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POWER SIMULATION OF EXTENDED-RANGE ELECTRIC TRACTOR BASED ON ADVISOR

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A simulation model of an extended-range electric tractor based on ADVISOR software is developed to study its related indicators (such as power). The working mode of the extended-range electric tractors is analyzed and a simulation model suitable for the extended-range electric tractors is developed based on ADVISOR software. A simulation working condition of the electric tractor is established, and the power performance of the extended-range electric tractor is simulated based on a secondary-level development of the simulation model. The results show that under transportation, the extended-range tractor is set to an initial SOC value of 0.4. The SOC value gradually increases from the initial value of 40% over time, then the SOC gradually began to decrease. Throughout the simulation process, the SOC value decreases by 6%. Under plowing conditions, the initial SOC value of the extended-range tractor is set to 0.5, and the range extender starts working when it drops to 40%. The total process power consumption is 13% of SOC.

Keywords: Extended-range electric tractor; ADVISOR; dynamic performance; working conditions

1. Introduction

With the increasing attention to global environmental issues, the high energy consumption and emissions of fuel powered tractors have become key constraints on their development. The rapid development of new energy technology has provided a new path for tractors to move towards electrification and green development [1-2]. In November 2019, Fiat Powertrain Technology and Steyr jointly exhibited a new hybrid concept tractor at the Hanover International Agricultural Machinery Exhibition in Germany. It adopts an innovative architecture and series hybrid mode, equipped with four independently driven wheel hub motors. Compared with fuel tractors, this hybrid tractor can save 10% of fuel [3]. Compared with pure electric tractors, extended range tractors have a

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longer range, which can meet the needs of long-term agricultural operations and effectively solve the problem of short range caused by battery technology in electric tractors [4].

Simulation technology is indispensable and important to extended-range electric tractors. Liu et al. [5] developed a vehicle simulation model of an extended-range electric tractor based on Cruise software, conducted traction performance simulation, and proposed an equivalent model of rotary tillage unit, and the simulation results were good. Wu [6] established a vehicle model and plowing model of an extended-range electric tractor based on Simulink software, and simulated and analyzed the tractor performance before and after transmission ratio optimization. Yoo and Kim [7] designed a model of an electric tractor system based on ASM (Automotive Simulation Model) and established a complete simulation model of the electric tractor using Simulink and Carsim joint simulation methods.

We conducted a secondary-level development of ADVISOR software and simulated the power performance of extended range electric tractors. Through the simulation results, the power performance and endurance of extended-range electric tractors were explored.

2. Working mode of the extended-range electric tractor

2.1 Pure electric operation mode

When the state of charge (SOC) of the power battery pack is higher than the set threshold, that is, when the battery pack is fully charged, the range extender does not work, and the extended-range electric tractor will act as a fully electric tractor, with energy flow shown in Fig. 1. At this time, the power battery provides electrical energy to the drive motor based on the logical operation of the vehicle's power demand according to the instructions of the battery management system. The drive motor then outputs mechanical energy, which is distributed to the wheels and PTO through the transmission system, front axle, and rear axle.

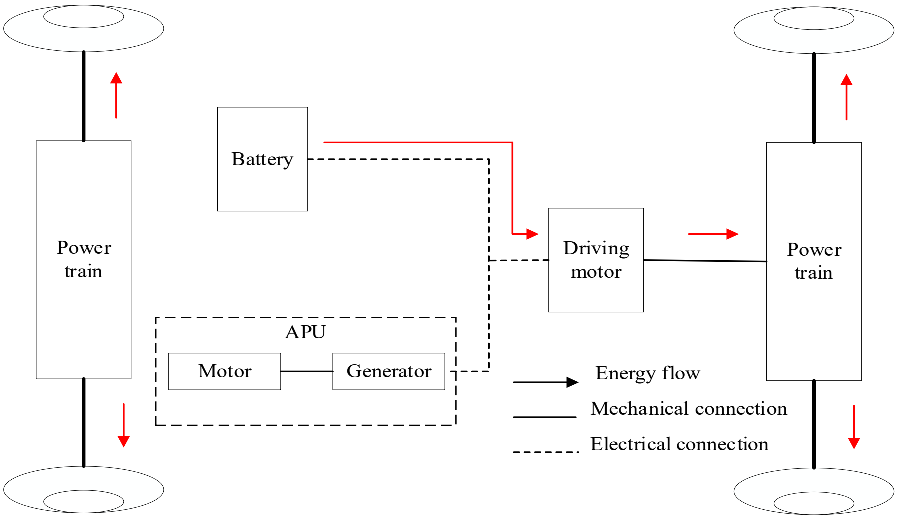


Fig. 1 Pure electric mode of the extended-range

2.2 Electric operation mode

When the SOC of the extended-range electric tractor is below the threshold and the power of the vehicle is insufficient, according to the set control strategy, if the power battery pack cannot meet the power demand of the vehicle, the engine of the range extender will start working. At this time, the energy source of the vehicle will come from the combustion of fuel by the engine in the range extender to supply and supplement the electrical energy of the battery. The energy flow in this mode is shown in Fig. 2.

