

# Influence and strategy optimization of fuel injection timing on PN and fuel consumption

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**Abstract.** During the development of a CN VI light vehicle equipped with a GDI gasoline engine, the phenomenon of high PN appeared. In response to the operating conditions of the engine running in the WLTC cycle, a corresponding SOI sweep was performed on the dyno bench. The PN emissions of the engine has reduced by optimizing of SOI. The results show that when the SOI is sufficiently advanced, the oil film formed by the collision of the spray and the piston causes the PN emissions to increase significantly. In order to avoid the deterioration of the PN emissions, the SOI should be appropriately postponed. In the low load conditions, it is more appropriate to calibrate the SOI at 295°C A and 290°C A. In the medium speed area, it is more suitable to set it at 300°C A or later. The SOI in the higher speed area can be slightly advanced if necessary. And the impact of SOI on fuel consumption is more obvious at low speeds, but it is not obvious at the conditions of medium to high loads and speeds.

## 1 Foreword

*Limits and measurement methods for emissions from light-duty vehicles (CN VI)* requires the number of PN emission of light vehicle cannot exceed  $6 \times 10^{11}$  in one WLTC cycle<sup>[1]</sup>. With the gradual implementation of China VI emission standards across the country, more and more manufacturers need to upgrade or update the powertrain system of their vehicle. In terms of hardware, many manufacturers have replaced injectors with more injection holes to improve the fuel atomization effect, while adding GPF to filter particulate matter<sup>[2-5]</sup>. The GDI engine also uses a higher-pressure oil pump to reduce the generation of PN. In terms of engine control strategy, it is also essential to adjust the injection strategy<sup>[6]</sup>. Compared with the control strategy calibration of the CN V that focuses on fuel consumption, the situation of particulate emissions also needs to be considered during the development of the CN VI project. In this paper, during the development of a CN VI model, the phenomenon of higher PN was encountered, and the condition spot was scanned on the engine dyno bench to complete the optimization of the injection time.

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## 2 Dyno Test Stand Construction and Data Acquisition

The parameters of the vehicle to be optimized are shown in Table1. The engine on the vehicle is a 1.8L inline four-cylinder dual-VVT GDI gasoline engine. The relevant engine parameters are shown in Table2. According to the CN VI standard and the relevant fuel consumption limit regulations, The relevant regulatory limits that need to be met are shown in Table3.

**Table 1.** Parameters of vehicle.

Reference Mass(kg)	Maximum Mass(kg)	Drive Mode	Engine assembly method	Gearbox	Main Reduction Ratio
2104	2649	FR	Longitudinal	6MT	4.3

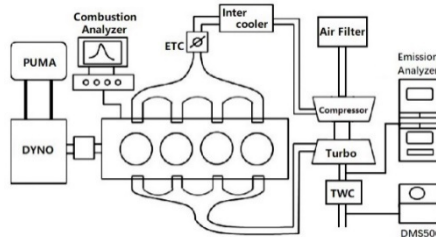
**Table 2.** Engine parameter.

Number of cylinders and cylinder arrangement	Engine capacity (CC)	Cylinder bore (mm)	Compression ratio	Fuel label
L4	1765	79	10.4	92# CN VI
Normal idle speed(r/min)	Engine Max speed (r/min)	Max design power/speed (kW/r·min <sup>-1</sup> )	Max design torque/speed (N·m/ r·min <sup>-1</sup> )	Injection pressure (MPa)
750	6800	165/6000	300/1800-5000	35

**Table 3.** Regulatory limits.

CO	THC	N·MHC	NOx	N2O	PM	PN	Fuel consumption
740 mg/km	80 mg/km	55 mg/km	50 mg/km	30 mg/km	3 mg/km	6.0×10 <sup>11</sup> #/km	9.1L/100km

The bench uses the AVL dynamometer and its PUMA console, and the PN measurement device is Cambustion DMS500. After the construction is completed, see Fig.1.



