Preliminary Study on the Applicability of an Electric Tractor (Part 1)*
—Energy Consumption and Drawbar Pull Performance—

Weerachai ARJHARN*1, Masayuki KOIKE*2, Tomohiro TAKIGAWA*2, Akira YODA*2, Hideo HASEGAWA*2, Banshaw BAHALAYODHIN*3

Abstract

The electric tractor (ET) was fabricated and tested as an innovative approach in providing conventional agricultural machinery which puts emphasis on zero emission and potential acceptability for women and the aged. The objectives of this study were to propose the prototype and investigate its performance for the sake of further improvement. The ET was fabricated by converting a 20 kW diesel tractor. The performance tests were focused on the energy consumption and drawbar pull characteristics of the ET. As the full-charge capacity of the battery used was 7.2 kW-h, the energy consumption and driving range were found to be 0.60 kW•h/km and 8.35 km, respectively. This performance showed an insufficient level, when considering farming requirements, due to the limited amount of battery supply as well as power transmission losses. However, the ET offered better drawbar pull performance. Since its overall mass was 1065 kg, it could attain 5.76 kN with 14% slip and 3.89 kN with 22% slip on asphalt and hard soil surfaces. The overall efficiency of the ET in transforming electrical power to the power available at the drawbar was 0.21-0.32 on asphalt and 0.17-0.24 on hard soil surfaces. In addition to this, the forthcoming design concept and further refinement were discussed.

Keywords: electric tractor, electric vehicle, agricultural tractor, sealed lead-acid battery, energy consumption, drawbar pull performance

I Introduction

In Japan, approximately 2.3 million units of agricultural tractors are currently employed in various scenes of application in farming practices. In most cases, their power sources use gasoline or diesel engines. However, farmers are aware that the exhaust gases emitted from these vehicles become the accelerating factors related to global warming as well as air pollution. In addition, as typical common problems in developed countries, Japanese agriculture is facing some difficulties such as a decrease in the farming population accompanied by the aging of farmers and, in part, the migration of agricultural labor from rural areas to urban centers due to industrialization. Under these situations, it is likely that more women and senior individuals become to dominate in the rural community.

Reflecting the above concerns, the electric tractor can seemingly contribute to alleviate such environmental and health impacts through the utilization of electric power. Also, to cope with manpower shortage on the farm, the ET will be able to provide a practical solution putting emphasis on the unique configuration design that can even accommodate women and the aged utilizing a universal design concept. In this study, the ET will be focused on as a vehicle that is designed specifically for agricultural purposes alone.

This paper deals with the preliminary approaches seeking the development of a desirable technological level of the ET. To implement this, firstly, the prototype was fabricated so as to investigate basic vehicular performance equipped with proper instrumentation. Secondly, both drawbar pull and travel performance tests were conducted to study its preliminary performance. Finally, the energy consumption was discussed for the sake of practical acceptability. Based on these findings, further versatile and unique...
modifications are to be proposed in a following paper.

II Literature Review

Recent studies have showed that the ET offered some unique advantages over a comparable diesel-powered counterpart. It is considerably quieter and is subjected to less vibration which leads to improved ride comfort[12]. It also has a pollution-free trait, hence it can be operated inside a greenhouse and close to people’s living space and/or livestock without causing any physical problems[3]. The ET is simpler in design and easier in manufacturing because there is no need to mount an engine, mechanical transmission unit, fuel reservoir, exhaust muffler, and other components normally found in the conventional tractor[4]. For a commercialized electric vehicle (EV), the necessary amount of parts could be almost half of those of a conventional gasoline-fuelled vehicle.

In addition, an electric motor has a bigger advantage for hauling tasks. For instance, it can supply 150% of its rated power for about 10 min to climb a hill, or 200% of its rated power to overcome an impact load[5] due to the motor characteristics exhibiting sharp torque rise when encountering a heavy load and sudden decrease of motor speed[6].

However, scientists have pointed out some drawbacks of the ET including its limited driving range [km] that results from the lower energy density of batteries compared to petroleum fuel. From this specific viewpoint, batteries require a large mass to attain an equivalent driving range compared to gasoline or diesel originated energy.

The energy requirement of the ET for fieldwork has been investigated by model studies[7]. The outputs exerted from a model suggest that it is unlikely that the ET would be suitable for primary tillage assignments. However, it could be used for various activities including materials handling, seeding, spraying, and other light-load farm work.

The conceptual design of the ET was made to identify its possible applications in agriculture[8]. The ET powered by industrial lead-acid batteries in 1981 would have little or no usefulness for primary tillage assignments. However, it could be used for various activities including materials handling, seeding, spraying, and other light-load farm work.

