Comparative Study on the Macroscopic Characteristics of Gasoline and Ethanol Spray from a GDI Injector under Injection Pressures of 10 and 60 MPa

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ABSTRACT: To reduce particulate matter (PM) emissions from vehicles powered by gasoline direct injection (GDI) engines, increasing the fuel injection pressure has been one promising approach. However, a comparison of macroscopic characteristics between gasoline and ethanol from a GDI injector under an ultrahigh injection pressure of more than 50 MPa has not been reported. The experimental study presented in this paper can provide some new and valuable information about comparing and analyzing the macroscopic characteristics of gasoline and ethanol spray from a GDI injector in both front and side views under injection pressures of 10 and 60 MPa. The experimental results show that compared to ethanol, gasoline spray has a slight advantage in $L_S$ (penetration of whole spray), $L_C$ (penetration of core region of spray), $\theta_S$ (spray cone angle), and $R_I$ (irregularity of spray boundary) under both $P_I$ (injection pressure) = 10 MPa and $P_I$ = 60 MPa, which would promote a more homogeneous mixture of air and fuel. Furthermore, the advantage of gasoline in $\theta_S$ is more pronounced under $P_I$ = 60 MPa. At the end of injection, $S_S$ (area of whole spray) of gasoline is around 2% larger than ethanol, while its advantage in $S_C$ (area of core region of spray) can be around 5%. With the increase of $P_I$ from 10 to 60 MPa, a marked increase of $R_S$ (the ratio of $S_C$ to $S_S$) and $R_I$ indicates that atomization and air–fuel mixture homogeneity can be significantly improved for both gasoline and ethanol spray. Besides, a minor revision to the Dent model helps achieve a significant improvement in the prediction accuracy of $L_S$ for both gasoline and ethanol spray under injection pressures of 10 and 60 MPa.

1. INTRODUCTION

Reducing particulate matter (PM) emissions from vehicles has been a major challenge for improving air quality in recent years. Due to its superior fuel economy and power performance, the gasoline direct injection (GDI) technology has been a mainstream technology of vehicle engines. However, vehicles powered by GDI engines are usually superior to those powered by port fuel injection (PFI) engines and even diesel engines with the diesel particulate filter (DPF). Furthermore, it is challenging to meet the stricter vehicle emission standards for PM emissions. In 2017, Euro 6c standard set a new limit of $6 \times 10^{11}$/km to particle number for GDI-powered vehicles, instead of $6 \times 10^{12}$/km of Euro 6b standard.

To improve air–fuel mixture quality and reduce PM emissions, increasing fuel injection pressure of GDI injector has been widely implemented and studied as one promising approach. The key findings in this area are summarized in Table 1, and the detailed descriptions are also found as follows.

Regarding the common GDI fuel injection pressure ranging up to 20 MPa, Whitaker et al. found that by increasing injection pressure from 0.4 to 15 MPa, the evaporation rates of fuel droplets can be improved during cold start in a single-cylinder optical GDI engine. Sabathil et al. concluded that with the increase of injection pressure from 6 to 20 MPa, particle number emissions of a GDI engine have a significant reduction of around 60% under cold operating condition of 30 °C coolant temperature. Lee et al. demonstrated that a linear reduction of around 5 mm in the droplet diameter can be observed for n-heptane sprays with the increase of injection pressure from 5 to 10 MPa and to 20 MPa. By analyzing soot radiation luminosity,
In summary, previous research has examined the effects of high fuel injection pressure on the characteristics of GDI spray. However, a few publications are reported on macroscopic spray characteristics, particularly ethanol spray, under an ultrahigh injection pressure higher than 50 MPa. Besides, the comparison of macroscopic characteristics between gasoline and ethanol from a GDI injector under an ultrahigh injection pressure is still unknown. Nowadays, to help achieve carbon neutrality and further reduce PM emissions, liquid biofuels have been proposed as common alternative fuels and a hotspot in academia. 27−34 Hence, it is essential to conduct a comparative study on macroscopic characteristics of gasoline and ethanol spray from a GDI injector under an ultrahigh injection pressure higher than 50 MPa.

