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Hybrid Diesel-Electric Drivetrain for Small Agricultural Field Machines

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HYBRID DIESEL-ELECTRIC DRIVETRAIN FOR SMALL AGRICULTURAL FIELD MACHINES

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ABSTRACT. *In this project, a series electric drivetrain sized for small agricultural machinery was developed and tested. Electric drives have noted benefits in simplicity, controllability, integration with other electronics such as those that provide autonomous action, and in efficiency over a wide operating range. Their biggest drawback for agricultural use is the limited capacity of electrical energy storage. A series hybrid drivetrain provides a method to overcome these capacity constraints through the use of chemical energy storage. The series hybrid drivetrain in this research was designed using well-established components. It consisted of a diesel-electric generator, a lead acid battery pack, a motor controller, and independent electric motors for each wheel with associated gearboxes to produce speeds and torques suitable for ground drive. Although these components are commercially available, they have not been integrated into a hybrid drivetrain before. The goal of this project was to test this drivetrain to determine its baseline performance and investigate the efficiencies of the various drivetrain components when operating under different conditions. The drivetrain efficiency was tested using a 2 × 2 × 2 factorial test in which the factors were average load level (30% or 40% of full load), load profile type (variable or constant), and size of the battery pack (170 or 340 A·h). The efficiencies of the three main components of the drivetrain were monitored in this testing: the diesel-electric generator, the battery system, and the ground drive. Of the tested factors, only load level had an effect on efficiency and then only on the overall efficiency and on the efficiency of the battery system. The other system components were not appreciably impacted by any of the factors. Large battery packs were not necessary to maintain efficiency even with variable loads, which indicates that future machines could consider more advanced (but more expensive) types of batteries, as less capacity would be required. Agricultural engineers interested in using electric motor drives because of their various benefits can use a series hybrid design to overcome their energy storage limitations and realize consistent efficiencies in a variety of operating conditions.*

Keywords. *Electric power, Energy, Machinery, Series hybrid.*

Many different agricultural field robots have begun appearing in recent years as research projects (Komasilovs et al., 2013; Leidenfrost et al., 2013) or even commercial products. These robots are a variety of sizes, from large tractors such as Kinze's Autonomous Harvest System (McMahon, 2012) to small rovers like Harvest Automation's machines that move nursery plants (Jones, 2015). These designs use different sensors, automation algorithms, control architectures, and even drive systems. Harvest Automation's commercially successful nursery robot focuses on simplicity, and one design decision was to use off-the-shelf electrical components to keep the entire propulsion system simple (Jones, 2014). Electric drives, which consist of motors and inverters, have few moving parts, have seen years of service in many demanding industries, and are inherently easy to integrate with automation electronics as they are based on similar electrical technology. They are widely used in systems as diverse as propeller drives on battleships, traction drives on trains and fork trucks, and for all types of motion control in mining equipment. The simplicity of integration has also led to widespread use of electric motors in many robotic systems (Price and Hall, 2012; Singh et al., 2005). Unfortunately, as pointed out by Blackmore et al. (2002), completely electrical systems are impractical for much field agricultural use because the energy density of the electrical energy storage is insufficient with current battery technology. Batteries sized for all-day agricultural operations quickly become too expensive or in some cases impossible to transport reasonably (Alcock, 1984). In the more than 30 years since Alcock's analysis, the energy density of lead acid technologies has only improved from 0.148 MJ kg^{-1} (Alcock, 1984) to 0.198 MJ kg^{-1} (Zu and Li, 2011). Even the most promising current battery technology, lithium-ion, is only improving at a 5% annual rate (Crabtree, 2015), and this rate is insufficient for fully electric mobile machines to completely replace diesel and gas engines in most current applications (Crabtree, 2015).

Despite the limitations of battery power, electromechanical equipment in agriculture can still be beneficial. Electric motor control advances, specifically the advent of isolated gate bipolar transistors since the late 1980s, have allowed for

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better control of electric systems as they have developed over the years. These improvements have led to the use of electric drives on agricultural implements (Stoss et al., 2013). Using electrically driven implements allows for better implement control, as well as enabling implement redesigns and improvements (Buning, 2010). When electric motors are used in the drivetrain, they provide very rapid response to torque demands; motors can be attached to individual wheels for four-wheel traction control, and torque and power consumption can be monitored easily and accurately (Hori, 2004).

Outside of agriculture, other mobile equipment industries have seen shifts from internal combustion (IC) drivetrains to electric systems. These transitions have been driven by requirements for high torque and high precision in applications with high variability in duty cycle (Woods, 2016). In the fork truck industry, these requirements have caused electric fork truck models to outsell IC vehicles consistently since the 1980s, and the electric market share continues to increase (Bachman, 2013; ITA, 2016). Additionally, other benefits have appeared as this transition has occurred. The electrical drivetrains used in these systems are simple compared to the IC versions, with electric motors often tied directly to drive wheels through a simple speed-reduction gearbox. Yale Materials Handling, a manufacturer of both IC and electric fork trucks, has found that the electric models with their fewer moving parts have 40% lower maintenance costs, 30% longer life, and suffer less downtime than IC versions (Yale, 2015). Electric models have zero emissions (Simon and Stevanus, 2008), which is important in industries with sensitive products such as food handling (Bachman, 2013), and are quieter, which improves worker well-being (Simon and Stevanus, 2008). Interestingly, this transition has not occurred based on the most advanced or efficient electrical drive technologies, such as Li-ion batteries or permanent magnet AC motors, but rather has been successful using standard lead acid batteries and AC induction motors. While potentially less efficient or advanced, these technologies have a long record of reliable, cost-effective service and have a developed supply base producing over one million motors and drives each year (Woods, 2016).

