A BIAS OPTIMIZATION METHOD FOR IMPROVING FARMING TRUCK TRANSMISSION RATIO BASED ON HOPE INTERVAL
/
基于希望区间的农用载货汽车传动比偏置优化方法的研究

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ABSTRACT
Farming truck engine operating conditions are typically far from the optimal economic region. In this study, we selected a 5-ton farming truck as the research subject and built a digital vehicle model by using Advanced Vehicle Simulator (ADVISOR) software. We set the operating condition as CYC-NYTRUCK and used transmission ratio as a variable. The objective function was set up based on the fuel consumption, which corresponded to the transmission ratio. By adopting the optimum method of hope interval, all levels of farming truck transmission ratios can be optimized. Then, we used a different gearbox ratio with a design based on different variables, and calculated fuel consumption. Results showed that the hope interval for the optimum transmission ratio fell within the range of 30% to 40%. Within the hope interval, we reduced the variable and resigned the transmission ratio. After calculation, the corresponding transmission ratio for the least fuel consumption was obtained. Keeping the transmission ratios for the 1st and 5th gears constant, the transmission ratios for the 2nd, 3rd, and 4th gears were adjusted to 4.97, 3.11, and 1.95 respectively. The fuel consumption of the transmission ratio after optimization was reduced by 1.2 L/100 km. Furthermore, the acceleration time within 0 km/h to 80 km/h was less than 0.1 s. Overall, the optimized transmission ratios greatly improved the fuel economy and power performance of the farming truck. The research results could provide reference to parameter optimization and application of the transmission system of the farming truck.

摘要
针对农用载货汽车发动机使用工况远离最佳经济区域的情况，本文以某 5 吨农用载货汽车为例，利用 ADVISOR 软件，构建了数字化的汽车模型，选取 CYC-NYTRUCK 工况，以传动比为变量，根据传动比对应的油耗量建立了目标函数，采用基于希望区间的优化方法对农用载货汽车变速箱的各级传动比进行了优化。结果表明：根据不同的偏置量设计汽车变速箱传动比，计算传动比对应的油耗量，找到了最优传动比的希望区间为偏置量在 30%到 40%之间的区域；在希望区间内，缩小偏置量对传动比重新设计，经计算得到油耗最小值对应的传动比为：保持Ⅰ、Ⅴ档传动比不变，Ⅱ、Ⅲ、Ⅳ档传动比分别调整为 4.97、3.11 和 1.95；优化后传动比工作的耗油量降低了 1.2 L/100km；0-80 km/h 加速时间减少了 0.1s。优化后的传动比明显改善了农用载货汽车的燃油经济性和动力性，研究结果可以为农用载货汽车动力传动系统的参数优化设计和匹配提供参考依据。

INTRODUCTION

The good or bad aspects of the fuel consumption and power performance of farming trucks lie in the performance of the truck engine and the application of the engine and gearbox. During the design and production phases, the one-sided pursuit of fuel consumption or power performance is more common owing to the excessive classification on labour *(Oberpriller et al., 2008)*. However, if the engine and chassis are not seen as a whole in improving the performance of any assembly, this oversight would not help improve overall performance because of improper matching with other assembly *(Lvand Yongchen et al., 2011)*. According to the literature, the current operating conditions of domestic farming trucks are usually far away from the optimal economic region*(Costagliola et al., 2012)*, and the best application within its transmission system is not yet realized. Hence a reasonable design and application to improve a farming truck's transmissionsystem could enhance transportation efficiency and reduce the fuel consumption of these farming trucks. Based on the above, this is a valuable research subject with practical significance.

