



# Article Optimization of Miller Cycle, EGR, and VNT on Performance and NOx Emission of a Diesel Engine for Range Extender at High Altitude

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**Abstract:** Due to the increasing sales of extended-range hybrid vehicles and the increasingly stringent emission regulations for light vehicles in China, the performance and emission of diesel engines for range extenders in the plateau region have attracted increasing attention. In order to obtain the superior performance of diesel engines for range extenders operating at high altitudes, a multi-objective optimization of the optimal economic operating point of the diesel engine was performed at an altitude of 1960 m. A diesel engine system model with MC-EGR-VNT (MEV) technology was developed using GT-Power based on the data of the engine bench to analyze the effects of the Miller cycle (MC), exhaust gas recirculation (EGR), and variable nozzle turbine (VNT) technologies on the power, economy, and emission performance of high-speed diesel engines. The response surface method (RSM) design was carried out with the Miller cycle rate (MCR), EGR value opening, VNT nozzle opening as variable factors and torque, brake-specific fuel consumption (BFSC), nitrogen oxide (NOx) emission as optimization objectives based on Box Behnken Design (BBD). The optimization results showed that the torque and BFSC remained almost constant, and NOx emission decreased by 59.5% compared with the original machine. The proposed multi-objective optimization method could make the diesel engine with a MEV system achieve a good comprehensive performance.

Keywords: MEV; RSM; optimization; diesel engine; range extender; high altitude

# 1. Introduction

Energy conservation and emission reduction is an urgent topic for countries all over the world. China is committed to expanding the country's independent contribution by adopting more effective policies and measures. The goal is to reach the peak of carbon dioxide emission by 2030 and achieve carbon neutrality by 2060. In 2016, the transportation sector accounted for 18% of global carbon dioxide emission into the atmosphere, and this proportion is rising every year [1]. The depletion of conventional energy sources and increasingly stringent emission regulations are forcing internal combustion engines to move toward lower pollution, lower fuel consumption, and higher specific power.

The extended-range hybrid electric vehicle has been widely studied for its special advantages in energy saving and emission reduction [2]. Compared with gasoline engines for range extenders, the diesel engines are typically more efficient, have more torque, and are more durable, which has led to the increased use of diesel engines in medium and large extended-range hybrid passenger cars [3,4]. At high altitudes, low atmospheric environmental pressure has caused many adverse effects on diesel engines, such as a decrease of the dynamic performance and reliability, increase of fuel consumption, and NOx emission [5]. In China, about 26% of the territory is above 1000 m above the sea level, and more than



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**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). 15 million vehicles operate within these high-altitude areas [6]. In Europe, about 19.1% of the population lives above 1000 m above the sea level, and nearly 100 million people live in high-altitude conditions [7]. In Latin America, most large cities are located at high altitudes (>2000 m) [8]. Therefore, improving the performance of high-speed diesel engines for range extenders at high altitudes has attracted the attention of more and more researchers.

The power performance, fuel economy performance, and emission performance of high-speed diesel engines mainly depend on the combustion effect in the cylinder. The valve train and fuel supply system are two main factors that affect the combustion in the cylinder of a diesel engine. High-pressure common rail technology is gradually maturing, as there is not enough technology with which space can be explored. The valve train of a traditional diesel engine with a diesel cycle can no longer meet the increasingly stringent emission limit requirements. The Miller cycle has attracted the attention of diesel engine manufacturers and scientific research institutions due to its unique intake and exhaust form.

MC is a low-temperature combustion technology of an internal combustion engine that realizes an expansion ratio greater than the compression ratio by adjusting the valve to close early or late [9], which can greatly reduce NOx generation and has a high effective thermal efficiency and fuel-saving effect [10]. Zhao et al. [11] verified that the power performance and thermal efficiency of the Miller cycle engine are superior to the Otto cycle and Atkinson cycle. Al-Sarkhi et al. [12–14] showed that an accurate model analysis is particularly important to accurately predict the cycle performance and can be used as a reference for the actual MC engine design. Ebrahimi et al. [15,16] analyzed the relationship between the MC engine performance and compression ratio, air-fuel ratio, and stroke length based on the finite time thermodynamic method. Wei et al. [17] applied the MC of early inlet valve closure (EIVC) to medium-speed marine diesel engines to achieve efficient combustion and low NOx emission. Their results revealed that proper EIVC can reduce pressure, temperature, and NOx emission. At 50% and 25% loads, the emission of NOx decreased by 17.8% and 14.9%, respectively, compared with the base engine. The relevant research reports on the joint application of MC and cutting-edge electronic control technologies are gradually increasing. The main research objects of MC are extended from the initial marine medium and low-speed diesel engines to the vehicle high-speed diesel engines. The main research methods are extended from the initial simulation research to the simulation combined with test verification. The research focus is extended from the initial MC technology to the coordinated control of MC combined with turbocharging technology, EGR technology, or VNT technology.

With the development of turbocharging technology and electronic control technology, the disadvantage of a MC diesel engine with a large intake loss under high-speed or heavy duty conditions has been improved. The application of MC technology is transferred from medium and low-speed diesel engines to high-speed diesel engines, which makes the combined application of MC-EGR possible. Cui et al. [18] adopted the coupling optimization of MC and adjustable two-stage marine turbocharging system to reduce the NOx emission of marine diesel engines by 30% and improve the fuel economy. Wang et al. [19] built a predictive one-dimensional numerical model to study the effect of the Miller cycle based on the coupling relationship between a marine low-speed two-stroke engine and proposed the demand of the Miller cycle for a turbocharger and relevant guidance for a turbocharger rematch based on the thermodynamic analysis. Wu et al. [20] used the coordinated control of MC and VNT to give the diesel engine both faster dynamic response characteristics of torque and to ensure a 10% reduction in the peak NOx emission, with a slight increase in soot emission.

