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Optimization Method of Speed Ratio for Power-Shift Transmission of Agricultural Tractor

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Abstract: The speed ratio parameters of transmission are crucial factors that affect a vehicle's power, economy, and comfort. Due to the complex working conditions, multiple working modes, and wide range of speed ratios of agricultural tractors, designing and optimizing speed ratio parameters in power-shift transmissions is a challenging task. This paper proposes a transmission speed ratio optimization method based on the life cycle speed utilization rate of general-purpose agricultural tractors. The speed ratio parameters are optimized and solved using the genetic algorithm, with multi-gear power-shift transmissions in agricultural tractors as the research subject. The optimization results and simulation analysis show that the optimized speed ratio has more and denser gears in the common operating speed range while ensuring the general-purpose agricultural tractors' use requirements. Compared to commonly used geometric series speed ratios, tractors using the optimized speed ratio parameters in this paper can significantly improve fuel economy. Most importantly, this provides a practical method reference for optimizing speed ratios in multi-gear gearboxes with complex structures.

Keywords: power-shift transmission; speed ratio; optimization method; agricultural tractor

Citation: Li, B.; Pan, J.; Li, Y.; Ni, K.; Huang, W.; Jiang, H.; Liu, F. Optimization Method of Speed Ratio for Power-Shift Transmission of Agricultural Tractor. *Machines* **2023**, *11*, 438. https://doi.org/10.3390/machines11040438

Academic Editor: Domenico Mundo

Received: 7 March 2023
Revised: 25 March 2023
Accepted: 27 March 2023
Published: 29 March 2023

1. Introduction

The speed ratio parameters of an automatic transmission are important factors that affect a vehicle's driving and operating performance, power, and shifting smoothness [1–3]. Improving the adaptability of a vehicle's powertrain parameters to various operating conditions can significantly reduce fuel consumption while still meeting the use requirements and power performance.

Figure 1 shows a classic powertrain layout of a modern general-purpose agricultural tractor. Commonly used transmissions for modern tractors include power-shift transmissions, hydrostatic transmissions, hydraulic-mechanical continuously variable transmissions, etc. Among them, the power-shift transmission has the characteristics of reliable transmission of larger torque, lower maintenance cost, higher transmission efficiency, and it is widely used in modern tractors for general purposes. The working conditions of general-purpose agricultural tractors are complex, and there are many operating modes of agricultural tractors [4,5]. Therefore, general-purpose agricultural tractors must operate within a wide range of travel speeds [6]. This results in more gears being required for the power-shift transmission of agricultural tractors [7,8]. Designing the power-shift transmission structure and determining the appropriate speed ratio parameters is a significant area of research.

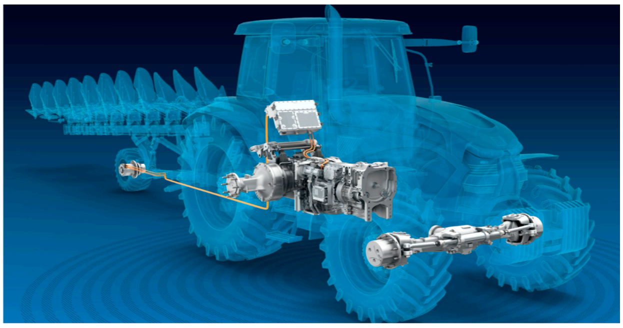

Figure 1. Schematic of agricultural tractor powertrain layout [9].

Numerous studies have been conducted regarding the design of transmission structures, the optimization of speed ratios, and the control of transmissions. Xia et al. [5] proposed a new power-cycle hydro-mechanical continuously variable transmission (PCHM-CVT) device for use in farm tractors. The effects of various structural parameters on the system performance were analyzed, a performance evaluation metric for the PCHMCVT was proposed, and a multi-objective optimization design numerical model was established, which utilized the NSGA-II multi-objective genetic algorithm to optimize the transmission. Morozov et al. [10] designed a two-speed electric delivery step van, built an AVL cruise simulation model and proposed an innovative approach for optimizing the gear transmission ratios. The time taken for the van to accelerate to 100 km per hour and the energy consumption under cyclic conditions were used as the objective functions for optimization. Multi-objective optimization solutions for the speed ratio were obtained based on the genetic algorithm, and its Pareto solution set was obtained.

Walker et al. [11] optimized the transmission ratio of a two-speed gearbox using the genetic algorithm. The sum of the energies consumed during the Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Driving Schedule (HWFET) driving cycles was used as the objective function value to enhance the robustness of the optimization outcomes. Kwon et al. [12] proposed a new approach for the multi-objective optimization of an electric vehicle (EV) equipped with a two-motor and two-speed powertrain system. The study also developed efficient surrogate models of each objective function using an artificial neural network and an adaptive sampling method to reduce the computational effort required during multi-objective optimization. The proposed approach aims to address the excessive computational burden associated with the optimization process. Gao et al. [13] investigated a novel two-speed I-AMT and optimized the gear ratios by using dynamic programming. An optimal shifting process without torque hole was achieved through feed-forward and feed-back control of the clutch and motor. Oh et al. [14] proposed optimization strategies for the gear ratio and shift schedule to enhance the energy efficiency of a wheel loader equipped with a dual-clutch transmission (DCT) and an automated manual transmission (AMT) in the V-pattern working cycle. Pedro et al. [15] used a divide-and-conquer approach to increase the overall output efficiency by obtaining the optimal torque distribution for the electric motors and applying a genetic algorithm to find the optimal value of the gear ratios. Eckert et al. [16] employed a multi-objective optimization for the internal combustion engine vehicle (ICEV) drivetrain design and gear shifting control aiming at the minimization of fuel consumption, exhaust emissions, and gearbox power losses. The optimization problem was solved by the interactive adaptive-weight genetic algorithm (I-AWGA) and comprised different design variables of the multi-speed transmission and differential system, considering constructive constraints.

