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Research on Electrical Boost Technology for Medium-Duty Diesel Engines

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Abstract: To meet the increasingly stringent fuel consumption standards and reach the internationally advanced carbon emission levels, the electrification of diesel engine accessories is an important technological approach for energy conservation and emission reduction. Compared with the turbocharging system of traditional diesel engines, the electric boosting system can further improve the charging efficiency of diesel engines and enhance the low-speed torque, transient response, etc. Based on the one-dimensional engine performance simulation software, this paper respectively studies the influence of the electric boosting system on the overall performance of a mass-produced medium-sized diesel engine platform and the corresponding hybrid platform. Firstly, the influence of different layout forms of the electrical boost on the engine performance is studied based on the diesel engine platform. The results show that the series layout form is superior to the parallel one. When the electrical boost is arranged in series at the front, the low-speed torque is increased by 13%, the intake air volume is increased by 44%, and the brake specific fuel consumption (BSFC) is improved by 12%. When arranged in series at the rear, the torque is increased by 11%, the intake air volume is increased by 37%, and the BSFC is improved by 11%. However, considering that if the power consumption of the electrical boost's motor is sourced from the engine, the BSFC will deteriorate. With the expansion of future diesel engine electrification technologies, the motor can use the electric energy generated by brake power recovery and waste heat recovery. Therefore, the effect of applying the electrical boost in the hybrid vehicle platform is studied. The results show that when the hybrid engine can achieve the same power and torque targets, the series-rear layout form is superior to the series-front one. The specific fuel consumption can be optimized by up to 11%. The rear layout requires the addition of an intercooler, which will lead to an increase in cost. In conclusion, the electric boosting system based on the hybrid platform not only has the advantages of fast dynamic response and solving the turbo lag problem, but also can enhance the vehicle's power performance and fuel economy to a greater extent by optimizing the matching of the turbocharger and the electric boosting system. The electric boosting system based on medium-sized engines has a more promising commercialization prospect.

Keywords: diesel engine; electrification; hybrid power; electrical boost; fuel economy

1. Introduction

The increasingly strict environmental protection policies and fuel consumption regulations have put forward higher and higher requirements for commercial vehicles. To reach the internationally advanced carbon emission level by 2025, commercial vehicles require diesel engines to improve fuel economy while reducing particulate matter (PM) and NO_x emissions. Therefore, the energy-saving and emission-reduction technologies for diesel engines have been widely discussed. The use of exhaust gas turbocharging technology to improve the intake air density can not only increase the power per liter of diesel engines and reduce fuel consumption, but also effectively improve engine emissions [1].

Existing traditional diesel engines mainly increase the intake air volume of internal combustion engines

through turbocharging technology. In a turbocharging system, the atmosphere is pressurized by the compressor of the turbocharger and then enters the engine intercooler. The cooled pressurized gas enters the cylinder for combustion and power generation. The exhaust gas after power generation enters the turbine through the exhaust manifold to expand and do work, driving the compressor to operate at the same time. Finally, it is discharged through the after-treatment system [2]. Common turbochargers mainly include three types: fixed gate turbochargers (FGT), waste gate turbochargers (WGT), and variable geometry turbochargers (VGT). FGT is usually an uncontrollable turbocharger; in a WGT, the opening and closing of the bypass valve are mainly controlled by the compressor pressure. When the pressure is too high, part of the engine exhaust gas needs to be discharged through the bypass valve. In a VGT, the nozzle ring position can change unrestrictedly between open and closed states, enabling the adjustment of the eddy current flow channel outlet area, boost pressure, etc. [3].

The structure of the turbocharger determines that it is impossible to take into account both low-speed and high-speed conditions simultaneously. When using a WGT, the air-fuel ratio can be improved under low-speed conditions. Under high-speed conditions, to avoid overspeeding of the turbocharger and exceeding the maximum combustion pressure of the engine, the bypass valve needs to be opened for venting. The low-speed performance of a VGT is slightly better than that of a WGT, but when selecting a model, a compromise needs to be considered to match both low-speed and high-speed conditions. All turbochargers have problems such as compromised low-speed performance and poor dynamic response [4].

However, exhaust gas turbochargers need to use exhaust energy to overcome their moment of inertia drive, and there is a problem of slow transient response. Electrical boost has the potential to improve the responsiveness of turbochargers and improve diesel engine acceleration smoke, etc. The optimal matching of electrical boost with turbochargers has more advantages, such as improving inflation efficiency and improving low-speed torque [5,6].

The electrical boosting technologies mainly include electric electrical boost (E-boost), electric auxiliary turbochargers (electrical turbo, E-turbo), and electronic compound turbines, etc. The E-boost technology is usually used together with a conventional turbocharger [7,8], and is installed upstream or downstream of the conventional turbocharger. It increases the boost pressure and the engine's instantaneous response at low engine speeds, virtually eliminating the turbo lag phenomenon [9, 10]. At high speeds, the conventional turbocharger should undertake the boosting task as much as possible. At this time, the E-boost realizes the bypass function with the help of its self-adjusting bypass valve. Through integrated electronic devices, appropriate selection of the engine and corresponding matched engine electronic control system, the power performance, economy, and Noise- Vibration-Harshness (NVH) of the engine can achieve a good match [11,12]. Therefore, with the promotion of 48 V automotive circuits in the future and the improvement of battery and motor technology, as well as the progress of engine turbine compounding [13,14], waste heat recovery and other technologies [15], more efficient and cleaner diesel engine electrification technology or hybrid technology with electric supercharging is one of the important technical paths to meet the future demand for energy saving and emission reduction of vehicles [16,17].

In this paper, based on the mass-produced medium-sized diesel engine platform and an existing electric compressor platform, the simulation analysis of the electric boosting system based on the traditional diesel engine was carried out [18], A preliminary study was conducted on the performance impact and product matching of diesel engine electrification [19]. Then, based on the hybrid platform of the medium-sized engine, a technical study on the electrification of the electrical boosting system for typical hybrid operating conditions was carried out, laying a foundation for further system matching of the entire engine, bench tests, and road tests [20–22].

2. Basic Model Calibration

The base engine was calibrated based on a medium-sized diesel engine with a displacement of 5 L. The basic technical parameters of the diesel engine are shown in Table 1.

Table 1. Technical parameters of the engine.

