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Test Procedures and Results for Skidtric

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TEST PROCEDURES AND RESULTS

FOR SKIDTRIC

BY

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This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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ABSTRACT

Test procedures for a battery powered, electric, skid loader were developed and implemented. These procedures divided skid-steer operation into individual segments that were more readily tested than a complete routine. These segments included loader (lifting, lowering, bucket dump, and bucket tilt-back), constant velocity draft, acceleration draft, and turning operations. Battery power, as a function of the independent variables, was used in regression analysis to obtain prediction equations for battery power and energy. These equations were combined into a computer prediction model that was used to predict the energy requirements of Skidtric for specified tasks. Skidtric was judged to operate satisfactorily in all operational segments except turning, where prohibitively large amounts of power and energy were required to overcome the skidding resistance. Based on this, Skidtric was judged to be poorly suited to battery power in its present form. However, modification of the drive train to increase output torque at the wheels may improve the turning performance and make Skidtric suitable for battery electric power. Skidtric's side entry cab was found to be both safe and convenient for the operator.

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INTRODUCTION

The on-going electric vehicle research program at South Dakota State University's Agricultural Engineering Department has resulted in the development of two electric utility vehicles designated as Electric Choremaster I (EC-I) and Electric Choremaster II (Skidtric). Because of the experimental nature of these vehicles, the development of appropriate test procedures and the accumulation of test data has been required. Vik, (1985), and Thoreson, (1985), described the development and test procedures for EC-I. The development of Skidtric was described by Chicoine, et al., (1985). The development, implementation, and analysis of the results of test procedures for Skditric were performed during this research project.

The Electric Choremaster II (Skidtric) is a 30 to 37 kW class, battery powered, skid-steer loader (Chicoine, et al., 1985). Skidtric was designed and built during 1984-85 by the Agricultural and Electrical Engineering Departments of South Dakota State University. It is powered by tubular plate, lead-acid, batteries that have a nominal voltage of 72 V, an energy capacity of 320 Ampere-hours (Ah), and a weight of approximately 8.0 kN. Ground speed and direction control are accomplished via two silicon controlled rectifiers (SCRs) and a dual proportioning controller that operates two, series wound, dc traction motors. A hydraulic pump is powered by a compound wound dc motor. The loader arms were designed to permit side entry to the cab by the operator.

Skidtric was designed to evaluate a new type of skid-steer vehicle powered by electricity that appears safer and simpler than conventional skid-steer loaders and offers the advantage of reduced operating costs. Skidtric was intended as an alternative to similar petroleum powered vehicles (PPVs) and was seen as being especially advantageous in areas where the characteristics of electric vehicles (EVs) are superior to PPVs. Examples of these situations included operation inside buildings, where reductions in the levels of noise or pollution are preferable, or for intermittent chore duties where a PPV would be most likely to sit idling for a portion of the time.

Elamin, (1981), compared a battery powered lawn and garden tractor with a similarly sized gasoline powered tractor. Under similar loading conditions and uses, significant on farm energy use savings were documented for the electric tractor. Elamin concluded that these results could not be extrapolated to farm chore tractors due to the large difference in scales. He suggested similar testing and comparison of a larger vehicle. Vik, (1985), performed such a comparison, using the Electric Choremaster I (EC-I) developed at SDSU and a diesel equivalent, and found significant energy and cost savings of 57-67% for the electric version. However, these results cannot be extrapolated to a vehicle such as Skidtric due to the differences in scale and mode of propulsion. The information required from the tests performed on Skidtric included those variables and parameters that described Skidtric's performance, Skidtric's ability to perform the required tasks, the length of time that Skidtric would satisfactorily perform the specified tasks, the suitability of the controllers to skid-steer operation, and the suitability of skid-steer type vehicles to be powered by electricity stored in batteries.

The variables and parameters that described Skidtric's performance were specified as being the applied load (draft or bucket), motor current draw (traction and hydraulic), power and energy drawn from the battery (termed battery power and battery energy), power and energy required by the applied load as calculated from the theoretical considerations (termed calculated power and calculated energy), the length of time Skidtric would operate before the batteries needed to be recharged, and the length of time required to recharge the batteries. The applied load determined the calculated and battery power required to push or lift that load.

OBJECTIVES

The testing of Elamin, (1981), and Vik, (1985), indicated that, for certain applications, EVs could perform as well as PPVs. However, no such testing or comparison had been performed on a skid-steer type, electric vehicle. Cost comparisons of various types of PPVs and EVs including cars, trucks, vans, and tractors have been inconclusive (Bevilacqua and Hamilton, 1983, Leach, 1981, and Porter, 1981). Therefore, for the purposes of this project, cost comparisons were not considered for Skidtric with the recommendation that owning and operating cost comparison studies be made at a later time. Initial testing plans were focused on defining Skidtric's operating parameters, determining a performance base for comparison purposes, and developing a model for performance prediction.

The objectives of this project were to devise test plans for the Electric Choremaster II (Skidtric), perform these tests, evaluate the results, develop and evaluate a computer model to describe Skidtric's performance, and to recommend changes in both the vehicle and the model.

LITERATURE REVIEW

Electric Vehicles

Electric vehicle technology is not a recent development. Robert Davidson of Scotland built a crude EV in 1838, although concentrated efforts were not made to develop EVs until the 1880's (Shacket, 1979). In 1888, Fred M. Kimbal and Co. of Boston introduced the first electric automobile, five years before the Duryeas' original gasoline model and by 1900 EV sales were over $18 million per year (Shacket, 1979). However, EVs were rapidly overtaken by PPVs due to the range and weight limitations posed by the EV batteries and over the years, public interest in EVs has grown and faded somewhat erratically. Serious interest was rekindled in electric vehicles during the 1973 "oil crisis" (Kevala, et al., 1986, and Christianson, et al., 1985) and significant advances were made in EV technology. Wouk, (1986), listed several examples of improved EV technology including: 1) the evolution of controllers from series-parallel, contactor switching to transistorized, virtually trouble-free, electronic speed controllers; 2) the development of "smart" battery chargers that tailor each charge to the immediate needs of the battery and reduced over, under, or unequal charging; 3) wider use of separately excited, dc, shunt motors rather than the traditional series wound, dc motor; and 4) the development of experimental ac propulsion systems using dc-to-ac power inverters. Wouk also stated that much progress had been made in the development of high energy density batteries. For example, the specific energy density of lead-acid batteries has increased from 28 Wh/kg to 35 Wh/kg, and the nickel-iron (Ni-Fe) battery has been made commercially available, although lead-acid remain the only batteries in widespread use. Battery accessories such as single-point watering (Wouk, 1986) and special vent caps that recombine the hydrogen and oxygen produced during battery overcharge into water (Blickwedel and Hand, 1983) have greatly reduced battery maintenance requirements.

EVs have often been used in specialty applications, where their characteristics were well suited to the required tasks. Christianson, et al., (1985), cited the following typical examples: delivery vans, mining vehicles, aircraft tow vehicles, forklifts, golf carts, and lawn mowers. For these uses their quiet, nearly pollution free operation and high torque capabilities are especially advantageous.

Resen, (1981), found that modern EVs have performance capabilities that equal or exceed those of PPVs in terms of low noise and pollution levels, physical size, and maneuverability, as well as safety and maintenance time requirements. EVs have also exhibited easy starting characteristics, short duration overload capabilities, longer life and are especially well suited to start and stop operations (Christianson, et al., 1985).

The acceptance of EVs has been limited by several factors, such as, a limited range of operation, the required charging base location, heavy batteries, and higher intial cost, (Shacket, 1979). The limited operating range is associated with the use of heavy batteries that have resulted from the relatively low energy densities (energy per unit battery mass) of commercially available batteries. That is, a large battery mass has been required to store enough electrical energy to power the EV for adequate lengths of time. Permanent charging base stations are required to recharge EV batteries unless on-board charging equipment is used and an adequate power supply is readily available when needed (Shacket, 1979). Also, long recharge times have been typical with battery systems because slower charge rates and longer charging times have given the battery the most complete charge. Recent advances in battery charge acceptance, and "smart" charger technology that "tailors" the charge to the battery's needs, have resulted in some reduction of these problems (Wouk, 1986).

Higher initial costs have been cited as a potential limitation on EV acceptance, (Resen, 1981, Christianson, 1985, Bevilacqua and Hamilton, 1983, Porter, 1981, Leach, 1981, and Christianson, et al., 1985). Additionally, Bevilacqua and Hamilton, (1983), discussed US Department of Energy (USDOE) demonstration projects for which EV costs were determined to be $0.803/mile, or three times higher than comparable PPVs. Leach, (1981), stated that initial near term EV costs were substantially higher than for PPVs, however, long term savings from lower maintenance and fuel costs could offset the initial difference and make EVs more competitive. Porter, (1981), echoes Leach's assessment, citing milk delivery trucks in Great Britain as an example. According to Porter, the electric delivery trucks initially cost approximately 26% more than a diesel equivalent truck, but resulted in reduced maintenance and fuel costs by 35% and 50%, respectively. Porter estimated that the use of EVs constituted payback period of around 27 months. Bevilacqua and Hamilton, (1983), cited a Chrysler Motors Study that concluded that in mass production, the EV version of a subcompact automobile would initially cost 60% more than the PPV counterpart, but would require 40% less in maintenance costs and would have a 20% greater useful life. Kevala, et al., (1986), found USDOE electric test vehicle operating and maintenance costs to be higher than comparable PPVs, but concluded that the higher maintenance costs were not inherent to EV design, but rather were due to inadequately trained personnel, improper equipment, and a general lack of EV knowledge. Similarly, Bevilacqua and Hamilton, (1983), reported that US Postal Service studies found the higher EV costs were due to the experimental nature of EVs, low production volumes, inexperienced EV operators and manufacturers, and the immaturity of EV technology. A higher initial cost and savings of 57-76% over the life of EC-I, the electric tractor built at South Dakota State University (SDSU) was predicted by Vik, (1985).

EV applications being actively developed and tested at the time of this research project included fleet operations of vans and light trucks, personal and commercial commuting cars, motorcycles, and specialized application vehicles such as mining vehicles, golf carts, and fork lift trucks. Examples of the electric vans and trucks included the Griffon van, produced in England by the Bedford Commercial Vehicle Division of General Motors (GM) Overseas Corp. and the electric van series from Lucas Batteries, Ltd. (now Lucas Chloride) of Birmingham, England. The Griffon vans were tested on the SAE J227a C driving cycle (repeated acceleration, constant veloctiy cruising, deceleration, braking and idle time operation (SAE, 1976)) and the results indicated that the vehicles had a range of 105 km, accelerated from zero to 48 km/hr in 11 s, and had an ac energy consumption of 0.5 kWh/km (O'Connell, 1986).

O'Connell added that the Griffon van was also involved in fleet use evaluations in seven North American utility districts including Detroit Edison, Tennessee Valley Authority (TVA), and Hydro-Quebec, although no results had yet been reported. The Lucas van series has been in use for some time in England's fleet operations including postal delivery, taxi service, and airport-to-hotel shuttle services (Shacket, 1979). The Lucas Electric Midi-Bus, with a top speed of 80 km/hr and a low speed range of 180 km, has been in service between Manchester and Birmingham, England since early 1975. The Lucas Electric Limousine, specially built for carrying passengers, has a minimum range of 113 km with top speed capabilities of 80 km/hr. Additional examples of EV van fleet use are found in the U.S. Postal Service, whose EV research had included testing such vehicles as the Otis P-500 van, the Battronic Mini-van, the JMJ Omni four-door sedan, the Marathon C-360 van, and the Ford Fiesta two door conversion car (Cole and Gerlach, 1983), as well as the AM General, Jeep style postal van (Shacket, 1979).

Examples of commercially available electric automobiles include: the two passenger Chevrolet Electrovette with a range of 80 km at 48 km/hr and top speed capabilities of 85 km/hr; the Electricar 1, a four passenger Renault Le Car conversion, produced by C.H. Waterman Industries, with top speed of 88 km/hr and a cruising range of 96-128 km; and the

"Change of Pace" sedan and wagon based on the AMC Pacer with a range of 64-97 km and top speed in excess of 89 km/hr (Shacket, 1979). Additional examples include the Jet Industries Electrica, a converted Ford Escort with a travel range of 82 km and a maximum speed of 102 km/hr; the SCT Electric Pickup, a converted Volkswagen pickup with a maximum speed of 99 km/hr and a range of 113 km; and the Grumman-Olson Kubvan delivery vehicle with maximum speed of 85 km/hr and a travel range of 58 km (Driggans, 1983). It must be noted that the examples listed here represent only a few of the many electric vehicles either undergoing testing, or in actual use at the time of this research.

The electric tractor is another area of EV application that has been experimentally developed. Ihrig, (1960), described a 15-kW, battery powered tractor developed by Allis-Chalmers for small utility work. Turrel, (1969), presented the Electric Experimental Tractor (EXT). This tractor, equivalent to a 9 kW gasoline tractor, was intended for mowing, snow blowing, and other small utility tasks. Gervasio, et al. (1984) described the TEMA battery powered tractor developed in Italy for field applications. The TEMA tractor was scheduled for testing beginning in 1984. Vik, (1985), and Thoreson, (1985), described the Electric Choremaster I (EC-I) electric tractor developed at South Dakota State University (SDSU). EC-I was developed as a 60-

kW class, four-wheel drive tractor intended for chore and general utility work. Skidtric, the skid-steer type loader on which this research is based, was described in terms of vehicle design, and electrical and mechanical components by Chicoine, et al., (1985).

Skidtric was developed as a 30 to 37 kW, four-wheel drive, skid-steer type, utility loader intended for general loader and utility use especially in areas with limited space. A lead-acid battery pack, with a nominal dc voltage level of 72, provided power for three motors via solid state, SCR-type, controllers. Two compound wound, variable speed, reversible, dc motors were used to power the drive train. One motor was connected directly to each set of drive wheels through a 16:1 chain drive reduction system (Figure 1). A

dual proportioning controller was used to adjust the speed of each drive motor in response to the position of a joystick type control lever. The joystick control lever used variable resistance potentiometers to adjust the signal to the control panel, thereby adjusting vehicle speed. External cooling fans were required for the drive motors to remove heat generated at low speeds, with high output power demands. Turns were made either by operating the motors at different speeds, or in opposite directions, causing Skidtric to pivot about its effective center of gravity

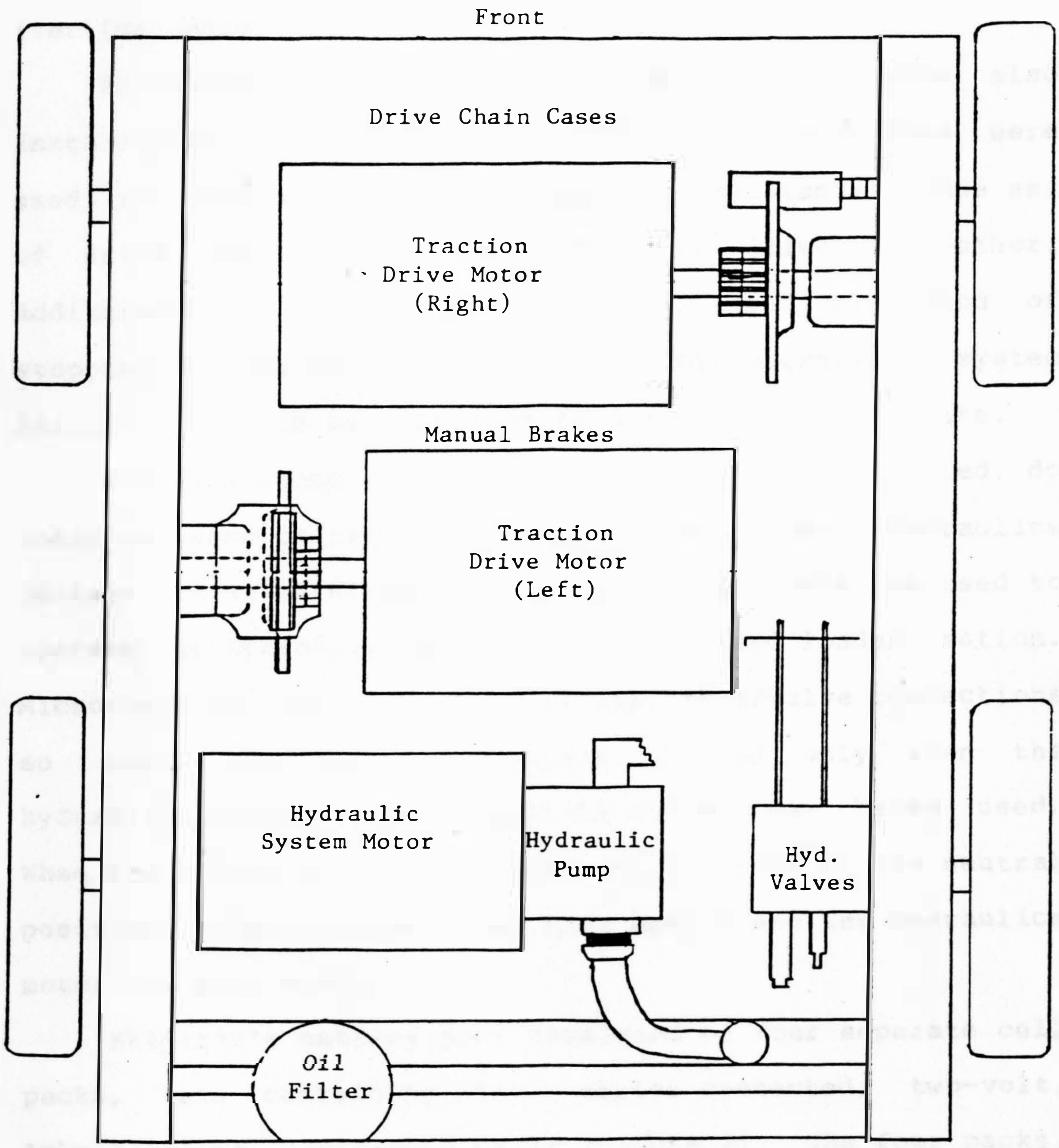


Figure 1. Skidtric's drive motor configuration

(vertical axis).

Individual, foot operated, disc brakes were also installed on each set of drive wheels. These brakes were used to make minor turns by applying resistance to one set of drive wheels while continuing to drive the other. Additionally, the manual brakes provided a method of stopping the vehicle in the event of electrical system failure and could be locked on to act as a parking brake.

A series wound, constant speed, internally cooled, dc motor was used to power the pump for the loader hydraulics package. A multi-directional, cable-type lever was used to operate the hydraulic valves that controlled loader motion. Micro-switches were installed at the cable/valve connections so that the hydraulics motor started only when the hydraulics lever was moved and the loader was being used. When the hydraulic control lever was returned to the neutral position, the micro-swithces were opened and the hydraulics motor was shut down.

Skidtric's battery pack consisted of four separate cell packs, each containing nine, series connected, two-volt, tubular plate, lead-acid cells (Figure 2). The four packs, connected in series, created a 36 cell battery, weighing approximately eight kN, with measurements of 0.46 m tall by 0.8 m long by 0.86 m wide. Battery voltage was rated as 72 V nominal (36 cells * two volts per cell), but ranged from

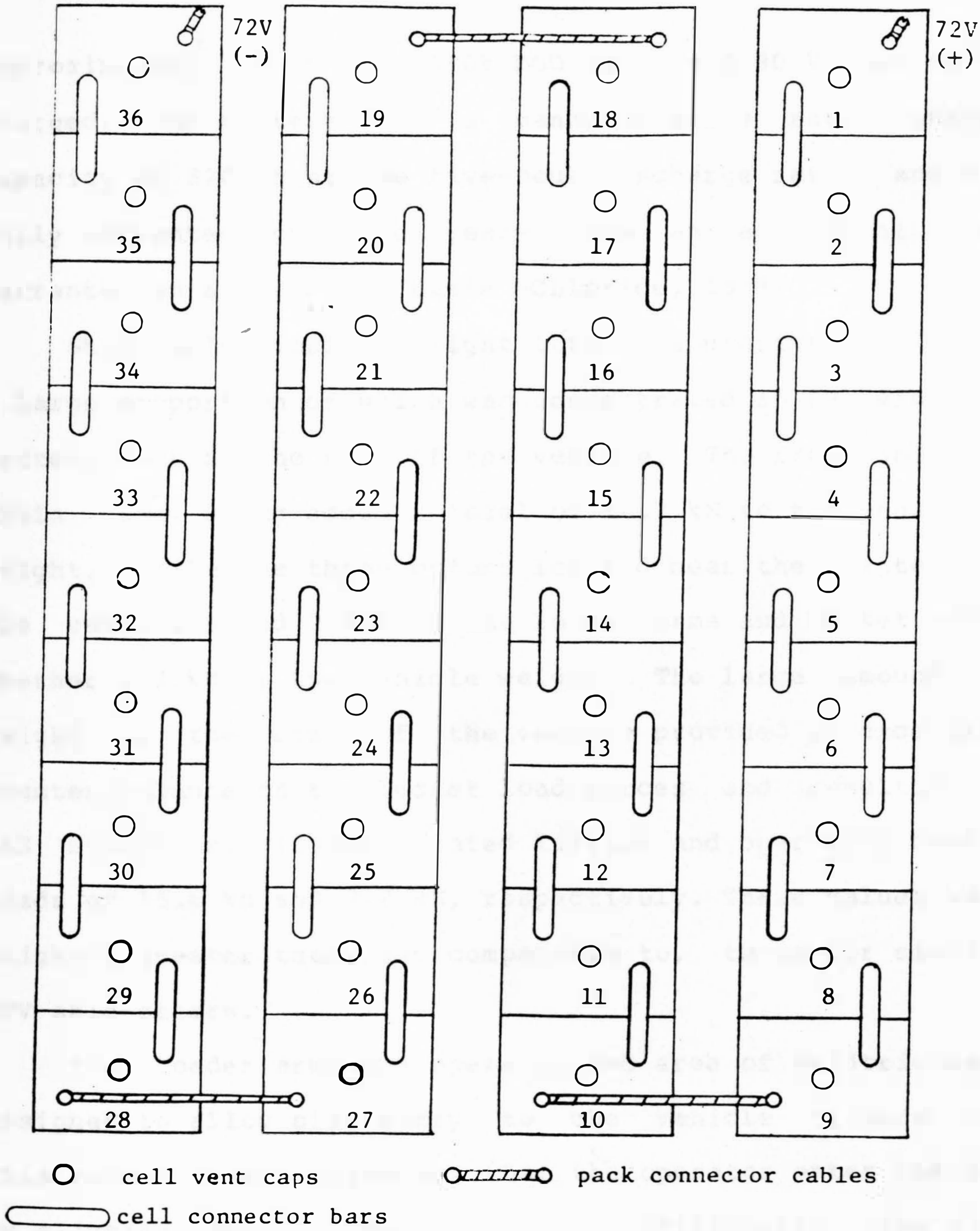


Figure 2. Battery pack configuration

approximately 60 V at 100% DOD to around 80 V when fully charged. The battery had a manufacturer's rated energy capacity of 320 Ah at the five-hour discharge rate, and was fully warranted for three years with an additional year warranted on a pro-rated basis (Chloride, 1983).

Skidtric's vehicle weight totaled approximately 27 kN, a large proportion of which was concentrated in the eight kN battery pack at the rear of the vehicle. The frame and two chain case units added a total of 10.7 kN to the vehicle's weight, while the three motors located near the center of the vehicle added 2.9 kN. The loader arms and bucket added another 4.2 kN to the vehicle weight. The large amount of weight at the rear of the vehicle provided an excellent counter balance to the bucket load forces and resulted in SAE Standards, (1980), rated lifting and operating bucket loads of 15.6 kN and 7.8 kN, respectively. These values were slightly greater than, but comparable to, those for similar PPV skid-steers.

The loader arms and operator cab area of Skidtric were designed to allow side entry to the vehicle (figure 3). This removed the requirement that the operator enter the cab by climbing over the loader bucket. Additionally, the side entry design allowed the operator to safely exit the cab without climbing under the bucket if he/she was using Skidtric in a task where the loader had to be left in the

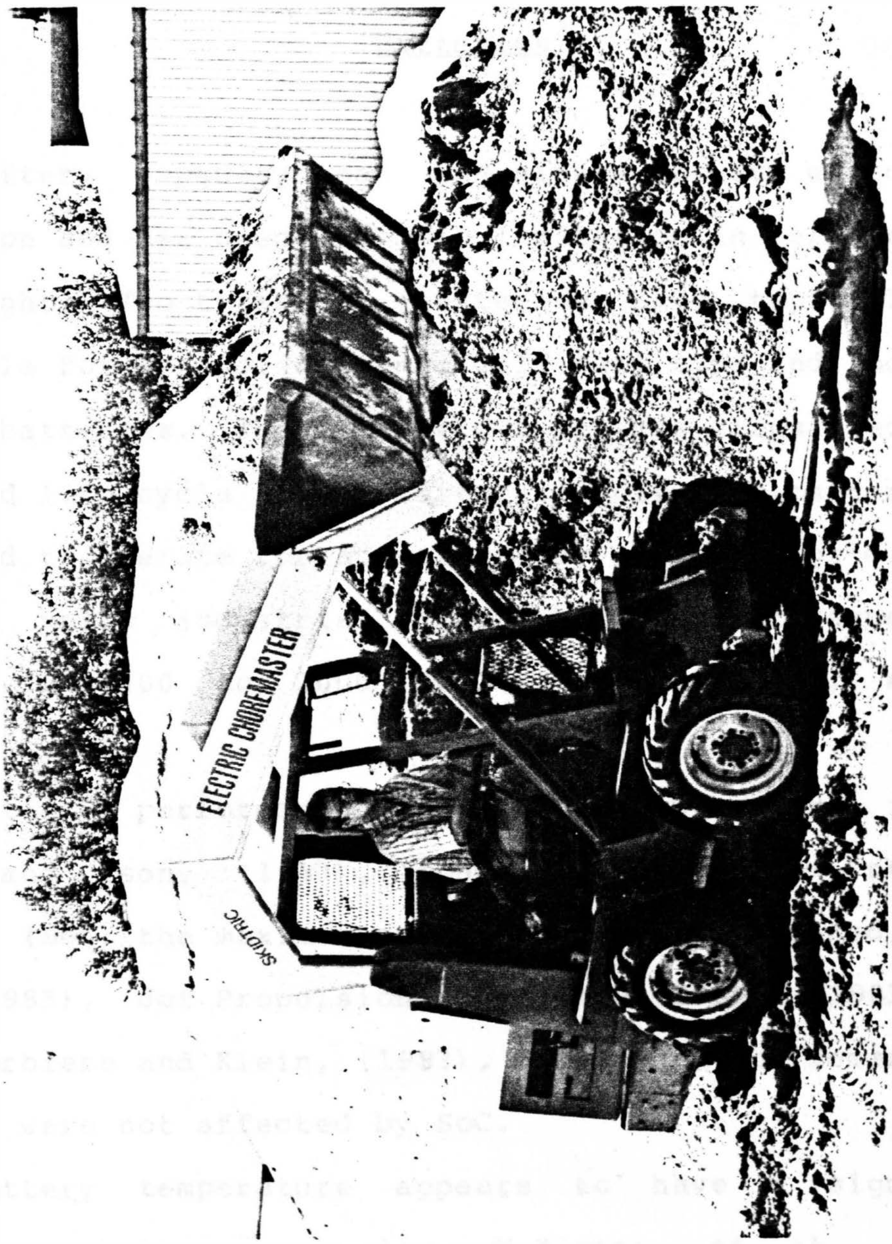


Figure 3. Skidtric

raised position.

Batteries

Battery capacity has the single largest effect on EV operation and has been the main limitation in terms of range and weight. Two types of batteries have typically been available for EV applications; golf cart type and industrial grade batteries. These battery types are classified by the expected life cycle of the battery. Golf cart batteries are expected to operate for approximately 200 charge-discharge cycles, while industrial grade batteries are expected to operate from 500 to 2000 cycles (Christianson, et al., 1985).

Battery performance is affected by several factors. Fenton and Olson, (1983), found that at a low state-of-charge (SoC) the maximum power output was decreased, while Vik, (1985), Jet Propulsion Laboratory (JPL), (1981), and Von Courbiere and Klein, (1983), found that low demand power outputs were not affected by SoC.

Battery temperature appears to have a significant affect on battery capacity. McKinney, et al., (1983), Hewitt and Bryant, (1982), and Vinal, (1955), stated that the battery capacity gradient has a decrease in battery capacity of one percent per one degree Celsius temperature drop. Nowak, (1983), found that the rate of capacity decrease was 4.1% and 12.5% per 10 degree Celsius for 54 to 25 deg. C and 25 to (-20) deg. C, respectively. Thoreson, (1985a), reported that maximum power capacity of the battery was not significantly affected by low electrolyte temperature but that the total length of time the battery could provide power was reduced. However, Thoreson did not perform extensive tests on the effect of electrolyte temperature on the capacity or performance of batteries. He also stated that using proper management and procedures to keep the electrolyte temperature in the recommended working range of 25^{o}C to 30^{o}C could minimize these effects on battery performance. According to Thoreson, (1985a), and Christianson, (1985), proper management and procedures include storing the EV in a heated building, or a sheltered area, using heated tape or heating blankets and insulation to maintain battery temperature, scheduling battery charging in a manner so as to utilize the heat generated by the charging process, or a combination of these. Thoreson, (1985), found that charging the battery raised the electrolyte temperature approximately 10^{o}C.

Other factors affecting battery performance cited by Christianson, et al., (1985), included discharge current, age of the battery, operating voltage, time between uses, and charging procedures. Thoreson, (1985), and

Christianson, et al., (1985), also listed management as an important factor in battery performance and life. According to these researchers, battery management includes using care not to over-charge or discharge the battery, performing regular, suggested maintenance, and maintaining the electrolyte temperature in the range recommended for the specific battery type. Recommended electrolyte temperatures vary depending on the type of battery. For example, Nowak's, (1983), testing showed that lead-acid batteries produced optimum capacity at or above 38^{o}C, while sodium-sulfur (Na-S) batteries require working temperatures around 350^{o}C (Brood, 1985). Nowak, (1983), also reported that lead-acid batteries suffered a 10% loss of the maximum capacity if the battery was operated at 25^{o}C, and a 35% loss at 0^{o}C.

In commercially available battery systems, the lead-acid battery introduced in 1866 still sets the standard for state-of-the-art battery systems, although recent modifications such as reducing internal resistance, reducing water loss during charging, and circulating the electrolyte to reduce stratification, have greatly improved lead-acid battery performance (Brood, 1985). Commercially available lead-acid batteries have energy densities in the range of 23-28 Watt-hours/kilogram (Wh/kg) and cycle lives of 600-1200 charge/discharge cycles or three to six calendar years for daily cycles (Jensen, et al., 1986, and O'Connell, 1986). Brood, (1985), stated that lead-acid batteries have life expectancies of approximately 800 charge/discharge cycles. In contrast, Christianson, et al., (1985), reported that lead-acid batteries can have energy densities of 40 Wh/kg and laboratory lives of 1500 cycles. Brood, (1985), listed an energy density of 42 Wh/kg for advanced lead-acid batteries. These values appear to be optimistic when compared to the commercially available battery capabilities.

The nickel-hydrogen (Ni-H) battery is another commercially available storage system. Ni-H batteries are sealed-air, maintenance free systems with energy densities slightly greater than lead-acid batteries and estimated lives of 10,000 cycles or 20 years (Brood, 1985). Ni-H systems have shown excellent pulse and high discharge rate capabilities, good low-temperature performance, and operate on hydrogen pressure that varies directly with SoC. This pressure variation can be used as a simple SoC indicator (Brood, 1985). Brood, (1985), listed the relatively high cost of materials as the major disadvantage of Ni-H systems.

The nickel-iron (Ni-Fe) battery system is also nearing commercial production and use. The Ni-Fe battery has tubular-plate construction, low-to-medium capability, and a reputation for being a long-lasting, nearly indestructable battery (Brood, 1985). Kelledes, (1986), also cited long life and tolerance to abuse, as well as adequate performance at any SoC and consistent energy storage for guaranteed vehicle range as Ni-Fe system advantages. Jensen, et al., (1986), reported a specific energy of 55 Wh/kg and an energy density of 116 Watt-hours/liter (Wh/l) (both at the three hour discharge rate), a specific peak power capability of 153 W/kg at 50% DOD, an energy efficiency of 62%, and a cycle life of 1000 charge/discharges for the SAFT (France) Ni-Fe battery. Jensen, et al., also tested the SAF NIFE (Sweden) Ni-Fe battery and found a specific energy and an energy density of 45-50 Wh/kg and 95-100 Wh/kg, respectively, at the three hour discharge rate, values for specific power of 100 W/kg at 50% DOD and 80 W/kg at 20% DOD were obtained. Cost of the SAB NIFE was reported to be $540-$630/kWh (Jensen, et al., 1986). New construction concepts for Ni-Fe systems make the Ni-Fe battery apparently well suited to EV applications. According to Brood, (1985), a cell voltage of 1.37 V per cell remains the primary liability of the system, while O'Connell, (1986), cited high material cost as the major problem.

The sodium-sulfur (Na-S) battery system has been used to a limited extent and is still largely under experimental development. The Na-S system offers excellent specific energy and specific power, high efficiency and a four to five year life of approximately 1400 cycles, but also requires an operating temperature around 350°C (Brood, 1985). Jensen, et al., (1986), reported that the CGE (France) Na-S battery had a specific energy of 215 Wh/kg, an energy density of 380 Wh/l, a specific power greater than 90 W/kg, and an energy efficiency of 67%. Cost of this battery was reported to be $96/kWh without the necessary temperature management equipment (Jensen, et al., 1986). Jensen, et al., (1986), also cited the BBC (Germany) Na-S battery system that demonstrated a specific energy of 80 Wh/kg at the two hour discharge rate and a specific peak power of 120 W/kg. Cross, (1985), lists small size, no maintenance over its five year life, and an energy density five times that of present lead-acid batteries as the major advantages of the Na-S battery system. Both Brood, (1985), and Cross, (1985), cite the operating temperature of 350°C as the major disadvantage of the Na-S system and stress the importance of operating safety. Similarly, Haskins and Minck, (1983), referred to EV battery safety as "paramount", especially with Na-S systems, and cited the following factors as concerns: 1) operating personnel in close proximity to the batteries during operation; 2) the close packing and number of cells required would create a large mass to be secured and thermally managed; and 3) road shock and vibration could cause internal ceramic failure at a higher than normal rate.

Haskins and Minck, (1983), reported that two factors, unique to Na-S systems create special safety hazards: 1) both the sodium and sulfur are liquid at the 350°C operating temperature, making them easily combined during a reaction and 2) the sodium and sulfur are separated by ceramic tubes that can fracture allowing the sodium and sulfur to combine creating a large, uncontrolled, thermal reaction. Safety precautions proposed by Haskins and Minck include using separate internal containers to isolate and protect the sodium reservoir from the hot reactants and using a metering device to limit the rate of sodium outflow in the event of a tube fracture, thereby, limiting the resulting thermal reaction. In an effort to overcome the temperature problem of the Na-S battery, Chloride Silent Power, a division of the Chloride Group, and the Electricity Council of Britain, have developed a method of heating and insulating Na-S systems so that the 350°C operating temperature can be reached and maintained for satisfactory operation (Cross, 1985). The insulation developed for the Na-S battery consists of two stainless steel walls with an evacuated air gap filled with packed aluminum foil to reflect radiant heat. Electric heaters are used to warm the battery during the charging process and the insulation pack is designed to keep the batteries at operating temperature for several days. This temperature control would make the Na-S battery a much more practical system for EV applications. Additionally, an intermediate temperature, Na-S type system has been developed and shows promise for EV applications (Brood, 1985). This system operates between 180^{o}C and 250^{o}C, has specific energy of 457 Wh/kg, specific power of 321 W/kg, and produces a nominal 4.2 V per cell (Brood, 1985).

Other battery systems under development include the zinc-bromine (Zn-B), the aluminum-air (Al-air) and two, room temperature, lithium battery systems. The Zn-B battery has a specific energy approximately double that of lead-acid systems and uses low cost reactants, but is plagued with five to ten percent parasitic losses created by internal chemical reactions (Brood, 1985). The Al-air battery has a theoretical energy density greater than gasoline and is mechanically recharged by feeding solid Al slugs into the system (Brood, 1985). The aluminum slugs serve as the battery anode and are consumed as the battery discharges, creating a benign powder, reaction by-product of pure, partially dry, hydrargillite ($(AlCOH)_3$) that may be recycled into new anodes and must be removed occasionally from the battery (O'Connell, 1981). Brood, (1985), cited low operating efficiency and significant heat generation as the major liabilities of the Al-air system. The two, lithium systems both operate at room temperature, have four times the energy density of lead-acid and nickel-cadmium systems, and produce a nominal cell voltage of 2.8 to 3.2 V (Brood, 1985). The capabilities and characteristics of the above battery systems and other potential systems are summarized in Table 1 (Brood, 1985).

Table 1.[a] Characteristics of battery systems

System	Cell voltage (V)	Energy density (Wh/kg)	Peak Power (W/kg)	Cycle life (cycles)	Cost ($/kWh)	Efficency (%)
Commercial						
Lead-acid	2.01	42[b]	105	800	80[b]	75
Nickel-hydrogen	1.38	45	300	10,000	200	70
Near-commercial						
Nickel-zinc	1.74	60	200	400	200	70
Nickel-iron	1.37	54	120	1,100	200	60
Lithium-iron sulfide	1.33	95	87	900	50-80	70
Under development						
Sodium-sulfur	2.10	120	180	500	85	80
Zinc-bromine	1.80	65	74	400	40	65
Zinc-chlorine	2.10	65	75	1,400	100	60+
R & D						
Aluminum-air	1.60[c]	300	190	(goal)[d]	50-60[e]	40
Iron-air	1.28	94	74	1000(goal)	50[e]	45
Lithium-iron disulfide	1.76	125	150	1000(goal)	50-80[e]	70
Zinc-air	1.40	100	125	250	50[e]	50

[a] Brood, 1985.
[b] Some disagreement exists on the actual energy density value available from lead-acid and on the cost of lead- acid batteries. The values presented in this table are listed as presented in Brood (1985).
[c] 2.7 is theoretical voltage.
[d] 160,000 km or five-year life (auto batteries).
[e] Estimated.

Controllers

Speed control of dc motors can be achieved by adjustment of the armature voltage, adjustment of the magnetic field, or by a combination of both (Lo, 1979). The most common speed control method has traditionally been armature voltage adjustment.

