

# Study on Compound Injection Technology in Gasoline Engines

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**Abstract**—This paper described the compound injection (PFDI) technology that combines the port fuel injection (PFI) and gasoline direct injection (GDI) system, and optimized the injection parameters by experiments to meet different requirements for mixture concentration at different conditions to improve power performance and fuel economy, and reduce emissions. The two typical gasoline engine fuel systems, PFI and GDI, were studied and their power, fuel economy performance and emissions were compared by experiments. The experiments show that the two systems have different adapting conditions and the particulate emission is the most drawbacks for the GDI engine. The advantages and current application of the PFDI system were studied and the future application strategy was discussed. The results indicate that the PFDI system can fully utilize the advantages of PFI and GDI and achieve lower emissions and better fuel economy, prominently reduce the particulate emission. The PFDI system has been implemented by several OEM to meet the Euro 6+ emission standards.

**Keywords**—Gasoline Engine; Port Fuel Injection (PFI); Gasoline Direct Injection (GDI); Compound Injection (PFDI); Emission

## I. INTRODUCTION

As environmental pollution and energy crisis become increasingly prominent and vehicle emission regulations are increasingly stringent, automobile manufacturers are motivated to develop new technologies to reduce emissions and improve fuel economy (FE)<sup>[1]</sup>. The GDI engine injecting fuel directly into the cylinder has many advantages, including improving engine volumetric efficiency & knock limit, increasing Compression Ratio (CR), and eliminating the fuel “blow-through” which results in improvements in FE and torque/power<sup>[2]</sup>. Besides, the engine cold start capability is improved. Thus GDI becomes a prevailing trend in the gasoline engine development<sup>[3]</sup>. However, disadvantages of GDI engines with large amount of particulate emissions, poor performance at low load and low speed conditions, high pressure fuel pump friction, fuel dilution in oil, and the fuel system tick noise at idles are challenges for modern automobiles.

Some automobile manufacturers have introduced compound injection (PFDI) technology to gasoline engines. The PFDI engine which implements both PFI and GDI injection with a intake port injector and a cylinder injector can fully take advantages of PFI and GDI<sup>[4]</sup>. The aim of this paper is to describe the PFDI system optimization of injection parameters to meet different requirements for

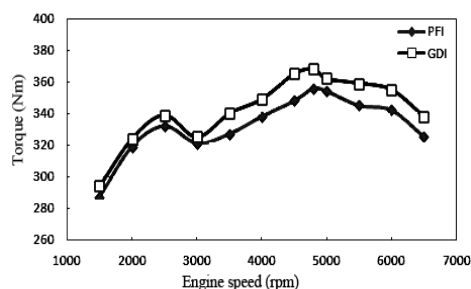
mixture concentration, improving load performance and FE, and reducing emissions. The PFI system can help to resolve the GDI engine fuel dilution in oil as well as fuel system tick noise, and improve idle combustion stability. With Euro 6.3 emission standards being implemented, the PFDI system becomes crucial to meet the emission standards.

## II. ANALYSES ON THE GDI SYSTEM

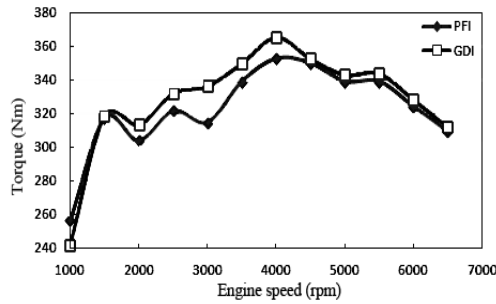
### A. The advantages of GDI system

#### 1) Improvement in torque/power, efficiency, knock limit, FE, and cold start capability

For the GDI engine, the fuel is injected, atomized, and vaporized in cylinders whose latent heat can be used to reduce the intake charge temperature<sup>[5]</sup>. Based on the ideal gas law, the cooler air has higher density. Considering that the Hv of gasoline is about 350 kJ/kg, specific heat of charge is about 1.0 kJ/kgC and A/F (air/fuel) ratio is 14.6, it can be concluded that the total charge cooling potential of GDI due to vaporization is about 40°C. If 100% of potential charge cooling is utilized, it would result in 7-8% charge density improvement which means 7-8% torque/power improvement. It would also result in about 6 degrees knock limited spark increase which brings 1 CR increase. With practical limitations, only about 50% of the charge cooling capability is utilized in real systems which will result in about 3% of engine torque/power and volumetric efficiency improvements. Fig. 1 shows torque improvements of GDI vs. PFI from two engines which are tested with both PFI and GDI and other systems kept common during testing. Fig. 2 and Fig. 3 show the GDI improvements in volumetric efficiency and Knock Limit Spark Angle (KLSA) from one of the engines in Fig. 1.