Currently, there are two research methods used in terms of simulation and optimization on vehicle power transmission system: theoretical research and method research. Theoretical research includes the optimization method as well as the application and design for a power transmission system by integrating test and optimization algorithm, among others. Meanwhile, method research includes the development and application of the transmission system simulation software, the optimization of the design of transmission strategy *(Chih-Hsien et al., 2012)*, and so on. Simulation prediction research on vehicle power performance and fuel economy had been carried out in foreign countries in the earlier 1960s. From these, related simulation programs have been developed, such as GP-SIM program developed by General Motors, the TOFEP program developed by Fort Co., and the CSVFEP program developed by Nissan Co., to name a few *(Xiaomeng and Fuqiang et al., 2012)*. With the development of computer technology and numerical computation method, the relatively mature types of software in this field include AVL-Cruise from Austria, Advanced Vehicle Simulator (ADVISOR) from the USA, etc. *(Xiaohua et al., 2008; Thomasand Talon et al., 2012)*. In China, research on this field only began in the 1980s. The main studies were carried out on subjects, such as mathematical models for vehicle power transmission systems, application of simulation software, simulation research under given operating conditions, vehicle application design under fuzzy comprehensive evaluation theoretical guidance, reliability optimization research carried out by utilizing agent model technology, and so on *(Abdel-Halim, 2013; Zulkefli et al., 2011; Schwickart et al., 2014;Anile, 2013)*.

In terms of the optimization method, a number of feasible methods have been proposed by scholars both here and abroad, including Ratnaweera, who adopted fuzzy theory as guidance for designing a transmission system parameter and solving mathematical model by particle swarm method *(Karra, 2014)*; Lu Xi, who applied the genetic algorithm *(Shamekhi et al., 2014)*, and Zaman et al. *(Zaman et al., 2011; Dunweiet al., 2010)* who employed interval optimization methods in the study of parameter optimization of transmission system.

By analyzing several studies, the research on the simulation and optimization of vehicle power transmission system has, to a certain extent, provided theoretical basis for solving problems in designing transmission parameters and their optimization. However, the abovementioned simulation software designs and the optimization methods developed are all based on a common vehicle; less attention has been given to farming trucks.Many problems in the use of farming truck still exist, especially in terms of fuel economy and power performance. By considering the above problem, and using a 5-ton farming truck, in this article, we proposed a bias transmission ratio optimization method based on the hope interval, through which we optimized the design of each level of transmission ratio of the gearbox. The findings of this research could provide reference in improving the power transmission system of a farming truck and serve as reference in finding the best application between engine and power transmission system.

MATERIAL AND METHOD

Usually, the distribution of transmission ratios for farming trucks is based on a geometric series. However, the number of teeth in the gearbox of a farming truck is a discrete variable. In relation to this, all transmission ratio levels of the gearbox are usually biased with the optimal results, thereby affecting the vehicle power transmission system design *(Osornio et al., 2013)*. In this article, we take a 5-ton farming truck as an example. Similar to what is shown in Figure 1 below, by utilizing ADVISOR, we optimized the design on transmission ratio based on the hope interval optimization method. Our aim is to improve the fuel economy and power performance of the farming truck.

Fig.1 –The 5-ton farming truck used as the test vehicle

Constructing a digital vehicle using ADVISOR

ADVISOR is a vehicle performance simulation software developed by the US National Renewable Energy Laboratory (NREL) in MATLAB and SIMULINK software environments. ADVISOR uses a graphic user interface (GUI) that allows users to conveniently modify vehicle parameters *(Markel et al., 2002)*. A quick analysis of several factors, such as the fuel economy, power performance, and so on, of a traditional car, pure electric vehicle, or hybrid vehicles can be performed by utilizing this software.

Establishment of the engine sub module

The universal characteristic curve of a farming truck shows the fuel consumption under different RPMs and load conditions, which can be expressed as the relation (1):

$$g_e = \sum_{j-0}^{s} \sum_{i=0}^{j} A\left[\frac{1}{2e}(j+1)(j+2) - j - 1 + i\right] M^i n^{j-1} \tag{1}$$

Where g_e is the engine fuel consumption rate, g/kW•h; M is engine valid torque, N•m; and n represents rotate speed, r/min.