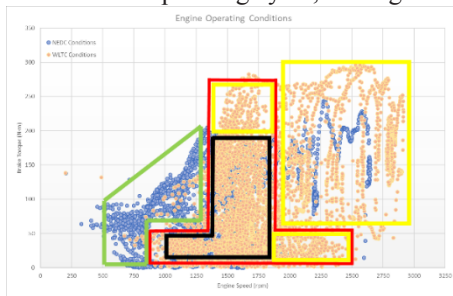
**Fig. 1.** Schematic diagram of engine bench.

In the test, the pressure and temperature valves of the engine inlet and exhaust system, the measured gas pollutants and the PN value are connected to the PUMA console. The IMEP of engine and heat release measured by the combustion analyzer are also connected to the PUMA console. In addition, INCA is used to connect to the ECU and read internal signals. During the test, after the engine is warmed up, the oil temperature and the water

temperature are controlled at about 90°C by the thermostatic system of the bench. The engine speed is controlled by PUMA, and the engine torque request is controlled by INCA, so that the engine can be stabilized at a certain operating condition. When the engine operating condition is stable, a set of 10s steady-state data is measured. The test results are based on the optimal ignition advance angle and stoichiometric mixture. The same VVT opening is used under the same working conditions.

### 3 Test results and analysis

At the current stage, the vehicle's fresh emission level is evaluated using the WLTC cycle, while the vehicle's fuel consumption level is evaluated using the NEDC cycle<sup>[1,7]</sup>. Collect the relevant data of the vehicle in the NEDC cycle and the WLTC cycle, and draw the operating point of the engine in the corresponding cycle, see Figure 2.



**Fig. 2.** The engine conditions between NEDC cycle and WLTC cycle.

It can be found that the engine operating conditions in the WLTC cycle are concentrated in:

1. 1000r/min-2250r/min, 0N·m-50N·m, medium and low speed and low load working conditions.
2. All load conditions at 1500r/min and 1750r/min. It is marked with a red border in Fig.2.

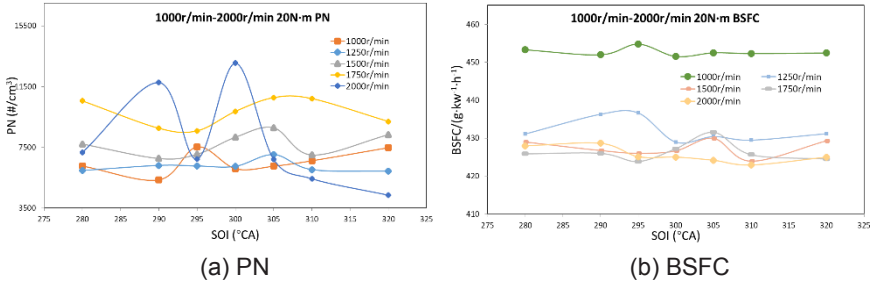
Compared with the NEDC cycle, the WLTC cycle uses the engine speed of 2000r/min-2500r/min and the torque of 0N·m-50N·m. Torque 50N·m-300N·m partial conditions. This part needs to focus on the emission effect of particulate matter, which is marked with a yellow border in Fig.2. In addition, the engine operating conditions used by NEDC need to focus on the performance of fuel consumption, which is marked with a green border in Fig.2. For the black frame, both fuel consumption and particulate emissions must be considered.

#### 3.1 Test result and optimization of bench sweep point

In this bench test, according to the corresponding working conditions included in the black frame in Figure 2, different fuel Injection Start Time (SOI) was selected for the sweep point, which is relative to the Before Top Dead Center (BTDC).