(a) Comparison on torque between PFI and GDI of engine #1



(b) Comparison on torque between PFI and GDI of engine #2

Figure 1. Comparison on torque between PFI and GDI.

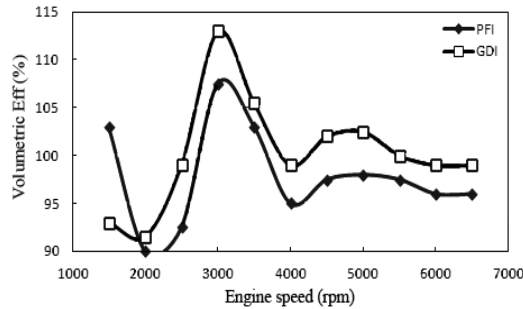


Figure 2. Comparison on efficiency between PFI and GDI.

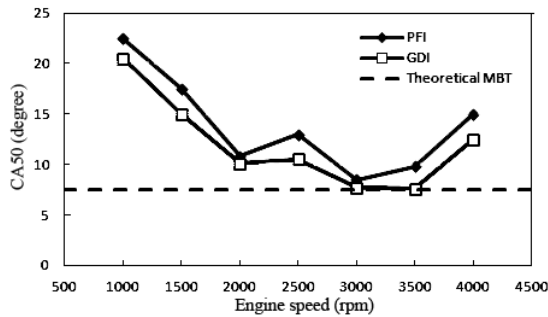
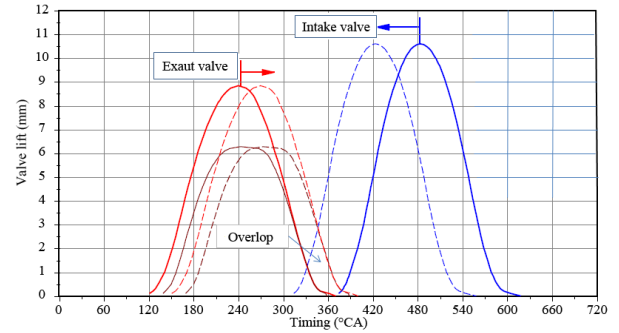


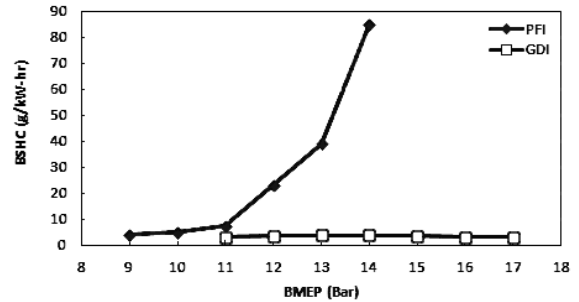
Figure 3. Comparison on efficiency between PFI and GDI.

## 2) Eliminate the fuel "blow-through"

PFI systems produce a liquid fuel film on intake valve and port. At high engine load conditions, due to valve overlap, some of the liquid fuel will be carried from intake port directly to exhaust port by fresh air (called scavenging or blow-through) which results in higher HC emissions and lower FE. Conversely, GDI systems inject fuel directly into cylinders so that they have minimal liquid fuel. It can be seen from Fig. 4, due to the blow-through that the PFI engine's BSHC (Brake Specific Hydro Carbon) increases



(a) Overlap



(b) The blow-through effect on BSHC of PFI and GDI engine

Figure 4. The overlap and blow-through effect on BSHC

## 3) Improve cold start capability

The PFI engine provides a poor control over the A/F entering the cylinder during the cold start. Besides, the wall wetting of cold surfaces causing high HC emissions<sup>[6][7]</sup>. While the GDI engine injects gasoline directly into the cylinder, it provides fast response to controlling the A/F. The GDI engine provides higher fuel pressure which leads to better fuel atomization, in combination with the suitable piston shape, injection timing and injection ratio can result in better mixture of fuel and air<sup>[8]</sup>. These factors lead to good transient response, making the start smoothly and quickly for GDI system. Besides, the GDI engine can make the catalysts, which are efficient only at high temperature, warm up quickly, reducing the unburned HC emissions<sup>[9]</sup>.

