Feasibility Study of Motor Powered Agricultural Tractors Based on Physical and Mechanical Properties of Energy Sources

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Abstract

The alternate power utilization instead of Internal Combustion Engine (ICE) in an agricultural tractor (AT) was studied by simulation approach for the drivelines of electric battery (EB), fuel cell (FC) and reformed methanol fuel cell (RMFC). The working hours were considered 4 with comparison of weight, volume, soil pressure, and fuel efficiency. In weight comparison, 12% overweight in FC-AT, 16% overweight in RMFC-AT, and 99% overweight of EB-AT were observed for the rated output power of light duty tractor (17.25 kW). Less than 5% overweight of FC-AT and RMFC-AT, and 39%–62% overweight of EB-AT were observed for rated output power of medium and heavy-duty tractor (33.75–75.00 kW). Soil pressure in the root-growing block was observed less than 130 kPa for EB-AT, FC-AT, RMFC-AT in the rated output power from 17.25–75.00 kW. In all the alternatives, ±5% fluctuations in the volume were observed. In the design stage, we proposed, that FC-AT was the best alternative considering weight, volume, and soil pressure. Furthermore, the analytical software AVL Cruise was used for vehicle drive line system to find out how weight affects the performance for 75.00 kW EB-AT. The analysis was designed for 4 working hours with full load at 20 km/h of velocity using AVL Cruise. The peak velocity was found less than 14.1 km/h, and constant working time was only 3 hours, because of the severe overweight by EB storage.

Keywords

agricultural tractor, electric battery, electric motor, fuel cell, simulation

Introduction

Depletion of fossil fuels, increasing environmental concerns regarding air pollution, and smart life style encourage to develop new energy resources for vehicles, such as EB (electric battery), FC (fuel cell) and RMFC (reformed methanol fuel cell). About 65% CO₂ emission comes from fossil fuel and agroforestry industry including the agricultural tractor (AT) contributes 24% of this emission (IPCC 2014). Most of them come from ICE (internal combustion engine) based agroforestry machinery.

Fig. 1 shows that efforts of a century by the researchers to save the energy or use new types of energy systems in vehicle manufacturing to achieve a more sustainable society (Mikalsen and Roskilly 2007, Colares 2008, Deal III 2010, Hoyer 2008, Andújar and Segura 2009). However, these new technologies have been applied to agroforestry machinery behind of automobiles. Many researchers had tried to improve the fuel efficiency of ICE. Due to the defects of its design and physical principle of ICE, the heat loss is unavoidable and the fuel efficiency is hard to exceed 40%. Thus, the fuel efficiency is about 28–30% of standard ICE (Faria et al. 2012). For the whole system and under high load working condition, the final fuel efficiency of an ICE vehicle is only about 17.8% (Pollet et al. 2012). Not only low efficiency, but also ICE emits waste gases and particle air...
pollutants, such as SO$_2$, NO$_x$, CO$_2$, and PM2.5, causing air pollution and climate change (Reşitoğlu et al. 2015). Thus, ICE is not competent for the long-term strategy, and researchers noticed that electric motor based vehicles is able to be competitive to ICE automobile considering zero emissions.

The purpose of this research is to clarify the possibility of motor powered agricultural tractors based on physical and mechanical properties of EB, FC and RMFC as substitute energy sources of ICE satisfied with working time and safety level of soil pressure incorporated with the specifications of agricultural tractor, and industrial products, and reviewing previous studies.

Materials and Methods

Performance of ICE and Electric motor

Though diesel engine has a wider low fuel consumption band, high power and high torque cannot be achieved at the same time (Challen and Baranescu 1999). When heavy duty torque working band is in low section of engine rotation, the total power of the engine cannot be worked out. When rotation speed is increased, the output power is also enhanced. The output power can be expressed as follows:

$$ P = \frac{M \times N}{9550} \quad (1) $$

where $P$ is the output power [kW]; $N$ is the engine rotation speed [rpm] and $M$ is the torque [Nm]. When the rated output power $P$ is fixed, engine rotation speed $N$ and engine torque $M$ are in inverse relation. The actual performance achieves at 70–80% of its peak torque. ICE cannot start up and may cause its engine flameouts when overloaded.

Electric motor always tries to obtain rated rotation speed and maintain it, even if the high load was set at the start (Nam 2010). However, when the rated power is higher than 7.5 kW and the direct starting could not forward, a voltage-dropping starter or y-Δ connection is needed to avoid its burnout. Furthermore, the maximum starting up load is only about 60% of the rated load (Liu et al. 2011). The electric motor can bear 3–7 times over current shock regarding overload ability. The asynchronous electric motor can run safely reach at 200% of normal rated load for a few minutes without decreasing rotational speed (Hori 2004). Thus, an electric motor's torque is biased within its tolerance; the rotation speed barely influences. The energy efficiency of standard motors in the typical range is 83–92% (Hasanuzzaman et al. 2011). For high load working vehicles such as AT, constant high output ability and momentary overload ability are very important. Furthermore, electricity as the energy source of the motor can be generated in environmental friendly ways by the renewable resources (Lange and Linn 2008).