Thyristors and resistors have commonly been used to adjust armature voltage on the dc motors used in EVs. Thyristors are electronic switches that are capable of high speed switching operations in response to a trigger signal. Switching the thyristor on and off rapidly "chops" the voltage to the motor and produces an output train of pulses whose average voltage value is less than the input voltage (Ramshaw, 1973). The ratio of on-time to off-time determines the voltage value received by the motor and, subsequently, the motor speed. Some thyristor-type controllers are equipped with a by-pass contactor that allows energy from the battery to flow directly to the motor during full power draw situations, bypassing the controller device and eliminating the associated losses (Christianson, et al., 1985).

The use of resistors to increase or decrease resistance in the power line can also adjust the speed of dc motors. Common resistance controllers are comprised of resistors that are connected and disconnected via simple switches, resulting in discreet changes of resistance, and subsequently, motorspeed (Unnewehr and Nasar, 1982).

Battery switching is another method that utilizes simple switches to adjust motor speed. This control method consists of connecting individual batteries together in series or parallel to produce the desired voltage (Unnewehr and Nasar, 1982). Since the batteries are connected and disconnected as discreet and independent units, the motor voltage adjustment, and therefore the motor speed, is not continuously variable.

The most recent developments in dc motor speed control have been in the area of transistorized speed controllers. The transistorized controllers operate in a manner similar to the thyristor controls with the exception that the energy (current) drawn from the battery is taken in a smooth, constant fashion rather than a chopped, pulsed flow (Prans and Chaya, Jr., 1986). For example, if a 60 A current was required by the motor, the thyristor controller would chop the energy from the battery, sending a pulsed current of approximately 400 A amplitude at about five millisecond intervals, whereas, the transistorized controller would receive 60 A dc current from the battery and send a pulse width modulated current to the motor at a frequency of two kilohertz (kHz) (Prans and Chaya, Jr., 1986). The current from the transistorized controller appears to be more constant becaused of the higher frequency and lower current amplitude.

Certain advantages and disadvantages are associated with each type of motor speed controller. According to Pearman, (1980), silicon controlled rectifiers (SCRs), the most common type of thyristor, are small, maintenance free, reliable, low cost, not affected by vibration, operate at very high switching speeds, and provide smooth, continuous speed control over their operating range. Pearman, (1980) also states, however, that SCRs may fail at overvoltage or overcurrent conditions unless they are protected and may be subject to false actuation by transient voltages from other switching devices. They produce a 0.5 to 1.5 V drop that may have significant effects in some applications. Additionally, Davis, (1971), cites an operating temperature limit of 150^{o}C for SCRs. Thoreson, (1985), found that SCR overheating posed a potential problem for steady, high-power use of EC-I. During Thoreson's tests, a drop in current flow corresponding to an increased SCR temperature was noted. No such drop occured when fans were used to cool the SCR controllers. Unnewehr and Nasar, (1982), state that resistance and battery switching are both simple and inexpensive, but do not provide continuous control, resulting in jerky vehicle motion. Energy loss and inefficiency due to heat generation are also inherent characteristics of resistance control (Unnewehr and Nasar, 1982, and Lo, 1979).

AC Propulsion Systems

The mainstay of the electric vehicle propulsion system has traditionally been the dc, series-wound motor (O'Connell, 1986). Series wound, dc motors offer easy speed control and good starting torque capabilities, as well as being able to directly use the dc power from storage batteries. The development of ac propulsion systems has been hindered by the cost, weight, and the complexity of the dc-to-ac power inverters (O'Connell, 1986, and Rippel, 1986). However, O'Connell and Rippel also credit recent improvements in intergrated circuits and power transducers with dramatically cutting the costs and reducing the inverter weight, making ac systems more competitive with dc systems. Kelledes, (1986), and Gritter, et al., (1986), cited light weight, high speed capabilities, high efficiency, reliability, low cost, and durability among the advantages of ac propulsion systems. Kelledes, (1986), indicated that the major difficulty associated with ac propulsion systems was in selecting the appropriate battery voltage. The cost of the necessary transistors increases with higher current carrying capacity (lower voltage), while battery costs increase and potential energy capacity decreases with larger batteries (higher voltage) (Kelledes, 1986). According to Rippel, (1986), the optimum battery voltage for ac propulsion systems in terms of component cost and capability is approximately 200 V dc. Examples of ac propulsion systems under development include the DSEP system (Gritter, et al., 1986) and the JPL experimental unit (Hamilton, 1986, and O'Connell, 1986). The DSEP system utilizes a three-phase, induction, ac motor rated at 29.8 kW continuous power with a base speed of 5500 rpm, a nominal battery voltage of 168 V, a two speed, manually shifted transaxle, and a microprocessor based controller using the field oriented approach. The motor and transaxle are oil cooled with a top motor speed of 11,500 rpm. Hamilton, (1986), reported that the experimental, JPL ac system was smaller, lighter, and cheaper than other dc or ac systems and did not require: 1) a special transaxle; or 2) specially built power transducers; but instead uses low cost, readily available components; and 3) liquid cooling for the inverter, but rather used a forced air system. However, the system is not yet fully developed and significant safety hazards exist, including the fact that the dc-to-ac inverter might remain permanently connected to the battery with no contactors for emergency disconnections. In addition, the transformerless charger did not isolate the vehicle from the power line or the ground. These hazards will be somewhat reduced when the safety system and vehicle control system have been formulated and installed (Hamilton, 1986). Hamilton, (1986), compared several ac and dc propulsion systems. range of control systems. O'Connell (1986) performed a similar comparison on the JPL ac propulsion system and a Chrysler dc system (Table 2).

Table 2. Comparison of Chrysler dc and JPL ac propulsion systems.

System	Cost ($)	Mass (kg)	cost/unit rated power ($/kW)	mass/unit rated power (kg/kW)
Chrysler dc	2938	155	113	6.0
JPL ac[a]	2244	133	75	4.4

[a]Experimental unit.

Skid-steer Loaders

Skid-steer loaders are widely used in material handling, landscaping, excavation, and general utility applications. Important features of skid-steer loaders that facilitate their use in these applications include compact size, easy maneuverability, and the ability to turn about their own axis (Chicoine, et al., 1985).

Skid-steer loaders are typically manufactured with gasoline or diesel engines. However, the Phil Reed Equipment Co. of Orlandao, Florida modified Clark-Melroe skid-steer loaders to operate on ac electric power (Vig, 1986). An ac motor receiving electric power through a cord was used to replace the internal combustion (IC) engine. The skid-steers continued to use the standard drive-train components. Consequently, efficiency losses through the hydrostatic transmission and pump were still present. Even with these losses, the vehicle performed well and cost less to operate than a similar PPV unit (Vig, 1986). However, vehicle range was limited by the length of the power cord and this restricted the vehicle to in-building or close proximity use. Additionally, the power cord posed a potential safety hazard in that it could become tangled about the machine or severed during operation. This hazard was reduced by running the cord overhead wherever possible.

Testing Information

Electric vehicle testing can be divided into two basic types of tests, component testing and vehicle testing. According to Marte and Bryant, (1983), the battery has the single largest affect on EV performance, therefore, battery testing should comprise the majority of component testing. Carter and Todd, (1983), reporting on TVA/EPRI (Electric Power Research Institute) testing procedures, divided battery testing into acceptance, in-vehicle, and static load tests. These tests checked the condition of the battery as it was delivered, the performance of the battery under actual use conditions, and defined a battery performance base by constant current discharge procedures, respectively. For this project, battery capacity and performance during discharging and charging were the only component tests performed.

Battery Testing

Thoreson, (1985), divided battery testing into two areas; battery capacity and cycle life. Battery capacity was tested by discharging the battery under specified, controlled conditions and recording parameters such as battery voltage, discharge current, electrolyte temperature, specific gravity, and time. Many proposed methods and standards exist for battery discharge tests and the conditions specified for the tests vary with the testing organization or researcher. The TVA/EPRI Electric Vehicle

Test Facility (EVTF), (Carter and Todd, 1983), Fenton and Olson, (1983), Hornstra and Yao, (1982), and the National Electrical Manufacturers Association (NEMA), (1974), are a few of the researchers who have proposed standard methods of discharge testing batteries. These methods were similar in that each used a constant current draw from the battery, however, each specified current draw was different. TVA/EPRI recommended a discharge current of 50 A or 75 A until an average voltage below 1.75 volts/cell was reached. Fenton and Olson recommended a constant discharge of 75 A until any group of six cells averaged 1.75 volts/cell. Hornstra and Yao recommended that lead-acid batteries be discharged at the manufacturer's recommended rate until 1.75 volts/cell was reached. NEMA's Standard IB-2, (1974), recommended a constant discharge rate equal to one sixth of the battery's rated six hour capacity and a fully discharged state of 1.70 volts/cell.

Parameters measured at the TVA/EPRI EVTF, as reported by Carter and Todd, (1983), during battery testing included voltages of all battery modules (groups of cells), the battery's terminal voltage, discharge current, and the battery temperature at four to 13 locations. Signal values were read by a digital voltmeter (DVM) connected to a Hewlett-Packard computer. Fenton and Olsen, (1983), also measured battery current, battery terminal voltage, and module voltage, along with Ampere-hours (Ah) and Watt-hours (Wh). A clamp-on ammeter, a DVM, an Ah meter, and a Wh meter were used to measure these parameters. Additionally, Fenton and Olsen used strip chart recorders to record battery current versus time and battery terminal voltage versus time.

Thoreson, (1985), discharged the batteries of EC-I at a rate equal to the six hour discharge rate (the rated battery capacity in Ah divided by six hours) until an average cell voltage of 1.70 volts was reached. Data collected included discharge current, total battery voltage, voltages of groups of four consecutive cells, temperatures and specific gravities of two pilot cells, and the discharge time. From this information, actual battery capacity and the total energy received from the battery were determined. Resistor banks and a water rheostat connected in parallel were used as the discharge resistive load. Data were collected by a microcomputer based data acquisition system (DAS) as described by Stange, et al., 1982, and Thoreson, 1985. This DAS was comprised of a Hewlett-Packard microcomputer, a Hewlett-Packard scanner, and a Hewlett-Packard digital multimeter (DMM). These acted as the controller, multiplexer, and readout device, respectively.

Thoreson's, (1985), project time did not exceed the life of the battery. He was, therefore, only able to provide an estimate of the battery's life from available literature and manufacturer's information. The life of Skidtric's battery was estimated in a similar manner for this project.

Vehicle Testing

Bryant, (1983), divided vehicle tests into two types: engineering tests and "how people drive" tests. Engineering tests were seen as desirable because they offer controlled circumstances and repeatability during testing. This allows parameters and conditions to be varied to determine their effect on the performance of the vehicle. "How people drive" tests are desirable because they offer performance results from the vehicles as they were likely to be used.

Marte and Bryant, (1983), further divided engineering tests into dynamometer and track tests. Dynamometer testing was performed in a laboratory under strictly controlled conditions, whereas track testing was performed under specified track conditions. The track tests offered somewhat of a compromise between laboratory tests and actual use tests. Opinions differed as to which type of test would provide the most useful and desirable results. Fenton and Olson, (1983), recommended the dynamometer test as being most useful because the exact vehicle adjustments and ambient environment could be closely controlled and replicated as desired. The Society of Automotive Engineers (SAE) Standards, (1976), and the TVA/EPRI EVTF procedures (Carter and Todd, 1983, Driggans, 1983, and Barnett, et al., 1986), recommended track tests as the major portion of EV testing. Nowak, (1981), and Menga, et al., (1981), prefered the "how people drive" tests. Cole and Gerlach, (1983), reported that the U.S. Postal Service EV testing program consisted of three parts; laboratory, engineering, and field tests. The laboratory testing consisted of checking the vehicles and chargers for proper functioning and performing the break-in procedures. The engineering tests consisted of track tests divided into acceleration, top speed, gradeability, and range tests, while field evaluation and testing consisted of actual vehicle use. The TVA/EPRI plan for track tests included vehicle dc energy consumption, vehicle ranges at a constant 35 mile per hour (mph) and on the SAE J227a C cycle (Society of Automotive Engineers, 1976), maximum speed, acceleration, braking, and radio frequency interference tests. Thoreson, (1985), performed a combination of tests, using laboratory and track tests to gather initial data, then actual use tests to check the performance of the vehicle and accuracy of the more controlled test results.

Agricultural Tractors

Testing of agricultural tractors differs significantly from the test routines for most EVs. Available EV testing information deals mainly with electric cars, vans, and other road vehicles, and consequently, does not include all the information or parameters that would affect agricultural vehicles and/or electric tractors. The American Society of Agricultural Engineers (ASAE) Standards, (1986), has established a standard testing procedure for agricultural tractors. The ASAE Standards, (1986), define an agricultural tractor as "a vehicle designed and advertised to pull, propel, and supply power to operate machinery used in agricultural operations." Performance tests are divided into two areas: mechanical power outlet performance and drawbar performance. Mechanical power outlet tests measure performance at a power outlet such as a power take-off (pto) or belt pulley. These tests include maximum power-fuel consumption tests, power at standard pto speed tests, and varying power-fuel consumption tests. The maximum power-fuel consumption tests are used to determine the maximum power available from the mechanical power outlet(s) and to measure corresponding fuel consumption. This test must last a minimum of two hours. The varying power-fuel consumption tests are used to determine the fuel consumption and engine speed when power is varied. Six power levels are used for 20 min each during these tests. Parameters measured include fuel consumption and engine speed at each load. The power at standard pto speed test is run only when the engine speed at maximum power does not correspond to the engine speed at the SAE and ASAE standard pto speeds and is used to determine the power and fuel consumption at the standard pto speed.

Drawbar performance tests include: maximum drawbar power; varying drawbar power, fuel consumption, and the sound level at the operator's station; drawbar pull versus travel speed; and exterior sound level tests. The ASAE Standards, (1986), specify three types of track surfaces for the tractor testing. In descending order of preference, these surfaces are concrete, bituminous surfaces (asphalt), and earth. A concrete track must have a minimum number of expansion joints and a uniform, "belted" finish. Earth surfaces must be well packed, free of loose material, and uniformly maintained for all tests. The maximum drawbar power test is used to determine the maximum pulling power of the tractor in not more than 12 forward gears or travel speeds. Ballast is added if it is regularly sold as an accessory by the manufacturer. Slip could not exceed 15% for wheeled tractors and 7% for tracked vehicles. The varying drawbar power, fuel consumption, and sound level tests are performed to determine three things: 1) determine fuel consumption at various power demands; 2) determine the sound level at the operator's station at each of these powers; and 3) determine whether the tractor will maintain a selected drawbar pull for 10 hours and measure the fuel consumed during the 10 hour run. The drawbar pull versus travel speed test is used to determine the lugging ability of the tractor and is performed by increasing the drawbar load so that the speed of the drive wheels are reduced by approximately 10% for each run. The wheel speed at the maximum drawbar pull is defined as 100%. Exterior sound level tests are designed to measure the noise level that an observer would be exposed to at a specified distance from the tractor.

The Nebraska Tractor Test (NTT) station at the University of Nebraska-Lincoln conduct tractor tests according to the ASAE Standards, with the addition of a maximum drawbar power without ballast test (Barger, et al., 1982). This test procedure is identical to the maximum drawbar power with ballast except that all added ballest is removed from the tractor.

Design and rating standards are also available for agricultural loader vehicles, however, no standard procedures are available specifically for testing skid-steer loader performance. SAE wheeled loader standards also apply to design and operating safety aspects, but again, do not address testing procedures (Society of Automotive Engineers Standards, 1980). These Standards define the SAE rated tipping load as the minimum weight at the center of gravity of the bucket that will cause the rear wheels to leave the ground. The SAE rated operating load is 50% of the SAE rated tipping load. The most extensive testing programs for skid-steer loaders at the time of this project were performed by the skid-steer manufacturers, but these procedures were not publicly available (Vig, 1986).

Instrumentation

Electric Vehicle

Two basic types of instrumentation systems have been used to record data from EV vehicle testing. These are strip chart recorders and microprocessor based systems. The TVA/EPRI EVTF used a combination of strip chart recorders and a computer-based DAS to record and process the necessary parameters and variables, including electrolyte temperature, battery voltage, motor current, battery power, speed, distance, acceleration, and time (Carter and Todd, 1983). Hall effect sensors were used to measure the current and voltage, and a fifth wheel connected to a two-channel strip chart recorder was used to record the speed, acceleration, and distance travelled. Nowak, (1981), used strip chart recorders in conjunction with in-line, current shunts, and a fifth wheel to determine energy consumption, battery current, battery voltage, battery power, vehicle acceleration, vehicle speed, and vehicle range. Blom, et al., (1981), used a microprocessor-based DAS equipped with magnetic tape storage, an internal clock, and analog-to-digital converters along with current shunts, voltage dividers, and Hall effect transducers to monitor and record motor current, battery voltage, electrolyte temperatures, time, and speed during EV testing. Similarly, Chaya, Jr. and Prans, (1986), developed and used a computer-based DAS utilizing a current shunt, a 16-to-1 voltage divider, and an analog-to-digital converter along with other necessary signal conditioning circuitry to record motor current, battery voltage, distance, speed, acceleration, and time. Battery power was computed by multiplying the instantaneous values of current and power (Chaya, Jr. and Prans, 1986).

The sampling rate of most DASs may be adjusted to read values at a desired frequency. Blom, et al. (1981) used a sampling rate of one point per second, i.e. each parameter monitored was measured once every second. The DAS developed by Chaya, Jr. and Prans, (1986), sampled each parameter signal at half second intervals for up to 320 s. Marte and Bryant, (1981), and Thoreson, (1985), used sampling rates that gathered data at the highest possible rate allowed by the equipment. This rate varied with equipment capability. The DAS used in this project, and by Thoreson, was capable of reading six channels per second. The rate at which each parameter (channel) was recorded was, therefore, dependent on the total number of channels to be read. If two parameters were to be recorded, each was read three times per second for a total of six channels per second. If six parameters were to be recorded each channel was read only once per second, for a total of six channels per second.

Agricultural Tractors

Many instrumentation systems for data acquistion on agricultural tractors have been developed in recent years. Grevis-James and Bloome, (1982), developed an analog, performance monitoring, instrumentation system for agricultural tractors. This system did not record data and was intended solely to aid the operator in analyzing instantaneous tractor performance. Drawbar power, ground speed, and drive wheel speed were monitored by a strain-gaged hole in the tractor drawbar and two magnetic pickups with slotted discs, respectively. Slip was computed from the measured speeds by a microchip mounted in the readout device. System output was displayed on an analog dial meter mounted near the operator.

Tompkins and Wilhelm, (1983), developed a permanently mounted, computer-based, tractor DAS to monitor fuel consumption, travel speed, drive wheel speed, implement draft, and axle torque. These parameters were monitored by an in-line fuel meter, a free-floating fifth wheel, a magnetic speed sensor mounted on the drive wheel, a three-point hitch dynamometer similar to the one built by Johnson and Voorhees, (1979), and strain gage rosettes on the drive axles. Drive wheel slip and drawbar power were calculated from the wheel and ground speeds, and ground speed and draft, respectively. Sampling intervals were adjustable between 0.01 s and 4.5 min, and the data collected was stored on cassette tapes. The system was powered by a portable generator mounted on the tractor and all DAS controls were mounted near the operator for easy accessibility. Tompkins and Wilhelm noted that the magnetic pickup sensors occasionally gave spurious readings due to vibratons present at certain loads and recommended that these sensors be replaced with optical encoders. These researchers also questioned the reliability of the fifth wheel output on rough ground surfaces, but found that on smooth surfaces, the readings produced were accurate.

Grevis-James, et al., (1983), also developed a microcomputer based DAS for agricultural tractors. This system used an in-line fuel meter to monitor fuel consumption, a strain gage mounted in a hole drilled in the drawbar to measure implement draft, rotary encoders mounted on driven and non-driven wheels to measure wheel speed and ground speed, and a Hall effect magnetic transducer to measure engine speed. Again, wheel speed and drawbar power were calculated from recorded parameters.

The system used for monitoring Skidtric was based on the system developed by Stange, et al., (1982), and modified by Thoreson, (1985). This DAS was a microcomputer based system that used a fifth wheel to measure ground speed, a pto torque transducer to measure pto torque output, the three-point hitch dynamometer built by Johnson and Voorhees, (1979), to measure implement draft, a tachogenerator mounted on a driven wheel to measure wheel speed, and a hydraulic flow meter and pressure gage to measure hydraulic oil flow and pressure (Stange, et al., 1982). Fuel consumption was not measured due to vibrational interference with the flow meter. Wheel slip and drawbar power were again calculated values. System power was provided by a portable ac generator. Thoreson, (1985), modified this DAS for use on EC-I by adding in-line current shunts and a voltage divider to monitor motor currents and battery voltage, respectively. He also removed the hydraulic flow and pressure sensors. After researching and experimenting with various methods of measuring ground speed, Thoreson also replaced the fifth wheel speed sensor with a Doppler effect radar gun. This system was further modified and used for Skidtric's testing program because it had the capability to perform the desired tasks and because it had already been proven and used in a similar testing program by Thoreson. The necessary modifications included reinstalling the fifth wheel in place of the radar gun, adding two magnetic wheel speed sensors, and using two different in-line current shunts to measure motor currents.

Performance Prediction Models

A number of models have been developed to predict the performance of EVs. Wolfson and Gower, (1983), have documented and discussed some of the models available including "The computer simulation of automobile use patterns for defining battey requirements for electric cars," by H.J. Schwartz, "An electric vehicle simulation," by D.J. Dobner and E.J. Woods, "Electric vehicle models for the Texas Instruments TI-59 programming calculator," by P. Jordan, L. Schmidt, and S. Chozanoff, et al. (see Wolfson and Gower, 1983, for the complete list). The majority of the models listed by Wolfson and Gower were directed towards the performance of EVs intended for on-road vehicles such as cars, delivery vans, and light trucks. In contrast, Alcock, (1983), developed a model that predicted the performance of electric tractors for field operations, based on several factors including, implement width, speed, time, and efficiency. In addition to these factors, EV management was also considered in Alcock's model. Included in management considerations were the rate of discharge, battery temperature, previous depth of discharge (DOD), regular maintenance, and storage periods. However, the inherent differences between the requirements of a tractor intended for field operation and a skid-steer vehicle intended for utility and chore duties makes direct application of this model inappropriate.

Factor Effects on Performance

EV performance depends to a large extent on the performance capabilities of the battery. Therefore, Skidtric's performance was expected to closely mirror battery performance. The rate of discharge was expected to affect the total capacity output of the battery, and as the rate of discharge increased, the usable capacity of the battery was expected to decrease. Conversely, as the discharge rate was decreased, the usable battery capacity was expected to increase. Consequently, it was expected that the current level would affect the amount of time Skidtric would operate in a satisfactory manner. Research by Fenton and Olsen, (1983), concluded that low SoC had a significant impact on the available power at maximum demands. However, Vik, (1985), the Jet Propulsion Laboratory, (1981), and Von Courbiere and Lein, (1983), found that low level power outputs were unaffected by SoC. Therefore, the SoC was expected to significantly affect the power output only at high power demands.

Ambient air temperature and electrolyte temperature were expected to affect the length of time the vehicle would run before charging was required, but were not expected to affect the instantaneous power capabilities (Thoreson, 1985). That is, the battery was expected to have full power capacity at low temperatures for instantaneous draws, but was not expected to operate for the same length of time that it would at a warmer electrolyte temperature. This was supported by the research of McKinney, et al., (1983), Hewitt and Bryant, (1982), Nowak, (1983), and Vinal, (1955), who all found a decrease in total battery capacity at lower electrolyte temperatures. Ambient air temperature was also expected to affect the amount of power required for a given task, especially hydraulic loader operations, since low air temperatures were expected to cause the hydraulic oil to thicken and thus require more power to pump the more viscous oil through the system. Similarly, Dippold, (1981), reported that for a vehicle starting at 21°C, the motor torque required during the first mile was 38% greater than the motor torque required 29 miles later when the vehicle was warmed up.

The surface conditions on which the vehicle was operated were expected to affect the performance of the vehicle (Alcock, 1985). A soft, deformable surface was expected to require more power for vehicle movement than a hard, nondeformable surface due to increased sinkage and consequently, increased resistance to skidding. Wet, slippery surfaces were expected to require less power to turn the vehicle by skidding than would a dry surface due to decreased frictional forces. The main parameters expected to affect Skidtric's performance were battery capabilities, the surface conditions, and the applied bucket and/or draft loads.

TEST PROCEDURES

Battery Tests

The battery is the single largest factor affecting vehicle operation and performance, thus it was important to determine its capabilities and monitor changes in its capacity and performance over time. Charge and discharge tests provided the data needed to determine the capacity of the battery and establish a performance base.

Battery charging tests provided information on the amount of energy required to return the batteries to a full state of charge, the temperature change of the electrolyte during the charge, and the number of Ampere-hours required to charge the battery. The discharge tests provided information on the energy capacity of the battery and an estimation of the length of time the battery could discharge at certain current withdrawal levels.

The variables measured during battery tests included overall battery voltage, current drawn from the battery by the resistive load, electrolyte temperature of four representative cells, voltages of nine, four-cell modules, and specific gravity and temperature of two test cells. All information except the specific gravities and temperatures of the two, test cells were monitored and stored by a computer DAS. The specific gravities and temperatures of the test cells were recorded manually. Battery energy and energy capacity were calculated by the DAS from data collected during the discharge tests. Battery energy was computed by multiplying current draw, battery voltage, and time. Energy capacity in Ah was calculated by multiplying the current draw in amperes by the time of the discharge in hours. Each parameter was calculated for the time period between the data collections by the DAS and a running total was kept over the total test time to compute the total battery energy and the energy capacity. Approximately 100 data points were collected for each variable measured or computed over the period of the discharge tests.

Instrumentation

The equipment used for the charge/discharge tests included resistor banks and a water rheostat, a voltage divider, an in-line current shunt, five thermocouples, and the DAS equipment (Figure 4). The resistor banks and the water rheostat were connected in parallel to provide the resistive load through which the battery was discharged. Switches on the resistors were used to adjust the current flow by varying the resistance connected to the battery.

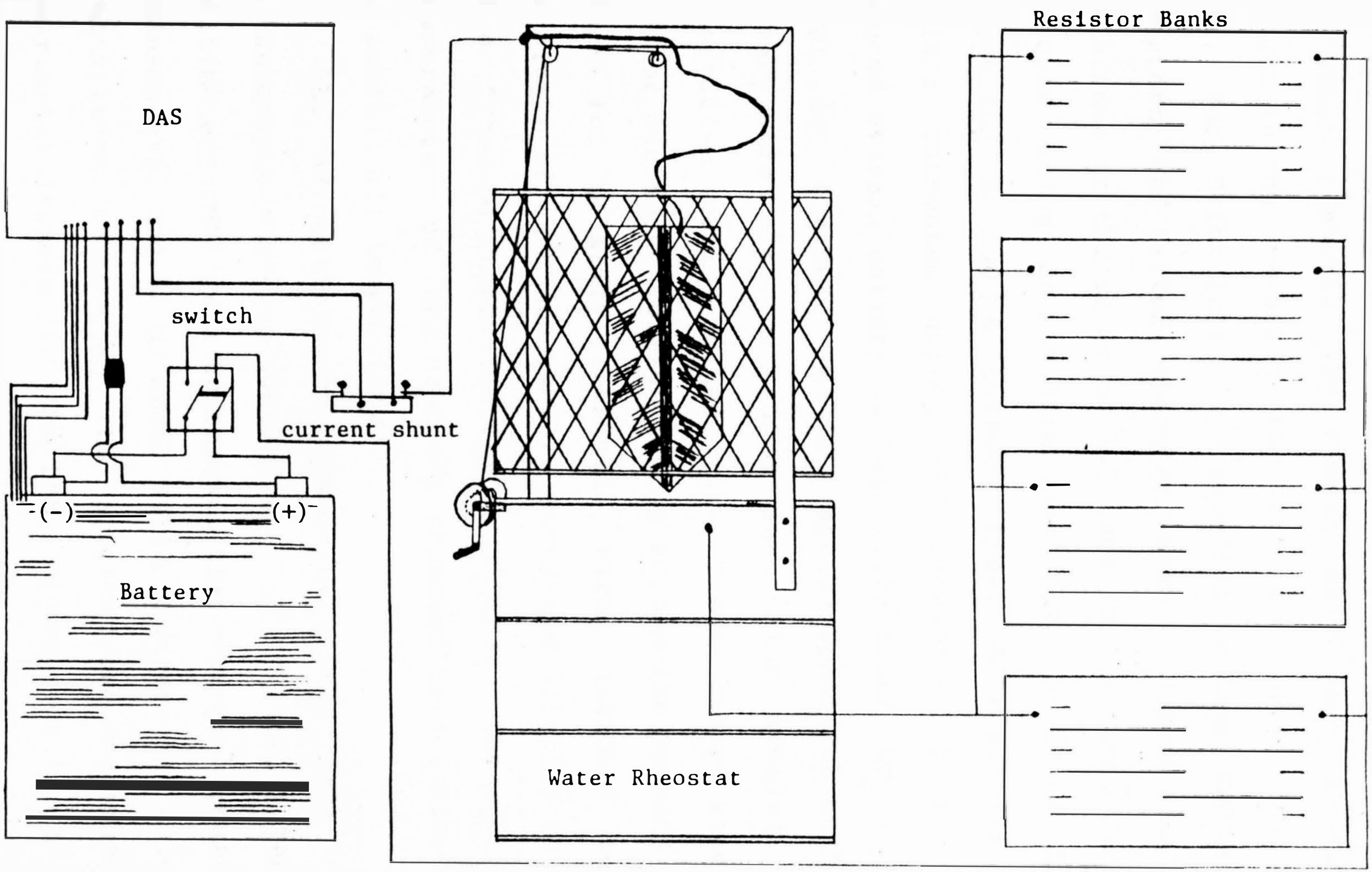


Figure 4. Discharge Test Equipment

The water rheostat was subsequently used to make small changes in the resistance to closely control the current flow. For Skidtric's 72 V (nominal voltage) battery, the resistors and water rheostat were adjusted to provide resistance in the range of 1.1 ohms to 1.4 ohms. Current was measured using an in-line shunt rated at 50 mV of voltage output for a 100 A current flow. A resistive voltage divider connected across the terminals of the battery reduced overall battery voltage 11.75 times to a readable level for the DAS. The 36, series connected cells of the battery were also separated into nine modules of four consecutive cells (Figure 5). These groups were used to monitor discharge voltage trends across the battery and to check for polarity reversal. Wires attached to the end terminals of each module were connected directly to the DAS. Five "T"-type thermocouples monitored the electrolyte temperatures of four randomly selected test cells, as well as ambient air temperature.

The DAS consisted of a Hewlett-Packard (HP) model 85 micro-computer as the controller, an HP model 3478A digital multimeter (DMM) used to measure the voltage signals of the transducers, and an HP model 3495A scanner that acted as the multiplexer connecting the appropriate transducer to the multimeter (Figure 6). The DMM was accurate to ±0.04% and ±0.02% of the measurement on the 30 mV and 30 V ranges,

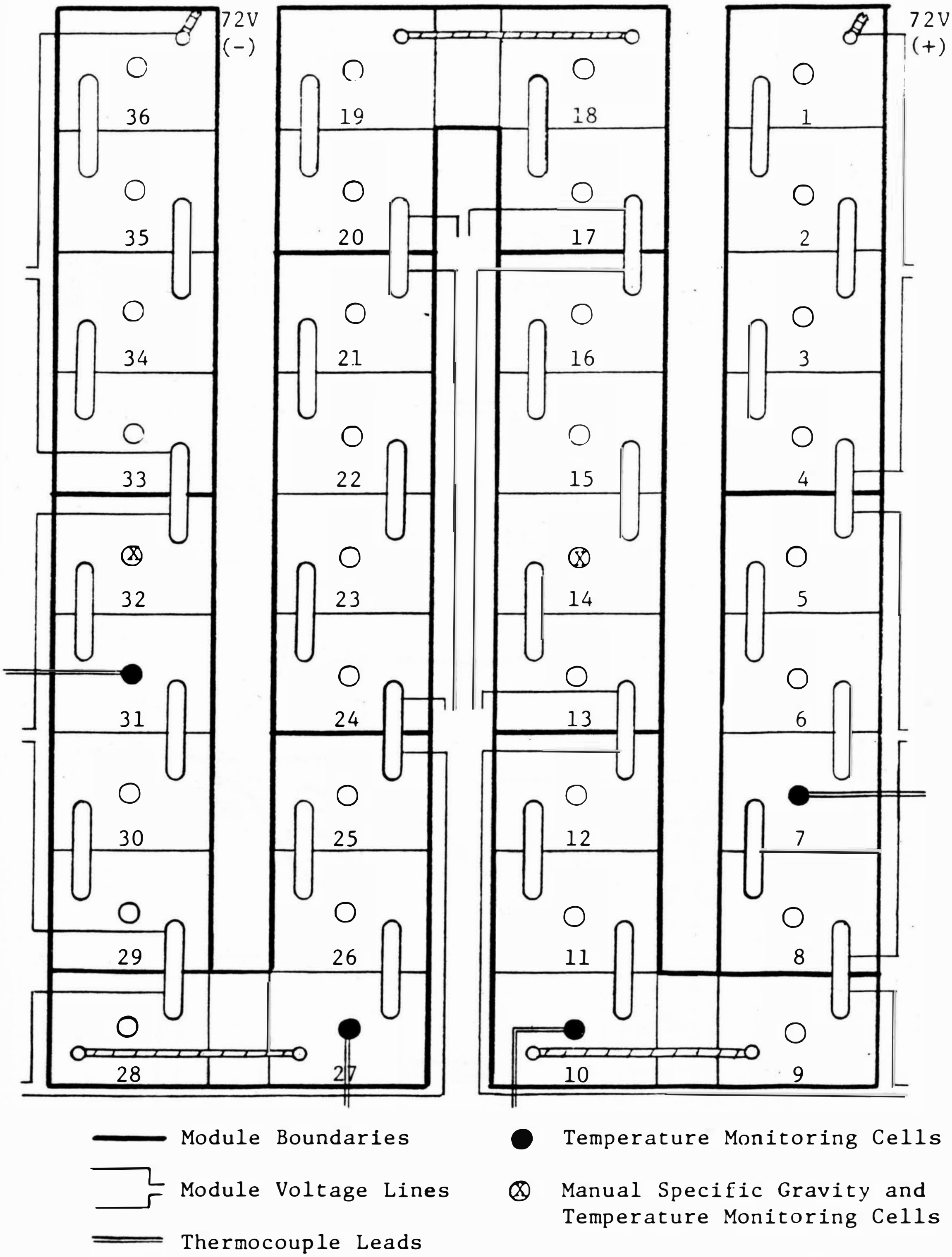


Figure 5. Battery Transducer Configuration

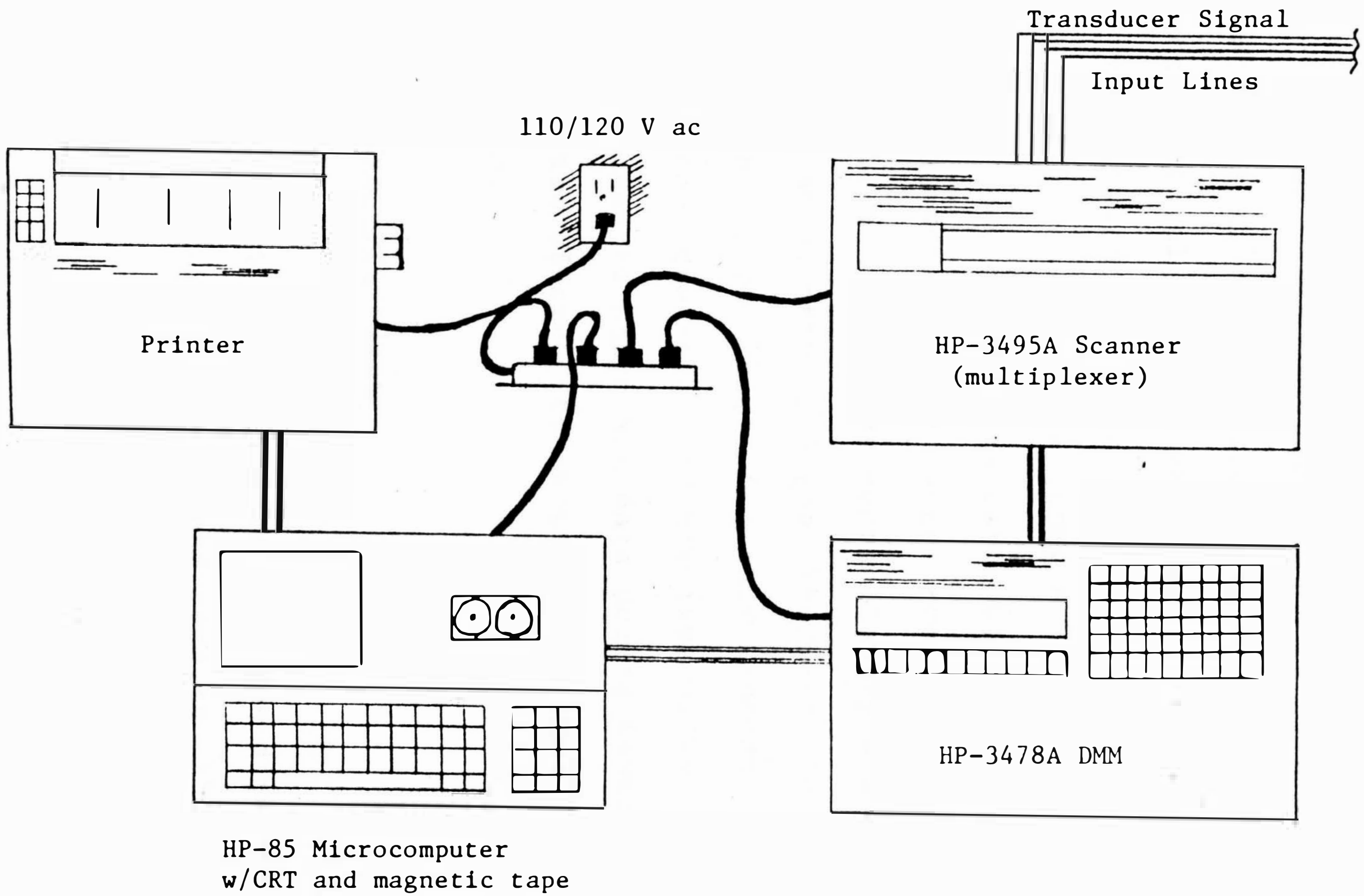


Figure 6. DAS Equipment for Discharge/Charge Tests

respectively (Hewlett-Packard, 1981). Calculated current values, computed by the 2000 A/V multiplier from the in-line shunt voltage and read on the DMM's 30 mV (.03 V) range, were accurate to ±0.024 A ([.04%/100%]*2000 A/V * .03 V). Recorded terminal voltage, converted by the 11.75 multiplier from the voltage divider and read on the 30 V range, was accurate to ±0.071 V ([.02%/100%] * 11.75 V/V * 30 V). The groups of four consecutive cells were read directly by the DMM on the 30 V range and were accurate ±0.020% of the measurement. The DAS was controlled by a modified version of the program written by Bryan Thoreson for his testing project. The flow chart for this program is presented in Figure 7. Cassette tapes and the tape drive built into the HP-85 were used to store the data during testing. Later the data was transferred to magnetic disks for storage and manipulation.

