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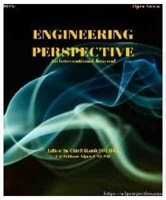

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Modeling of an Electric Tractor and Determining Energy Consumption Values for Different Duties

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ABSTRACT

In this study, a model of an electric tractor was created in MATLAB / Simulink environment, and performance and fuel consumption values were determined. The power transmission system, control unit, electric motor model, energy consumption, and battery subsystems of the electric tractor are included. Reference is made to a study in the literature, as there is no standardized test procedure for tractors. The energy consumption values of the electric tractor for rotary harrow, atomizer, and shredder duties have been examined. In determining the performance of the electric tractor, only the maximum speed value was included. If the reduction ratio of the electric tractor is 50, 60, 70, 80, 90, 100, the maximum speed values and the amount of energy consumed during the process of different duties were determined and evaluated. If the reduction ratio is below 50, no results could be obtained because he could not fulfill his duties in this study. It has been determined that if the reduction ratio is 50, the electric tractor consumes 3.985, 1.266, and 3.787 kWh energy in rotary harrow, atomizer, and shredder duties, respectively. It has been determined that if the reduction ratio is 100, the electric tractor consumes 3.604, 1.145, and 3.535 kWh energy in rotary harrow, atomizer, and shredder duties, respectively. It is concluded that if the reduction ratio of the electric tractor is 50, 60, 7, 80, 90, and 100, it reaches the maximum speed values of 62.25, 51.91, 44.52, 38.97.34.65, and 31.19 km / h, respectively.

Keywords: Agriculture; Electric vehicle; Modelling; Non-Road mobile machineries; Tractor

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1. Introduction

In recent years, there has been increasing attention paid to the electrification of non-road mobile machinery, focusing on the machinery involved in construction and agricultural applications [1]. The tractor is a wheeled or tracked vehicle used for the traction of agricultural machinery [2]. This explanation remains quite simple for a machine, which currently involves a multitude of applications. This machine has been considered one of the advances, which significantly influences agriculture during the twenty-first century. Electric Tractor will save farmers' time because the electric tractor will be that its motor won't have around 300 sections that accompany the engine of a diesel tractor. Battery trading, regenerative braking, power reversal, and fast charging are among the features of the electric tractor. Electric tractors vary from traditional tractors in that they are driven by either diesel or gasoline. They are powered by electronic batteries that can recharge simply by plugging them into a socket [3,4]. The electric tractor is deliberate by zero-emission, which is harmless to the ecosystem [5,6,7].

Electric tractors have several advantages over their diesel counterparts. Most prominently, they don't produce CO2 emissions or other air pollution directly [8]. Indeed, the electricity they use is generated by natural gas or other fossil fuels or a blend of energy sources [9]. Electric tractors have fewer moving parts, which means fewer issues. As a result, repair and maintenance costs are reduced, and the tractor can operate for more extended periods [10,11]. Electric tractors are efficient; it gives excellent accuracy when it works. When it comes to converting thermal energy into mechanical energy, the diesel tractor is 35% efficient. Compare that with charging or discharging batteries 80% with the efficiency, while electric tractors are more efficient. The adoption of electric machines and battery technologies together with efficient diesel engines or, in some cases, replacing them in full electric configurations can reduce or completely avoid local pollutant emissions [12,13,14]. Electric motors have certain drawbacks, such as charging and the need for costly line extensions [15]. Furthermore, speed-controlled motors are very expensive and necessitate a lot of specialized equipment, making installation more difficult.

This machinery is involved in various operations with different intensities; therefore, there is increasing interest in electrification, as the powertrain could achieve better versatility. For example, the hybrid powertrain could fulfill heavy operation requirements by combining ICE and Electric Machine (EM). Moreover, the proper power management of the load point of ICE and EM would allow better efficiency to be achieved for the overall system. On the other hand, working in pure electric mode only with the EM could be sufficient for light operations [16]. This latter case brings attractive benefits, such as reducing local emissions on crop fields or inside greenhouses, and reducing noise and vibration, improving the comfort and health of operators. Furthermore, other studies regarding the advantages of consumption and working autonomy have been carried out [17,18].