In this paper, the experimental study aims to provide new information on the difference in the macroscopic characteristics of gasoline and ethanol spray from a GDI injector under injection pressures of 10 and 60 MPa. A comparative analysis was presented for the gasoline and ethanol spray in front and side views, via the key parameters of macroscopic spray characteristics, including spray penetration, cone angle, area, and irregularity. The findings of this study will not only provide a new and deep understanding of macroscopic spray characteristics under an ultrahigh injection pressure of GDI injectors but also help develop the theoretical basis about reducing PM emissions from vehicles by promoting a more homogeneous air–fuel mixture under an ultrahigh fuel injection pressure.

## 2. EXPERIMENTAL SETUP AND METHOD

### 2.1. Experimental Setup

The experimental investigation was conducted with a high-speed schlieren imaging system, as shown in Figure 1. The system mainly includes an optical...
schlieren subsystem, a high-speed camera, a fuel tank, a high-pressure pump, a GDI injector, a programmable electronic control unit (ECU), and a computer. The phenomenon of schlieren was first observed and described by Hooke\textsuperscript{35,36} in 1665. Afterward, the schlieren imaging system was developed around 1860 by Toepler\textsuperscript{37} to detect schlieren in glass used to make lenses. As presented in Table 2, compared to other optical diagnostic methods, the distinguishing characteristic of the schlieren imaging method is that the gas–liquid two-phase image can be detected simultaneously. Hence, the schlieren imaging method has been widely used to study the gas flow and spray characteristics in academia.\textsuperscript{38−41} The evolution of the spray was captured by a high-speed camera (Fastcam SA1.1), which is capable of acquiring images of “768 × 768 pixels at 10,000 frames per second (FPS)” and “512 × 512 pixels at 20,000 FPS”.

To get more comprehensive information of spray, the images were captured in both front and side spray views. Figure 2 shows the spray sketch map of the test GDI injector, which is from a dual-injection spark ignition (SI) engine and has five nozzles of 0.174 mm diameter. Table 3 presents the properties of gasoline and ethanol used in this study. During the experiment, a metal holder was used to ensure the injector stability and its perpendicularity to the ground. Fuel was injected into an ambient condition of 293 ± 0.5 K and 0.1 MPa. The fuel injection pressure was set to be 10 and 60 MPa, representing a conventional pressure and an ultrahigh pressure for the fuel injection of GDI injectors, respectively. The injection pulse was set to be 2.8 ms because a long pulse can help present the whole spray development process. To ensure the safety of the experiment site, air extraction was frequently conducted by an air extractor. Besides, each experimental condition was repeated 30 times to improve the accuracy of results, which minimizes the error to make the results fully satisfy the demand of the analysis and discussion in this paper.

### Table 2. Comparison of Main Optical Diagnostic Methods

| method                  | macroscopic observation | microscopic observation | gas–liquid two-phase observation |
|-------------------------|-------------------------|-------------------------|----------------------------------|
| backlighting            | good                    | poor                    | not applicable                   |
| planar laser scattering | average                 | poor                    | not applicable                   |
| microphotography        | not applicable          | good                    | not applicable                   |
| schlieren               | good                    | poor                    | good                             |

### Table 3. Fuel Properties

| fuel type | gasoline | ethanol |
|-----------|----------|---------|
| chemical formula | C\textsubscript{5}–C\textsubscript{12} | C\textsubscript{2}H\textsubscript{5}OH |
| relative molecular mass | 95–120 | 46 |
| gravimetric oxygen content (%) | <1 | 34.78 |
| research octane number | 95 | 107 |
| density (293 K) (kg/L) | 0.73 | 0.789 |
| kinematic viscosity (293 K) (mm\textsuperscript{2}/s) | 0.71 | 1.52 |
| surface tension (293 K) (N/m) | 22 | 21.97 |
| boiling range (K) | 303–473 | 351 |
| low heating value (kJ/kg) | 44 300 | 26 900 |
| latent heat of vaporization (kJ/kg) | 370 | 840 |
| laminar flame speed (293 K) (m/s) | 0.33 | 0.5 |
| stoichiometric air–fuel ratio | 14.7 | 8.95 |

2.2. Image Processing and Key Parameters. Figure 3 summarizes the flowchart of the image processing procedure using MATLAB in this study. First, the captured images were converted to grayscale while removing the background. Second, appropriate thresholds were set to remove the image noise and extract the spray boundary. Afterward, the results of macroscopic spray characteristics were obtained by calculation. Regarding the noise reduction and spray boundary extraction, it is necessary to extract the region of high spray concentration as it affects the seriousness of the spray interactions with the cylinder wall and piston crown. Hence, after several attempts, 2
and 14% of the lightest pixels were chosen to be the thresholds in this study, obtaining the whole spray and core region of spray for each image, respectively.