Motor powered plans by different energy sources

Output torque is the most important parameter for AT. The electric motor powered AT was supposed to have higher outputted torque, overcome overload of farming, and higher performance compared to ICE-AT. Also, the drive line from the engine to the wheel (powertrain) of ICE-AT doesn’t equip with not only fuel tank and engine but also clutch, gearbox, and shaft. These parts of powertrain have a high mechanical loss of energy in general. In this research, three motors powered AT by EB, FC, and RMFC were evaluated through simulation research. Comparisons of energy density and final efficiency among EB, FC, and RMFC are listed in Table 1.

EB vehicle has a very high-energy efficiency of 66.5% (Pollet et al. 2012). However, the energy density of batteries is low as

![Fig. 1 Trends of power units for alternate sources including biofuel for commercial automobile](image-url)
100–150 Wh/kg (Scrosati and Garche 2010) that equals 0.36–0.54 MJ/kg of lithium-ion battery. The battery has about 1/100 energy density compared with 43.5 MJ/kg of diesel fuel. Therefore the cruising ability of EB vehicle is much lower than an ICE vehicle while the weight is unchanged. Also, charging time of batteries for an all-electric vehicle requires much longer than ICE vehicle (Thomas 2009). A thermal energy loss is occurred in charging 300 kWh capacities for EB-AT. 80 kW of charging power for residential circuit is difficult to access.

FC by using hydrogen is the most attractive energy unit to achieve a longer durability. The FC eliminates emissions on the tank-to-wheel path; the hydrogen used for fuel can be produced from many sources with high-energy consumption (Helmolt and Eberle 2007). FC generates electricity to charge the batteries on board or connect to the motors directly via ultra-capacitor. Only water is emitted during its working. Gaseous hydrogen has a very high energy density in weight, 143 MJ/kg. Total weight of stored hydrogen as gaseous condition is 5.7% of tank weight according to TOYOTA technology (Nonobe 2017). It means 19 kg capacity of tank can store only 1 kg liquid hydrogen, energy density is 7.2 MJ/kg (9.8 MJ/L). Furthermore, the efficiency of a fuel cell unit is about 51.8%, and the energy loss in other electric devices the final efficiency is about 41.6% (Moore et al. 2006).

Storing high-pressure hydrogen on board cannot satisfy the safety of AT as an industrial product, and affects the vehicle weight quite high. To solve these technological subjects, the concept of RMFC was proposed. RMFC of power system uses an on board methanol reformer to reform the methanol into hydrogen. Then the hydrogen is used to generate electricity through FC (Andreasen et al. 2014). Methanol has a relatively high energy density, 21 MJ/kg (16.6 MJ/L), and can be stored in anti-corrosion treated tanks like diesel and gasoline. The on-board methanol reformer is still in progress of research with a conversion efficiency of 70%–90% (Kim and Kwon 2009). In this study, the final fuel efficiency of a RMFC is estimated to be 33.28%.

FC vehicle and RMFC vehicle use batteries as the current buffer, and recycling devices for braking energy. Ultra-capacitor is installed more often because of its high charging and discharging efficiency, long life time, and small size for heavy duty vehicles instead of a battery. A full-size battery is not necessary and its spare space can be used other parts in use of RMFC. The FC-AT with 75 kW output power, HN2 (New Atlas 2009) produced by New Holland company was only installed a 12 kWh battery as indispensable energy storage medium. The battery properties affect the final performance severely. The resistance of a traveling vehicle is much lower than a working vehicle. The comparisons between passenger vehicle and AT were shown in Table 2.

**Specific data and equation for calculation**

In this study, 5 John Deere tractors, the output power from 23–100 horse power (17.25–75.00 kW) were selected to simulate for motor powered AT according to the basic physical properties of ICE-AT (Table 3) (John Deere 2017). Similar output powered electric motors were selected as the power source to achieve the same working performance. Motor driving parts such as energy storage part, fuel conversion part, and other necessary parts were also considered in the layout design of ICE-AT, EB-AT, FC-AT and RMFC-AT (Fig. 2) (Table 4). The power unit of conventional tractors was divided into four main parts: engine, gearbox and clutch, power transmission, and fuel storage unit to check the physical rationality analysis. A small and simple gearbox was enough to meet the demand of wide range rotation speed of motors. Also, a clutch was not required because of no-idling.