Ratzinger et al. created conventional, fully electric, serial hybrid, and parallel hybrid non-road vehicles. The model they created examined the effects of these vehicle structures and charging methods on CO2 emission emissions. They made use of mathematical equations in the modeling process. They observed a 20% reduction in CO2 emission when using the "charge-depleting" method instead of the "charge-sustaining" method on the serial hybrid vehicle. The vehicle structures discussed in the study determined that the conventional vehicle emitted 26.4, the fully electric vehicle 20.6, the parallel hybrid vehicle 23.1, and the serial hybrid vehicle 21.1 kg CO2 / h. Therefore, this study concluded a fully electric vehicle structure according to CO2 emission [19]. The work in [20] addresses the operational feasibility of agricultural tractors powered by electricity. The performed study is based on developing a small-scale prototype of EVs rated at 40 W using a DC motor. Besides, introducing a theoretical configuration for the electric tractor using a single electric motor is analyzed. However, a detailed analysis of the motor drive and control system associated with the electric tractor is not presented, and the performance evaluation of a real scale prototype.

On the other hand, the performance of a micro tractor is investigated in [21] using three different types of motors: a three-phase alternating current motor rated at 2.2 kW, 220 Vac, and 3465 rpm; a DC motor rated at 2.2 kW, 36 Vdc, and 2900 rpm; and an ICE rated at 2.6 kW and 3600 rpm. Zhang et al. worked on a new design scheme of the Electric tractor drive system, simplifies the power transmission mode, makes the chassis layout more flexible and simpler, puts forward the design theory and method of the driving system, and combines the case to design and calculate, completes the drive motor, the transmission, Parameter design and main performance analysis of main components such as Powerpack. The research shows that the 5km/h of the Power battery is 6.7h to meet the present 6h requirements [22]. Zhang et al. constructed an agricultural machine endowed with an industrial DC motor and performed plowing tests in different types of soils. The obtained results concluded that as the working depth of the plow increased, the electric motor torque oscillated with great amplitudes correlated with the soil resistance heterogeneity [23]. Thus, the research led to finding various ways to design and optimize the drive train system of such electric tractors [24]. Xiaofei et al., an electric AWD tractor, was developed based on a power transmission system.

A simulation model reflecting the specifications of this electric AWD tractor was developed and verified using measured data from driving tests conducted under off-road and on-road conditions. The measured data were converted to torque using equations and were used for simulation conditions. A comparison of the simulation analysis results with the measured data showed that the torque generated on the axle was similar in value and shape, and we found no significant differences in the statistical analysis results. Although the SOC level showed a significant difference in the statistical analysis results, the rate of change per minute, and the SOC, the simulation results were reliable. The axle torque is closely related to the SOC level because it is proportional to the current supplied from the battery to the electric motor. As the measured data for both factors matched the simulation results, we determined that the operating time of the platform can be estimated through simulation. The workable time of the electric AWD tractor was estimated through simulation models and existing research data. As a result of the simulation, the workable time for plow tillage using the electric AWD tractor was estimated to be about 2.4 h. The results are less than the target hours (three hours) of work. In future studies, performance could be improved through battery optimization through a simulation [25].

In this study, an electric tractor model was created in MATLAB / Simulink environment. Energy consumption values and some performance values were determined in different duties on the created model. Rotary harrow, atomizer, and shredder are handled as missions. The energy consumption and performance values obtained because of the study were evaluated.

2. Material and Methods

In this study, an electric tractor's performance and energy consumption values were examined by creating a model in Matlab/Simulink environment. The effect of the power transmission reduction ratio on the maximum tractor speed was investigated. The energy consumption values of the electric tractor under different reduction ratios and different duty conditions were obtained and examined. The electric vehicle control system, power transmission system, electric motor, resistance forces, and battery models were created. Some of the electric tractor and simulation parameters used in the modeling process are given in Table 1.

Table 1. Electric tractor and simulation parameters

Parameters	Value
Mass	2500 kg
Battery voltage	700 V
Battery capacity	50 kWh
Electric motor max torque	320 Nm
Electric motor max speed	12000 rpm
Transmission ratio	50, 60, 70, 80, 90, 100
Aerodynamic coefficient	0.68
Wheel diameter	1500 mm
Powertrain systems efficiency	0.97

2.1 Modeling of Electric Tractor Control System

The electric tractor model consists of many systems and subsystems. These systems work simultaneously with each other. The control scheme, including the system and subsystems of the electric tractor, is given in Figure 1.