The mass balance of the prototype was significantly affected by the allocation of batteries. Two battery compartments were prepared in the front and rear portions where five units each of the batteries were housed. In this layout, the mass balances of the front and rear axles were approximately 45:55.
Table 2  Main specifications of the ET

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base tractor</td>
<td>Kubota GT-8</td>
</tr>
<tr>
<td>Make and model</td>
<td>2,820 x 1,410 x 1,500 [mm]</td>
</tr>
<tr>
<td>Size</td>
<td>1,500 [mm]</td>
</tr>
<tr>
<td>Overall mass</td>
<td>1,065 [kg]</td>
</tr>
<tr>
<td>Motor</td>
<td>Advanced D.C. Motor, Inc.</td>
</tr>
<tr>
<td>Make</td>
<td>DC series wound</td>
</tr>
<tr>
<td>Rated power</td>
<td>11.4 [kW] 1 h rated</td>
</tr>
<tr>
<td>Rated power</td>
<td>20 [kW] 5 min rated</td>
</tr>
<tr>
<td>Rated power</td>
<td>43 [kW] peak</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>170 [mm]</td>
</tr>
<tr>
<td>Overall length</td>
<td>386 [mm]</td>
</tr>
<tr>
<td>Mass</td>
<td>38 [kg]</td>
</tr>
<tr>
<td>Controller</td>
<td>Curtis Instruments, Inc.</td>
</tr>
<tr>
<td>Make</td>
<td>MOSFET PWM Chopper</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>15 [Hz]</td>
</tr>
<tr>
<td>Battery</td>
<td>Japan Storage Battery Co., Ltd.</td>
</tr>
<tr>
<td>Make</td>
<td>sealed lead-acid</td>
</tr>
<tr>
<td>Voltage/capacity</td>
<td>120 V/60 A - 3 h rated capacity</td>
</tr>
<tr>
<td>Mass</td>
<td>21.3 [kg/unit]</td>
</tr>
<tr>
<td>Number of units</td>
<td>10 units</td>
</tr>
</tbody>
</table>

The converted tractor increased its overall mass by roughly 200 kg compared to the original tractor. Of this mass increment, the fractions of the batteries occupy nearly 20%. The battery fraction has been defined as the proportion of the total battery mass to the overall mass of the vehicle.

2. Experimental procedures

The procedures of the experiments were designed to investigate ET performance in terms of travel and drawbar pull performance in relation to the energy consumption. The recommended test codes of the Japan Electric Vehicle Association Standard (JEVS) were adopted in some trials, including the range test method and the energy consumption test method of electric vehicles. Then, the drawbar pull performance test was conducted following the Agricultural Tractor Test Code (1)

(1) Energy consumption and range test

The purpose of this test was to determine the energy consumption, $E_c$ [kW-h/km] and driving range [km] of the ET. The definition of the $E_c$ is the energy used by the ET over a particular traveling distance. The experiment was conducted under a predetermined route or shuttle pattern on flat, asphalt road. This specific pattern is supposed to simulate the driving pattern within rural communities.

The test was performed at 80% of full throttle, while the allowable limit of the potentiometer was set at 4 kΩ. Once the maximum gear ratio was selected as an operating speed, the ET tended to move at almost constant speed. However, with the advancement of battery consumption, its travel speed started to decrease gradually. The test was suspended when its speed reached 80% of its normal speed. The particular traveling distance along this test was called the driving range of the vehicle.

The data acquisition and processing system utilized a Pentium-233MHz personal computer which contained two units of A/D converters and counter interfaces, respectively. It received and stored data collected from up to 26 input channels at the sampling rate of 20 Hz. The measured items included the current discharged by the motor, system voltage, motor speed, and travel speed. Almost all of the data were correctly recorded and a necessary data processing unit was mounted on the vehicle.

The current passing through the motor was measured indirectly using a 500 A-50 mV capacity shunt resistor. When the current passed through the shunt, a small voltage was developed proportionally to the hydraulic control system as well as the power steering system, was installed separately. Fig. 1 shows the major electric components on the prototype. The overview of the prototype is shown in Fig. 2. Its selected specifications can be seen in Table 2. The converted tractor increased its overall mass by roughly 200 kg compared to the original tractor. Of this mass increment, the fractions of the batteries occupy nearly 20%. The battery fraction has been defined as the proportion of the total battery mass to the overall mass of the vehicle.
Fig. 3 Wiring diagram and selected components

Current. The small volume of voltage became 100 times larger by using a fabricated amplifier. This amplifier was composed of the integrated circuit AD 524 C. The calibration constant of this instrument was specified by a digital ammeter and confirmed to be 0.013 V/A with a sufficient coefficient of regression, 0.99.