EGR can effectively regulate NOx emission, but its limitations become significant when the engine is operated under high load conditions. In addition, with the increase of the load at high altitude areas, the smoke intensity changes greatly with the EGR rate [21]. A larger EGR rate leads to low combustion efficiency and poor combustion effectiveness, which, in turn, leads to poor power and economy [22]. However, combining EGR with another technology, such as intake air humidification or MC, has considerable potential to solve these problems and reduce NOx emission. Therefore, combining MC technology with EGR technology is an effective way to further reduce NOx emission and improve the power and economy of diesel engines at high altitudes [23].

Yan et al. [24,25] proposed a joint optimization method of the EGR rate and MCR to improve the fuel economy and NOx reduction of low and medium-speed diesel engines, proving the necessity of the joint use of MC and EGR technologies. Wang et al. [26] conducted an experimental study on the effect of MC combined with EGR on the performance of adjustable two-stage turbocharged diesel engines. Their results showed that the combination of the medium MCR and medium EGR rate not only reduced NOx emission but also significantly improved the fuel economy and power performance compared with the use of a high EGR rate alone. Millo [27] evaluated the effect of EGR combined with MC technology on medium-speed marine engines and found that the fuel consumption increased slightly and NOx emission decreased by 90% compared with the original engine. In order to evaluate the potential and limits of MC-EGR technology, Rinaldini et al. [28] optimized the MC high-speed diesel engine with EGR by conducting experimental studies and a simulation analysis. The results of the study showed that the fuel economy, NOx, and soot emission decreased by 2%, 25%, and 60%, respectively, compared with the original engine at part-load and full-load operating conditions and indicated that the application of MC in high-speed diesel engines is feasible and promising.

The coordinated application of MC, EGR with turbocharging, and low-temperature combustion technology is the mainstream technology research direction for diesel engines under the stage VI emission limit for passenger cars in China [29–31]. However, there are still some problems in the engineering application of MC in high-speed diesel engines. The low intake volume of high-speed light duty diesel engines leads to larger intake throttle losses at low speeds or under heavy load conditions, which, in turn, makes it more likely to result in an insufficient air-fuel ratio. In high altitude areas, the MC diesel engine has to face the problems of difficult control of the EGR rate and slow response speed of EGR after introducing EGR technology. Therefore, the introduction of more efficient intake intercooling technology, real-time and variable MCR valve actuation technology, and efficient boosting technology (multi-stage boosting technology and VNT technology) has gradually become a more ideal solution to solve the intake and exhaust backlash of high-speed MC diesel engines and broaden the scope of EGR applications [32–34]. VNT technology can adjust the nozzle ring cross-sectional area of the turbine to enable the turbocharger to respond quickly to higher boost pressure demands at lower engine speeds [35], which can effectively solve the above problems. However, the strong coupling between EGR and VNT increases the difficulty in system control, and the coupling control of VNT-EGR attracts more and more attention.

The research on the combined application of VNT-EGR has focused on the transient response and emission control strategies under transient operating conditions. Wang et al. [36] designed a dual-input and dual-output control system for VNT and EGR using the quantitative feedback theory, which can make the boost pressure of the diesel engine better transiently following the performance under most working conditions, and the EGR valve does better following the performance during the idling and transient processes. Oh et al. [37] investigated the mechanism of VNT and EGR working together based on a neural network algorithm for indirect adaptive control. Their results showed that the EGR has better followability of the target values and control environment adaptation under transient operating conditions compared with the original diesel engine. It is difficult to realize and improve the EGR rate of ordinary turbocharged and intercooled diesel engines because of the deficit between intake and exhaust at low-speed or high-load conditions. The problem of intake and exhaust reversal is more prominent when the diesel engine is operated at high altitudes. As the altitude increases, the efficiency of the turbocharger compressor decreases, and the stable working range narrows, leading to surge in advance and difficulty in adjusting the optimal air-fuel ratio, which, in turn, leads to problems such as the rising exhaust temperature, large fluctuations in the EGR rate, and slow EGR response [38]. MC-EGR technology can further improve the diesel engine emission performance and reduce the difficulty of MAP widening of the EGR rate. The coordinated control of MC and VNT can further enhance the advantages of MC technology and improve the power response characteristics of high-speed diesel engines. The coupled control of EGR and VNT allows the MC diesel engine to further reduce the NOx emission and improve the response characteristics of the power and EGR [39,40].

However, the EGR flow and turbine blades are driven by exhaust energy. When the EGR valve opening is constant, a change in the nozzle ring opening of the VNT will cause a change in the exhaust pressure and intake pressure, which, in turn, will cause a change in the EGR flow. When the VNT nozzle ring opening is constant, a change in the EGR valve opening will cause a change in the exhaust pressure, which, in turn, will also cause a change in the boost pressure. As the MCR changes, the air-fuel ratio and combustion conditions of the engine will also change, which, in turn, will cause changes in the intake and exhaust pressures. Therefore, the air system by MEV coordinated control is a complex control system with multiple inputs and outputs, and there is a tightly coupled relationship between the inputs and outputs. Moreover, there is a clear complementary relationship of the technical advantages between the MC, EGR, and VNT. Tang et al. [41] carried out a collaborative optimization study of EGR and a MC coupled turbocharging system on a marine diesel engine based on particle swarm optimization. Their method achieved NOx and BSFC optimization under full loads. At present, there are few domestic and international studies on the relationship between the coupling of MC, EGR, and VNT technologies on high-speed diesel engine performance and emission performance published in the literature.

