Analysis of power requirement of a prototype four-wheeled electric vehicle under different off-road conditions

M Ali1, M Chowdhury1,2, M N Islam1, K Rasool1, H S Lee3, and S O Chung1,2

1Department of Agricultural Machinery Engineering, Graduate School, Chungnam National University, Daejeon, Republic of Korea
2Department of Smart Agricultural Systems, Graduate School, Chungnam National University, Daejeon, Republic of Korea
3SB Industry Co. Ltd., Cheonan, Republic of Korea

E-mail: sochung@cnu.ac.kr

Abstract. Different types of vehicles are used for various agricultural activities. Most agricultural vehicles have high power, which makes them inconvenient for elderly and female farmers in difficult farm conditions, such as irregular, inclined, and low-traction terrains. Therefore, the objective of this study is to evaluate the power requirement of a four-wheeled electric vehicle (4WEV) on various off-road conditions. In this study, the experiments were conducted on typical Korean farm roads by considering different slope, load, and road conditions as factors for the power requirement analysis. The torque data were obtained for 0°, 5°, 10°, and 15° slopes with 100, 300, and 500 kg payloads. The rotational speed of the wheel was constant at 50, 60, or 70 rpm for each slope and payload condition on concrete and asphalt roads. The average power required by the 4WEV was recorded to be 0.84 ± 0.025 kW and 0.85 ± 0.087 kW with 500 kg payload on 15° inclined concrete and asphalt roads, respectively. Similarly, the minimum power recorded was 0.29 ± 0.023 kW and 0.31 ± 0.069 kW with 500 kg payload at 70 rpm wheel speed on completely horizontal concrete and asphalt roads, respectively. The 60 and 50 rpm speeds showed the maximum and minimum power at 15° and 0° slopes, respectively, during the experiment. However, the maximum power requirement varies with the load condition and wheel speed under different off-road conditions. The developed 4WEV could satisfactorily scale 15° slopes with 500 kg payloads without any difficulty.

1. Introduction
Agriculture is considered a major field in which multifunctional vehicles are needed to perform various farming activities. At a commercial scale, multiple types of internal-combustion-engine-powered vehicles are used to perform these activities. However, these vehicles are seldom inconvenient due to engine inefficiency, uneven terrain, road inclination, and low traction. Moreover, heavy vehicles are costly and require skilled labour to handle them. These issues can be solved by developing eco-friendly and high-efficiency vehicles or by considering the alternative of electric vehicles (EV) [1–3]. Although EVs are mainly designed for urban use, recently, they have been widely used in several fields, including...
forestry and agriculture. In agriculture, EVs are preferred owing to their eco-friendly power source. The four-wheeled electric vehicle (4W EV), analyzed in this study, is powered by an electric battery [4, 5], which not only addresses environmental issues but also improves the power transmission efficiency of the vehicle. Furthermore, EVs play a major role in devising energy policies around the world by reducing the reliance on fossil fuels [6].

The growing use of EVs in the agricultural sector motivated us to design an optimal power delivery system. Therefore, it is necessary to analyze the load spectrum and power requirement of the main components of the vehicle based on road conditions and field operations. An essential and integral component of all EVs is the drive motor [7, 8]. The amount of torque produced by the drive motor plays an important role in ascertaining the performance of the EV, as it is responsible for moving the vehicle. In other words, the calculated torque defines the power that comes from the drive motors.

Many studies have been conducted on the load and power analysis of internal-combustion-engine-powered agricultural vehicles [9–13]. However, there is a lack of research on the power requirement analysis of 4WEVs. Furthermore, special considerations, such as payload capacity and off-road performance, are required for the power analysis of 4WEVs if they are to be used by elderly people and female farmers.

Power requirement analysis is essential for improving the power efficiency of any agricultural vehicle, which varies with the road condition and field operation. The overall objective of this study is to analyze the power requirement and evaluate the performance of the prototype 4WEV (SB Industry Co. Ltd., Republic of Korea) on different slope, load, and road conditions.