##### 3.1.1 Results of Sweep Point of Engine under Low Load Conditions

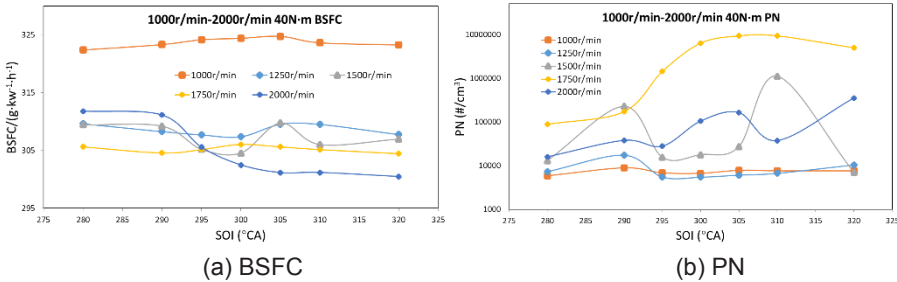
The operating points of 20N·m and 40N·m in the speed range of 1000r/min-2250r/min were selected respectively, and the sweep point test of SOI was conducted every 5°CA within the range of 280°CA-320°CA. The test results are as follows:



**Fig. 3.** PN & BSFC results of sweep point of 20N·m conditions in 1000r/min–2000r/min.

Fig.3 shows the trend of PN emissions and Brake Specific Fuel Consumption (BSFC) with SOI in the 20N·m load region at different speeds. The Fig.3(a) shows that under 20N·m load conditions, BSFC has a gradual decrease trend with increasing speed, and at 1000r/min the fuel consumption performance is the worst. SOI has a certain effect on fuel consumption. With the advance of SOI, the BSFC performance has decreased in fluctuations, and the trend is not obvious. Comparing the performance under different operating conditions, when SOI is at 300°CA and 310°CA, the performance is better, but the performance is worse at 305°CA.

At 20N·m operating conditions, the PN emissions are basically in the range of 3500 #/cm<sup>3</sup>-16000 #/cm<sup>3</sup> as the shown in Fig.3(b). At low speeds, the PN emissions gap is not obvious. When the speed increases to 1750r/min, the PN emissions increase significantly, and at 2000r/min, the PN has a more obvious effect. As can be seen from Fig.3(b), when the SOI is at 295°CA and 310°CA, the overall performance of PN is better.



**Fig. 4.** PN & BSFC results of sweep point of 40N·m conditions in 1000r/min–2000r/min.

In the 40N·m operating condition, the fuel consumption is much lower than the 20N·m operating condition, as Fig.4(a) shown. The same as the behaves as 20N·m, the BSFC at 1000r/min is different from other speed operating conditions. In the low load range, with the engine speed and the load increases, the fuel consumption performance becomes better and better. Due to the rate of BMEP increases in IMEP. And the effect of combustion efficiency in low-load operating conditions is not obvious. From the perspective of the impact of SOI, similar to the 20N·m operating condition, there is a downward trend in fluctuations. The top SOI is conducive to the performance of fuel consumption. As Fig.4(b) shown, PN emissions rise to the range of 5E3-1E7 in the 40N·m operating condition. The engine consumes more fuel, which means that the ability to manufacture PN has also improved. In the 1000r/min and 1250r/min operating conditions, PN shows an upward trend in fluctuation with the advance of SOI. At 1500r/min, 1750r/min, and 2000r/min operating conditions, SOI has a great influence on PN, and can differ by 1 to 2 orders of magnitude. Especially at 1750r/min, when the SOI advances to 300°CA, the PN emissions

quickly rise from  $1E5$  to  $1E7$ . Compared with the  $20N\cdot m$  operating condition results in Fig.3,  $295^\circ CA$  is a better choice. But this SOI is not the best choice for fuel consumption.

On the whole, there is no trend that PN and fuel consumption are completely consistent. In the case of better fuel consumption, the PN emissions are relatively high. Due to the different number of PN particles in different working conditions, the number of particles varies greatly, and the intermediate phase differs by several orders of magnitude. Therefore, under light load conditions of  $20 N\cdot m$ , the PN results of a smaller order of magnitude will not have a particularly large impact on emissions. At the same time, considering the error of the test instrument, the trend is not obvious, and the fuel consumption performance should be focused. So for  $20N\cdot m$  working conditions, SOI can choose  $300^\circ CA$  or advance to  $310^\circ CA$ . For  $40N\cdot m$  working conditions, PN has been greatly affected by SOI. Overall,  $295^\circ CA$  is more suitable. Although the PN emission at  $1750r/min$  is abandoned here, considering the smoothness in the calibration table, the pursuit of the optimal choice under each operating condition should be avoided.