Spanoudakis et al. [17] conducted an experiment using a prototype electric vehicle to assess energy consumption with different gear ratio usage on a single-speed transmission. They performed dynamic simulations to compare and evaluate different gear ratio setups, providing insights into their impact on energy consumption. The correlation of experimental and simulation data was used to validate the dynamic model and evaluate the results for selecting the optimal gear ratio. Zhu et al. [5] proposed a mechanic-electronic-hydraulic powertrain system (MEH-PS) integrating an electro-mechanical hybrid system and hydro-mechanical composite transmission to meet the operational requirements of the tractor. They completed the scheme conception and structure design and selected power sources and transmission components based on the relevant work content of the tractor. Xia et al. [18] proposed a power-shift control strategy for the transmission of a tractor with large horsepower based on torque and speed transition, which aimed to deliver multiple targets and multiparameter optimization of power-shift control. Siddique et al. [19] developed a simulation model, a mathematical model of sliding velocity, a moment of inertia, and clutch engagement pressure of the clutch pack using the powertrain and configurations of the real power-shift transmission (PST) tractor. The sensor fusion method was used to precisely measure the proportional valve pressure by the test bench, which was applied to the simulation model. He et al. [20] aimed to optimize the electricity consumption of a pure electric logistics vehicle under New European Driving Cycle (NEDC) working conditions. To achieve this, they designed two-speed transmission gear ratios to replace the fixed gear ratio and developed a new shift schedule that is compatible with the electric motor. Their objective was to reduce the vehicle's electricity consumption.

The studies highlighted above indicate that, in terms of the optimization strategies for the vehicle transmission speed ratios, most current studies were based on various typical standard driving cycles (such as NEDC, UDDS, HWFET, V-pattern working cycle etc.). However, agricultural tractors are versatile machines that are required to carry different agricultural tools to work effectively in various operating modes. Additionally, the loads in different operation modes vary widely, and the operating conditions are complex. It is difficult to obtain accurate standard cycle driving conditions to express the actual operating conditions of general-purpose agricultural tractors. Therefore, the above-mentioned speed ratio optimization methods based on standard cycle conditions cannot be directly applied to general-purpose agricultural tractors.

In this paper, a transmission speed ratio optimization method that is based on the vehicle's life cycle travel speed utilization rate is proposed. The speed ratio parameters are optimized and solved based on the genetic algorithm, taking the agricultural tractor with multi-gear power-shift transmission as the research object. This will provide a crucial theoretical basis and a valuable reference for the design of power-shift transmissions for agricultural tractors.

2. Methods

2.1. Research Object

In the field of agricultural tractors, power-shift transmissions are typically classified as partial power-shift transmissions or full power-shift transmissions. Different structural forms and gear distributions have different restrictions on optimization, so it is necessary to analyze the structural characteristics of different types of power-shift transmissions.

A partial power-shift transmission is typically composed of two parts: a power-shift gearbox section and a non-power-shift gearbox. This allows for partial gears to be shifted without interrupting the power flow. Moreover, its gear arrangement and speed ratio distribution are limited due to the series connection between the front power-shift gearbox and rear range gearbox. Power-shift clutch, free-wheeling, and planetary gear train are used to form the power-shifting device of Several typical partial power-shift transmissions, such as torque booster of CASE IH and 'Multi Power' of Massey Ferguson [21]. Combined with rear non-power-shift gearboxes, the final multi-gear partial power-shift transmissions can be formed. The partial power-shift transmission of CLAAS AXION 800 series tractor consists of a power-shifting device with 6 power-shift speeds, a power-shifted high-low mode module, and a range/reverse module [22]. What they have in common is that each set of gears corresponds to the speed ratio of multiple transmission gears.

A full power-shift transmission allows for all gears to be dynamically shifted without interrupting the power flow. It is usually composed of multiple clutches and planetary gear trains, making its structure relatively complicated. For example, the John Deere 50 series tractor has a full power-shift transmission with a total of 15F + 4R power-shift gears using planetary gear trains [23]. The full power-shift transmission for Ford 971 tractor is mainly composed of three clutches, three brakes, a freewheel, and a plurality of planetary gear trains, with a total of 10F + 2R power-shift gears [24]. The full power-shift transmission of the New Holland TG series tractor has a total of 24F + 6R power-shift gears, with the structure of a fixed axis [24]. The full power-shift transmission of the New Holland TM190 series tractor also adopts a fixed shaft arrangement, and all shift operations are performed by operating the clutch, which can form 19F + 6R gears [25].