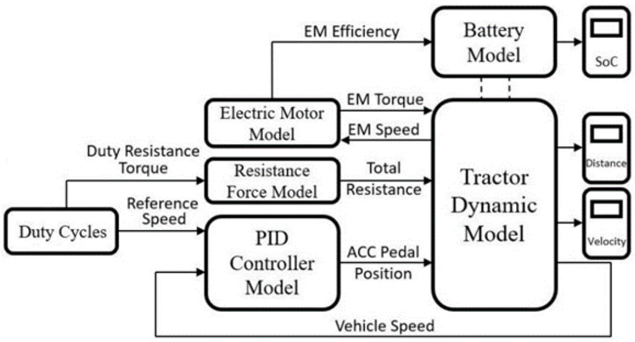

Figure 1. Schematic representation of electric tractor systems

PID controls carry out gas and brake pedal control of the electric tractor. The speed information of the duty cycle is accepted as the reference speed of the tractor. The reference speed is transferred to the PID controller model, and the instantaneous speed information is obtained from the vehicle dynamic model. The PID controller thus calculates the accelerator and brake pedal position. The PID control model is shown in Figure 2.

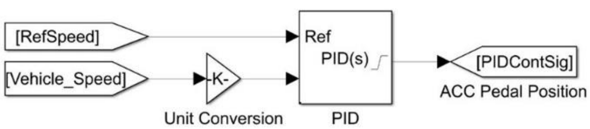

Figure 2. PID controller model

2.2 Modeling of Electric Tractor Powertrain System

In the electric tractor, the power transfer between the electric motor and the wheels is carried out by the powertrain system. The schematic representation of the electric tractor power transmission system is shown in Figure 3.

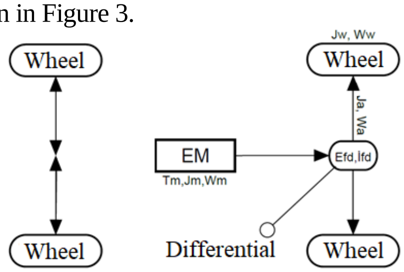

Figure 3. Schematic representation of the power transmission system

The angular acceleration of that shaft is calculated by dividing the net torque acting on a shaft by the moment of inertia of that shaft. By integrating the angular acceleration, the angular velocity of that shaft is obtained. With this principle, the transfer function of the electric vehicle powertrain is derived. The transfer function representing the electric vehicle powertrain system is given in Equation 1.

$$\omega_w = \int_t \frac{T_m i_{fd} \eta_{fd} - T_L}{J_m i_{fd}^2 \eta_{fd} + 2J_a + 4J_w} dt \tag{1}$$

In the equation, Tm represents engine torque, ifd represents differential reduction ratio, ηfd represents differential efficiency, Ja represents axle moment of inertia, and Jw represents wheel moment of inertia. TL represents the torque to the total load acting on the tractor and is calculated by adding the resistance forces acting on the tractor and the duty cycles.

2.3 Modeling of Electric Motor Model

In the electric motor model used on the electric tractor, Remy brand HVH250-090 model electric motor maps, which can produce a maximum torque of 320 Nm and reach a maximum speed of 12000 rpm, are used. The speed, torque, and efficiency maps of the electric motor are shown in Figure 4.

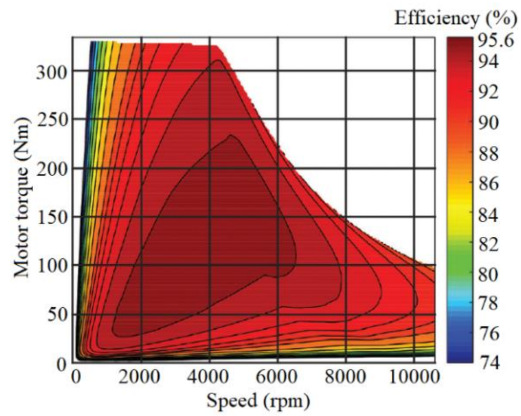

Figure 4. Electric motor speed, torque, and efficiency map

The engine speed calculated in the tractor dynamic model is transmitted to the electric motor subsystem. In the electric motor model, the maximum output torque of the motor is determined using the 2D motor torque map, and the motor efficiency is determined using the 3D motor efficiency map. The Simulink model of the electric motor is shown in Figure 5.