Discharge Test Procedure

The initial step in performing the discharge test was to connect the DAS and the transducers to the battery and conductor lines. Before the full test was started, a short trial run was performed to check for proper operation of the instrumentation system and to adjust the resistor banks and water rheostat so that the current drawn was approximately

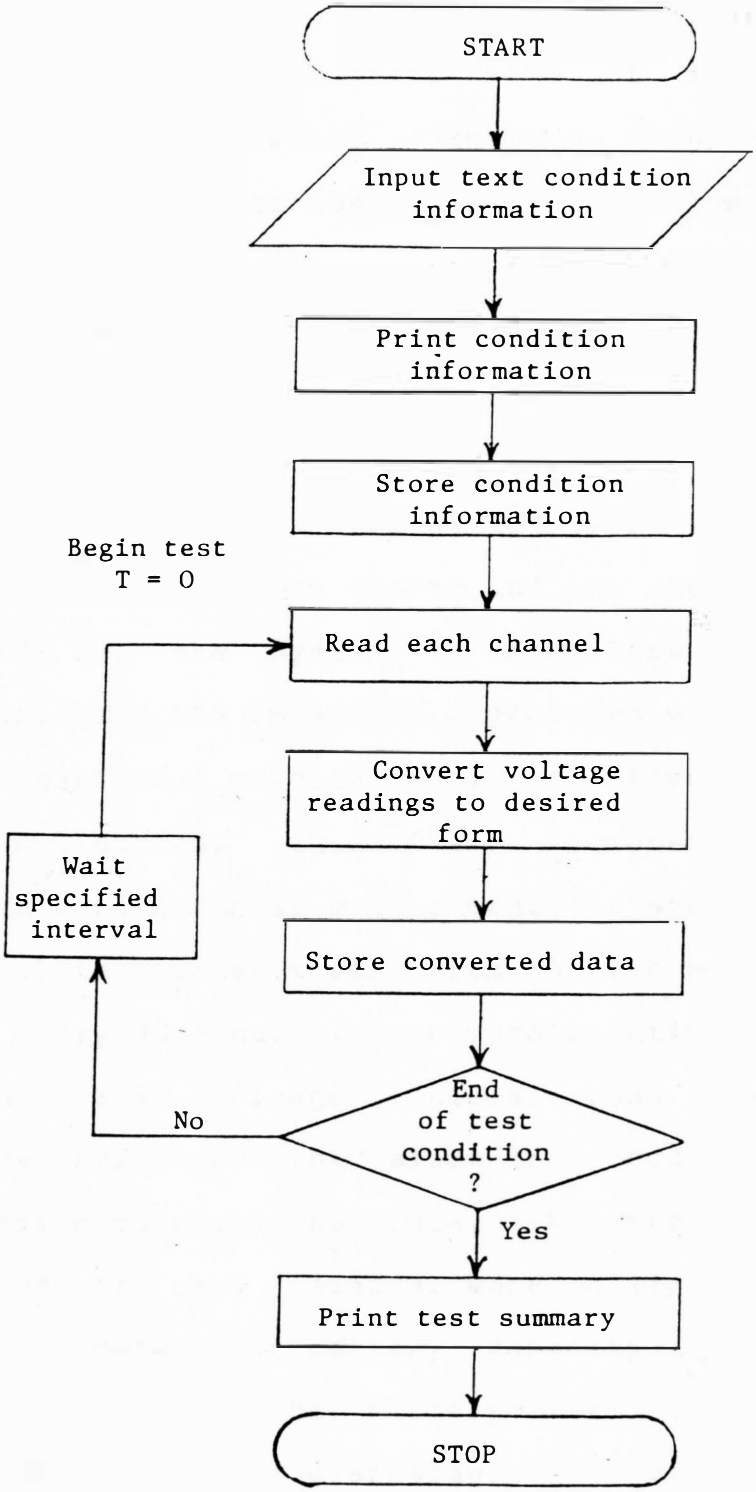


Figure 7. Discharge/Charge DAS Program Flowchart

at the six hour discharge rate of 53.3 A. The water rheostat was initially adjusted so that less than one half of the contact plate was submerged to allow for current draw adjustment.

Testing started when the system had been checked and adjusted (Appendix B-1). Background information such as test name, date, time, operator, and location were entered and stored on tape. The switch connecting the battery and the resistive load was closed and one to two seconds was allowed for the system to stabilize before the DAS was started. The DAS immediately measured each of the variables once, performed calculations, and stored the data on tape. Data collection, thereafter, occured at three minute intervals with manual measurements of specific gravity and electrolyte temperatures from the two specified test cells taken every 30 minutes. Energy calculations assumed that the current and voltage values read each time were representative of the values that occured between the data collection points. Therefore, the current and power values measured at each interval were multiplied by the interval time to determine battery capacity in Ah and kWh, respectively. As the battery terminal voltage decreased over the time of the discharge, the water rheostat contact plate was lowered further into the water so that contact area would be increased, thereby decreasing the resistance so that the current flow rate was maintained at approximately 53.3 A. A portable DMM connected to the in-line shunt continually monitored the current flow and the rheostat was adjusted, as necessary, according to this reading.

Data collection continued until any one of the nine battery modules reached 6.8 volts (1.70 volts per cell average). Once any cell group reached 6.8 volts all groups were monitored, but not recorded, continuously by the DAS, and cell groups falling below 6.8 volts were identified for manual checking to guard against polarity reversal (current flow into a cell from the surrounding cells). If such a reversal had occurred the test would have been terminated immediately, however no cells reversed polarity and the discharge continued with both DAS and manual monitoring until the terminal battery voltage reached 61.2 volts or 1.70 volts per cell average, over all 36 cells. This was considered to be 100% DOD and the energy removed from the battery at this point was the maximum available battery capacity. Final measurements of all variables were taken immediately prior to disconnecting the switch to the resistor banks and terminating the test.

Charging Test Procedure

The battery charging tests were performed immediately after the discharge tests (Appendix B-2). The instrumentation system, DAS, and controlling program used for the charging tests were the same as those used during the discharge tests with the exceptions that the resistive load was replaced by the battery charger, the DAS leads on the in-line shunt were reversed, and the test termination criteria was zero or negative current flow into the battery rather than a terminal battery voltage value. Also, since the time required to recharge the batteries was expected to be significantly greater than the time required to discharge them, periodic manual measurements of specific gravity and temperature were not taken. An internal voltage sensing relay engaged the charger's built-in timer when the battery voltage exceeded 85 V and automatically shut the charger off three hours later. Similarly, the program controlling the DAS was modified to automatically terminate data collection when the current flow from the charger reached zero amperes.

When all necessary modifications had been made, the battery charger was started and allowed to stablize for a few seconds. The DAS was then started and the system was monitored for a few data collection cycles, then left to operate unsupervised. Charging time was expected to exceed 13 hours.

Vehicle Tests

The primary objectives of the vehicle tests were to: 1) determine the power requirements for individual segments of skid-steer operation; 2) use those results to develop equations describing the power requirements of the respective segments; and 3) use those relationships and equations to develop a model that would predict power and energy requirements for specified cycles. Secondary objectives included gathering further data to check the accuracy of the developed model and to determine how long the vehicle would operate at various load levels.

The vehicle tests consisted of defined and controlled cycle segments that were considered to be representative of actual vehicle use. These segments were defined as loader operation, ground motion and duration tests. The ground motion tests were subdivided into constant velocity, acceleration, and turning tests. Loader operation was divided into lifting, lowering, dumping, and tilting-back. Since nearly all uses of a skid-steer loader could be represented by a combination of these segments it was decided to test and determine the energy relationships of each segment seperately rather than to perform the tests on specific, complete cycles. The relationships developed were used in a computer prediction model to calculate the expected energy requirements and running time of Skidtric as a function of the draft and/or bucket load, speed, and time.

Data gathered during the testing included directly measured variables and calculated values. The measured variables consisted of battery voltage, current to the traction and hydraulic motors, draft in the form of supply and output voltages from strain gages, ground speeds from a trailing fifth wheel and from motor speed sensors, hydraulic oil temperature, and time. Battery power and energy, calculated power and energy, and efficiencies were computed from the measured variables.

The terms battery power and battery energy represented the amount of power and energy removed from the battery by Skidtric in performing a specified task. Battery power and energy were calculated by multiplying the measured current draw by the measured battery voltage, and battery power by the time that power was drawn, respectively. Battery power and energy included losses through Skidtric's systems.

The calculated power and energy values represented the amounts that would be required to perform a specified tasks as calculated from theoretical equations. Calculated power and calculated energy were computed by multiplying forces (draft or bucket loads) by speeds and calculated power by the time that power was required, respectively. Calculated power and energy do not include or consider losses through

Skidtric's controller, motor, drivetrain, hydraulic, and battery systems.

System efficiencies were subsequently calculated by dividing calculated power or energy by the respective battery power or energy. These efficiencies represented the portion of the battery power or energy that actually performed the physical task desired and were not used to overcome system losses.

Instrumentation

Transducers used during the vehicle tests included a resistive voltage divider, two in-line current shunts, two magnetic motor speed sensors, a fifth wheel speed sensor, a three point hitch dynamometer, and three thermocouples. These transducers monitored battery voltage, current to the motors, apparent ground speed of the wheels, true ground speed, draft, and hydraulic oil temperature, respectively. The vehicle test instrumentation transducers are depicted in Figure 8.

The voltage divider was connected across the battery terminals and reduced the battery voltage by 11.75 times to a level that was safe and readable by the DAS. The in-line current shunts were installed in the power cables between the battery and the vehicle controllers. One shunt was used

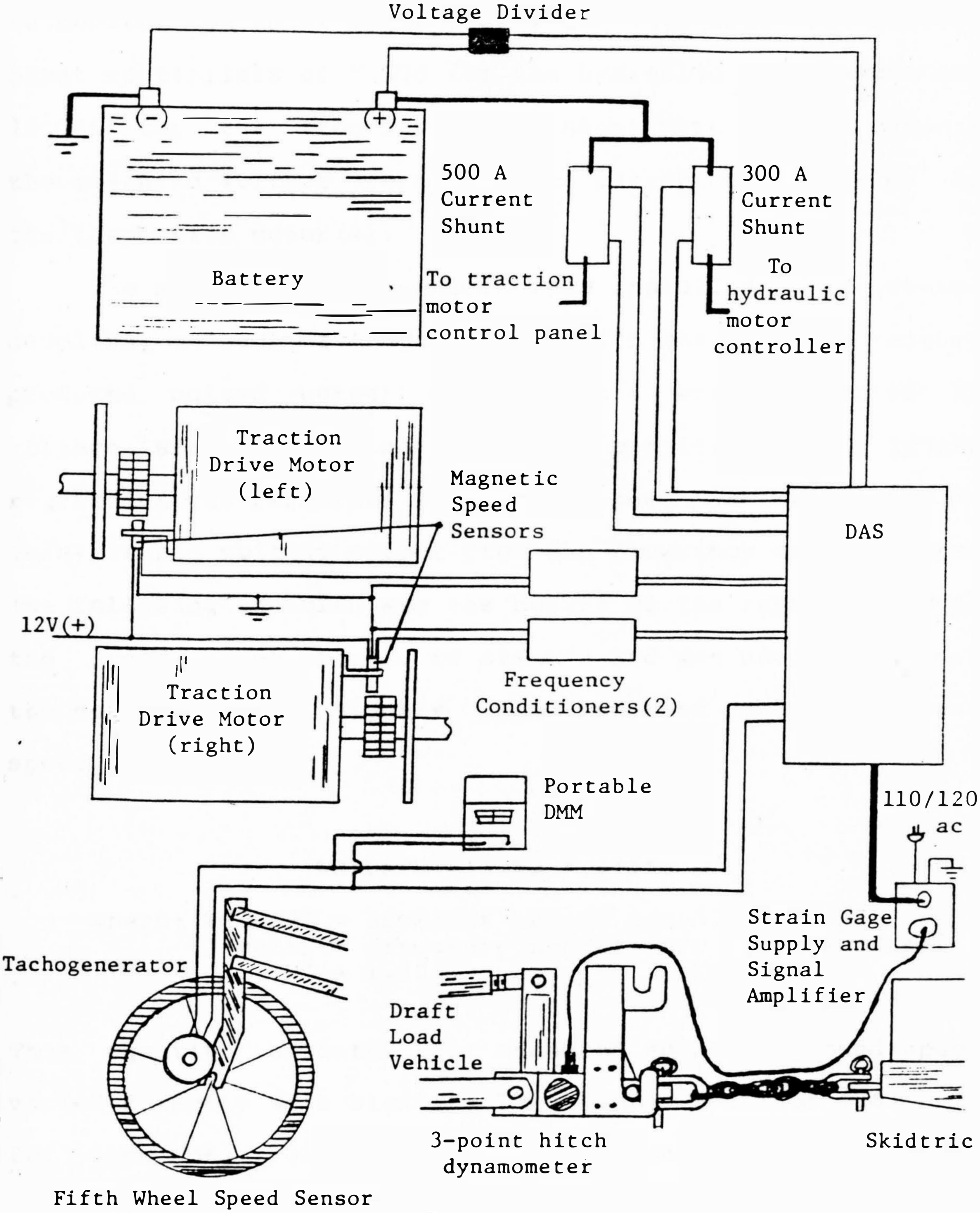


Figure 8. Instrumentation for Vehicle Tests

to monitor the total current draw for both traction motors. Shunt multipliers of 6,000 for the hydraulic motor shunt and 10,000 for the traction motors shunt were used to convert the measured voltage drops into the current being drawn by the respective motor(s).

The magnetic speed sensors were installed over chain-couplers on each of the two, traction motors. The sensors produced pulsed output signals that were converted to voltage signals by two frequency conditioners. A linear regression was performed for ground speed in meters/second (m/s) versus voltage output from the frequency conditioners. The following equation was the result of the regression over the speed range of zero to six m/s and was used to convert the voltage output signals into apparent vehicle ground speed in m/s:

$$WGRDSPD = 1.62 * volts$$

where: WGRDSPD = apparent ground speed, (m/s)
volts = frequency conditioner voltage output
R^2 = 1.00

This equation indicated that measured apparent ground speed varied directly with signal voltage by a factor of 1.62 m/s for each one volt change. It was assumed that the wheel speeds of the left and right sides were identical during straight line operation (acceleration and constant velocity), and consequently, that the apparent ground speed of the vehicle could be determined from only one sensor during these tests. Both sensors were used during the turning tests since the right and left wheels were driven at different speeds and in opposite directions.

True ground speed was measured by a fifth wheel that was able to move freely in the vertical plane. A tachogenerator driven by the non-powered wheel produced a voltage output whose magnitude was directly proportional to the speed of travel. A linear regression of ground speed versus voltage output over the range of zero to six m/s resulted in the following equation for ground speed:

$$TGRDSPD = 14.4 * volts$$

where: TGRDSPD = true vehicle ground speed, (m/s)
volts = tachogenerator voltage output, (V)
$R^2 = 1.00$

This equation indicated that measured true ground speed equalled 14.4 m/s for each volt generated by the tachogenerator.

A three-point hitch dynamometer measured draft loads during the ground motion testing. The dynamometer, built by Johnson and Voorhees, (1979), at SDSU, consisted of a strain gaged, aluminum tube to which mounting brackets were attached. These allowed the dynamometer to be placed between Skidtric and the load vehicle. Before use, the dynamometer was calibrated against known loads to check its accuracy and conversion equation. A linear regression of known load versus the ratio of dynamometer output voltage over input supply voltage for the low range resulted in the following equation:

$$DRAFT = 13.846 * Eo/Es$$

where: DRAFT = horizontal draft load, (kN)
Eo = strain gages output, (mV)
Es = strain gage supply, (V)
R^2 = 1.00

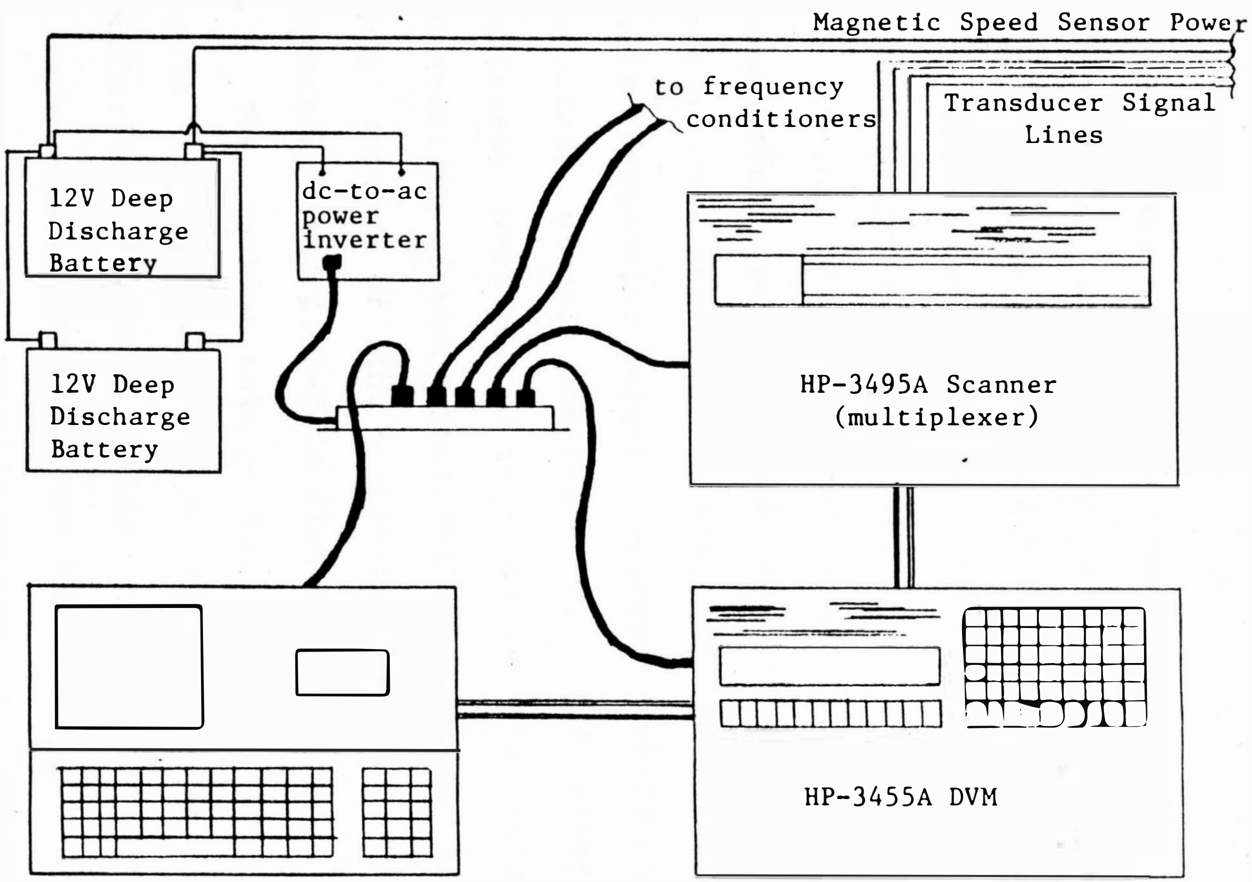
This equation was within 3.5% of Johnson and Voorhees' original calibration equation and indicated that for each increase of one in the ratio value, measured draft increased by one kN.

Three thermocouples were used in conjunction with a Fluke monitoring system to measure and record hydraulic oil temperatures during a short series of loader operation tests. The oil temperature was monitored to check for a relationship between oil temperature and power requirements. Since analysis indicated little correlation (R^2=0.56) between oil temperature and power required, no further oil temperature data were recorded.

Miscellaneous equipment used during testing included the power supply/amplifier for the dynamometer, a hydrometer to measure specific gravity of the battery, a stopwatch to monitor time for the operator's convenience, and a portable

DMM connected to the trailing fifth wheel to serve as a speedometer during the acceleration and constant velocity tests.

The DAS used for the vehicle tests was identical to the DAS used for the battery tests with the exception that the HP-3478B DMM was replaced by an HP-3455A DVM (Figure 9). The DAS used an HP-85 microcomputer as the controller, an HP-3495A scanner as the multiplexer and an HP-3455A digital voltmeter (DVM). The DVM was accurate to ±0.015% and ±0.013% of voltage readings to measure the voltage inputs from the transducers on the 0.1 V and 10 V ranges. respectively (Hewlett-Packard, 1976). The measured hydraulic motor current values, computed using a shunt multiplier of 6000 A/V read on the DVM's 0.1 V range, were accurate within ±0.09 A ([015%/100%] * 6000 A/V * .1 V). Similarly, the measured traction motor current values, computed with a shunt multiplier of 10 000 A/V read on the 0.1 V range, were accurate within ±0.15 A ([.015%/100%] * 10 000 A/V * .1 V). Measured battery voltage was accurate to ±0.015 V, on the 10 V range using the 11.75 voltage divider multiplier ([.013%/100%] * 11.75 V/V * 10 V). Voltage inputs from the motor speed sensors and the fifth wheel were read on the 0.1 V range and were accurate within ±0.26 m/s and ±0.02 m/s, respectively. Draft values were calculated from the ratio of output voltage to supply voltage. These voltages were both



HP-85 Microcomputer
w/CRT and magnetic tape

Figure 9. DAS Equipment for Vehicle Tests

read on the 0.1 V range with an accuracy of ±0.015% of the measurement. The dynamometer had a sensitivity of 6.99×10^{-5} (mV/V)*N. The power requirement for the DAS was 110/120 V ac that was supplied by a wall outlet during the loader operation tests and by a 12 V dc to 117 V ac power inverter connected to two 12 V, dc, deep cycle, automotive batteries during the ground motion tests.

Choices for the locations of the DAS and the transducers were limited by vehicle configuration and design. The transducers were, by necessity, located near their respective signal sources, while the DAS, power supplies, signal conditioners, and other miscellaneous equipment were placed in a box on Skidtric's roof, and the controlling microcomputer was mounted on a fender within easy access of the operator. The data collection program flowchart is depicted in Figure 10.

The sampling rate of the DAS was set to the maximum level of approximately six channels per second. The total number of data points collected was dictated by the time length of the test, but the number of times each channel was read depended primarily on the total number of channels to be read. For example, a test run of 120 seconds duration typically produced 778 data points. If two channels were to be read then each channel would be read 389 times. However, if six channels were to be read during a 120 second test,

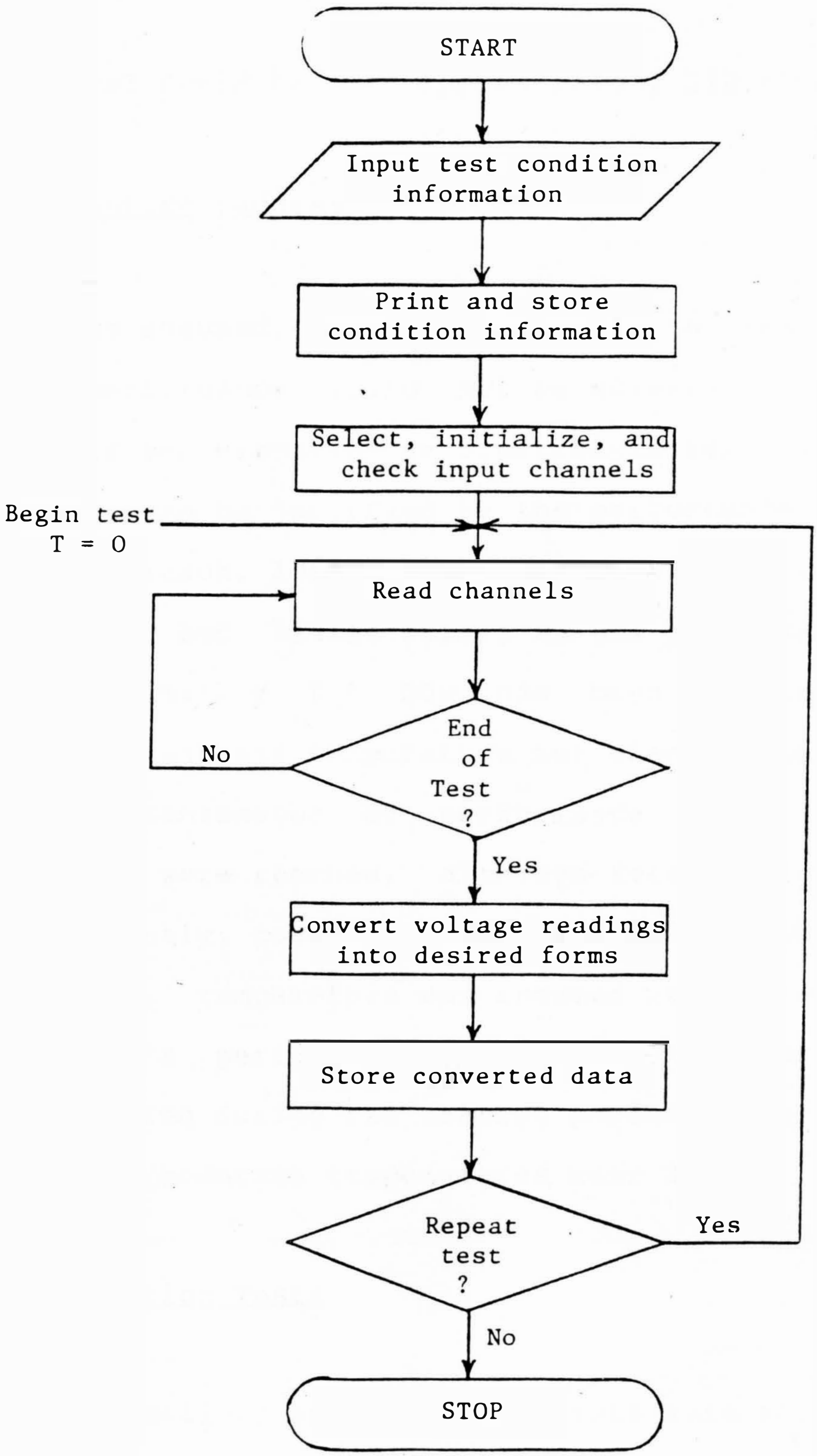


Figure 10. Vehicle Test DAS Program Flowchart

each channel would be read approximately 130 times.

Vehicle Test Procedures

It was assumed, before commencing a test run, that vehicle performance would not be affected by battery DOD, ambient air temperature, or electrolyte temperature. These assumptions can be justified by the performance test results of EC-I (Thoreson, 1985). Thoreson's tests showed both that battery DOD had little effect on the performance of an EV until approximately 80% DOD had been reached and that neither ambient air temperature nor electrolyte temperature affected instantaneous EV performance until temperatures around $0^{o}C$ were reached, although total battery capacity, and consequently, total time of operation, would be reduced. Additionally, temperature was assumed not to have an effect on Skidtric's performance because Skidtric was stored in a heated building during the testing period and all tests were performed at moderate temperatures near $20^{o}C$.

Loader Operation Tests

The objectives of the loader tests were to: 1) collect data that could be used to develop power versus load relationships for Skidtric's loader operation; 2) use those relationships to develop equations that could be used to predict the power and energy required by the loader at specified load levels; and 3) use those equations in a computer model to predict the total energy and power needs of Skidtric.

Skidtric's battery was fully charged and then allowed to sit for several hours to stabilize before beginning the loader tests. Skidtric had been maneuvered into testing position before the battery had received its final charge and the wheels were blocked to prevent unintentional rolling during testing. It was not moved again until all loader tests were complete. The weights used as the loads throughout the tests were added and removed using another loader vehicle. The exact test procedure used is listed in Appendix B-3.

Lift/lower tests. Each testing run was started and ended with the hydraulic motor off and the loader in its lowest position. The bucket was kept in the maximum rolled back position throughout the test. The test length was selected as 120 seconds so that each test cycle consisted of seven consecutive lifts and lowers to the extreme high and low positions, respectively, at the maximum possible speed. The on-demand switching system was used and time was allowed for the motor to stop between lift/lowers. Any time remaining in the test after the seventh lift/lower cycle was allowed to expire with the motor off. The hydraulics motor was shut off between all test runs during data processing. When the DAS had completed the necessary computations and data storage the cycle was repeated at the specified load level.

The load levels used were 0 kN (no added weight), 1.51 kN, 3.48 kN, 4.166 kN, 6.036 kN, and 7.646 kN. These weights were selected due primarily to their availability. Test runs at each load were replicated a total of nine times. Bucket loads were each replicated three times consecutively in ascending order, three times consecutively in descending order, and, again, three times consecutively in ascending order. The testing order of loader operation is given in Table 3 and is indicated by the number in each cell.

Table 3. Lift/lower operation order of testing.

Test Run Replication	Load (kN)					
	0.00	1.51	3.48	4.166	6.036	7.646
1	1[1]	4	7	10	13	16
2	2	5	8	11	14	17
3	3	6	9	12	15	18
4	34	31	28	25	22	19
5	35	32	29	26	23	20
6	36	33	30	27	24	21
7	37	40	43	46	49	52
8	38	41	44	47	50	53
9	39	42	45	48	51	54

[1] Numbers indicate the order in which the loads were used.

Ideally, from the statistical standpoint, the loads would have been randomly assigned. However, the magnitude of these weights made handling them difficult and it was decided that three consecutive replications in ascending, descending, and ascending order satisfactorily approximated random assignment while reducing the number of times each weight was handled (Tucker, 1986).

<u>Bucket tests.</u> The smallest three bucket loads used for the lift/lower tests were also used for the bucket dump/tilt tests. Test loads were limited to zero kN, 1.51 kN, and 3.48 kN because of concerns regarding effective securing of the larger loads in the bucket when tilted down. For satisfactory data collection, each load had to remain firmly

attached to the bucket during the complete cycle. Such attachment of the larger loads was not possible without significant alterations to the bucket. Bucket operations were also felt to be only a small fraction of complete skid-steer use and consequently it was decided to limit bucket testing to the smallest three loads.

Each test was started and ended with the bucket in the maximum rolled-back position. The loader arms were raised high enough to allow full bucket movement without hitting the floor and were not moved during the bucket testing. The on-demand hydraulics feature was used and the motor was allowed to stop between each dump/tilt. A test time of 120 s was selected, allowing seven dump/tilt cycles in each test run. The loads were used in consecutive order to minimize handling and each was replicated three times (Appendix B-4). The testing order for the bucket tests is listed in Table 4.

Table 4. Loading order for bucket tests.

Test Run Replication	Load (kN)		
	0.00	1.51	3.48
1	1[1]	4	7
2	2	5	8
3	3	6	9

[1] Numbers indicate the order in which the loads were used.

<u>Parameters.</u> The parameters measured during the loader tests

were battery voltage, current flow to the hydraulic motor, the time at each data point reading and the total time of the test. Instantaneous battery power required to lift the load was found by multiplying consecutive instantaneous voltage and current readings. Instantaneous battery energy was calculated by multiplying instantaneous power by the interval of time over which the power was applied. Instantaneous theoretical power and energy were calculated by multiplying the weight force by the lifting rate, and the weight force by the distance lifted, respectively. These data were computed and initially stored on cassette tapes in the micro-computer's internal tape drive unit and later transferred to magnetic disk storage.

Constant Velocity Draft Tests

The objectives of the constant velocity draft tests were to: 1) collect data to develop power versus load and speed relationships for Skidtric; 2) use those relationships to develop equations to compute the power and energy required by Skidtric at specified load and speed levels; and 3) use those equations in a computer model to predict energy and power needs of Skidtric. A secondary objective was to determine the maximum draft power available from the vehicle.

Based on the assumption that battery DOD did not affect the performance of the vehicle, it was considered unnecessary to have the battery fully charged at the beginning of each testing day. Consequently, the battery was recharged only when it reached 80% DOD. Throughout the testing period, the battery was charged and maintained according to the manufacturer's specifications and allowed to stabilize before tests were performed. All other vehicle maintenance, including lubrication, tire pressure, and cleaning, were performed as specified by the respective manufacturers.

Dry asphalt was chosen as the test track surface because it was readily available and offered a nearly ideal traction surface with little sinkage. Additionally, the tests performed on dry asphalt could easily be repeated at other locations and provide comparable results. Skidtric's rolling resistance on asphalt was measured and accounted for in the data analysis. The test track was level and relatively uniform across its length. The track was approximately 150 meters long which allowed a 60 second test run at maximum velocity to be completed. The track length included the distance required for the vehicle and the load to reach the desired final velocity before beginning data collection. Ideally, Skidtric should also have been tested on deformable soils and wet, slippery surfaces. However, such surfaces were not used due to the difficulty in maintaining uniformity over the period of the tests, problems with extreme sinkage due to the softness of the ground, and a shortage of time.

The speeds for the tests were selected as 0.5 m/s, 1.0 m/s, 2.0 m/s, and 3.0 m/s. These speeds were selected as being typical speeds at which Skidtric might be operated with 3.0 m/s considered a maximum safe operating speed. Each test run was assigned a velocity in random order. This served to remove possible effects that battery DOD could have on Skidtric's performance despite the earlier stated assumption, and the possiblity of operational memory for the battery that may have built up with repeated operation at a set velocity. The operator monitored vehicle speed using a portable DMM connected to the fifth wheel.

Three vehicles towed in neutral served as three of the loads for the draft tests. Skidtric's internal rolling resistance (no applied draft load) was the the fourth load. The load vehicles were towed independently and in combinations that provided a variety of magnitudes of draft. Vehicles towed in neutral provided nearly a constant draft load independent of the speed travelled, therefore, the repeatability of the draft loads was easier to maintain. Approximate values of the applied draft loads were zero kN, 1.3 kN, 2.5 kN, and 5.0 kN.

Each draft load was repeated consecutively during the tests at each of the randomly assigned velocities. The experimental design used for the constant velocity draft tests is listed in Table 5. The numbers one, two, three, and four indicate the order in which the target velocities were used within each replication.

Table 5. Experimental Design for constant velocity draft tests.

Draft Load	Test Run Replication	Assigned Travel Speed Order			
		1	2	3	4
1	1	4[1]	2	3	1
	2	1	3	4	2
	3	4	1	3	2
2	1	4	3	2	1
	2	3	4	2	1
	3	4	1	3	2
3	1	1	3	2	4
	2	4	2	1	3
	3	2	1	3	4
4	1	3	4	1	2
	2	3	4	2	1
	3	4	2	3	1

1 Numbers in horizontal rows indicate the order in which each speed was used during each test replication.

Each day, Skidtric was driven to the test track for testing and was returned to the shop when testing was completed for that day. The vehicle was stored inside overnight and charged as necessary to maintain the battery.

Before beginning a test, Skidtric and the load vehicle(s) were maneuvered into a position such that a completely straight run could be made. Skidtric was then connected to the load and the computer was initialized. When the DAS was ready and had been checked for correct operation, Skidtric and the load vehicle(s) were accelerated to the desired velocity. This velocity was maintained for a short distance to be sure that it was nearly constant before data collection was started. Skidtric, with the load vehicle(s) in tow, was driven in a straight line at the selected velocity until the data collection for the run was complete. At the end of the 60 second test period the DAS terminated data collection and began the data processing in which the raw data was converted from voltage readings from the transducers into the desired parameter form that were then stored on tape. During the data processing and storage, Skidtric and the load vehicle(s) were maneuvered into position to begin the next test run. This procedure was repeated until each speed and load combination had been recorded a minimum of three times (Appendix B-5).

The parameters recorded during the constant velocity draft tests were battery voltage, current to the traction motors, true ground speed, apparent ground speed, draft, and time. With the exception of time, these data were collected as voltage signals from the transducers, then processed and stored on tape as volts, amps, m/s, m/s, and kN, respectively.

The parameters calculated from the data gathered were power and energy. Power (kW) was calculated as the average battery power drawn by Skidtric and the average calculated power required for the load. The respective instantaneous powers were calculated by multiplying the instantaneous values of battery voltage by the instantaneous values of motor current, and the instantaneous values of draft by the instantaneous values of velocity. The average powers were computed by summing the respective instantaneous powers for each complete run and dividing the total by the number of instantaneous points recorded. Energy consumed was also found in terms of the battery and calculated energy consumed. These energies were calculated by multiplying the respective power by the total time that the power was applied or required. The time of each run was recorded internally by the DAS and stored on tape with the remainder of the data collected.

Acceleration Draft Tests

The objectives of the acceleration draft tests were to: 1) collect data to develop an acceleration power versus load relationship for Skidtric; 2) use that relationship to develop equations to compute the power and energy required by Skidtric for accelerating a given load; and 3) use those equations in a computer model to predict the power and energy requirements of Skidtric for specified tasks. A secondary objective was to determine the maximum acceleration rates at various draft loads.

The battery was maintained and charged as needed, but was not arbitrarily recharged at the end of each day. Normal battery and vehicle maintenance was performed as specified by the manufacturers and the vehicle was allowed to stabilize before tests were performed.

It was assumed that Skidtric would always be accelerated at the maximum possible rate. This assumption was justified because Skidtric normally accelerated at the maximum possible rate until the desired final velocity was reached. Assuming the maximum acceleration rate improved test repeatability since the speed control was instantaneously moved to the maximum speed position and held there until the maximum possible speed was reached. This assumption removed the need for a manually adjusted acceleration rate that would have been difficult to repeat.

The track surface selected for the acceleration tests was dry asphalt because it provided good traction and allowed test conditions to be easily repeated. Other surfaces such as tilled soil, sod, and wet, slippery surfaces were considered but determined to be too difficult to adequately define for repeatability.

Three vehicles towed in neutral were used as three of the draft loads for the acceleration tests with no applied draft load serving as the fourth load. These loads not including Skidtric's rolling resistance provided an average draft range of zero to five kN with a maximum draft value of approximately 15 kN during acceleration with the largest load. Skidtric's rolling resistance was measured over a range of speeds and was found to be approximately a constant value. Each draft load was replicated three times in successive order. The experimental design for the acceleration tests is given below (Table 6).

Table 6. Experimental design for acceleration tests.