It can be seen from the above that the structure and transmission scheme of a tractor gearbox determines the number of power-shift gears available. As the main parameters of the vehicle powertrain, gear distribution, and speed ratio are important parameters that strongly influence power and fuel economy. It is usually desirable to arrange denser gears in the speed section where the tractor is frequently used to increase gear utilization, increase the probability of the engine working in the high-efficiency zone, and improve the power and fuel economy of the tractor-implement combination. However, in order to reduce the complexity of the power-shift transmission, most of the transmission gearboxes adopt the way of a series arrangement of the main and auxiliary parts, which means that changing any group of gear ratios affects multiple gears. Additionally, different power-shift transmissions have varying gear arrangements, which can make designing and optimizing speed ratio parameters challenging.

This paper classifies power-shift transmissions into two categories for speed ratio optimization based on analyzing their gear distribution characteristics:

1. The transmission features shift gears that operate independently of one another, allowing for full power-shifting capabilities.
2. Depending on the gear distribution, some or all the gears in the transmission may have a structural influence on each other, enabling either partial or full power-shifting functionality.

2.2. Optimization Method

2.2.1. Speed Characteristics of Agricultural Tractors

This study proposes a method for optimizing the transmission speed ratio based on the agricultural vehicle's life cycle travel speed utilization rate. The first step is to obtain data on the tractor's speed utilization rate throughout its life cycle. A general-purpose modern agricultural tractor can operate at speeds ranging from 2 km/h to 50 km/h in the forward direction, with different proportions of speed ranges used at various stages of its life cycle.

Researchers have statistically analyzed the relative service time of each speed range and depicted frequency histograms of usage, as shown in Figure 2 [26]. It shows that the speed range from 4 km/h to 20 km/h has a relatively high usage rate. The relative usage rate of the speed range 4 to 20 km/h is as high as 76% from Resch's statistics, and that of Renius' statistics is as high as 93%. Speed in this range is generally used for most types of farm work, whereas speeds in the other ranges are primarily used for field or road transportation with a lower frequency of use. Although usage rates may vary slightly due to different regions, farming practices, and statistical methods, the overall trend remains the same. This study utilizes statistics from Resch and Renius to illustrate the speed ratio optimization method.

By combining the statistical data from both experts shown in Figure 2, a linear coordinate diagram of the speed usage frequency in the entire life cycle of an agricultural tractor is created (see Figure 3). This linear coordinate diagram provides a clear and intuitive representation of the characteristics of speed usage frequency in the whole life cycle of the agricultural tractor. It shows that the time and frequency of use for a modern general-purpose agricultural tractor are significantly higher in the speed range used for common field operations, such as leveling, seeding, and crop-related tasks, compared to the speed ranges used for creeping and transportation conditions.

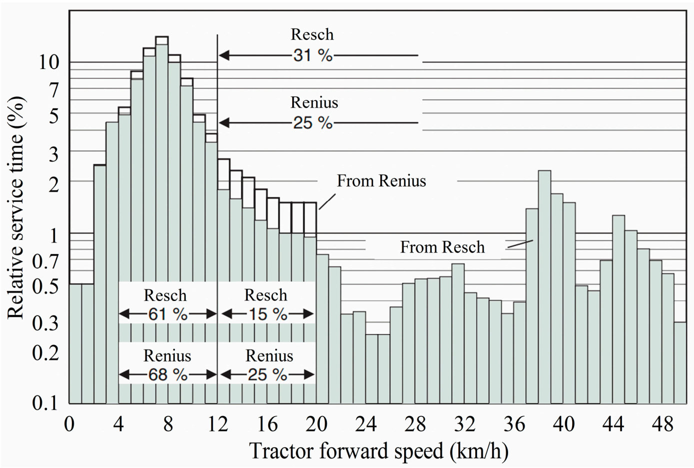

Figure 2. The speed statistics of a tractor throughout its life cycle from Resch and Renius [26].

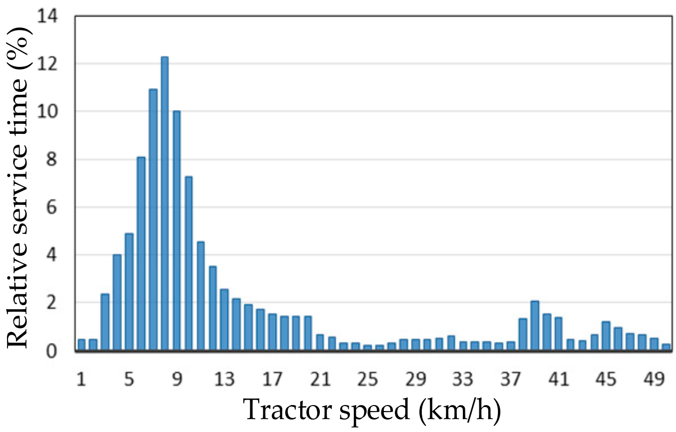

Figure 3. The linear coordinate diagram of the speed usage frequency in the whole life cycle of the agricultural tractor.

Figure 3 shows a discrete linear coordinate diagram of the frequency of speed usage throughout the entire life cycle of an agricultural tractor. Based on the data in Figure 3, a continuous curve is fitted using the Newton–Raphson method. Using tractor speed on the x-axis and time weight on the y-axis, Figure 4 is created to provide calculation weights for speed ratio optimization.