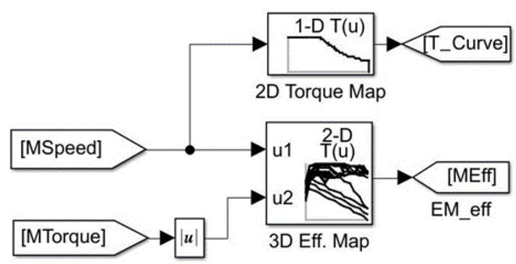

Figure 5. Electric motor Simulink model

2.4 Electric Tractor Resistance Force Model

The road resistances that the electric tractor encounters during the movement process are included in the model. Calculation of the acceleration resistance force is carried out by Equation 2. In the equation, m represents the tractor mass, and a represents the acceleration.

$$F_i = ma \tag{2}$$

The rolling resistance force encountered by the electric tractor is calculated by Equation 3. Thus, Cr is the rolling resistance coefficient, and g is the gravitational acceleration.

$$F_r = mgC_r \tag{3}$$

Since high speeds are not reached in agricultural vehicles and construction machines, the aerodynamic resistance force is not considered very important and can be neglected. In this model, the maximum speed values that the electric tractor can reach are calculated. Therefore, the aerodynamic drag force is included in the model. The aerodynamic drag force is calculated by Equation 4. In the equation, Cd is the aerodynamic drag coefficient, A_f is the front section area, and V is the vehicle speed.

$$F_a = 0.5\rho C_d A_f V^2 \quad (4)$$

The sum of the resistance forces acting on the electric tractor is calculated by Equation 5.

$$F_{Load} = F_i + F_a + F_r \quad (5)$$

The calculation of the total resistance torque is calculated by the product of the total resistance force and the radius of the wheel and is given in Equation 6.

$$T_{resistance} = F_{resistance} \times r_w \quad (6)$$

The Simulink model, in which the resistance forces acting on the electric vehicle and the torque values affected by the duties are calculated, is given in Figure 6.

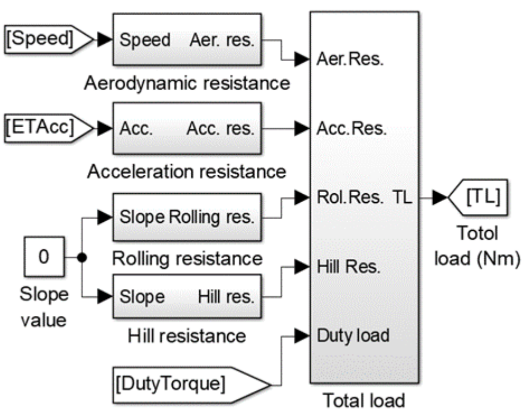

Figure 6. Model of resistance forces on the electric tractor

2.4 Electric Tractor Resistance Force Model

The energy consumption values of the electric tractor in rotary harrow, atomizer, and shredder duties were obtained. Since there are no standard test procedures established for the duties of the electric tractor, the cycle values of the duties are taken from the reference source [26,27]. The speed and torque cycles of the duties were created by making the necessary adjustments in the referenced graphics. The speed cycles of the duties are shown in Figure 7. Rotary harrow and atomizer duty has a speed of 3.4 km / h, and shredder duty has a speed of 5 km / h. Rotary harrow duty is performed for 800 seconds, atomizer duty for 250 seconds, and shredder duty for 700 seconds.

Torque graphics of the duty cycles used in the study are given in Figure 8. The highest torque values were encountered in the rotary harrow mission. Conversely, the lowest torque value was obtained in the shredder duty.