In addition, the system voltage was verified through a voltage reduction circuit which divided the system voltage by 38.4. Thus, it could measure the system voltage without damaging the A/D converter board. Using the IBX-3127 isolated A/D converter, the data related to both current and system voltage could be collected. A schematic diagram of measuring items is shown in Fig. 3.

In addition, the motor speed was measured by installing a photo sensor and reflector to determine the number of revolutions of the motor shaft. The ON/OFF signal was fed to the IBX-6206 counter board. Utilizing the timer of the computer, the speed of the motor could be evaluated.

Furthermore, a fifth wheel was used to determine the travel speed. The basic components of the fifth wheel consisted of a tire radius of 10.58 cm, sprocket teeth of 240 units, and a magnetic pick-up sensor. The pulse signal of the sensor was converted to voltage by an FV converter, then conveyed to the IBX-3133 A/D converter for data processing. The calibration results suggested the availability of a sufficient level of accuracy for asphalt and smooth roads. In this case, the calibration constant was found to be 0.185 V·Eh/km.

(2) Drawbar pull performance test

One of the important tasks of the ET was considered to be providing the traction that overcomes the loads on the farm. Therefore, its drawbar pull performance was discussed in terms of drawbar pull and drawbar power. Also, the overall ET efficiency, \( \eta_o \), was evaluated as the conversion efficiency of battery energy into drawbar power.

The experiments were performed on both asphalt and hard soil surfaces. The method of the lowest gear setting at 80% of full throttle followed the code regarding the energy consumption and range test. The different combination of loads was applied by a dynamometer-car which is capable of adjusting the tractive resistance up to maximum load. The test combinations were divided into five levels in terms of applied loads by using the engine brake of the dynamometer-car.

Using the on-board measuring system described above, the energy requirement for each level of load could be evaluated. However, this data processing system needed some modifications in order to determine other necessary parameters such as the drawbar pull and slip. To implement this approach, a load-cell was used to measure the drawbar pull. The strain amplifier received the output signal from the load-cell before it was forwarded to the IBX-3133 A/D converter board.

In order to measure the revolution speed of wheel, four photo sensors and four reflectors were placed at the wheel mounting positions on a driving shaft and inside a wheel, respectively. These photo sensors generated the ON/OFF signals, which were individually connected to the CNT-24 counter board for the measurement of each wheel speed. A simplified schematic diagram of this data processing system is shown in Fig. 4 (12)

‡W Results and Discussion

1. Energy consumption and driving range

The amount of \( E_c \) could be determined by the integration of both the power discharged and travel speed curves with respect to time, \( t \), as follows:

\[
E_c = \int P_e(t) \, dt
\]

where \( v \) is travel speed [km/h] and \( P_e \) is power discharged from the battery [kW]. In other words, its physical meaning encompasses the ratio of the energy discharged from the batteries and the driving range.

The results of the energy consumption and range tests were represented in Fig. 5. It is not really necessary to mention that multiplication of the current and voltage produces the power. Taking into account this fact, the real-time fluctuations of \( P_e \) are recorded and...
discussed as shown in Fig. 6. This figure shows that the travel speed and power discharged were gradually decreasing from 13.5 km/h to 10.8 km/h and 12.5 kW to 6.5 kW, respectively. These were caused by the depletion of the battery energy. From the equation (1), the driving range in this test was determined experimentally to be 8.35 km and the overall energy consumed by the electric motor in travel was 4.99 kW•h. These results indicate that the ET exerted a certain amount of Ec of 0.60 kW•h/km.

The estimated value of Ec of the ET is about 0.40 kW•h/km when the ET was assumably operated for 1.3 h on one full-charge at full rated load. Under this setting condition, the driving range became as much as 18 km. As stated above, the limitation in terms of driving range exists at all times as long as lead-acid batteries are installed. However, this is not disadvantageous because there are some alternative practical ideas to use the ET for specific agricultural assignments. In fact, most of the stored energy can be consumed by vehicle operation. Together with the advancement of energy, the vehicle started to show gradual reduction of travel speed which was recognizable later at the laboratory. The depth of discharge (D.O.D) is defined as the amount of energy consumed against the full-charge capacity of the battery. Throughout these experiments, the battery capacity was found to be 7.2 kW•h and the electric energy delivered from the battery was 4.99 kW•h or approximately 70% D.O.D for maintaining its travel speed. On the other hand, the 30% remaining energy was confirmed as being capable to move the ET at a slower pace until stall. As expected above, when the available energy at 70% D.O.D was secured, the driving range seemingly was 12 km. Since this estimation disregarded some mechanical losses that took place in the power transmission units, a somewhat lower level of driving range was evaluated in this particular trial.