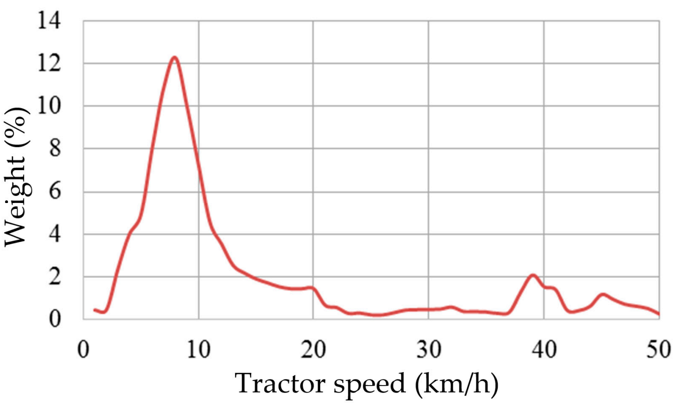

Figure 4. Calculation weight based on speed usage frequency.

2.2.2. Optimization Based on Genetic Algorithm

The number of gears in power-shift tractors is typically large, and there are numerous parameters that need to be determined. Achieving optimal results through simple trials and calculations can be challenging. Compared to traditional optimization methods, the genetic algorithm can handle a wide range of problem types without requiring explicit mathematical models or constraints. It can also search for solutions in large search spaces and deal with multi-objective optimization problems. Additionally, the genetic algorithm is robust to noise and can handle non-differentiable, non-continuous, and non-linear objective functions. Therefore, this paper proposes the use of a genetic algorithm to design and optimize the speed ratio of each gear pair. The specific process is outlined below:

(1) Objective Function

With the objective of minimizing fuel consumption per unit mileage in a calculation cycle, the fitness function is defined as follows:

$$\min Q_d(X) = \frac{Q_z(X)}{S_z(X)} = \int_0^y \frac{P(t)b_e(t)}{102v(t,\ X)\rho_d g}dt\ , \tag{1}$$

$$v = 0.377\frac{n_e r}{i_t}\ , \tag{2}$$

$$P = 0.377\frac{T_e n_e}{9550}\ , \tag{3}$$

where Q_d is the fuel consumption per unit mileage (L), Q_z is the total fuel consumption (L), S_z is the mileage in a calculation cycle (km), P is the engine power (kW), b_e is the specific fuel consumption (g/(kW·h)), v is the tractor speed (km/h), ρ_d is the fuel density (kg/L), g is the gravitational constant (N/kg), n_e is the engine speed (rpm), r is the radius of the drive wheel (m), i_t is the speed ratio, T_e is the engine torque (N·m), X is the parameters to be optimized, y is the total time (s), respectively.

(2) Optimization Variable

To reduce fuel consumption in this study, the transmission speed ratio of each gear is considered the optimization variable. In the first category, it is assumed that all shift gears in the transmission are structurally independent of each other. Therefore, the total speed ratio of each gear is directly used as the optimization variable. Assuming that the gearbox has a total of 16 gears, the optimization variables are as follows:

$$X = (i_{t1},\ i_{t2},\ i_{t3},\ i_{t4}\ \ldots,\ i_{t13},\ i_{t14},\ i_{t15},\ i_{t16}) = (x_1,\ x_2,\ x_3,\ x_4\ \ldots,\ x_{13},\ x_{14},\ x_{15},\ x_{16}), \tag{4}$$

wherein i_{t1} to i_{t16} are the total speed ratios of each gear from 1 to 16 gears, respectively.

In the second category, some or all of the gears in the transmission have structural interdependence and can achieve partial or full power-shift function. Therefore, the optimization variable is the transmission ratio of each pair of gear pairs. Assuming that the front and rear gearboxes are connected in series and arranged for sequential shifting, and each gearbox has four gears. The arrangement of two gearboxes in series makes the total number of forward gears 16, and their gear ratios (i_1 to i_{16}) of the entire transmission can be expressed by Equation (5). The optimization variables for forward gears are expressed by Equation (6).

$$\begin{bmatrix} i_1 & i_2 & i_3 & i_4 \\ i_5 & i_6 & i_7 & i_8 \\ i_9 & i_{10} & i_{11} & i_{12} \\ i_{13} & i_{14} & i_{15} & i_{16} \end{bmatrix} = \begin{bmatrix} i_{a1} \\ i_{a2} \\ i_{a3} \\ i_{a4} \end{bmatrix} \times [i_{b1}\ , i_{b2}\ , i_{b3}\ , i_{b4}] = \begin{bmatrix} i_{a1}i_{b1} & i_{a1}i_{b2} & i_{a1}i_{b3} & i_{a1}i_{b4} \\ i_{a2}i_{b1} & i_{a2}i_{b2} & i_{a2}i_{b3} & i_{a2}i_{b4} \\ i_{a3}i_{b1} & i_{a3}i_{b2} & i_{a3}i_{b3} & i_{a3}i_{b4} \\ i_{a4}i_{b1} & i_{a4}i_{b2} & i_{a4}i_{b3} & i_{a4}i_{b4} \end{bmatrix}, \tag{5}$$

$$X = (i_{a1},\ i_{a2},\ i_{a3},\ i_{a4},\ i_{b1},\ i_{b2},\ i_{b3},\ i_{b4}) = (x_1,\ x_2,\ x_3,\ x_4,\ x_5,\ x_6,\ x_7,\ x_8), \tag{6}$$

wherein i_{a1} to i_{a4} are the speed ratios of each gear in the front gearbox, respectively; i_{b1} to i_{b4} are the speed ratios of each gear in the rear gearbox, respectively.