In this study, some key parameters are given to help illustrate and analyze macroscopic spray characteristics: $P_I$ is the fuel injection pressure and $t$ is the time after start of fuel injection (ASOI). As shown in Figure 4, referring to the society of automotive engineers (SAE) J2715 standard, $L_S$ is the penetration of whole spray; $L_C$ is the penetration of the core region of spray; $\theta_L$ is the spray cone angle, which is the sum of $\theta_L$ and $\theta_R$; and $S_S$ and $S_C$ are the areas of whole spray and core region of spray, respectively. The ratio of $S_C$ to $S_S$ is represented by a dimensionless number ($R_S$) as shown in eq 1, which reflects the quality of spray atomization to some extent.

$$R_S = \frac{S_C}{S_S} \quad (1)$$

The quality of spray atomization can also be affected by the irregularity of spray boundary, which is defined by $R_I$ as shown in eq 2.

$$R_I = \frac{C}{C_E} \quad (2)$$

Here, $R_I$ denotes the irregularity of spray boundary, $C$ denotes the perimeter of spray boundary, and $C_E$ denotes the perimeter of a hypothetical cycle whose area is equivalent to the spray. Figure 5 is depicted to help better understand $R_I$. Larger $R_I$ means that there are more folds and bulges at the boundary of spray. On the contrary, lower $R_I$ means that the droplet clusters of spray are more compact, which usually leads to a clearer and smoother spray boundary.

3. RESULTS AND DISCUSSION

3.1. Breakup Characteristics. In this study, $t_B$ denotes the time of spray breakup, which is calculated based on the Hiroyasu and Arai model as shown in eq 3.43 Besides, $t_{BS}$ is introduced to denote the appearance time of a branch-like structure in Figure 6. In 1990, Azetsu et al.44 first introduced the branch-like

![Figure 4](image_url) Determination of penetration, cone angle, and area for whole spray and core spray.

![Figure 5](image_url) Determination of a hypothetical cycle for $R_I$ calculation.

![Figure 6](image_url) Example of branch-like structure.
structure, which indicates that the distribution heterogeneity of fuel droplets is improved, leading to a more homogeneous mixture of air and fuel.44,45

\[ t_B = 28.65 \frac{\rho_f D_N}{[\rho_A (P_I - P_A)]^{0.5}} \]  

(3)

Here, \( \rho_f \) denotes the mass density of the fluid; \( D_N \) denotes the nozzle diameter; \( \rho_A \) denotes the mass density of ambient gas; \( P_I \) denotes the fuel injection pressure; and \( P_A \) denotes the ambient pressure.

Figure 7 shows \( t_B \) and \( t_{BS} \) values of gasoline and ethanol spray. It can be seen that the \( t_B \) values of gasoline and ethanol are, respectively, 1.05 and 1.14 ms under \( P_I = 10 \) MPa, while the corresponding values are 0.43 and 0.46 ms under \( P_I = 60 \) MPa. Regarding \( t_{BS} \), it is also a bit earlier for gasoline spray than ethanol. It suggests that compared to ethanol spray, a more homogeneous air–fuel mixture can be expected from gasoline spray under both \( P_I = 10 \) MPa and \( P_I = 60 \) MPa. Moreover, under an ultrahigh injection pressure, both \( t_B \) and \( t_{BS} \) are advanced by around 0.7 ms compared to those of \( P_I = 10 \) MPa. Therefore, masses of liquid ligaments and small droplets are much easier to be detached from spray jets, decreasing the kinetic energy of spray development in the axial direction.

3.2. Spray Penetration. In this section, the experimental results of both \( L_S \) and \( L_C \) are presented to describe the spray development process in the axial direction. Moreover, to help better understand the correlations between the experimental data and semiempirical model predictions, the \( L_S \) values of the original Dent model and the revised Dent model are compared and analyzed.