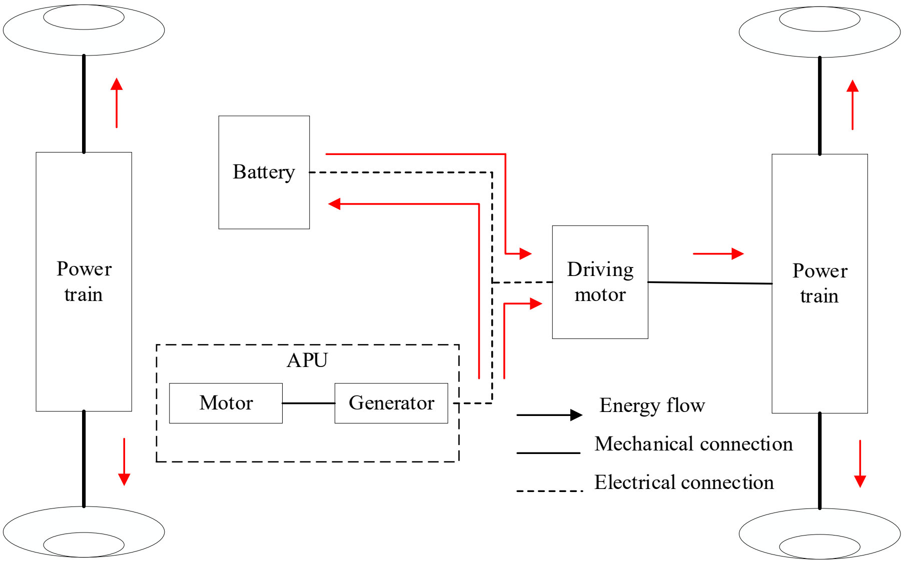


Fig. 2 Extended-range mode of the extended-range electric tractor

2.3 Parking charging operation mode

When the vehicle completes its work or needs to replenish power, the charger can be used to transform and rectify the AC voltage to charge the power battery. At this time, the energy flow is stored in the battery pack as electrical energy from the grid, as shown in Fig. 3.

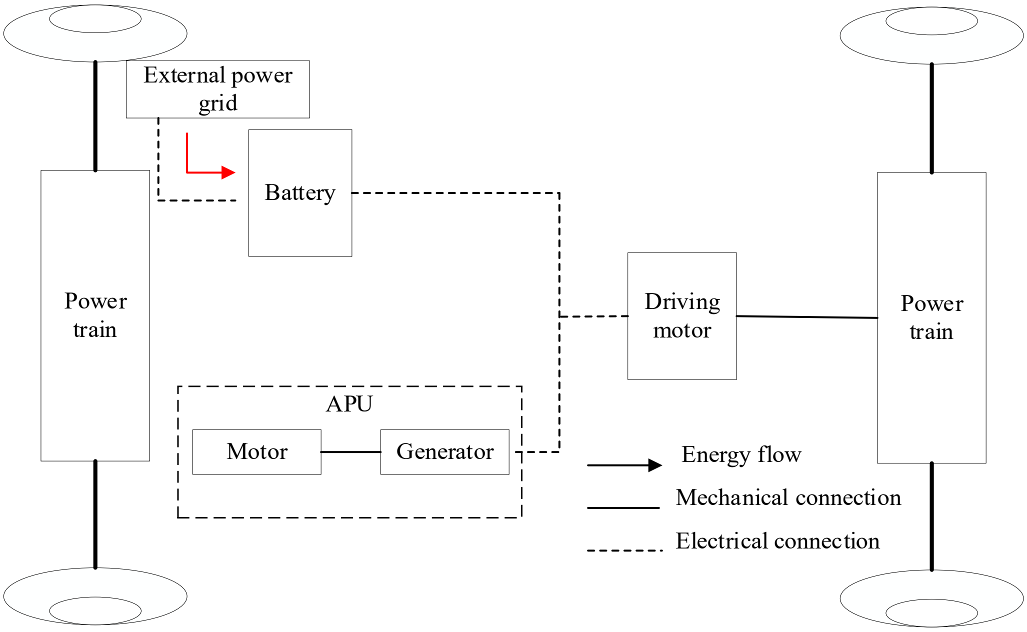


Fig. 3 Parking and charging mode of the extended-range electric tractor

3. Development of simulation system for the extended-range electric tractor

Compared with electric vehicles, electric tractors have complex operating conditions and usually require traction operations. However, current simulation software for electric vehicles is mostly used for electric vehicles and lacks electric tractor models [8-11]. ADVISOR software is an open-source software platform based on Matlab/Simulink environment. It supports a secondary-level development based on the requirements and characteristics of different components in extended-range electric tractors [12], as well as establishes simulation models suitable for extended-range electric tractors [13-15].

The simulation module of the extended-range electric tractor includes the whole vehicle module, rear wheel drive module, battery module, motor module, range extender module, wheel module, and transmission module, as shown in Fig. 4.