The working hours for conventional and motor powered tractors were set to be 4 hours as 2-shifts-day working with refueling or charging in noon break time. Weight and volume of the gearbox and main shaft parts were estimated by the data of transmission products of EATON company (EATON company 2017) (Table 3). In gear selection, 5 and 6 forward, 1 reverse manual gearbox (maximum output torque: 400Nm, 60 kg, 50 L) of product number FSO-2505 was selected for light duty tractor. The gearbox (maximum output torque: 700–825 Nm, 134 kg, 80 L) of product number FS-5206 was selected for

### Table 1: Comparisons of energy density and final efficiency among ICE (internal combustion engine), EB (electric battery), FC (fuel cell), RMFC (reformed methanol fuel cell)

| Fuel type  | Energy density | Final efficiency |
|------------|----------------|-----------------|
| ICE        | Diesel         | 43.50 MJ/kg     | 18.00%         |
| EB         | Battery        | 0.36–0.54 MJ/kg (100–150 Wh/kg) | 66.50%         |
| FC         | Hydrogen       | 7.20 MJ/kg      | 41.60%         |
| RMFC       | Methanol       | 21.00 MJ/kg     | 33.28%         |

### Table 2: Comparison between EV (electric vehicle) as passenger vehicle and EB-AT (agricultural tractor powered by electric battery) based on same maximum power of HN2 (New Atlas 2009)

| Fuel type | Maximum power | Power in use | Fuel consumption rate |
|-----------|---------------|--------------|-----------------------|
| EV        | 75 kW         | 22.0 kW (100 km/h) | 0.22 kWh/km           |
| EB-AT     | 75 kW         | 37.5 kW (half load, 5 km/h) | 7.50 kWh/km           |
medium duty tractor. The gearbox (maximum output torque: 1,900–2,200 Nm, 245 kg, 160 L) of product number FA-14810 was selected for heavy duty tractor. Furthermore, 50% of engine weight and 70% of gearbox’s volume were estimated and used corresponding to same power and size of them for a track vehicle in this research. A 35CrMo material (density: 7.75 g/cm³) was selected for the main shaft to satisfy 203–207 MPa of shear stress (Gong et al. 2016).

The rationality was evaluated by the weight and volume difference between conventional driving parts and motor driving parts. Driving parts, engine, fuel tank, gearbox and shaft in the conventional ICE-AT, motors and battery in EB-AT, motors, fuel cell unit, and hydrogen tank in FC-AT, and motors, methanol reformer, fuel cell unit and methanol tank in RMFC-AT were considered for design in Fig. 2. If motor driving parts are lighter and smaller than conventional ones, it is considered that the motor driving plan is applicable for alternative power utilization. On the opposite, if the motor driving parts are oversized too much that influence the working performance decreases. In these cases, this plan is judged as unsuitable.

Table 3 Physical properties of ICE-AT (agricultural tractor powered by internal combustion engine) for 4 models (1023E, 5045E, 5055E, 5065E, 5100E) of tractor produced by John Deere (John Deere 2017)

| Model (John Deere) | 1023E | 5045E | 5055E | 5065E | 5100E |
|-------------------|-------|-------|-------|-------|-------|
| Output power [kW] | 17.25 | 33.75 | 41.25 | 48.75 | 75.00 |
| Weight [kgf]       | 610.0 | 2,450.0 | 2,550.0 | 2,550.0 | 3,600.0 |
| Volume [L]         | 3,248.7 | 6,902.0 | 6,902.0 | 6,902.0 | 10,969.7 |
| Wheelbase [mm]     | 1,450.0 | 2,050.0 | 2,050.0 | 2,050.0 | 2,300.0 |
| Engine             |       |       |       |       |       |
| Model              | 3NTM74F | 3029T | 3029D | 3029H | PWX4045 |
| Power [kW]         | 17.25 | 33.75 | 41.25 | 48.75 | (75.00) |
| Weight [kgf]       | 88.0 | 205.0 | 317.0 | 328.0 | 396.0 |
| Volume [L]         | 94.7 | 340.5 | 309.6 | 344.8 | 523.2 |
| Gearbox            |       |       |       |       |       |
| Weight [kgf]       | 60 | 134 | 245 |       |       |
| Volume [L]         | 50 | 80 | 160 |       |       |
| Fuel tank          |       |       |       |       |       |
| Weight [kgf]       | 22.0 | 65.0 | 65.0 | 65.0 | 89.0 |
| Volume [L]         | 21.2 | 68.0 | 68.0 | 68.0 | 94.6 |
| Fuel consumption rate L/h | 4.9–5.3 | 9.9–10.7 | 12.0–12.9 | 14.3–15.3 | 22.5–24.2 |
| Working hours Hour [h] | 3.9–4.3 | 6.4–6.9 | 5.3–5.7 | 4.4–4.8 | 3.9–4.2 |
| Gearbox1)          |       |       |       |       |       |
| Weight [kgf]       | 44.0 | 102.5 | 158.5 | 164.0 | 198.0 |
| Volume [L]         | 30.8 | 71.8 | 110.9 | 114.8 | 138.6 |
| Main shaft2) (hollow) |       |       |       |       |       |
| Weight [kgf]       | 4.9 | 15.7 | 21.5 | 24.0 | 38.2 |
| Volume [L]         | 1.0 | 3.2 | 4.3 | 4.9 | 7.7 |
| Total parts        |       |       |       |       |       |
| Weight [kgf]       | 158.9 | 388.2 | 562.0 | 581.0 | 721.2 |
| Volume [L]         | 147.7 | 483.5 | 492.8 | 532.5 | 764.1 |