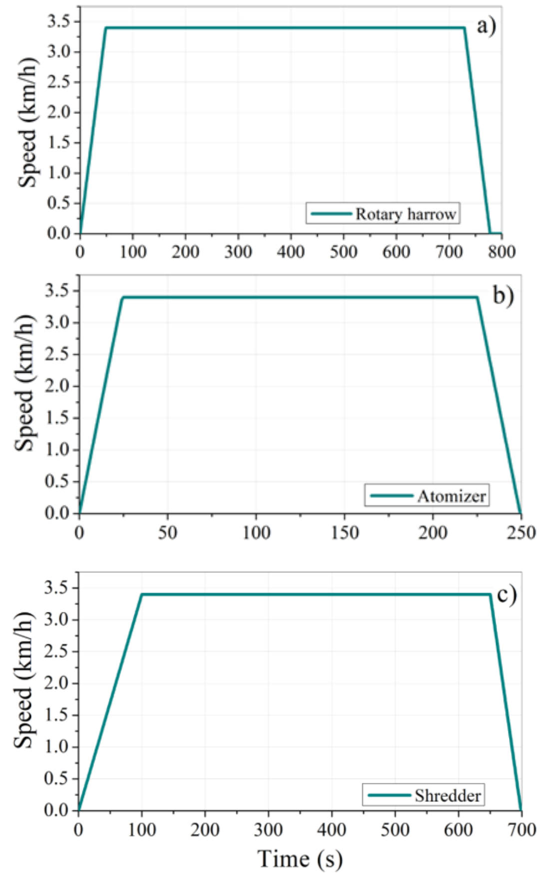

Figure 7. Duty cycle speed graph for rotary harrow (a), atomizer (b) and shredder (c)

3. Result and Discussion

In this study, energy consumption and performance values for different duties are calculated by creating a model of an electric tractor. In the simulation process, three different speed cycles were used to reach a maximum speed of 3.4 km / h and 5 km / h for the electric tractor. The results, including comparing the actual speed and reference speed values of the electric tractor during the rotary harrow, atomizer, and shredder missions, are shown in Figure 9

Suppose the total reduction ratio of the electric tractor is 70. In that case, the instantaneous efficiency values of the electric motor obtained during the rotary harrow, atomizer, and shredder missions are shown in Figure 10. Thus, an electric tractor rotary harrow, atomizer, and shredder duties have been observed to have reached the minimum 81%, 83%, 85%, and maximum 88%, 88%, 91% efficiency values, respectively.

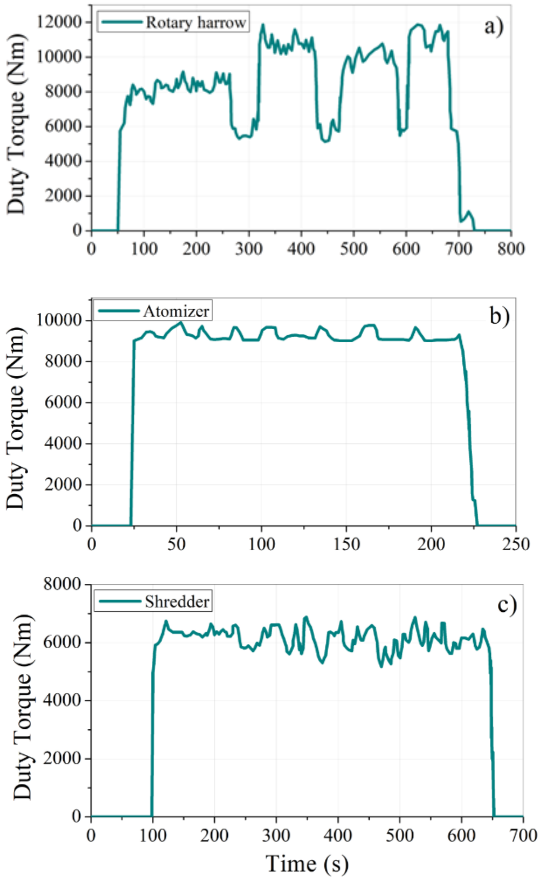

Figure 8. Duty cycle torque graph for rotary harrow (a), atomizer (b) and shredder (c)