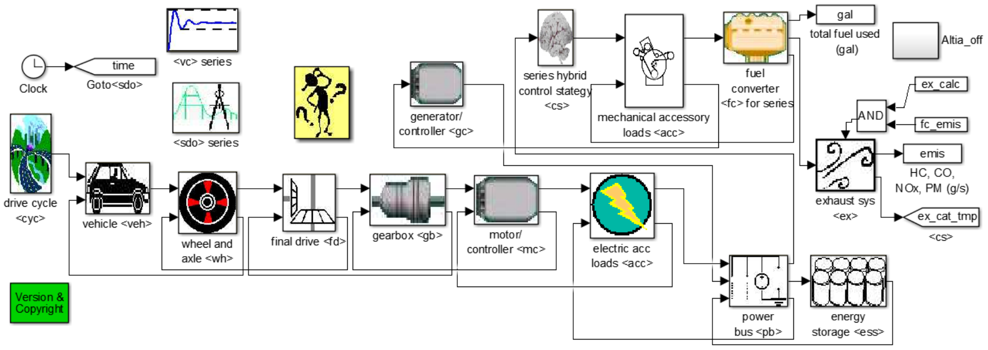


Fig. 4 Diagram of the tractor vehicle model

3.1 Establishment of the vehicle model

The schematic diagram of the force analysis of the extended-range tractor is shown in Fig. 5.

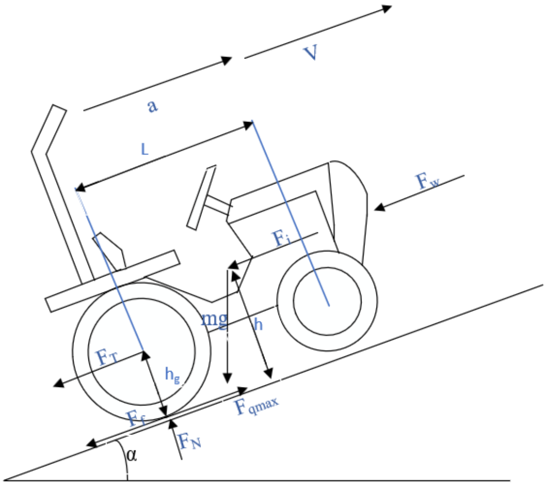


Fig. 5 Schematic diagram of the tractor force analysis

As shown in Fig. 5, the balance for a tractor moving in a straight line on a slope can be expressed as follows:

$$P_{q\max} - F_T - F_f - F_w - F_i = ma \tag{1}$$

The rolling friction resistance F_f is expressed as follows:

$$F_f = Gf\cos\alpha = mg\cos\alpha(f_1 + f_2 V_{aver}) \tag{2}$$

The climbing resistance F_i is expressed as follows:

$$F_i = G\sin\alpha = mg\sin\alpha \tag{3}$$

The air resistance F_w is expressed as follows:

$$F_w = \frac{1}{2}\rho C_{\mathrm{d}} A V_{aver}^2 \tag{4}$$

where ρ represents the air density; C_d represents the coefficient of air resistance, A represents the windward area in the direction of tractor travel (m²), and V_{aver} is the average velocity. Under plowing, the tractor pulls the plowshare to work, resulting in additional traction resistance, F_T. Therefore, it is necessary to secondarily develop the simulation model and add the traction resistance module to the vehicle power performance model, the rear drive required speed calculation submodule, and the maximum driving force limitation submodule during this process [16]. The simulation module for the extended-range electric tractor is shown in Fig. 6.

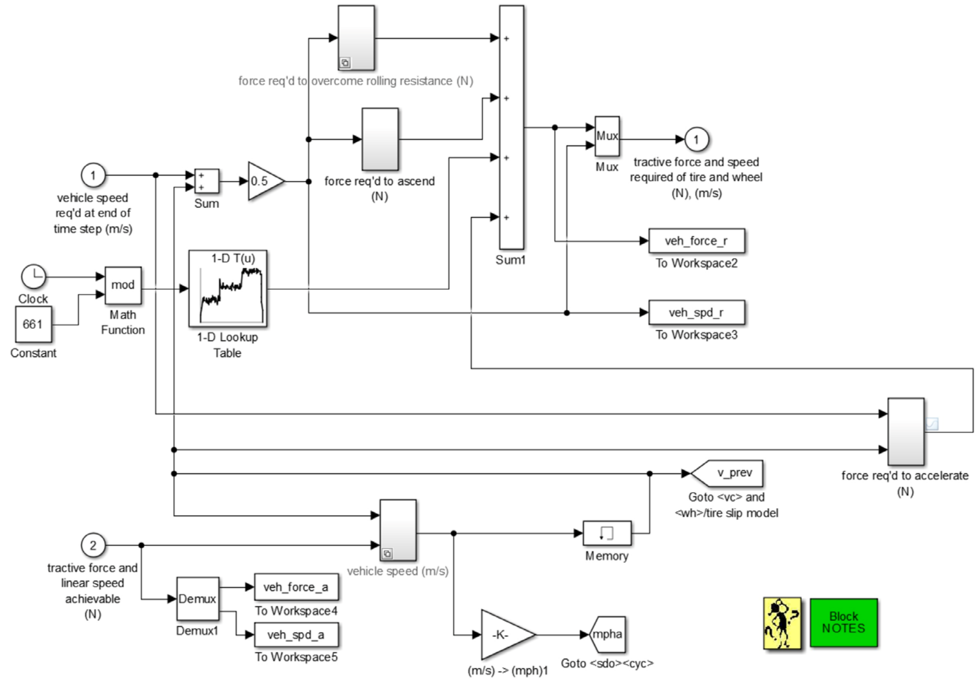


Fig. 6 Vehicle module

3.2 Establishment of the tractor rear wheel drive module

Based on the original front wheel drive module, the rear-wheel-drive module are further developed and improved [17]. According to the design requirements, the driving force required by the vehicle should be within the maximum driving force range that the road surface can withstand. The maximum final speed of the vehicle should also be in the maximum speed under the maximum traction force that can be provided by the road surface. Therefore, necessary modifications are made to the drive module of the vehicle on the ADVISOR platform.