1) Eaton 2017
2) Estimated

Table 4 Selected parts for EB (electric battery), FC (fuel cell), and RMFC (reformed methanol fuel cell) from ICE (internal combustion engine) as driveline with power unit of motor powered agricultural tractor

|         | ICE | EB | FC | RMFC |
|---------|-----|----|----|------|
| Diesel engine       | ○   |    |    |      |
| Clutch             | ○   |    |    |      |
| Gearbox            | ○   |    |    |      |
| Shaft              | ○   |    |    |      |
| Differential gear  | ○   | ○  | ○  | ○    |
| Motor              | ○   | ○  | ○  |      |
| Fuel cell          | ○   |    | ○  |      |
| Battery            | ○   |    |    |      |
| Hydrogen tank      | ○   |    |    |      |
| Methanol tank      | ○   |    |    |      |
| Diesel tank        | ○   |    |    |      |
| Methanol Reformer  | ○   |    |    |      |
The estimated weight and volume of the shaft can be calculated by following equation:

$$\tau = \frac{T_s}{W_T}$$

where $\tau$ is allowable shear stress [Pa], $T_s$ is the torque load on the shaft [Nm], $W_T$ is the coefficient of crossing torsion [m$^3$]. $T_s$ can be calculated by the following expressions:

$$T_s = \frac{9550 \times P_s}{N_s}$$

$W_T = \text{for hollow } \frac{\pi \times D^3}{16} \left(1 - \alpha^4\right), \text{or for solid } \frac{\pi \times D^3}{16}$

$N_s$ is the shaft rotation speed [rpm] can be calculated by equation (6), $P_s$ is the output power on shaft [kW], $\alpha$ is the rate of inner diameter $d$ and outer diameter $D$. $\alpha$ can be calculated as follows:

$$\alpha = \frac{d}{D}$$

where $d$ is the inner diameter [m] and $D$ is the outer diameter [m]. The shaft rotation speed can be expressed as:

$$N_s = \frac{V \times 60 \times R_d}{3.6 \times C}$$

where $V$ is the vehicle velocity [km/h]; $C$ is the tire circumference [m] and $R_d$ is the reduction ratio of differential gear. In this study, $\alpha$ was set to be 0.6 and reduction ratio of differential $R_d=2$ and when vehicle velocity $V=5$ km/h, output power $P$ reached its peak output torque, and a 15% safety coefficient was added to the output power $P_s$. Based on this hypothesis, the $D$ can be calculated as:

$$D = \frac{9550 \times 16 \times 115 \times 3.6 \times P_s \times C}{60 \times \pi \times (1 - 0.4^2) \times R_d \times V \times \tau}$$

The lengths of the main shafts were calculated based on the wheelbase data; it is estimated that the length of main shafts is 2/3 of the wheelbase. Thus, the estimated weight and volume of the shaft can be calculated by the following expressions: (Table. 3).

$$W_s = 1000 \times \pi \times \left(\frac{D}{2}\right)^2 \times \left(\frac{0.6 \times D}{2}\right)^2 \times \frac{2}{3} \times L_2 \times 7.75$$

$$V_s = 1000 \times \pi \times \left(\frac{D}{2}\right)^2 \times \frac{2}{3} \times L_2$$

Fig. 2 Layout design of ICE-AT (agricultural tractor powered by internal combustion engine), EB-AT (agricultural tractor powered by electric battery), FC-AT (agricultural tractor powered by fuel cell), RMFC-AT (agricultural tractor powered by reformed methanol fuel cell)
where $W_S$ is the estimated shaft weight [kgf], $L_2$ is the wheel base [m], and $V_S$ is the estimated shaft volume [L].

EB vehicles use synchronous motors as their power source because the synchronous motor can be used as both engine and generator, and recycled energy conversion using braking system. Also, the rotor of a synchronous motor is made by a permanent magnet. Thus a synchronous motor has no copper loss, and this allows synchronous motors to have a very high efficiency. However, a synchronous motor usually has a complex structure and not as stable as asynchronous ones. Also, the overhear under high output power condition causes demagnetization (Lu 2016).

In this study, the asynchronous motor was intended to apply on AT. Asynchronous motors have a more simple structure than synchronous motors and easier to maintain. Therefore asynchronous motor fits for condition of farming. Also, AT is usually designed working at a low and steady state of speed, normally within 30 km/h and less than 10 km/h in working, the energy loss in braking system was insignificant and can be ignored. Furthermore, asynchronous motors have a relatively high starting up torque and allow tractor for various working condition. The electric motor data was consulted by ABB (2016) data base; machine type is AC 3-phase 4 poles asynchronous motor.

The electric motor in EB vehicles is usually special and customized, has a lighter weight, smaller volume, better and more stable working performance under different rotational speeds. The electric motor by the mass production of normal industry cannot reflect the real features of vehicle motors, however some part of these data can show a potential and adaptation for tractor design. In this study, a double-engine driving mode was selected for higher efficiency, better land grasping ability, better weight distribution through 4WD system. For double engines driving, two engines were installed on front and rear axles respectively, so there was no main shaft connection between axles, and the control of each wheel. Because the motors can be installed on axles directly and more adjustable design could be feasible. The motor selection considering different phisical rationality, required energy for 4 hours a full load of each type AT (Table 5).