## B. The disadvantages of GDI system

### 1) High GDI fuel pump friction

The GDI system contains a high pressure fuel system and a low pressure fuel system. The pressure of the high pressure fuel system can reach 25-35MPa. The high pressure (HP) pump of the GDI engine is usually a cam-driven mechanical pump with three or four lobes. The pump friction leads to mechanical loss. For the three lobes pump, it usually takes 0.35Nm engine torque to drive and the mechanical loss can reach 1.5kPa. For the four lobes pump, it usually takes 0.6Nm engine torque to drive and the mechanical loss can reach 2.5kPa. It is estimated that 10kPa mechanical loss induces about 1% decline in fuel economy. The engine crank torque needed to overcome the friction is shown in Fig. 5.

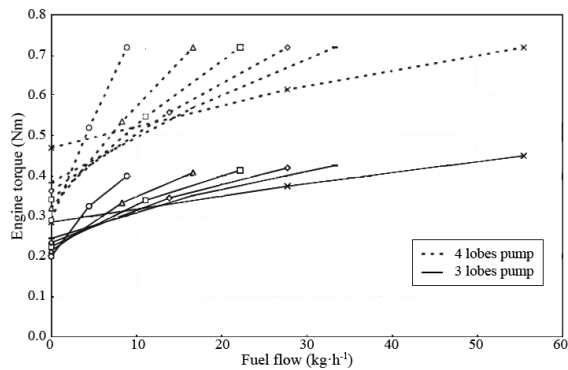


Figure 5. Engine crank torque needed to overcome pump friction

## 2) Fuel Dilution in Oil

Piston is traveling down in the intake stroke injection process. If injecting too earlier, fuel hits the piston and a fuel film is generated impeding total fuel evaporation and efficiency<sup>[3]</sup>. If injecting too later, piston moves out of the way and the fuel hits the bore wall and is pumped into the crank case going into oil. Therefore, GDI has much severe fuel dilution in oil than PFI. Fig. 6 shows that PFI engines have extremely low fuel dilution comparing to GDI engines.

## 3) GDI system tick noise

GDI system noise is mainly from the HP pump and fuel injectors. And it is prominent in idling and some other low speed and low load conditions.

The cam-driven HP pump of the GDI engine is shown in Fig. 7. Pressure is generated by a mechanical control valve (MCV). It can be seen from Fig. 8 that the opening and closing process of the MCV produce shock and vibration which radiate noise through the HP pump and the engine structures. Meanwhile, the driving cam causes cyclical changes in pressure, resulting in the GDI system producing shock and vibration. Besides, the continuous pressure wave in the rail provokes noise propagating into air.