In summary, the study of the MEV coupling relationship is essential to improve the operating performance and emission characteristics of diesel engines for range extenders at high altitudes. In this project, the influence characteristics of the MC, EGR, and VNT as single factors on the engine torque, BFSC, and NOx emission, respectively, at 1960 m when the diesel engine is at the optimum economic operating point are analyzed. The intrinsic law of the interaction of the factors in the coupled control process of the MEV system was investigated. The above study can provide some guidelines for achieving the improved EGR response and power response of diesel engines, as well as obtaining the best air–fuel ratio, and can provide a reference for the development of MEV coordinated control strategy and the calibration of MEV system parameters.

## 2. Research Methodology

## 2.1. Research Process

Figure 1 depicts the research process of this study. According to the engine parameters, the engine model was established with GT-Power software, and the influence of the MCR, EGR value opening, and VNT nozzle opening as separate factors on the torque, BFSC, and NOx emissions was simulated and analyzed. Based on the simulation results of the engine model, the BBD experiment design of the corresponding surface was carried out, and the influence of MEV coupling on the torque, BFSC, and NOx emissions was analyzed. Based on the results of the response surface analysis, the MEV coupling effect was optimized with the optimization tool of Design Expert software, and the optimization results were compared with the original data. The optimization results were input into the engine simulation model for the simulation analysis, and the simulation results were further compared with the optimization results.



Figure 1. Research process.

## 2.2. Determine the Miller Cycle Form

The project adopts the D19 high-pressure common rail diesel engine as the prototype, which is equipped with VNT technology and a high-pressure EGR system. Table 1 shows the relevant important technical parameters.

#### Table 1. Engine specifications.

Parameter Description	Details		
Engine type	Four-stroke, in-line four cylinders, direct injection		
Air intake system	Turbocharged, inter-cooled		
Bore $\times$ Stroke	$80 \text{ mm} \times 92 \text{ mm}$		
Displacement	1.85 L		
Compression ratio	18.5:1		
Turbocharger	Honeywell GT C1446VZ		
Rated power	82 kW at 4000 r/min		
Peak torque	265 N. m at 2200 r/min		
Injection system	Bosch common-rail system CRS2-16		
Peak injection pressure	160 MPa		
PCP	≤16.5 MPa		
Maximum EMGT	≤780 °C		

According to the structural parameters of the engine, a one-dimensional simulation model of the diesel engine was established by GT-Power software, as shown in Figure 2. The simulation model includes an environment module, intake and exhaust pipe module, injector model, Woschni-GT heat transfer model, Chen Flynn friction model, compressor and turbine model, etc. The high-pressure EGR system takes air from the exhaust manifold, flows into the intake manifold through the EGR valve and EGR cooler, mixes with fresh air, and then enters the cylinder for combustion. The MAP data of the compressor and variable nozzle turbine are input from the data provided by the turbocharger manufacturer. The extended Zeldovich mechanism is used to predict NOx generation. The inlet valve lift curves with different MCRs are constructed as input to simulate the influence of different MCRs on the diesel engine performance and NOx generation. This project analyzed two MC methods: early intake valve closing (EIVC) and later intake valve closing (LIVC). The intake duration and the closing time of the intake valve were adjusted while keeping the maximum lift of the intake valve unchanged.

Figure 3 depicts the intake valve lift curves of the original engine and the improved Miller cycle engine. As shown in the figure, the intake valve closing angle of the original engine is 592 °CA, and the MCR corresponding to the intake valve closing timing is 0 °CA (M0). Through an independent valve panel to accurately control the inlet valve closing time and a series of calculations, the ranges of the intake valve delayed closing angle and intake valve advance closing angle were determined to be 0–60 °CA (M0–M60) and -60-0 °CA (M-60–M0), respectively. The closing time of the intake valve was simulated for each delay or advance of 10 °CA.



Figure 2. Engine model.



Figure 3. Improved intake valve lift curve of the diesel engine.

Figure 4 shows the influence of MCR on the diesel torque, BFSC, and NOx under different loads. When the load was constant, with the increase of the MCR, the torque remained unchanged, the BFSC increased slightly, and the NOx decreased significantly. When the MCR was fixed, the torque and NOx emission increased, and the BFSC decreased with the increase of the engine load. In EIVC mode, the torque and BFSC of the diesel engine remained unchanged, and the NOx decreased obviously with the increase of the MCR in the range of -200 °CA. On the contrary, in LIVC mode, the torque and NOx decreased significantly, while the BFSC remained unchanged with the increase of the MCR. Since the engine for a range extender often operates in the economic zone, the best economic engine operating point (2200 r/min, 100% load) was selected for this project. Therefore, for the high-speed light duty diesel engine D19, the Miller cycle in EIVC mode was selected, and the MCR value in EIVC mode was taken as a positive value.



Figure 4. Effect of MCR on the diesel engine torque, BFSC, and NOx under different loads.

## 2.3. Modelling Verification with Engine Test Data

The schematic diagram of the experimental device is shown in Figure 5. The main instruments and equipment used in the test include the dynamometer, measurement and control system, cooling water constant temperature system, fuel constant temperature device, oil constant temperature device, electronic control calibration system, cylinder pressure acquisition system and analysis software, emission measurement system, atmospheric pressure simulation device, etc.



Figure 5. Schematic diagram of the experimental setup.

A hydrodynamic dynamometer WE31N (Yike, Hangzhou, China) was connected to the engine to measure the engine torque. The engine speed (r/min) was measured with a magnetoelectric sensor. The fuel mass flow was measured using a fuel consumption meter FCMA (Yike, Hangzhou, China). The air mass flow was measured using a laminar flow meter LFE300 (Toceil, Shanghai, China). The inlet air charge was cooled with controlled flow water with the temperature stabilized at  $40 \pm 3$  °C. The coolant and lubricant temperatures at the engine inlet were controlled by a dedicated thermostatic circuit, and they were stabilized at  $80 \pm 5$  °C and  $95 \pm 5$  °C, respectively.