(3) Constraints

For the first category, the speed ratio of any two adjacent gears must meet certain requirements to avoid excessive redundancy or size of the gearbox. Specifically, the ratio of the speed ratio of the low gear to the high gear should be greater than 1.1 and less than 1.6 for any two adjacent gears. Additionally, constraints are set based on the travel speed range of general-purpose agricultural tractors. Therefore, the optimization constraints for the first category of general-purpose agricultural tractors can be expressed as follows:

$$\begin{cases} 1.6x_2 \geq x_1 \geq 1.1x_2 \\ 1.6x_3 \geq x_2 \geq 1.1x_3 \\ 1.6x_4 \geq x_3 \geq 1.1x_4 \\ \cdots\cdots \\ 1.6x_{14} \geq x_{13} \geq 1.1x_{14} \\ 1.6x_{15} \geq x_{14} \geq 1.1x_{15} \\ 1.6x_{16} \geq x_{15} \geq 1.1x_{16} \end{cases}, \tag{7}$$

$$\begin{cases} 1.8 \leq 0.377\frac{n_{em}r}{x_1} \leq 2 \\ 50 \leq 0.377\frac{n_{em}r}{x_{16}} \leq 50.5 \end{cases}, \tag{8}$$

wherein n_{em} is the rated engine speed.

For the second category, the overall speed ratio in each gear is determined by multiplying the speed ratios of each pair of gears in the power transmission line of the drive train. Different transmission gears need to share multiple pairs of gears and affect each other, so the mutual influence relationship between them should be expressed clearly in the constraints of optimization.

(4) Optimization Process

The optimization process in this study utilizes a genetic algorithm, as shown in Figure 5. Initialization: Initialize a population of potential solutions randomly. Evaluation: Evaluate each individual in the population using the fitness function. Selection: Select a subset of individuals from the population based on their fitness values. Recombination: Create new individuals by combining genetic material from selected individuals through crossover. Mutation: Introduce random changes to the genetic material of newly created individuals through mutation. Replacement: Replace some individuals in the population with newly created individuals. Termination: Determine if a termination condition has been met, such as reaching a maximum number of generations or achieving a satisfactory solution. If not, go back to step two. The parameters used for the genetic algorithm are set as follows: initial population size of 100, crossover fraction of 0.8, elite count of 15, evolution generations of 80, migration fraction of 0.2, and a stall generation limit of 10.

During the optimization process, the fitness function value is calculated each time using the steps shown in Figure 6.

The process starts by fixing a throttle opening and changing the target travel speed successively from 2 km/h with a step length of 0.01 km/h. This loop continues until the speed reaches 50 km/h. After completing the small calculation cycle, the throttle opening is changed by 0.1% until it reaches 100% (the initial throttle opening is 1%), marking the end of a large calculation cycle. The genetic algorithm automatically adjusts the speed ratios of all gears (optimization variable) and repeats the above calculation process to continuously optimize the fuel consumption per unit mileage. The optimization variables that correspond to the optimal fitness function value are identified as the final optimal value for the system.

In the optimization calculation process, the transmission gear is automatically adjusted to achieve the target driving speed. If two gears can both reach the target speed, the gear with the lower fuel consumption rate is selected. If no gear can reach the target speed, the gear and speed closest to the target are chosen. The simulation operation time at each speed during the optimization process is distributed based on the time weight shown in Figure 4. This ensures that the optimization process reflects the speed usage frequency and conditions in the entire life cycle of an agricultural tractor.

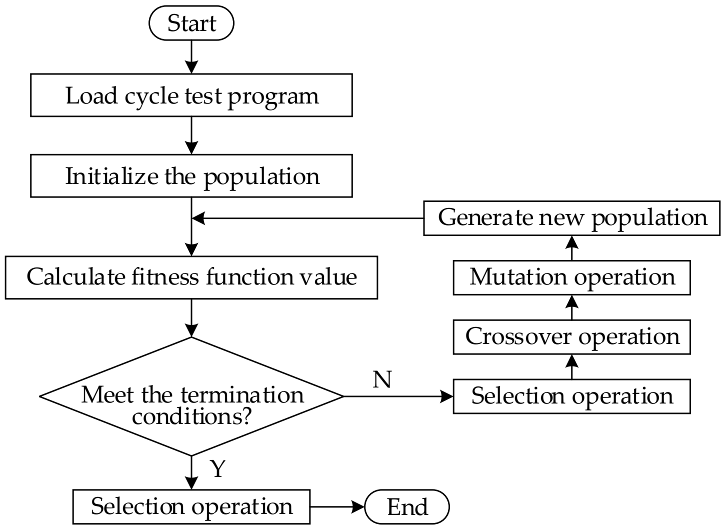

Figure 5. Flow chart of transmission speed ratio optimization by genetic algorithm.