Type	Parameter
	In-Line 4-Cylinder Four-Stroke, Water-Cooled, Air-to-Air Intercooler
Turbocharger	WGT
Bore/mm	110
Stroke/mm	132
Displacement/L	5
Compression ratio	17.3
Ignition sequence	1-5-3-6-2-4

The engine's overall power output was measured by a dynamometer. The inlet mass flow rate was measured upstream of the compressor. The uncertainties of the measuring instruments are shown in Table 2. An automatic data acquisition and processing system was established in the engine test bench to measure engine steady-state average parameters. The engine operation conditions (speeds, loads) were controlled by a computer, which was connected to the engine electronic control units (ECU).

Table 2. The uncertainties of the measurement instruments.

Instrument	Measured Quantity	Uncertainty
Inductive pick-up sensor	Engine speed	±10 r/min
Dynamometer	Engine torque	±0.1%
Sensyflow air mass flow meter	Air mass flow rate	±1%
AVL fuel mass flow meter	Fuel consumption	±0.12%
K-type thermocouple	Temperature	±0.75%
Strain gauge	Pressure	±0.2%

Based on the technical parameters of the engine, a model was established through the 1D performance process simulation software of the engine, and the base engine was checked according to the experiment data. The calibration results are shown in Figure 1. The deviation between the calibration result and the experiment result is guaranteed within 5%. The values of the deviation are shown in Table 3.

Table 3. The deviation of the measurement instruments.

Speed (r/min)	2300	1700	1200	800
Torque deviation (%)	0.34	0.35	0.32	−2.03
Air mass deviation (%)	−2.50	−0.26	−0.64	−5.00
BSFC deviation (%)	−0.56	1.27	0.97	−2.63
AFR deviation (%)	−0.01	0.00	0.01	−0.02

(a) Torque comparison of experiments and simulations

(b) Air flow mass comparison of experiments and simulations

(c) BSFC comparison of experiments and simulations

(d) Air Fuel Ratio comparison of experiments and simulations
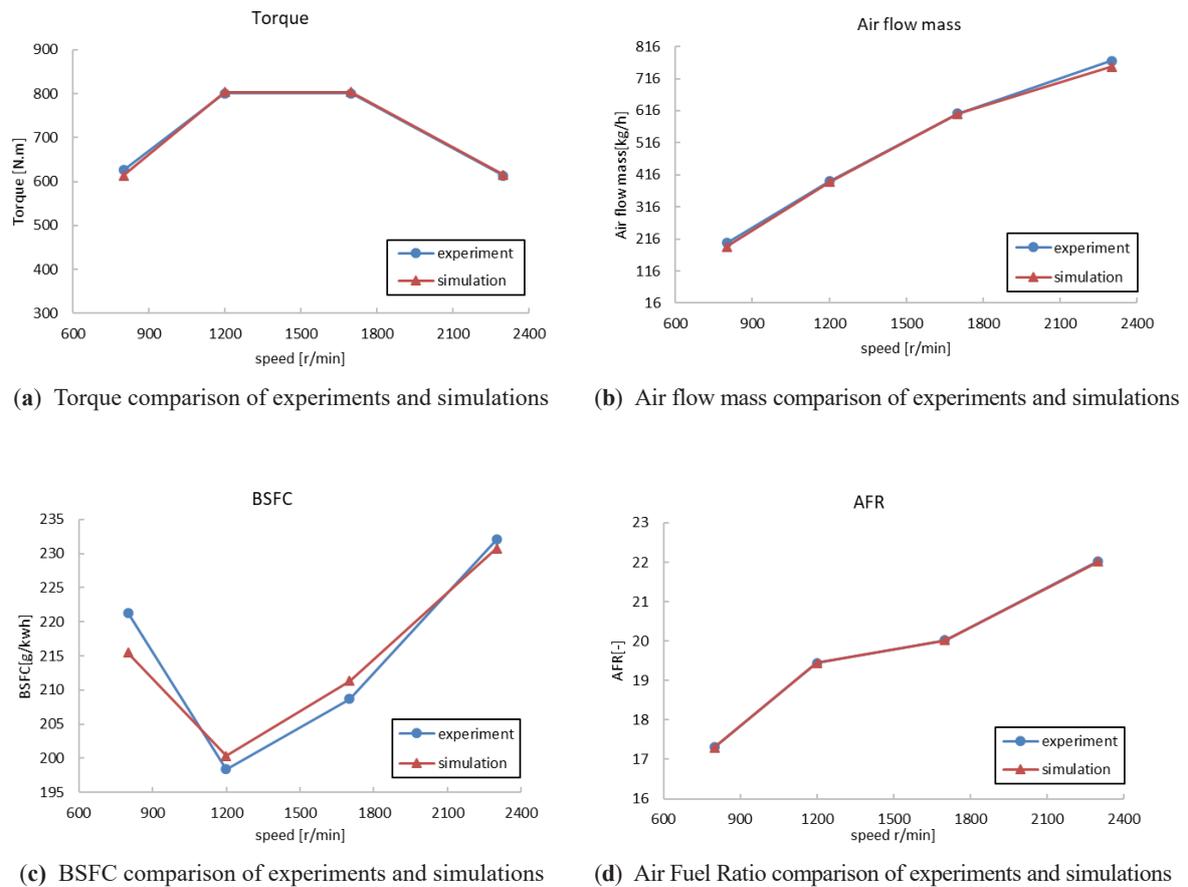
Figure 1. Calibration results of the model.

3. The Electrical Boost

The electrical boost is mainly composed of a compressor and a high-speed motor. Figure 2 shows the sample of the electrical boost used in this research. Electric pressurization technology mainly uses high-speed motors to drive the compressor. The electric compressor has the effect of replenishing air, and the response is fast, so that the engine can be pressurized without lag at low speed. If a bypass valve is connected to the electric supercharger in parallel, the throttle loss in non-supercharging conditions can be avoided [16].

Figure 2. Electrical boost sample.

The arrangement forms of the electrical boosting system are mainly divided into parallel system, front series system, and rear series system, as shown in Figure 3.