Although currently impractical for general agricultural use, the benefits of completely electric drivetrains have driven various research projects to investigate ways to make them more usable. The SAPHT project used solar panels to try to extend the range and operating time of electric vehicles (Mousazadeh et al., 2010). Earlier researchers also investigated electric drivetrains in agriculture with a focus on reducing reliance on imported oil (Buck et al., 1983). These researchers considered the effects of different batteries or even running power lines across fields. The Choremaster was a project in which an entire electric vehicle was developed for agricultural tasks that more closely resembled those in material handling, which it was hoped would prove more amenable to the power densities available with electric vehicles (Thoreson et al., 1986).

In this project, we focused on another method to gain some of the benefits of electric drive: a series hybrid drivetrain. Numerous technologies can be employed in a series hybrid drivetrain. New compressed natural gas turbine engines (Wright, 2015) and optimized permanent magnet motors are available for a variety of applications (Camilleri et al., 2012; Woolmer and McCulloch, 2006). Battery technologies and chemistries continue to evolve (Pollet et al., 2012). Although these developments are intriguing and exciting, this project began by employing techniques that had enabled other successful conversions to electric motors and focused on established technologies. Therefore, the series hybrid drivetrain in this project used the electrical technologies that have proven successful in the fork truck industry, with the addition of a diesel generator. The entire drivetrain consisted of a diesel generator, a lead acid battery pack, AC induction motors, and motor controllers. The generator was a design used for backup power in demanding DC applications, such as telecommunications towers. For this project, the generator was customized to charge the lead acid batteries at the 80 V standard used in the fork truck industry. Although these components and technologies have a long record of successful application in mobile equipment and other industries, they have not been integrated into a series hybrid drive train, as was done in this project. Therefore, the appropriate sizing of components like the battery pack and the overall operating characteristics were unknown. The primary goal of this project was to test this drivetrain to determine its baseline performance and investigate the efficiencies of the various drivetrain components when operating under different conditions. To advance toward this goal, testing methods were developed with the objective of revealing the overall efficiency and the efficiencies of the various components of the series hybrid drivetrain with different load levels, load patterns, and battery capacities.

METHODS AND MATERIALS

The basic structure of the hybrid drivetrain is shown in figure 1. The size of the drivetrain is approximately that of a small tractor, and it is therefore similar to the smaller robotic fleets proposed by several researchers (Blackmore et al., 2002; Emmi et al., 2013; Pitla et al., 2010). The electric drivetrain runs at a nominal 80 VDC. The electric ground drive consists of a motor controller (DaulAC-2, Zapi Group, Poviglio, Reggio Emilia, Italy) and two 7.8 kW AC induction motors (TSA240-160-203, Schabmüller GmbH, Berching, Germany). According to manufacturer testing and specifications, the motor efficiency varies in a narrow range from 0.812 to 0.916 at all speeds above 39% of the maximum. Each motor was coupled to a gearbox (S8C.3009.1, PMP, Coseano, Italy) to provide a 29:1 reduction and the proper speed range for ground drive. The ground drive wheels are normally bolted directly to these gearboxes; however, in this project, the wheels were replaced with direct coupling to the test equipment. This configuration represents a widely used and well-tested electric drivetrain within the fork truck industry. The battery pack was lead acid and was constructed from 8 V batteries (T875, Trojan Battery Co., Santa Fe Springs, Cal.) connected in series and parallel to produce the 80 V nominal voltage and the various storage amounts required by different test scenarios. The diesel generator (8340P-40515, Polar Power, Carson, Cal.) integrates a

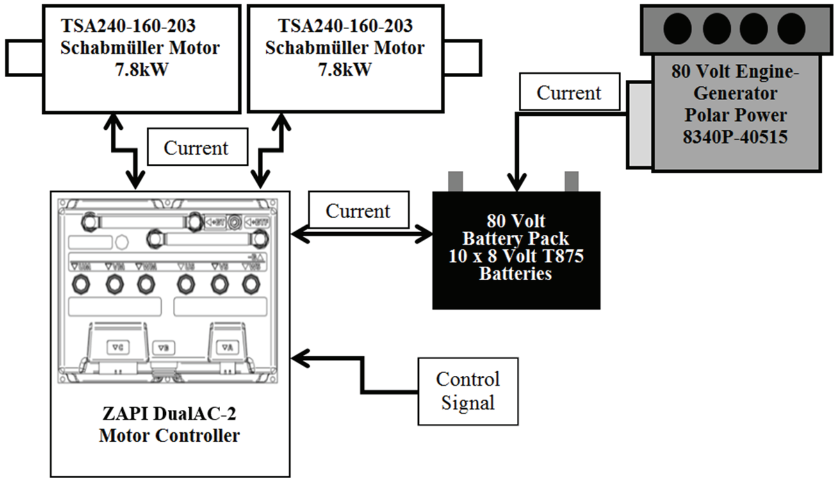

Figure 1. Hybrid drivetrain component diagram.

20 kW diesel engine (404D-15, Perkins Engines, Peterborough, UK) with a generator, charge controller, and engine accessories necessary for operation, such as the cooling and exhaust packages. The diesel generator was originally designed for charging lead acid batteries for backup power in telecommunications systems, and the generator windings had to be customized and the built-in charge controller reconfigured to operate at the 80 V nominal voltage used by the rest of the components in the drivetrain. For charge control, a multi-stage lead acid charging profile was used. The generator started automatically when the system voltage fell below 80 V. It then supplied current up to a maximum of 275 A at the system voltage. As the batteries were recharged, the system voltage gradually increased and less current flowed into the battery. When a system voltage of 94 V was reached, the charge controller began monitoring current flowing into the battery. When this charging current fell below 20 A, the generator began its shutdown, and the charging process was completed several seconds later.