2. Materials and Methods

2.1. Structure and principle of the power transmission system

The 4WEV was developed considering specific vehicle parameters and field operating environments. The specifications of the 4WEV are shown in Table 1.

| Item                                      | Specification                      |
|-------------------------------------------|------------------------------------|
| Vehicle dimension (length × width × height) (m) | 1.8 × 0.85 × 0.7                   |
| The gross weight of the vehicle (kg)      | 650                                |
| Maximum load capacity (kg)                | 500                                |
| Maximum forward speed (km/h)              | 3                                  |
| Single DC motor (24 V)                    | 0.40 kW @ 3400 rpm                 |
| Battery (amp)                             | 100                                |
| Wheel diameter (m)                        | 0.46                               |

The vehicle is mainly comprised of a drive unit, main body, and power transmission unit. The drive unit of this vehicle was controlled via electrical circuits. The major elements of the power transmission unit of the 4WEV were the DC motor, battery, power converter, and coupling. The power was transmitted by the direct coupling between the two gears. The required power generated by the batteries and motors was supplied directly to each wheel through gears. The schematic of the power transmission system of the 4WEV is shown in Figure 1. A spur gear (72.3 mm diameter, 27 teeth with 1:1 ratio) and bevel gear (64 mm diameter, 20 teeth with 1:1 ratio) were used for the front and rear wheels, respectively, for testing the 4WEV.
2.2. Vehicle power estimation

2.2.1. Torque and angle sensor attachment

A torque sensor (TRS605 FUTEK, Advanced Sensor Technology Inc., California, USA) was installed on the rear axle for measuring the required axle power of the 4WEV. The torque sensor was synchronized with the motor driveline and both the components were rotated at the same speed. At 60 Hz, the rated power and speed of the motor were 0.40 kW and 3400 rpm, respectively. An inverter (SV-iG5A; LS Electric Co. Ltd., Anyang, Republic of Korea) was configured with an on/off switch to control the rotational speed of the motor. A data acquisition device (NI 6212, National Instruments Corp., Austin, Texas, USA) and LabVIEW software (version 2010, National Instruments Corp., Austin, Texas, USA) were used to record the sensor data. The placement of the torque sensor is shown in Figure 2. A high-precision inclinometer (SST420, Shanghai Vigor Technology Development Co., Ltd., Shanghai, China) was used to measure the inclination of the roads.

![Figure 1](image1.png)

**Figure 1.** The power transmission system of the 4WEV.

![Figure 2](image2.png)

**Figure 2.** (a) 4WEV prototype used in the experiment. The numbers indicate the (1) laptop with the data acquisition system, (2) load, (3) rear wheel, (4) battery, and (5) front wheel. (b) Location of the torque sensor on the rear axle.
2.2.2. Experimental data collection
The 4WEV was developed to facilitate transportation activities on farms. The power requirement experiment of the 4WEV was performed on two different but typical Korean farm roads, as shown in Figure 3, at three different, forward speeds of 1, 2, and 3 km/h, respectively.

The performance parameters of the 4WEV were assessed for multiple payload capacities (maximum load = 500 kg) and slopes (maximum inclination = 15°). The experimental conditions are shown in Table 2. The rotational speed of the wheel axle was fixed at 50, 60, and 70 rpm to determine the torque on the rear wheels during the experiment. Loads of 100, 300, and 500 kg were used to assess the power requirement and torque on 5°, 10°, and 15° inclined roads. Furthermore, each test was repeated thrice. The average maximum power requirement was calculated using the following equation.

$$P = \frac{T \times W}{9.549}$$  \hspace{1cm} (1)

Where $P$ is the power (W), $T$ is the torque (Nm), and $W$ is the wheel rotational speed (rpm).

| Variable            | Specification          |
|---------------------|------------------------|
| Forward speed (km/h)| 1, 2, and 3            |
| External load (kg)  | 100, 300, and 500      |
| Slope (°)           | 5, 10, and 15          |
| Road type           | Concrete or asphalt    |

2.3. Statistical analysis
All experiments were replicated three times, and the recorded results were indicated as the mean ± standard deviation. The statistical significances were examined using a one-way ANOVA method (Tukey’s multiple range test) at a level of 5%.