(**a**) Parallel system

(**b**) Front series system

(**c**) Rear series system
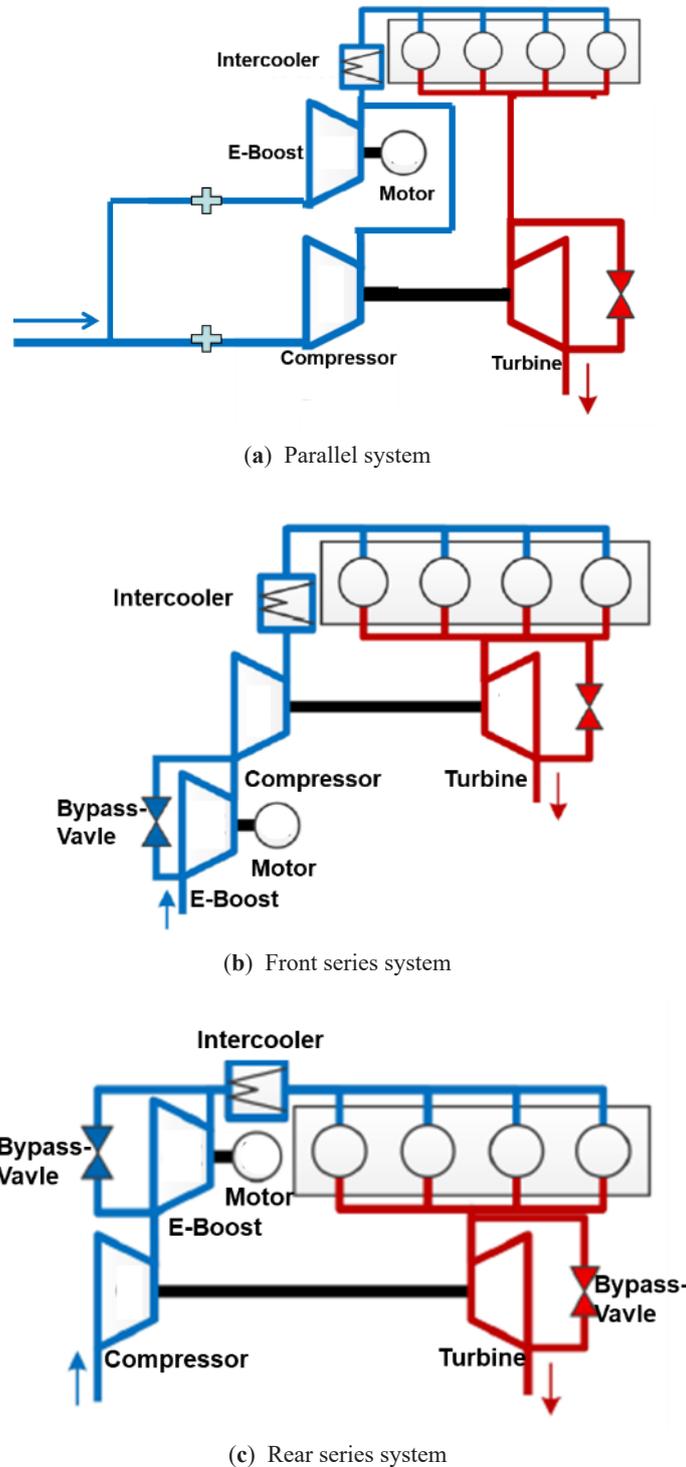
Figure 3. Layout of the electrical boosting system.

4. Research on Parallel E-Boosting System

The one-dimensional performance simulation model of the parallel electrical boosting system is set up, as shown in Figure 4. To explore the potential of power and economy improvement of the engine, the

pressure ratio of the turbocharger and the fuel injection and air-fuel ratio of the engine was adjusted, and the increase of maximum power torque, economy and low-speed torque after the parallel arrangement of the electrical boost and the compressor of turbocharger was compared.
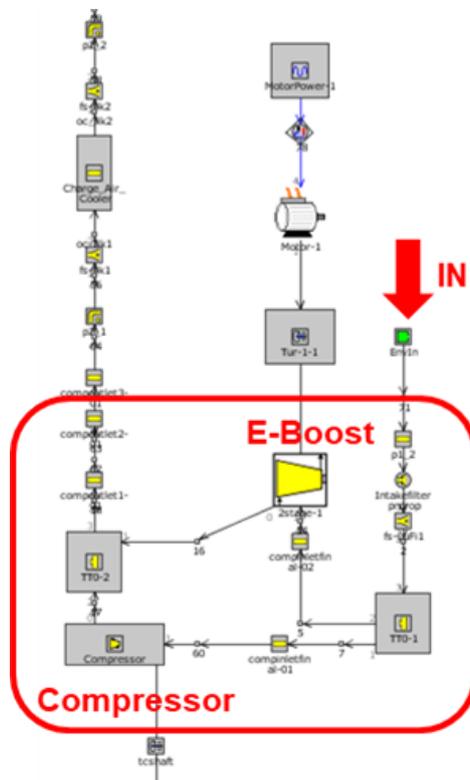
Figure 4. Parallel electrical boosting model.

The simulation results of the parallel electrical boosting system are shown in Figure 5. As can be seen from Figure 5, the parallel arrangement has an effect on power torque, with the maximum low-speed torque increased by 9%, air flow mass improved by 42%, BSFC improved by 9% when motor power consumption was not considered, and BSFC worsened by 10% when motor power consumption was considered.

Considering the expansion of future electrification technology, the motor can use brake power to recover power generation and waste heat to recover power generation, so the power consumption of the motor can be temporarily ignored when evaluating the improvement of fuel consumption of the system.

The map of the pressure end of the electrical boost and turbocharger is shown in Figure 6. Compared with the compressor of the turbocharger, the maximum flow rate of the electrical boost is only 1/2 of the maximum flow rate of the compressor, and the maximum pressure ratio is about 3/4 of the compressor.

Under high-speed conditions, the inlet and outlet pressures of the compressor and the electrical boost in parallel arrangement are the same, but the flow rate and pressure ratio range are quite different, resulting in that when the flow rate and pressure ratio are within the compressor pulse spectrum range, electrical boost will run outside the pulse spectrum range because of the same pressure ratio with the compressor.