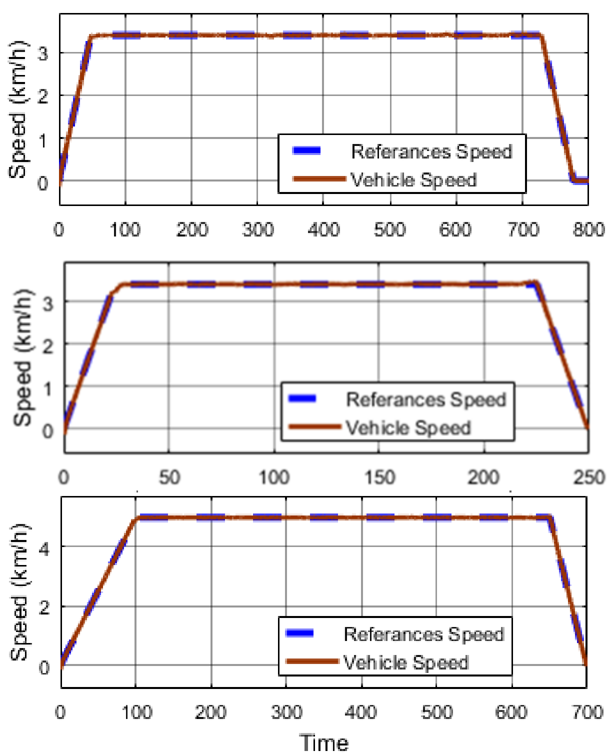

Figure 9. Comparison of References and Vehicle Speed for rotary harrow (a), atomizer (b), shredder (c)

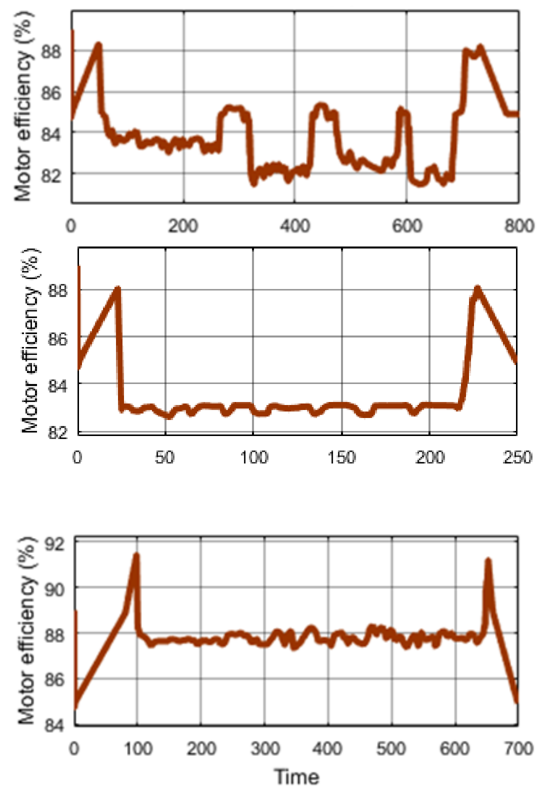

Figure 10. Motor efficiency graph for rotary harrow (a), atomizer (b), shredder (c)

It has been observed that if the reduction ratio of the electric tractor is 70, it can go over 40 km / h. If the reduction ratio is 70, energy consumption values have been calculated in rotary harrow, atomizer, and shredder missions and are given in Figure 11. Rotary harrow duty takes 800 seconds, atomizer duty takes 250 seconds, and shredder duty lasts 700 seconds. Therefore, it is seen that the energy consumption is low due to the low duty time of the atomizer.

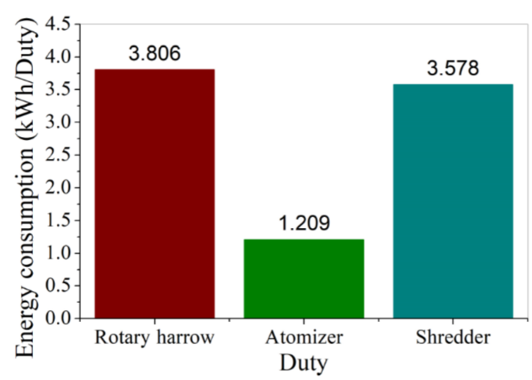

Figure 11. Energy consumption values of the electric tractor in different duties

Suppose the reduction ratio value is lower than 50. In that case, the torque value that can perform the specified duties cannot be exceeded, and the tractor cannot travel at reference speed values. Using the electric tractor in three different duties, the situation of 50, 60, 70, 80, 90, and 100 reduction ratio was examined. The graphic containing the energy consumption values of the electric tractor depending on different duties and different reduction ratios is given in Figure 12. During the