The maximum driving force F_{qmax} under extreme conditions is expressed as follows:

$$F_{q\max} = W_r \mu_{\max} \tag{5}$$

where W_r refers to the driving load on the driving wheel, and $\mu_{\max}$ is the maximum adhesion coefficient of current ground. The magnitude of W_r is expressed as follows:

$$W_r L = F_T h_g + G\cos\alpha L_1 + F_i h + F_j h \tag{6}$$

Then:

$$W_r = F_T \frac{h_g}{L} + mg\cos\alpha \frac{L_1}{L} + mg\sin\alpha \frac{h}{L} + ma\frac{h}{L} \tag{7}$$

where L is the wheelbase of an extended range electric tractor, m; L_1 is the front wheelbase that constitutes the wheelbase, m; h is the distance from the center of mass of the tractor to the ground, m; h_g is the distance from the suspension point to the ground, m.

The average velocity V_{aver} of the iteration step size is expressed as follows:

$$V_{aver} = \frac{1}{2}(V_t + V_0) \tag{8}$$

where V_t is the actual maximum final velocity, and V_0 is the initial velocity.

The acceleration a of the iteration step size is expressed as follows:

$$a = \frac{(V_t - V_0)}{d_t} \tag{9}$$

Substituting the variables of Eqs. (2)- (9) into Eq. (1), the actual maximum final velocity V_t of the iteration step size of the tractor under extreme driving force can be obtained as follows:

$$V_t = \frac{mg\frac{L_1}{L}\mu_{\max}\cos\alpha - mg(f_1\cos\alpha + \sin\alpha) - \frac{1}{2}mgf_2\cos\alpha V_0}{\frac{3}{8}\rho C_d A V_0 + \frac{1}{2}mgf_2\cos\alpha + \mu_{\max}\frac{h}{L}\frac{1}{dt} + \frac{m}{dt}} \times \\ \frac{-\frac{1}{8}\rho C_d A V_0^2 - \mu_{\max} m \frac{h}{L}\frac{V_0}{dt} + \mu_{\max} mg\frac{h}{L} + m\frac{V_0}{dt} - F_T}{\frac{3}{8}\rho C_d A V_0 + \frac{1}{2}mgf_2\cos\alpha + \mu_{\max}\frac{h}{L}\frac{1}{dt} + \frac{m}{dt}} \tag{10}$$

On this this, when the tractor reaches its braking limit, the maximum braking force is the negative value of the maximum driving force. The minimum final velocity V_t within the iteration step of the tractor at the maximum braking force can be calculated as follows:

$$V_t = \frac{-mg\frac{L_1}{L}\mu_{\max}\cos\alpha - mg(f_1\cos\alpha + \sin\alpha) - \frac{1}{2}mgf_2\cos\alpha V_0}{\frac{3}{8}\rho C_d A V_0 + \frac{1}{2}mgf_2\cos\alpha + \mu_{\max}\frac{h}{L}\frac{1}{dt} + \frac{m}{dt}} \times \\ \frac{-\frac{1}{8}\rho C_d A V_0^{\,2} + \mu_{\max} m\frac{h}{L}\frac{V_0}{dt} - \mu_{\max} mg\frac{h}{L} + m\frac{V_0}{dt} - F_T}{\frac{3}{8}\rho C_d A V_0 + \frac{1}{2}mgf_2\cos\alpha + \mu_{\max}\frac{h}{L}\frac{1}{dt} + \frac{m}{dt}} \quad (11)$$

According to Eq. (11), the traction limit speed module established in ADVISOR is shown in Fig. 7.