As observed in Figure 8, under \( P_I = 60 \) MPa, the maximum \( L_S \) of gasoline is 143 mm, reaching the optical field boundary of the test at 3.2 ms ASOI, which is 0.2 ms earlier than ethanol. Under \( P_I = 10 \) MPa, the maximum \( L_S \) of gasoline and ethanol is 121.03 and 113.83 mm, respectively. A similar trend can also be found in the comparison of \( L_C \) in Figure 9. Compared to ethanol, gasoline has a slight advantage of around 5 mm in \( L_C \) after the end of injection (\( t = 2.8 \) ms ASOI). These observations demonstrate that the \( L_S \) and \( L_C \) of gasoline are only slightly larger than those of ethanol. The difference can be attributed to two opposite effects as follows.

First, it is strongly affected by Bernoulli’s principle, as presented in eq 4. Due to the relatively high fluid density compared to gasoline, ethanol would cause a reduction of spray flow velocity under the same condition of \( P_I \) and height for an injector.

\[ \frac{1}{2} \rho_f v^2 + \rho_A g z + P = C \]  

(4)

Here, \( \rho_f \) denotes the mass density of the fluid; \( v \) denotes the fluid flow velocity; \( g \) denotes the gravitational acceleration; \( z \) denotes the elevation of the point above a reference plane; \( P \) denotes the pressure at the chosen point; and \( C \) denotes a constant.

Second, the kinematic viscosity of gasoline is much lower than that of ethanol, as listed in Table 3. Hence, compared to ethanol, the flow of gasoline spray tends to be more turbulent as it possesses a larger Reynolds number (Re) calculated in eq 5.46 It would increase the negative impact of breakup on spray tip velocity, which reduces the advantage of gasoline in \( L_S \) compared to ethanol, particularly under \( P_I = 60 \) MPa condition with a larger Re.

\[ \text{Re} = \frac{UD_d}{\nu} \]  

(5)

Here, \( \text{Re} \) denotes the Reynolds number; \( U \) denotes the normal incident velocity; \( D_d \) denotes the droplet diameter; and \( \nu \) denotes the kinetic viscosity.

Another finding of Figures 8 and 9 is the change in the growth rate of \( L_S \) and \( L_C \) as time progresses. The growth rates of all of the curves show a general decline trend, and an earlier decline can be observed under \( P_I = 60 \) MPa. This is mainly because of the branch-like structure and air resistance, which would
increase the tendency of spray breakup and the negative impact on the velocity of spray tip.

Regarding semiempirical equations about $L_s$ prediction, a simplified method named the Dent model was proposed in 1971, which considers injection time and ambient temperature, as shown in eq 6. Furthermore, based on the experimental results of $L_s$ in this research, a revised version of Dent model is developed in eq 7 to provide a better match. The coefficient of determination $R^2$ is introduced in eq 8 to evaluate the match quality of the models with experimental data of $L_s$. A higher value of $R^2$ represents that the model’s result would be a better match. $R^2$ of 1 denotes that the model regression predictions perfectly match the experimental data.

$$L_s = 3.07 \left( \frac{P_i - P_A}{\rho_A} \right)^{0.25} \left( D_{inj} \right)^{0.5} \left( \frac{294}{T_A} \right)^{0.25}$$  \hspace{1cm} (6)

$$L_s = 3.07 \left( \frac{P_i - P_A}{\rho_A} \right)^{0.245 - 0.00002} \left( D_{inj} \right)^{0.5} \left( \frac{294}{T_A} \right)^{0.25}$$  \hspace{1cm} (7)

Here, $L_s$ denotes the spray penetration; $P_i$ and $P_A$ denote the fuel injection pressure and ambient pressure, respectively; $\rho_A$ denotes the mass density of ambient gas; $D_{inj}$ denotes the nozzle diameter; $t$ is the time ASOI; and $T_A$ denotes the ambient temperature.

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} = 1 - \frac{\sum_{i=1} \left( y_i - f_i \right)^2}{\sum_{i=1} \left( y_i - \bar{y} \right)^2}$$  \hspace{1cm} (8)

Here, $R^2$ denotes the coefficient of determination; $SS_{res}$ and $SS_{tot}$ denote the residual sum of squares and the total sum of squares, respectively; $y_i$ and $f_i$ denote the experimental and predicted values of $L_s$, respectively; and $\bar{y}$ is the mean of experimental values of $L_s$.