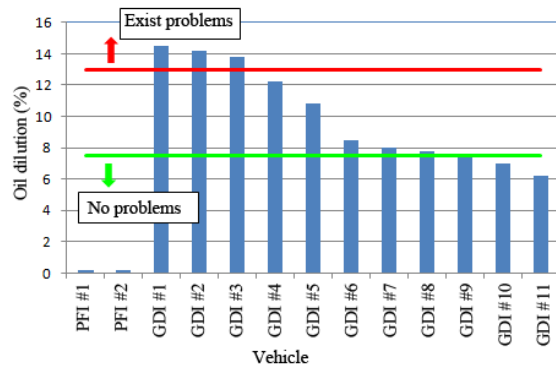


Figure 6. Oil dilution

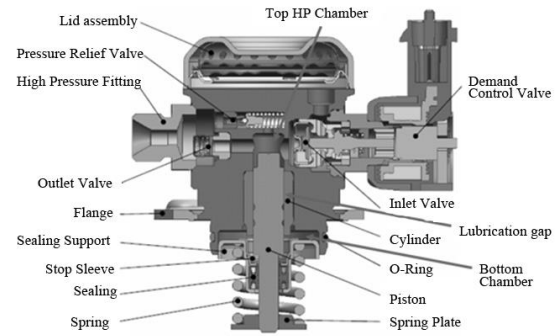


Figure 7. Impacts on GDI fuel tick

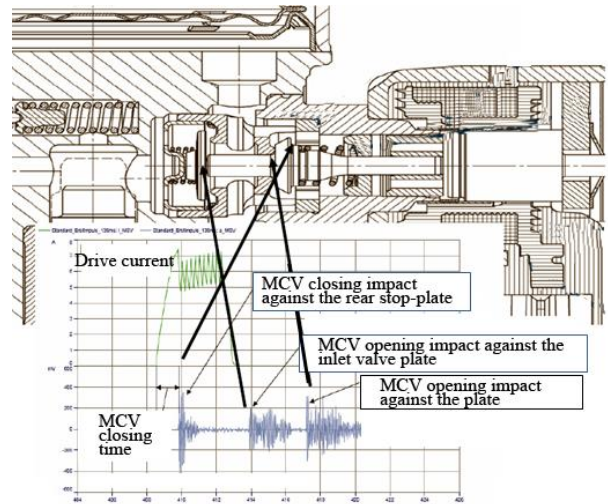


Figure 8. Pump collision in the MCV opening and closing process

## III. COMPARISON BETWEEN PFI AND GDI

PFI and GDI systems are compared in several conditions. To ensure the accuracy, the tested engines have the same displacement and are tested with both PFI and GDI.

### A. Comparison on power and FE between PFI and GDI

The comparison on PMEP and BSFC between PFI and GDI are shown in Fig. 9 and Fig. 10. The lines represent the percent difference between PFI and GDI (PFI-GDI). It can be seen from the two figures that PFI performs better than GDI in the low speed and low load conditions while opposite in high speed and high load conditions.

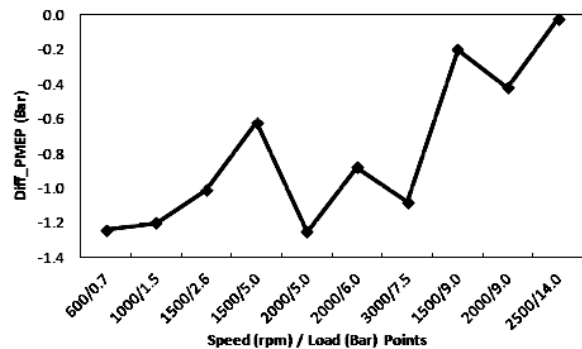


Figure 9. Difference PMEP of PFI and GDI

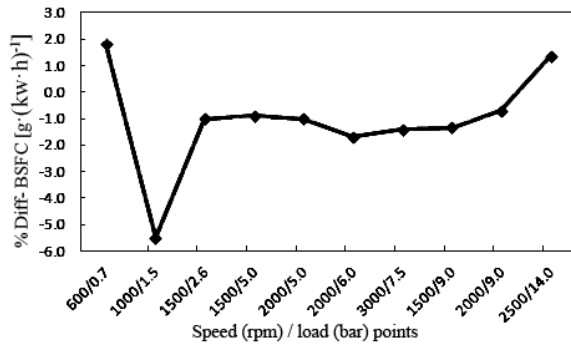
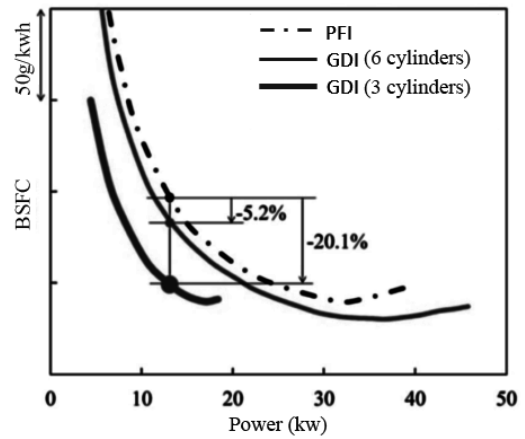


Figure 10. Difference BSFC of PFI and GDI

To study the FE of PFI and GDI systems, an automobile manufacturer conducted a research on a 2.0L and a 1.0L engine. For the 1.0L engine, the PFI is better than the GDI by about 1.2%. While for the 2.0L engine, the FE of GDI is improved about 1%.