By adopting the method of surface fitting, the parameters could be solved in this model. The established regression model is given by the relation (2):

$$\begin{bmatrix} Z_1 \\ Z_2 \\ \cdots \\ Z_n \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 & x_1^2 & x_1y_1 & y_1^2 & x_1^s & x_1^{s-1}y_1 & \cdots & y_1^s \\ 1 & x_2 & y_2 & x_2^2 & x_2y_2 & y_2^2 & x_2^s & x_2^{s-1}y_2 & \cdots & y_2^s \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & x_n & y_n & x_n^2 & x_ny_n & y_n^2 & x_n^s & x_n^{s-1}y_n & \cdots & y_n^s \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \\ \cdots \\ a_{k-1} \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \cdots \\ e_n \end{bmatrix} \tag{2}$$

where n is the number of test points, $\{a_0, \cdots, a_{k-1}\}$ is the coefficient to be determined in the model, $\{e_1, \cdots e_n\}$ is the random error, and k is the series of polynomial $(k=(s+1)(s+2)/2)$.

Expressing this in matrix form yields by the relation (3):

$$Z = G \bullet A + E \tag{3}$$

where G is $N \times k$-matrix, Z and E are all $N \times 1$ column vectors, and A is the K order vector.

By using the least squares method, the coefficient vector of regression equation can be calculated, and the regression equation of test data is obtained, which is given by the relation (4):

$$Z = \left(1,\quad x,\quad y,\quad x^2,\quad xy,\quad y^2,\quad x^3,\quad x^2y,\quad xy^2,\quad y^3,\quad \cdots \quad y^n\right) \begin{bmatrix} a_0 \\ a_1 \\ \cdots \\ a_{k-1} \end{bmatrix} \tag{4}$$

By utilizing MATLAB and the function of three-dimension curve plotting, the universal characteristic curve of the farming truck engine is obtained, similar to what is shown in Figure 2 below.

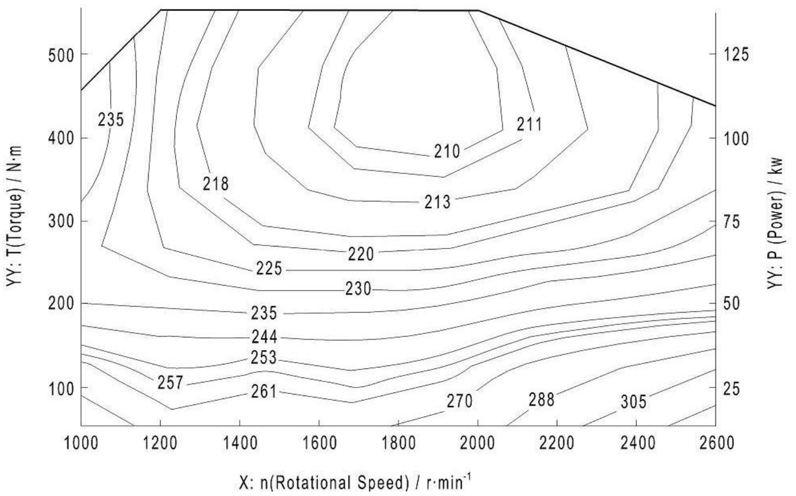

Fig.2 -The universal characteristic of the 5-ton farming truck engine

The program image2map.m in ADVISOR can scan and transfer the universal characteristic curve to the corresponding data file. A new engine model is constructed by scanning the farming truck engine's universal characteristic curve and embedding the data file into the engine database.

Establishment of the transmission system modules

According to the universal characteristic curve of the test vehicle, we can confirm that the transmission ratio of the main reducer is 5.3, the maximum transmission ratio of the gearbox is 6.515, and the minimum transmission ratio of the gearbox is 1.00. We employed a 5-speed gearbox and designed the transmission ratio of each gear according to geometric series. The transmission ratios from the 1st to 5th gears are 6.515, 4.096, 2.56, 1.6, and 1.00, respectively. We digitized the 5-speed gearbox of the farming truck and embedded it into the transmission sub module of ADVISOR. The main instructions are given by:

Gb-ratio=[6.515 4.096 2.56 1.6 1.00]*5.3,

where 5.3 is the transmission ratio of the main reducing gear, and the data in the bracket are the transmission ratios from the 1st to 5th gears, respectively.

Selection of driving cycles

As shown in Figure 3 below, the CYC-NYTRUCK operating condition in ADVISOR is selected to simulate the fuel consumption of the 5-ton farming truck.