### 3.1.2 Results of sweep point of engine in 1750r/min conditions

For the engine operating conditions around  $1750r/min$  that are frequently used in the WLTC cycle, the operating point of the speed of  $1750r/min$  and the torque of  $60N\cdot m$ - $160N\cdot m$  were selected for the sweep point test of SOI. The test results are as follows:

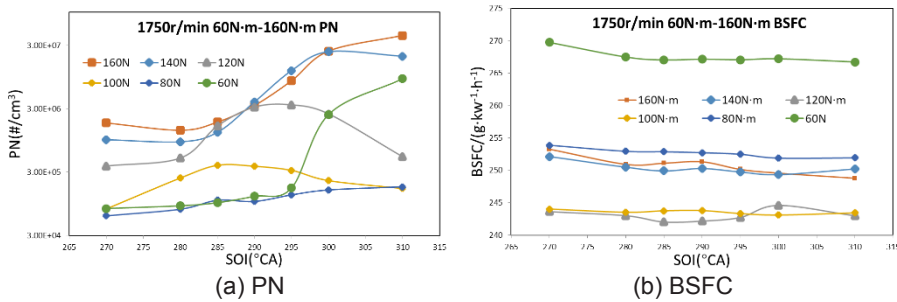


Fig. 5. PN & BSFC results of sweep point of conditions in 1750r/min.

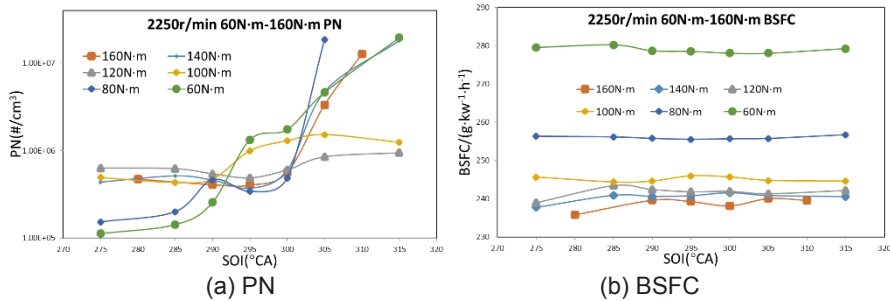
As shown in Fig.5(a), at  $1750r/min$  conditions, PN emissions cover the range of  $1E5$  to  $1E8$ , with a large degree of change. As the load increases, the PN emission level gradually deteriorates, and at the same time, SOI has a significant effect on the PN emission. In the  $60N\cdot m$  load, the delay of SOI can cause PN degradation by two orders of magnitude. When the SOI advances to  $305^\circ CA$ , PN emissions begin to be bad. The performance of PN emissions also differs greatly under higher load conditions. Under the conditions of  $100N\cdot m$  and  $120N\cdot m$ , PN emissions tend to deteriorate first and then decline with the advance of SOI. The highest points of its PN emissions are at  $285^\circ CA$  and  $295^\circ CA$ , respectively. Under the operating conditions of  $140N\cdot m$  and  $160N\cdot m$ , there is also a trend that PN's emission results become worse as SOI advances, so it is necessary to adjust the injection strategy for PN. From Fig.5(a), the PN performance is better at the later injection timing. Except for individual operating points, the performance of PN emissions gradually deteriorates with the increase of SOI. In order to improve the results of PN emissions, the latter SOI should be considered.