3. Results and Discussion
3.1. Power required for field operations
Different parameters were responsible for the fluctuations in the power requirement. The results showed that the power requirement changed based on the road condition and payload on the vehicle. When the speed of the wheel changed, the required power also changed. Moreover, both parameters are directly proportional to each other. However, as the inclination angle changed, the torque on the rear wheel also changed. Nevertheless, the motor produced the required power depending on the vehicle speed.

3.2. Power required on a concrete road
Table 3 shows the average maximum power required for driving the 4WEV on different slopes under various conditions. On the concrete road inclined at 15°, the 4WEV produced a maximum power of 0.84 ± 0.025 kW, 0.69 ± 0.055 kW, and 0.61 ± 0.037 kW for the 500 kg load, 0.70 ± 0.069 kW, 0.57 ± 0.020 kW, and 0.51 ± 0.084 kW for the 300 kg load, and 0.41 ± 0.081 kW, 0.32 ± 0.022 kW, and 0.29 ± 0.079 kW for the 100 kg load when the wheel speeds were 70, 60, and 50 rpm. The results show a minimum power requirement when the inclination is 0°. However, the maximum power was produced by the motor for the payload of 500 kg on the 15° slope at all-wheel speeds, whereas the motor produced minimum power when the inclination was 0°.
The experimental results of power requirement analysis of the 4WEV on concrete roads are shown in Table 3.

| Wheel speed (rpm) | Applied load (kg) | Average maximum power requirement per wheel (kW) | Slope (degree) |
|------------------|-------------------|------------------------------------------------|---------------|
|                  |                   |                                                | 0  | 5  | 10 | 15 |
| 70               | 500               | 0.29 ± 0.023                                     | 0.50 ± 0.039 | 0.73 ± 0.071 | 0.84 ± 0.025 |
|                  | 300               | 0.23 ± 0.075                                     | 0.41 ± 0.048 | 0.52 ± 0.036 | 0.70 ± 0.069 |
|                  | 100               | 0.13 ± 0.012                                     | 0.22 ± 0.090 | 0.31 ± 0.061 | 0.41 ± 0.081 |
| 60               | 500               | 0.26 ± 0.014                                     | 0.41 ± 0.021 | 0.61 ± 0.019 | 0.69 ± 0.055 |
|                  | 300               | 0.21 ± 0.081                                     | 0.36 ± 0.083 | 0.44 ± 0.030 | 0.57 ± 0.020 |
|                  | 100               | 0.13 ± 0.026                                     | 0.18 ± 0.056 | 0.28 ± 0.068 | 0.32 ± 0.022 |
| 50               | 500               | 0.21 ± 0.062                                     | 0.37 ± 0.075 | 0.53 ± 0.055 | 0.61 ± 0.037 |
|                  | 300               | 0.18 ± 0.079                                     | 0.29 ± 0.070 | 0.37 ± 0.063 | 0.51 ± 0.084 |
|                  | 100               | 0.11 ± 0.033                                     | 0.15 ± 0.036 | 0.21 ± 0.019 | 0.29 ± 0.079 |

3.3. Power required on asphalt road

The power required by the 4WEV on the asphalt road was different compared to that on the concrete road because of different surface friction coefficients. The slopes of 5°, 10°, and 15° required 0.52 ± 0.050 kW, 0.75 ± 0.040 kW, and 0.85 ± 0.087 kW maximum power for the 500 kg load, 0.42 ± 0.078 kW, 0.54 ± 0.056 kW, and 0.71 ± 0.011 kW for the 300 kg load, and 0.26 ± 0.045 kW, 0.34 ± 0.011 kW, and 0.43 ± 0.050 kW for the 100 kg load at 70 rpm wheel speed. By contrast, at 60 and 50 rpm wheel speeds, the 4WEV required lesser average power compared to that at 70 rpm. This is due to the relationship between torque, power, and speed. The average maximum power required by the 4WEV under different conditions on asphalt roads is shown in Table 4.