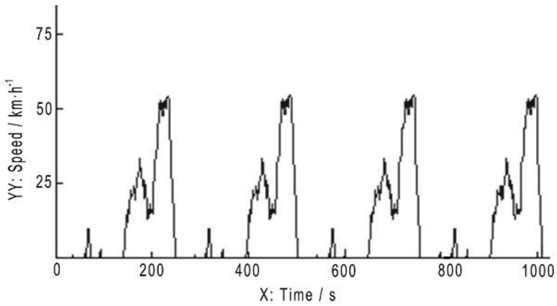

Fig.3 -CYC-NYTRUCK operating condition

Farming trucks usually run in a slow speed; hence, the economic fuel consumption under low speed is required. The condition of the CYC-NYTRUCK has the highest speed of 54.72 km/h and the average speed of 12.16 km/h. In designing the transmission ratios of all the gears for the original gearbox under geometric series, we assume that the probability of use of all gears is equal. However, when the farming truck is driving under CYC-NYTRUCK, it is obvious that the probability of use under the low speed block is higher. In order to adapt to the farming truck that operates under low speed block most of the time, we must reduce low-grade spacing by changing the design of the gear transmission ratios from the original geometric series to the bias geometric series. Here, we take the relation (5) as the applicable design.

$$\frac{i_{gk}}{i_{gk+1}} < \frac{i_{gk+1}}{i_{gk+2}} \tag{5}$$

where i_{gk} ,i_{gk+1}, and i_{gk+2} are the transmission ratios of the three adjacent gears, respectively.

Construction of the optimized objective function

Once the engine model of the farming truck is constructed, we can now utilize ADVISOR to optimize the transmission ratio of each gear in the farming truck gearbox via interval optimization method.

Objective function

For every set of vehicle transmission ratios, we can calculate the fuel consumption under the designated operating condition by using ADVISOR. The aim of optimization is to determine the best fuel economy. Selecting the cycle operating condition in Figure 3 to work out the fuel economy, we arrive at the relation (6):

$$\min\ f(X) = com\_FE \tag{6}$$

where com_FE refers to the fuel consumption calculated under CYC-NYTRUCK operating condition, L/h, where the relation (6) is the objective function.

Optimization variable

The original transmission ratio of the selected farming truck is designed under geometric series, and the resulting transmission ratios from the 1st to 5th gears are i_{g1}=6.515, i_{g2}=4.096, i_{g3}=2.56，i_{g4}=1.60, and i_{g5}=1.00, respectively. In order to ensure that the climbing performance and the maximum speed are unchanged, we use the bias optimization method to obtain the 2nd, 3rd, and 4th gear transmission ratios with the ig5=1.00 and ig1=6.515 unchanged. From this, the optimization variables can be obtained using,, which is given by the relation (7):

$$X = [i_2, \quad i_3, \quad i_4]^T = [x_{i2}, x_{i3}, x_{i4}]^T \tag{7}$$

where x_{i2}, x_{i3}, and x_{i4} are the bias amounts, respectively.

Constraint condition

The farming truck transmission system parameters that have been optimized should meet the requirements on fuel economy and power performance. Hence, fuel economy should be the target of optimization and accelerating time (an important evaluation index for vehicle power performance) is taken as the constraint condition, and its constraint function *(Jimin et al., 2012)* is given by the relation (8):

$$t \leqslant 12.2 \tag{8}$$

where *t* is the accelerating time from 0 km/h to 80 km/h.

RESULTS

Implementation of interval bias optimization method

After analyzing the parameters of farming truck and the application under the CYC-NYTRUCK operating condition, the transmission ratio of the gearbox is offset to the low speed direction, which is beneficial to the fuel economy. Owing to the difficulty of judging the optimized bias variable, the transmission ratio that is originally distributed based on geometric series must be redesigned. We calculated 10 sets of transmission ratios, whose bias amounts are within 5% to 50%; the bias increase amount corresponding to each set of transmission ratio is at 5%. Based on ADVISOR, we could simulate and calculate the fuel consumption corresponding to each set of transmission ratio after the bias is set. The results are shown in Table 1 below.