Draft Load	Test Run Replication	Final Speed
1	1	Maximum possible
	2	"
	3	"
2	1	"
	2	"
	3	"
3	1	"
	2	"
	3	"
4	1	"
	2	"
	3	"

During the test period, Skidtric was stored inside when not in use and driven to and from the test track each day. Before beginning a test, Skidtric and the load vehicle(s) were maneuvered into a position that allowed a completely straight test run. Skidtric and the load vehicles were then connected and the computer initialized. When the DAS was ready and had been checked for correct operation, data collection was started and Skidtric and the load vehicle(s) were accelerated to maximum possible velocity, braked to a stop, accelerated to maximum velocity, braked to a stop, etc., until the 60 second test had been completed. At the end of the test the DAS terminated data collection and began processing the raw data from the transducers into the desired forms. The processed data was then automatically stored on tape and the DAS reset for another run. During the data processing, Skidtric and the load vehicle(s) were maneuvered into position for the next test run. This procedure was repeated a minimum of three times for each draft load (Appendix B-6).

The variables recorded during the acceleration tests were battery voltage, current to the traction motors, true ground speed, apparent ground speed, draft, and time. All data, except time, were collected from the transducers as voltage values then converted to the appropriate units. Time was recorded internally by the controlling computer.

Parameters calculated from the data gathered were power and energy. Power (kW) was calculated as the average battery power drawn by Skidtric and the average calculated power required for each draft load. The respective instantaneous powers were calculated by multiplying the instantaneous battery voltage by the instantaneous motor current and the instantaneous draft by the instantaneous velocity. The average powers were computed by summing the instantaneous powers for each complete run and dividing by the number of instantaneous points recorded. Energy consumed was also calculated as battery and calculated energies. These energies were calculated by multiplying the respective power by the time that power was applied or required.

Turning Tests

The objectives of the turning tests were to: 1) collect data to develop the relationship between power required and the load carried in the bucket for Skidtric; 2) use that relationship to develop equations to compute the power and energy required by Skidtric to turn carrying a specified load; and 3) use those equations in a computer model to predict the energy and power needs of Skidtric. Also, Skidtric's turning performance needed to be defined and quantified so that design improvements could be recommended.

It had been found in prior use that Skidtric had a great deal of difficulty turning on high friction, rough, or soft surfaces when carrying certain bucket loads. Consequently, the track surface chosen for the turning tests was smooth concrete, which provided less turning resistance than either asphalt or soil surfaces. It was also found in prior use that Skidtric turned well on slippery surfaces (mud, ice, snow, etc.) provided that a solid base prevented excessive sinkage. However, it was decided that these surface types were too difficult to duplicate for repeated testing.

Six bucket loads were used during the turning tests (Appendix B-7), zero kN (empty bucket), 1.51 kN, 3.48 kN, 4.166 kN, 6.036 kN, and 7.646 kN. The loads were used in ascending order to minimize handling. The turn tests were performed at the maximum possible rate of turn to improve test repeatability. Also, since Skidtric was unable to turn at full power with certain bucket loads, tests at a lower rates of turn (less applied power) were pointless since no turn could be made. Ninety degree turns were used as the representative turning angle. Turns of less than 90° were found to be difficult to measure and at the zero kN load level Skidtric turned too quickly for adequate data to be collected. Turns of 180° were considered for the tests but were not used because of the vehicle momentum factor that became evident during longer turns. Turns between 90° and 180° were not considered because of difficulty in measuring and repeating them during the test runs.

For the turn tests, Skidtric was positioned in a cleared area and the appropriate load was placed in the loader bucket. The position (direction) was noted by the operator so that turns of 90° could be made. The computer was initialized and the DAS checked for proper operation. A 30-second test length was selected because the high power demand associated with turning could damage vehicle control components if applied for longer than 30 seconds continuously. When the DAS was ready, data collection was started. Skidtric was turned through a 90° angle, stopped, turned through a 90^{o} angle, stopped, etc. until the 30-second test was finished. The data was then processed and stored on tape and Skidtric was repositioned for the next test. Each test was repeated three times for each of the six bucket loads. The order of testing for the turning operation is given below (Table 7).

Table 7. Loading order for turning operation tests.

Rate of Turn	Test Repli-cation	Bucket loads					
		0.00	1.51	3.48	4.166	6.036	7.646
Maximum Possible	1	1[1]	4	7	10	13	16
	2	2	5	8	11	14	17
	3	3	6	9	12	15	18

[1] Numbers indicate the order in which the laods were used.

If a 90^{o} turn could not be completed in the 30-second test period, the total number of degrees turned was measured, recorded and later used to compute the turning rate for that test run.

The parameters recorded during the turning tests were battery voltage, current draw by the traction motors, left and right wheel speeds, and time. All data except time were intially collected from the transducers as voltage values and converted during processing to appropriate units. Time was measured and recorded internally by the controlling computer.

The parameters calculated for the turning tests were battery power drawn, battery energy consumed, calculated power required, and calculated energy required. Instantaneous battery power was calculated from the product of the instantaneous battery voltage and the instantaneous motor current. Average battery power was found by summing the instantaneous powers and dividing by the total number of instantaneous points collected. Average battery energy consumed per turn was found by multiplying the average battery power by the average time the power was drawn during a 90° turn. The calculated power and energy required during the turns were computed from the frictional force existing between the tires and the floor and the force required to accelerate the vehicle mass through a 90° turn.

Duration Tests

The objectives of the duration test were to determine the time Skidtric would perform a typical, repetitive cycle and to use the results of the test to estimate typical run times for the vehicle.

The routine used for the duration test (Appendix B-8) consisted of acceleration to full forward speed, constant velocity at full speed for approximately 30 meters, stopping the vehicle by plug braking, turning the vehicle 180°, and lifting and lowering the loader five times. This cycle was repeated until the battery DOD reached 80%. No load was carried in the loader bucket or towed by Skidtric and the battery was fully charged at the start of the test. The hydraulic motor ran continuously during the test because the on-demand hydraulic feature had not yet been installed on Skidtric.

The parameters monitored during the duration test were battery DOD (from specific gravity measurements) and time. The battery DOD, used as a measure of the useful energy remaining in the battery, was checked every half hour until 70% DOD was reached and every 15 minutes thereafter until it reached 80%. Time was recorded at the beginning and at the end of the test using the same clock. The difference between the times was considered to be the length of time that Skidtric operated. Periods of inactivity during operator changes and state-of-charge measurements were considered minor in relation to the length of time Skidtric operated and were not included in the results.

Model Check Test

The objectives of the model check test were to collect data from a precisely defined routine of skid-steer operations and use that data to calculate the energy requirements of Skidtric. The measured power and energy values resulting from this routine were used to check the accuracy of the individual prediction equations and the comprehensive model.

The routine used for the model check test consisted of the operational segments previously tested during the equation development tests. Segments were assigned and performed in an order that represented actual task use (Figure 11 and Appendix B-9). This routine was divided into two testing sections because the time required exceeded the 120 s DAS time limit. The bucket and draft loads, used for these tests were 1.869 kN and 2.0 kN, respectively. All data was gathered and processed in the same manner and by the same DAS as those used for the equation development vehicle tests. The model check run was replicated three times in the same segment order to minimize the effects of any random occurances during the tests.

Data collected during the model check tests were battery voltage, hydraulic motor current, traction motors current, apparent ground speed, true ground speed, draft, and time. The values of battery voltage and motor current for each segment were used to calculate the battery power that was then multiplied by the time to compute battery energy consumed for each operation segment. The segment energies were summed to determine the energy consumed for the entire routine. The routine was then entered into the prediction model and the resulting segment and routine energies were compared to the measured values to determine the accuracy of the prediction model output.

RESULTS AND DISCUSSION

Battery Tests

Initial battery tests indicated that Skidtric's battery characteristics did not vary significantly from those found by Thoreson, (1985), in his battery testing routine of EC-I's battery pack. Since the primary objectives of the Skidtric research project dealt with defining and quantifying vehicle performance rather than battery characteristics, only two general discharge and charge tests were performed. The purpose of these tests was to quantify the performance and capacity of the battery used on Skidtric, and compare the data obtained to the manufacturer's claims in order to establish a performance base. This performance base provided a comparison for the results of other battery tests so that changes in battery performance or capacity over time would be noted.

Discharge Tests

Two discharge tests were performed, the first in August 1985 and the second in May 1986. Approximately 30 battery charge/discharge cycles were obtained between the two tests.

Both tests were performed with the same equipment and at the six-hour discharge rate of approximately 53.3 A (Table 8).

Table 8. Six-hour battery discharge test results.

Test Date	Discharge current (A)	Battery capacity (Ah)	Battery dc energy (kWh)	Discharge Time (min)
August 1985	53.3	283.8	19.9	319.9
May 1986	53.3	305.5	21.4	344.5

The manufacturer claimed a battery capacity of 320 Ah at the five-hour discharge rate (Chloride, 1983). Electrolyte temperature rose approximately 3.5°C from 23.5°C to 27°C during the August, 1985 test and approximately 2.0°C from 28°C to 30°C during the May, 1986 test. These temperature increases were typical for lead-acid batteries.

Charge Tests

Two charge tests were also performed, each immediately following a discharge test. The objective of the charge tests was to collect data that allowed an overall battery efficiency statement to be made. The DAS and controlling program used for the discharge tests was also used to gather data for the battery charging tests and, again, recorded data every three minutes. However, the time required to recharge the batteries was significantly greater than the time required to discharge them and a memory overflow error resulted from the greater volume of data. This error caused data collection to be terminated before charge was completed and, consequently, the tôtal energy required to recharge the batteries was not recorded. Modification of the program so that data was collected every six minutes doubled the amount of time the DAS monitored the charge cycle. However, data from the longer charge cycle again exceeded the memory space available and data collection was terminated. Since only two battery discharge and charge tests had been planned and battery charge data was of secondary importance to this project, further battery testing was not performed. It is recommended, however, that complete battery tests be performed as part of Skidtric's continuing testing plans. In lieu of charge test results, daily charge records indicated that approximately 19 to 26 kWh ac were required to fully recharge Skidtric's batteries from 70% to 80% range of DOD.

Vehicle Tests

Data from the individual vehicle test segments were analyzed seperately and equations were developed that predicted the power required at various loads for each type of operation. To accomplish this, a hardcopy of the data was printed and the data points for each segment were identified. From the selected data, relationships were developed between the respective dependent and independent variables. These relationships were derived as equations that were subsequently used in a computer model to predict the energy required to complete a specified task or routine. All equations were first developed in terms of battery power, and the energy consumed was then computed by multiplying the power by the time for which the power was applied:

$$ENERGY = POWER * TIME$$

where: ENERGY = predicted battery energy consumed, (kWh)
POWER = predicted battery power required, (kW)
TIME = length of time power was required, (s)

Skidtric's battery power was calculated by multiplying the motor current drawn and the battery voltage:

$$BATPOWER = CURRENT * VOLTAGE / 1000$$

where: BATPOWER = battery power required, (kW)
CURRENT = motor current, (A)
VOLTAGE = battery voltage during current draw, (V)

Calculated power was found by multiplying the load force applied and the true speed at which the load was moved:

$$CALPOWER = FORCE * SPEED$$

where: CALPOWER = calculated power required, (kW)
FORCE = force resulting from load, (kN)
SPEED = rate of load movement, (m/s)

True ground speed was to be measured by the fifth wheel described in the instrumentation section of the test procedures. However, comparing the speeds recorded by the fifth wheel with the apparent ground speeds recorded by the speed sensors on Skidtric's driven wheels, it was found that the fifth wheel sensor produced speed readings in excess of the drive wheel sensors. This indicated that Skidtric was being pushed or pulled with its drive wheels sliding. Since this situation was not possible under the test conditions, it was reasoned that one of the speed sensing instruments was producing faulty readings. Both speed sensing systems were recalibrated but no change or error was found. Since the fifth wheel demonstrated the greatest variability in speed readings and the slip of Skidtric's drive wheels was low due to the weight of the vehicle, the asphalt track surface, and the speed travelled, it was assumed that the apparent ground speed recorded by the drive wheel sensors approximated true ground speed closely enough to be used for the calculated power derivations. It should be noted that calculated powers computed with the motor sensor speeds were slightly greater than the true values, since some slip must exist between the wheels and the track surface.

Loader Operation

The loader operation tests provided the data necessary to develop the relationship between bucket load and required power for the loader operations. These equations were used in a computer model to predict the energy required by Skidtric to perform specified tasks.

Six loads were used in data collection and analysis: zero kN (empty bucket), 1.51 kN, 3.48 kN, 4.166 kN, 6.036 kN, and 7.646 kN. Test runs at each load were replicated nine times for data collection, with three runs each made in ascending, descending, and ascending loading order to simplify the load handling requirements.

The power required for each of the seven lifts and lowers within each test was calculated and an average power value was computed. A regression equation for power required to raise the loader as a function of bucket load was obtained from the 54 average power values. Predicted battery energy was calculated by multiplying the predicted power by the time the power was applied. The data used to develop the equations assumed that the loader movement was from the fully lowered position to the fully raised position and back at the maximum possible rate of movement. The data collected during lifting and lowering operation testing are provided in Appendices C-1 and C-2, respectively.

The measured battery power required for lifting the loader ranged from 6.10 kW to 11.01 kW for the load range of zero kN to 7.646 kN. Current drawn by the hydraulic motor ranged from 87 A to 163 A, with an average current draw of 124 A. Lifting times ranged from 3.6 s to 4.8 s, with an average lifting time of 4.2 s. Power required, motor current drawn and lifting times increased as the magnitude of the bucket loads increased.

The battery power measured for lowering the loader ranged from 9.90 kW to 4.40 kW for the load range of zero kN to 7.646 kN. Current drawn by the hydraulic motor ranged from 127 A to 63 A, with an average current draw of 96 A. Lowering times ranged from 3.0 s to 4.3 s, with an average lowering time of 3.3 s. As the magnitude of the bucket load increased during the lowering tests, energy consumed and motor current drawn decreased, indicating that the bucket weights added energy to the system during the lowering segments, and that the powered requirement was assisted by the potential energy stored in the raised loader.

Seperate equations were developed for raising and lowering Skidtric's loader because the load raised during actual use was often partially or completely dumped off, leaving a different load value to be lowered. The lifting equation that resulted from the regression of bucket load versus battery power required was (Figure 11):

$$POWER_{LIFT} = LOAD * 0.49 + 6.70$$

where: $POWER_{LIFT}$ = battery power required by Skidtric to lift LOAD, (kW)
LOAD = bucket load lifted, (kN)
R^2 = 0.86

This equation indicated that the minimum power required to raise the loader was 6.70 kW and that the power required increased by 0.49 kW for every kN increase in bucket load. The regression equation for bucket load versus lowering power consumed was (Figure 12):

$$POWER_{LOWER} = 8.16 - LOAD * 0.38$$

where: $POWER_{LOWER}$ = battery power required by Skidtric to lower LOAD, (kW)
LOAD = bucket load lowered, (kN)
R^2 = 0.72

This equation indicated that the maximum power required to lower the loader was 8.16 kW and that the required power decreased by 0.38 kW for every kN increase in bucket load.

For the lifting segments, a significant relationship was found between TIME and LOAD. The following equation resulted from a regression of TIME versus LOAD and was used to predict the required lifting time as a function of the

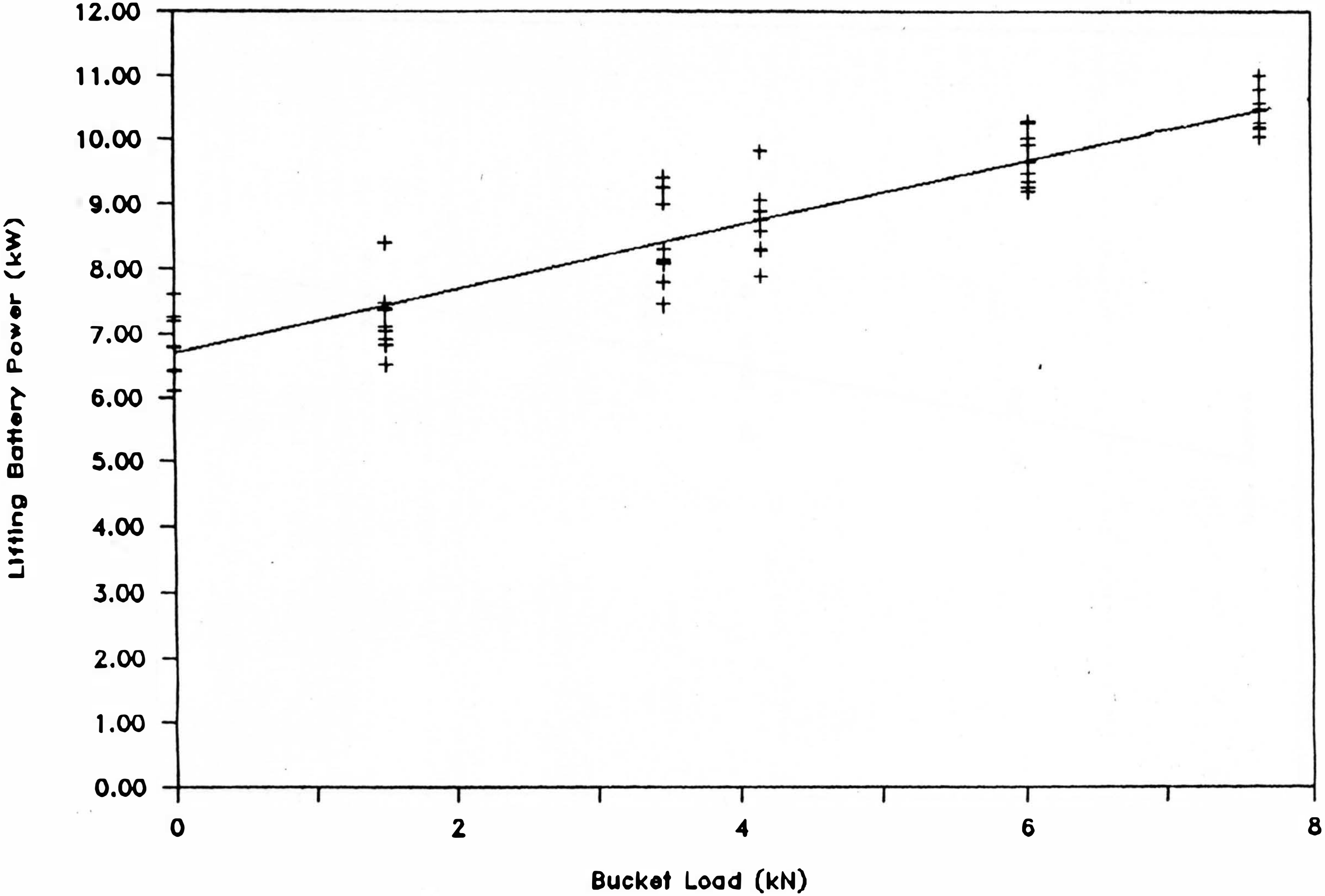


Figure 11. Lifting battery power vs. bucket load

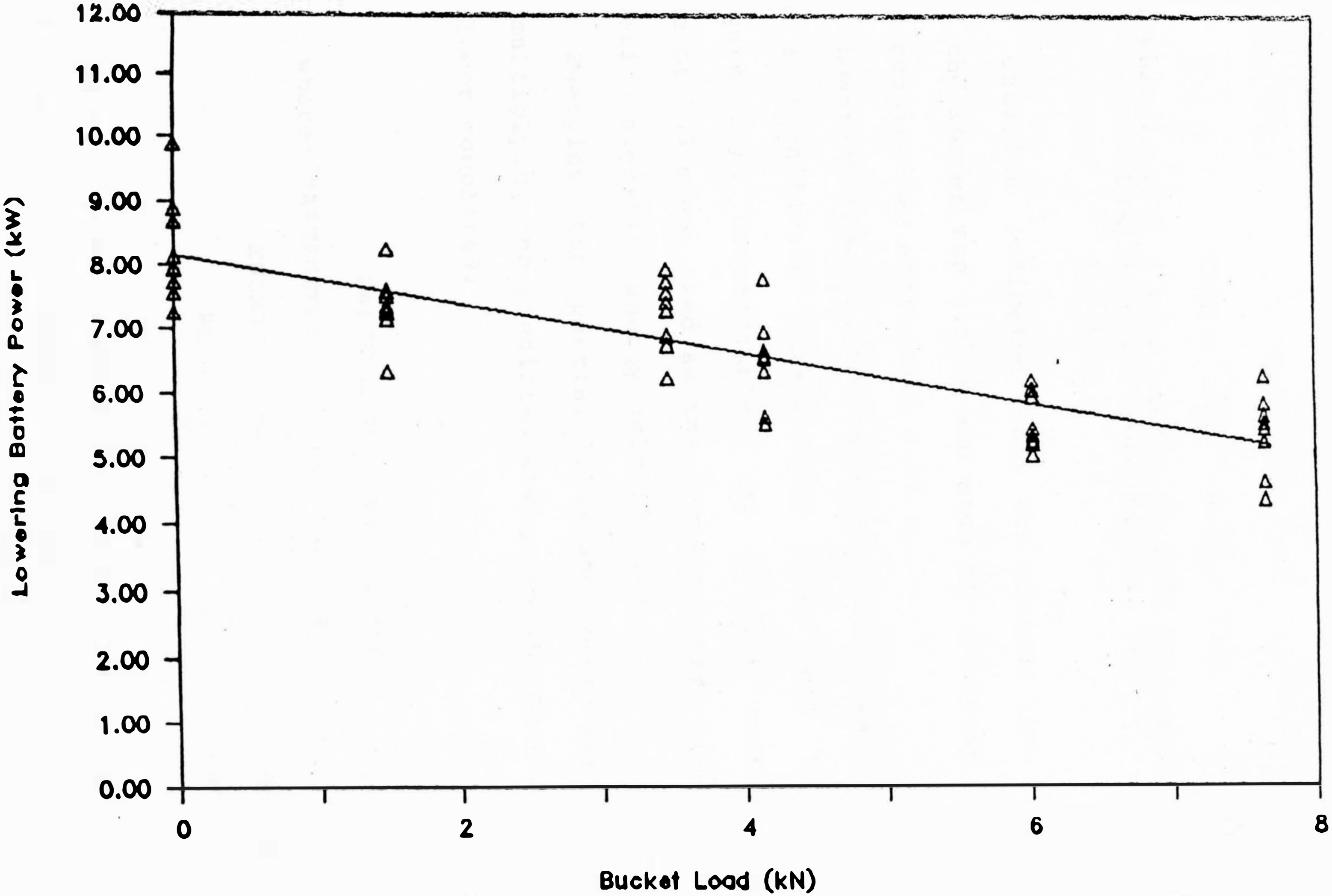


Figure 12. Lowering battery power vs. bucket load

load lifted (Figure 13):

$$TIME = LOAD * 0.11 + 3.81$$

where: TIME = time needed to lift LOAD one time, (s)
LOAD = bucket load lifted, (kN)
R^2 = 0.86

This equation indicated that the minimum time required to lift the loader was 3.81 s and each kN increase in bucket load required an additional 0.11 s.

Lowering times varied so widely within each bucket load that a significant relationship could not be developed (Figure 14). Consequently, the overall average lowering time of 3.3 s was used as the representative time value for lowering operation energy calculations.

Energies for partial lifts and lowers were calculated by multiplying the predicted energy by the percent of lift or lower completed:

$$PARTENERGY = ENERGY * PL$$

where: PARTENERGY = energy required for partial lift or lower, (kWh)
ENERGY = energy required for complete lift or lower, (kWh)
PL = portion of lift or lower completed, (decimal)

Battery power applied, calculated power required, and efficiency values averaged across the nine replications along with the predicted power from the previous lifting and

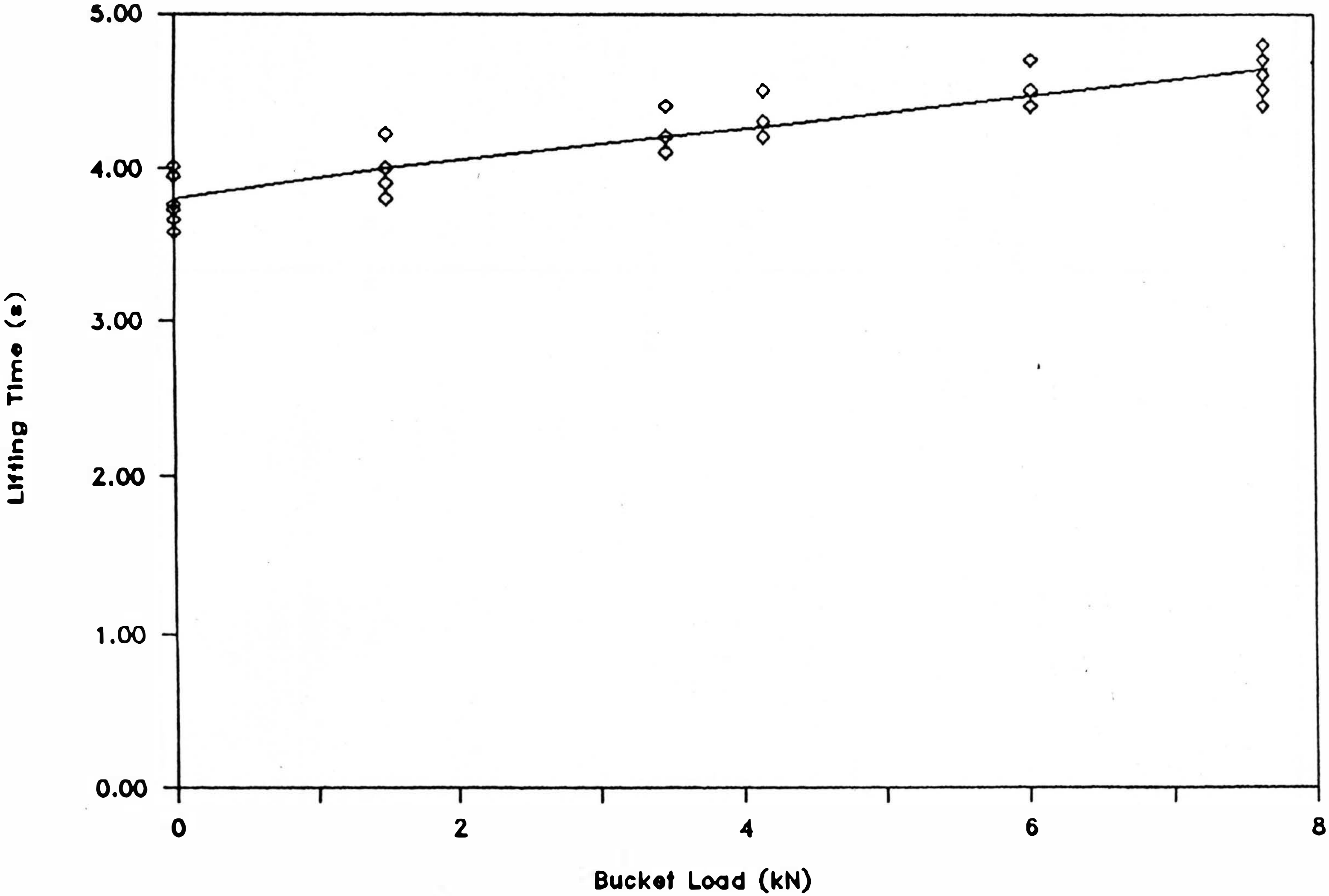


Figure 13. Lifting time vs. bucket load

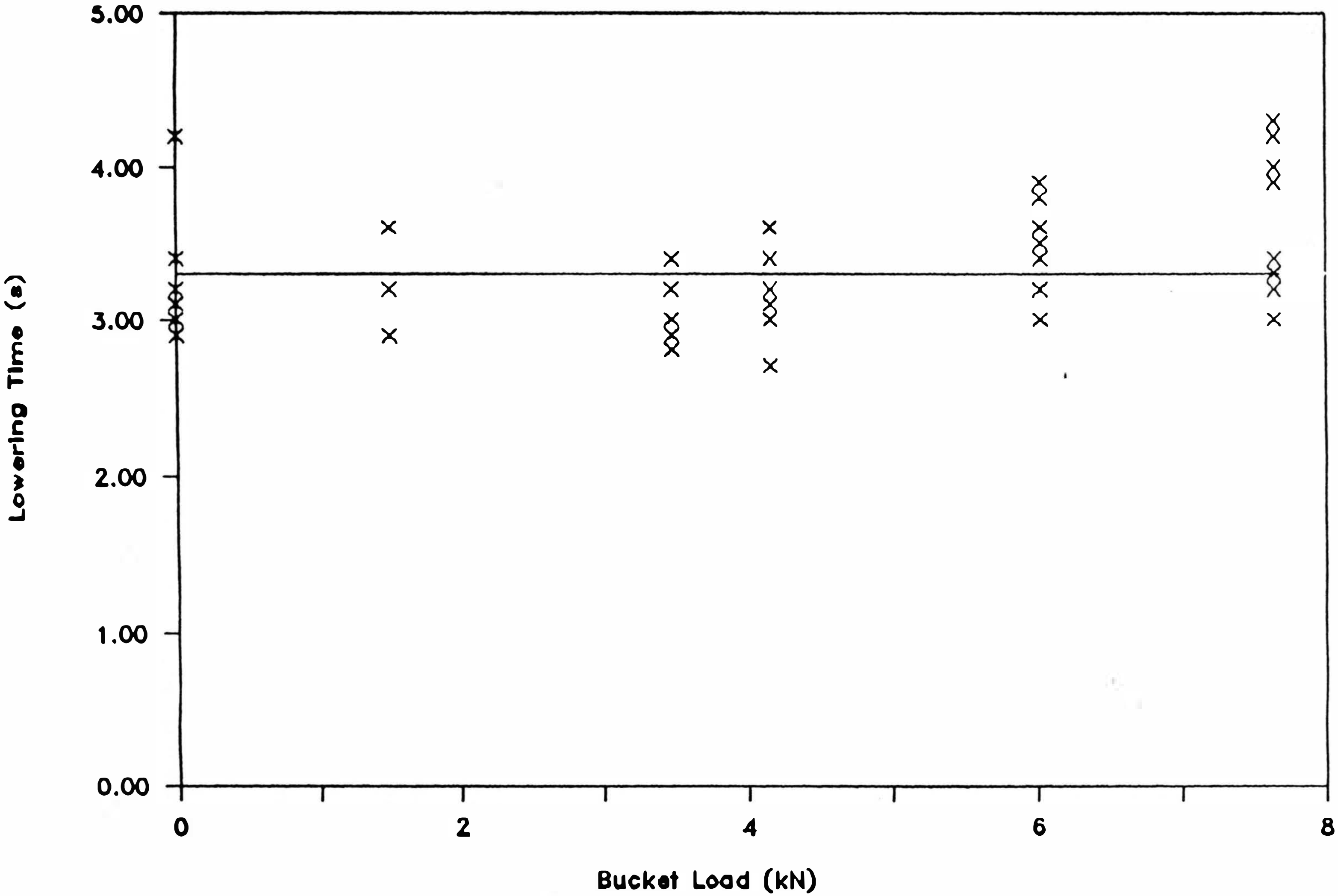


Figure 14. Lowering time vs. bucket load

lowering equations for each of the loads are provided in Table 9.

Table 9. Averaged loader operation test results.

Average				Predicted power (kW)
Load (kN)	Battery power (kW)	Calculated[1] power (kW)	Efficiency[2] (%)	
Lifting:				
0.00	6.87	1.85	26	6.70
1.51	7.23	2.74	37	7.44
3.48	8.38	3.74	44	8.70
4.166	8.73	4.06	46	8.73
6.036	9.71	4.91	50	9.65
7.646	10.43	5.65	54	10.43
Lowering:				
0.00	8.23	-[3]	-	8.16
1.51	7.37	-	-	7.58
3.48	7.20	-	-	6.83
4.166	6.53	-	-	6.57
6.036	5.56	-	-	5.86
7.646	5.43	-	-	5.24

[1]

$$\text{Calculated power} = \frac{\text{Load force} * \text{lifted distance}}{\text{Time of lift}}$$

Calculated power included the weight of the loader bucket and loader arms. These were not included as load values in the regression analysis.

[2]

$$\text{Efficiency} = \frac{[\text{Calculated power}]}{\text{Battery power}} * 100\%$$

[3] Calculated energies and efficiencies were not computed for the hydraulic lowering tests because the energy input from the battery to the system was used solely to overcome friction and line restrictions within the hydraulic system. Lowering the bucket loads released the potential energy stored in the raised loader and weight.

Bucket Operation

Dump-off and tilt-back loader operations were also tested. However, safety concerns regarding the effective securing of larger loads to the bucket prevented complete testing and data collection. This resulted in an incomplete set of data in terms of equation development. Consequently, the average values of the energy data that had been collected for dumping and tilting the bucket, 2.0 Wh and 4.7 Wh, respectively, were used as estimates of energy consumed by the dump-off and tilt-back functions (Table 10).

Table 10. Averaged bucket operation test results.

Load[1] (kN)	Average: Battery energy (Wh)	Average: Calculated[2] energy (Wh)	Average: Efficiency[3] (%)	Predicted energy (Wh)
Dump-off:				
0.00	2.0	-[4]	-	2.0
1.51	1.8	-	-	2.0
3.48	2.3	-	-	2.0
Averages	2.0	-	-	2.0
Tilt-back:				
0.00	4.6	0.4	9	4.7
1.51	4.3	0.6	19	4.7
3.48	5.2	1.3	25	4.7
Averages	4.7	0.9	18	4.7

[1]Loads larger than 3.48 kN were not tested.

[2]
$$\text{Calculated power} = \frac{\text{Load force} * \text{lifted distance}}{\text{Time of dump/tilt}}$$

Bucket weight was included in calculated power, but was not used in the prediction equation development.

[3]
$$\text{Efficiency} = \frac{[\text{Calculated power}]}{\text{Battery power}} * 100\%$$

[4]Calculated energies and efficiencies were not computed for the dump-off tests because the energy input from the battery to the system was used solely to overcome friction and line restrictions within the hydraulic system. Lowering the bucket loads released the potential energy stored in the raised bucket and weight.

Constant Velocity Draft Operation

The constant velocity draft tests provided the data necessary to develop a relationship between draft, speed, and the battery power required for draft operations. This equation was used in a computer model to predict the energy required by Skidtric to perform specified tasks.

Four travel velocities and four draft loads were used for the constant velocity draft tests. The representative target velocities were arbitrarily selected as 0.5 m/s, 1.0 m/s, 2.0 m/s and 3.0 m/s. During testing, steady operation at each of these velocities across the entire length of the test course was desired. However, maintaining the exact desired velocity throughout the test run was extremely difficult because of operator adjustments, instrument error, and changes in track conditions. The total range of actual travel speeds tested covered from 0.5 m/s to 3.3 m/s.

The draft loads were provided by three load vehicles towed in neutral and Skidtric's rolling resistance. The magnitudes of each of the draft loads varied slightly with changes in the speed travelled. The total draft range was from zero kN to 5.7 kN, but could not be assigned exact, constant values. Skidtric's rolling resistance was measured over the range of test speeds and an overall average resistance value of 1.66 kN with a standard deviation of 0.446 was determined. The measured draft value, plus the average rolling resistance, represented the true value of draft that Skidtric had to overcome during draft operations. The draft load thus ranged from 1.66 kN to 7.4 kN with Skidtric's rolling resistance included.

Each combination of draft load and travel velocity was replicated three times providing a total of 48 data collection runs. Target velocities were randomly assigned, but each draft load was used consecutively until all tests for that load were completed. The data collected during the constant velocity draft tests are listed in Appendix C-3.

Instantaneous values of battery power, calculated power, draft, and speed were computed for each replication and the average of the instantaneous values was found for each run. The average values of battery power, draft, and speed from each of the 48 test runs were used in a multiple regression analysis to develop the equation for battery power as a function of draft and speed. The resulting equation was:

CONVELPOW = DRAFT * 2.71 + SPEED * 3.16 - 6.89

where: CONVELPOW = battery power required to move Skidtric in straight line motion with a specified load and specified speed, (kW)
DRAFT = applied towing load, including rolling resistance, (kN)
SPEED = travel velocity of Skidtric, (m/s)
R^2 = 0.92

This equation indicated that battery power required increased 2.71 kW for each kN increase in draft load and increased 3.16 kW for each m/s increase in ground speed.

The times for the constant velocity draft tests depended on the distance and speed travelled and could not be predicted as functions of the draft load. Therefore, the time of constant velocity operation was either directly known or was computed by dividing the distance travelled by the ground speed:

TIME = DISTANCE / SPEED

where: TIME = time of constant velocity operation, (s)
DISTANCE = distance travelled during constant veloctiy operation, (m)
SPEED = veloctiy travelled, (m/s)

Calculated power was divided by the respective battery power to compute energy efficiency for the draft operation. It was reasoned that the calculation of energy efficiency from power data was justified because both calculated and battey power would be multiplied by the same time value to determine the amount of energy used. Battery and calculated power requirements ranged from 1.96 kW to 23.04 kW, and from 1.11 kW to 18.21 kW, respectively. The current drawn by the traction motors ranged from 29 A to 356 A, depending on the draft and speed levels chosen. The values of battery power, calculated power, draft, and speed, averaged over the replications, along with efficiency and predicted are listed in Table 11.

Table 11. Averaged constant velocity draft test results.

Average					Predicted power (kW)
Draft (kN)	Speed (m/s)	Battery power (kW)	Calculated power (kW)	Efficiency[2] (%)	
1.660	0.8	2.07	1.32	64	0.12
1.660	1.1	2.49	1.74	70	0.94
1.660	2.0	3.94	3.29	84	3.89
1.660	3.0	5.53	4.96	90	7.07
2.530	0.6	2.50	1.51	60	1.85
2.471	1.0	3.35	2.56	76	3.09
2.560	2.0	5.46	5.02	92	6.25
2.558	3.0	7.93	7.68	97	9.54
3.269	0.6	3.81	1.88	49	3.80
3.645	1.1	6.70	4.09	61	6.55
4.152	1.9	11.31	8.06	71	10.53
4.705	2.8	17.22	13.11	76	14.70
5.716	0.7	7.53	4.05	54	10.86
6.000	1.1	10.29	6.72	65	12.94
6.852	2.1	19.53	14.61	75	18.46
7.267	2.4	22.66	17.73	78	20.56

1 Calculated power = Draft Force * Travel velocity

2 Efficiency = [Calculated power] / Battery power * 100%

The efficiencies determined indicated that Skidtric operated most efficiently at higher speeds with low draft loads. Efficiency dropped as load increased and speed decreased.

Acceleration Draft Operation

The acceleration draft tests provided the data necessary to develop a relationship between Skidtric's draft load and the battery power required for acceleration. This equation was used in a computer model to predict Skidtric's energy requirement for a specified task.

The four draft loads used for the constant velocity draft tests were also used for the acceleration draft tests. Acceleration tests were replicated three times for each of the four draft loads used and each load was used continuously until all tests for that load had been completed. The data collected during the acceleration tests are listed in Appendix C-4.