The final efficiency of EB, FC, and RMFC were 66.5%, 41.6% and 33.28% respectively in (Table 1). The heating values were 141.79 MJ/kg of hydrogen and 23 MJ/kg of methanol. Total required fuel can be estimated using the following expressions:

For electricity,

$$E = \frac{P \times T}{\eta}$$  \hspace{1cm} (10)

where $E$ is the electricity [kWh], $P$ is the power in [kW], $\eta$ is the efficiency [%], and $T$ is the working time [h].

For hydrogen and methanol,

$$F_m = \frac{3.6 \times P \times T}{\eta \times h}$$  \hspace{1cm} (11)

where $F_m$ is the fuel mass [kg], $P$ is the power [kW], $\eta$ is the efficiency [%], $T$ is the working time [h], and $h$ is the fuel heating value [MJ/kg].

The frontier gaseous hydrogen storage technology can store the hydrogen at a pressure of 700 bar with 5.7% of weight ratio percentage which means to storage 1 kg hydrogen under 700 bar, about 17.5 kg material is needed to make the tank. The pressure, volume and temperature relation can be expressed as:

$$P_g \times V_g \times n \times R \times T_k = \text{constant}$$  \hspace{1cm} (12)

where $P_g$ is the pressure [Pa], $V_g$ is the volume [m$^3$], $n$ is amount of substance [mol], $T_k$ is the temperature in kelvin [K] and $R$ is the Avogadro constant (8.314 J/kg/mol). When the temperature is 300 K, the volume of can be calculated by the following expressions:

$$V_g = n \times 3.53 \times 10^{-5}$$  \hspace{1cm} (13)

| Table 5 | Physical properties of selected motors for suitable desired power for 4 models (1023E, 5045E, 5055E, 5065E, 5100E) of tractor produced by John Deere |
|---|---|---|---|---|---|
|Model (John Deere) | 1023E | 5045E | 5055E | 5065E | 5100E |
| Desired power [kW] | 17.25 | 33.75 | 41.25 | 48.75 | 75.00 |
| Model | Front | Rear | Front | Rear | Front | Rear | Front | Rear |
| Motor power [kW] | M3AA-132MA-4 | M3AA-132SMH-4 | M3AA-160MLD-4 | M3AA-180MLD-4 | M3AA-180MLC-4 | M3AA-180MLC-4 | M3AA-180MLC-4 | M3AA-200MLC-4 |
| Motor power | 7.5 | 15.0 | 22.0 | 22.0 | 30.0 | 30.0 | 30.0 | 45.0 |
| Weight [kgf] | 142.0 | 209.0 | 280.0 | 317.0 | 423.0 |
| Volume [L] | 50.6 | 91.4 | 118.0 | 137.5 | 188.3 |

Referred by low voltage process performance motors (ABB 2016)
Theoretically, 56.7 g/L of hydrogen can be stored under 300 K and 700 bar, however, 40 g/L of hydrogen under different storage temperatures exists as a practical example (Hwang and Verma 2014). The battery stack was designed as same as Tesla EB, using Panasonic NCR18650B as the single unit. For a single unit, the 18,650 lithium battery had 676 Wh/L and 243 Wh/kg of energy density. The stack could supply 6.3 kWh energy (Justia Patents 2011). The energy density of methanol was 23 MJ/kg (0.792 kg/L). The fuel tank should be designed 3 mm thick 316 austenitic stainless steel and anti-corrosion treated (Ramgopal and Amancherla 2005). The density of this type of material was around 7.98 kg/cm³. The storage amount of fuel or energy, the results of storage medium are listed for EB, FC and RMFC (Table 6).

The contact length of AT tires to the soil can be estimated by the deformation rate on the diameter of the tire. In this research, 2.5% of deforming rate was used (Guo et al. 2016). The contact lengths \( L \) can be calculated by the following expression (Fig. 3):

\[
L = 2 \times \sqrt{0.5 \times D_T^2 - 0.475 \times D_T^2}
\]  

(14)

where \( L \) is the Contact lengths and \( D_T \) is the Tire diameter [m]. The maximum weight can be calculated as:

\[
W_{MAX} = 100 \times P_P \times A_C
\]

\[
= 100 \times P_P \times (2 \times W_F \times L_F + 2 \times W_R \times L_R)
\]

(15)

where \( W_{MAX} \) is the maximum weight [kgf], \( P_P \) is the permitted pressure [kPa], \( A_C \) is the Contact area \([m^2]\), \( W_F \) is the front tire contact width \([m]\), \( L_F \) is the front tire contact length \([m]\), \( W_R \) is the rear tire contact width \([m]\), and \( L_R \) is the rear tire contact length \([m]\).