Table 1

Fuel consumption of the farming truck with the bias of transmission ratio

No.	Fuel Consumption (L/100 km)	Bias	x_{i2}	x_{i3}	x_{i4}
1	54.6	5%	4.217	2.637	1.648
2	54.1	10%	4.338	2.714	1.696
3	54.0	15%	4.459	2.791	1.744
4	54.1	20%	4.58	2.868	1.792
5	54.2	25%	4.701	2.945	1.84
6	54.0	30%	4.822	3.022	1.888
7	53.8	35%	4.943	3.099	1.936
8	53.9	40%	5.064	3.176	1.984
9	54.4	45%	5.185	3.253	2.032
10	54.5	50%	5.306	3.33	2.08

Using the second-order polynomial to fit the results, we achieved the diagram of fuel consumption in relation to bias transmission ratio, as shown in Figure 4 below.

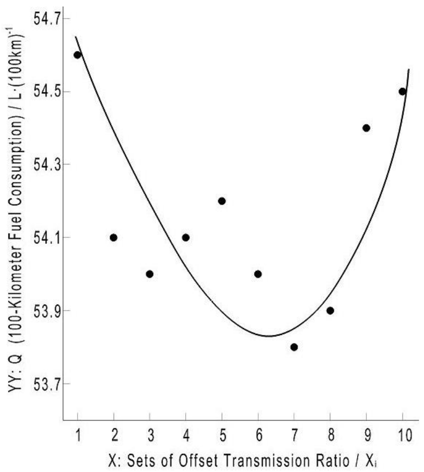

Fig.4 -Fuel consumption fitted by second-order polynomial

By analyzing Table 1 and Figure 4, we conclude that the fuel consumption between set 6 and set 8 has the minimum value, which is between 53.9 L/100 km to 54.0 L/100 km. Then, the bias amount for set 6 transmission ratio is 30%, whereas that for set 8 is 40%. We conclude that the bias amount range of 30% to 40% is a low fuel consumption range. Hence, this interval is the hope interval where we can locate the optimized transmission ratio. Given that the bias amount assigned must be recalculated, we thus calculated 10 sets of transmission ratios whose bias amounts are within 31% to 40%. Here, the bias increase amount corresponding to each set of transmission ratio is at 1%. Based on ADVISOR, we could simulate and calculate the fuel consumption corresponding to each set of transmission ratio after the reset bias. The results are shown in Table 2 below.

Table 2

Fuel consumption calculated under totally biased transmission ratio within the hope interval

No.	Fuel Consumption (L/100 km)	Bias	x_{i2}	x_{i3}	x_{i4}
1	54.0	31%	4.846	3.037	1.898
2	54.0	32%	4.870	3.053	1.907
3	53.95	33%	4.895	3.068	1.917
4	53.8	34%	4.919	3.084	1.926
5	53.75	35%	4.943	3.099	1.936
6	53.75	36%	4.967	3.114	1.946
7	53.7	37%	4.991	3.130	1.955
8	53.75	38%	5.016	3.145	1.965
9	53.75	39%	5.040	3.161	1.974
10	54.1	40%	5.064	3.176	1.948

Using the second-order polynomial to fit the results, we achieved the curve shown in Figure 5 below.