Test Equipment

The test equipment was set up to monitor the overall flow of energy from the diesel fuel to the final motor output. Diesel use, the power flowing from the generator, the power flowing in and out of the batteries, the power flowing into the motor controller, and the final mechanical output power of the system were all recorded. This allowed separating the effects of the three main components in the drive train: the diesel generator, the battery system, and the electric ground drive.

Electrical Power Monitoring

A data acquisition (DAQ) board (USB-6259, National Instruments, Austin, Tex.) was used to record the voltage at the battery pack, the current going from the generator to the batteries, and the current going from the batteries to the load. These signals were sampled at 100 Hz and averaged over 1 s to produce the value for that second. The voltage of the battery pack was measured using a voltage divider to scale the voltage to within the range measurable by the DAQ. The currents were measured with current transducers (HASS 300-S, LEM USA, Milwaukee, Wisc.) attached to the DAQ board.

Fuel Consumption Monitoring

The fuel consumption was monitored by placing the 18.9 L fuel tank on a digital scale adjacent to the engine and measuring the combined weight of the fuel and tank. The scale (CD-11, Ohaus, Florham Park, N.J.) reported the fuel weight to the nearest 25 g every second. This data were logged from the scale by serial connection and synchronized with the electrical power data.

Dynamometer

The dynamometer (33 cm DYNOmite water-brake absorber, Land & Sea, Inc., Concord, N.H.) was capable of producing torque loads up to 1200 N·m at 3000 rpm. The torque load placed on the drivetrain was controlled by adjusting the water flow through the absorber using a manually operated valve. However, the speed from the drivetrain was at ground drive rates, which reached a maximum at only 150 rpm, so a speed increaser was necessary between the drivetrain output and the water brake to ensure that the water brake was operated at a more appropriate speed of 1800 rpm during testing.

The wheels on the drivetrain to be tested were replaced with sprockets to eliminate slip and enable a direct mechanical connection to the water brake. The speed increase was accomplished with two stages of roller chain connection and one 1:6 gearbox, for a combined 1:12 increase. The torque measurement of the water brake was calibrated before the experiments using weights for a linear voltage response from 0 to 404 N·m. The exact efficiency of the speed increaser was not determined, as all tests in this experiment were comparison tests and the mechanical construction of the increaser within the narrow speed range of the test conditions ensured that its efficiency would remain constant in all test scenarios. Based on the components, the expected increaser efficiency was between 92% and 96% (Lodge and Burgess, 2002).

The rotational speed of the dynamometer was measured with a Hall effect transducer and instrumented through the DAQ board and software that were included with the dynamometer. This speed was recorded at 1 Hz for the duration of each test. The torque load generated by the dynamometer was recorded with a force transducer (SSM-AJ-500, Interface, Inc., Scottsdale, Ariz.), which was attached to a torque arm 22.9 cm from the center of the dynamometer. This signal then went through an instrumentation amplifier (INA126, Texas Instruments, Dallas, Texas) before going to the same DAQ board that recorded voltage and current. Like the voltage and current measurements, the torque signal was logged at the same 100 Hz rate and averaged over 1 s.

Test Design

The experiment was a 2 × 2 × 2 factorial design. The three tested factors were battery pack size, load level, and load pattern. Two levels were tested for each factor. Battery pack capacity is a significant cost driver in hybrid systems, and the battery pack's weight and volume have large impacts on the machine structure. Although the electric drivetrain used in this project was well-established, its battery capacity had been developed based on the typical required operation between charging opportunities. The hybrid system removed this capacity requirement, as charging could now occur at any time, so testing was performed to compare the efficiencies of different battery capacities. Another factor in this experiment compared a variable load with a steady load, as variable loading was confirmed by Hansson et al. (2003) to cause lower fuel efficiency in standard agricultural drivetrains, and one of the oft-cited benefits of hybrid systems is their ability to handle variable loading (Pollet et al., 2012). The final factor in this testing was the load level, which was included to determine the effect of load size on the relative efficiencies of the different components of the drivetrain.

The test began with the battery pack fully charged and the generator set to shut off when the built-in charge controller indicated that it was no longer needed. Each test scenario consisted of a 45 min active loading period, which permitted capturing several on/off cycles of the diesel generator. During active loading, the motor controller was set to run the ground drive motors at full speed, and the dynamometer provided the desired load on the ground drive. After the active loading period, the load from the dynamometer was removed and the ground drive stopped. The generator was then allowed to run until the batteries were fully charged and automatic shutdown occurred. Fuel consumption, power transmission, and drivetrain status monitoring began with the active loading and continued during the recharge period. This was done to ensure that the system was stabilized and that the batteries were at the same state of charge at the start and end of every test. For each scenario, two replications were conducted. Each test took several hours, as each test included active load time, time to ensure that the system was back to initial conditions, and time to adjust the equipment for the next scenario. All tests were conducted within several weeks in an indoor controlled environment to ensure consistent conditions.

Battery Pack

The battery pack was tested at two capacities: 170 and 340 A·h. The 170 A·h battery pack was created using ten 8 V, 170 A·h deep-cycle lead acid batteries connected in series (T875, Trojan Battery Co., Santa Fe Springs, Cal.). This produced an 80 V (nominal) battery pack with a capacity of 170 A·h. The second battery pack was created using two of these 80 V packs connected in parallel, for a total of 20 batteries and 340 A·h of energy storage capacity.

Load Levels

The two load levels were an average load value of 54 N·m of torque (high load) and 41 N·m of torque (low load), which was 75% of the high load, as measured at the dynamometer. The load resistance was varied through the dynamometer until the desired torque output was attained. These levels corresponded to a combined average motor output of 40% of full motor output for the high load and 30% for the low load level.