Fig.5(b) shows the fuel consumption performance under various operating conditions at a speed of  $1750r/min$ . As the load increases, the BSFC of the engine decreases first and then rises, reaching the optimal fuel consumption at  $100N\cdot m$  and  $120N\cdot m$ . For the change trend of fuel consumption under each load, with the advance of SOI, fuel consumption has

decreased in fluctuations. This downward trend is not obvious under the operating conditions of 100N·m and 120N·m. On the whole, as fuel injection advances, fuel consumption decreases and PN rises. For the selection of SOI, it should be as far as possible to reduce fuel consumption on the premise of avoiding it falling in areas where PN rises significantly. It is more appropriate to choose at 290°CA.

### 3.1.2 Results of sweep point of engine at medium speed and medium & high load conditions

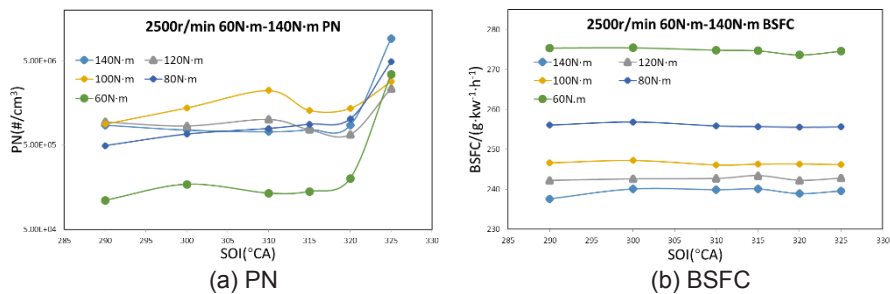
Compared with the NEDC cycle, the WLTC cycle uses a higher engine speed and higher load region. Considering the large gas flow in this region, high PN emissions will have a more significant impact on the emissions results. Therefore, the speed of 2250r/min 2500r/min, load 80N·m, 100N·m, 120N·m, 140N·m, 160N·m operating are selected to sweep SOI point.



**Fig. 6.** PN & BSFC results of sweep point of conditions in 2250r/min and medium-high load.

Fig.6 shows the changes of PN and fuel consumption with SOI at various loads at 2250r/min. As can be seen in Figure 6a, at the 60N·m and 80N·m operating conditions, the PN gradually increases with the advance of the SOI. When the SOI is in advance, the PN emission results even exceed the higher load operating conditions. For the operating point of 100N·m to 160N·m, when the SOI is from 275°CA to 295°CA, the PN emissions have basically not changed, or even decreased. However, when the SOI is advanced to 300°CA, the PN emissions increased significantly.

As for the fuel consumption, as shown in Fig.6(b), as the load increases, the engine fuel consumption gradually decreases, from 120N·m to a larger load, the specific fuel consumption can reach 240 g/(kw · h) or less. For the change of SOI, the fuel consumption performance is not sensitive, basically maintained at the same level. At higher load conditions, the fuel consumption at the later injection time will be lower.



**Fig. 7.** PN & BSFC results of sweep point of conditions in 2500r/min and medium-high load.

At the operating point of 2500r/min, see Figure 7, except that the PN emission is lower at 60N·m, the PN of other operating conditions is basically the same order of magnitude. The trend of PN emission with SOI is similar to the 2250r/min operating condition, and it is also insensitive to the injection time when the fuel is injected later. When the SOI advances to a certain position, PN emissions increase significantly. For 2500r/min operating conditions, the SOI that causes the PN to rise is higher than 2250, which appears at 315°CA - 320°CA. The fuel consumption trend is similar to the 2250r/min operating condition. As the load increases, the specific fuel consumption gradually decreases. Compared with 2250r/min, the engine fuel consumption level changes with SOI is less obvious.

On the whole, for the engine at medium and high speed and high load conditions, the effect of SOI on fuel consumption is not obvious, but the effect on PN is obvious. Therefore, in the point selection process, you can choose the later point of SOI, such as 280°CA to 290°CA.