A comparison of the simulation calculation and test results of the torque, BFSC, intake mass flow, and turbine inlet temperature for the original engine external characteristic conditions at 1960 m altitude is shown in Figure 6. At the optimal economic operating point (2200 r/min, 100% load), the simulated trends of the engine torque, BFSC, intake mass flow, and turbine inlet temperature were generally consistent with those of the experimental data. The average errors between the simulated and experimental results were within 5%, indicating that the accuracy of the model could meet the calculation requirements.



Figure 6. Comparison between the simulation results and test results at 2200 r/min, 100% load.

## 3. Results and Discussion

# 3.1. Single Factor Analysis

The torque and BSFC are important performance indexes of the diesel engine for the range extender. When the engine is running at the optimal economic operating point, the mixture in the cylinder burns more completely, and the soot emission is less at this time, so  $NO_x$  emission is the main emission indicator concerned. Therefore, the influence of the MCR, EGR value opening, and VNT nozzle opening on the torque, BSFC, and  $NO_x$  emission at the optimal economic operating point of the diesel engine at the altitude of 1960 m was studied.

#### 3.1.1. Influence of MCR on Torque, BFSC, and NOx Emission

Figure 7 depicts the impact of different MCRs on the engine performance and emission when the engine was operating at the optimal economic operating point. It could be seen from Figure 7a–c that, when the MCR was between 0 °CA and 20 °CA, while the increase of the MCR, torque, and BFSC remained unchanged and NO<sub>x</sub> emission decreased slowly. However, when the MCR was in the range of 20~60 °CA, the torque, BFSC, and NO<sub>x</sub>

emission changed significantly with the increase of the MCR. When the MCR was 60 °CA, the torque and  $NO_x$  emission were decreased by 2.6% and 58.5%, respectively, and the BFSC was increased by 2.7%.



Figure 7. Effects of the MCR on the performance and emission of a diesel engine.

Compared with the closing time of the original intake valve, the intake valve of the MC diesel engine in EIVC mode is closed in advance during the compression stroke or the intake stroke, which will cause the intake air in the cylinder to be insufficient and then lead to the reduction of air–fuel ratio. It could be seen from Figure 7d,e that, when the MCR was in the interval of 0–20 °CA, the intake flow decreased with the increase of the MCR. The intake flow rate and air–fuel ratio were reduced by 4.5% and 4.6%, respectively, due to the early closing of the throttle. It could be seen that the intake of the high-speed diesel engine at 100% load was sufficient, and a small change in the air–fuel ratio had almost no effect on the combustion effect in the cylinder, while the torque and BFSC remained unchanged. On the contrary, when the MCR is in the range of 20–60 °CA, with the increase of the MCR, the air–fuel ratio decreased significantly, resulting in the worse combustion effect in the cylinder, and then, the maximum burst pressure decreased, the torque decreased significantly (Figure 7a), and the BFSC increased significantly (Figure 7b).

The generation of NOx mainly depends on the oxygen concentration, combustion temperature, and reaction time in the combustion process. Figure 7f shows the influence of the MCR on the turbine inlet temperature. When the MCR was 60 °CA, the inlet temperature of the turbine was 158 °C higher than that of the original engine, and the MCR at this time leaded to less air intake and a decrease of 25.7% in the air–fuel ratio (Figure 7e). In addition, the total specific heat capacity of the working medium in the cylinder decreased during combustion, but the amount of fuel injection did not change much, so the average temperature in the cylinder increased after ignition. From the above analysis, it could be seen that the large MCR led to the increase of the combustion lag period, which led to the increase of the heat release from premixed combustion. The reduction of the oxygen content in the mixture caused by the MC has a stronger inhibitory effect on NO<sub>x</sub> emission than the promotion effect of the rise of the exhaust temperature.

## 3.1.2. Influence of EGR Value Opening on Torque, BFSC, and NOx Emission

For a turbine with a fixed nozzle section, the intake flow rate and air–fuel ratio are constant in the absence of EGR. A too-high air–fuel ratio may lead to the increase of the oxygen content in the cylinder and higher NOx emission. A too-small air–fuel ratio may lead to deterioration of the combustion and decrease of the power performance. In the presence of EGR, exhaust gases that do not participate in combustion are mixed into the intake air, resulting in a reduction in the amount of fresh recharging that actually enters the cylinder. Figure 6a–c shows the influence of the EGR value opening on the diesel engine torque, BFSC, and NOx emission when the MCR was 0 °CA and VNT nozzle opening was 40%. When the EGR value opening was between 0% and 20%, the torque decreased by 1.9%, BFSC increased by 2%, and NOx emission decreased by 58.4%.

Figure 8e depicts that the increased EGR value opening reduced the air–fuel ratio by 16.3%. The decrease in the oxygen concentration in the cylinder resulted in a delay in the combustion initiation point, resulting in a deterioration of the combustion process and a gradual decrease in the maximum cylinder pressure (Figure 8d). Although the pressure and temperature at the end of the compression in the cylinder were increased, they were still insufficient to compensate for the effect of the reduction of the air–fuel ratio on the ignition time delay. With the increase of the EGR value opening, the torque gradually decreased (Figure 8a), and the BFSC increased (Figure 8b).



Figure 8. Effects of the EGR value opening on the performance and emission of a diesel engine.