At the same time, through the flow judgment of the two pressure ends, it can be seen that under high-speed conditions, electrical boost does not flow through and electrical boost does not work, which is equivalent to the layout structure of the original machine. At this time, the power potential of the parallel layout electrical boosting system is the same as the turbocharger of the original machine and has nothing to do with the electrical boost.
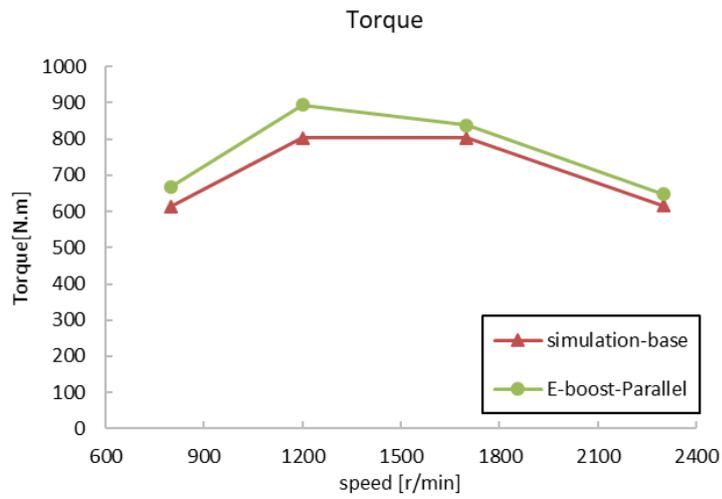
(**a**) Torque comparison between the parallel type and the base
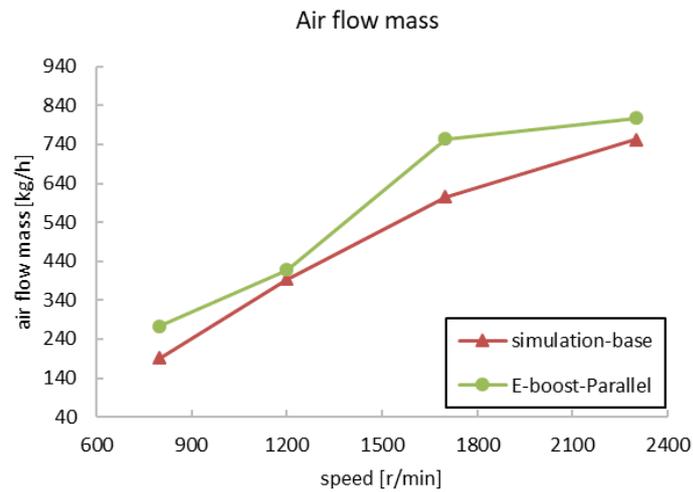
(**b**) Air flow mass comparison between the parallel type and the base
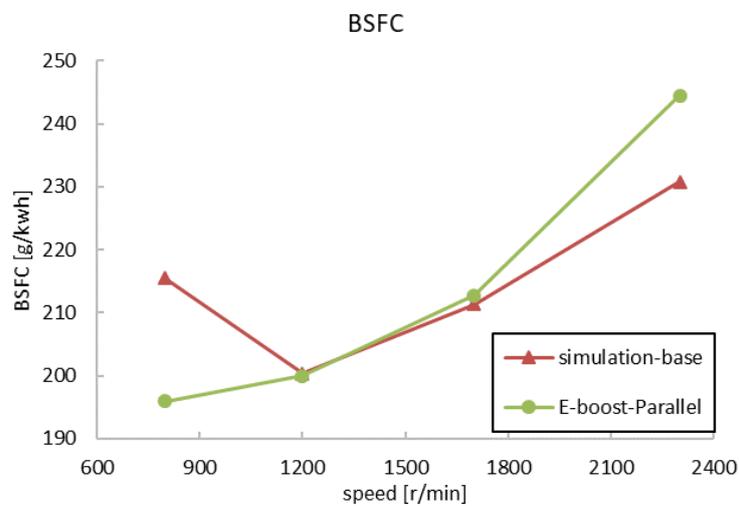
(**c**) BSFC comparison between the parallel type and the base

Figure 5. Performance of the parallel type.
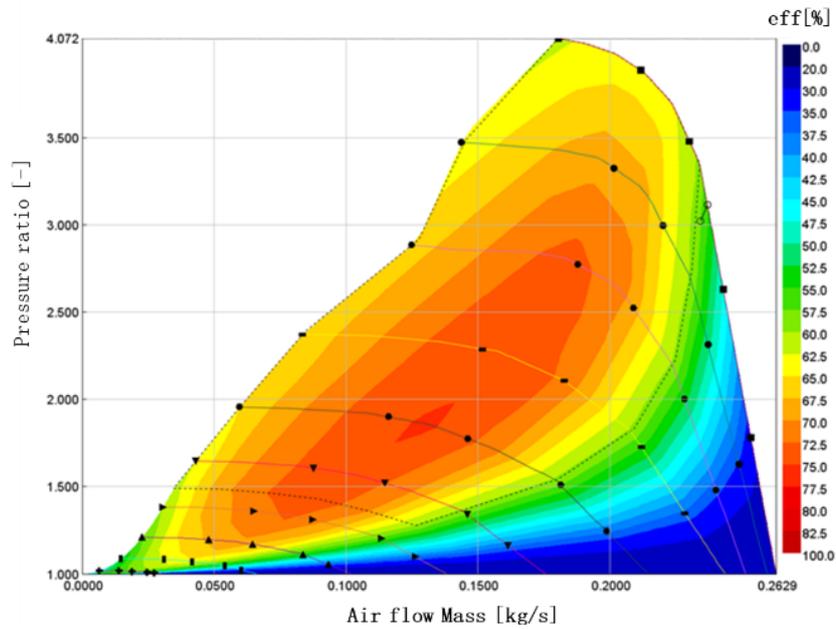
(a) Map of the compressor
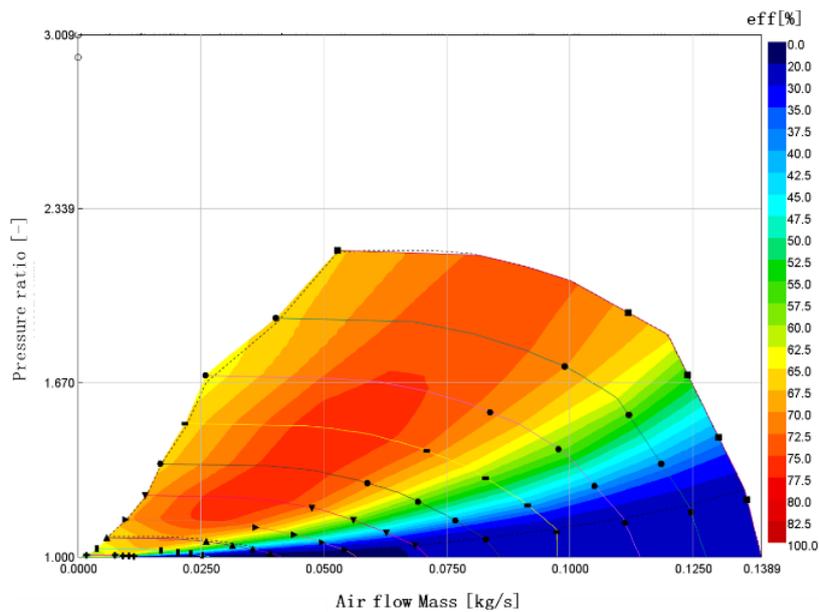
(b) Map of the Electrical boost

Figure 6. Comparison of map between electrical boost and compressor.