### 3.2 Result analysis

From the above data, the trend of fuel consumption is not obvious. In low-speed and low-load operating conditions, it shows that as SOI advances, fuel consumption decreases in fluctuation. As engine speed and load increase, fuel consumption changes with SOI less obvious. From the analysis point of view, one is that the fuel consumption meter has errors. When the two adjacent SOI operating conditions have no obvious effect on the fuel consumption, the error of the fuel consumption meter will mislead the results. Therefore, under medium-high speed and medium-high load conditions, the engine output power increases, the amount of fuel consumed per unit time rises, and the influence of the fuel consumption meter error decreases, making the change in fuel consumption smoother. In addition, when the engine operating conditions are changed, the ignition angle and other parameters will be adjusted at the same time as the injection time is changed, so that the engine is in the best state at this injection time, and this process will take some time until the engine operating conditions are stable. Different degrees of engine stability will also affect the fuel consumption results. This will also affect the PN measurement results.

In addition, it should be considered that although the VVT combination is fixed when the SOI sweeps, the opening of VVT is different under different speeds and loads. This reflects that under some operating conditions, the changes in fuel consumption and PN with load are not monotonous, and it also shows to some extent that the performance of PN and fuel consumption with SOI is not consistent under different speed loads.

As for the impact of SOI on PN emissions, the main consideration is the formation of the mixed gas. The formation of the mixed gas is partly affected by the injection timing, and partly by the strength and speed of the intake tumble at different speeds. From the perspective of the mechanism of particulate matter formation, part of the richer gas mixture, incompletely evaporated oil droplets, and the oil film formed on the cylinder wall and the piston crown are the reasons for the formation of particulate emissions<sup>[8]</sup>. The GDI gasoline engine injects fuel directly into the cylinder, and the mixture formation time is shorter, which is not conducive to the emission of particulate matter. In the low-load area, the engine requires less fuel injection, and higher injection pressure will cause the injection pulse width is very short, and it is possible to enter the nonlinear region of the injector, resulting in the actual air-fuel ratio of oil and gas is not near the average equivalent ratio, and reducing the rail pressure will have an impact on PN emissions, these need to be balanced.

In addition, the influence of the piston position on the injection effect must also be considered during the intake and compression processes. Under low speed and low load conditions, when the SOI advances to about 295°CA, the engine is in the state of the intake



stroke and the piston is descending. Considering the position of the piston, the oil injection will cause a part of the oil to hit the top of the piston. When the SOI is advanced to about 330°CA or more, the PN emissions in some operating conditions have decreased, because the opening time of the intake valve is shorter, the average turbulent kinetic energy of the gas in the cylinder is higher, and give fuel a longer evaporation time, which is conducive to PN emissions.

When the engine runs to medium-high speed and medium-high load, the oil film on the top of the piston formed by the earlier fuel injection has a more obvious effect on PN emissions, and the phenomenon of PN decline earlier no longer occurs because the engine speed increases, the time between the intake and compression strokes becomes shorter, the time to evaporate the oil film also decreases, and the unevaporated oil film causes the deterioration of PN emissions. There is another point, comparing the 2250r/min and 2500r/min operating conditions, the turning point of SOI caused PN emission deterioration in the 2500r/min operating conditions appeared earlier, at 320°CA. Analysis believes that at higher speeds, the piston movement speed is accelerated. Although the fuel injection is earlier, the higher movement speed of the piston prevents the fuel from forming an oil film on the top of the piston. This can be referred to when the injection speed needs to be calibrated at a higher speed.

## 4 Conclusion

(1) The earlier injection time will cause the fuel to be injected to the piston crown to form an oil film, resulting in a serious deterioration of PN emissions. Therefore, the final fuel injection should not be too forward.

(2) Considering the difference in speed of the piston at different engine speed conditions, if there is a demand for engine fuel injection at other times, the choice of SOI can be slightly forward to the premise with the speed.

(3) There are many influencing factors under low-load engine conditions, and the performance trends of PN and fuel consumption are not obvious. It should be based on actual tests to balance various considerations as the result of SOI selection.

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