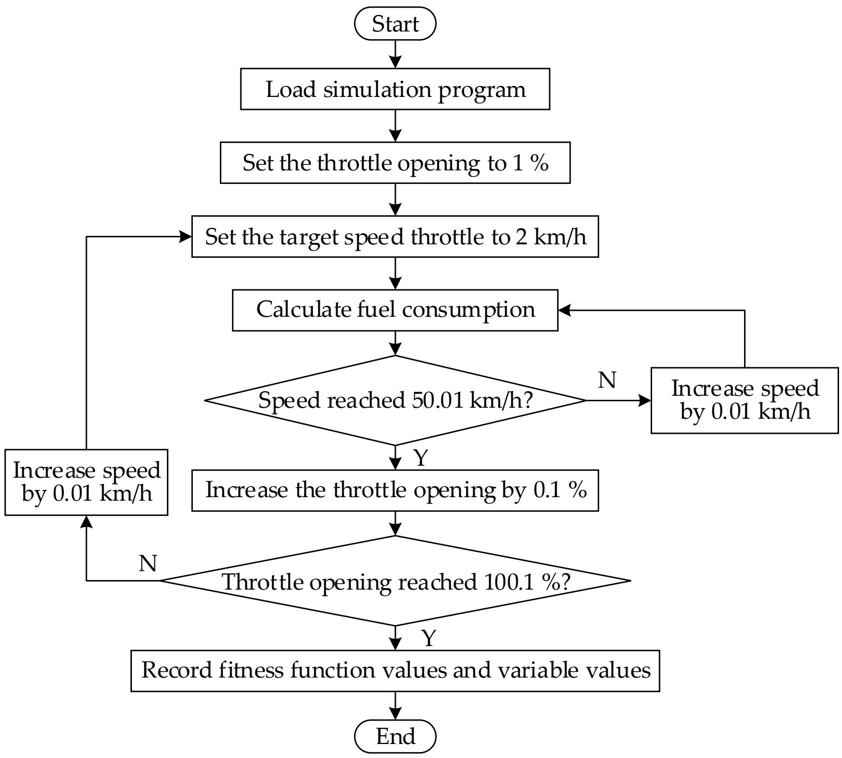

Figure 6. Flow chart of calculating the fitness function value.

3. Modeling and Simulation

The optimization process and simulation verification are both based on the mathematical model of the tractor-implement combination. In this paper, the mathematical model is established for optimization and analysis. The simulation model is built using MATLAB/Simulink and includes modules for the display, driver inputs, transmission, vehicle, engine, implements, control system, and more. Figure 7 illustrates the interface and structure of the simulation model. The 'Driver inputs' module is used to output the driver's operations, including accelerator opening and brake signals. The 'CI_Engine' module is used to simulate the output characteristics of the diesel engine. The 'Control logic' module is used to generate an automatic shift schedule. The 'Transmission' module is used to store gear parameter information and change gear. The 'Vehicle' and 'Implements' modules are used to generate traveling and working loads. The 'Display' module is used to display vehicle status information in the real-time simulation. Some basic parameters of the tractor used in the simulation are listed in Table 1.

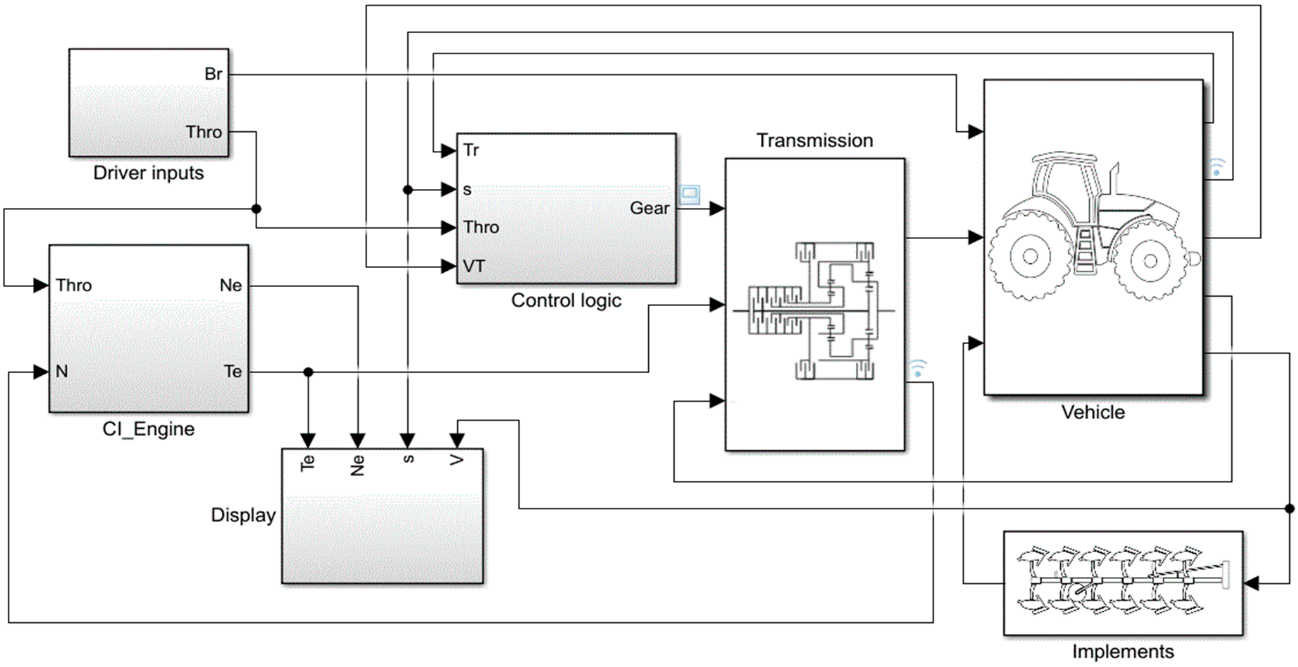

Figure 7. The interface and structure of the simulation model.