**Figure 10** presents the comparison of $L_s$ between the experimental data and semiempirical model predictions. It is apparent that there is an obvious gap between the original Dent model and the experimental results. Using the original Dent model, $R^2$ is 0.8654 and 0.6898 for gasoline and ethanol under $P_i = 10$ MPa, respectively. Moreover, the corresponding $R^2$ is only 0.0691 and 0.1222 under $P_i = 60$ MPa, due to the increased evaporation rate of gasoline. This is mainly because the parameters in the equation of Dent model were determined based on diesel fuel, which contains more carbon atoms in longer chains, leading to slower evaporation than gasoline.

In consideration of the promotion of $P_i$ on the breakup and evaporation of spray, the index of pressure item is modified in the revised Dent model as shown in eq 7. It can be seen that $L_s$ between experimental data and revised Dent model predictions are in good agreement. The value of $R^2$ significantly increases to around 0.99 for both gasoline and ethanol.

### 3.3. Cone Angle, Area, and Irregularity

In this section, the parameters of $\theta_s$, $S_s$, $S_C$, $R_s$, and $R_R$ are compared and analyzed between gasoline and ethanol. The experimental data are collected from the spray images of both front and side views by rotating the injector 90 degrees along its axis.

**Figure 11** shows the $\theta_s$ values of gasoline and ethanol in front and side spray views. It indicates that the $\theta_s$ of gasoline is larger than that of ethanol regardless of front or side view, particularly under $P_i = 60$ MPa. The difference can mainly be explained by the larger Re of gasoline, leading to the larger vortex scale, stronger turbulence kinetic energy, and branch-like structure on the boundary of gasoline spray. Hence, the gap of $\theta_s$ between gasoline and ethanol is widened.

Besides, it can be found that as time progresses, the changing trend of $\theta_s$ of gasoline is similar to that of ethanol under both $P_i = 10$ MPa and $P_i = 60$ MPa. At the beginning of fuel injection, a marked increase can be found in all of the curves of $\theta_s$. Especially from 0.4 ms ASOI to 0.6 ms ASOI under $P_i = 60$ MPa, $\theta_s$ increases by 13.77 and 12.22° for gasoline and ethanol, respectively. This is mainly because the cavitation phenomenon of injector nozzles can be enhanced during the nozzle opening, leading to stronger turbulence kinetic energy. After a while of nozzle opening, spray flow becomes more stable. Furthermore, the process of spray atomization and evaporation can be further improved because of the smaller droplets and larger surfaces. Hence, $\theta_s$ exhibits a gradual decrease from 0.6 ms ASOI to 2.8 ms ASOI.

![Figure 10. Comparison of $L_s$ between experimental data, original Dent model, and revised Dent model.](image-url)
around 2.6 ms ASOI. Finally, $\theta_S$ has a recovery due to the turbulence by the closing process of nozzle near 2.8 ms ASOI, particularly under $P_I = 60$ MPa.

Figures 12 and 13 present the $S_S$ and $S_C$ values of gasoline and ethanol in both front and side spray views. On the whole, it can be seen that all of the curves of $S_S$ and $S_C$ almost increase linearly as time progresses. Compared to $P_I = 10$ MPa, there is a significant increase in both $S_S$ and $S_C$ under $P_I = 60$ MPa. Moreover, there is a slight difference in $S_S$ and $S_C$ between gasoline and ethanol. The diffusion of gasoline is further promoted by the higher velocity and Re compared to ethanol. At 2.8 ms ASOI, the $S_S$ value of gasoline is around 2% larger than that of ethanol, while that for $S_C$ can be around 5%.

Besides, it can be found that $S_C$ is considerably smaller than $S_S$ regardless of $P_I$. This finding can be further explained by $R_S$ (ratio of $S_C$ to $S_S$), as shown in Figure 14. Three main characteristics are found for $R_S$ in front and side spray views, as follows.

First, similar trends in $R_S$ are observed for gasoline and ethanol as time progresses. With the increase of $P_I$ from 10 to 60 MPa, a marked increase of $R_S$ indicates that the air–fuel mixture homogeneity for gasoline and ethanol spray of GDI injector can be greatly improved under an ultrahigh injection pressure.