It indicates that adding GDI to a naturally aspirated engine only has 0-1% of BSFC improvement and larger benefit on larger engines while little or no benefit on small engines. And the FE improvements of GDI engine largely come from: the increase of CR when GDI is applied in turbocharged or supercharged engines, engine downsizing due to the about 3% improvement of torque, and the improvement of the start/stop capability.

Due to the increase of CR, the GDI engine can reduce displacement while don't compromise in power. The comparison on power and FE between a Honda Acura 3.7L PFI engine and a 3.5L GDI engine are given in Fig. 11.



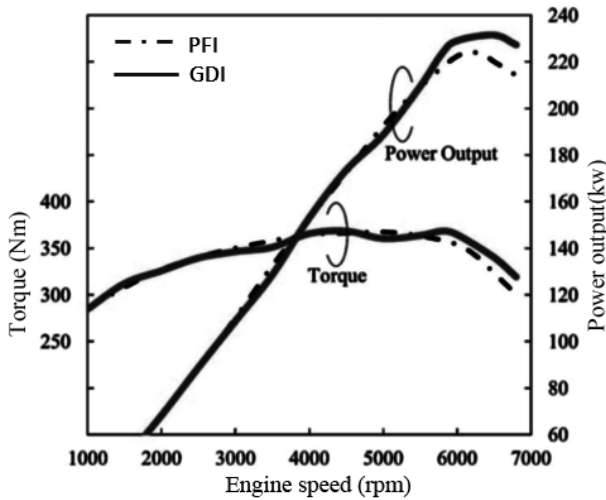
(b) The comparison on FE

Figure 11. The comparison on power and FE between a 3.7L PFI engine and a 3.5L GDI engine

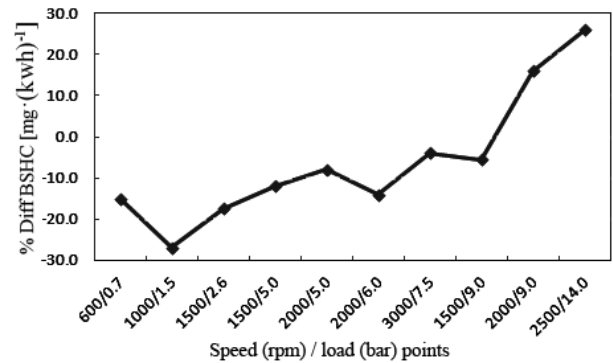
### B. Comparison on emissions between the PFI and the GDI engine

The PFI engine has the advantage of providing an almost perfectly homogeneous mixture at spark timing, while the GDI engine induces some residual large-scale fuel heterogeneities. Consequently, the GDI engine has higher CO emissions which are dependent on the degree of heterogeneities. Even in some conditions, the GDI engine can have lower CO emissions than the PFI<sup>[2]</sup>. The comparison on CO and HC emissions are shown in Fig. 12. The curves represent the percent difference between the PFI emissions and the GDI emissions. It indicates that PFI has lower CO and HC emissions than GDI in low speed and low load conditions, while GDI has lower CO and HC emissions than PFI in high speed and high load conditions.

Datas show that PFI and GDI have similar NOx emissions. Since the mixture is heterogeneous and fuel impinges on surfaces of piston and cylinder unexpectedly, the GDI engine may form large amount of soot in the combustion process and emit much more particulates than the PFI<sup>[10][11]</sup>. The particulate number (PN) of the PFI and the GDI engine are shown in Fig. 13. For the GDI engine, cold-start and acceleration conditions contributes most of the PM emission over NEDC<sup>[12]</sup>.



