (gear > 1.5 & gear <= 2.5) gtval = g2
  else if (gear > 2.5 & gear <= 3.5) gtval = g3
  else if (gear > 3.5 & gear <= 4.5) gtval = g4
  else if (gear > 4.5 & gear <= 5.5) gtval = g5
  else gtval = 0

  # For use in making shaftspeed=0 when key is being turned.
  # Car speed = -1 when key is being turned (in drivecycle).
  if (speed < 0) k1val = 0
```

```
  else k1val = 1
  }

# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #

equations {
  gt : gt = gtval
  k1 : k1 = k1val
  }

######################################################################

# Netlist
# convert voltage input -> speed in km/h
elec2var.1 p m v_kmh

# convert speed in km/h -> speed in m/s
gain.ms v_kmh v_ms = k=(10/36)

# calculate tire rpm from speed in m/s
gain.trpm v_ms t_rpm = k=60/(3.14159*d)

# Calculate engine rpm based on differential gear ratio 'gd',
# transmission gear ratio 'gt', tire rpm 't_rpm', and
# engine idle rpm 'eid'
gain.erpm1 t_rpm e_rpm1 = k=gd
mult.erpm2 e_rpm1 gt e_rpm2
map1d.1 e_rpm2 e_rpm = data=[(0,eid), (eid,eid), (100000,100000)]

# calculate shaftspeed (rpm)
gain.rpm e_rpm shaft_rpm1 = k=gea

# Make sure the alternator shaftspeed_rpm = 0 when the starter is on
mult.shaft_rpm shaft_rpm1 k1 shaft_rpm

# convert rpm to rad/s
gain.rads shaft_rpm shaft_rads = k=3.14159/30

# Convert output to rotational_vel
var2w_radps.out shaft_rads shaft 0

}
```

Appendix G

Simulation Profile Sheet

G.1 Parameters Used and Plots Recorded

Table G.1: Profile Sheet

Date	
Design	
Drivecycle	
Loadcycle	
Alternator	
42V Battery Parameters (Ah, s.o.c., temp)	
14V Battery Parameters (Ah, s.o.c. temp)	
DC/DC Converter imax (A)	

Table G.2: Plots Recorded

Graphs Plotted	Saber Variable
Drivecycle	drivecycle
Alternator Shaftspeed (rpm)	shaftspeed_rpm
Alternator Output Current	i(short.i_alt)
Alternator Output Power	i(short.i_alt) * alternator
Voltage at Alternator Output	alternator
42V Battery State of Charge	soc(batt_pb_1.batt_pb_42v)
14V Battery State of Charge	soc(batt_pb_1.batt_pb_14v)
Current into DC/DC Converter	i(short.i_converter_in)
Current out of DC/DC Converter	i(short.i_converter_out)
Voltage at Input of Converter	v_converter_in
Voltage at Output of Converter	v_converter_out
Power at Input of Converter	i(short.i_convert_in) * v_converter_in
Power at Output of Converter	i(short.i_converter_out) * v_converter_out
Current Supplied to all 42V Loads	i(short.i_42v_bus) - i(short.i_42v_batt)

Table G.2: Plots Recorded

Graphs Plotted	Saber Variable
Current on 42V bus from Alternator	i(short.i_42v_bus)
Current into 42V Battery	i(short.i_42v_batt)
Voltage on 42V Bus	bus_42v
Voltage at Plus Terminal of 42V Battery	batt_42v
Power Consumed by all 42V Loads	(i(short.i_42v_bus) * bus_42v) - (i(short.i_42v_batt) * batt_42v)
Power on 42V Bus from Alternator	i(short.i_42v_bus) * bus_42v
Power at Plus Terminal of 42V Battery	i(short.i_42v_batt) * batt_42v
Current Supplied to all 14V Loads	i(short.i_14v_bus) - i(short.i_14v_batt)
Current on 14V Bus from Converter	i(short.i_14v_bus)
Current into 14V Battery	i(short.i_14v_batt)
Voltage on 14V Bus	bus_14V
Voltage at Plus Terminal of 14V Battery	batt_14v
Power Consumed by all 14V Loads	(i(short.i_14v_bus) * bus_14v) - (i(short.i_14v_batt) * batt_14v)
Power on 14V Bus from Converter	i(short.i_14v_bus) * bus_14v
Power at Plus Terminal of 14V Battery	i(short.i_14v_batt) * batt_14v

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