The large amount of  $N_2$  and  $CO_2$  in the EGR exhaust gas dilutes the working medium in the cylinder, resulting in a slower combustion rate, which, in turn, leads to an increase in the combustion duration. When the EGR value opening was 20%, the turbine inlet temperature increased by 62 °C compared to the original engine (Figure 8f), which should have resulted in an increase in the NOx emission. However, relative to the promotion of NOx production by the increase in the maximum combustion temperature, the reduction of the air-fuel ratio of the mixture played a dominant role in inhibiting NOx generation. Thus, as the EGR value opening increased, the NOx emission decreased significantly (Figure 8c). Figure 9a–c shows the effects of the VNT nozzle opening on the diesel engine torque, BFSC, and NO<sub>x</sub> emission when the MCR was 0 °CA and EGR value opening was 0%. When the VNT nozzle opening was between 40% and 60%, the torque decreased by 3.4%, BFSC increased by 3.5%, and NO<sub>x</sub> emission decreased by 38.1%.



Figure 9. Effects of VNT valve opening on the performance and emission of a diesel engine.

Although the air density and oxygen content are relatively small at the altitude of 1960m, the exhaust energy is sufficient at the optimum economic operating point of the diesel engine. When the VNT valve opening was 40%, the air–fuel ratio maximized the combustion efficiency, and the engine had the highest cylinder pressure and maximum torque output. With the further increase of VNT nozzle opening, the reduction of the compressor efficiency led to the reduction of the intake air flow and insufficient air–fuel ratio. The decrease in the air–fuel ratio reached 21.79% when the VNT nozzle opening reached 60% (Figure 9e). At the same time, the prolongation of the ignition delay period and the delay of the combustion starting point led to the slow combustion speed in the diffusion combustion phase. When the VNT nozzle opening was between 40% and 60%, the average decrease of the maximum cylinder pressure in the cylinder was 19.41% (Figure 9d), the torque decreased (Figure 9a), the combustion thermal efficiency decreased, and the BFSC increased (Figure 9b).

At high altitudes, a decrease in the engine intake pressure resulted in a decrease in the flow of air into the cylinders. At the same time, the reduction of the oxygen content in the cylinder reduced the fuel gas mixing rate in the middle and late stages of combustion, leading to serious afterburning. With the increase of the VNT nozzle opening, the boost pressure and intake air flow decreased. The increase of premixed combustion proportion led to the increase of the initial heat release in the cylinder and the increase of the maximum combustion temperature in the cylinder (Figure 9f). When the reduction of the oxygen content played a dominant role in the inhibition of NOx generation, the NOx emission decreased with the increase of the VNT nozzle opening (Figure 9c).

## 3.2. Response Surface Optimization

## 3.2.1. Experimental Design

Box Behnken design is a design method in response to the surface design. It can carry out tests within the range of  $3\sim7$  factors. The number of tests is generally  $15\sim62$ . It can evaluate the nonlinear effects of factors. It is applicable to tests where all factors are measured values. Multiple continuous tests are not required when using it. Due to the low air–fuel ratio under high load conditions, when the opening of the EGR valve and VNT are at the highest level at the same time, the air–fuel ratio will be too low, and the combustion will be abnormal. The Box Behnke test plan does not arrange all test factors as the highest level test combination. Therefore, this method was selected to avoid the phenomenon of the low air–fuel ratio at the full-load operating point. The optimal economic operating condition (2200 r/min, 100% load) of the engine was selected for the response surface analysis. MCR (X<sub>1</sub>), VNT nozzle opening (X<sub>2</sub>), and EGR value opening (X<sub>3</sub>) were selected as test factors, and the torque (Y<sub>1</sub>), BSFC (Y<sub>2</sub>), and NOx (Y<sub>3</sub>) were used as response parameters to design a three-factor, three-level response surface test. The test results were calculated using GT-Power. The test factors and levels were shown in Table 2, and the test results were shown in Table 3.

Table 2. Factors and levels of the test.

Lovols	Factors EGR Value Opening X <sub>3</sub> (%)				
Levels —	MCR X <sub>1</sub> /(°CA)	VNT Nozzle Opening X <sub>2</sub> /(%)	EGR Value Opening X <sub>3</sub> /(%)		
-1	0	36	0		
0	20	44	10		
1	40	52	20		

Test Number	MCR X <sub>1</sub>	VNT Nozzle Opening X <sub>2</sub>	EGR Value Opening X <sub>3</sub>	Torque Y <sub>1</sub>	BSFC Y <sub>2</sub>	NOx Y <sub>3</sub>
1	40	52	10	253.7	217.1	1.9
2	20	52	0	257.5	213.8	9
3	20	52	20	254	216.8	4.1
4	20	44	10	259	212.6	6.4
5	20	44	10	259	212.6	6.4
6	0	36	10	260.4	211.49	5.8
7	20	44	10	259	212.6	6.4
8	0	44	0	261.4	210.7	12.4
9	20	36	0	264.4	208.1	13
10	0	52	10	256	215.1	6.5
11	20	36	20	258.3	213.2	3
12	20	44	10	259	212.6	6.4

Table 3. Test results.

Test Number	MCR X <sub>1</sub>	VNT Nozzle Opening X <sub>2</sub>	EGR Value Opening X <sub>3</sub>	Torque Y <sub>1</sub>	BSFC Y <sub>2</sub>	NOx Y <sub>3</sub>
13	40	44	20	255.9	215.1	3.9
14	20	44	10	259	212.6	6.4
15	40	44	0	259.6	212.1	8.4
16	40	36	10	260.8	211.1	5.5
17	0	44	20	256.5	214.6	4.1