Load Patterns

Two load patterns were tested to determine how the drivetrain responded to variable real-life loading versus idealized constant average loading (fig. 2). This variable loading pattern was not meant to test efficiency in any particular application but rather to reveal the effects of a variable loading pattern on the drivetrain. While a completely artificial and arbitrary pattern could have been selected, a real-world pattern was developed from engine loads recorded during a corn stover baling operation to provide a pattern based on an actual agriculture operation. The average tractor engine output during this operation was 40%. The dynamometer could not be adjusted quickly enough to match the 1 s data rate from the recorded engine loading pattern. Therefore, the recorded load pattern was downsampled to 1 min time periods. The downsampled mean, mode, first quartile, median, third quartile, and standard deviation were all between zero and six percentage points of the similar statistics from the recorded values. This downsampled load pattern was used to set the load on the dynamometer during the variable load pattern tests. The applied load in the variable load pattern varied from 25% to 81% of full load. The recorded variable load pattern's average matched that of the high load level (40%) but had to be scaled down by 75% to create the variable load pattern for the low load level.

Test Scenarios

The 2 × 2 × 2 factorial design resulted in the eight test

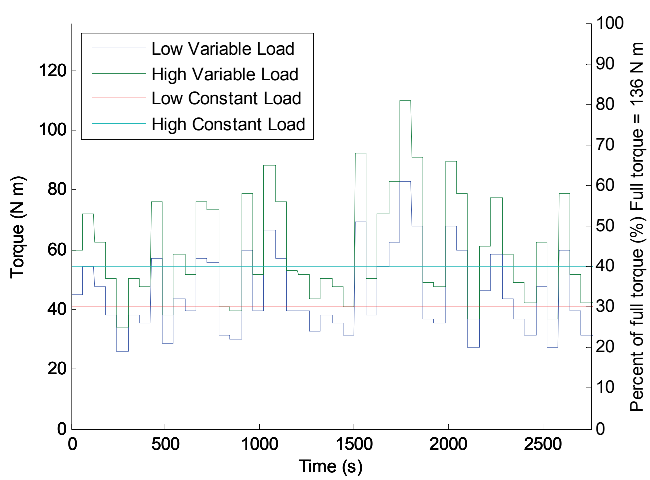

Figure 2. Graph of the load patterns and levels tested, where full torque is the maximum continuous torque of the motors (136 N·m).

scenarios shown in table 1. Two replications were performed of each test scenario in a randomized order. In addition to the factor levels for each scenario, table 1 includes scenario descriptions for each test scenario that will be used in the Results and Discussion section. Battery size tests are described as large or small, and load levels are described as high or low. During testing, scenario 6 was inadvertently replicated three times, and the data were kept for statistical analysis. With scenario 8, a data recording error occurred in one of the tests, so only one test was available for processing. The error was not discovered until post-processing the data after the drivetrain had been dismantled and was no longer available for testing.

RESULTS ANALYSIS METHODS

The variables of interest in this project were the energy efficiencies of the individual components and the overall efficiency of the drivetrain. Energy efficiency is the ratio of total energy that left a component or system divided by the energy provided to that component or system. The energy into or out of a component was determined from the 1 s power measurements. For the mechanical power provided by the ground drive, power was calculated every second from the measured torque and rotational speed of the dynamometer. For the electrical power transfer, the power was calculated from the measurements of voltage and current flowing between components. Total energy for the mechanical and electrical power was calculated through trapezoidal integration of the discrete power samples. The fuel energy was calculated directly from the energy density of the diesel fuel and the amount of fuel consumed. The density and volumetric energy content values used in these calculations were taken from Brown and Brown (2003). These measurements of total energy transfers were then used to calculate the efficiency of the overall drivetrain and its individual components in each test for each of the test scenarios.

To determine which variables significantly affected the overall drivetrain efficiency and the efficiencies of its components, the data were subjected to statistical analysis. An analysis of variance (ANOVA) was calculated for several dependent variables (the efficiencies of the drivetrain and its components), with the independent variables corresponding to the factors (battery size, load level, and load pattern). All statistical analyses presented in this article were conducted through the Applied Statistics Laboratory at the University of Kentucky to ensure that proper statistical techniques were employed at all times.

RESULTS AND DISCUSSION

OVERALL EFFICIENCY

The overall efficiency is the ratio of the energy dissipated at the dynamometer divided by the energy in the fuel consumed during the entire test. This fuel consumption includes the fuel used to bring the batteries back to their fully charged state after the active loading period. Overall efficiency varied within a tight range from 16% to 19% (fig. 3). This overall efficiency is quite low, as it includes the inherently inefficient diesel engine.

The results of the ANOVA on overall efficiency are shown in table 2. Only the load level had a significant effect on overall efficiency with a p-value of 0.0136, well below a 5% significance level. The high load level was more efficient, with an average overall efficiency of 19% compared to 17.2% for the low load level. Interestingly, the p-value for battery size was very high at 0.4893, indicating that this factor had very little discernable effect on the outcome. In addition, the p-values for the interactions between factors were high, indicating that interaction effects were not noticed in this test.

INDIVIDUAL COMPONENT RESULTS

Diesel Generator Efficiency

As expected in a series hybrid drivetrain, the diesel generator had very consistent efficiencies in all scenarios (fig. 4). The ANOVA analysis found no significant factors that caused changes in diesel generator efficiency. Although

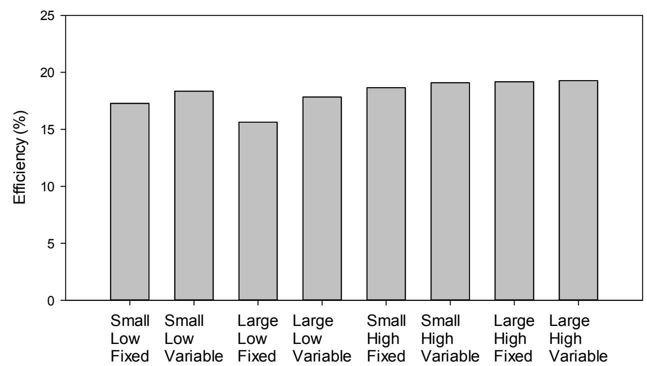

Figure 3. Overall efficiency for each test scenario.