Table 1. Basic parameters of the simulation tractor.

Parameters	Value
Rated power of engine (kW)	175
Rolling radius of wheels (m)	0.95
Mass of tractor weight (kg)	9000
Mechanical efficiency of drive system	0.87

This study utilizes a diesel engine with a power output of 175 kW and a rated torque of 765 N·m at an engine speed of 2200 rpm. The mapping characteristics of the engine, based on test data, are presented in Figure 8. The simulation employs the mean engine torque model, which represents the engine torque as a function of the engine speed and throttle opening, as described by Equations (9) and (10). The engine model is used to compute fuel consumption during both the optimization process and simulation verification.

$$T_e = f(n_e,\ \beta), \tag{9}$$

$$b_e = f(n_e,\ T_e), \tag{10}$$

where β is engine throttle opening (%).

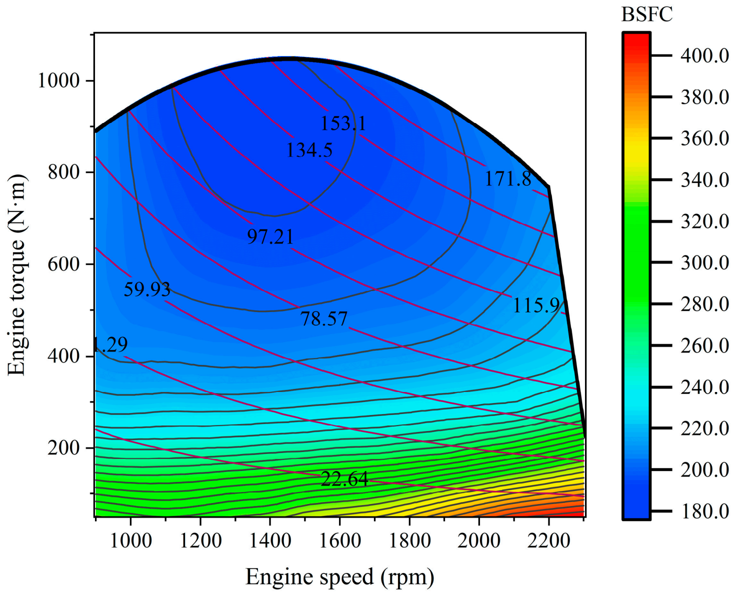

Figure 8. The engine mapping characteristics.

4. Results and Discussion

This paper presents an optimization approach to improve the gear ratios of general-purpose agricultural tractors, using the first category of power-shift transmission as an example. Figure 9 shows the optimization results of the speed ratio parameters for this category. As expected, the 16-speed ratio parameters for gears 1 to 16 are arranged in descending order. The speed ratios between adjacent gears are relatively large in the 1st to 4th and the 13th to 16th gears, whereas they are relatively small in the 4th to 13th gears. This arrangement guarantees more gears in the speed range commonly used by general-purpose agricultural tractors, which results in more efficient use of as many gears as possible.

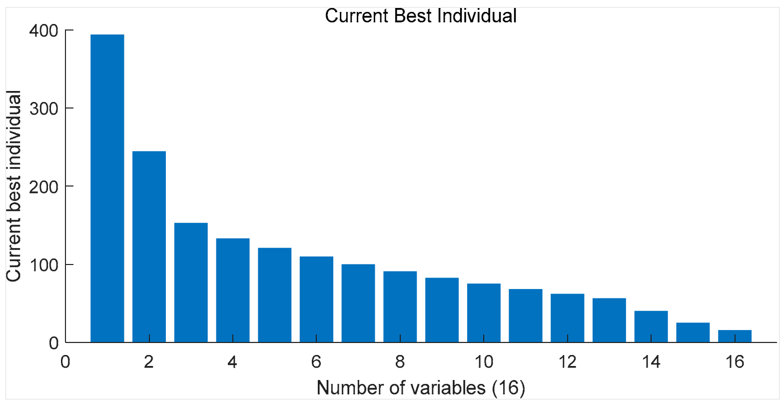

Figure 9. Optimization results based on genetic algorithm for the first category.

The specific optimized values of speed ratio parameters for general-purpose agricultural tractors are presented in Table 2. The table indicates that the maximum ratio of the speed ratios of adjacent gears is approximately 1.6, which occurs in the low-speed and high-speed gear ranges. Conversely, the minimum ratio of the speed ratios of adjacent gears is approximately 1.1, which appears in the medium-speed gear range. These findings demonstrate that the optimization results comply with the specified constraints, thereby avoiding excessive gear redundancy resulting from a gear ratio span that is too small, as well as shifting difficulties arising from a gear ratio span that is too large.

Table 2. Optimized speed ratio data.

Speed Ratio	Value	Speed Ratio	Value	Speed Ratio	Value	Speed Ratio	Value
i_{t1}	394	i_{t5}	121	i_{t9}	82.6	i_{t13}	56.4
i_{t2}	244.7	i_{t6}	110	i_{t10}	75.1	i_{t14}	40.3
i_{t3}	152.9	i_{t7}	100	i_{t11}	68.3	i_{t15}	25.2
i_{t4}	133.1	i_{t8}	90.9	i_{t12}	62.1	i_{t16}	15.7

$$v_t = 0.377\frac{n_e r}{i_t}, \quad (11)$$

Equation (11) enables the calculation of the theoretical driving speed of a tractor (v_t) based on the engine speed, equivalent wheel radius, and speed ratio of each gear. This paper establishes the stable engine speed range as 850–2200 rpm and the driving wheel radius as 0.95 m. Using these parameters, the tractor speed ranges for all forward gears were calculated and presented in Figure 10.