3.2.2. Analysis of Variance (ANOVA)

In the response surface model, a second-order polynomial fit is sufficient to express the true response parameters in the experimental design. In combination with the regression analysis of variance (ANOVA) in Table 2, a quadratic polynomial was fitted between the factors and response parameters to obtain the regression equations for the torque  $(Y_1)$ , BSFC  $(Y_2)$ , and NOx  $(Y_3)$ . The regression equations are shown in Equations (1)–(3):

$$Y_{1} = 260.77 + 0.22X_{1} + 0.38X_{2} - 0.62X_{3} - 4.21 \times 10^{-3}X_{1}X_{2} + 1.5X_{1}X_{3} + 8.13 \times 10^{-3}X_{2}X_{3} - 1.83 \times 10^{-3}X_{1}^{2} - 8.33 \times 10^{-3}X_{2}^{2},$$
(1)

$$Y_{2} = 212.38 - 0.19X_{1} + 0.37X_{2} + 0.52X_{3} + 3.75 \times 10^{-3}X_{1}X_{2} - 1.13 \times 10^{-3}X_{1}X_{3} - 6.56 \times 10^{-3}X_{2}X_{3} + 1.56$$
(2)

$$Y_3 = -3.34 + 0.27X_1 + 0.85X_2 - 1.46X_3 - 6.72 \times 10^{-3}X_1X_2 \mp 4.75 \times 10^{-3}X_1X_3 + 0.02 \times 10^{-3}X_2X_3 - 1.94 \times 10^{-3}X_1^2 - 0.01 \times 10^{-3}X_2^2 + 0.02 \times 10^{-3}X_3^2$$

$$(3)$$

The ANOVA results of the model are shown in Table 4. The *p*-values of the model for the torque, BFSC, and NO<sub>x</sub> were less than 0.0500, respectively, indicating significant regression of the model. In order to ensure the adaptability and accuracy of the model, the predictive ability of the model was evaluated, and the significance of the regression model was tested. The coefficient of determination R<sup>2</sup> and the adjusted determination coefficient R<sup>2</sup><sub>adj</sub> were used to evaluate the approximation degree of the regression model, and the predictive determination coefficient R<sup>2</sup><sub>pred</sub> was used to evaluate the regression model. The calculation equation of the coefficient of determination R<sup>2</sup> was shown in Equation (4):

$$R^{2} = \frac{S_{SR}}{S_{ST}} = \frac{S_{SR} - S_{SE}}{S_{ST}} = 1 - \frac{\sum_{i=1}^{n} (\hat{y} - y_{i})^{2}}{\sum_{i=1}^{n} (y_{i} - y)^{2}},$$
(4)

where  $S_{ST}$  is the total sum of squares,  $S_{SR}$  is the sum of regression squares,  $S_{SE}$  is the sum of squared residuals,  $\overline{y}$  is the predicted value of the response surface,  $\hat{y}_i$  is the true value of the response at the ith observation,  $\overline{y}$  is the mean value of the response values, and n is the number of permutation runs or observations of the experimental design.  $R^2$  is a measure of the complete fit, reflecting the degree to which the response surface conforms to the given data, and usually requires an  $R^2$  value above 0.9. The calculation equation of  $R^2_{adj}$  was shown in Equation (5):

$$R_{adj}^{2} = 1 - \frac{S_{SE}/(n-p)}{S_{ST}/(n-1)} = 1 - \frac{n-1}{n-p} \left(1 - R^{2}\right),$$
(5)

where p is the number of regression coefficients in the model,  $R_{adj}^2$  representing the correlation degree between all independent variables and dependent variables. The closer  $R_{adj}^2$ 

was to 1, the better the regression effect would be. The calculation equation of  $R_{pred}^2$  was shown in Equation (6):

$$R_{\text{pred}}^{2} = 1 - \frac{v_{\text{PRESS}}}{S_{\text{ST}}} = 1 - \frac{\sum_{i=1}^{n} (y_{i} - \hat{y}_{i})^{2}}{\sum_{i=1}^{n} (y_{i} - \overline{y})^{2}},$$
(6)

where  $v_{PRESS}$  is the sum of squares of the prediction errors,  $\hat{y}_i$  is the predicted value of the response at the ith observation,  $\overline{y}$  is the mean value of the response values,  $R_{pred}^2$  represents the predictive power of the original regression model fitted by running all permutations of the n observations, the value of  $R_{pred}^2$  should be greater than 0.8~0.9, and the difference between the value of  $R_{pred}^2$  and  $R^2$  should not be greater than 0.2~0.3.

 Table 4. ANOVA results.

Evaluation Index	Variance Source	Sum of Squares	Freedom	Mean Square	F Value	<i>p</i> -Value
	model	115.69	9	12.85	537.22	< 0.0001
	X <sub>1</sub>	2.31	1	2.31	96.59	< 0.0001
	X <sub>2</sub>	64.41	1	64.41	2691.81	< 0.0001
	X <sub>3</sub>	41.40	1	41.40	1730.36	< 0.0001
Torguo	$X_1X_2$	1.82	1	1.82	76.16	< 0.0001
V.	$X_1X_3$	0.36	1	0.36	15.04	< 0.0061
11	$X_2X_3$	1.69	1	1.69	70.63	< 0.0001
	$X_1^2$	2.29	1	2.29	95.71	< 0.0001
	$\chi^{\overline{2}}_{2}$	1.22	1	1.22	50.84	< 0.0002
	$\chi_3^{\overline{2}}$	0.032	1	0.032	1.35	< 0.2838
	Residuals	179.98	7	25.71		
	model	79.79	9	8.87	306.47	< 0.0001
	$X_1$	1.53	1	1.53	52.93	< 0.0002
	X <sub>2</sub>	44.65	1	44.65	1543.50	< 0.0001
	X3	28.13	1	28.13	972.22	< 0.0001
PEEC	$X_1X_2$	1.44	1	1.44	49.78	< 0.0002
DSFC V-	$X_1X_3$	0.20	1	0.20	7.00	< 0.0331
12	$X_2X_3$	1.10	1	1.10	38.11	< 0.0005
	$X_1^2$	1.64	1	1.64	56.86	< 0.0001
	$\chi^2_2$	0.95	1	0.95	32.84	< 0.0007
	$\chi_3^{\overline{2}}$	0.042	1	0.042	1.46	< 0.2668
	Residuals	0.20	7	0.029		
	model	139.49	9	15.50	177.13	< 0.0001
	X <sub>1</sub>	10.35	1	10.35	118.30	< 0.0001
	X <sub>2</sub>	4.20	1	4.20	48.06	< 0.0002
	X3	95.91	1	95.91	1096.13	< 0.0001
NOv	$X_1X_2$	4.62	1	4.62	52.83	< 0.0002
NOX Va	$X_1X_3$	3.61	1	3.61	41.26	< 0.0004
12	$X_2X_3$	6.50	1	6.50	74.31	< 0.0001
	$X_1^2$	2.53	1	2.53	28.90	< 0.0010
	$X_{2}^{2}$	2.06	1	2.06	23.58	< 0.0018
	$\chi_3^{\overline{2}}$	10.44	1	10.44	119.37	< 0.0001
	Residuals	0.61	7	0.087		