### Table 6 Required energy and weight and volume of full fueled energy storage medium using EB (electric battery), FC (fuel cell), RMFC (reformed methanol fuel cell) for 4 hours full load in 4 models (1023E, 5045E, 5055E, 5065E, 5100E) of tractor produced by John Deere

| Model (John Deere) | 1023E | 5045E | 5055E | 5065E | 5100E |
|-------------------|-------|-------|-------|-------|-------|
| Desired power [kW] | 17.25 | 33.75 | 41.25 | 48.75 | 75.00 |
| EB (Lithium battery) |       |       |       |       |       |
| Electricity [kWh]  | 112.0 | 202.0 | 265.0 | 313.0 | 452.0 |
| Weight [kgf]       | 621.6 | 1,125.7 | 1,478.5 | 1,747.4 | 2,520.2 |
| Volume [L]         | 264.3 | 478.7 | 628.7 | 743.0 | 1,071.5 |
| FC Hydrogen [kg]   | 4.5   | 8.2   | 10.7  | 12.6  | 18.2  |
| Weight [kgf] (Hydrogen+tank) | 83.5 | 152.1 | 198.4 | 233.7 | 337.5 |
| Volume [L] (Hydrogen+tank) | 88.3 | 156.7 | 204.2 | 240.2 | 343.5 |
| FC unit weight [kgf] | 8.6  | 16.9  | 20.6  | 24.4  | 37.5  |
| FC unit volume [L] | 5.6  | 10.9  | 13.3  | 15.7  | 24.2  |
| RMFC Methanol [kg] | 34.7 | 63.2 | 82.5 | 97.1 | 140.2 |
| Weight [kgf] (Methanol+tank) | 52.8 | 93.2 | 120.2 | 140.4 | 199.8 |
| Volume [L] (Methanol+tank) | 44.9 | 81.5 | 106.2 | 124.8 | 179.9 |
| Reformer Weight [kgf] | 51.4 | 100.5 | 122.8 | 145.2 | 223.3 |
| Reformer Volume [L] | 13.8 | 27.0 | 33.0 | 39.0 | 60.0 |
| FC unit weight [kgf] | 8.6 | 16.9 | 20.6 | 24.4 | 37.5 |
| FC unit volume [L] | 5.6 | 10.9 | 13.3 | 15.7 | 24.2 |

![Fig. 3 Contact length of AT (agricultural tractor) wheel](image-url)
Results and Discussion

Difference weight, volume, and soil pressure

After replacement of driving parts, within 5% fluctuation of weight and volume for FC-AT and RMFC-AT in the rated output power from 33.25–75.00 kW for medium and heavy ICE-AT considering 4 hours farming time was clarified in our simulation. Overweight of light duty AT was 12% for FC-AT and 16% for RMFC-AT. However, 99% of overweight for EB-AT in rated output power of 17.25 kW for light ICE-AT was observed including over 35% of overweight in other sizes of AT. The increasing trend of output power in medium and heavy duty tractor were affected due to overweight, similar trends also observed in proportionally for EB-AT. All plans showed within ±5% of volume fluctuation (Fig. 4, Fig. 5 and Fig. 6).

These results from the analysis reflected the characteristics of high power density [kW/m³] of a diesel engine, the high energy density of diesel fuel [kJ/L], and low energy density of the battery. We have found that FC-AT, RMFC-AT, and EB-AT had complex energy conversion systems and superiority in light duty drive line. RMFC-AT had a relatively high energy density, however weight of the reformer was large in this calculation. Compare with volume, weight was important in the design of drive line parts replacement to prevent the overweight of AT. If the applied pressure by the overweight of AT on soil exceeds 130 kPa, the soil structure was changed at a depth of 32 to 37 and 52 to 57 cm, the soil begins to be compacted, and permeability of water and gases is influenced (Hamza and Anderson 2005). If the pressure exceeds 2 MPa, root growth was stopped. Normal tillage does not affect soil density to a depth of 30 cm (Weber et al. 2000). Thus, the soil pressure limit was set as below 130 kPa in this research. Fig. 6 shows the deformation rate and the comparison between overweight and limitation of soil compaction (130 kPa) are shown in Table 7. In these results, overweight did not reach to the soil compaction limit. However, severe overweight could influence and decrease the final work-

![Comparison of weight for replacement of AT (agricultural tractor) driving parts for ICE (internal combustion engine), EB (electric battery), FC (fuel cell), and RMFC (reformed methanol fuel cell) for 4 models (1023E, 5045E, 5055E, 5065E, 5100E) of tractor produced by John Deere](image1)

![Comparison of volume for replacement of AT (agricultural tractor) driving parts for ICE (internal combustion engine), EB (electric battery), FC (fuel cell), and RMFC (reformed methanol fuel cell) four 4 models (1023E, 5045E, 5055E, 5065E, 5100E) of tractor produced by John Deere](image2)
In this study, we compared the value of soil compaction in ICE-AT and BE-AT as static load by the equation (14) and (15). Since it is known that the value of dynamic load is several times as large as the static load, the dynamic load may exceed the allowable value of 130 kPa when the static load increases. For example, assuming that the dynamic load is twice of the static load, the value of soil compaction due to the dynamic load during the ICT-AT traveling was all below the allowable value of 130 kPa or less. But, the value of soil compaction by BE-AT, FC-AT and RMFC-AT caused exceeding the allowable value of 130 kPa in some cases. Thus, sufficient attention in design stage is needed, and examining the influence for soil compaction in repeated traveling by the tractor is also required.