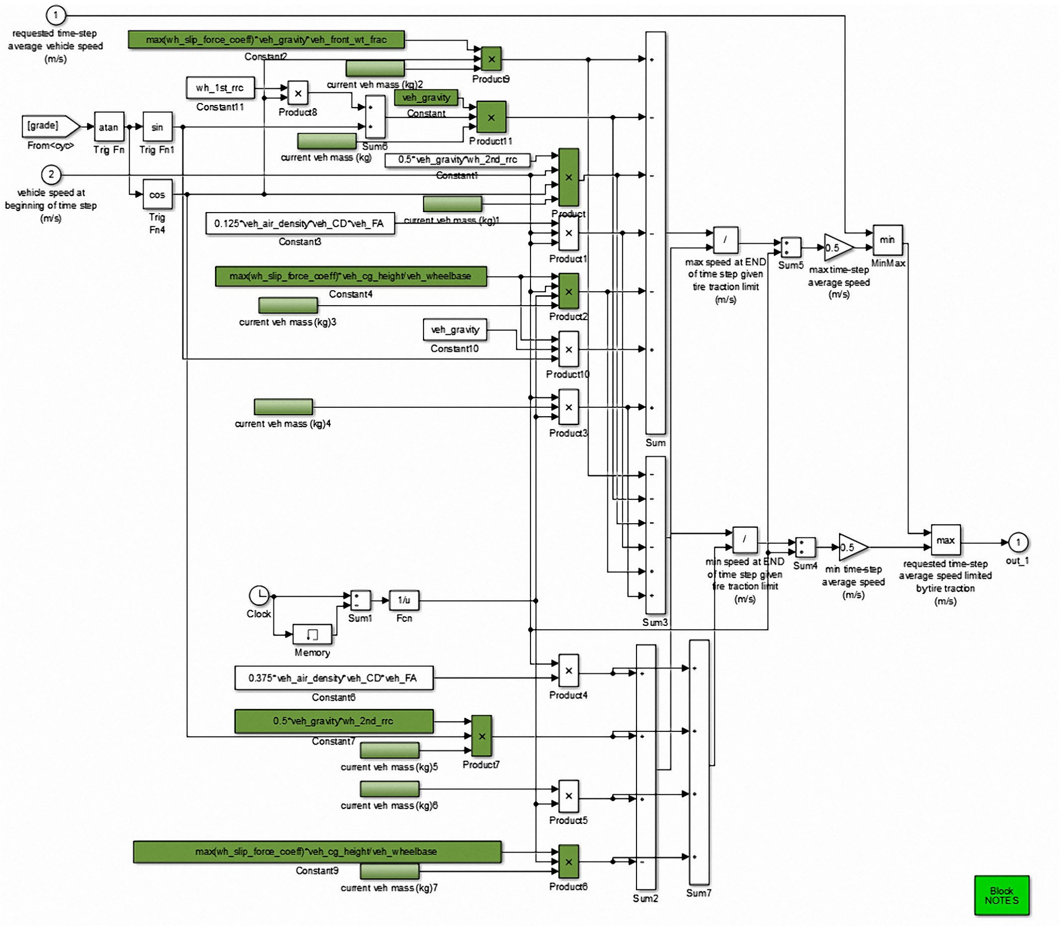


Fig. 7 Calculation module of tractor demand speed

According to the front driving module in the module library, the maximum adhesion force on the driving wheel is taken as the maximum driving force [18-19]. The magnitude of the maximum driving force is calculated as follows:

$$F_{q\max}=[mg\cos\alpha\frac{L_1}{L}\mu_{\max}+(2m\frac{h}{L}\frac{V_{aver}-V_0}{dt}+mg\sin\alpha)\mu_{\max}+F_T\frac{h_g}{L}]\mu_{\max} \quad (12)$$

According to the formula, the maximum drive limit submodule established in ADVISOR is shown in Fig. 8.

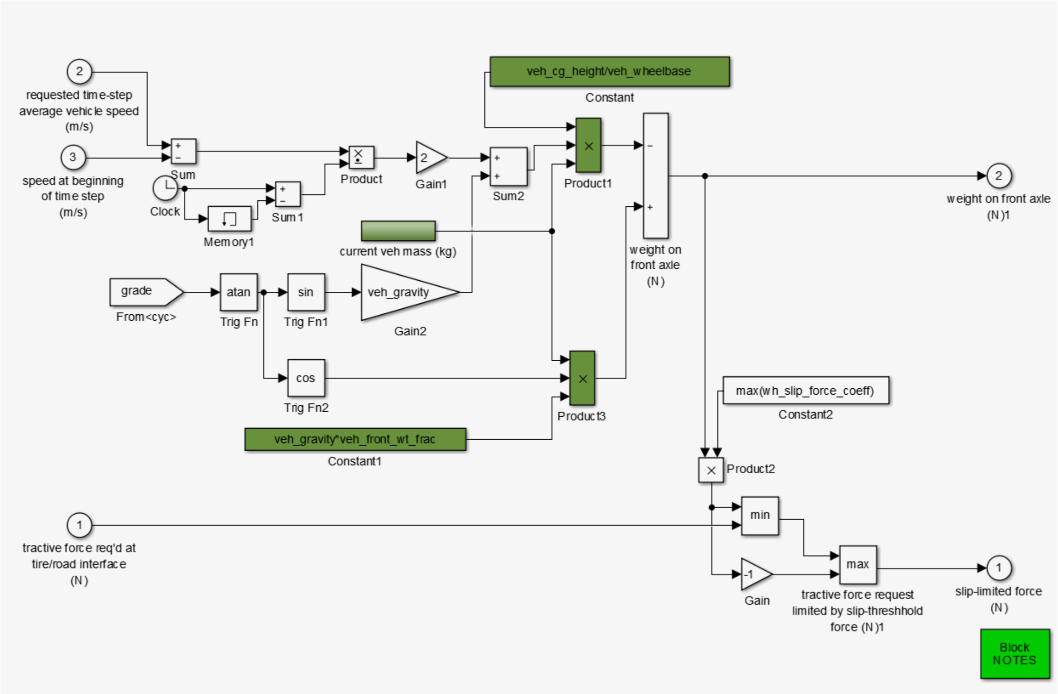


Fig. 8 Limiting submodule of the tractor driving force

3.3 Establishment of the range extender module

(1) Simulation module of the range extender

The range extender module consists of two parts: the engine module and the generator module [17]. The engine module mainly provides the required torque and speed to the generator module. The generator module is responsible for outputting the corresponding power generation based on the requirements of input torque and speed [18]. Based on this, the range extender module is established as shown in Figs. 9 and 10.