Second, from the angle of injection time, $R_S$ is relatively high at the initial stage, followed by a sharp decline, and then remains stable throughout the injection process. Moreover, the decline is more pronounced under $P_I = 60$ MPa. This is mainly due to the influence of spray breakup, which increases the quality of spray atomization and the proportion of lean fuel mixture area.

Third, the curves of $R_S$ mainly range from 0.7 to 0.85 in the front view of spray, while $R_S$ is usually around 0.65 in the side view. This is mainly because the four spray jets are close to overlapping in the spray side view, as shown in Figure 2, limiting the display area of spray compared to the front view of spray. It means that it is helpful to understand more comprehensive spray information by obtaining images from different views.

Figure 15 shows the comparison of $R_I$ between gasoline and ethanol in both front and side spray views. It can be observed that $R_I$ is very sensitive to $P_I$ for both gasoline and ethanol. Under $P_I = 60$ MPa, the curves of $R_I$ mainly range from 1.6 to 2.2, which is much higher than those under $P_I = 10$ MPa. This is largely because the frequent occurrence of branch-like structures and breakup can be greatly enhanced under an ultrahigh $P_I$, which would accelerate the progress of primary and secondary atomization, improving the air–fuel mixture homogeneity. Another important feature in Figure 15 is that the $R_I$ value of gasoline is slightly larger than that of ethanol, which is directly related to the larger vortex scale and branch-like structure on the boundary of gasoline spray. This would further accelerate the
atomization of gasoline spray, producing more tiny droplets that more easily evaporate and mix with air.

4. CONCLUSIONS
An experimental study on gasoline and ethanol spray from a GDI injector was conducted using a high-speed schlieren imaging system. The macroscopic spray characteristics of gasoline and ethanol were compared and analyzed in front and side views under injection pressures of 10 and 60 MPa. The findings also provide some new insights to help understand the breakup, atomization, and evaporation processes of gasoline and ethanol spray from a GDI injector under an ultrahigh injection pressure of more than 50 MPa. The main conclusions of this paper are summarized as follows.

(1) Compared to ethanol, a more homogeneous air–fuel mixture can be expected from gasoline spray under both \( P_I = 10 \text{ MPa} \) and \( P_I = 60 \text{ MPa} \). With the increase of \( P_I \) from 10 to 60 MPa, both \( t_b \) and \( t_{0.5} \) are advanced by around 0.7 ms.

(2) Compared to ethanol, gasoline has a slight advantage in \( L_S \) and \( L_C \). As time progresses, the growth rates of both \( L_S \) and \( L_C \) show a general decline trend and an earlier decline can be observed under \( P_I = 60 \text{ MPa} \).

(3) Based on the experimental data of gasoline and ethanol spray, a minor revision to the index of pressure item helps achieve a significant improvement in the \( L_S \) prediction accuracy of the Dent model. The value of \( R^2 \) significantly increases to around 0.99 under both \( P_I = 10 \text{ MPa} \) and \( P_I = 60 \text{ MPa} \).

(4) \( \theta_b \) of gasoline is larger than ethanol in both front and side spray views, particularly under \( P_I = 60 \text{ MPa} \). As time progresses, the changing trend of \( \theta_b \) for gasoline and ethanol is similar under both \( P_I = 10 \text{ MPa} \) and \( P_I = 60 \text{ MPa} \).

(5) Compared to \( P_I = 10 \text{ MPa} \), there is a significant increase in both \( S_S \) and \( S_C \) under \( P_I = 60 \text{ MPa} \). At the end of injection, the \( S_S \) of gasoline is around 2% larger than ethanol, while its advantage in \( S_C \) can be around 5%.

(6) With the increase of \( P_I \) from 10 to 60 MPa, a marked increase of \( R_S \) and \( R_I \) indicates that the progress of atomization and air–fuel mixture homogeneity can be greatly promoted for both gasoline and ethanol spray of GDI injector.

(7) Under both \( P_I = 10 \text{ MPa} \) and \( P_I = 60 \text{ MPa} \), the \( R_I \) value of gasoline is slightly larger than that of ethanol, which would further accelerate the spray breakup and atomization, producing more tiny droplets that more easily evaporate and mix with air.

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**Notes**

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**ABBREVIATIONS**

ASOI after start of injection

DPF diesel particulate filter

ECU electronic control unit
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