The evaluation results of each response surface model are shown in Table 5. It could be seen that the values of  $R^2$ ,  $R^2_{adj}$ , and  $R^2_{pred}$  were all above 0.92, and the difference between the  $R^2_{pred}$  and  $R^2$  of each response surface model was less than 0.2, which indicates that the obtained response surface models had a good consistency and predictive ability of the test results.

Responses Determinate Coefficient R <sup>2</sup>		Adjusted Determinate Coefficient R <sup>2</sup> <sub>adj</sub>	Prediction Determinate Coefficient R <sup>2</sup> <sub>adj</sub>	
Torque	0.9986	0.9986	0.9986	
BFŜC	0.9975	0.9975	0.9975	
NOx	0.9956	0.9956	0.9956	

Table 5. Each response surface model evaluation.

#### 3.2.3. Analysis of the Influence of MEV Coupling on Torque, BSFC, and NOx

Figure 10 shows the 3D response surface plot of the effect of the interaction of three factors: MCR, EGR value opening, and VNT nozzle opening on the torque, BFSC, and  $NO_x$  emission when the diesel engine is operated at the economic operating point.

Figure 10a,b depicts the coupling effect of MC and VNT on the torque, BFSC, and  $NO_x$  emission when the EGR value opening was at the 0 level (10%). When the VNT nozzle opening was in the range of 36–40% and the MCR was in the range of 1535 °CA, the maximum torque and minimum BFSC values were found. When the VNT nozzle opening was a large value, with the increase of the MCR, the intake air volume decreased significantly, which led to the decrease of the combustion quality in the cylinder, the decrease of torque, and the increase of BFSC. When the VNT nozzle opening was a small value, the turbocharger efficiency was improved, which made up for the intake charge loss caused by the MC and improved the combustion quality. With the increase of the MCR, the torque first increased and then decreased, and the BFSC first decreased and then increased. Figure 10c depicts the effect of the coupling effect of MC and VNT on  $NO_x$  emission. Only when the VNT nozzle opening and MCR were higher,  $NO_x$  emission decreased significantly. The superposition of a larger VNT nozzle opening and a larger MCR resulted in a sharp reduction in the intake air volume and the oxygen concentration in the mixture, thus leading to a significant reduction in NOx emission. Considering the torque, BFSC, and NOx emission, the VNT nozzle opening and MCR should not be too small or too large.

Figure 10d,e reveals the effect of coupling between EGR and MC on the torque and BFSC when the VNT nozzle opening was at 0 level (44%). When the EGR value opening was in the range of 0–10% and the nozzle of the MCR was in the range of 0–30 °CA, the maximum torque and minimum BFSC values were found. When EGR value opening was fixed, the MCR had no obvious effect on the torque and BFSC. When the MCR was fixed, the torque decreased with the increase of the EGR value opening, and the BFSC increased with the increase of the EGR value opening. When the EGR and MC were coupled, the appropriate MCR could share the influence of the EGR value opening on the power and economy of the diesel engine. Figure 10f shows the coupling effect of EGR and MC on NOx emission. When the EGR value opening was at a large value, the MC had no obvious influence on NOx emission reduction. When the EGR value opening was a small value, NO<sub>x</sub> emission decreased significantly with the increase of the MCR. Based on the above analysis, the EGR value opening and MCR could not be too small or too large.

Figure 10g,h displays the effect of coupling between EGR and VNT on the torque and BFSC when the MCR is at 0 level (20 °CA). When the EGR value opening was in the range of 0–15% and the VNT nozzle opening was in the range of 36–44%, the maximum torque and minimum BFSC values were found. When the VNT nozzle opening was fixed, the torque decreased and BFSC increased with the increase of the EGR value opening. When the EGR value opening increasing. VNT nozzle opening determines the turbine frontend pressure, affects the compressor efficiency, and then affects the air–fuel ratio of the mixture. When the EGR and VNT were coupled, the compressor efficiency and air–fuel ratio increased with the reduction of the VNT nozzle opening, making up for the effect of a too-low air–fuel ratio caused by excessive EGR value opening. Figure 10i reveals the coupling effect of EGR and VNT on NOx emission. When the VNT nozzle opening was fixed, NOx emission

decreased with the increase of the EGR value opening. When the VNT nozzle opening was a small value, a large EGR rate was generated, resulting in a significant reduction in NOx emission. In consideration of the torque, BFSC, and NOx emission, the EGR value opening and VNT nozzle opening could not be too large or too small.



Figure 10. Influence of MEV coupling on the torque, BSFC, and NOx emission.