2. Drawbar pull characteristics

This design concept partly contains the mechanical capability that is able to accommodate the basic performance requirement. To propose a satisfactory level of ET, this sort of design feature may be incorporated from the beginning stage of the design process.

In these experiments, the drawbar power which was defined as the tractive ability developed by the driven wheels was investigated under both asphalt and hard soil surface conditions. Fig. 7 shows the result of the experiments in conjunction with drawbar pull, drawbar power, and slip. In the case of asphalt trials, the actual drawbar pull became 5.76 kN at 14% slip. At this particular condition, the drawbar pull exerted by the ET was 5.42 kW. Under hard soil condition (CI = 980 kPa), the ET produced 3.89 kN in drawbar pull and 3.36 kW in drawbar power at 22% slip. Moreover, the drawbar pull took 9 kN and 6 kN at 100% slip on the asphalt and hard soil surfaces, respectively. Though the ET was converted with nominal power of 10.25 kW, it generated the traction coefficient equivalent to a 20 kW diesel tractor. This is because an electric motor is able to accept excessive loads to some extent. In these tests, the DC motor could exert the power up to 21 kW even though its capacity at normal continuous rating was 10.25 kW only. It could handle excessive power such as 11.4 kW at 1h rating, 20 kW at 5 min rating, and a 43 kW peak for a few seconds. Another factor is that the specific power of the battery enabled the ET to provide greater performance. Regarding the whole set of sealed lead-acid batteries, it contains...
Table 3 Results of the drawbar pull performance test

<table>
<thead>
<tr>
<th>Surface condition</th>
<th>Drawbar pull [kN]</th>
<th>Travel speed, v [km/h]</th>
<th>Drawbar power, $P_D$ [kW]</th>
<th>Slip [%]</th>
<th>Power discharge, $P_E$ [kW]</th>
<th>Energy efficiency, $\eta_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt</td>
<td>1</td>
<td>8.22</td>
<td>1.90</td>
<td>4.34</td>
<td>51.07</td>
<td>21.06</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.71</td>
<td>2.31</td>
<td>4.94</td>
<td>39.47</td>
<td>19.35</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6.83</td>
<td>2.71</td>
<td>5.15</td>
<td>20.34</td>
<td>16.20</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5.76</td>
<td>3.39</td>
<td>5.42</td>
<td>14.18</td>
<td>17.31</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4.42</td>
<td>3.79</td>
<td>4.65</td>
<td>7.76</td>
<td>15.84</td>
</tr>
<tr>
<td>Hard soil</td>
<td>1</td>
<td>5.86</td>
<td>1.85</td>
<td>3.01</td>
<td>50.80</td>
<td>18.03</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5.21</td>
<td>2.22</td>
<td>3.22</td>
<td>40.97</td>
<td>17.07</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.86</td>
<td>2.58</td>
<td>3.48</td>
<td>33.41</td>
<td>16.11</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.89</td>
<td>3.11</td>
<td>3.36</td>
<td>22.26</td>
<td>14.27</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.04</td>
<td>3.60</td>
<td>3.04</td>
<td>13.03</td>
<td>13.79</td>
</tr>
</tbody>
</table>

The values of $\eta_0$ were found to be 0.21–0.32 and 0.17–0.24 on asphalt and hard soil surfaces, respectively. Accordingly, the proportional relationship between $P_E$ and the drawbar pull is shown in Fig. 8. In this result, the $P_E$ increased linearly with respect to the drawbar pull. When the drawbar pull equaled zero, the ET required a sustained $P_E$ of 10 kW that was consumed by the power transmission and motion resistance. It is of interest to note that the amount of $P_E$ being more than 10 kW was provided for the drawbar pull.

The comprehensive investigation found that $\eta_0$ exceeded the overall efficiency of a diesel tractor\(^{33}\). The practical reason for using a galvanic element comes from the fact that the overall efficiency of a diesel engine has limitation in terms of a theoretical value of approximately 60%, and practical ones are much lower. A battery can convert the energy of its chemicals with more than 95% efficiency theoretically, and over 60% practically\(^{14}\).