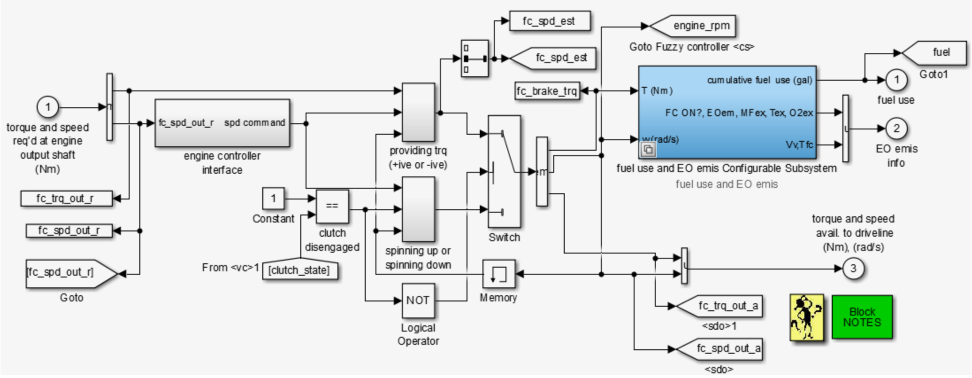


Fig. 9 The engine module

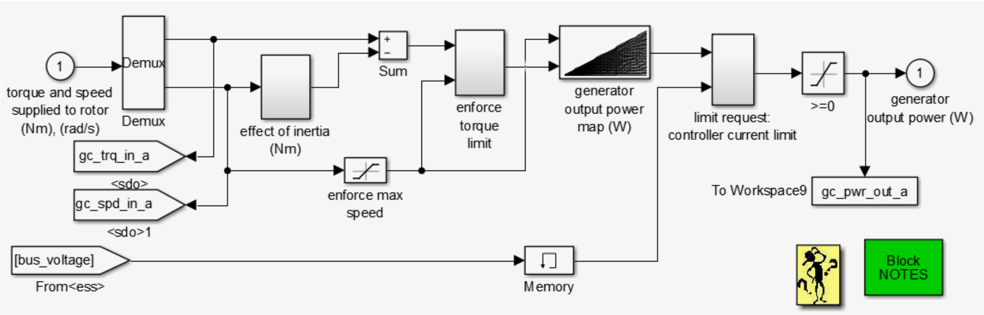


Fig. 10 Generator module

(2) Control strategy of the range extender

According to the three working modes of the extended-range electric tractor, its opening and closing are determined by the battery level and overall power demand. Taking the *SOC* value of the battery and the output power of the motor as the criteria, the maximum and minimum thresholds of *SOC* and power set in the *ECU* controller of the range extender are compared. It is controlled according to the logic operation shown in Fig. 11.

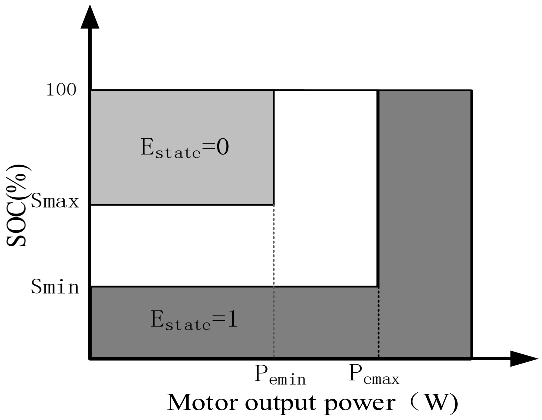


Fig. 11 Start-stop strategy

1) Using *SOC* value as the first criterion, the minimum threshold value S_{min} is set. When *SOC* is lower than the minimum threshold value, the range extender should work, that is, E_{state}=1, entering the range extender operation mode;

2) When the *SOC* value is higher than the lower threshold S_{min}, the required power will be used as the second criterion, and the maximum safe required power P_{emax} will be set. When the required power P_e is higher than this value, it means that the battery will be overloaded and discharged. At this time, the range extender starts working, that is, E_{state}=1, entering the range extender operation mode;

3) To reduce the possibility of frequent start-stop near the threshold value and ensure battery safety, a buffer zone needs to be set up. First, an absolute no-start zone should be set up, which is the area where E_{state}=0. The upper limit S_{max} and motor power safety threshold P_{emin} are set for the battery. When *SOC* is higher than the upper threshold and P_e is lower than P_{emin}, the battery can fully support the power supply of vehicle and is at a completely safe power output. At this time, the tractor will enter pure electric mode;

4) The area between E_{state}=0 and E_{state}=1 is used as a buffer, and the range extender is in the previous state, thus avoiding frequent starts in the threshold area without a buffer. At the same time, the minimum downtime is increased to 30 s to ensure safety.

4. Simulation results and analysis

4.1 Main parameters of the extended-range electric tractor

The main technical parameters of the developed extended-range electric tractor are shown in Table 1.