Table 2. ANOVA results for overall efficiency.

Source	p-Value
Load level	0.0136
Battery size	0.4893
Load level × Battery size	0.266
Load pattern	0.1172
Load level × Load pattern	0.2766
Battery size × Load pattern	0.7026
Load level × Battery size × Load pattern	0.544

Table 1. Drivetrain configurations tested.

Factor	Test Scenario 1	2	3	4	5	6	7	8
Battery size (A·h)	170	170	340	340	170	170	340	340
Average load level (N·m)	41	41	41	41	54	54	54	54
Load pattern	Fixed	Variable	Fixed	Variable	Fixed	Variable	Fixed	Variable
Scenario description	Small Low Fixed	Small Low Variable	Large Low Fixed	Large Low Variable	Small High Fixed	Small High Variable	Large High Fixed	Large High Variable
Number of tests	2	2	2	2	2	3	2	1

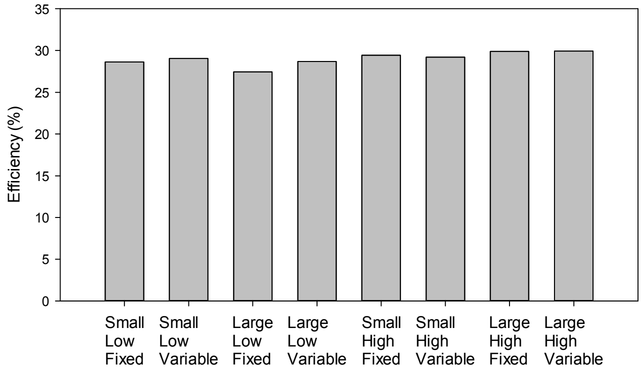

Figure 4. Diesel generator efficiency for each test scenario.

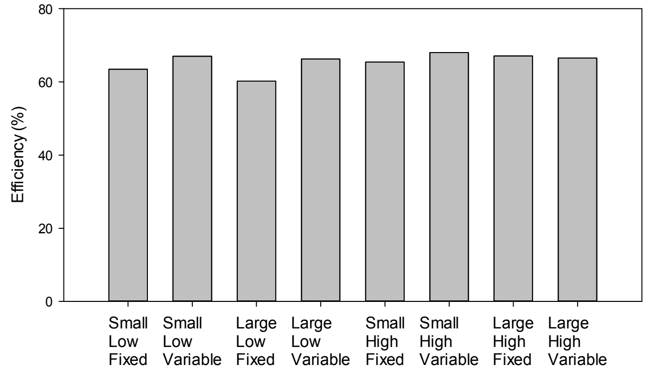

Figure 5. Electric ground drive efficiency for each test scenario.

the scenarios represent significantly different conditions, the hybrid drivetrain allowed the diesel generator to be decoupled from the load. When loads were low, the diesel generator either charged the batteries or shut down to eliminate extended operation in low efficiency, low load conditions. This resulted in a nearly constant efficiency for the diesel generator in all scenarios. In this study, it was not possible to distinguish between the efficiencies of the engine and the generator, as the tightly integrated package resulted in engine components (flywheel) also serving as generator components (rotor). However, the Perkins engine specification manual (Perkins, 2009) states that the 404D-15 engine at the operating point used in this study generates 24.6 kW of power while consuming 73.6 kW of fuel, for an efficiency of 33.4%. The average efficiency of the fuel to electrical energy conversion for the entire diesel generator was 29%. This indicates that the electric generator portion of the engine/generator combination had an efficiency of 87%.

Diesel Generator Operating Time

In addition to the diesel generator efficiency, the operating time of the diesel generator was considered for each of the test scenarios. Operating time varied from a low of 81% of the length of the test to continuous operation (100%). An ANOVA was performed to determine which factors had a significant impact on operating time. An initial ANOVA found that the battery pack had little to no effect. Under the direction of the statisticians of the Applied Statistics Laboratory, the ANOVA was repeated with the battery pack size removed as a factor (table 3). Both load level and load pattern were significant factors for operating time at an $\alpha = 0.05$ level of significance. The generator ran more during tests with high load (mean operating time of 94% of the test) compared to low load (mean of 85%) and more when under a constant load (mean of 93%) than a variable load (mean of 87%). Even though these factors caused differences in operating times, they did not significantly affect the generator's efficiency, as shown in the preceding section. The generator was able to maintain its efficiency levels in these different loading scenarios by shutting down when it was only lightly loaded or when the batteries were fully charged.

Table 3. ANOVA results for generator operating time.

Source	p-Value
Load level	0.0005
Load pattern	0.0108
Load level × Load pattern	0.5017

Ground Drive Efficiency

The efficiencies of the ground drive were also very similar (between 60% and 68%) for all test scenarios (fig. 5). An ANOVA was unable to find any significant difference in the ground drive efficiency for any of the considered factors. This result confirms that this series hybrid system delivered a recognized strength of electric motors: relatively high efficiencies across a wide range of operating points. The efficiencies shown in figure 5 were calculated from the electrical energy going into the motor controller and the energy dissipated by the dynamometer. As such, these numbers represent the entire ground drive system. In addition to the active motor controller and electric motors, they include the efficiency of the gearbox. The values also include the consistent and small efficiency loss due to the speed increasers used on the dynamometer.