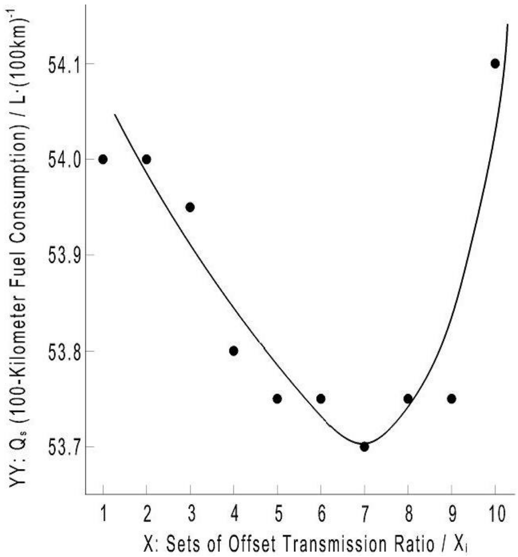

Fig.5 - Fuel Consumption fitted by second-order polynomial in hope interval

By analyzing Table 2 and Figure 5, we conclude that the fuel consumption between set 7 and set 8 is the minimum value, which is between 53.7 L/100 km to 53.75 L/100 km. The bias amount for set 7 transmission ratio is 35%, whereas that for set 8 is 40%. We further conclude that there exists a low fuel consumption range within the bias amount of 35% to 40%. Locating the minimum fuel consumption point in Figure 5, when the bias amount of transmission ratio is 36.5%, the farming truck consumes the minimum fuel. Then, we round-off the number for bias amount. When the bias amount of transmission ratio is at 36%, the transmission ratios calculated for the corresponding 5 gears are i_{g1}=6.515, i_{g2}=4.97, i_{g3}=3.11, i_{g4}=1.95, and i_{g5}=1.00, respectively. These are the transmission ratios of the gearbox at the minimum fuel consumption value.

Analysis of the optimization result

Once the optimal transmission ratios for all gears of the gearbox of the farming truck are obtained, we use ADVISOR to calculate the respective fuel consumption rates and power performances of the test farming truck before and after the optimization. The calculation results are shown in Table 3 below.

Table 3

Comparison of power performance, fuel consumption, and all transmission ratios of the farming truck before and after optimization

Item	Before Optimization	After Optimization	Rate of Change
i_{g1}	6.515	6.515	—
i_{g2}	3.976	4.97	—
i_{g3}	2.284	3.11	—
i_{g4}	1.428	1.95	—
i_{g5}	1.00	1.00	—
Fuel Consumption Qs （L/100 km）	55.1	53.9	-2.18%
0 km/h to 80 km/h Accelerating time (s)	12.2	12.1	-0.82%

By comparing the results shown in Table 3, we can see that there is a large discrepancy between the original scheme and the optimized scheme. After the optimization, the fuel consumption per 100 km is reduced from 55.1 L/100 km to 53.9 L/100 km; the accelerating time within 0 km/h to 80 km/h is also reduced from 12.2 s to 12.1 s. Transmission ratio is thus improved in the optimized scheme compared with the original scheme; furthermore, the fuel economy and power performance are also greatly improved.

CONCLUSIONS

For the reason that farming truck engine operating conditions are far from the optimal economic regions, in this article, we selected a 5-ton farming truck as research subject. We adopted the optimization method based on hope interval. We also performed optimization analysis of all the transmission ratios of the farming truck gearbox. The main conclusions are stated below.

(1) By analyzing the design method of traditional farming truck transmission and its operating conditions, we have concluded that distributing each gear’s transmission ratios based on geometric series is unreasonable. We proposed an optimization method of bias transmission ratio based on hope interval and find that this method is reasonable and feasible in actual conditions.

(2) We chose the fuel consumption of farming truck under CYC-NYTRUCK as the objective function. Then, we took the transmission ratios of the 2nd, 3rd, and 4th gears as design variables and considered the accelerating time within 0 km/h to 80 km/h as constraint condition. We optimized the objective function based on ADVISOR. The transmission ratios corresponding to the minimum fuel consumption obtained are as follows: keeping the 1st and 5th gears constant, the transmission ratios of the 2nd, 3rd, and 4th gears are adjusted to 4.97, 3.11, and 1.95, respectively. From the optimization result, we observe the accuracy of the optimized model as well as the feasibility of the proposed optimization method.

(3) By comparing the fuel economy and power performance of the farming truck before and after optimization, we have found that the fuel consumption for 100 km is reduced by 2.18%, and accelerating time from 0 km/h to 80 km/h is reduced by 0.82%. Thus, the optimization method of bias transmission ratio based on hope interval has a significant effect on improving vehicle fuel economy and power performance. This finding can be used as a reference in improving the power transmission system of a farming truck and the reasonable application between the engine and power transmission system.

Combining the requirements on fuel economy and power performance, we studied the optimization of all the transmission ratios of a farming truck gearbox, through which some beneficial conclusions are obtained. Nevertheless, owing to the complexity of a vehicle power transmission system, several issues still need further research, including the simulation of real operating conditions by selecting more accurate mathematical modeling, the comprehensive evaluation of the power transmission system of farming truck with the combination of emission performance, and the establishment of an expert database on vehicle performance simulation, to name a few.

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