Under low-speed conditions, the electrical boost flow is within the pulse spectrum range, and the pressure ratio exceeds the range. Therefore, it can be attempted to reduce the pressure ratio by adjusting the motor power, as shown in Figure 7. The effect of motor power on torque and specific fuel consumption is: the greater the motor power, the greater the potential to improve torque, and the better the specific fuel consumption. Therefore, even if the motor power is reduced, the parallel arrangement is still too large for the electrical boost pressure ratio, and even if electrical boost can work within the flow range under low-speed conditions, the pressure ratio still does not meet the map requirements.
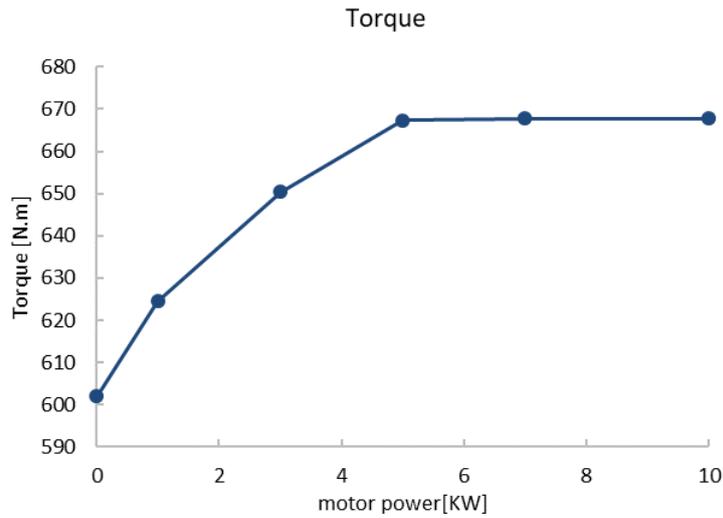
Torque

(**a**) Torque performance at different motor powers
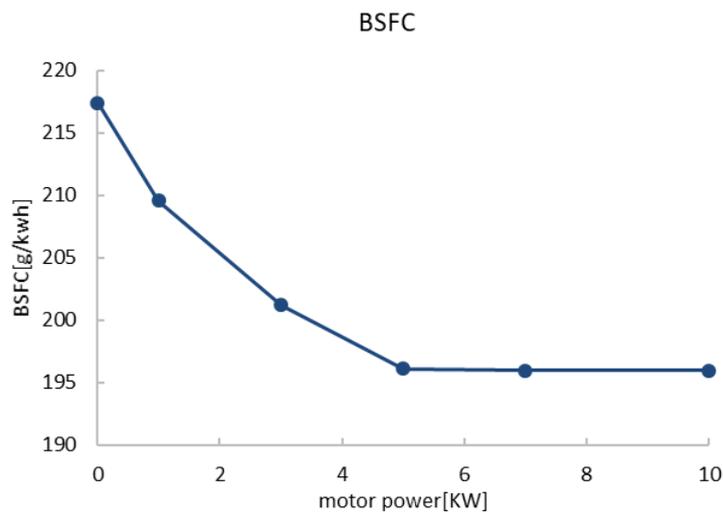
BSFC

(**b**) BSFC performance at different motor powers

Figure 7. Performance at different motor powers.

To sum up, in the parallel arrangement, the electrical boost only works at low speed, so the power performance cannot be improved. At low speeds, the electrical boost and the turbocharger need to have the same pressure ratio, but the actual electrical boost has a smaller pressure ratio range than the turbocharger, which will cause the electrical boost not to work. Therefore, although the parallel type is relatively simple, it requires an electrical boost of similar size to the turbocharger, and the two are rematched to achieve the optimal effect.

5. Research on Series E-Boosting System

The one-dimensional performance simulation model of the electrical boosting system is shown in Figure 8. According to the position relationship between the electrical boost and the compressor of the turbocharger, the series electrical boosting system can be divided into two types: front series and rear series. To ensure that the water-cooling temperature of the electrical boost does not exceed the limit value, the intercooler of the electrical boost is added at the rear end of the compressor. In addition, a bypass line with a bypass valve switch is added to ensure the safety of the electrical boost when it is not working. To explore the potential of improving the power performance and economy of the engine, by adjusting the pressure ratio of the turbocharger, adjusting the fuel

injection and air-fuel ratio of the engine, and adjusting the switch of the bypass valve, the potential of improving the maximum power torque, economy and low-speed torque of the electrical boost and the compressor of turbocharger of the front and rear series system were compared and analyzed.

(**a**) Front series system   (**b**) Rear series system
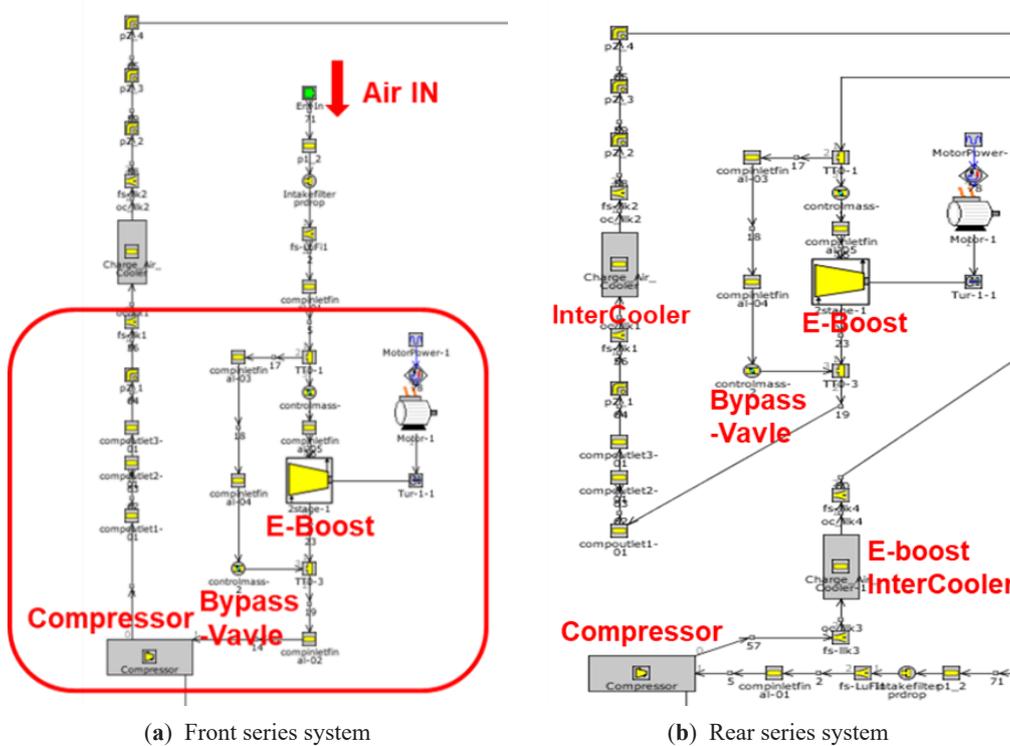
Figure 8. Series electrical boosting model.