Rotary Harrow mission, 3,985, 3,882, 3,806, 3,746, 3,674 and 3,604 kWh energy consumption were respectively. The atomizer duty, respectively, 1.266, 1.233, 1.209, 1.19, 1.168, and 1.145 kWh energy consumption, was realized. The Shredder mission, 3.787, 3.683, 3.578, 3.485, 3.408, and 3.535 kWh energy consumption, was achieved, respectively. If the reduction ratio of the electric tractor was increased from 50 to 100, energy savings of 9.56% were achieved in rotary harrow duty, 9.55% in atomizer duty, and 6.65% in shredder duty.

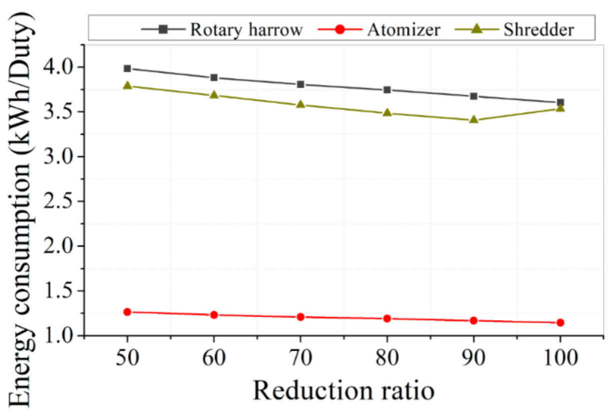

Figure 12. Fuel consumption value (kWh) for different duty and reduction ratio

The maximum speed performance values of the electric tractor in different reduction ratios are shown in Figure 13. For example, if the reduction ratio is 50, 60, 7, 80, 90, and 100, it is seen that the maximum speed values are 62.25, 51.91, 44.52, 38.97.34.65, and 31.19 km / h, respectively.

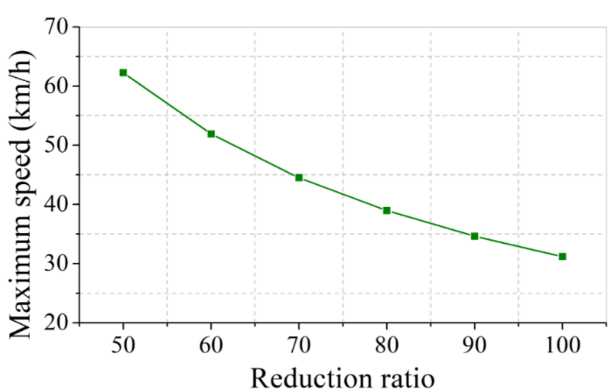

Figure 13. Performance characteristic for different reduction ratio

4. Conclusion

In this study, a model of an electric tractor has been created, and different duties have investigated energy consumption. If the reduction ratio of the electric tractor is 50, it has been determined that it consumes 3.985, 1.266, and 3.787 kWh energy in rotary harrow, atomizer, and shredder duties, respectively. If the reduction ratio is below 50, the energy consumption values are not included, since the required torque value cannot be provided for the duties dealt with in the study. The effect of the electric tractor reduction ratio on energy consumption values was determined. If the reduction ratio value is 100 instead of 50, it was observed that the energy consumption decreased by 9.56%, 9.55%, and 6.65% in rotary harrow, atomizer, and shredder duties, respectively. If the reduction ratio value is 100 instead of 50, the result is that the maximum vehicle speed drops from 62.25 km / h to 31.19 km / h.

Nomenclature

F_i	Acceleration resistance force
F_r	Rolling resistance force
C_r	Rolling resistance coefficient
A_f	Frontal area of the tractor
F_a	Aerodynamic drag force
C_d	Aerodynamic drag coefficient
r_w	Radius of the wheel

Conflict of Interest Statement

The Authors declare that there is no conflict of interest.

CRediT Author Statement

Venkata Krishna Teja Thallapalli: Data curation, Resources, Methodology

Ahmet Onur Kıyaklı: Conceptualization, Visualization, Writing–review & editing, Validation

Tolga Kocakulak: Investigation, Supervision, Writing-original draft, Project administration

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