The draft loads were measured continuously during the accelerations and were found to reach their maximum values at the beginning of each acceleration and then decrease as vehicle speed increased (Figure 15). Typical measured draft values for the three applied loads during the acceleration runs ranged from two kN to 13 kN for the largest draft load,

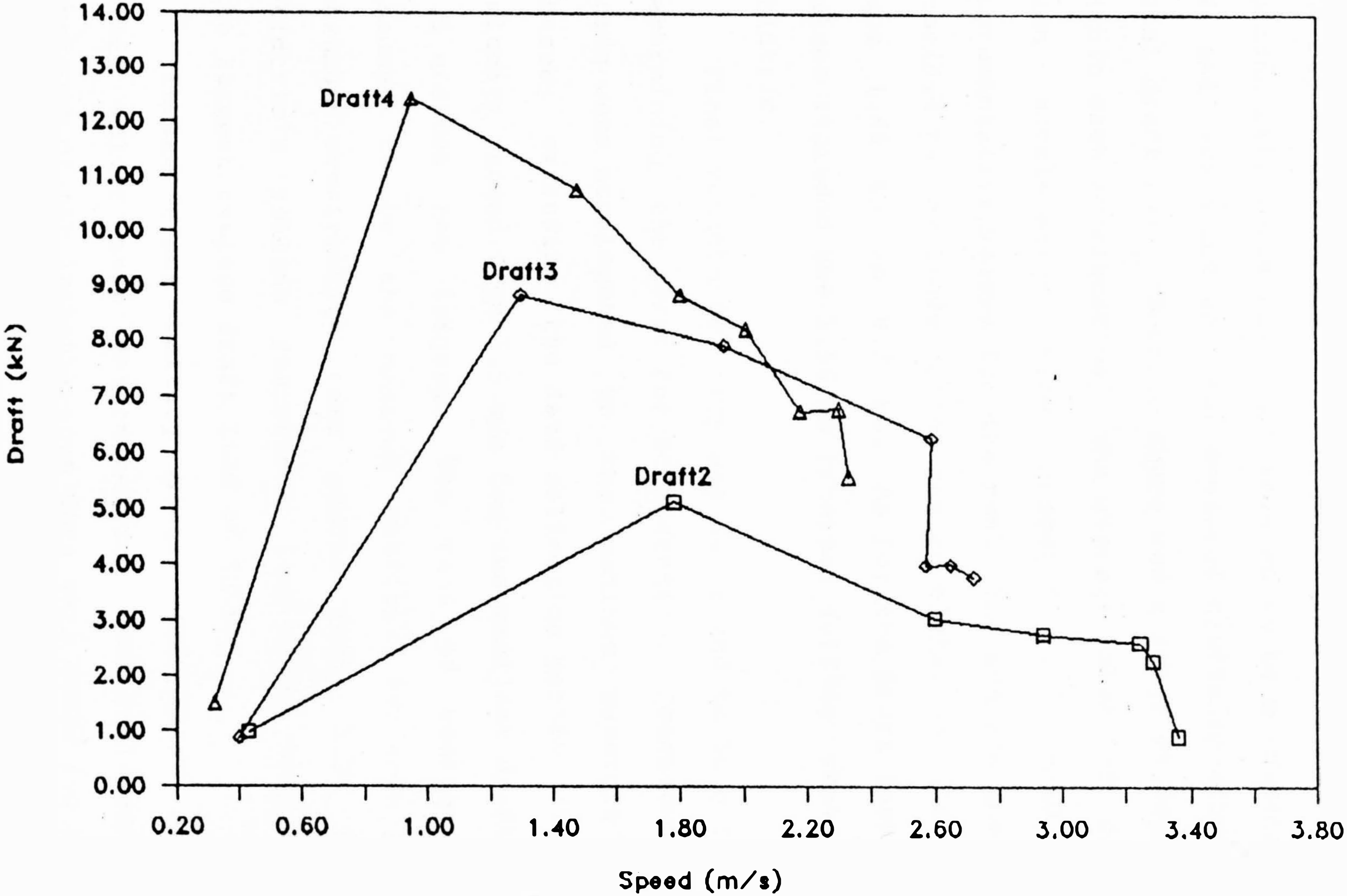


Figure 15. Change in draft load vs. change in speed

and one kN to four kN for the smallest. Skidtric's internal rolling resistance was again assumed to be a constant 1.66 kN and was added to these measured drafts to determine the total draft load. Because there was a range of draft values within each acceleration, the average values of draft for each acceleration wėre computed and used as the representative values for the run. The average draft values provided by the loads during the acceleration tests ranged from 1.66 kN to 9.7 kN. As for the draft tests, these values included the 1.66 kN internal rolling resistance of Skidtric.

Final vehicle velocity was not found to be a factor in determining the power for acceleration. Consequently, all loads were accelerated to the maximum possible velocity thereby extending the data collection period. The maximum velocity ranged from 3.5 m/s for the smallest draft load, to 2.5 m/s for the largest. The rate of acceleration was assumed to be the maximum possible for each load. The maximum acceleration rate ranged from 1.5 m/s^2 for Skidtric's rolling resistance load alone, to 0.3 m/s^2 with the largest average draft load of 13 kN.

Instantaneous battery power, calculated power, and draft values were determined for each replication and the averages of the instantaneous data were found for each test run. The averages of the battery and calculated powers ranged from 14.21 kW to 26.06 kW, and 4.66 kW to 15.57 kW, respectively. The average values of battery power and draft from each replication were used in a regression analysis to develop the following equation to compute battery power as a function of average draft (Figure 16):

$$ACCPOW = DRAFT * 1.45 + 11.60$$

where: ACCPOW = battery power required to accelerate Skidtric for a given load, (kW)
DRAFT = load pulled or pushed, (kN)
R^2 = 0.98

This equation indicated that a minimum of 11.60 kW was required to accelerate Skidtric and that the required power increased 1.45 kW for each kN increase in average draft load.

A regression equation of acceleration rate against average draft load was obtained (Figure 17):

$$ACCEL = 0.81 - DRAFT * 0.062$$

where: ACCEL = Skidtric's predicted acceleration rate with draft LOAD, (m/s^2)
DRAFT = draft value applied during acceleration (kN)
R^2 = 0.93

This equation indicated that Skidtric's maximum acceleration rate was 0.81 m/s^2 and that this rate decreased 0.062 m/s^2 for each kN increase in average draft load. The draft load

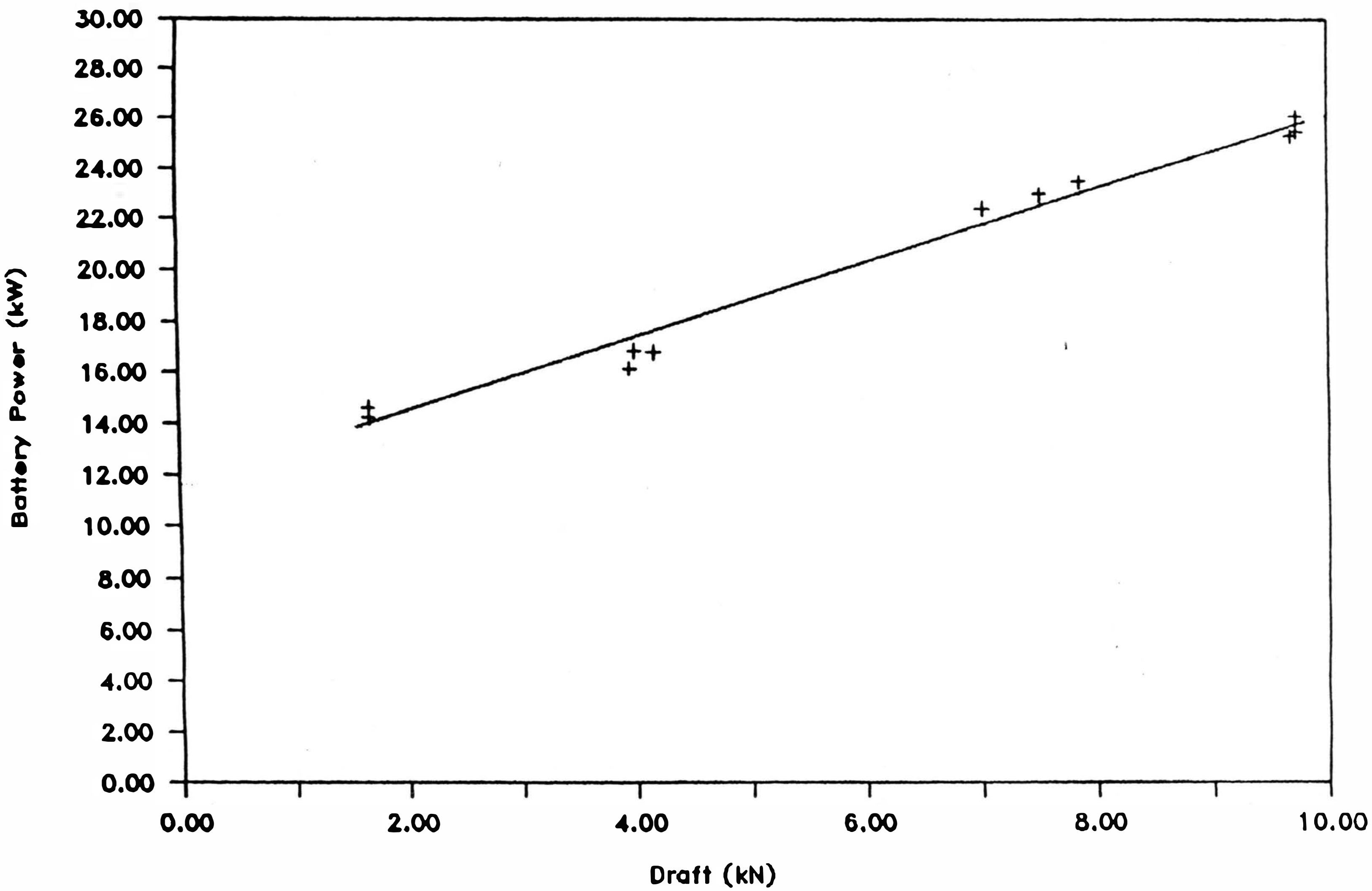


Figure 16. Battery power vs. average draft for acceleration

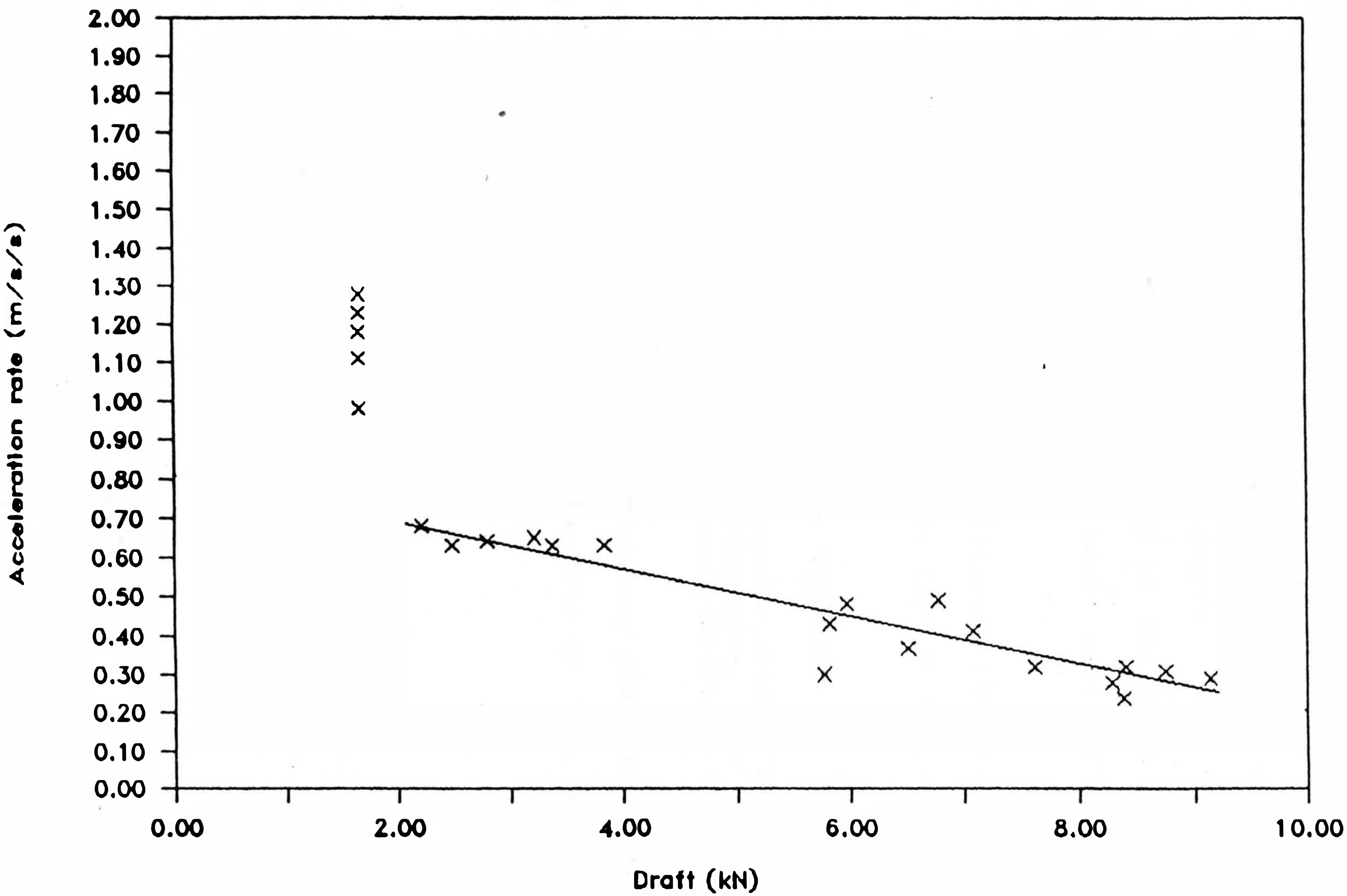


Figure 17. Acceleration rate vs. average draft load

values included Skidtric's rolling resistance. As can be seen from the graph (Figure 17), the acceleration rates corresponding to the rolling resistance value of 1.66 kN were inconsistent with the trend of the other data points. It was, therefore, decided to omit this data from the regression analysis.

The predicted acceleration rate was then divided by the desired final velocity to find the time of the acceleration:

$$TIME = ACCEL \ / \ VELOCITY$$

where: TIME = time of acceleration, (s)
ACCEL = acceleration rate, (m/s^2)
VELOCITY = final travel velocity, (m/s)

This time was multiplied by the battery power to compute the battery energy used. Averaged results of the acceleration tests are given below (Table 12).

Table 12. Averaged acceleration draft test results.

Average				Predicted power (kW)
Draft (kN)	Battery power (kW)	Calculated[1] power (kW)	Efficiency[2] (%)	
1.66	14.48	4.69[3]	32	14.01
4.0	16.60	10.01	60	17.47
7.5	22.96	14.11	61	22.45
9.7	25.60	14.93	58	25.71

[1] Calculated power = Draft Force * Travel velocity

[2] Efficiency = [Calculated power] / Battery power * 100%

[3] Calculated with 1.66 kN assumed to be the average rolling resistance.

Turning Operation

The turn tests provided the data necessary to develop a relationship between bucket load and turning power. This equation was used in a computer model to predict the energy requirements of Skidtric. The turn test results also showed that Skidtric's turning operation was the most energy intensive operation segment and the one with the poorest vehicle performance in terms of ability to complete the required task.

The six bucket loads used for the loader operation tests were also used as the loads for the turn tests. The values of these loads were zero kN (empty bucket), 1.51 kN, 3.48 kN, 4.166 kN, 6.036 kN, and 7.646 kN. A 30-second test length was selected and each load was replicated three times in ascending loading order. The data collected during the turning tests are listed in Appendix C-5.

Ninety degree turns were used as the standard turn unit because they were easily measured and repeated, and minimized vehicle momentum during turning. Each replication contained up to eight, 90° turns, depending on the bucket load carried and Skidtric's effective rate of turn. With a bucket load of 7.646 kN, Skidtric was unable to complete a 90° turn during any of the three, 30-second test replications. In these cases, power was applied throughout the entire test until time expired, and the total angle turned through was measured, recorded, and used to calculate the rate of turn. Battery power was computed and recorded as usual for these runs.

Instantaneous battery power was calculated for each 90° turn and an average power was found for each replication. The following regression equation, predicting battery power consumed as a function of load carried in the bucket, was derived (Figure 18):

$$\text{TURNPOW} = \text{LOAD}^3 * 0.054 - \text{LOAD}^2 * 0.76 + \text{LOAD} * 3.04 + 21.72$$

where: TURNPOW = battery power required to turn Skidtric carrying LOAD, (kW)
LOAD = bucket load carried by Skidtric, (kN)
R^2 = 0.57

This equation indicated that a minimum of 21.72 kW was

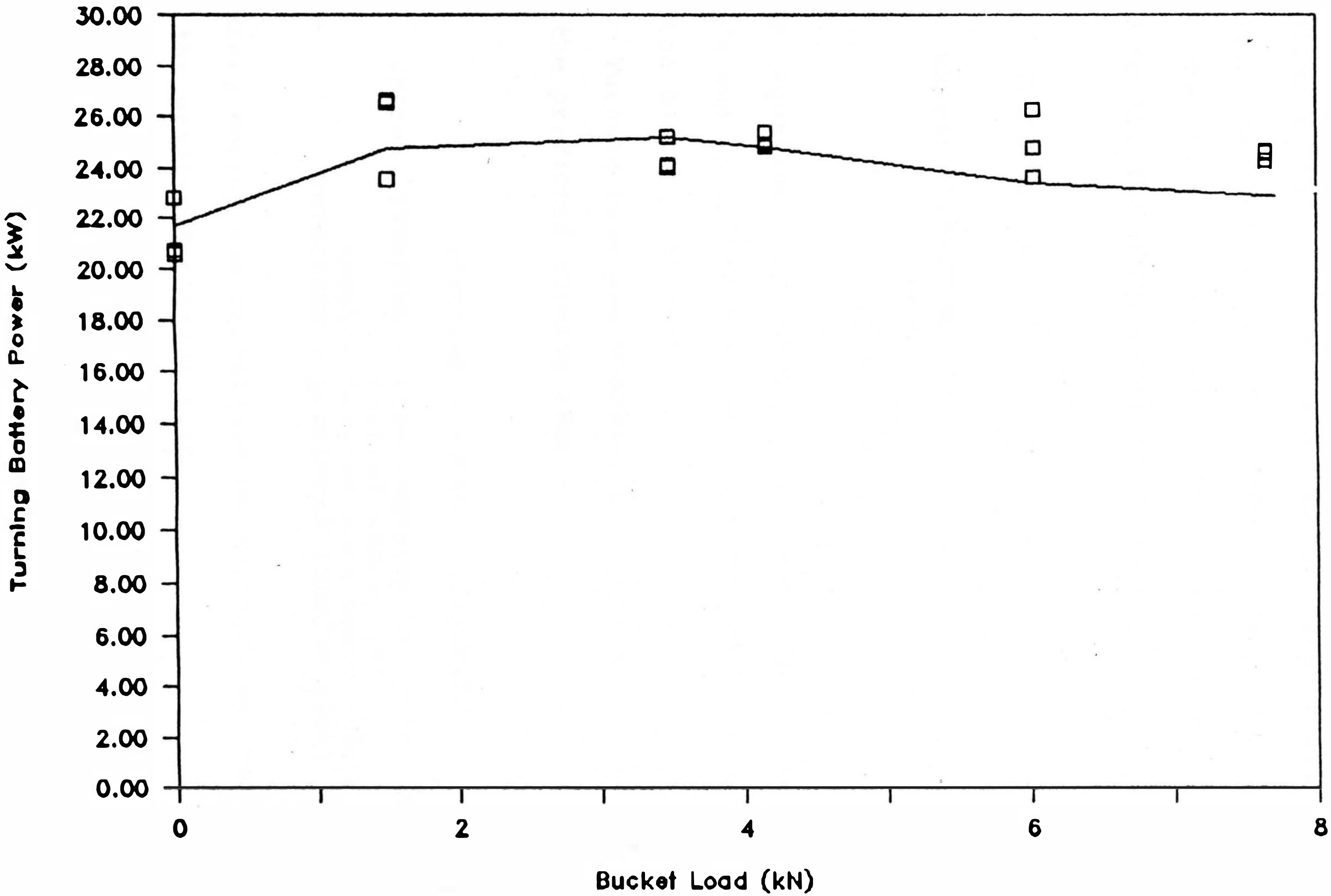


Figure 18. Battery power vs. bucket load for turning

required to turn Skidtric and that turning power increased or decreased according to the bucket load carried.

The turning rate was predicted as a function of bucket load by the following equation (Figure 19):

$$TURNSPEED = 94.62 - LOAD * 73.86 + LOAD^2 * 19.36 - LOAD^3 * 1.47$$

where: TURNSPEED = turning rate, (deg/s)
LOAD = bucket load carried through turn, (kN)
$R^2 = 0.96$

This equation predicted a maximum turning rate of 94.62 deg/s and indicated that the turning rate varied according to the bucket load carried.

Turning time was computed by dividing the angle turned by the predicted turning rate:

$$TURNTIME = ANGLE / TURNSPEED$$

where: TURNTIME = time required to turn through the desired angle, (s)
ANGLE = desired turn angle, (deg)
TURNSPEED = predicted rate of turn, (deg/s)

Battery energy was calculated by multiplying battery power by the predicted turning time.

Battery power required for turning Skidtric ranged from 20.60 kW to 26.64 kW, with an overall average of 24.32 kW. Calculated power ranged from 0.54 kW to 45.69 kW, with an overall average value of 12.56 kW. The calculated power

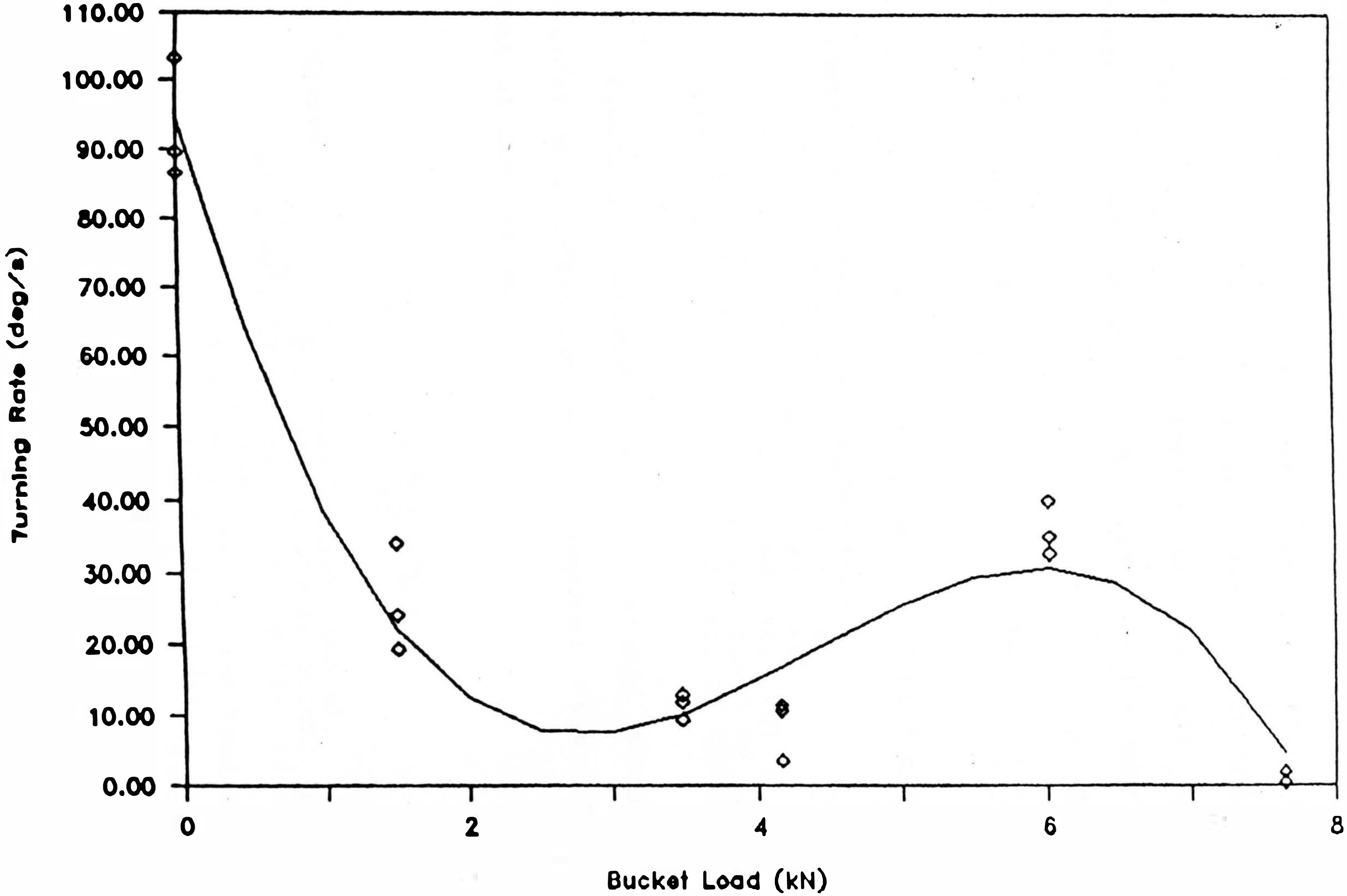


Figure 19. Turn rate vs. bucket load

calculations were based on the torques resulting from the sliding friction between the tires and the floor, and from accelerating the total vehicle mass through the angle of turn. The coefficient of friction between the tires and concrete floor was assumed to be 0.71, (Baumeister, 1978), and the bucket load carried was included in Skidtric's weight. Friction torque was calculated as:

$$T_f = 0.71 * (LOAD + 28) * (0.5 * PI * r_a)$$

where: T_f = friction torque, (kN-m)
0.71 = coefficient of friction
LOAD = bucket load carried, (kN)
28 = Skidtric's empty weight, (kN)
r_a = average radius of arc moved by tires, (m)
$0.5*PI*r_a$ = circumference of 90^o arc of radius r_a, (m)

This equation assumed that all wheels moved through identical arcs. Mass torque was computed using Skidtric's moment of inertia as:

$$T_m = \frac{m * (l^2 + w^2) * a}{12}$$

where: T_m = mass torque, (kN-m)
a = angular acceleration, (rad/s^2)
$m*(l^2+w^2)/12$ = moment of inertia of rectangular prism
m = total vehicle and load mass, $\frac{(LOAD + 28(kN))}{9.81 \ m/s^2}$ (metric ton)
l = vehicle length, (m)
w = vehicle width, (m)

Calculated power was calculated as:

$$CALPOW = ANGVEL * (T_f + T_m)$$

where: CALPOW = calculated calculated power required by Skidtric to turn due to friction and accelerating mass, (kW)
ANGVEL = angular turning veloctiy, (rad/s)

The values computed in determining calculated power for turning as well as the angular acceleration for each load are listed below (Table 13).

Table 13. Calculated power data for turning operation.

Load (kN)	Angular accel. [rad/s^2]	Torque Fric. (kN-m)	Torque Mass (kN-m)	Power (kW)	Ratio Fric./Total	Ratio Mass/Total
0	3.3	16.7	11.5	45.69	0.59	0.41
1.51	0.2	17.6	0.9	8.37	0.95	0.49
3.48	0.04	18.7	0.2	3.75	0.99	0.01
4.166	0.03	19.1	0.1	2.88	0.99	0.01
6.036	0.5	20.2	2.1	14.11	0.91	0.09
7.646	8.4×10^{-4}	21.2	0.0037	0.54	1.00	0.00

Vehicle weight and mass were assumed to be uniformly distributed over Skidtric's length and width for these calculations. The variation of the angular velocity and the necessary approximations during the calculations introduced significant uncertainty into the computed results. The large acceleration for the zero kN load resulted in a large mass torque and power. Larger loads increased Skidtric's resistance to turn and decreased both the angular velocity and angular acceleration. This resulted in the lesser values for calculated power at the heavier loads. The last two columns of Table 13 list the percentage of power required by the friction resistance and the mass acceleration, respectively. The average battery power, calculated power, efficiency, predicted battery power, and turn rate for each test load are listed in Table 14.

Table 14. Averaged turning operation test results.

Average					Predicted power (kW)
Load (kN)	Turn rate (deg/s)	Battery power (kW)	Calculated[1] power (kW)	Efficiency[2] (%)	
0.00	93.1	21.44	45.69	213[3]	21.72
1.51	26.0	25.57	8.37	33	24.76
3.48	11.4	24.48	3.75	15	25.37
4.166	8.6	25.05	2.88	12	25.10
6.036	36.2	24.89	14.11	57	24.27
7.646	1.5	24.52	0.54	2	24.74

[1]Calculated power was calculated as the power required to overcome friction between Skidtric's tires and the floor and move the vehicle and load mass at the listed rate of turn.

[2]
$$\text{Efficiency} = \left[\frac{\text{Calculated power}}{\text{Battery power}}\right] * 100\%$$

[3]Efficiencies greater than 100% indicate that output power or energy for the system was greater than the input power or energy. This violates the First Law of Thermodynamics.

Overall energy efficiency using these values was 52%. Current drawn by the traction motors during the turning tests ranged from 343 A to 479 A with an overall average current of 435 A. Rates of turn ranged from 0.49

degrees/second (deg/s) to 103.2 deg/s with an overall average turn rate of 29.4 deg/s.

Skidtric's ability to skid (turn) was highly dependent on the vehicle's weight distribution (front to rear) on the wheels (Figure 20). When no bucket load was carried, the majority of Skidtric's weight rested on the rear wheels allowing the front wheels to skid. As the bucket loads were applied and increased, Skidtric's weight distribution became more evenly distributed causing both sets of wheels to skid, and consequently, the skidding resistance was increased. Loads over six kN reversed the weight distribution, allowing the back wheels to skid. Eventually, however, larger loads increased total vehicle weight to the point that turning became difficult simply because of the added weight.

Duration Operation

The duration test provided data related to the length of time Skidtric would operate continuously performing a specified routine. This data was used to develop an estimate of the longest time that Skidtric would run under light duty use. This estimate was used mainly for publicity and promotion purposes, rather than as a scientific vehicle desciption parameter.

The duration test routine was composed of acceleration

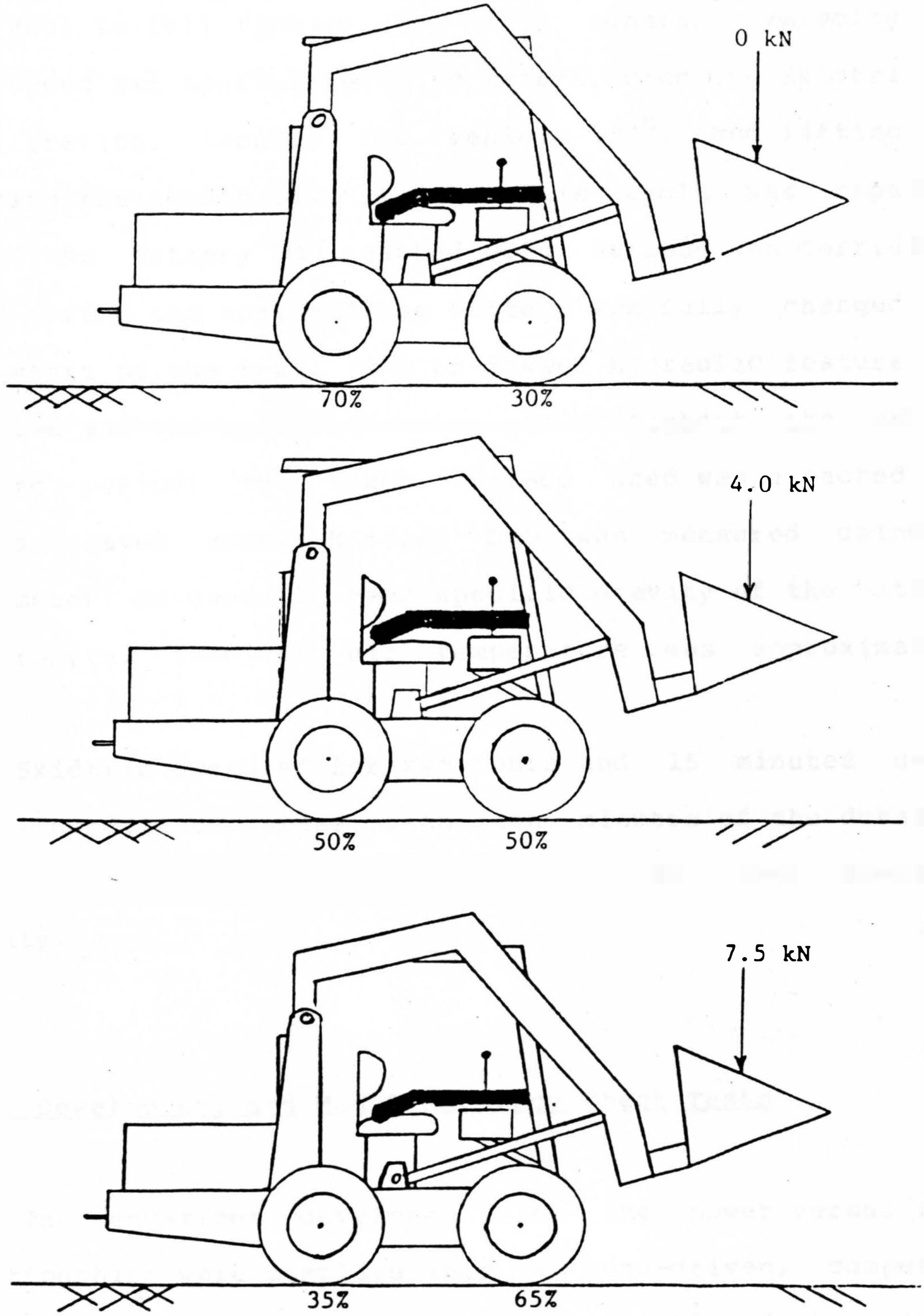


Figure 20. Skidtric's change of weight distribution with change in bucket load

from rest to full forward velocity, constant velocity at full speed for approximately 30 meters, stopping Skidtric by plug braking, turning the vehicle 180°, and lifting and lowering the loader five times. This cycle was repeated until the battery DOD reached 80%. No load was carried or towed during the test and the battery was fully charged at the start of the test. The on-demand hydraulic feature was not used and the hydraulic motor ran throughout the entire testing period. The track surface used was a packed and graded gravel road. Battery DOD was measured using a hydrometer to manually read specific gravity of the battery electrolyte. Ambient air temperature was approximately 24°C.

Skidtric operated for two hours and 15 minutes under these conditions. Less than ten minutes of the duration test time were used to change operators and check specific gravity.

<u>Model Development and Model Accuracy Check Tests</u>

The equations developed from the power versus load relationships were complied into a menu-driven, computer-based, energy prediction model that allowed the user to select any operation segment and specifiy the applied load and other controlling factors as needed to simulate the desired task routine. Operation segments could be entered from a menu in any order and the values for each segment were computed by seperate subroutines that used the appropriate equation(s) and controlling factors. Any number of operation segments could be used in the routine and the total number used depended solely on the amount of available energy remaining in the battery.

Output from the model was presented in tabular form and included the segment names, applied load (draft or bucket), travel speed (forward or turning), angle turned, segment energy used, cumulative energy used, and energy remaining in the battery. At the end of the routine, the model computed and printed the total running time used by the routine, the predicted running time remaining for this routine based on the remaining battery energy, and the total running time predicted for the routine with Skidtric's battery fully charged. A sample model output is provided in Table 15 and the complete prediction program is listed in Appendix D.

The accuracy of the prediction model was checked by performing a simple routine and measuring the battery power required and energy used, then entering the same routine into the model and computing the predicted values of power and energy (Tables 16-18). The test routine used for the model check was a varied cycle that included all operation

Table 15. Sample output from prediction model.

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	3.0	1.0	0.0	1.9	2.3	18.4	9.7	10.1	21990
ConVel	3.0	1.0	0.0	5.0	7.3	8.9	12.4	22.5	21978
Tiltba	2.0	0.0	0.0	0.5	7.8	6.9	0.9	23.4	21977
Accel	0.0	2.0	0.0	2.8	10.6	14.0	10.9	34.3	21966
ConVel	0.0	2.0	0.0	3.0	13.6	3.9	3.3	37.6	21962
Turn	2.0	12.6	90.0	7.2	20.8	25.2	50.1	87.8	21912
Raise	2.0	0.0	0.0	3.8	24.6	6.7	7.1	94.8	21905
Accel	0.0	0.5	0.0	0.7	25.3	14.0	2.7	97.6	21902
Dump	2.0	0.0	0.0	2.0	27.3	3.7	2.0	99.6	21900
Tiltba	0.0	0.0	0.0	2.5	29.8	6.9	4.7	104.3	21896
Accel	0.0	0.5	0.0	0.7	30.5	14.0	2.7	107.1	21893
Turn	0.0	94.6	90.0	1.0	31.4	21.7	5.7	112.8	21887

Total running time used (hrs): 0.009
Total predicted running time remaining (hrs): 1.7
  Realistic time (119% predicted): 1.5
Total running time predicted for this cycle (hrs): 1.7
  Realistic time (119% predicted): 1.5

Table 16. Prediction model output for model check run 1.

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Raise	1.9	0.0	0.0	4.0	4.0	7.6	8.5	8.5	21992
Lower	1.9	0.0	0.0	3.3	7.3	7.4	6.8	15.3	21985
Raise	1.9	0.0	0.0	4.0	11.3	7.6	8.5	23.8	21976
Lower	1.9	0.0	0.0	3.3	14.6	7.4	6.8	30.6	21969
Accel	1.7	1.5	0.0	2.5	17.1	16.4	11.2	41.8	21958
ConVel	1.7	1.5	0.0	20.0	37.1	6.9	38.1	79.9	21920
Turn	1.9	14.6	90.0	6.2	43.2	25.1	43.0	123.0	21877
Accel	1.7	1.3	0.0	2.1	45.4	16.4	9.7	132.7	21867
Raise	1.9	0.0	0.0	4.0	49.4	7.6	8.5	141.2	21859
Lower	1.9	0.0	0.0	3.3	52.7	7.4	6.8	148.0	21852
Accel	1.7	1.0	0.0	1.6	54.3	16.4	7.5	155.5	21845
Turn	0.0	94.6	90.0	1.0	55.3	21.7	5.7	161.2	21839
Accel	5.9	2.0	0.0	5.7	61.0	22.5	35.6	196.8	21803
ConVel	3.7	2.1	0.0	5.0	66.0	14.3	19.9	216.7	21783
Accel	5.5	1.0	0.0	2.7	68.6	22.0	16.3	232.9	21767
ConVel	3.3	1.1	0.0	15.5	84.1	10.1	43.2	276.2	21724
Turn	0.0	94.6	90.0	1.0	83.2	21.7	5.7	281.9	21718
Raise	0.0	0.0	0.0	3.8	87.0	6.7	7.1	280.0	21711
Lower	0.0	0.0	0.0	3.3	90.3	8.2	7.5	296.5	21704

Total running time used (hrs): 0.026

Total predicted running time remaining (hrs): 1.9

Realistic time (119% predicted): 2.2

Total running time predicted for this cycle (hrs): 1.9

Realistic time (119% predicted): 2.2

Table 17. Prediction model output for model check run 2.