Battery System Efficiency

The battery system efficiency (fig. 6) was calculated based on the energy produced by the generator and that consumed by the motor controller. Battery system efficiencies ranged from 93% to 98%. The main component was the battery, but the efficiency level does not directly represent the base battery efficiency, as power could also flow directly from the generator to the motor controller and never charge or discharge the battery. An ANOVA was performed with these data; however, as with the overall efficiency, the battery pack size had almost no effect (p-value of 0.77). Therefore, as with the diesel generator operating time and under the direction of the statisticians of the Applied Statistics Laboratory, the ANOVA was repeated with the battery pack factor removed (table 4). This ANOVA found that load level

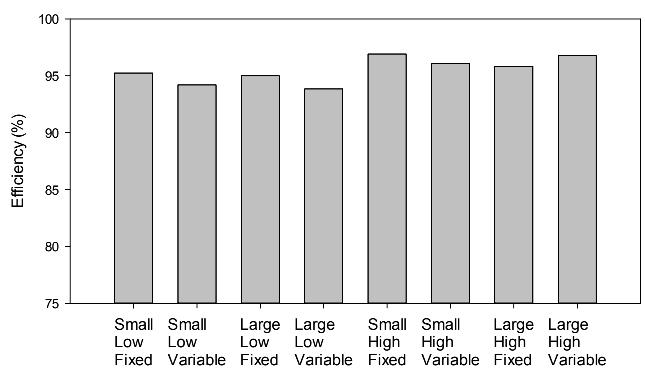

Figure 6. Battery system efficiency for each test scenario.

Table 4. ANOVA results for battery system efficiency.

Source	p-Value
Load level	0.0422
Load pattern	0.4464
Load level × Load pattern	0.5324

was a significant factor in the battery system efficiency. The system was more efficient at high load levels, with a mean efficiency of 96.3% at high loads and 94.5% at low loads. The other factors were not significant.

Battery Pack Efficiency

Energy was stored in the battery when the generated power was greater than the power provided to the motors, and energy was removed from the battery when it was less. Actual battery efficiency was calculated by comparing the stored energy to the removed energy. In test runs with the fixed, high-level load, the generator rarely turned off, so little or no energy was removed from the batteries. In scenarios with appreciable energy use from the battery, the efficiency ranged from 72% to 84%. The battery discharge rate naturally varied widely during all the tests and was dependent on the loading condition when the generator shutdown and turned over power supply responsibilities to the battery pack. The peak discharge rate was just over 300 A, but discharging at this rate was limited to less than a minute during a single test. The most common discharge rates were between 150 and 175 A. Using standard battery charging terminology, the maximum discharge rate represents a nearly 2C discharge rate based on the 140 A·h battery pack, while the normal discharge rate was just over 1C. These are very high discharge rates for lead acid batteries, so it was assumed that doubling the battery pack size, and thus halving the C rating, would significantly boost battery and overall system efficiency. However, as demonstrated by the ANOVAs, doubling battery pack size had little impact on overall efficiency.

DISCUSSION

Of the tested factors, only load level had a significant impact on any efficiency measure, and its effect was only noticeable in the battery system efficiency and the overall efficiency. As with other power generation and transmission systems, a closer match between average load and system component capacities resulted in higher efficiencies. Other conditions, such as varying load levels, which research demonstrates hurts efficiencies in conventional drivetrains (Hansson et al., 2003), had no significant effect on the efficiency of this system. For the diesel generator or ground drive system, no factors had any effect on efficiency. Effects were only significant for the battery system, and then only the load level had any impact. Interestingly, battery capacity was highly insignificant, with p-values so high that the statisticians removed battery capacity as a factor in several ANOVAs.

The complete lack of impact from the battery capacity was one of the most surprising results from this experiment. The normal discharge rate in the tests was 0.5C for the large battery pack and 1C for the small battery pack. Although these are large loads for lead acid batteries, these tests showed that increasing the capacity and decreasing the C rating of the discharge had no significant effect on efficiency. Batteries are large, heavy, and relatively expensive. If large battery packs are necessary to maintain efficiency, this requirement will place significant restrictions on vehicle design. Smaller battery packs would make this drivetrain feasible for applications demanding smaller, lighter, and less expensive vehicles.

In addition, the seemingly low overall efficiencies of 16% to 19% with an average of 18% (or 1.83 kWh L^{-1} of fuel) for the hybrid system are actually not much different from the efficiencies of current commercial tractors at loading rates close to the 40% average load tested here. In the Nebraska Tractor Test Lab, a similarly sized machine (Case IH DX 48 with a maximum power of 30.56 kW) only provided 1.92 kWh L^{-1} of fuel at 44% of full load (Bashford, 2004). This project and its methods were developed to compare the hybrid system in different operating scenarios and not to compare it with other drivetrains, so this example should not be considered a direct comparison of these two drivetrains. However, this example illustrates that overall efficiencies are similar between this basic hybrid drivetrain and conventional drivetrains. For applications in which the controllability, flexibility, or other features of electric drives make them desirable, the hybrid drivetrain provides a method to achieve these benefits without sacrificing the range of conventional combustible fuels.

This study has several implications for engineers interested in employing a series hybrid drivetrain to obtain the controllability of electric motors with the range and operating time of internal combustion engines. First, a large battery pack is not necessary. This will enable designers to use smaller battery packs without fear of efficiency losses. However, some battery capacity will still be necessary to enable use of widely available, mass-manufactured electric motors and motor controllers, as these common components require a battery for voltage stability. Applications that consider significantly reducing battery capacity so that discharge currents are above 1C should perform testing to ensure that these capacity levels are adequate for the other functions that the battery provides, such as voltage stabilization.