(a) The comparison on power



(a) Comparison on CO emissions

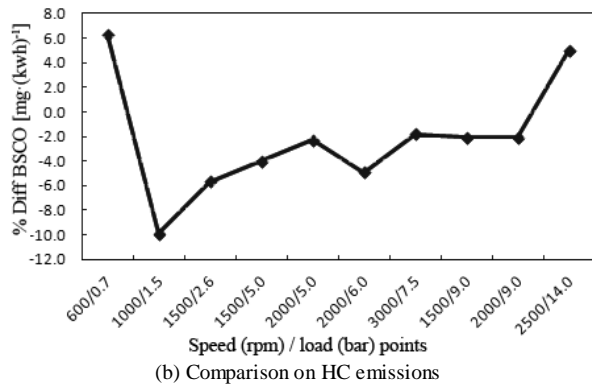


Figure 12. Comparison on CO and HC emissions between the PFI and the GDI engine

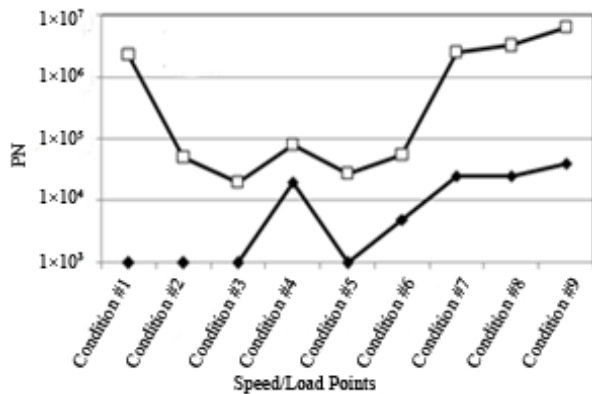


Figure 13. The PN emission of the PFI and the GDI engine

#### IV. STUDY ON THE PFDI TECHNOLOGY

##### A. The advantages of the PFDI system

The PFDI system combines the PFI injection with the GDI injection. The PFI system is used at lower speed and load conditions to improve FE by about 1%, reduce particulate emissions (PM and PN) and the GDI system tick noise at idle, improve the combustion stability at idle, and nearly eliminate the fuel dilution. The GDI system is used at cold start and higher speed and load conditions to reduce cold start emission, improve the FE by about 3% through engine downsizing, and increase the CR for boosting engine. By controlling the injection parameters of the two injection systems, the PFDI system can meet different mixture concentration requirements of the engine under different conditions, avoiding too lean and too rich area. Consequently, the PFDI system can reduce emissions and torque fluctuation, and improve combustion quality, FE and driving ability<sup>[13]</sup>. It can reduce HC emissions by around 20% in the high idling and cold start conditions<sup>[4]</sup>. The vehicles using the technology are expected to meet the ultra-low emission standards.

The technology has been applied in some models of Audi, Toyota and Honda vehicles. The Audi engines implement the PFDI technology with multiple injection strategy to improve fuel economy and reduce particulate matter, which successfully meet the Euro 6 emission standards.

##### B. The implementation strategy of the PFDI system

For the Audi engine, the PFI and GDI are used independently and in different conditions. The PFI is mainly used in low speed and low load conditions and the GDI is mainly used in moderate and high load conditions, as well as cold start condition to warm up the catalyst quickly. Its control strategy is shown in Fig. 14.

In other engines using PFDI technology, the GDI is used during the cold start to heat the catalysts quickly and high speed and high load conditions to increase efficiency and reduce fuel consumption and particulate emissions. And the PFI is used in the idling and low speed and low load conditions to reduce the tick noise and particulate emissions. In some cases, they are used simultaneously. A possible detailed explanation of future implementation strategy is shown in Fig. 15.

The PFDI system can be optimized by matching the injection parameters. Researchers have studied the influence of mixing the GDI and PFI injections on particulate emissions formation. The results are shown in Fig. 16, which indicates that when the ratio of PFI and GDI injection is 25-35% to 75-65%, the particulate emissions are lowest. And larger GDI ratio leads to an over-rich area and lower charge temperature, forming more particulates and deteriorating the spark ignition and early flame propagation process<sup>[14][4]</sup>. The GDI injection contains intake stroke injection and compression stroke injection, experiments show that when the injection ratio of PFI injection, GDI intake stroke injection and GDI compression stroke injection is 30% to 40% to 30%, the particulate emissions are lowest.

Adopting the strategy shown in Figure 15, the PFDI system can strongly reduce the particulate emissions. The particulate emissions of a GDI engine and a PFDI engine with different calibrations are shown in Fig. 17.