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Raise	1.9	0.0	0.0	4.0	4.0	7.6	8.5	8.5	21992
Lower	1.9	0.0	0.0	3.3	7.3	7.4	6.8	15.3	21985
Raise	1.9	0.0	0.0	4.0	11.3	7.6	8.5	23.8	21976
Lower	1.9	0.0	0.0	3.3	14.6	7.4	6.8	30.6	21969
Accel	1.7	1.5	0.0	2.5	17.1	16.4	11.2	41.8	21958
ConVel	1.7	1.5	0.0	20.0	37.1	6.9	38.1	79.9	21920
Turn	1.9	14.6	90.0	6.2	43.2	25.1	43.0	123.0	21877
Accel	1.7	1.6	0.0	2.6	45.9	16.4	12.0	134.9	21865
Raise	1.9	0.0	0.0	4.0	49.9	7.6	8.5	143.4	21857
Lower	1.9	0.0	0.0	3.3	53.2	7.4	6.8	150.2	21850
Accel	1.7	1.3	0.0	2.1	55.3	16.4	9.7	159.9	21840
Turn	0.0	94.6	90.0	1.0	56.3	21.7	5.7	165.7	21834
Accel	5.6	1.5	0.0	4.1	60.3	22.1	25.0	190.7	21809
ConVel	3.8	1.7	0.0	5.0	65.3	13.2	18.3	209.0	21791
Accel	3.8	1.0	0.0	2.1	67.4	19.6	11.3	220.3	21780
ConVel	3.3	1.1	0.0	14.5	81.9	9.9	40.0	260.3	21740
Turn	0.0	94.6	90.0	1.0	82.9	21.7	5.7	266.1	21734
Raise	0.0	0.0	0.0	3.8	86.7	6.7	7.1	273.2	21727
Lower	0.0	0.0	0.0	3.3	90.0	8.2	7.5	280.6	21719
Raise	0.0	0.0	0.0	3.8	93.8	6.7	7.1	287.7	21712
Lower	0.0	0.0	0.0	3.3	97.1	8.2	7.5	295.2	21705

Total running time used (hrs): 0.027
Total predicted running time remaining (hrs): 2.0
  Realistic time (119% predicted): 2.3
Total running time predicted for this cycle (hrs): 2.0
  Realistic time (119% predicted): 2.4

Table 18. Prediction model output for model check run 3.

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Raise	1.9	0.0	0.0	4.0	4.0	7.6	8.5	8.5	21992
Lower	1.9	0.0	0.0	3.3	7.3	7.4	6.8	15.3	21985
Raise	1.9	0.0	0.0	4.0	11.3	7.6	8.5	23.8	21976
Lower	1.9	0.0	0.0	3.3	14.6	7.4	6.8	30.6	21969
Accel	1.7	1.3	0.0	2.2	16.8	16.4	9.9	40.6	21959
ConVel	1.7	1.4	0.0	17.0	33.8	6.5	30.9	71.5	21929
Turn	1.9	14.6	90.0	6.2	40.0	25.1	43.0	114.5	21886
Accel	1.7	1.9	0.0	3.1	43.1	16.4	14.4	128.8	21871
Raise	1.9	0.0	0.0	4.0	47.1	7.6	8.5	137.3	21863
Lower	1.9	0.0	0.0	3.3	50.4	7.4	6.8	144.1	21856
Accel	4.6	2.0	0.0	4.6	55.0	20.7	26.4	170.6	21829
ConVel	3.2	1.2	0.0	6.0	61.0	10.1	16.8	187.3	21813
Accel	4.2	1.0	0.0	2.2	63.2	20.1	12.4	199.7	21800
ConVel	3.7	1.9	0.0	13.0	76.2	13.6	49.2	249.0	21751
Turn	0.0	94.6	90.0	1.0	77.2	21.7	5.7	254.7	21745
Raise	0.0	0.0	0.0	3.8	81.0	6.7	7.1	261.8	21738
Lower	0.0	0.0	0.0	3.3	84.3	8.2	7.5	269.3	21731
Turn	0.0	94.6	90.0	1.0	77.2	21.7	5.7	275.0	21725
Raise	0.0	0.0	0.0	3.8	88.1	6.7	7.1	282.1	21718
Lower	0.0	0.0	0.0	3.3	91.4	8.2	7.5	289.6	21711

Total running time used (hrs): 0.025
Total predicted running time remaining (hrs): 1.9
  Realistic time (119% predicted): 2.3
Total running time predicted for this cycle (hrs): 2.0
  Realistic time (119% predicted): 2.3

segments and represented a simplified, actual task. The loads and speeds used during the model check tests were different from the values used for the equation development tests so that no segment was biased towards the original load or speed. The complete routine was replicated three times so that random occurances did not seriously affect the data collected. All tests were performed on dry, level asphalt with the battery properly maintained, although not necessarily fully charged.

Analysis of results was divided into two segments: accuracy checks of the individual prediction equations and accuracy of the complete model. The measured energy values were assumed to be the true values in each case.

Matched pairs, t-tests were used to compare the model predicted power and the test measured power for each operational segment of the model check runs. Statements of significance for these comparisons are listed in Table 19a-e.

Table 19a. Matched pair, t-test results for the lifting power prediction equation.

Operation Segment	Measured Power (kWh)	Predicted Power (kWh)	Difference
lifting	7.54	7.62	-0.08
	6.91	7.62	-0.71
	7.29	7.62	-0.32
	5.81	6.71	-0.89
	6.94	7.62	-0.68
	6.77	7.62	-0.84
	6.76	7.62	-0.85
	5.68	6.71	-1.03
	6.54	6.71	-0.17
	5.74	6.71	-0.97
	7.08	7.62	-0.53
	7.29	7.62	-0.32
	6.44	7.62	-1.18
average difference =			-0.66
standard error of mean =			0.10
level of significance =			.01

Table 19b. Matched pair, t-test results for the lowering power prediction equation.

Operation Segment	Measured Power (kWh)	Predicted Power (kWh)	Difference
lowering	5.40	7.45	-2.04
	5.71	7.45	-1.73
	6.69	7.45	-0.75
	6.38	7.45	-1.06
	5.26	7.45	-2.19
	5.59	7.45	-1.86
	6.15	7.45	-1.30
	5.09	7.45	-2.35
	6.57	7.45	-0.88
	7.90	8.16	-0.26
	7.55	8.16	-0.61
	7.35	8.16	-0.81
	6.75	8.16	-1.41
average difference =			-1.33
standard error of mean =			0.18
level of significance =			.01

Table 19c. Matched pair, t-test results for the constant velocity draft power prediction equation.

Operation Segment	Measured Power (kWh)	Predicted Power (kWh)	Difference
constant velocity	3.52	2.36	1.16
	10.82	9.79	1.03
	7.78	5.57	2.21
	4.21	2.36	1.85
	11.48	8.65	2.83
	7.68	5.43	2.25
	2.71	2.04	0.67
	12.55	5.57	6.98
	7.39	9.13	-1.74
average difference =			1.91
standard error of mean =			0.77
level of significance =			.05

Table 19d. Matched pair, t-test results for the acceleration power prediction equation.

Operation Segment	Measured Power (kWh)	Predicted Power (kWh)	Difference
acceleration	3.56	14.01	-10.45
	6.94	14.01	-7.07
	1.65	14.01	-12.36
	2.93	14.01	-11.08
	6.63	14.01	-7.38
	2.66	14.01	-11.35
	2.53	14.01	-11.48
	21.52	14.01	7.52
	19.86	20.10	-0.24
	7.93	19.54	-11.61
	12.63	19.70	-7.08
	7.90	17.18	-9.28
	15.18	18.28	-3.10
	11.08	17.73	-6.65
average difference =			-7.26
standard error of mean =			1.47
level of significance =			.01

Table 19e. Matched pair, t-test results for the turning power prediction equation.

Operation Segment	Measured Power (kWh)	Predicted Power (kWh)	Difference
turning	25.60	25.10	0.51
	14.12	21.72	-7.59
	23.45	21.72	1.73
	20.94	25.10	-4.15
	28.98	21.72	7.26
	16.39	21.72	-5.32
	20.39	25.10	-4.71
	21.28	21.72	-0.44
	21.72	21.72	0.00
average difference =			-1.41
standard error of mean =			1.51
level of significance =			.5

The results of the matched pair t-tests indicated that the values of predicted and measured energy were significantly different on a statistical basis for the raising, lowering, acceleration, and constant velocity segments. However, on an absolute magnitude basis, the values were judged to be an acceptable estimate of the measured energy values. The values of predicted and measured energy for the turning segments were not significantly different as indicated by the .5 level of significance. The noted differences in the predicted and measured energies may have resulted from variations in the rate of load movement or other factors that could not be accounted for in the equations. These results seem to indicate that the accuracy of the prediction equations could be improved.

The predicted and measured energies for the complete model were compared as percent error based on the difference of the predicted energy from measured energy. This method was used rather than a matched pair t-test because only two degrees of freedom were available to explain random error and deviation, and consequently, a significant statistical statement could not be made. Results from the energy comparisons of the complete model are listed in Table 20.

Table 20. Energy comparisons of predicted and measured energy values of complete model output.

Model Check Run	Measured Energy (Wh)	Predicted Energy (Wh)	Difference	% Error[1]
1	246.9	296.5	49.6	20
2	249.6	295.2	45.6	18
3	243.3	293.8	46.3	19
Average	246.6	293.8	47.2	19

[1] $\% \text{ Error} = \frac{[\text{Predicted Energy} - \text{Measured Energy}]}{\text{Measured Energy}} * 100\%$

These results show that for the model check routine used, the prediction model was accurate overall within 19% of the measured values and percent errors ranged from 18% to 20%. The calculated results of the model consistantly predicted a higher energy use than was measured and, therefore, to obtain a more accurate value based on the model's prediction, all run times were increased by 19%. This adjustment was accounted for in the calculation of the realistic run times computed by the program at the end of the task routine.

The computer model was developed as an aid in calculating and predicting the power and energy required by Skidtric and was used primarily to determine the suitability of Skidtric to perform specified tasks based on the predicted battery power and energy, available battery power and energy, and the predicted length of run time (Table 21).

Table 21. Sample model output for specific task.

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	0.0	0.5	0.0	0.7	1.1	14.0	2.7	3.1	21997
ConVel	2.5	0.5	0.0	3.0	4.1	6.0	5.0	8.1	21992
Tiltba	1.0	0.0	0.0	0.5	4.6	6.9	0.9	9.1	21991
Raise	1.0	0.0	0.0	1.2	5.8	7.2	2.3	11.4	21989
Accel	0.0	0.5	0.0	0.7	6.5	14.0	2.7	14.1	21986
ConVel	0.0	0.5	0.0	2.0	8.5	-0.8	-0.4	13.7	21986
Turn	1.0	38.7	90.0	2.3	10.8	24.1	15.6	29.3	21971
Raise	1.0	0.0	0.0	2.7	13.5	7.2	5.5	34.7	21965
Accel	0.0	0.5	0.0	0.7	14.2	14.0	2.7	37.5	21963
Dump	1.0	0.0	0.0	2.0	16.3	3.7	2.0	39.5	21961
Tiltba	0.0	0.0	0.0	2.5	18.7	6.9	4.7	44.2	21956
Accel	0.0	0.5	0.0	0.7	19.4	14.0	2.7	47.0	21953
Lower	0.0	0.0	0.0	3.3	22.7	8.2	7.5	54.4	21946
Turn	0.0	94.6	90.0	1.0	23.7	21.7	5.7	60.2	21940
Lower	0.0	0.0	0.0	0.3	24.0	8.2	0.7	60.9	21939

Total running time used (hrs): 0.007
Total predicted running time remaining (hrs): 2.4
Realistic time (119% predicted): 2.8
Total running time predicted for this cycle (hrs): 2.4
Realistic time (119% predicted): 2.8

In this example, a task routine was entered into the model and the results were printed. Skidtric's suitability to perform the routine was judged primarily by the length of time it was predicted to operate. For this example, it was arbitrarily decided that Skidtric must be able to operate a minimum of two hours to be considered suitable. As can be seen in the predicted results, Skidtric would perform this routine for 2.07 hours and was therefore suitable for use.

The model was also used to determine general trends in Skidtric's performance as a function of changes in the applied loads, (Tables 22-28). The routine used for this example was identical to the routine used in the suitability example except that the bucket load was changed each time to examine the effect of lowering loads on Skidtric's operating time. Subsequent routines were computed with bucket loads of two, three, four, five, six, and seven kN, (Tables 22-28). The adjusted predicted total run time from each routine was then plotted against bucket load (Figure 21). The model results and plot helped to determine the optimum operating bucket load for Skidtric to achieve the longest possible running time. This load was determined to be either less than two kN or in the range of five to seven kN. Similarily, Table 29-34 and Figure 22 were used to determine the optimum ground speed to minimize Skidtric's energy use while performing a specified routine. This

Table 22. Example model output for a routine with changing bucket load (1.0 kN).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	0.0	0.5	0.0	0.7	1.1	14.0	2.7	3.1	21997
ConVel	2.5	0.5	0.0	3.0	4.1	6.0	5.0	8.1	21992
Tiltba	1.0	0.0	0.0	0.5	4.6	6.9	0.9	9.1	21991
Raise	1.0	0.0	0.0	1.2	5.8	7.2	2.3	11.4	21989
Accel	0.0	0.5	0.0	0.7	6.5	14.0	2.7	14.1	21986
ConVel	0.0	0.5	0.0	2.0	8.5	-0.8	-0.4	13.7	21986
Turn	1.0	38.7	90.0	2.3	10.8	24.1	15.6	29.3	21971
Raise	1.0	0.0	0.0	2.7	13.5	7.2	5.5	34.7	21965
Accel	0.0	0.5	0.0	0.7	14.2	14.0	2.7	37.5	21963
Dump	1.0	0.0	0.0	2.0	16.3	3.7	2.0	39.5	21961
Tiltba	0.0	0.0	0.0	2.5	18.7	6.9	4.7	44.2	21956
Accel	0.0	0.5	0.0	0.7	19.4	14.0	2.7	47.0	21953
Lower	0.0	0.0	0.0	3.3	22.7	8.2	7.5	54.4	21946
Turn	0.0	94.6	90.0	1.0	23.7	21.7	5.7	60.2	21940
Lower	0.0	0.0	0.0	0.3	24.0	8.2	0.7	60.9	21939

Total running time used (hrs): 0.007

Total predicted running time remaining (hrs): 2.4

Realistic time (119% predicted): 2.8

Total running time predicted for this cycle (hrs): 2.4

Realistic time (119% predicted): 2.8

Table 23. Example model output for a routine with changing bucket load (2.0 kN).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	0.0	0.5	0.0	0.7	1.1	14.0	2.7	3.1	21997
ConVel	2.5	0.5	0.0	3.0	4.1	6.0	5.0	8.1	21992
Tiltba	2.0	0.0	0.0	0.5	4.6	6.9	0.9	9.1	21991
Raise	2.0	0.0	0.0	1.2	5.8	7.7	2.6	11.6	21988
Accel	0.0	0.5	0.0	0.7	6.5	14.0	2.7	14.4	21986
ConVel	0.0	0.5	0.0	2.0	8.5	-0.8	-0.4	13.9	21986
Turn	2.0	12.6	90.0	7.2	15.7	25.2	50.1	64.1	21936
Raise	2.0	0.0	0.0	2.8	18.5	7.7	6.0	70.1	21930
Accel	0.0	0.5	0.0	0.7	19.2	14.0	2.7	72.8	21927
Dump	2.0	0.0	0.0	2.0	21.2	3.7	2.0	74.8	21925
Tiltba	0.0	0.0	0.0	2.5	23.7	6.9	4.7	79.6	21920
Accel	0.0	0.5	0.0	0.7	24.4	14.0	2.7	82.3	21918
Turn	0.0	94.6	90.0	1.0	25.3	21.7	5.7	88.0	21912
Lower	0.0	0.0	0.0	0.3	25.7	8.2	0.7	88.8	21911

Total running time used (hrs): 0.007
Total predicted running time remaining (hrs): 1.8
  Realistic time (119% predicted): 2.1
Total running time predicted for this cycle (hrs): 1.8
  Realistic time (119% predicted): 2.1

Table 24. Example model output for a routine with changing bucket load (3.0 kN).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	0.0	0.5	0.0	0.7	1.1	14.0	2.7	3.1	21997
ConVel	2.5	0.5	0.0	3.0	4.1	6.0	5.0	8.1	21992
Tiltba	3.0	0.0	0.0	0.5	4.6	6.9	0.9	9.1	21991
Raise	3.0	0.0	0.0	1.2	5.8	8.2	2.8	11.9	21988
Accel	0.0	0.5	0.0	0.7	6.5	14.0	2.7	14.6	21985
ConVel	0.0	0.5	0.0	2.0	8.5	-0.8	-0.4	14.2	21986
Turn	3.0	7.5	90.0	12.0	20.5	25.5	84.7	98.9	21901
Raise	3.0	0.0	0.0	2.9	23.4	8.2	6.6	105.5	21895
Accel	0.0	0.5	0.0	0.7	24.1	14.0	2.7	108.2	21892
Dump	3.0	0.0	0.0	2.0	26.1	3.7	2.0	110.2	21890
Tiltba	0.0	0.0	0.0	2.5	28.6	6.9	4.7	115.0	21885
Accel	0.0	0.5	0.0	0.7	29.3	14.0	2.7	117.7	21882
Lower	0.0	0.0	0.0	2.3	31.6	8.2	5.2	122.9	21877
Turn	0.0	94.6	90.0	1.0	32.6	21.7	5.7	128.7	21871
Lower	0.0	0.0	0.0	1.0	33.6	8.2	2.2	130.9	21869

Total running time used (hrs): 0.009
Total predicted running time remaining (hrs): 1.6
Realistic time (119% predicted): 1.9
Total running time predicted for this cycle (hrs): 1.6
Realistic time (119% predicted): 1.9

Table 25. Example model output for a routine with changing bucket load (4.0 kN).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	0.0	0.5	0.0	0.7	1.1	14.0	2.7	3.1	21997
ConVel	2.5	0.5	0.0	3.0	4.1	6.0	5.0	8.1	21992
Tiltba	4.0	0.0	0.0	0.5	4.6	6.9	0.9	9.1	21991
Raise	4.0	0.0	0.0	1.3	5.9	8.7	3.1	12.1	21988
Accel	0.0	0.5	0.0	0.7	6.6	14.0	2.7	14.9	21985
ConVel	0.0	0.5	0.0	2.0	8.6	-0.8	-0.4	14.4	21986
Turn	4.0	14.7	90.0	6.1	14.7	25.2	42.9	57.3	21943
Accel	0.0	0.5	0.0	0.7	15.4	14.0	2.7	60.0	21940
Dump	4.0	0.0	0.0	2.0	17.4	3.7	2.0	62.1	21938
Tiltba	0.0	0.0	0.0	2.5	19.9	6.9	4.7	66.8	21933
Accel	0.0	0.5	0.0	0.7	20.6	14.0	2.7	69.5	21930
Lower	0.0	0.0	0.0	2.3	22.9	8.2	5.2	74.8	21925
Turn	0.0	94.6	90.0	1.0	23.9	21.7	5.7	80.5	21919
Lower	0.0	0.0	0.0	1.0	24.9	8.2	2.2	82.8	21917

Total running time used (hrs): 0.007
Total predicted running time remaining (hrs): 1.8
  Realistic time (119% predicted): 2.1
Total running time predicted for this cycle (hrs): 1.8
  Realistic time (119% predicted): 2.1

Table 26. Example model output for a routine with changing bucket load (5.0 kN).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	0.0	0.5	0.0	0.7	1.1	14.0	2.7	3.1	21997
ConVel	2.5	0.5	0.0	3.0	4.1	6.0	5.0	8.1	21992
Tiltba	5.0	0.0	0.0	0.5	4.6	6.9	0.9	9.1	21991
Raise	5.0	0.0	0.0	1.3	5.9	9.1	3.3	12.4	21988
Accel	0.0	0.5	0.0	0.7	6.6	14.0	2.7	15.1	21985
ConVel	0.0	0.5	0.0	2.0	8.6	-0.8	-0.4	14.7	21985
Turn	5.0	25.2	90.0	3.6	12.2	24.7	24.5	39.1	21961
Raise	5.0	0.0	0.0	3.0	15.2	9.1	7.7	46.9	21953
Accel	0.0	0.5	0.0	0.7	15.9	14.0	2.7	49.6	21950
Dump	5.0	0.0	0.0	2.0	17.9	3.7	2.0	51.7	21948
Tiltba	0.0	0.0	0.0	2.5	20.4	6.9	4.7	56.4	21944
Accel	0.0	0.5	0.0	0.7	21.1	14.0	2.7	59.1	21941
Lower	0.0	0.0	0.0	2.3	23.4	8.2	5.2	64.3	21936
Turn	0.0	94.6	90.0	1.0	24.4	21.7	5.7	70.1	21930
Lower	0.0	0.0	0.0	1.0	25.4	8.2	2.2	72.3	21928

Total running time used (hrs): 0.007
Total predicted running time remaining (hrs): 2.1
Realistic time (119% predicted): 2.5
Total running time predicted for this cycle (hrs): 2.1
Realistic time (119% predicted): 2.5

Table 27. Example model output for a routine with changing bucket load (6.0 kN).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	0.0	0.5	0.0	0.7	1.1	14.0	2.7	3.1	21997
ConVel	2.5	0.5	0.0	3.0	4.1	6.0	5.0	8.1	21992
Tiltba	6.0	0.0	0.0	0.5	4.6	6.9	0.9	9.1	21991
Accel	0.0	0.5	0.0	0.7	5.3	14.0	2.7	11.8	21988
ConVel	0.0	0.5	0.0	2.0	7.3	-0.8	-0.4	11.3	21989
Turn	6.0	30.3	90.0	3.0	10.3	24.3	20.1	31.4	21969
Raise	6.0	0.0	0.0	1.3	11.6	9.6	3.6	35.0	21965
Accel	0.0	0.5	0.0	0.7	12.3	14.0	2.7	37.7	21962
Dump	6.0	0.0	0.0	2.0	14.3	3.7	2.0	39.8	21960
Tiltba	0.0	0.0	0.0	2.5	16.8	6.9	4.7	44.5	21956
Accel	0.0	0.5	0.0	0.7	17.5	14.0	2.7	47.2	21953
Lower	0.0	0.0	0.0	2.3	19.8	8.2	5.2	52.5	21948
Turn	0.0	94.6	90.0	1.0	20.8	21.7	5.7	58.2	21942
Lower	0.0	0.0	0.0	1.0	21.8	8.2	2.2	60.4	21940

Total running time used (hrs): 0.006
Total predicted running time remaining (hrs): 2.2
  Realistic time (119% predicted): 2.6
Total running time predicted for this cycle (hrs): 2.2
  Realistic time (119% predicted): 2.6

Table 28. Example model output for a routine with changing bucket load (7.0 kN).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	0.0	0.5	0.0	0.7	1.1	14.0	2.7	3.1	21997
ConVel	2.5	0.5	0.0	3.0	4.1	6.0	5.0	8.1	21992
Tiltba	7.0	0.0	0.0	0.5	4.6	6.9	0.9	9.1	21991
Raise	7.0	0.0	0.0	1.4	6.0	10.1	3.9	12.9	21987
Accel	0.0	0.5	0.0	0.7	6.7	14.0	2.7	15.7	21984
ConVel	0.0	0.5	0.0	2.0	8.7	-0.8	-0.4	15.2	21985
Turn	7.0	21.0	90.0	4.3	13.0	24.3	28.9	44.1	21956
Raise	7.0	0.0	0.0	3.2	16.2	10.1	9.0	53.1	21947
Accel	0.0	0.5	0.0	0.7	16.9	14.0	2.7	55.9	21944
Dump	7.0	0.0	0.0	2.0	18.9	3.7	2.0	57.9	21942
Tiltba	0.0	0.0	0.0	2.5	21.3	6.9	4.7	62.6	21937
Accel	0.0	0.5	0.0	0.7	22.0	14.0	2.7	65.4	21935
Lower	0.0	0.0	0.0	2.3	24.4	8.2	5.2	70.6	21929
Turn	0.0	94.6	90.0	1.0	25.3	21.7	5.7	76.3	21924
Lower	0.0	0.0	0.0	1.0	26.3	8.2	2.2	78.6	21921

Total running time used (hrs): 0.007
Total predicted running time remaining (hrs): 2.0
  Realistic time (119% predicted): 2.4
Total running time predicted for this cycle (hrs): 2.0
  Realistic time (119% predicted): 2.4

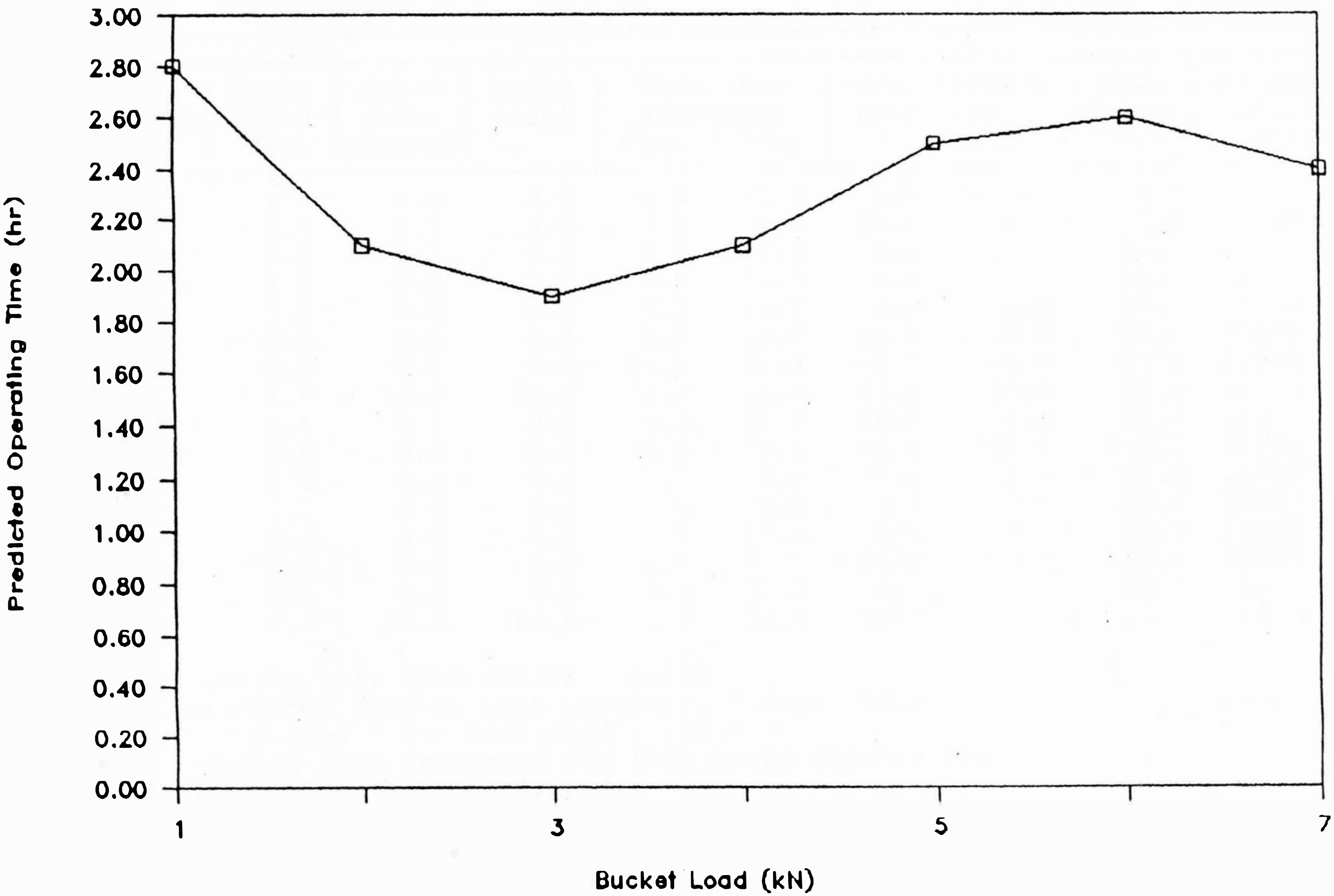


Figure 21. Predicted operating time vs. bucket load for a specified routine

Table 29. Example model output for a routine with changing ground speed (0.1 m/s).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	2.5	0.1	0.0	0.2	0.6	17.6	0.9	1.3	21999
ConVel	2.5	0.1	0.0	12.0	12.6	4.7	15.7	17.0	21983
Tiltba	1.0	0.0	0.0	0.5	13.1	6.9	0.9	17.9	21982
Raise	1.0	0.0	0.0	1.2	14.3	7.2	2.3	20.3	21980
Accel	0.0	0.1	0.0	0.1	14.4	14.0	0.5	20.8	21979
ConVel	0.0	0.1	0.0	10.0	24.4	-2.1	-5.8	15.1	21985
Turn	1.0	38.7	90.0	2.3	26.7	24.1	15.6	30.6	21969
Accel	0.0	0.1	0.0	0.1	26.9	14.0	0.5	31.2	21969
ConVel	0.0	0.1	0.0	45.0	71.9	-2.1	-25.9	5.3	21995
Raise	1.0	0.0	0.0	2.7	74.6	7.2	5.5	10.8	21989
Dump	1.0	0.0	0.0	2.0	76.6	3.7	2.0	12.8	21987
Tiltba	0.0	0.0	0.0	2.5	79.1	6.9	4.7	17.5	21982
Accel	0.0	0.1	0.0	0.1	79.2	14.0	0.5	18.1	21982
Lower	0.0	0.0	0.0	2.3	81.5	8.2	5.2	23.3	21977
Turn	0.0	94.6	180.0	1.9	83.4	21.7	11.5	34.8	21965

Total running time used (hrs): 0.023
Total predicted running time remaining (hrs): 14.6
  Realistic time (119% predicted): 17.4
Total running time predicted for this cycle (hrs): 14.7
  Realistic time (119% predicted): 17.5

Table 30. Example model output for a routine with changing ground speed (1.0 m/s).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	2.5	1.0	0.0	1.8	2.2	17.6	8.8	9.2	21991
ConVel	2.5	1.0	0.0	12.0	14.2	7.6	25.2	34.4	21966
Tiltba	1.0	0.0	0.0	0.5	14.7	6.9	0.9	35.3	21965
Raise	1.0	0.0	0.0	1.2	15.9	7.2	2.3	37.7	21962
Accel	0.0	1.0	0.0	1.4	17.3	14.0	5.5	43.1	21957
ConVel	0.0	1.0	0.0	10.0	27.3	0.8	2.2	45.3	21955
Turn	1.0	38.7	90.0	2.3	29.6	24.1	15.6	60.9	21939
Accel	0.0	1.0	0.0	1.4	31.0	14.0	5.5	66.3	21934
ConVel	0.0	1.0	0.0	7.0	38.0	0.8	1.5	67.8	21932
Turn	1.0	38.7	90.0	2.3	40.3	24.1	15.6	83.4	21917
Accel	0.0	1.0	0.0	1.4	41.7	14.0	5.5	88.8	21911
ConVel	0.0	1.0	0.0	45.0	86.7	0.8	9.7	98.6	21901
Raise	1.0	0.0	0.0	2.7	89.5	7.2	5.5	104.0	21896
Dump	1.0	0.0	0.0	2.0	91.5	3.7	2.0	106.1	21894
Tiltba	0.0	0.0	0.0	2.5	94.0	6.9	4.7	110.8	21889
Accel	0.0	1.0	0.0	1.4	95.4	14.0	5.5	116.3	21884
Lower	0.0	0.0	0.0	3.3	98.7	8.2	7.5	123.7	21876
Turn	0.0	94.6	180.0	1.9	100.6	21.7	11.5	135.2	21865

Total running time used (hrs): 0.028
Total predicted running time remaining (hrs): 4.5
  Realistic time (119% predicted): 5.4
Total running time predicted for this cycle (hrs): 4.5
  Realistic time (119% predicted): 5.4

Table 31. Example model output for a routine with changing ground speed (2.0 m/s).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	2.5	2.0	0.0	3.6	4.0	17.6	17.6	18.0	21982
ConVel	2.5	2.0	0.0	12.0	16.0	10.7	35.7	53.7	21946
Tiltba	1.0	0.0	0.0	0.5	16.5	6.9	0.9	54.7	21945
Raise	1.0	0.0	0.0	1.2	17.7	7.2	2.3	57.0	21943
Accel	0.0	2.0	0.0	2.8	20.5	14.0	10.9	67.9	21932
ConVel	0.0	2.0	0.0	10.0	30.5	3.9	10.9	78.9	21921
Turn	1.0	38.7	90.0	2.3	32.8	24.1	15.6	94.4	21906
Accel	0.0	2.0	0.0	2.8	35.6	14.0	10.9	105.4	21895
ConVel	0.0	2.0	0.0	7.0	42.6	3.9	7.7	113.0	21887
Turn	1.0	38.7	90.0	2.3	44.9	24.1	15.6	128.6	21871
Accel	0.0	2.0	0.0	2.8	47.7	14.0	10.9	139.5	21861
ConVel	0.0	2.0	0.0	45.0	92.7	3.9	49.3	188.8	21811
Raise	1.0	0.0	0.0	2.7	95.5	7.2	5.5	194.2	21806
Dump	1.0	0.0	0.0	2.0	97.5	3.7	2.0	196.3	21804
Tiltba	0.0	0.0	0.0	2.5	100.0	6.9	4.7	201.0	21799
Accel	0.0	2.0	0.0	2.8	102.8	14.0	10.9	211.9	21788
Lower	0.0	0.0	0.0	3.3	106.1	8.2	7.5	219.4	21781
Turn	0.0	94.6	180.0	1.9	108.0	21.7	11.5	230.9	21769

Total running time used (hrs): 0.030
Total predicted running time remaining (hrs): 2.8
  Realistic time (119% predicted): 3.3
Total running time predicted for this cycle (hrs): 2.9
  Realistic time (119% predicted): 3.5

Table 32. Example model output for a routine with changing ground speed (3.0 m/s).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	2.5	3.0	0.0	5.4	5.8	17.6	26.3	26.7	21973
ConVel	2.5	3.0	0.0	12.0	17.8	13.9	46.3	73.0	21927
Tiltba	1.0	0.0	0.0	0.5	18.3	6.9	0.9	74.0	21926
Raise	1.0	0.0	0.0	1.2	19.4	7.2	2.3	76.3	21924
Accel	0.0	3.0	0.0	4.2	23.7	14.0	16.4	92.7	21907
ConVel	0.0	3.0	0.0	10.0	33.7	7.1	19.7	112.5	21888
Turn	1.0	38.7	90.0	2.3	36.0	24.1	15.6	128.0	21872
Accel	0.0	3.0	0.0	4.2	40.2	14.0	16.4	144.4	21856
ConVel	0.0	3.0	0.0	7.0	47.2	7.1	13.8	158.2	21842
Turn	1.0	38.7	90.0	2.3	49.5	24.1	15.6	173.8	21826
Accel	0.0	3.0	0.0	4.2	53.7	14.0	16.4	190.1	21810
ConVel	0.0	3.0	0.0	45.0	98.7	7.1	88.8	279.0	21721
Raise	1.0	0.0	0.0	2.7	101.5	7.2	5.5	284.4	21716
Dump	1.0	0.0	0.0	2.0	103.5	3.7	2.0	286.5	21714
Tiltba	0.0	0.0	0.0	2.5	106.0	6.9	4.7	291.2	21709
Accel	0.0	3.0	0.0	4.2	110.2	14.0	16.4	307.6	21692
Lower	0.0	0.0	0.0	3.3	113.5	8.2	7.5	315.1	21685
Turn	0.0	94.6	180.0	1.9	115.4	21.7	11.5	326.5	21673

Total running time used (hrs): 0.032

Total predicted running time remaining (hrs): 2.1

Realistic time (119% predicted): 2.5

Total running time predicted for this cycle (hrs): 2.2

Realistic time (119% predicted): 2.6

Table 33. Example model output for a routine with changing ground speed (4.0 m/s).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	2.5	4.0	0.0	7.2	7.6	17.6	35.1	35.5	21964
ConVel	2.5	4.0	0.0	12.0	19.6	17.1	56.8	92.4	21908
Tiltba	1.0	0.0	0.0	0.5	20.1	6.9	0.9	93.3	21907
Raise	1.0	0.0	0.0	1.2	21.2	7.2	2.3	95.7	21904
Accel	0.0	4.0	0.0	5.6	26.9	14.0	21.8	117.5	21882
ConVel	0.0	4.0	0.0	10.0	36.9	10.3	28.5	146.0	21854
Turn	1.0	38.7	90.0	2.3	39.2	24.1	15.6	161.6	21838
Accel	0.0	4.0	0.0	5.6	44.8	14.0	21.8	183.4	21817
ConVel	0.0	4.0	0.0	45.0	89.8	10.3	128.4	311.8	21688
Raise	1.0	0.0	0.0	2.7	92.5	7.2	5.5	317.3	21683
Dump	0.0	0.0	0.0	2.0	94.5	3.7	2.0	319.3	21681
Tiltba	0.0	0.0	0.0	2.5	97.0	6.9	4.7	324.0	21676
Accel	0.0	4.0	0.0	5.6	102.6	14.0	21.8	345.9	21654
Lower	0.0	0.0	0.0	3.3	105.9	8.2	7.5	353.4	21647
Turn	0.0	94.6	180.0	1.9	107.8	21.7	11.5	364.8	21635

Total running time used (hrs): 0.030
Total predicted running time remaining (hrs): 1.8
  Realistic time (119% predicted): 2.1
Total running time predicted for this cycle (hrs): 1.8
  Realistic time (119% predicted): 2.1

Table 34. Example model output for a routine with changing ground speed (5.0 m/s).