A second implication of this study is that a variable load is no worse for efficiency than a perfectly steady load. Many of the applications envisioned for small field robots will be highly variable, as the machines will be expected to perform very precise farming operations that will require constantly changing their movements to match the inherent variability in the field. Although the variable loading pattern did not affect the efficiency of this system, every application is different. Testing will be needed to fine-tune a series hybrid drivetrain to a particular application to ensure that the loading pattern of the application does not impact the drivetrain differently. It may also be necessary to consider variations in speed for specific applications. This testing was performed at full motor speed, as the efficiency of the motors at this speed was 0.87. This full-speed efficiency was close to the center of the range of efficiencies (0.81 to 0.92) that the motors would experience across a wide range of speeds (39% to 100% of maximum speed). If significant operating periods are expected at speeds below this range, separate testing should be performed to confirm the efficiency, as the efficiency of electric motors drops quickly as the speed decreases toward a locked stall.

A final implication of this study is that, as with almost all drivetrain designs, it is better to more closely match the power requirements of the load with the power that can be produced by the drive motors. Although the series hybrid system decoupled the engine from the load and electric motors have relatively flat efficiency curves compared to other motor technologies, the load level still produced a discernable impact on efficiency. Designers of systems with series hybrid drivetrains should attempt to match motor size and expected load levels for their application.

This drivetrain does not fully demonstrate the potential of hybrid systems. The goal of this project was to use a drivetrain constructed using developed, well-established, and cost-effective technologies, as they represent the starting place for engineers interested in increasing the operating range of electric drives. One of the most intriguing findings of this study is that large capacity battery packs are not necessary for efficiency. While more expensive battery technologies, such as lithium-ion, are cost-prohibitive at large capacities, they may become feasible at smaller sizes. Using more advanced battery chemistries would permit the use of advanced battery management systems and increase the energy density (Pollet et al., 2012). These systems could provide more stable voltage levels and better regulate the load placed on the generator, which could improve the efficiencies of the generator, the motors, and the motor controllers. Further, although the battery system was one of the most efficient at 94% to 97%, its primary component (the battery) was itself only 72% to 84% efficient and thus has room for improvement. Given that the battery capacity requirements are limited, more advanced battery chemistries and more versatile charge controllers could be feasible.

CONCLUSION

A hybrid drivetrain can provide machinery with the controllability, flexibility, and simplicity of electric motors without the operating time penalties imposed by the energy density of batteries. The hybrid system tested in this study was adept at adjusting to different loading scenarios and maintained consistent efficiencies in most cases. The overall efficiency was significantly impacted only by the load size, and the system was more efficient when the load more closely matched its full load capacity. Of the individual components, the diesel generator and the electric ground drive were not affected by any of the tested factors. The battery system efficiency was impacted by the load level, but not by the other factors. Interestingly, battery capacity had an insignificant effect on any efficiency measure. This indicates that smaller-capacity battery packs could be used in future systems with series hybrid drivetrains. For field robotic applications, a smaller battery pack would be useful in reducing the weight, size, and overall cost of the machine. In many robotic applications, the automation is intended to enable the machine to match the inherent variability of the field, so the lack of a negative impact on efficiency due to the variable loading patterns is also important. The results of this study demonstrate that series hybrid drivetrains are a feasible method to attain the operating times necessary for work in agricultural fields without sacrificing the benefits of electrical power systems.

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REFERENCES

Alcock, R. (1984). Battery powered vehicles for field work. *Trans. ASAE, 26*(1), 10-13. http://dx.doi.org/10.13031/2013.33866

Bachman, K. (2013). No-, low-emissions lift trucks clear the air. *The Fabricator* (1 Aug. 2013), 76-79. Retrieved from http://www.thefabricator.com/article/materialshandling/no--low-emissions-lift-trucks-clear-the-air

Bashford, L. L. (2004). Nebraska tractor test 1836A: Case IH DX48 diesel 12 speed. Lincoln: NE: University of Nebraska, Tractor Test Laboratory.

Blackmore, S., Have, H., & Fountas, S. (2002). A specification of behavioural requirements for an autonomous tractor. In Q. Zhang (Ed.), *Automation technology for off-road equipment* (pp. 33-42). St. Joseph, MI: ASAE. http://dx.doi.org/10.13031/2013.10067

Brown, R. C., & Brown, T. R. (2003). The biorenewable resource base. In *Biorenewable resources: Engineering new products from agriculture* (pp. 59-76). Hoboken, NJ: John Wiley & Sons.

Buck, N. L., Hughes, H. A., Resen, M., & Alcock, R. (1983). Electric vehicle designs for agricultural applications. *Trans. ASAE, 26*(3), 646-650. http://dx.doi.org/10.13031/2013.33994

Buning, E. A. (2010). Electric drives in agricultural machinery: Approach from the tractor side. Presented at the 21st EIMA International in Bologna, Italy. Retrieved from http://www.clubofbologna.org/ew/documents/KNR_Buning.pdf

Camilleri, R., Woolmer, T., Court, A., & McCulloch, M. D. (2012). Investigation into the temperature profile of a liquid cooled YASA AFPM machine. In *Proc. 6th IET Intl. Conf. Power Elelctronics, Machines, and Drives*. Stevenage, UK: Institution of Engineering and Technology. http://dx.doi.org/10.1049/cp.2012.0281

Crabtree, G. (2015). The joint center for energy storage research: A new paradigm for battery research and development. In *Proc. Physics of Sustainable Energy III: Using Energy Efficiently and Producing It Renewably.* College Park, MD: American Institute of Physics. http://dx.doi.org/10.1063/1.4916174