Table 4. Experimental results of power requirement analysis of the 4WEV on asphalt roads.

| Wheel speed (rpm) | Applied load (kg) | Average maximum power requirement per wheel (kW) | Slope (degree) |
|------------------|-------------------|------------------------------------------------|---------------|
|                  |                   |                                                | 0  | 5  | 10 | 15 |
| 70               | 500               | 0.31 ± 0.069                                     | 0.52 ± 0.050 | 0.75 ± 0.040 | 0.85 ± 0.087 |
|                  | 300               | 0.24 ± 0.023                                     | 0.42 ± 0.078 | 0.54 ± 0.056 | 0.71 ± 0.011 |
|                  | 100               | 0.16 ± 0.056                                     | 0.26 ± 0.045 | 0.34 ± 0.011 | 0.43 ± 0.050 |
| 60               | 500               | 0.26 ± 0.067                                     | 0.43 ± 0.070 | 0.63 ± 0.031 | 0.72 ± 0.010 |
|                  | 300               | 0.23 ± 0.064                                     | 0.37 ± 0.020 | 0.45 ± 0.068 | 0.60 ± 0.098 |
|                  | 100               | 0.14 ± 0.050                                     | 0.23 ± 0.044 | 0.30 ± 0.031 | 0.35 ± 0.060 |
| 50               | 500               | 0.24 ± 0.052                                     | 0.37 ± 0.049 | 0.55 ± 0.028 | 0.62 ± 0.069 |
|                  | 300               | 0.20 ± 0.015                                     | 0.31 ± 0.049 | 0.40 ± 0.018 | 0.52 ± 0.089 |
|                  | 100               | 0.13 ± 0.030                                     | 0.16 ± 0.070 | 0.27 ± 0.080 | 0.31 ± 0.014 |
3.4. Maximum power requirement comparison for various slope conditions

Figure 4 (a)–(d) shows the average maximum power requirements for different load conditions (100, 300, and 500 kg). The maximum power required changes depending on the load condition. In this experiment, there was no significant difference between the maximum load conditions, even at different slope conditions. For 100 and 300 kg loads, the power required for driving the 4WEV on asphalt and concrete road conditions were very similar. However, the power differences observed between 5° and 15° inclined roads were minimal. When the inclination was 10°, there was no difference in power requirement between asphalt and concrete roads for the minimum load. However, the calculated data showed that additional power was required when the vehicle carried maximum loads. By contrast, high power was necessary to ascend slopes in off-road conditions. The overall experiment suggests that concrete roads required less power than asphalt roads. It may happen due to a higher coefficient of friction on the road surface because it increases the distributing torque that effects a bit on the required power in the concrete road surface.

The various letters on the bars show the differences according to Tukey’s multiple range test ($P \leq 0.05$).
4. Conclusions
In this study, basic tests were conducted to analyze the power consumption for different slope, load, and road conditions to improve the power efficiency of the developed 4WEV. The torque data were collected by driving the 4WEV at 0°, 5°, 10°, and 15° inclined concrete and asphalt roads with 100, 300, and 500 kg loads. The prototype 4WEV exhibited satisfactory results for each condition. A maximum load of 500 kg is recommended for a maximum road inclination of 15° for the safe use of this vehicle. Besides, economic evaluation and durability test is an important issue for the development of 4WEV in agricultural sectors. The existing prototype EV is under development; the future research would follow the standard evaluation approaches for extending the EV reliability. Further experiments on different surface conditions (e.g. earthen, grassland) based on the response surface methodology (RSM) for each road condition and modifications to the developed vehicle will be performed to enable elderly and female farmers to perform various agricultural farm activities.

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