3.2.4. Optimization of MEV Parameters

Diesel engines for range extenders often operate at optimum economic conditions, so it is necessary to optimize the MEV parameters corresponding to this condition. Combining the boundary conditions of each factor, a parametric optimization mathematical model was established in order to maximize the torque and reduce fuel consumption and  $NO_x$  emission. The objective function and constraints are shown in Equation (7):

s.t. 
$$\begin{cases} \max F(X_1, X_2, X_3) = Y_1 \\ \min F(X_1, X_2, X_3) = Y_2 \\ \min F(X_1, X_2, X_3) = Y_3 \\ 0^{\circ} CA \le X_1 \le 40^{\circ} CA \\ 36\% \le X_2 \le 52\% \\ 0\% \le X_3 \le 20\% \end{cases}$$
(7)

The optimization module of Design Expert 10.0.3 software was used to optimize and analyze the constraint indicators, and the optimal results were obtained: The torque was 260.5 N·m, BSFC was 211.4 g/(kW·h), and NOx was 5.3 g/(kW·h) when the MCR was 40 °CA, VNT nozzle opening was 36%, and EGR value opening was 10.9%. Based on the above analysis results, the appropriate selection of MCR, EGR value opening, and VNT nozzle opening can make the MEV system play a very good technical advantage. The MEV system solves the contradiction between the torque, BFSC, and NOx emission and meets the comprehensive performance requirements of diesel engines for range extenders.

In order to verify the accuracy of the optimized results, the optimized values of MCR, EGR value opening, and VNT nozzle opening were input into the GT-Power simulation model for a simulation test at 2200 r/min and 100% load. It was repeated three times, and the average value was used. It can be seen from Table 6 that the torque and BFSC generated by the optimized MEV variable combination do not change significantly compared with the simulation results, and the deviation between the simulation value and the predicted value of NOx emissions is very small, with the maximum deviation not exceeding 5.36%. This shows that the second-order regression model of each response obtained by the response surface method can reflect the correlation between factors and response values, and the model has good prediction accuracy.

**Table 6.** Validation of optimized results by response surface method at engine speed 2600 r/min, 100% load.

MCR/°CA	EGR Value Opening/%	VNT Nozzle Opening/%	Responses	Simulation Value	Optimization Value	Error/%
40	10.9	36	Torque/N∙m BFSC/g/(kW∙h) NOx/g/(kW∙h)	260.9 211.2 5.6	260.5 211.4 5.3	$0.15 \\ -0.09 \\ 5.36$

### 4. Conclusions

In this study, the diesel engine for the range extender was studied at 1960m altitude and at the optimum economic operating point (2200r/min, 100% load). A one-dimensional simulation model of a diesel engine was established using GT-Power to analyze the effects of the MC, EGR, and VNT technologies as single factors on diesel engine torque, BFSC, and NOx emission. The coupling law among MCR, VNT nozzle opening. and EGR value opening is studied by the response surface method. The application effect of MEV coupling is analyzed theoretically. The main conclusions are as follows:

1. The results of the single-factor analysis show that MCR has little effect on the torque and BFSC in the range of 0–20 °CA. The influence of MCR on the torque and BFSC increased significantly in the range of 20–60 °CA (torque decreased by 2.6% and BFSC increased by 2.7%). The NOx emission decreases by 58.4% with the increase of the MCR when the MCR is within the range of 0–60 °CA. The torque decreases by 1.9%, BFSC increases by 2.0%, and NOx emission decreases by 58.4% with the increase of the EGR value opening when it is in the range of 0–20%. The torque decreases by 3.4%, BFSC increases by 3.5%, and NOx emission decreases by 38.1% with the increase

of the VNT nozzle opening, when VNT nozzle opening is in the range of 40–60%. MC, EGR, and VNT technologies have different effects on the torque and BFSC of high-speed diesel engines, but they can significantly reduce NOx emission.

- 2. The results of the multifactor analysis show that the proper selection of the MEV system coupling parameters (MCR, EGR value opening, and VNT nozzle opening) overcomes the shortcomings of single-factor application in high-speed diesel engines. After optimization to the response surface methodology, the torque and BFSC remained unchanged and NOx emission decreased by 59.5% compared with the original machine. The larger MCR and smaller VNT valve opening, together with the smaller EGR rate, can keep the engine torque and BFSC unchanged while keeping the NOx emission at a lower level. MEV system coupling improves the endurance of the high-speed diesel engine to the EGR rate, providing more possibilities to reduce NOx emissions.
- 3. These findings can help diesel engines for range extenders obtain a better performance and less NOx emission in plateau areas. There are limitations in this study, as follows, and they need to be addressed in future research. First of all, this study only optimized and verified the MEV system parameters at the optimal economic operating point of a diesel engine for a range extender under one operating mode (single-point control energy management strategy). In the follow-up work, the method will be used to study other operating points of different operating modes (multipoint control energy management strategy and power follow energy management strategy). Secondly, because MEV technology is part of the diesel engine air system and one of the main functions of the MEV system is to reduce the impact of NOx emissions. This study did not analyze the influence of other systems or key parameters of the diesel engine, nor did it analyze the emission of particulate matter (PM), which is another major emission of diesel engines). In further studies, the diesel engine power, economy,  $NO_x$  emission, PM emission, and other indicators will be systematically studied in combination with the fuel injection system parameters and other key operating parameters.

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#### Nomenclature

- MC Miller cycle
- EGR exhaust gas recirculation
- BBD Box Behnken design
- MCR Miller cycle rate
- EIVC early intake valve closing
- LIVC later intake valve closing
- VNT variable nozzle turbine
- RSM response surface method
- BFSC brake specific fuel consumption
- MEV MC-EGR-VNT
- NOx nitrogen oxides
- PM particulate matter

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