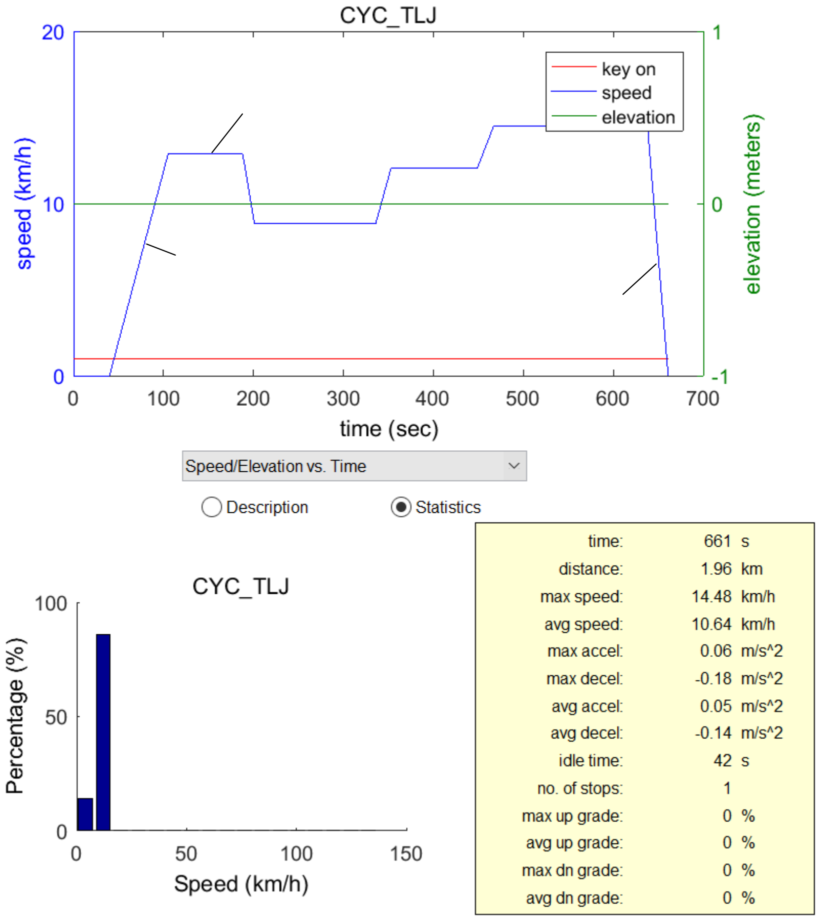
Table 1

Main parameters of the extended-range electric tractor

Vehicle components	Parameter Design	Design value
	Vehicle mass /kg	1200
Vehicle parameters	Load /kg	220
	Endurance /h	2
Battery pack	Nominal voltage /V	72
	Rated capacity /kwh	23.3
	Number of batteries /pieces	24
Drive motor	Rated output/kw	12
	Maximum power /kw	18.4
	Rated speed /r.min^{-1}	2400
Range-Extender	Capacity of tank /L	5
	Output voltage /V	72

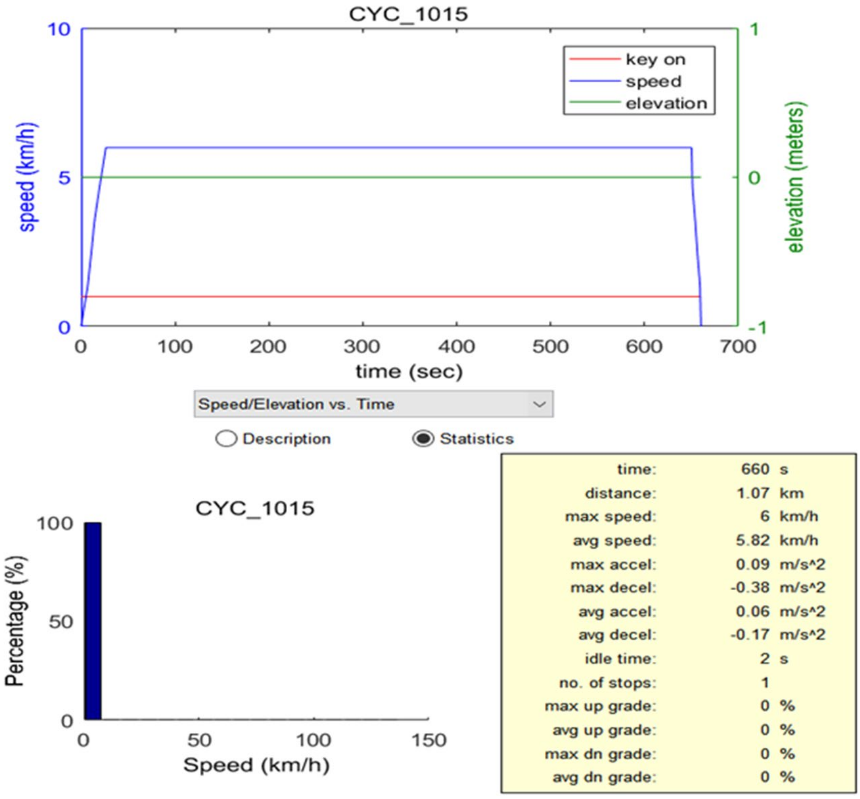
4.2 Test conditions

The commonly used working conditions for tractors are transportation and plowing operations. Therefore, separate transportation and plowing operating conditions have been established [19]. The CYC-TLJ operating condition is taken as the transportation operation condition, with a running time of 661 s, a running distance of 1.96 km, an average speed of 10.64 km/h, a maximum speed of 14.48 km/h, and a maximum acceleration of 0.06 m/s2, as shown in Fig. 12. The CYC-1050 working condition is used as the plowing operation condition, with a running time of 660 s, a running distance of 1.07 km, an average speed of 5.58 km/h, and a maximum speed of 6 km/h, as shown in Fig. 13.