![Figure 6](image)

**Fig. 6 Comparison in percentage of weight and volume for replacement of AT (agricultural tractor) driving parts for ICE (internal combustion engine), EB (electric battery), FC (fuel cell), and RMFC (reformed methanol fuel cell) for 4 models (1023E, 5045E, 5055E, 5065E, 5100E) of tractor produced by John Deere**

**Table 7 Pressure specification for replacement of AT (agricultural tractor) driving parts for ICE (internal combustion engine), EB (electric battery), FC (fuel cell), and RMFC (reformed methanol fuel cell) in 4 models (1023E, 5045E, 5055E, 5065E, 5100E) of tractor produced by John Deere**

| Model (John Deere 2017) | 1023E | 5045E | 5055E | 5065E | 5100E |
|-------------------------|-------|-------|-------|-------|-------|
| Output power [kW]       | 17.25 | 33.75 | 41.25 | 48.75 | 75.00 |
| Front tire model        | 18×8.5–10 | 7.5–16 R1 | 9.5–24 R1 | 9.5–24 R1 | 12.4–24 R1 |
| Rear tire model         | 26×12–12 | 13.6–28 R1 | 14.9–28 R1 | 16.9–28 R1 | 18.4–30 R1 |
| Contact area [m²]¹)     | 0.16  | 0.35  | 0.44  | 0.49  | 0.61  |
| ICE-AT Soil pressure [kPa] | 37.36 | 68.60 | 56.80 | 51.00 | 57.84 |
| BE-AT Soil pressure [kPa] | 74.40 | 95.10 | 83.44 | 80.67 | 93.53 |
| FC-AT Soil pressure [kPa] | 42.0 | 68.3 | 55.4 | 50.9 | 59.1 |
| RMFC-AT Soil pressure [kPa] | 43.2 | 69.5 | 56.4 | 51.9 | 60.5 |
| Limitation of soil compaction [kPa] ²) | 130.00 |

¹) Contact area [m²] is based on the deforming rate of 2.5% (Guo et al. 2016). This value may fluctuate during a real working condition, however, in this case the value is fixed for a simple calculation.

²) 130.00 kPa: This value is based on a normal wheat land (Hamza and Anderson 2005), in real situation, due to different soil type and moisture content, the value may be changed.
Vehicle drive line system

Measuring and simulating the load of the tractor using the data of agricultural working is the most realistic and ideal verification method to obtain the performance of motor powered agricultural tractors. However, agricultural work load for the tractor, the soil condition, energy consumption of the tractor operation with traveling and related factors should be considered. On the other hand, the performance of an electric tractor that replaced a diesel engine to an electric motor can be verified, if we can calculate the ratio of the power source of the tractor for running and agricultural work. Therefore, we assume a traveling pattern with no load, and load patterns assumed in agricultural working, and simulate the change in voltage of the battery and SOC (state of charge) simulation. The software for vehicle drive line system (AVL Cruise) was used for simulation to find out how overweight factor affects the working performance. The 75 kW EB-AT was selected as the highest severe overweight plan. Dimension parameters and velocity parameters of the 75 kW EB-AT were same as John Deere E5100 tractor. A 4-wheel driving plan with double motor powered was considered. No gearbox and a high reduction ratio planetary gear were used to be the final drive. The comparison of layout for conventional AT and motor based AT, and the 75 kW EB-AT are shown in Fig. 7 and Fig. 8.

Resistance parameters based on the recommended data equipped in software database of AVL cruise were used. The linear running resistance was 10 N/(km/h) for velocity of AT, and the square running resistance was 3.3 N/(km/h)^2 for acceleration of AT to tire rolling resistance factors were defined as 4% at 0.001 km/h, 3.6% at 10 km/h, 3.8% at 20 km/h and 4% at 30 km/h. Other basic parameters of the 75 kW AT were used according to the references (Cao 2014, Xu 2012, Wang and Sun 2014) (Table 8) (Fig. 9).

Asynchronous motors were selected from ABB (2016), model M3AA-180MLC-4 and M3AA-200MLC-4, four poles aluminum frame AC motor. Panasonic lithium ion NCR18650B battery was used as the single unit. Two cycle runs of working condition with a full load, and traveling condition were defined in this simulation. Velocity changing of the 75 kW EB-AT was simulated with decreasing of SOC and increasing of thermal loss. 10 km/h and 20 km/h speeds for 5 minutes were set reciprocally in full load working condition and cycle run. The 5kW EB-AT was set to be 30 km/h for 5 minutes without load was set in traveling condition (Fig. 10). Fig. 11 and Fig. 12 show battery voltage, current and SOC, and tractor working velocity, acceleration, and distance for six times cycle run, total running time 1 hour under full load condition and traveling condition (without load).