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Dump	0.0	0.0	0.0	0.4	0.4	3.7	0.4	0.4	22000
Accel	2.5	5.0	0.0	9.0	9.4	17.6	43.9	44.3	21956
ConVel	2.5	5.0	0.0	12.0	21.4	20.2	67.4	111.7	21888
Tiltba	1.0	0.0	0.0	0.5	21.9	6.9	0.9	112.6	21887
Raise	1.0	0.0	0.0	1.2	23.0	7.2	2.3	115.0	21885
Accel	0.0	5.0	0.0	7.0	30.0	14.0	27.3	142.3	21858
ConVel	0.0	5.0	0.0	10.0	40.0	13.4	37.3	179.6	21820
Turn	1.0	38.7	90.0	2.3	42.4	24.1	15.6	195.2	21805
Accel	0.0	5.0	0.0	7.0	49.4	14.0	27.3	222.5	21778
ConVel	0.0	5.0	0.0	7.0	56.4	13.4	26.1	248.6	21751
Turn	1.0	38.7	90.0	2.3	58.7	24.1	15.6	264.1	21736
Accel	0.0	5.0	0.0	7.0	65.7	14.0	27.3	291.4	21709
ConVel	0.0	5.0	0.0	45.0	110.7	13.4	167.9	459.4	21541
Raise	1.0	0.0	0.0	2.7	113.5	7.2	5.5	464.8	21535
Dump	1.0	0.0	0.0	2.0	115.5	3.7	2.0	466.9	21533
Tiltba	0.0	0.0	0.0	2.5	118.0	6.9	4.7	471.6	21528
Accel	0.0	5.0	0.0	7.0	125.0	14.0	27.3	498.9	21501
Lower	0.0	0.0	0.0	3.3	128.3	8.2	7.5	506.4	21494
Turn	0.0	94.6	180.0	1.9	130.2	21.7	11.5	517.9	21482

Total running time used (hrs): 0.036
Total predicted running time remaining (hrs): 1.5
  Realistic time (119% predicted): 1.8
Total running time predicted for this cycle (hrs): 1.5
  Realistic time (119% predicted): 1.8

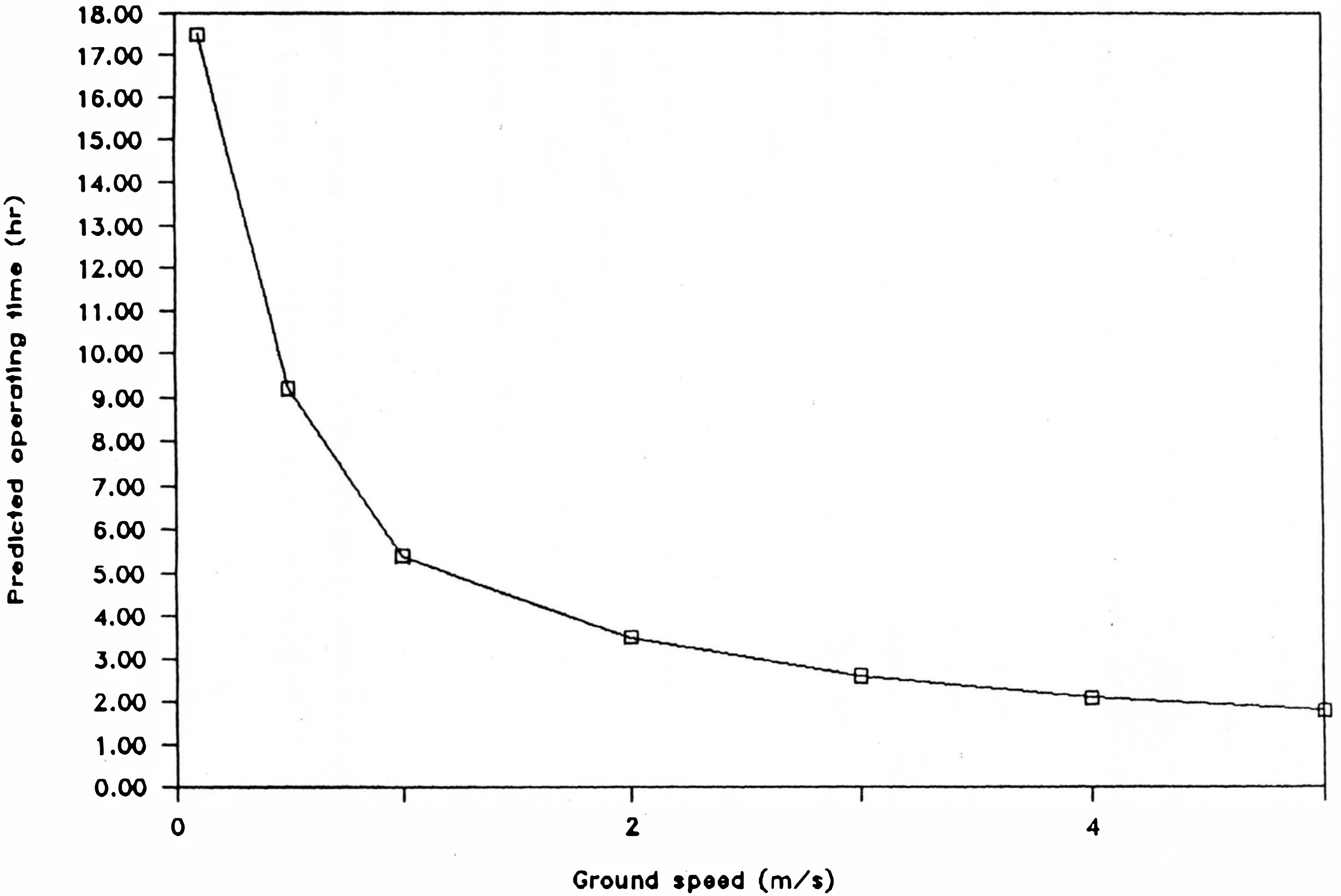


Figure 22. Predicted operating time vs. travel speed for a specified routine

routine was different than the previous example. From these results, it was determined that Skidtric would operate longest when driven at the slowest feasible speed.

An additional use of the prediction model was computing the predicted power required for the individual routine segments. Table 35 and Figure 23 show the power required to move a fixed draft load of 2.5 kN at various speeds in the range of 0.1 m/s to 4.0 m/s for acceleration and constant velocity draft operation. In this example, the cumulative energy and energy remaining columns of the model output are meaningless.

Several limitations have been noted regarding use of the prediction model. First, it was noted that entering a low speed and light draft load, such as 0.5 m/s and zero kN, respectively, in the constant velocity segment resulted in a negative power and energy prediction. Negative power (energy) output subtracted from the available battery energy represents a numerically positive value and as such, the program adds energy to the battery rather than subtracting the energy used. Negative power and energy were computed in this load and speed area because the prediction equation had not been forced through the origin with data points of zero kN load, zero m/s speed, and zero kW power required. Second, negative power and energy were also computed for the acceleration segment if an average draft load greater than

Table 35. Example model output for determining power requirements.

Task Segment	Draft /Load (kN)	Speed (m/s) (deg/s)	Angle (deg)	Time used (seconds) Seg.	Time used (seconds) Cum.	Power (kW)	Segment Energy (Wh)	Cum. Energy (Wh)	Energy Remain (Wh)
Accel	2.5	0.1	0.0	0.2	0.2	17.6	0.9	0.9	21999
Accel	2.5	0.5	0.0	0.9	1.1	17.6	4.4	5.3	21995
Accel	2.5	1.0	0.0	1.8	2.9	17.6	8.8	14.0	21986
Accel	2.5	1.5	0.0	2.7	5.6	17.6	13.2	27.2	21973
Accel	2.5	2.0	0.0	3.6	9.1	17.6	17.6	44.8	21955
Accel	2.5	2.5	0.0	4.5	13.6	17.6	22.0	66.7	21933
Accel	2.5	3.0	0.0	5.4	19.0	17.6	26.3	93.1	21907
Accel	2.5	3.5	0.0	6.3	25.3	17.6	30.7	123.8	21876
Accel	2.5	4.0	0.0	7.2	32.4	17.6	35.1	158.9	21841
ConVel	2.5	0.1	0.0	100.0	132.4	4.7	130.9	289.8	21710
ConVel	2.5	0.5	0.0	20.0	152.4	6.0	33.2	323.0	21677
ConVel	2.5	1.0	0.0	10.0	162.4	7.6	21.0	344.0	21656
ConVel	2.5	1.5	0.0	6.7	169.1	9.1	16.9	361.0	21639
ConVel	2.5	2.0	0.0	5.0	174.1	10.7	14.9	375.9	21624
ConVel	2.5	2.5	0.0	4.0	178.1	12.3	13.7	389.5	21610
ConVel	2.5	3.0	0.0	3.3	181.4	13.9	12.9	402.4	21598
ConVel	2.5	3.5	0.0	2.9	184.3	15.5	12.3	414.7	21585
ConVel	2.5	4.0	0.0	2.5	186.8	17.1	11.8	426.5	21574

Total running time used (hrs): 0.052
Total predicted running time remaining (hrs): 2.6
  Realistic time (119% predicted): 3.1
Total running time predicted for this cycle (hrs): 2.7
  Realistic time (119% predicted): 3.2

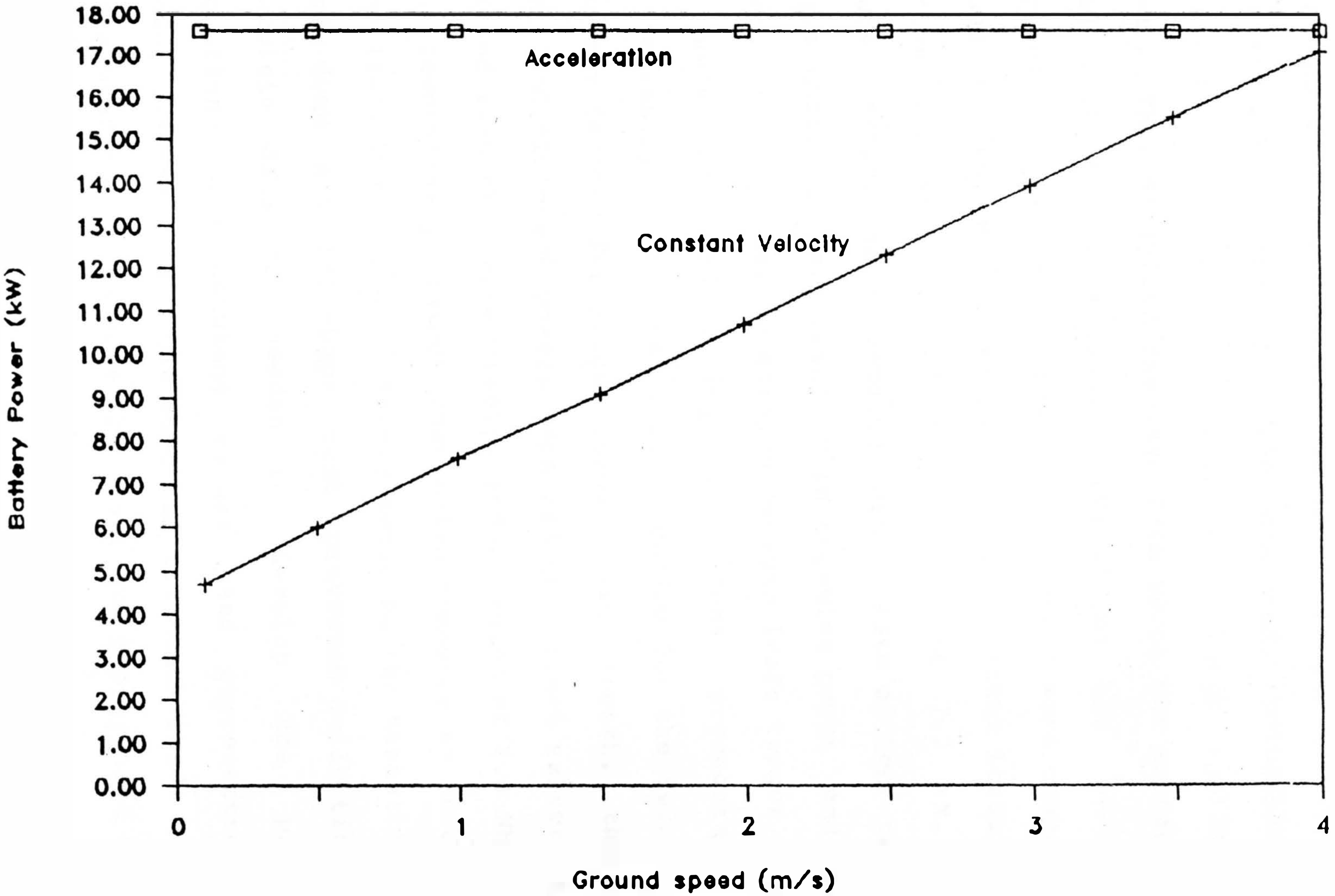


Figure 23. Predicted power required vs. travel speed for a specified routine with a fixed bucket load

13 kN was entered. For average drafts larger than 13 kN, a negative acceleration rate was computed, indicating that Skidtric would not accelerate with large applied draft loads. This situation resulted from using the average draft load over the acceleration period as the independent variable. Again, negative power and energy were computed and added to the output results. Third, bucket loads carried during turns were limited to a maximum of 7.7 kN. Larger loads resulted in a computed turning rate of less than zero deg/s that, again, resulted in negative power and energy used. This situation existed because loads larger than 7.7 kN were not used during the test procedures, and consequently, the prediction equation for the turning rate was not defined for larger loads. And, fourth, the bucket dump and tilt-back powers were assigned fixed values of 3.66 kW and 6.86 kW, respectively, and energies of 2.0 Wh and 4.7 Wh, respectively, rather than being computed as functions of the load. Difficulty in safely securing the bucket loads for the dump and tilt-back test prevented collection of the complete data set needed to develop the prediction equations. The constant values used represented average power and energy for the dump and tilt-back loads tested and were used to approximate the power and energy used by these segments.

SUMMARY AND CONCLUSIONS

Testing procedures for Skidtric, the Electric Choremaster II, were developed and implemented. The tests considered each portion of skid-steer operation seperately and were designed to measure variables for each segment that defined and quantified Skidtric's performance. The operation segments considered were acceleration and constant velocity draft operation, turning, and loader operation. Loader operation included raising and lowering the loader and dumping and tilting back the bucket.

The battery power measured during these tests was used in regression analysis with the respective independent variable(s) to develop equations describing the relationships for each segment. These equations were:

1. Loader lifting:

$$POWER_{LIFT} = LOAD * 0.49 + 6.70$$

where: $POWER_{LIFT}$ = battery power required by Skidtric to lift LOAD, (kW)
LOAD = bucket load lifted, (kN)
R^2 = 0.86

2. Loader lowering:

$$POWER_{LOWER} = 8.16 - LOAD * 0.38$$

where: $POWER_{LOWER}$ = battery power required by Skidtric to lower LOAD, (kW)
LOAD = bucket load lowered, (kN)
R^2 = 0.72

3. Constant velocity draft:

$$CONVELPOW = DRAFT * 2.71 + SPEED * 3.16 - 6.89$$

where: CONVELPOW = battery power required to move Skidtric in straight line motion with a specified load and specified speed, (kW)
DRAFT = applied towing load, including rolling resistance, (kN)
SPEED = travel velocity of Skidtric, (m/s)
R^2 = 0.92

4. Acceleration draft:

$$ACCPOW = DRAFT * 1.45 + 11.60$$

where: ACCPOW = battery power required to accelerate Skidtric for a given load, (kW)
DRAFT = load pulled or pushed, (kN)
R^2 = 0.98

5. Turning:

$$TURNPOW = LOAD^3 * 0.054 - LOAD^2 * 0.76 + LOAD * 3.04 + 21.72$$

where: TURNPOW = battery power required to turn Skidtric carrying LOAD, (kW)
LOAD = bucket load carried by Skidtric, (kN)
R^2 = 0.57

Bucket dumping and tilt-back tests could not be completed at enough load levels to provide adequate data for equation development. Therefore, the average energy values of the tests completed were used as estimates of the required power. These energies were 2.0 Wh and 4.7 Wh, respectively.

The equations and energy estimates were used to develop a computer-based prediction model to compute the expected energy use and requirements of Skidtric. Results of the model accuracy test routine indicated that the overall model predicted an energy use 19% greated than the energy actually consumed for that routine. Predicted operating times were, therefore, 19% lower than the actual operating times and an adjustment factor of 19% was incorporated into the model. The model's predictions were then considered to be satisfactory for input values contained in the range of test conditions. The results of the model's calculations were used to determine the suitability of Skidtric to perform specified task routines.

Battery performance tests were also performed and were divided into discharge and charge portions. The discharge tests were used to determine the energy capacity of the battery which was then compared to the capacity claimed by the manufacturer. The results of the two discharge tests were battery capacities of 283.8 Ah for the first test, and 305.5 Ah for the second test at the six-hour discharge rate. These capacities were less than the manufacturer's rating of

320 Ah at the five-hour discharge rate, however, the test results indicated that the battery capacity was increasing. Electrolyte temperature increased from 23.5^{o}C to 27^{o}C during the first discharge test and increased from 28^{o}C to 30^{o}C during the second test. The rise in electrolyte temperature was typical of results found by other battery researchers.

The charging tests were used to determine the amount of energy required to recharge the batteries and allow an overall battery efficiency statement to be made. Difficulties with the data collection program prevented a complete set of charging data from being collected.

The variables and parameters that described Skidtric's performance were determined to be:

1) applied load (bucket and draft),
2) speed for ground motion (forward, reverse and turning),
3) battery power and energy required,
4) battery power and energy available,
5) length of time Skidtric would perform a specified task, and
6) length of time required to recharge Skidtric's battery pack.

Skidtric's length of operation time was found to be the major determinant of it's suitability to perform specified tasks. The magnitude of the applied load, the operating speed, and the available battery energy were the major factors in determining Skidtric's operation time. The simplified, no-load task routine performed during Skidtric's duration test resulted in a measured continuous operating time of two hours and 15 minutes.

The EV controllers used on Skidtric performed well for the dual motor speed and directional control required by the skid-steer vehicle, especially during tight maneuvering in small areas. It was noted, however, that during continuous straight-line, draft operation, Skidtric turned slightly to the left. This indicated an unequal speed adjustment of the drive motors. Changing the adjustment of the dual signal proportioning card reduced the involuntary turning during constant velocity operation. However, this adjustment caused sharp turns to the right during rapid accelerations, especially under a draft load. No satisfactory intermediate signal setting was found and, consequently, a compromise adjustment that included both unwanted turns was used.

Physically small potentiometers on the joystick control lever that controlled vehicle direction and speed occasionally failed causing loss of electrical, vehicle control. These potentiometers could be replaced with electrically similar, but physically larger, potentiometers to reduce the failure problem.

Skidtric was judged to be poorly suited to the use of battery-stored, electrical power based on the prohibitively large amounts of power and energy required for turning Skidtric. These requirements stemmed from the frictional force resisting the skidding of one or both sets of wheels during turns and the low output torque available at the drive wheels. The large weight inherent with EV's caused the large sliding resistance for Skidtric, especially on high friction, and on deformable, surfaces. Increased torque output at the drive wheels was expected to increase Skidtric's ability to overcome the frictional resistance and reduce the power and energy requirements.

Skidtric's side entry cab design was found to be both convenient and safe for the operator. Entering the vehicle from the side removed the difficulties and dangers of climbing over (or under) the bucket and around the vehicle's controls.

Design Recommendations

Skidtric

1) Increase output torque at the drive wheels by increasing the gear reduction from 16:1 to 32:1, or by using greater torque output, lower speed motors.
2) Install physically larger sized, but electrically similar potentiometers on the joystick control lever.
3) Use a power transformer to reduce the 72 V, dc, battery voltage to 12 v dc to power the accessories.

4) Relocate accessory fuse box so as to be easily accessible without removing the fire wall.
5) Widen the manual brake pedal mounts for easier operator use.

Future Vehicles

1) Use a steerable axle or articulated frame for steering rather than skid-type steering to reduce power and energy demands.
2) Make all controls (hydraulic, ground motion, steering, etc.) electric rather than cable to reduce their resistance to movement and operator fatigue.

Future Testing of Skidtric

1) Repeat the test procedures on other operating surfaces, such as, sod, tilled soil, wet surface.
2) Expand the energy prediction model to include these surfaces.
3) Perform complete battery testing (charge and discharge) in both the capacity and performance areas considering such factors as temperature and DOD.
4) Perform subjective testing by individuals not associated with the project to judge public acceptance of EV skid-

steers.

5) Perform cost evaluations to determine cost of owning and operating Skidtric.

6) Compare Skidtric's performance with similarly sized PPV skid-steer vehicles.

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APPENDICES

APPENDIX A: LIST OF SYMBOLS

Symbol	Explanation
A	Ampere
ac	alternating current
Ah	Ampere hour
ASAE	American Society of Agricultural Engineers
^oC	degrees Celsius
DAS	data acquisition system
dc	direct current
deg, ^{o}	degrees
deg/s	degrees per second
DMM	digital multimeter
DOD	depth of discharge
DVM	digital voltmeter
EC-I	Electric Choremaster I
EPRI	Electric Power Research Institute
EV	electric vehicle
EVTF	electric vehicle test facility
HP	Hewlitt-Packard
hr, hrs	hours
IC	internal combustion
JPL	Jet Propulsion Laboratory
kHz	kiloHertz
kN	kiloNewton
kN-m	kiloNewton-meter
kW	kiloWatt
kWh	kiloWatt-hour
m	meter
min	minute
mV	milliVolt
m/s	meter per second
m/s^2	meter per second per second
Na-S	Sodium-Sulfur (battery)
NEMA	National Electrical Manufacturers Association
Ni-Fe	Nickel-Iron (battery)
NTT	Nebraska Tractor Test
PPV	petroleum powered vehicle
rad/s	radian per second
rad/s^2	radian per second per second
s	second
SAE	Society of Automotive Engineers
SCR	silicon controller rectifier
SDSU	South Dakota State University

SoC	state of charge
TVA	Tennessee Valley Authority
USDOE	United States Department of Energy
V	Volt
W/kg	Watts per kilogram
Wh	Watt-hours
Wh/kg	Watt-hours per kilogram
W/l	Watt-hours per liter

APPENDIX B: TEST PROCEDURES

B-1: Battery discharge test procedures:

Procedures:

1. Check Skidtric's battery DOD. If less than 40%, connect to resistive load or operate Skidtric to discharge battery to 80% DOD. Connect to load and use to adjust.
2. Maneuver Skidtric into position for discharge test.
3. Connect charger and fully charge the battery.
4. Allow battery to stabilize for several hours after the charge is complete.
5. Connect battery to resistive load, but leave switch open.
6. Attach the transducers to the battery:

    a. four thermocouples randomly assigned,
    b. nine module voltage leads across four-cell groups,
    c. current leads to in-line, current shunt:
        1. DAS leads,
        2. portable DMM leads.
    d. resistive voltage divider across battery terminals.

7. Initialize DAS:

    a. Enter background data:
        1. filename,
        2. test date and time,
        3. battery SoC,
        4. test operator name,
        5. test name,
        6. environmental temperature and wind speed,
        7. test location and surface conditions.
    b. Check transducers:
        1. correct null signals, and
        2. proper operation/signal generation.
    c. Place DAS in holding state.
    d. Replace program tape with blank data tape.

8. Record manual measurements of specific gravity (DOD) and electrolyte temperature of the designated test cells (14 and 32).
9. Close the switch between the battery and the resistive load.
10. Wait three to four seconds for the system to stabilize, then start the DAS.
11. Monitor discharge current via the portable DMM connected to the current shunt. When current drops below 53.2 A lower the water rheostat contact plate until current is at least 53.3 A but not higher than 53.4 A.
12. Manually record test cell electrolyte temperatures and

specific gravities (DOD) every 30 minutes.

13. The DAS will read, process, and store data every three minutes. When the voltage of any one of the nine modules reaches 6.8 V, the DAS will monitor, but not record, the module voltages continuously and display their voltages on the CRT screen. Any module falling below 6.8 V must be checked manually for polarity reversal. If reversal occurs, the discharge must be stopped immediately. Otherwise, the test continues until terminal battery voltage reaches 61.2 V (100% DOD).
14. When terminal voltage reaches 61.2 V, a final data set is recorded and the switch connecting the battery to the resistive load is opened, terminating the discharge test.

<u>Data collected:</u>

1. Discharge current, (A)
2. Battery voltage, (V)
3. Electrolyte temperature of four randomly selected cells, (^{o}C)
4. Module voltage of groups of four cells, (V)
5. Battery DOD from manual specific gravity readings of two test cells, (%)
6. Manual electrolyte temperature of two test cells, (^{o}C)
7. Time of discharge, (min)

<u>Calculated values:</u>

1. dc battery energy, (kWh) =
   Voltage (V) * Discharge current (A) * Time (hr)
2. Battery capacity, (Ah) =
   Discharge current (A) * Time (hr)

B-2: Battery charge test procedures:

Procedures:

1. Perform charge test immediately after discharge test if electrolyte temperature allows. Damage to the battery could occur if left at 100% DOD for more than a short time.
2. Disconnect resistive load from battery leads and connect the battery charger.
3. Reverse DAS and portable DMM leads on the in-line current shunt.
4. Modify controlling program termination criteria to be zero or negative current flow.
5. Check electrolyte temperature. If above 30°C, ventilate to cool and delay charging until temperature reaches 30°C or less.
6. Replace data tape with a blank cartridge.
7. Record the ac energy reading from the charger's power meter and the specific gravity level of the battery.
8. Initialize the DAS in the same manner as for the discharge tests.
9. Turn the charger to "Daily Charge" setting.
10. Wait two to three seconds for the system to stabilize and start the DAS.
11. Monitor three or four data collection cycles to be sure the DAS is operating correctly.
12. Further supervision is not required and manual specific gravity and electrolyte temperature readings need not be made unless the data is desired. The charge test is expected to take 13 to 17 hours to complete.
13. When the charging test is complete, disconnect charger from battery. Record ac energy reading from charger meter and battery specific gravity.
14. If complete battery tests are being performed the following procedures should be included:
    - Supervise the entire charging process until complete.
    - Monitor and record specific gravity and electrolyte temperature manually every 30 minutes.

Data collected:

1. Charge current, (A)
2. Battery voltage, (V)
3. Electrolyte temperature of four randomly selected cells, (°C)
4. Module voltage of groups of four cells, (V)
5. Battery DOD from manual specific gravity readings of two test cells, (%)*

6. Manual electrolyte temperature of two test cells, (°C)*
7. Time of charge, (min)
8. ac energy input, (kWh)

*If complete supervision is provided for entire test.

Calculated values:

1. dc battery energy input, (kWh) =
   Voltage (V) * Charge current (A) * Time (hr)
2. Battery capacity, (Ah) =
   Charge current (A) * Time (hr)

B-3: Loader operation test procedures:

Lift/Lower test procedures:

1. Maneuver Skidtric into testing position and block wheels to prevent undesired rolling during testing.
2. Check battery DOD. If greater than 40% DOD, recharge battery to ensure adequate energy to complete tests.
3. Initialize DAS:

   a. Enter background data:
      1. filename,
      2. test date and time,
      3. battery SoC,
      4. test operator name,
      5. test name,
      6. environmental temperature and wind speed,
      7. test location and surface conditions, and
      8. desired length of test, (120 s).

   b. Select desired channels.
   c. Check transducers:
      1. correct null signals, and
      2. proper operation/signal generation.

   d. Place DAS in holding state.
   e. Replace program tape with blank data tape.

4. Place load in Skidtric's bucket and secure it.
5. Use hydraulic on-demand feature.
6. Tilt the bucket to maximum roll-back position.
7. Lift and lower the loader several times at maximum rate without the DAS to check Skidtric for proper operation and to get a feeling for the vehicle controls and timing.
8. Let hydraulics motor stop and system stabilize.
9. Start DAS and wait one or two seconds.
10. Raise the loader to maximum height at maximum possible rate.
11. Let the hydraulic motor stop.
12. Lower the loader to lowest position at the maximum possible rate.
13. Let the hydraulic motor stop.
14. Repeat steps 10 - 13 for a total of seven cycles. If, at any point, a complete lift/lower cycle cannot be completed in the time remaining before the DAS terminates data collection, stop and let the time expire.
15. The loader should be in the lowered position with the motor off at the end of the test.
16. The computer will process raw data and store the desired parameters on a data tape. Change bucket load during

this time if necessary.

17. Repeat steps 4 - 16 at each load three times consecutively. Use the loads in ascending, descending, and ascending order of weight to minimize handling for a total of nine replications (or 54 runs).
18. When data tape is full, insert a blank cartridge and press "CONTINUE".
19. At end of complete test, check battery DOD and charge if greater than 70%. If DOD is between 50% and 70%, operate to discharge to 70 - 80% and then recharge.

Load values used:

Load number	Weight value (kN)
1	zero (empty bucket)
2	1.51
3	3.48
4	4.166
5	6.036
6	7.646

Data collected:

1. Current to the hydraulics motor, (A)
2. Battery voltage, (V)
3. Time of test, (s)

Calculated values:

1. Battery power (kW) = $\frac{[\text{voltage (V)} * \text{current (A)}]}{1000}$
2. Calculated power (kW) = load (kN) * rate of load movement (m/s)
3. Battery energy (Wh) = Battery power (kW) * Time (s) * 3600 $\frac{(s)}{hr}$ * 1000 $\frac{(W)}{kW}$
4. Efficiency (%) = $\frac{[\text{Calculated power (kW)}]}{\text{Battery power (kW)}}$ * 100%

B-4: Bucket operation:

Test procedures:

1. Maneuver Skidtric into testing position and block wheels to prevent undesired rolling during testing.
2. Check battery DOD. If greater than 40% DOD, recharge battery to ensure adequate energy to complete tests.
3. Initialize DAS:

    a. Enter background data:
        1. filename,
        2. test date and time,
        3. battery SoC,
        4. test operator name,
        5. test name,
        6. environmental temperature and wind speed,
        7. test location and surface conditions, and
        8. desired length of test, (120 s).
    b. Select desired channels.
    c. Check transducers:
        1. correct null signals, and
        2. proper operation/signal generation.
    d. Place DAS in holding state.
    e. Replace program tape with blank data tape.

4. Place load in Skidtric's bucket and secure it.
5. Use hydraulic on-demand feature.
6. Raise the loader high enough so that neither the bucket nor the load contacts the floor during the tests.
7. Tilt the bucket to maximum roll-back position.
8. Dump-off and tilt-back the bucket several times at maximum rate without the DAS to check Skidtric for proper operation and to get a feeling for the vehicle controls and timing.
9. Let hydraulics motor stop and system stabilize.
10. Start DAS and wait one or two seconds.
11. Dump the bucket to the maximum down position at maximum possible rate.
12. Let the hydraulic motor stop.
13. Tilt-back the bucket to maximum rolled-back position at the maximum possible rate.
14. Let the hydraulic motor stop.
15. Repeat steps 11 - 14 for a total of seven cycles. If, at any point, a complete dump/tilt cycle cannot be completed in the time remaining before the DAS terminates data collection, stop and let the time expire.
16. The bucket should be in the maximum rolled-back position

with the motor off at the end of the test.

17. The computer will process raw data and store the desired parameters on a data tape. Change bucket load during this time if necessary.
18. Replicate steps 4 - 17 at each load three times consecutively. Use the loads in ascending order of weight to minimize handling.
19. When data tape is full, insert a blank cartridge and press "CONTINUE".
20. At end of complete test, check battery DOD and charge if greater than 70%. If DOD is between 50% and 70%, operate to discharge to 70 - 80% and then recharge.

Load values used:

Load number	Weight value (kN)
1	zero (empty bucket)
2	1.51
3	3.48

Data collected:

1. Current to the hydraulics motor, (A)
2. Battery voltage, (V)
3. Time of test, (s)

Calculated values:

1. Battery power (kW) = $\frac{[\text{voltage (V)} * \text{current (A)}]}{1000}$
2. Calculated power (kW) = load (kN) * rate of load movement (m/s)
3. Battery energy (Wh) = Battery power (kW) * Time (s) * 3600 $\frac{(s)}{hr}$ * 1000 $\frac{(W)}{kW}$
4. Efficiency (%) = $\frac{[\text{Calculated power (kW)}]}{\text{Battery power (kW)}}$ * 100%

B-5: Constant velocity draft operation:

Test procedures:

1. Check battery DOD. If greater than 40% DOD, recharge battery to ensure adequate energy to complete tests.
2. Drive Skidtric and load vehicle (if any) to test track.
3. Maneuver Skidtric and load into a position that allows a straight run with no steering required and connect them via a three-point hitch dynamometer mounted on the load vehicle's three-point hitch.
4. Initialize DAS:

   a. Enter background data:
      1. filename,
      2. test date and time,
      3. battery SoC,
      4. test operator name,
      5. test name,
      6. environmental temperature and wind speed,
      7. test location and surface conditions, and
      8. desired length of test, (60 s).

   b. Select desired channels.

   c. Check transducers:
      1. correct null signals, and
      2. proper operation/signal generation.

   d. Place DAS in holding state.

   e. Replace program tape with blank data tape.

5. Accelerate Skidtric, towing load vehicle in neutral, to the specified speed. Maintain this speed for a few seconds to be sure speed is stable before starting DAS.
6. Monitor speed with a portable DMM connected to the fifth wheel speed sensor.
7. Start DAS and maintain specified speed until DAS stops data collection.
8. At end of test, computer will process raw data and store on tape. During this time, reposition Skidtric and load vehicle for next, straight-line run.
9. Repeat steps 4 - 8 using each load vehicle consecutively, but randomly assigning each of the four target speeds.
10. Replicate the entire test three times.
11. When data tape is full, replace with blank cartridge and press "CONTINUE".
12. At end of test, check DOD. If greater than 70%, recharge the battery. If between 50% and 70%, operate to 70% - 80%, then recharge.

Load vehicles used:

Load vehicle	Approx. Draft Value (kN)	Total
Skidtric' RR	1.66 (no load roll. resistance)	1.66
sm. tractor	1.3 (plus Skidtric's RR)	2.96
lg. tractor	2.5 (" " ")	4.16
2 lg. trac.	5.0 (" " ")	6.66

Target velocities used:

Speed number	Target value (m/s)
1	0.5
2	1.0
3	2.0
4	3.0

Data collected:

1. Current to the traction motors, (A)
2. Battery voltage, (V)
3. Ground speed, (m/s)
   a. apparent speed from motor speed sensor
   b. true speed from fifth wheel speed sensor
4. Draft from three-point hitch dynamometer, (kN)
5. Time of each run, (s)

Calculated values:

1. Battery power (kW) = $\frac{[\text{voltage (V)} * \text{current (A)}]}{1000}$
2. Calculated power (kW) = load (kN) * true ground speed (m/s)
3. Battery energy (Wh) = Battery power (kW) * Time (s) * 3600 $\frac{(s)}{hr}$ * 1000 $\frac{(W)}{kW}$
4. Efficiency (%) = $\frac{[\text{Calculated power (kW)}]}{\text{Battery power (kW)}}$ * 100%

B-6: Acceleration draft operation:

Test procedures:

1. Check battery DOD. If greater than 40% DOD, recharge battery to ensure adequate energy to complete tests.
2. Drive Skidtric and load vehicle (if any) to test track.
3. Maneuver Skidtric and load into a position that allows a straight run with no steering required and connect them via a three-point hitch dynamometer mounted on the load vehicle's three-point hitch.
4. Initialize DAS:

    a. Enter background data:
        1. filename,
        2. test date and time,
        3. battery SoC,
        4. test operator name,
        5. test name,
        6. environmental temperature and wind speed,
        7. test location and surface conditions, and
        8. desired length of test, (60 s).
    b. Select desired channels.
    c. Check transducers:
        1. correct null signals, and
        2. proper operation/signal generation.
    d. Place DAS in holding state.
    e. Replace program tape with blank data tape.

5. Start DAS and let sit for one to two seconds.
6. Accelerate Skidtric and towed load vehicle to maximum possible speed at mmaximum acceleration rate by moving Skidtric's control lever instantaneously to the maximum speed position and holding it there until maximum speed is reached.
7. Monitor vehicle speed with a portable DMM connected to the fifth wheel speed sensor.
8. When maximum speed is reached, release Skidtric's control lever and brake the vehicles to a stop.
9. Tighten the chain/cable connecting Skidtric to the load vehicle slowly.
10. Stop for one to two seconds.
11. Repeat step 6 - 10 until the DAS ends data collection. If a full acceleration cannot be completed in the remaining time, allow the time to expire.
12. At the end of the test time, the computer will process and store the collected data. During this time, reposition Skidtric and the load vehicle for the next run.

13. Replicate the test three times.
14. When data tape is full, replace with a blank cartridge.
15. At end of test, check DOD. If greater than 70%, recharge the battery. If between 50% and 70%, operate to 70% - 80%, then recharge.

Load vehicles used:

Load vehicle	Approx. Average Draft Value (kN)	Total
Skidtric' RR	1.66 (no load roll. resistance)	1.66
sm. tractor	2.0 (plus Skidtric's RR)	3.66
lg. tractor	5.0 (" " ")	6.66
2 lg. trac.	7.5 (" " ")	9.16

Target velocity used:

Maximum possible for each draft load.

Data collected:

1. Current to the traction motors, (A)
2. Battery voltage, (V)
3. Ground speed, (m/s)
    a. apparent speed from motor speed sensor
    b. true speed from fifth wheel speed sensor
4. Draft from three-point hitch dynamometer, (kN)
5. Time of each run, (s)

Calculated values:

1. Battery power (kW) = $\frac{[\text{voltage (V)} * \text{current (A)}]}{1000}$
2. Calculated power (kW) = load (kN) * true ground speed (m/s)
3. Battery energy (Wh) = Battery power (kW) * Time (s) * 3600 $\frac{(s)}{hr}$ * 1000 $\frac{(W)}{kW}$
4. Efficiency (%) = $\frac{[\text{Calculated power (kW)}]}{\text{Battery power (kW)}}$ * 100%

B-7: Turning Operation:

Test procedures:

1. Check battery DOD. If greater than 40% DOD, recharge battery to ensure adequate energy to complete tests.
2. Maneuver Skidtric into testing position.
3. Initialize DAS:

    a. Enter background data:
        1. filename,
        2. test date and time,
        3. battery SoC,
        4. test operator name,
        5. test name,
        6. environmental temperature and wind speed,
        7. test location and surface conditions, and
        8. desired length of test, (30 s).

    b. Select desired channels.

    c. Check transducers:
        1. correct null signals, and
        2. proper operation/signal generation.

    d. Place DAS in holding state.

    e. Replace program tape with blank data tape.