The simulation results of the two series electrical boosting systems are shown in Figure 9. The low-speed torque and air flow mass increase by 13% and 44% under the series front. If motor power consumption is not taken into account, BSFC can improve by 12%, while fuel consumption deteriorates by 5% when motor power consumption is taken into account. The series rear lower torque is increased by 11%, the air intake is increased by 37%, the BSFC can be improved by 11% without considering the motor power consumption, and the fuel consumption is worsened by 7%, considering the motor power consumption.

In the series front arrangement, as shown in Figure 10, compare the intake state under the two conditions of opening and closing the bypass valve. When the bypass valve is opened in the series front arrangement, the compressor is located at the back end of the electrical boost and bypass pipelines and has the effect of pumping air, and the part of the electrical boost flow is insufficient by the bypass pipeline; When the bypass valve is closed, the bypass pipeline cannot play the role of air replenisher, the electrical boost flow range is insufficient, and the intake volume required by the supercharger cannot be reached, which will lead to insufficient gas volume and insufficient power in medium and high-speed conditions above 1200 r/min as shown in Figure 11.

Therefore, in the condition of 1200 r/min, it is necessary to open the bypass valve and turn off the motor to make the electrical boost not work, so that the medium-high speed is consistent with the original machine state.

In the rear series system, compare the performance of the two states of the bypass valve. When the bypass valve is closed, because the pressure after electrical boost is greater than the pressure before electrical boost, there is no intake flow in the bypass pipeline, and only when electrical boost is not working, the intake air flows into the engine intercooler from the bypass pipeline, which is equivalent to the base engine with only the turbocharger working separately.
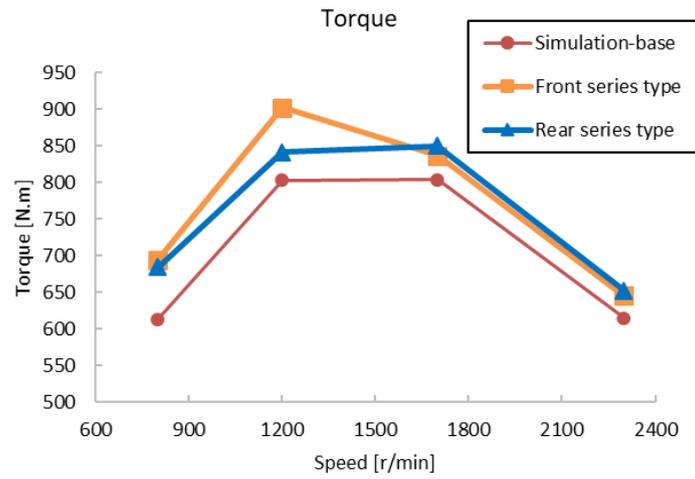
(**a**) Torque performance between different series types and the base one
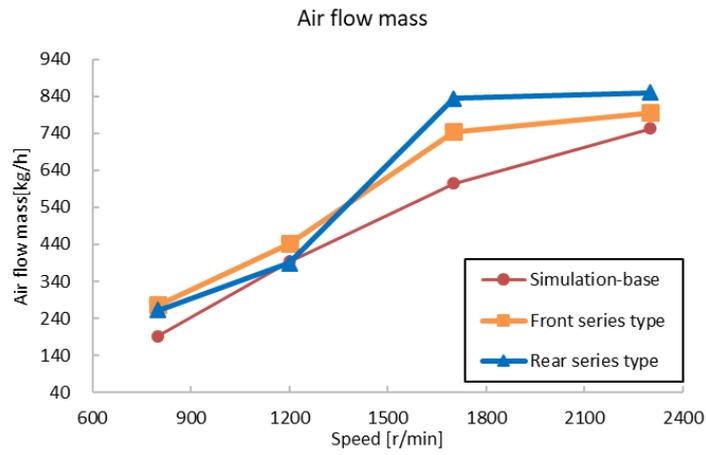
(**b**) Air flow mass performance between different series types and the base one
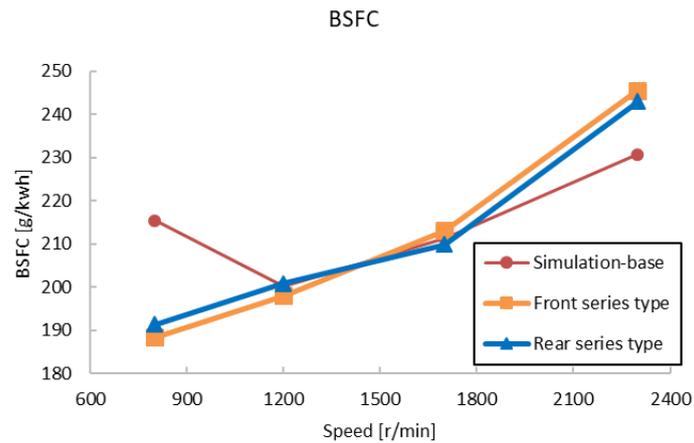
(**c**) BSFC performance between different series types and the base one