Since $\eta_0$ is considered to take a favorable or higher value by virtue of its energy consumption mode, this tendency is taken for granted and hence further improvement is needed. For an ET in a steady-state condition on flat terrain, the desirable power rating of the electric motor, $P_M$, is given by:

$$P_M = P_S + P_F + P_R$$

where $P_S$, $P_F$, and $P_R$ are the power to overcome friction in transmission, slip, and motion resistance, respectively. The tractive efficiency, $\eta_{tD}$, is defined by:

$$\eta_{tD} = \frac{P_D}{P_M} = \eta_T \eta_S \eta_R$$

where $\eta_T$, $\eta_S$, and $\eta_R$ are efficiency associated with transmission, slip, and motion resistance, respectively. In actual operation, the losses occurred in transforming electrical power to mechanical power due to the internal losses of the electric motor and the battery discharge characteristics. The $P_E$ can be expressed by:
where $\eta_M$ is the motor efficiency and $\eta_B$ is battery discharge efficiency. Substituting equation (5) into equation (2), the expression for $\eta_O$ becomes:

$$\eta_O = \eta_M \eta_B \frac{P_D}{P_M}$$  (6)

This can be rewritten as:

$$\eta_O = \eta_M \eta_B \eta_P$$  (7)

As can be seen in equation (7), the value of $\eta_O$ tends to increase by improving the amount of $\eta_B$. To increase the $\eta_B$, rational determination of the $\eta_M$, $\eta_S$, and $\eta_R$ is considered to be of importance. In this respect, mass distribution between front and rear axle seemingly influences against $\eta_B$.

The forthcoming design concept is perhaps worthwhile in that it proposes the intrinsic advantages of the ET, seeking improvement of tractive ability, safety, and ride comfort accompanied by some specific configuration designs. This configuration applied for the running device of an EV is to be done by using in-wheel motors, which are housed within each wheel independently. In the absence of a mechanical transmission system, the creation of adequate space for designing can be secured for engineers. As a result, women and the aged can become the new partners of farming operations, managing the ET comfortably in a way that could never be done before. The frame design allowed placing the batteries beneath the central portion of the vehicle in a form of compartment as shown in Fig. 9. This is referred to as the battery built-in frame. In this concept, the whole set of batteries can be shifted back and forth along the fixed guided frame which can achieve recommendable selection seeking better tractive efficiency. What is more, this structure allows a lower center of gravity for safer operation.

V Conclusions

The converted fabrication of a diesel tractor has been carried out to examine several performance aspects of an ET. Some experiences related to fabricating works and subsequent performance tests, results brought about some meaningful findings as listed below:

1) The energy consumption and range test indicated that the ET showed a driving range of 8.35 km per one full-charge. Consequently, the ET exerted the amount of $E_{EC}$ of 0.60 kW·h/km. The discharge characteristic of the battery implied that 70% D.O.D was guaranteed for maintaining the stable travel speed of the ET. The limited driving range was strongly influenced by the mechanical losses in power transmission units.

2) The drawbar pull performance showed that the ET was able to provide adequate tractive effort for a relatively short period. Its traction coefficient was found to be equivalent to that of a diesel tractor, although the continuous rated power level was lower. This salient advantage was due to the latest technological advancement of sealed lead-acid batteries which show higher specific power. Furthermore, the advantage of the DC motor included its ability to overcome excessive loads.

3) The overall efficiency of the ET exceeded that of the diesel tractor in most cases. Preliminary discussion regarding a proposed model was made to develop a perspective design concept.

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List of symbols

- $v$: travel speed [km/h]
- $E_C$: energy consumption [kW·h/km]
- $P_K$: power discharged from battery [kW]
- $P_S$: drawbar power [kW]
- $P_T$: power to overcome friction in transmission [kW]
- $P_S$: power to overcome friction in slip [kW]
- $P_K$: power to overcome friction in motion resistance [kW]
- $\eta_O$: overall efficiency
- $\eta_D$: tractive efficiency
- $\eta_T$: transmission efficiency
- $\eta_S$: slip efficiency
- $\eta_R$: motion efficiency
- $\eta_M$: motor efficiency
- $\eta_B$: battery discharge efficiency
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要 旨

市販ディーゼル機関搭載トラクタを改造して電気トラクタを試作し、そのエネルギー消費量とけん引性能について実験的解析を行った。供試した密閉式蓄電池の容量を 7.2 kWh・h としたとき、エネルギー消費量と回充電走行可能距離はそれぞれ 0.60 kWh・h/km と 8.35 km であった。その結果に基づいて、实用化に向けた回充電走行可能距離の改善策について検討した。けん引性能は、アスファルト路面において滑り率 14％で 5.76 kN、堅硬地において滑り率 22％で 3.89 kN となり、実用性に耐えうる性能を発揮するものと推察できた。総合エネルギー伝達効率についても、予測値に近い水準値を示すことが分かった。

[キーワード] 電気トラクタ、電気自動車、農用トラクタ、密閉型蓄電池、エネルギー消費量、けん引性能

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