4. Place load in Skidtric's bucket and secure it.
5. Operator must note position of Skidtric so 90° turns can be made.
6. Turn through several trial runs at maximum turning rate. (Use either right or left turns through ALL tests.) Move control lever to maximum turning position. Use the same position during all tests for repeatability.
7. Start DAS and wait one to two seconds.
8. Turn through 90° angle by quickly moving control lever to maximum turn position.
9. Release lever so that Skidtric stops at 90° from its original position. If Skidtric will not complete a full 90° turn, continue to hold control lever in the full turn position until time expires and measure the angle turned through.
10. Wait one to two seconds.
11. Repeat steps 8 - 10 until time expires. Do not start a turn if it cannot be completed before time expires.
12. At the end of the test, the computer will process and store the collected data. During this time, change bucket loads and reposition Skidtric, if necessary.
13. Replicate the test three times consecutively for each load.
14. When data tape is full, replace with a blank cartridge.

15. At end of test, check DOD. If greater than 70%, recharge the battery. If between 50% and 70%, operate to 70% - 80%, then recharge.

Load values used:

Load number	Weight value (kN)
1	zero (empty bucket)
2	1.51
3	3.48
4	4.166
5	6.036
6	7.646

Data collected:

1. Current to traction motors, (A)
2. Battery voltage, (V)
3. Time length of test, (s)
4. Angle turned through (if less than 90^{o}), (deg)

Calculated values:

1. Battery power (kW) = $\frac{\text{Current (A)} * \text{Voltage (V)}}{1000}$
2. Calculated power (kW) = Turn rate (deg/s) * $(T_f + T_m)$

where:

$$T_f = 0.71 * (LOAD + 28) * (0.5 * PI * r_a)$$

where:
T_f = friction torque, (kN-m)
0.71 = coefficient of friction
LOAD = bucket load carried, (kN)
28 = Skidtric's empty vehicle weight, (kN)
r_a = average radius of arc moved by tires, (m)
$0.5*PI*r_a$ = circumference of 90^{o} arc of radius r_a, (m)

$$T_m = \frac{m * (l^2 + w^2) * a}{12}$$

where: T_m = mass torque, (kN-m)

a = angular acceleration, (rad/s^2)

$m*(l^2+w^2)/12$ = moment of inertia of rectangular prism

m = total vehicle and load mass, $\frac{(LOAD + 28(kN))}{9.81\ m/s^2}$ (metric ton)

l = vehicle length, (m)

w = vehicle width, (m)

3. Turn rate (deg/s) = Angle turned (deg)/Turn time (s)
4. Efficiency (%) = $\frac{[\text{Calculated power (kW)}]}{\text{Battery power (kW)}}$ * 100%
5. Battery energy (Wh) =

   Battery power (kW) * Time (s) * 3600 $\frac{(s)}{hr}$ * 1000 $\frac{(W)}{kW}$

B-8: Duration Operation:

Test procedures:

1. Charge Skidtric's battery to 100% SoC (0% DOD).
2. Remove DAS.
3. Drive Skidtric to test track (packed and graded gravel).
4. Mark 30-m, straight line distance.
5. Position Skidtric at one end of 30-m track.
6. Record time to nearest minute.
7. Start hydraulic motor and let run during entire test. (On-demand feature was not connected at the time of the original test.)
8. Accelerate to full forward velocity.
9. Maintain constant, maximum velocity for remainder of 30-m distance.
10. Stop vehicle by plug braking.
11. Turn Skidtric 180^{o} to face the original starting point.
12. Raise and lower empty loader five times at maximum rate.
13. Repeat step 8 - 12 until battery SoC reaches 80% DOD. Check DOD by specific gravity with hydrometer every 30 minutes until 70% DOD, then every 15 minutes until DOD reaches 80%.
14. At 80% DOD, record time from same clock to nearest minute.
15. Return Skidtric to storage building and recharge batteries.

Loads used:

None.

Data collected:

1. Total time of operation, (minutes)

Calculated variables:

None.

B-9: Model Check Test:

Test procedures:

1. Check Skidtric's battery DOD, if greater than 60%, recharge.
2. Measure 30-m distance on level asphalt.
3. Position load vehicle at one end of 30-m track. Attach three-point dynamometer to load vehicle's hitch.
4. Place bucket load in Skidtric's bucket.
5. Drive Skidtric to end of track opposite the draft load vehicle.
6. Initialize DAS:

    a. Enter background data:
        1. filename,
        2. test date and time,
        3. battery SoC,
        4. test operator name,
        5. test name,
        6. environmental temperature and wind speed,
        7. test location and surface conditions, and
        8. desired length of test, (120 s).
    b. Select desired channels.
    c. Check transducers:
        1. correct null signals, and
        2. proper operation/signal generation.
    d. Place DAS in holding state.
    e. Replace program tape with blank data tape.

7. Start DAS.
8. Raise and lower Skidtric's loader with load two times at maximum rate.
9. Accelerate Skidtric to 2.0 m/s. Monitor speed with portable DMM connected to fifth wheel speed sensor.
10. Maintain constant 2.0 m/s for remainder of 30-m track.
11. Stop Skidtric by manual braking.
12. Turn Skidtric 90^{o} with bucket load.
13. Accelerate forward two meters.
14. Stop with manual brakes and hold position.
15. Raise and lower loader with bucket load once.
16. Remove bucket load without using hydraulic motor to dump bucket.
17. Accelerate two meters backwards.
18. Turn 90^{o} without bucket load.
19. Let time remaining in first, 120-s test segment expire.
20. Computer will process and store collected data.
21. Maneuver Skidtric to draft load and connect vehicles and dynamometer signal lines.

22. Start DAS.
23. Accelerate Skidtric and load vehicle to 2.5 m/s.
24. Maintain constant 2.5 m/s for 10 m.
25. Stop by manual braking.
26. Accelerate Skidtric and load vehicle to 1.5 m/s. (Tighten chain slowly first.)
27. Maintain constant 1.5 m/s for remainder of 30-m track (approximately 15 m).
28. Stop by manual braking.
29. Turn Skidtric 90^o with no bucket load.
30. Raise and lower empty loader once.
31. Allow remaining DAS time to expire.
32. Computer will process and store data.
33. Disconnect Skidtric and draft load vehicle.
34. Reposition draft vehicle at its starting position.
35. Place load in Skidtric's bucket and secure.
36. Reposition Skidtric in its starting position.
37. Replicate test (steps 7-36) three times.
38. When data tape is full, replace with blank cartridge and press "CONTINUE".
39. Check battery DOD. If greater than 70%, recharge. If between 50% and 70%, operate Skidtric to discharge battery, then recharge.

Loads used:

Bucket load: 1.869 kN
Draft load: 2.0 kN (large tractor)

Data collected:

1. Current to traction motors, (A)
2. Current to hydraulics motor, (A)
3. Battery voltage, (V)
4. Ground speed, (m/s)
   a. true speed from fifth wheel
   b. apparent speed from motor speed sensor(s)
5. Draft, (kN)
6. Time of each segment, (s)

Calculated values:

1. Battery power (kW) = $\frac{[\text{voltage (V)} * \text{current (A)}]}{1000}$
2. Calculated power (kW) = load (kN) * true ground speed (m/s)
3. Battery energy (Wh) = Battery power (kW) * Time (s) * 3600 $\frac{(s)}{hr}$ * 1000 $\frac{(W)}{kW}$
4. Efficiency (%) = [Calculated power (kW)] * 100%

Battery power (kW)

5. Equation accuracy = matched pair, t-tests
6. Model accuracy (%) =

$$\frac{[\text{Model pred. energy (kWh) - Measured energy (kWh)}]}{\text{Measured energy (kWh)}}*100\%$$

APPENDIX C: EQUATION DEVELOPMENT DATA

Table C-1. Lift Operation Test Data

Bucket Load	Replication	Motor Current (A)	Battery Voltage (V)	Lift Time[1] (S)	Battery Power (kW)
0	1	102	71.5	4.0	7.26
0	2	101	71.3	4.0	7.19
0	3	107	71.4	3.9	7.62
0	4	87	70.5	3.6	6.10
0	5	97	70.3	3.7	6.78
0	6	104	70.3	3.8	7.27
0	7	92	70.5	3.8	6.41
0	8	97	70.3	3.8	6.80
0	9	92	70.3	3.7	6.43
1.51	1	104	71.0	4.2	7.37
1.51	2	106	70.9	4.0	7.49
1.51	3	119	70.8	4.0	8.40
1.51	4	101	69.9	4.0	7.05
1.51	5	98	69.9	3.9	6.82
1.51	6	106	69.8	3.9	7.40
1.51	7	103	69.5	3.8	7.11
1.51	8	100	69.5	3.9	6.91
1.51	9	94	69.5	3.8	6.52
3.48	1	133	69.9	4.2	9.25
3.48	2	129	70.0	4.2	8.99
3.48	3	135	70.1	4.4	9.41
3.48	4	117	69.2	4.1	8.08
3.48	5	118	69.2	4.1	8.13
3.48	6	121	69.1	4.2	8.30
3.48	7	109	68.7	4.2	7.45
3.48	8	114	68.6	4.2	7.79
3.48	9	118	68.5	4.2	8.06
4.166	1	130	69.8	4.3	9.05
4.166	2	128	69.7	4.2	8.87
4.166	3	130	69.7	4.3	9.06
4.166	4	144	68.2	4.5	9.81
4.166	5	125	69.0	4.3	8.58
4.166	6	127	69.0	4.2	8.76
4.166	7	116	68.1	4.2	7.88
4.166	8	122	68.1	4.3	8.30
4.166	9	122	67.9	4.3	8.27

Table C-1. Lift Operation Test Data (cont.)

Bucket Load	Replication	Motor Current (A)	Battery Voltage (V)	Lift Time[1] (S)	Battery Power (kW)
6.036	1	150	68.8	4.4	10.26
6.036	2	144	68.7	4.5	9.90
6.036	3	140	68.8	4.4	9.65
6.036	4	152	67.9	4.7	10.29
6.036	5	147	68.3	4.5	10.02
6.036	6	137	68.4	4.5	9.34
6.036	7	138	67.0	4.5	9.25
6.036	8	138	67.1	4.7	9.19
6.036	9	142	66.8	4.4	9.47
7.646	1	155	68.3	4.6	10.56
7.646	2	154	68.0	4.5	10.45
7.646	3	151	68.0	4.6	10.26
7.646	4	162	68.2	4.7	11.01
7.646	5	150	68.0	4.6	10.16
7.646	6	148	67.9	4.4	10.03
7.646	7	159	66.2	4.7	10.48
7.646	8	163	66.2	4.8	10.77
7.646	9	154	66.1	4.7	10.18

[1]Full loader movement from lowest position to maximum height.

Table C-2. Lower Operation Test Data

Bucket Load	Replication	Motor Current (A)	Battery Voltage (V)	Lower Time[1] (S)	Battery Power (kW)
0	1	127	70.3	4.2	8.90
0	2	124	70.2	3.2	8.70
0	3	113	70.3	3.4	7.96
0	4	105	69.1	3.4	7.25
0	5	144	69.0	3.2	9.90
0	6	116	68.8	2.9	7.94
0	7	112	69.0	3.1	7.74
0	8	119	68.8	3.0	8.15
0	9	110	68.8	3.1	7.55
1.51	1	101	70.8	3.6	7.15
1.51	2	104	70.5	3.2	7.29
1.51	3	104	70.7	3.2	7.26
1.51	4	91	69.8	3.6	6.34
1.51	5	110	69.4	3.2	7.61
1.51	6	119	69.4	3.2	8.26
1.51	7	106	69.2	3.2	7.36
1.51	8	110	69.1	3.2	7.58
1.51	9	109	69.0	2.9	7.52
3.48	1	97	71.1	3.2	6.91
3.48	2	105	70.9	2.9	7.43
3.48	3	112	71.0	3.2	7.95
3.48	4	97	70.1	2.9	6.76
3.48	5	104	70.3	3.4	7.29
3.48	6	111	70.0	2.9	7.76
3.48	7	100	69.4	2.8	6.91
3.48	8	110	69.4	2.9	7.57
3.48	9	90	69.4	3.0	6.25
4.166	1	110	71.0	2.7	7.80
4.166	2	93	70.9	2.7	6.60
4.166	3	99	71.0	3.2	6.97
4.166	4	78	71.0	3.6	5.54
4.166	5	95	70.6	3.4	6.68
4.166	6	90	70.5	3.1	6.35
4.166	7	95	69.6	3.0	6.58
4.166	8	95	69.6	3.1	6.56
4.166	9	81	69.6	3.4	5.65

Table C-2. Lower Operation Test Data (cont.)

Bucket Load	Replication	Motor Current (A)	Battery Voltage (V)	Lower Time[1] (S)	Battery Power (kW)
6.036	1	71	71.5	3.6	5.07
6.036	2	88	71.2	3.2	6.23
6.036	3	84	71.4	3.2	5.97
6.036	4	74	71.4	3.9	5.29
6.036	5	86	71.0	3.6	6.08
6.036	6	74	71.0	3.5	5.25
6.036	7	77	69.9	3.4	5.38
6.036	8	79	69.7	3.0	5.49
6.036	9	75	69.9	3.6	5.24
7.646	1	74	71.4	3.0	5.29
7.646	2	80	71.4	3.2	5.69
7.646	3	77	71.6	4.0	5.48
7.646	4	88	71.7	4.3	6.29
7.646	5	78	71.4	3.4	5.57
7.646	6	82	71.4	3.3	5.87
7.646	7	67	70.2	4.2	4.68
7.646	8	63	70.2	3.9	4.40
7.646	9	79	70.1	3.9	5.49

[1]Full loader movement from maximum height to lowest position.

Table C-3. Dump Operation Test Data

Bucket Load (kN)	Replication	Motor Current (A)	Battery Voltage (V)	Dump Time (S)	Battery Energy (Wh)
0	1	175	70.6	2.7	5.3
	2	169	71.0	2.4	4.5
	3	152	70.7	2.5	4.1
1.51	1	169	70.6	2.4	4.4
	2	172	70.1	2.2	4.3
	3	174	70.2	2.2	4.3
3.48	1	186	70.1	2.9	5.9
	2	183	70.3	2.4	4.9
	3	171	70.4	2.6	4.9

Table C-4. Tilt-back Operation Test Data

Bucket Load (kN)	Replication	Motor Current (A)	Battery Voltage (V)	Tilt Time (S)	Battery Energy (Wh)
0	1	75	73.6	2.0	1.7
	2	86	73.6	1.9	2.0
	3	88	73.4	2.2	2.2
1.51	1	81	73.5	1.9	1.8
	2	81	73.7	1.7	1.7
	3	75	73.6	2.1	1.9
3.48	1	120	73.5	2.5	3.5
	2	79	74.1	1.7	1.6
	3	79	73.9	2.1	2.0

Table C-5. Constant Velocity Draft Operation Test Data

Draft (kN)	Ground-Speed (n/s)	Motor Current (A)	Battery Voltage (V)	Battery Power (kW)
1.66	.7	30	72.2	2.14
1.66	.8	29	71.9	2.07
1.66	.9	27	72.3	1.96
1.66	1.0	37	71.6	2.63
1.66	1.0	72	32.3	2.32
1.66	1.1	35	71.4	2.52
1.66	2.0	53	70.8	3.75
1.66	2.0	62	69.9	4.36
1.66	2.0	53	70.2	3.69
1.66	2.9	79	68.6	5.41
1.66	3.0	78	69.3	5.41
1.66	3.1	83	69.4	5.78
2.3	.5	29	74.6	2.18
2.6	.6	31	73.9	2.32
2.7	.6	41	72.9	3.01
2.4	1.0	46	73.7	3.36
2.4	1.1	42	72.9	3.05
2.5	1.1	50	72.8	3.63
2.4	1.9	73	72.2	5.25
2.6	1.9	78	71.5	5.58
2.6	2.1	78	70.8	5.54
2.5	2.7	111	70.6	7.82
2.5	3.0	112	70.1	7.88
2.6	3.0	121	69.4	8.38
2.6	3.0	117	68.9	8.06
2.6	3.3	109	69.2	7.52
3.4	.6	53	71.1	3.77
3.3	.6	52	71.9	3.74
3.1	.6	54	72.4	3.91
3.6	1.0	85	70.0	5.98
3.6	1.1	89	70.3	6.25
3.8	1.2	113	69.9	7.86
4.1	1.9	163	66.3	10.80
4.3	2.0	180	67.5	12.14
4.0	2.0	163	67.2	10.97
4.7	2.7	275	63.3	17.40
4.8	2.8	287	64.0	18.34
4.6	2.9	253	62.9	15.92
5.6	.7	97	73.3	7.09
5.7	.7	103	73.0	7.52
5.8	.7	111	72.1	8.00
6.0	1.0	137	71.8	9.84
6.0	1.1	145	70.7	10.27
6.0	1.2	151	71.4	10.75
6.7	2.1	277	66.2	18.35
6.9	2.1	289	66.9	19.29
7.0	2.2	323	64.9	20.96
7.2	2.4	350	63.3	22.11
7.4	2.4	356	64.1	22.85
7.3	2.5	354	65.1	23.04

Table C-6. Acceleration Operational Test Data

Load Number	Replication	Draft (kN)	Average Speed (M/S)	Motor Current (A)	Battery Voltage (V)	Time (S)	Battery Power (kW)
1	1	1.66	2.9	221	64.4	4.0	14.21
	2	1.66	2.8	231	64.2	4.1	14.62
	3	1.66	2.8	228	63.9	3.8	14.59
2	1	4.0	2.6	275	62.9	5.7	16.86
	2	4.0	2.6	261	62.3	5.3	16.14
	3	4.2	2.5	275	62.0	5.7	16.79
3	1	7.9	2.0	387	61.4	6.1	23.49
	2	7.0	1.9	371	61.7	5.5	22.41
	3	7.5	1.8	384	60.8	4.9	22.99
4	1	9.7	1.5	438	60.0	7.7	26.06
	2	9.7	1.5	435	59.9	7.2	25.46
	3	9.7	1.7	430	59.9	8.5	25.29

Table C-7. Turning Operation Test Data

Bucket Load (kN)	Replication	Motor Current (A)	Battery Voltage (V)	Turn Rate (deg/S)	Turn Time (S)	Battery Power (kW)
0	1	373	62.4	103.2	.9	22.83
	2	343	61.9	86.5	1.0	20.60
	3	349	60.9	89.6	1.0	20.88
1.51	1	449	59.7	34.3	2.6	26.64
	2	399	61.4	24.3	3.7	23.56
	3	453	59.1	19.4	4.6	26.53
3.48	1	470	53.9	12.9	7.0	25.25
	2	452	54.6	9.4	9.6	24.13
	3	475	52.4	11.8	7.6	24.05
4.166	1	455	55.8	10.7	8.4	25.39
	2	476	53.0	11.4	7.9	24.94
	3	479	51.8	3.6	16.6	24.82
6.036	1	426	59.6	40.3	2.2	24.77
	2	403	60.1	35.3	2.6	23.63
	3	458	58.1	33.0	2.7	26.27
7.646	1	439	55.6	1.9	30[1] (60)	24.29
	2	466	52.9	2.0	30[1] (60)	24.66
	3	469	52.5	.49	30[1] (15)	24.61

[1]Maximum test time. Test ended before one-90^{o} turn was completed. Numbers in ( ) indicate angle turned in degrees.

APPENDIX D: PREDICTION MODEL

<u>Note:</u> Equation predictions are valid only for input values within the ranges used for equation development. These ranges were:

	Minimum	Maximum
Loader bucket loads and turning (kN)	0	7.646
Applied draft loads: constant velocity and acceleration (kN)	0	5.5
Ground speed (m/s)	0.5	3.0

Load values outside these ranges will produce results, but the accuracy of those results cannot be assured. For example, ground speeds of less than 0.5 m/s with a zero kN draft load produce negative power and energy values.

```
5 '=========================================================================
10 '                   EC-II ENERGY USE COMPUTER MODEL
   '       Written: June 1986.     By:  Gregg Hanson.      Updated: 27 Mar 1987
20 '  Purpose: predict energy requirements of EC-II using relationships derived
   '  from testing.
25 '=========================================================================
30 'CLS:LOCATE 8,20:PRINT"SKIDTRIC ENERGY USE COMPUTER MODEL":LOCATE 10,12:PRINT
"Written by: Gregg Hanson.   Updated: March   1987":FOR I=1 TO 3000:NEXT I:CLS
31 GOSUB 10000
32 GOSUB 11000
33 CLEAR
34 CLEAR:CLS:LOCATE 4:PRINT"Enter task routine name:":INPUT I$
35 '-------------------------------------------------------------------------
    - Initialize arrays & variables & set = zero. ----------------------------
    --------------------------------------------------------------------------
36 CLS:LOCATE 8,8:PRINT "Do you want the results printed to a file (f), sent to
 the printer (p), or      printed on the screen (s)?":O$=INPUT$(1):
37 IF O$="s" OR O$="S" THEN FILE$="SCRN:" : GOTO 90
38 IF O$="p" OR O$="P" THEN FILE$="LPT1:" : GOTO 90
40 CLS:LOCATE 8,8:PRINT "What file do you want the results printed to?":INPUT FI
LE$
90 CLS:LOCATE 8:PRINT"Enter the number of segments in routine, if greater than 5
0. ENTER for default.":INPUT Z
91 IF Z=0 THEN Z=50
92 OPEN FILE$ FOR OUTPUT AS #2:WIDTH#2,80
93 DIM LLOAD(Z),SPEED(Z),ANGLE(Z),TIME(Z),TOTIME(Z),POWER(Z),ENERGY(Z),TOTEN(Z),
REENG(Z),T$(Z)
100 TOTEN=0:TOTIME=0 :AVENG=22000:Z=0
110 CLS:LOCATE 8:PRINT"Enter task segments in chronological order of occurance.
The program will promptyou for input. "
112 LOCATE 12,10:PRINT"First segment: A = acceleration":LOCATE 13,25:PRINT"C = c
onstant velocity":LOCATE 14,25:PRINT"T = turn":LOCATE 12,50:PRINT"R = raise load
er":LOCATE 13,50:PRINT"L = lower loader"
113 LOCATE 14,50:PRINT"D = dump bucket":LOCATE 15,50:PRINT"B = tilt back"
    :LOCATE 15,25:PRINT"E = end":LOCATE 16,50:PRINT"I = identical cycle(s)"
    :GOTO 120
114 LLOAD=0: SPEED=0: ANGLE=0: TIME=0: POWER=0: ENERGY=0
116 CLS:LOCATE  8,5:PRINT"Enter next segment: A = acceleration":LOCATE  9,25:PRI
NT"C = constant velocity":LOCATE 10,25:PRINT"T = turn":LOCATE  8,50:PRINT"R = ra
ise loader":LOCATE  9,50:PRINT"L = lower loader"
117 LOCATE 10,50:PRINT"D = dump bucket":LOCATE 11,50:PRINT"B = tilt back":
    LOCATE 11,25:PRINT"E = end":LOCATE 12,50:PRINT"I = identical cycle(s)"
120 S$=INPUT$(1) :IF S$="a" OR S$="A" THEN GOSUB 2000
121 IF S$="T" OR S$="t" THEN GOSUB 4000
122 IF S$="L" OR S$="l" THEN GOSUB 5030
123 IF S$="E" OR S$="e" GOTO 900
124 IF S$="c" OR S$="C" THEN GOSUB 3000
125 IF S$="R" OR S$="r" THEN GOSUB 5000
126 IF S$="D" OR S$="d" THEN GOSUB 5040
127 IF S$="B" OR S$="b" THEN GOSUB 5050
128 IF S$="I" OR S$="i" THEN GOSUB 9000
130 GOTO 114
900 GOSUB 7080
920 HTIME=TOTIME(Z)/3600:RTIME=REENG(Z)*HTIME/TOTEN(Z):TTIME=AVENG*HTIME/
    TOTEN(Z): TETIME=TTIME*1.19:RETIME=RTIME*1.19
```

```
925 PRINT#2,"":PRINT#2,"Total running time used (hrs):  ";:PRINT#2, USING "##.##
#"    ;RTIME
926 PRINT#2, "Total predicted running time remaining (hrs):  ";:PRINT#2, USING
    "##.#";RTIME;:PRINT#2, "  Realistic time (119% predicted):  ";:PRINT#2,
     USING "##.#";RETIME
927 PRINT#2, "Total running time predicted for this cycle (hrs):  ";:PRINT#2,
    USING "##.#";TTIME;:PRINT#2, "  Realistic time (119% predicted):  ";:
     PRINT#2, USING "##.#";TETIME:
928 IF Q$="s" OR U$="S" THEN PRINT:PRINT "Press any key to continue...":Y$=INPUT
$(1)
1000 CLS:LOCATE 8,10:CLOSE:PRINT "Would you like to compute another complete rou
tine?"     :Y$=INPUT$(1):PRINT :IF Y$="Y" OR Y$="y" THEN GOTO 34 ELSE 1130
1130 CLS: LOCATE 8,15: PRINT " Skidtric energy use model complete.":END
2000 '--------------Acceleration subroutine-----------------------------------
2010 T$="Accel"
2015 CLS: PRINT "            Acceleration segments.": PRINT
2020 INPUT "Enter final velocity AFTER acceleration in m/s";SPEED:PRINT
2025 INPUT "Enter the average draft load during acceleration in kN (max.=13 kN)"
;LLOAD :PRINT :LLOAD = LLOAD + 1.66 'for loads entered without rolling resist.
2043 ' - - - - - - Calculate the acceleration rate for given load - - - - - -
2045 ACCEL= .8149726-LLOAD*6.175595E-02   'R-squared= 0..9336
2050 TIME= SPEED/ACCEL : DIST = SPEED * TIME
2053 ' - - - - - - Calculate the acceleration power and energy - - - - -
2055 POWER = LLOAD * 1.453005410 + 11.59509737#   'R-squared= 0.9823
2060 ENERGY = POWER * TIME/3.6     'dividing by 3.6 is equivalent to multiplying
                                    by 1000 W/kW and dividing by 3600 s/min.
2065 TOTEN = TOTEN + ENERGY :TOTIME=TOTIME +TIME :LLOAD=LLOAD-1.66
2070 GOSUB 7000    '- - - - - - send to printing routine - - - - - -
2075 RETURN
3000 '---------------Constant velocity subroutine------------------------
3001 CLS: PRINT "          Constant Velocity segments":PRINT
3002 T$="ConVel"
3005 INPUT "Enter constant velocity operation speed in m/s";SPEED:PRINT
3006 IF SPEED = 0 THEN PRINT "***Zero velocity entered'***":GOTO 3005
3008 INPUT "Enter the draft load during constant velocity (kN)";LLOAD :PRINT
3009 LLOAD=LLOAD + 1.66   'use 3009 for loads w/o Skidtric Rolling resistance--
3011 PRINT "Do you know the TIME or DISTANCE of constant velocity? (T or D)"
   :D$=INPUT$(1): PRINT: IF D$= "T" OR D$="t" GOTO 3025
3015 INPUT "Enter the DISTANCE of constant velocity movement in m";DIST :PRINT
3020 TIME=DIST/SPEED : GOTO 3035
3025 INPUT "Enter the TIME of constant velocity movement in sec";TIME:PRINT
3030 DIST=TIME*SPEED
3035  POWER = LLOAD * 2.713140590 + SPEED * 3.163933090 - 6.890634450
3040 '    R-squared = 0.9222
3045 ENERGY = POWER * TIME/3.6
3050 TOTEN = TOTEN + ENERGY :TOTIME=TOTIME +TIME :LLOAD=LLOAD-1.66
3055 GOSUB 7000
3060 RETURN
4000 '--------------Turning subroutine-----------------------
4001 T$="Turn"
4010 CLS:PRINT "             Turning segments":PRINT
4020 INPUT "Enter the angle turned in degrees";ANGLE:PRINT
4030 INPUT "Enter the load carried through the turn in kN";LLOAD:PRINT
4040 SPEED= 94.62461-LLOAD*73.8597+LLOAD^2*19.35894-LLOAD^3*1.472846
4041 '    goodness of fit= .9590
4045 TIME = ANGLE/SPEED
4050 POWER = LLOAD^3 * 5.446065E-02 - LLOAD^2 *.762849540 + LLOAD * 3.044125810
                 + 21.715038250
4055 '  R-squared= .5749
```

```
4060 ENERGY = POWER * TIME/3.6
4065 TOTEN = TOTEN + ENERGY :TOTIME=TOTIME +TIME:GOSUB 7000
4070 RETURN
5000 '-------------Loader subroutine-------------------------
5010 CLS:PRINT "                  Loader operation segments":PRINT
5020 INPUT "Enter the bucket load to be raised in kN";LLOAD :PRINT
5021 T$="Raise":T=1
5022 TIME = LLOAD * .1099666 + 3.803277   ' R-squared= .8591
5023 INPUT "Enter the % of lift completed (press ENTER for full lift)":T:PRINT
5024 IF T=0 THEN T=1
5025 POWER = LLOAD * .48714677# + 6.70472737#      ' R-squared=.8637
5026 TIME=TIME*T
5027 ENERGY =POWER * TIME/3.6
5028 TOTEN = TOTEN + ENERGY :TOTIME=TOTIME +TIME
5029 GOSUB 7000  :RETURN
5030 CLS:PRINT"           Loader operation segments":  PRINT:
     INPUT "Enter the bucket load to be lowered in kN";LLOAD :PRINT
5031 T$="Lower" :T=1
5032 INPUT "Enter the % of lower completed (press ENTER for full lower)";T
     :PRINT:IF T=0 THEN T = 1
5033 TIME = 3.2987
5034 POWER = 8.15875237# -LLOAD*.38119911#       'R-squared= .7198
5035 TIME = TIME * T
5036 ENERGY = POWER * TIME/3.6
5037 TOTEN = TOTEN + ENERGY :TOTIME=TOTIME +TIME
5038 GOSUB 7000  :RETURN
5040 CLS:PRINT"           Loader operation segment":  PRINT:
     INPUT "Enter the bucket load to be dumped in kN";LLOAD :PRINT
5041 T$="Dump":T=1
5042 INPUT "Enter the % of dump completed (press ENTER for full dump)";T:PRINT
     :IF T=0 THEN T=1
5045 TIME= 2.0056*T: ENERGY = 2.039*T : POWER = 3.6599
5046 TOTEN = TOTEN + ENERGY :TOTIME=TOTIME +TIME
5048 GOSUB 7000  :RETURN
5050 CLS:PRINT"           Loader operation segment":  PRINT:
     INPUT "Enter the bucket load to be tilted back in kN";LLOAD :PRINT
5051 T$="Tiltback":T=1
5052 INPUT "Enter the % of tilt-back completed (press ENTER for full tilt-back)"
     ;T:PRINT:IF T=0 THEN T = 1
5054 TIME= 2.4823*T : ENERGY = 4.73*T  : POWER = 6.8598
5056 TOTEN = TOTEN + ENERGY :TOTIME=TOTIME +TIME
5058 GOSUB 7000  :RETURN
7000 '-----------Printing subroutine-----------------
7001 Z=Z+1:
7010 REENG=AVENG-TOTEN:IF REENG<0 THEN GOSUB 8000
7080 CLS:IF Z$="D" OR Z$="d" GOTO 7082
7081 IF S$="E" OR S$="e" THEN GOTO 7086 ELSE GOTO 7083
7082 LOCATE 8,3:PRINT "Available energy has been used. Skidtric must be recharge
d.":PRINT"Will not print last segment.":Z=Z-1 :GOTO 7086
7083 LLOAD(Z)=LLOAD:SPEED(Z)=SPEED:ANGLE(Z)=ANGLE:TIME(Z)=TIME:TOTIME(Z)=TOTIME:
     POWER(Z)=POWER:ENERGY(Z)=ENERGY:TOTEN(Z)=TOTEN:REENG(Z)=REENG:T$(Z)=T$
7084 IF Z$="I" OR Z$="i" THEN GOTO 7086
7085 RETURN
7086 PRINT#2, I$ 'lprint CHR$(27);"E":LPRINT I$:LPRINT CHR$(27);"F"
7087 PRINT#2, "-----------------------------------------------------------------
----------"
7088 PRINT#2, "-----------------------------------------------------------------
----------":PRINT#2, " Task  : Draft : Speed : Angle :  Time used  :Power :Segme
nt: Cum. : Energy"
7089 PRINT#2, "Segment: /Load : (m/s) : (deg) :  (seconds)  : (kW) :Energy :Ener
gy: Remain"
```

```
7090 PRINT#2, "          :   (N) :(deg/s):         : Seq. : Cum. :        : (Wh)   : (Wh
) :   (Wh)"
7091 PRINT#2, "--------------------------------------------------------------------------
-----------":H2=0
7092 FOR I=1 TO Z
7094 PRINT#2,USING "\     \":T$(I);:PRINT#2,USING "######.#";LLOAD(I),SPEED(I),AN
GLE(I);:PRINT#2,USING"#####.#";TIME(I),TOTIME(I),POWER(I);:PRINT#2,USING "######
.#";ENERGY(I),TOTEN(I);:PRINT#2,USING "#######";REENG(I)
7095 H2=H2+1 : IF H2/30=INT(H2/30) THEN LPRINT CHR$(12):H2=0
7096 'allows 30 lines per page. change denominator for more or less. That is,
      the number in the denominator = the number of lines printed per page.
7097 IF FILE$="SCRN:" AND H2/22=INT(H2/22) THEN PRINT:PRINT "Screen full. Press
any key when ready to continue...":Y$=INPUT$(1)
7098 NEXT I
7190 GOTO 920
7200 RETURN
8000 '-------------Overflow warning subroutine---------------
8010 FOR P=1 TO 3:CLS:LOCATE 8,25: PRINT "   *** WARNING *** " : BEEP
8011 FOR O=1 TO 1500: NEXT O :NEXT P
8020 LOCATE 13:PRINT "***  Total energy requested= ",TOTEN :PRINT "***  Energy a
vailable= ",AVENG :PRINT "***  Excess requested= ",REENG
8030 PRINT : PRINT "Do you wish to include(i) or delete(d) this segment?":
     Z$=INPUT$(1): PRINT
8050 RETURN
9000 '-----------Repeat identical cycle subroutine--------------
9010 CLS:PRINT"Identical cycle energy assumed to equal cumulative total energy t
o present.     Press 'Q' to quit identical cycles or any other key to continue."
:Y$=INPUT$(1)
9015 IF Y$="Q" OR Y$="q" GOTO 9090
9020 PRINT:INPUT "How many ADDITIONAL identical cycles do you want to compute":
     CYCLES :ENERGY = TOTEN
9030 FOR I= 1 TO CYCLES:Z=Z+1
9035 IF Q$="I" OR Q$="i" GOTO 9050
9040 LLOAD(Z)=-0!:SPEED(Z)=-0!:ANGLE(Z)=-0!:TIME(Z)=TOTIME:TOTIME(Z)=TOTIME(Z-1)
     + TOTIME:POWER(Z)=-0!:ENERGY(Z)=TOTEN:TOTEN(Z)=TOTEN(Z-1)+TOTEN:REENG(Z)=
     AVENG-TOTEN(Z)
9045 T$(Z)="Id-cyc":GOTO 9060
9050 TOTEN = TOTEN + ENERGY : REENG=AVENG-TOTEN
9052 TOTIME(Z)=TOTIME(Z-1)+TOTIME:TOTEN(Z)=TOTEN:REENG(Z)=REENG
9055 LPRINT "Identical cycle no. ";I+1;:LPRINT TAB(31);:LPRINT USING "####.###";
     TOTIME,TOTIME(Z);:LPRINT TAB(55);:LPRINT USING "###.####"; ENERGY,TOTEN,
     REENG
9060 NEXT I
9090 RETURN
10000 '-----------Opening animation sequence----------
10005 FOR I= 1 TO 20 STEP 2: CLS
10007 LOCATE 10
10008 PRINT"===================================================================="
10018 LOCATE 5,I:PRINT"            ___  ":LOCATE 5,43:PRINT"****     ":LOCATE 6,I
10020 PRINT"        /     \":LOCATE 6,42:PRINT"******       ":LOCATE 7,I
10030 PRINT"       ::      \":LOCATE 7,41:PRINT"********         ":LOCATE 8,I
10040 PRINT"      SKIDTRIC  \:\_":LOCATE 8,40:PRINT"**********       ":LOCATE 9,I
10050 PRINT"        O     O":LOCATE 9,40:PRINT"**********"
10080  FOR J=1 TO 400: NEXT J: NEXT I
10200 FOR I=1 TO 2:CLS:LOCATE 10
10208 PRINT"===================================================================="
10210 LOCATE 5,20:PRINT"            ___":LOCATE 5,43:PRINT"****":LOCATE 6,20
```

```
10220 PRINT"          /    \":LOCATE 6,42:PRINT"******":LOCATE 7,20
10230 PRINT"         ::       \":LOCATE 7,41:PRINT"*********":LOCATE 8,20
10240 PRINT"       SKIDTRIC  \:\_":LOCATE 8,40:PRINT"**********":LOCATE 9,20
10245 PRINT"         O    O":LOCATE 9,40:PRINT"**********"
10250  FOR J=1 TO 500: NEXT J:CLS:LOCATE 10
10252 PRINT"=======================================**********=================="
10253 LOCATE 3,22
10255 PRINT"              _______:\_*":LOCATE 4,22
10260 PRINT"           /  ":LOCATE 5,21
10270 PRINT"          /  ":LOCATE 5,43:PRINT"****":LOCATE 6,20
10280 PRINT"          :     ":LOCATE 6,42:PRINT"******":LOCATE 7,20
10290 PRINT"         ::":LOCATE 7,41:PRINT"*********":LOCATE 8,20
10300 PRINT"       SKIDTRIC ":LOCATE 8,40:PRINT"**********":LOCATE 9,20
10301 PRINT"         O    O":LOCATE 9,40:PRINT"**********"
10305  FOR J=1 TO 500: NEXT J:NEXT I:CLS:LOCATE 10
10308 PRINT"=========================================**********================="
10310 LOCATE 5,20:PRINT"            ___":LOCATE 5,43:PRINT"****":LOCATE 6,20
10320 PRINT"          /    \":LOCATE 6,42:PRINT"******":LOCATE 7,20
10330 PRINT"         ::       \":LOCATE 7,41:PRINT"*********":LOCATE 8,20
10340 PRINT"       SKIDTRIC  \:\_":LOCATE 8,40:PRINT"**********":LOCATE 9,20
10345 PRINT"         O    O":LOCATE 9,40:PRINT"**********"
10350  FOR J=1 TO 400: NEXT J
10355 LOCATE 14,17 :PRINT"      SPECIFIC TASK ENERGY USE MODEL"
10360 LOCATE 15,31:PRINT"FOR SKIDTRIC"
10365 FOR I=1 TO 3000: NEXT I:RETURN
11000 '---------Music subroutine---------
11010 A$="O3L4E-E-FGE-GFDE-E-FGL2E-L4DP4"
11020 B$="O3L4E-E-FGA-GFE-DO2L4B-O3L4CDL2E-E-"
11030 PLAY "T200XA$;"
11040 PLAY "T200XB$;"
11070 RETURN
```