Simulation results showed that SOC was decreased from 98% to 69% (29% was consumed) after 1-hour full load working time (Fig. 11). The thermal loss was caused due to battery’s internal resistance. The loss could be increased with further discharging. Though the battery was designed for a 4-hour-working demand, however, the tractor model could work in 3 hours or less. On the other hand, the 75 kW AT was designed to work under full load condition at a speed of 20 km/h. However, the simulation results show that the peak velocity under at the full load can only reach at speed of 14.1 km/h (Fig. 11). The overweight was one of the main factors for decreasing of working performance of the 75 kW AT.

The SOC was decreased from 98% to 94%, maximum velocity 32 km/h, and total driving distance was 37 km for 1 hour driving in traveling condition without load (Fig. 12). The tractor was able to run more than 22 hours constantly (distance of 814 km) with a fuel efficiency of 0.555 kWh/km, because the battery size was 5 times bigger than normal EVs and it was
Table 8  Basic parameters of the 75 kW EB-AT (agricultural tractor powered by electric battery) for traveling simulations conducted by the analysis software for vehicle driveline system (AVL Cruise).

| Parameter name | Value       | Parameter name              | Value       |
|----------------|-------------|-----------------------------|-------------|
| $L_1$          | 1,600 mm    | Theoretical maximum speed   | 30 km/h     |
| $L_2$          | 2,300 mm    | Constant resistant          | 500 N       |
| $L_3$          | 2,800 mm    | Linear resistant            | 20 N/(km/h) |
| $H$            | 800 mm      | Square resistant            | 3.3 N/(km/h)$^2$ |
| Front wheel diameter | 1,160 mm | Curb weight                 | 5,422 kgf   |
| Rear wheel diameter | 1,550 mm | Gross weight                | 5,822 kgf   |

Fig. 8  Layout for EB drive line tractor of 75kW tractor (AVL cruise)

$L_1$: distance of gravity center  
$L_2$: wheel base  
$L_3$: distance from hitch to front axle  
$H$: height of gravity center

Fig. 9  Layout of basic design parameters
without load. Compared with normal battery cars, such as Tesla model S, the battery capacity of Tesla model S was only 85 kWh. However it could run more than 500 km, the fuel efficiency was 0.17 kWh/km. Thus, it was clarified that overweight also had a severe influence on driving. The maximum velocity was higher than 30 km/h is shown in Fig. 12. Thus, the calculation of driveline design was based on the motor rated working speed (800–1,600 rpm). However, if the motor was working
faster than 1600 rpm, it still could work, but the output torque and efficiency was affected. To ensure the working hours, EB tractor consisted with a large battery, and was the main factor to increase the weight of AT, and high rolling resistance. AT is usually working in field, on soft soil, not like passenger vehicles are running on roads. So the resistance coefficient of a tractor was higher than passenger vehicle. The AT was not designed for travelling and highest speed was only about 30 km/h, though the power may still capable, the gearbox limits the output speed. For the next research, it is necessary to simulate the voltage change and SOC of the battery under various load fluctuations, and to carry out a simulation using the several type of load pattern and traveling speed as appropriate for real farm work.

Conclusions

The analysis for alternate power utilization instead of Internal Combustion Engine (ICE) in the tractor was studied using the drivelines of electric battery (EB), fuel cell (FC) and reformed methanol fuel cell (RMFC). The following conclusions are proposed from our results:

1) 99% of EB (electric battery)-AT, 12% of overweight in FC (fuel cell)-AT, 16% in RMFC (reformed methanol fuel cell)-AT had showed better performance for light duty agricultural tractors (AT). Under light duty situation, ICE-AT was lighter and smaller due to simple energy flow and energy conversion system.

2) Medium and heavy-duty tractors were more suitable to be reformed into motor driving ones from the viewpoint of overweight ration. However, the overweight trend became worse with increasing of the power.

3) All drivelines showed affordable volume results, the fluctuations are with ± 5% and FC driveline showed the best result, which was more compact than normal ICE-AT. While with the increase of output power, this volumetric advantage could weaken due to the low volumetric energy density of hydrogen.

4) The AVL Cruise simulation results showed that overweight of the 75 kW BE-AT would affect the peak working velocity under full load with 14.1 km/h. However the model was designed to operate at a speed of 20 km/h, and the constant working hours could be 25% shorter.

Abbreviation

| Abbreviation | Description |
|--------------|-------------|
| AT           | agricultural tractor |
| EB           | electric battery |
| EB-AT        | agricultural tractor powered by electric battery |
| EV           | electric vehicle |
| FC           | fuel cell |
| FC-AT        | agricultural tractor powered by fuel cell |
| FCV          | fuel cell vehicle |
| HEV          | hybrid electric vehicle |
| ICE          | internal combustion engine |
| ICE-AT       | agricultural tractor powered by internal combustion engine |
| RMFC         | reformed methanol fuel cell |
| RMFC-AT      | agricultural tractor powered by reformed methanol fuel cell |
| SOC          | state of charge |

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