Figure 9. Performance of the series E-Boosting system.
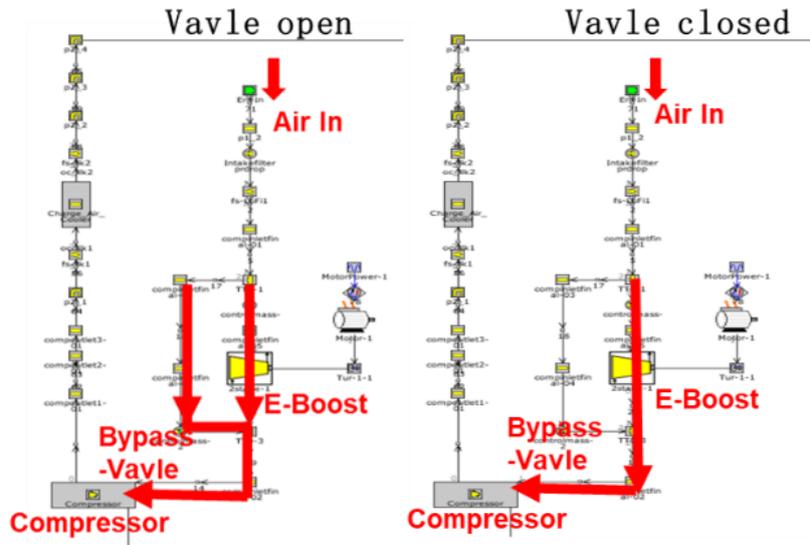
Figure 10. Comparison of series E-Boosting system.
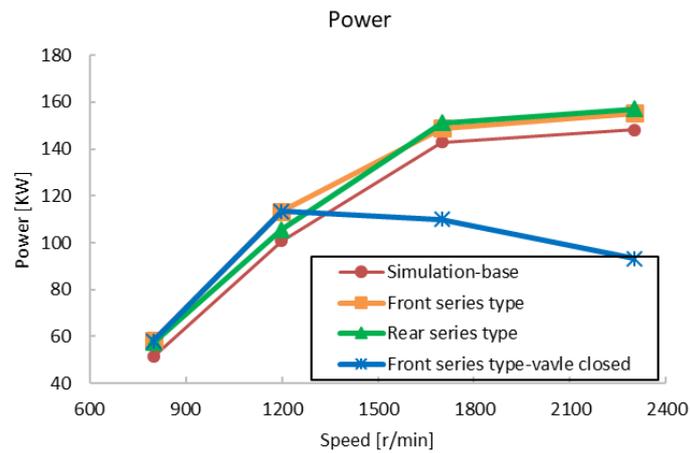
(**a**) Power performance between different series types
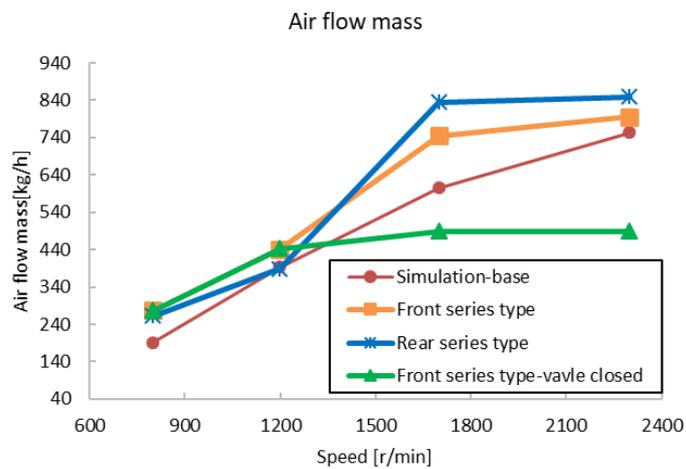
(**b**) Power performance between different series types

Figure 11. Performance of By-pass valve closed.

6. Study of Hybrid Conditions

Considering that if the motor power consumption of the electrical boost comes from the engine, the BSFC will deteriorate, so the application of the electrical boost in the hybrid vehicle platform can make full use of the electric energy. Therefore, the performance impact of the electrical boosting system under the transportation condition based on the hybrid engine is studied [17,18]. Therefore, the commonly used driving conditions of the medium-engine hybrid vehicle were selected for research, as shown in Figure 12.
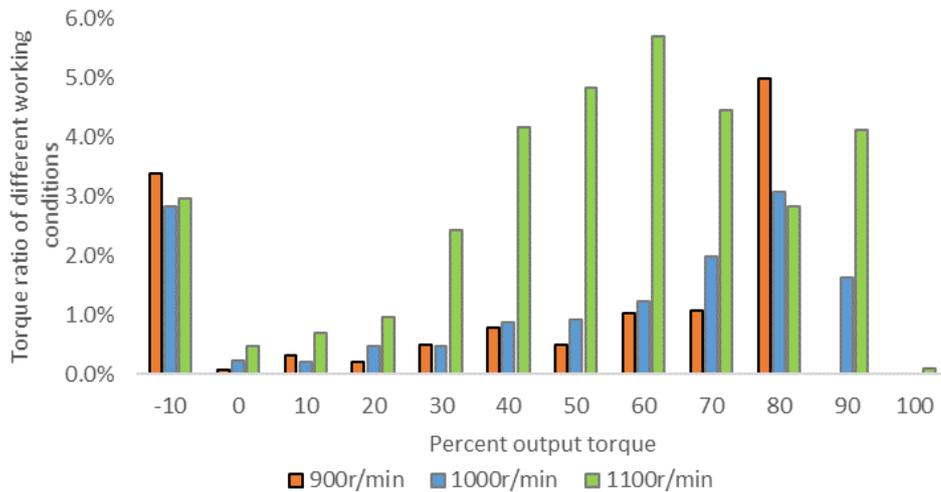
Figure 12. Torque ratio under different hybrid conditions.

The data of 3 typical working conditions with relatively large torque were selected to recalibrate the model, and then a series arrangement (including series front and series back) was selected for simulation analysis. The results are shown in Figure 13.