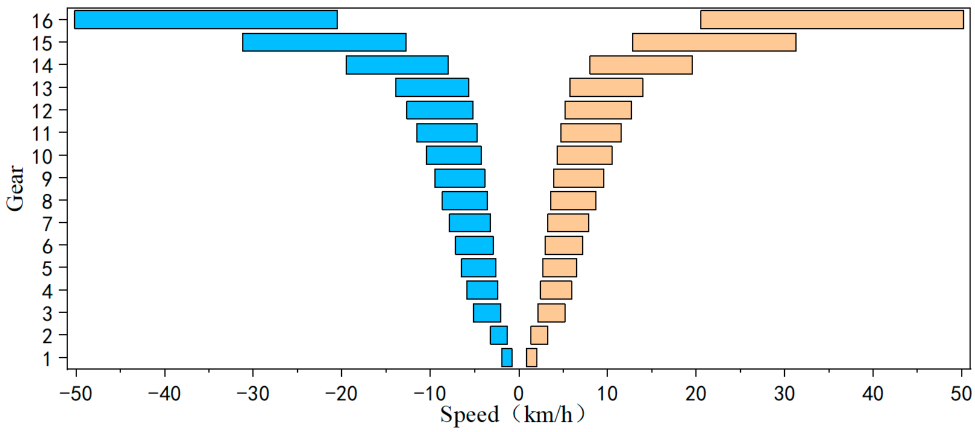

Figure 10. The theoretical driving speed of each gear of the optimized tractor.

The reverse gear ratio of the shuttle shifting device was set to 1, and the tractor speed ranges for all reverse gears were obtained accordingly. As shown in Figure 10, the tractor speed ranges from 1 to 50 km/h and from −1 to −50 km/h, which is sufficient for general-purpose agricultural tractors. Notably, the range of tractor speed from 4 to 20 km/h contains a higher number and density of gears than other speed ranges. This design enables the engine to operate in a high-efficiency area throughout the life cycle of the tractor, thereby increasing the potential for energy savings. Additionally, denser gears and smaller speed ratio steps within the common speed range can significantly reduce the impact, sliding friction, and shifting time during the shifting process, leading to improved shifting quality and increased clutch life.

A speed ratio optimization method for power-shift transmission systems in general-purpose agricultural tractors is presented. The method is based on the genetic algorithm and speed usage frequency over the tractor's whole life cycle. To demonstrate the effectiveness and advantages of this method, tractor operation simulations are conducted and compared under different loads. The tractor is run at a steady and uniform working speed under each speed value, with operation times set according to speed usage frequency, under loads ranging from 20% to 100% (increased by 5%), respectively. Simulation calculations are conducted using the speed ratio optimized in this paper as well as the commonly used geometric series speed ratio. The results indicate that using the speed ratio optimized in this paper results in a fuel savings of 2.7% for the tractor. This demonstrates the efficacy of the proposed method and provides a practical reference for optimizing speed ratios in complex multi-gear gearboxes.

5. Conclusions

The speed ratio parameters of transmission are crucial factors that affect a vehicle's power, economy, and comfort. Due to the complex working conditions, multiple working modes, and wide range of speed ratios of agricultural tractors, designing and optimizing speed ratio parameters in power-shift transmissions is a challenging task. In order to improve the comprehensive performance of the power-shift transmission of the tractor, in this paper, the operational characteristics of general-purpose agricultural tractors and the structural characteristics of different types of power-shift transmissions were analyzed. To address the limitations of the optimization strategies based on standard cycle conditions, a transmission speed ratio optimization method based on the life cycle speed utilization rate of a general-purpose agricultural tractor was proposed. The speed ratio parameters were optimized and solved based on the genetic algorithm, taking the agricultural tractor with multi-gear power-shift transmission as the research object. The optimization results and simulation analysis showed that the optimized speed ratio had the characteristics of more and denser gears in the common operating speed range under the premise of ensuring the use requirements of general-purpose agricultural tractors. Compared to the commonly used geometric series speed ratio, tractors using the optimized speed ratio parameters in this paper can significantly improve fuel economy. This research provides an important and practical method reference for optimizing speed ratios in complex multi-gear gearboxes of agricultural tractors.

Author Contributions: Conceptualization, B.L. and Y.L.; methodology, B.L.; software, J.P.; validation, B.L., K.N. and F.L.; formal analysis, W.H.; investigation, B.L.; resources, H.J.; data curation, B.L.; writing—original draft preparation, B.L.; writing—review and editing, B.L.; visualization, Y.L.; supervision, H.J.; project administration, B.L.; funding acquisition, B.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the National Natural Science Foundation of China under grant 52202508, in part by the Key Lab Open Project Fund of Industrial Fluid Energy Conservation and Pollution Control, Ministry of Education under grant 2022-JXGCKFKT-YB-04, in part by the Key Laboratory of Transportation Industry for Transport Vehicle Detection, Diagnosis and Maintenance Technology.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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