

Optimization Matching of Powertrain System for Self-Dumping Truck Based on Grey Relational Analysis

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ABSTRACT

In this paper, the performance simulation model of a domestic self-dumping truck was established using AVL-Cruise software. Then its accuracy was checked by the power performance and fuel economy tests which were conducted on the proving ground. The power performance of the self-dumping truck was evaluated through standing start acceleration time from 0 to 70km/h, overtaking acceleration time from 60 to 70km/h, maximum speed and maximum gradeability, while the composite fuel consumption per hundred kilometers was taken as an evaluation index of fuel economy. A L_9 orthogonal array was applied to investigate the effect of three matching factors including engine, transmission and final drive, which were considered at three levels, on the power performance and fuel economy of the self-dumping truck. Furthermore, the grey relational grade was proposed to assess the multiple performance responses according to the grey relational analysis. In this process, the principal component analysis was employed to determine the corresponding weights of the five indicators. Then the optimal combination of the engine, transmission and final drive was determined according to the Taguchi methodology. Finally, a confirmation test was conducted to verify the optimal matching factors obtained by the proposed approach. The results indicated that the fuel economy of the improved self-dumping truck has been improved prominently, whilst its power performance completely satisfies the engineering design requirement. Hence, the optimization method based on the Taguchi method and grey relational analysis is an effective approach for the optimization matching of the powertrain system.

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INTRODUCTION

With increasing fuel price, the cost of fuel for commercial trucks has been taken up a great proposition in the total vehicle operating costs. The annual costs of the commercial vehicles can be reduced significantly by a small reduction of fuel consumption on account of the high mileage of these kind vehicles. Since the past several decades, many methods have been proposed to improve the fuel economy of vehicles, through modifying the vehicle or manipulating driving patterns [1,2,3]. These methods are all performed by combining numerical simulation with actual testing, for reducing development and operational cost and time. LaClair, et al. [4] evaluated the impact of tire rolling resistance on vehicle fuel consumption, which was conducted by a physics-based model of a heavy-duty truck developed using the commercially-available software AVL-Crusie. Wang, et al. [5] investigated the factors affecting the city buses' fuel economy by the simulation model of a city bus based on the actual urban driving cycle. Ren, et al. [6] optimized the transmission ratio and some structural parameters of the automatic mechanical transmission in hybrid electric city bus for improving vehicle performance. Yang, et al. [7] developed a fuel consumption model for transit buses based on bus driving operation measurements.

In the complexly competitive scenario of commercial vehicle manufacturing, a main approach for improving fuel economy is reasonable match and optimum design of the powertrain system,

consisting of engine, transmission, final drive etc. On the other hand, the power performance is direct influenced by the powertrain system. Besides the good fuel economy, a good power performance for the self-dumping trucks is also important for carrying amounts of goods. Therefore, the fuel economy and power performance should be considered simultaneously in the process of optimization matching for powertrain system of self-dumping trucks. However, the requirements of powertrain system parameters for improving the fuel economy and power performance are usually in conflict with each other. Hence, a multi-criteria decision making method needs to be employed to address this problem.

Grey relational analysis (GRA) method, which was first developed by Prof. Deng, can be used to analyze the complicated interrelationship among the designated performance characteristics with a grey relational grade [8,9]. This approach provides an efficient solution to deal with the problems with incomplete, poor and uncertain information [10]. The GRA method has been applied to solve the multi-attribute optimization problems in a significant account of fields. Zheng, et al. [11] applied improved grey relational projection method to evaluate sustainable building envelop. Wang et al. [12] introduced a new hybrid method using design of experiment and grey relational analysis to solve multiple criteria decision making problems. Chen et al. [13] optimized the vehicle ride comfort and

$$F_c = \sum_{i=1}^n c_i \cdot F_i \quad (1)$$

where F_c is the composite fuel consumption; c_i represents the weight of constant speed fuel consumption; F_i is the constant speed fuel consumption.

Table 2 shows the weight of each constant speed fuel consumption. According to Equation (1), the composite fuel consumptions for simulation and test results were obtained and tabulated in Table 3. It is clear that the simulation result is close to the testing value with a relative error of 0.3%. This reveals that the simulation model is accurate enough for the fuel economy simulation.

Table 2. Weight of each constant speed fuel consumption

Speed (km/h)	30	40	50	60	70
Gear	8	9	9	9	9
Weight	0.05	0.10	0.25	0.30	0.30

Table 3. Comparison for simulation and test result of composite fuel consumption

Simulation (L/100km)	Test (L/100km)	Relative error (%)
28.2	27.9	0.9

In addition, the acceleration simulations, consisting of standing start acceleration from 0 to 70km/h and overtaking acceleration from 60 to 70km/h, are carried out at the same time. Then the comparison of power performance simulation and testing results was illustrated in Table 4. From this table, a good agreement is shown by comparing simulation with test results. This indicates that the simulation model has a better accuracy and can be used for power performance simulation.

Table 4. Results of power performance simulation and testing

Acceleration time	Simulation (s)	Test (s)	Relative error (%)
0-70km/h	39.65	39.97	-0.8
60-70km/h	8.89	8.36	6.3

DESIGN OF EXPERIMENTS

Matching Factors

There are many design factors affecting the fuel economy and power performance. Among the many factors, the engine, transmission and final drive are considered to be the most important ones here. Therefore, three engines, three transmissions and three final drives were taken as the alternatives. These components are in the same type but have different performance parameters. They can be assembled together in the self-dumping truck without changing the vehicle component layout. The three defined matching factors including

engine, transmission and final drive, and their performance parameters of different level were tabulated in Table 5, Table 6 and Table 7.

Table 5. Engine and its levels

Engine	E1 (Initial)	E2	E3
Number of cylinders	6	6	6
Engine displacement (L)	8.82	9.726	8.27
Maximum output power (kW)	215	247	177
Rated speed (RPM)	2200	1900	2200

Table 6. Transmission and its levels

Gear	T1 (Initial)	T2	T3
1	12.11	12.57	11.02
2	8.08	8.39	6.55
3	5.93	6.15	4.64
4	4.42	4.59	3.36
5	3.36	3.40	2.71
6	2.41	2.47	1.95
7	1.76	1.81	1.38
8	1.32	1.35	1.00
9	1.00	1.00	0.81

Table 7. Final drive and its levels

Final drive	D1 (Initial)	D2	D3
Final drive ratio	5.73	6.72	4.42

Fuel Economy and Power Performance Evaluation Indexes

In the present study, the fuel consumption and power performance simulations were carried out according to China National Standards GB/T27840-2011 and GB/T 12543-2009. Meanwhile, the power performance of the self-dumping truck was evaluated through standing start acceleration time from 0 to 70km/h, overtaking acceleration time from 60 to 70km/h, maximum speed and maximum gradeability, denoted as t_{0-70} , t_{60-70} , $V_{\max}$ and θ , respectively, while the composite fuel consumption per hundred kilometers, represented as F_c , was taken as an evaluation index of fuel economy.

Design of Experiments and Experimental Results

Taguchi's design of experiment (DoE) uses specially constructed tables named as "Taguchi orthogonal array" to design the experiments. This method can be used to investigate the whole parameter space with only a small number of experiments. In this study, a L_9 orthogonal array was applied to study the effect of