It can be seen from Figure 13 that both power and torque can reach the original engine level when the two series arrangement forms are adopted. Regardless of motor power consumption, the rear is better than the front, and the fuel consumption is optimized by up to 11%. The three working conditions are partial load, there is no supercharger overspeed problem, and there is no maximum combustion pressure overlimit problem. The electric compressor is more efficient in the rear series system, and the turbocharger is more efficient in the front series system.
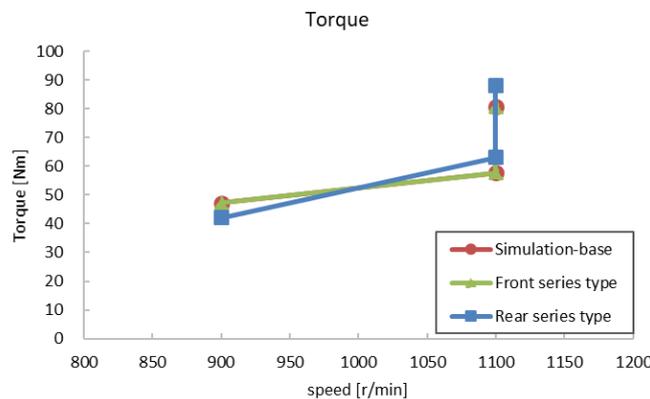
(a) Torque comparison between series types and base under hybrid conditions
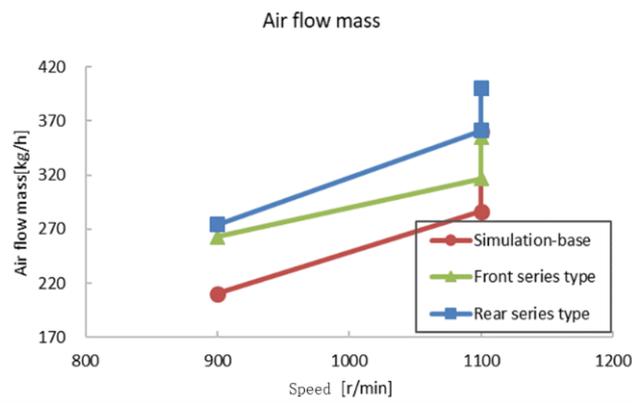
(**b**) Air flow mass comparison between series types and base under hybrid conditions
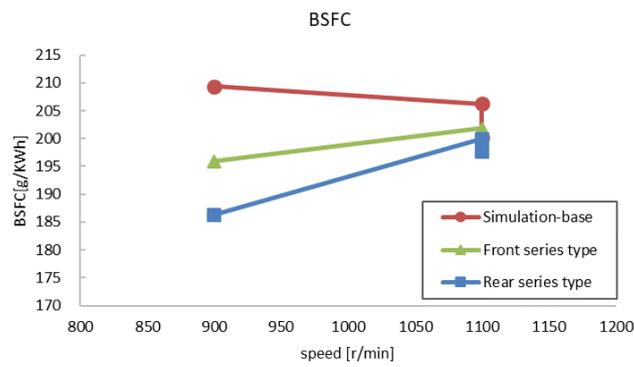
(**c**) BSFC comparison between series types and base under hybrid conditions
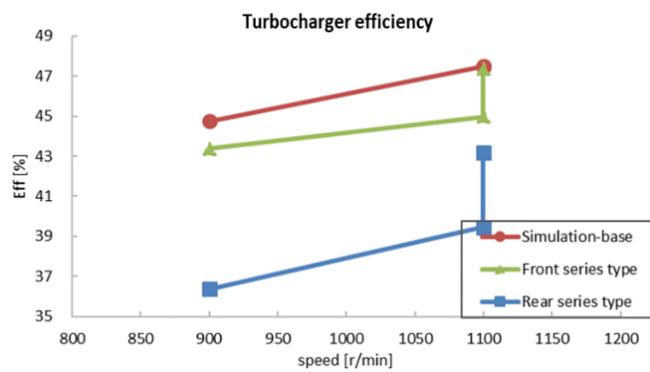
(**d**) Turbocharger efficiency comparison between series types and base under hybrid conditions
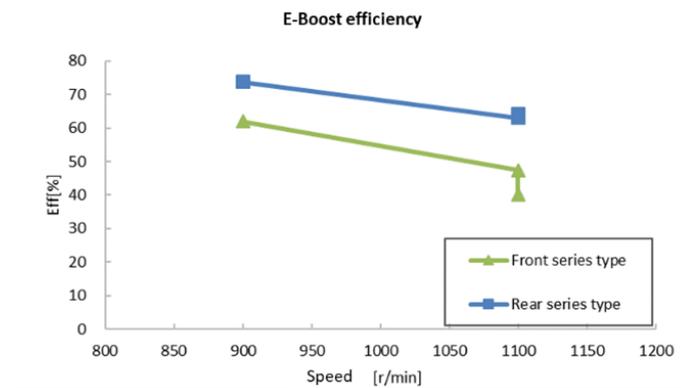
(**e**) E-Boost efficiency comparison between series types and base under hybrid conditions

Figure 13. Simulation results of the electrical boosting system under hybrid conditions.

7. Conclusions

The electrification of the diesel engine is an important technical way to save energy and reduce emissions. Compared with the turbocharging system of the traditional diesel engine, the electrical boosting system can further improve the charging efficiency of the diesel engine, and improve the low-speed torque and transient response. The conclusions of this paper are as follows:

(1) Based on a mass-produced medium-sized diesel engine platform and the corresponding hybrid platform, the influence of the electrical boosting system on power performance and fuel economy under the parallel layout, series-front layout, and series-rear layout of the electrical boosting system was studied. The results show that the parallel electrical boosting system can increase the low-speed torque by up to 9%, improve the intake air volume by 42%, and reduce the specific fuel consumption by 9%. However, when using the parallel layout, an electrical boost similar in size to the turbocharger needs to be used in combination and re-matched to achieve the best results.

(2) When arranged in series at the front, the low-speed torque can be increased by 13%, the intake air volume can be increased by 44%, and the BSFC (brake specific fuel consumption) can be improved by 12%. When arranged in series at the rear, the torque can be increased by 11%, the intake air volume can be increased by 37%, and the BSFC can be improved by 11%. However, an additional intercooler is required for the rear layout, which increases the cost. Moreover, the electric compressor only operates under low-speed conditions to increase torque and optimize fuel consumption. At high speeds, further optimization of the matching with the original engine turbocharger is needed.

(3) Under the typical hybrid operating conditions of the hybrid platform, both power and torque can reach the target levels. The rear layout is superior to the front layout. The specific fuel consumption can be optimized by up to 11%. The rear electrical boost has a higher efficiency, while the front turbocharger has a higher efficiency. There is still room for optimization in the existing matching schemes of the electric boosting system.

(4) For diesel engines, the larger the displacement, the larger the electrical boost required for matching, and the higher the requirements for the rotational speed, power, and reliability of the corresponding motor. Therefore, there are currently no mass-produced electrical boost for large-displacement diesel engines on the market. Thus, the electrical boosting system for medium-sized engines described in this paper has a more promising commercialization prospect.

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Informed Consent Statement: Not applicable.

Data AvailabilityStatement: Not applicable.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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