time:	661	s
distance:	1.96	km
max speed:	14.48	km/h
avg speed:	10.64	km/h
max accel:	0.06	m/s^2
max decel:	-0.18	m/s^2
avg accel:	0.05	m/s^2
avg decel:	-0.14	m/s^2
idle time:	42	s
no. of stops:	1	
max up grade:	0	%
avg up grade:	0	%
max dn grade:	0	%
avg dn grade:	0	%

Fig. 12 Transport test conditions



time:	660 s
distance:	1.07 km
max speed:	6 km/h
avg speed:	5.82 km/h
max accel:	0.09 m/s^2
max decel:	-0.38 m/s^2
avg accel:	0.06 m/s^2
avg decel:	-0.17 m/s^2
idle time:	2 s
no. of stops:	1
max up grade:	0 %
avg up grade:	0 %
max dn grade:	0 %
avg dn grade:	0 %

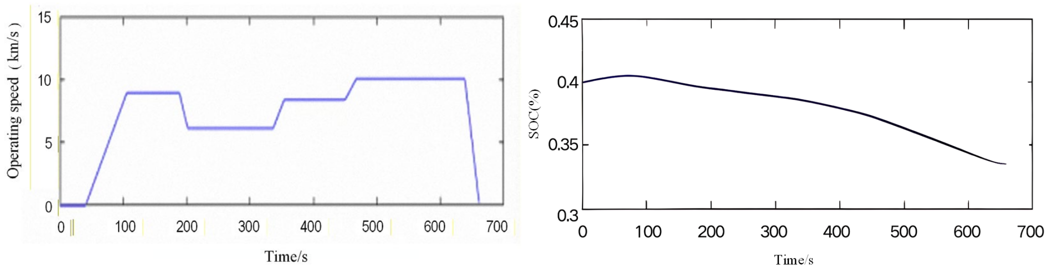
Fig. 13 Ploughing test conditions

4.3 Analysis of simulation results

(1) Transportation operation simulation

Using transportation conditions as simulation conditions, the extended range tractor is simulated, and the simulation results are shown in Fig. 14.

As shown in Fig. 14 (a), the operating speed of the tractor conforms to the speed curve of transportation, meeting the requirements of power performance. As shown in Fig. 14 (b), when the extended-range electric tractor operates under transportation, the SOC value gradually increases from the initial value of 40% over time due to the working of the extender. Then the SOC gradually began to decrease. When the tractor decreases, the SOC curve also decreases slightly. The SOC value decreases by 6% in the simulation.



(a) Operating speed (b) SOC

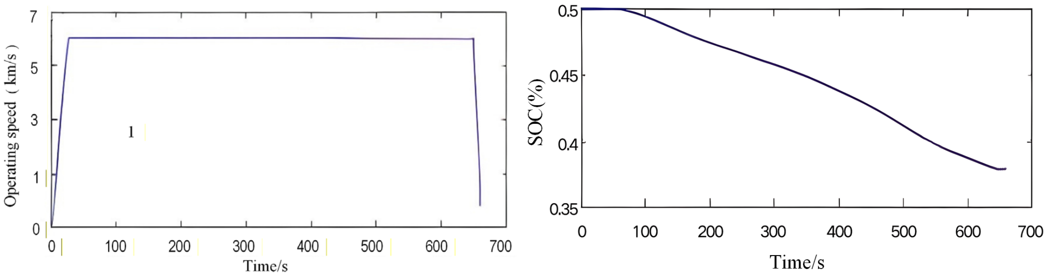
Fig. 14 Simulation results of transportation operations

As shown in Fig. (14), the simulation speed matches the set speed as shown in Fig. (12). This indicates that the speed control module is correct, and the vehicle parameter design meets the operational speed requirements.

(2) Simulation results of plowing

Using plowing as simulation conditions, the extended-range tractor is simulated, and the simulation results are shown in Fig. 15.

As shown in Fig.15 (a), the overall operating speed of the machine meets the requirements of plowing and the power performance. Fig. 15 (b) shows the variation curve of SOC under the starting of the range extender. As the workload increases, the SOC value gradually decreases from the initial value of 50% over time. When it decreases to 40%, SOC begins to decrease slowly as the extender starts working. Finally, after 11 minutes of plowing, the electricity level stabilizes at 37% of SOC, and the total process electricity level decreases by 13%. After conversion, when the range extender is activated, the extended-range electric tractor can extend its range by about 1 hour.



(a) Operating speed (b) SOC

Fig. 15 Simulation results of ploughing operation

5. Conclusion

A range-extended electric tractor model is developed in ADVISOR to evaluate its power performance, and main results are drawn as follows:

(1) A simulation model of an extended-range tractor based on ADVISOR software is developed. Two typical working conditions: transportation operation and plowing operation are simulated and analyzed. The developed model can meet the simulation requirements of extended-range electric tractors;

(2) Under transportation, the SOC value gradually increases from the initial value of 40% over time, and then the SOC gradually began to decrease. The SOC value decreases by 6% in the simulation;

(3) Under plowing, as the workload increases, the SOC value gradually decreases. Finally, after 11 minutes of plowing, the power consumption stabilizes at 37% of SOC, and the total process power consumption is 13% of SOC.

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