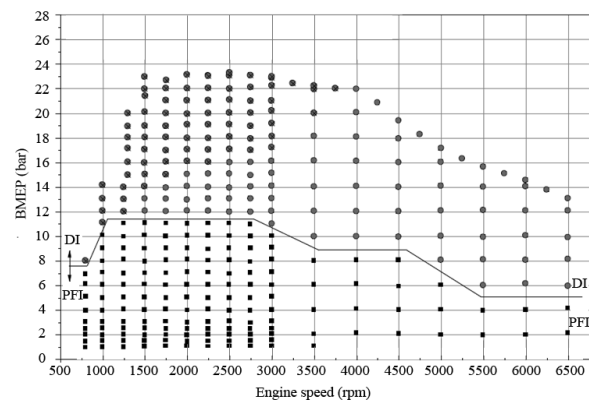


Figure 14. The Audi A5 PFDI control strategy



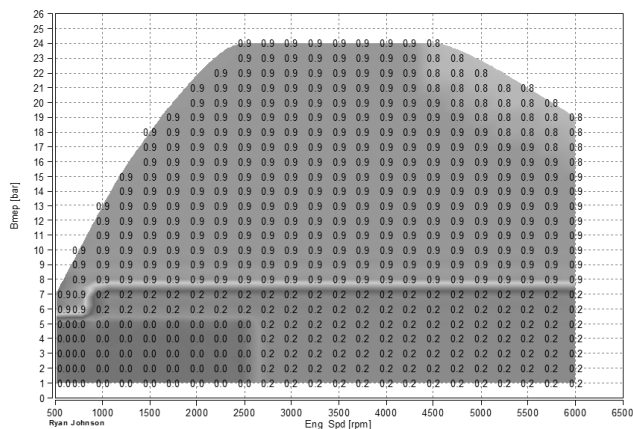


Figure 15. A possible detailed explanation of application strategy

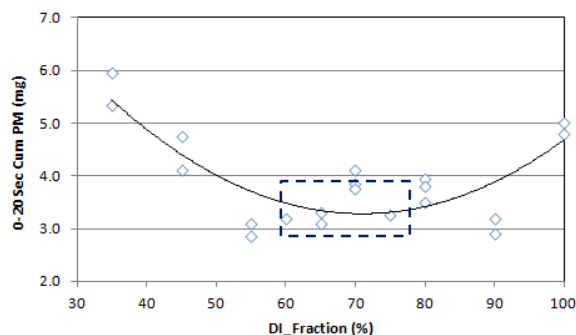


Figure 16. The influence of injection ratio on particulate emissions

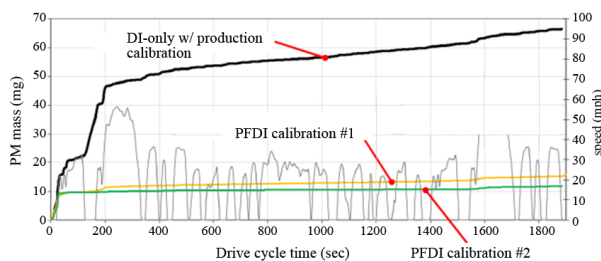


Figure 17. Cumulative PM mass of PFDI and GDI

Another factor to considerate is the injector deposit. If the GDI injector is not used for a period, the deposit will form at injector tip, which leads to changes in spray characteristic. Consequently, spray angle and envelope are likely to be affected, and spray penetration distance as well as droplet diameter can be increased. Injector deposits are primarily fuel-derived and created due to the low temperature auto-oxidation and high temperature pyrolysis<sup>[15]</sup> when there is no fuel flow through the injector. This is another reason why there is partial DI injection at low load conditions.

## V. CONCLUSIONS

The characteristics of the GDI system are: providing incremental charge cooling, which increases the charge density and effective CR; good FE performance at high speed and load conditions; lower cold start emissions; good stop/start capability.

The characteristics of the PFI system are good FE performance at low speed and load conditions; low particulate emissions (PM and PN); better combustion stability; low oil dilution and tick noise at idle.

The PFDI system can fully utilize the characteristics of PFI and GDI systems. It can meet different mixture concentration requirements of engines under different conditions with injection parameters optimized, resulting in FE improvement and emissions reduction. Especially the particulate emissions can be significantly reduced. Besides, it can reduce the fuel system tick noise and improve the idling stability.

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