Emmi, L., Paredes-Madrid, L., Ribeiro, A., Pajares, G., & Gonzalez-de-Santos, P. (2013). Fleets of robots for precision agriculture: A simulation environment. *Industrial Robot Intl. J., 40*(1), 41-58. http://dx.doi.org/10.1108/01439911311294246

Hansson, P. A., Lindgren, M., Nordin, M., & Pettersson, O. (2003). A methodology for measuring the effects of transient loads on the fuel efficiency of agricultural tractors. *Appl. Eng. Agric., 19*(3), 251-257. http://dx.doi.org/10.13031/2013.13657

Hori, Y. (2004). Future vehicle driven by electricity and control: Research on four-wheel-motored “UOT electric march II”. *IEEE Trans. Ind. Electron., 51*(5), 954-962. http://dx.doi.org/10.1109/TIE.2004.834944

ITA. (2016). Market intelligence: History of U.S. shipments. Washington, DC: Industrial Truck Assocation. Retrieved from

http://www.indtrk.org/market-intelligence
Jones, J. (2014). Three million and counting: How real robots are revolutionizing real nurseries. Technical Committee on Agricultural Robotics and Automation Webinar Series. Piscataway, NJ: IEEE Robotics and Automation Society.
Jones, R. (2015). Robots, container production, and the future of vegetable growing. *Growing Produce*. Retrieved from http://www.growingproduce.com/vegetables/robots-container-production-and-the-future-of-vegetable-growing/
Komasilovs, V., Stalidzans, E., Osadcuks, V., & Mednis, M. (2013). Specification development of robotic system for pesticide spraying in greenhouse. In Proc. *IEEE 14th Intl. Symp. Computational Intelligence and Informatics (CINTI)* (pp. 453-457). Piscataway, NJ: IEEE. http://dx.doi.org/10.1109/CINTI.2013.6705239
Leidenfrost, H. T., Tate, T. T., Canning, J. R., Anderson, M. J., Soule, T., Edwards, D. B., & Frenzel, J. F. (2013). Autonomous navigation of forest trails by an industrial-size robot. *Trans. ASABE, 56*(4), 1273-1290. http://dx.doi.org/10.13031/trans.56.9684
Lodge, C. J., & Burgess, S. C. (2002). A model of the tension and transmission efficiency of a bush roller chain. *J. Mech. Eng. Sci., 216*(4), 385-394. http://dx.doi.org/10.1243/0954406021525179
McMahon, K. (2012). Kinze's autonomous tractor system tested in field by farmers. *Farm Industry News* (12 Nov. 2012). Retrieved from http://farmindustrynews.com/precision-guidance/kinze-s-autonomous-tractor-system-tested-field-farmers
Mousazadeh, H., Keyhani, A., Javadi, A., Mobli, H., Abrinia, K., & Sharifi, A. (2010). Optimal power and energy modeling and range evaluation of a solar assist plug-in hybrid electric tractor (SAPHT). *Trans. ASABE, 53*(4), 1025-1035. http://dx.doi.org/10.13031/2013.32586
Perkins. (2009). Perkins 400D series engine specification manual. Peterborough, UK: Perkins Engines. Retrieved from http://www.auroragenerators.com/downloads/perkins/400D%20Engine%20Sales%20Manual.pdf
Pitla, S. K., Luck, J. D., & Shearer, S. A. (2010). Multi-robot system control architecture (MRSCA) for agricultural production. ASABE Paper No. 1008703. St. Joseph, MI: ASABE. http://dx.doi.org/10.13031/2013.36212
Pollet, B. G., Staffell, I., & Shang, J. L. (2012). Current status of hybrid, battery, and fuel cell electric vehicles: From electrochemistry to market prospects. *Electrochim. Acta, 84*, 235-249. http://dx.doi.org/10.1016/j.electacta.2012.03.172
Price, R. R., & Hall, S. G. (2012). Design, development, and testing of an autonomous boat to reduce predatory birds on aquaculture ponds. *Biol. Eng. Trans., 5*(2), 61-70. http://dx.doi.org/10.13031/2013.41399
Simon, D., & Stevanus, K. (2008). Powered industrial trucks (forklift) eTool. Washington, DC: Occupational Safety and Health Administration. https://www.osha.gov/SLTC/etools/pit/index.html
Singh, S., Burks, T. F., & Lee, W. S. (2005). Autonomous robotic vehicle development for greenhouse spraying. *Trans. ASAE, 48*(6), 2355-2361. http://dx.doi.org/10.13031/2013.20074
Stoss, K. J., Sobotzik, J., Shi, B., & Kreis, E. R. (2013). Tractor power for implement operation—Mechanical, hydraulic, and electrical: An overview. ASABE Publication No. 913C0113. St. Joseph, MI: ASABE.
Thoreson, B. P., Alcock, R., & Christianson, L. L. (1986). Electric choremaster I: Test procedures and results. *Trans. ASAE, 29*(5), 1259-1266. http://dx.doi.org/10.13031/2013.30306
Woods, M. (2016). The history of electrification in mobile applications/industries. Presented at the 2016 Agricultural Equipment Technology Conference.
Woolmer, T. J., & McCulloch, M. D. (2006). Axial flux permanent magnet machines: A new topology for high-performance applications. In *Proc. IET Hybrid Vehicle Conf.* (pp. 27-42). Stevenage, UK: Institution of Engineering and Technology. http://dx.doi.org/10.1049/cp:20060611
Wright, I. (2015). Cost-effective supply chain. Presented at the 2015 Electric and Hybrid Vehicle Technology Expo.
Yale. (2015). The truth about electric lift trucks. Cleveland, OH: Yale Materials Handling.
Zu, C.-X., & Li, H. (2011). Thermodynamic analysis on energy densities of batteries. *Energy Environ. Sci., 4*(8), 2614-2624. http://dx.doi.org/10.1039/C0EE00777C