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EXHAUST NANOPARTICLE EMISSIONS FROM INTERNAL COMBUSTION ENGINES: A REVIEW

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ABSTRACT−This paper reviews the particle emissions formed during the combustion process in spark ignition and diesel engine. Proposed legislation in Europe and California will impose a particle number requirement for GDI (gasoline direct injection) vehicles and will introduce the Euro 6 and LEV-III emission standards. More careful optimization for reducing particulate emission on engine hardware, fuel system, and control strategy to reduce particulate emissions will be required during cold start and warm-up phases. Because The diesel combustion inherently produces significant amounts of PM as a result of incomplete combustion around individual fuel droplets in the combustion zone, much attention has been paid to reducing particle emissions through electronic engine control, high pressure injection systems, combustion chamber design, and exhaust after-treatment technologies. In this paper, recent research and development trends to reduce the particle emissions from internal combustion engines are summarized, with a focus on PMP activity in EU, CARB and SAE papers and including both state-of-the-art light-duty vehicles and heavy-duty engines.

KEY WORDS : Particulate matter, Particle number, Gasoline direct injection, Particulate filter, Low carbon fuels

1. INTRODUCTION

Improving fuel consumption while simultaneously reducing exhaust emissions requires internal combustion engines that more energy efficient and environmentally friendly. The major challenge for advanced powertrains involves integration of downsizing and boosting in combination with various exhaust after-treatment technologies (Heywood and Welling, 2009; Johnson, 2009, 2010, 2011; Wu *et al*., 2011; Zhao *et al*., 1999).

As significant reduction of mobile source air toxic (MSAT) emissions has been achieved by the installation of a three-way catalyst (TWC) in a spark ignition engine (Cho *et al*., 2011; Hassaneen *et al*., 2009; Kwak *et al*., 2007; Peckham *et al*., 2011a; Samuel *et al*.,; 2010; Takeda *et al*., 1995) as well as a diesel particulate filter (DPF) and a de-NOx catalyst in common rail direct injection (CRDI) engines (Andrew *et al*., 2009; Austin *et al*., 2010; Brück *et al*., 2009; Czerwinski *et al*., 2011; Di-Penta *et al*., 2011; Paule *et al*., 2011). The introduction of higher fuel injection pressures, resulting in smaller fuel droplets, in combination with an improved engine control strategy and a DPF has greatly reduced particulate emissions from diesel engines, whereas gasoline direct injection (GDI) engines produce considerably more particles than conventional port fuel injection (PFI) ones (Basshuysen, 2009; Eastwood, 2008; Peckham *et al*., 2011b; Sabathil *et al*., 2011; Zhao, 1999).

Particulate matter (PM) pollutants are currently of high interest because medical findings indicate that adverse health effects are caused by aerosol particles in the ultrafine (< 100 nm diameter) size range that are associated with traffic, where internal combustion engines are the main source. (Dockery *et al*., 1993; Giechaskiel *et al*., 2007; Ostro, 1984; Pope *et al*., 1992; Vaaraslahti *et al*., 2005). Therefore, an investigation of the particle size distributions in vehicle emissions, particularly in relation to different types of fuels, is of great importance in understanding these adverse effects. Specific characteristics of particle number (PN) emissions have been defined, including the size, number, surface area and composition (Andersson *et al*., 2001; Arcoumanis *et al*., 2008; Dimou *et al*., 2011; Lee *et al*., 2009; Lee *et al*., 2010; Kittelson, 1998; Myung *et al*., 2009a).

Automotive particle emissions fall into two broad categories: 1) "Nucleation" mode particles, which are comprised primarily of condensed volatile material, mainly sulphate and heavy hydrocarbons, and have particle sizes that are typically less than 30 nm, 2) "Accumulation" mode particles, which are mainly carbonaceous in nature and have particle sizes larger than 30 nm (Kayes and Hochgreb, 1999; Kittelson, 1998; Soewono and Rogak, 2009).

Recent research in PM measurement has focused on the fact that, during cold start and at high acceleration points, GDI engines can emit a significantly higher PN concentration in comparison with diesel engines equipped with a diesel particulate filter (DPF). These emissions are in the

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Table 1. Past, current and proposed European emissions standards (* GDI engine only, ** all gasoline engines).

		Gasoline				Diesel			
		EURO 4	EURO 5a	EURO 5b	EURO 6	EURO 4	EURO 5a	EURO 5b	EURO 6
		Jan, 2005	Sept. 2009	Sept. 2011	Sept. 2014	Jan. 2005	Sept. 2009	Sept. 2011	Sept. 2014
THC	mg/km	100	100	100	100	-	-	-	-
NMHC	mg/km		68	68	68	-	-	-	-
HC+NOx		-	-	-	-	300	230	230	170
NOx	mg/km	80	60	60	60	250	180	180	80
CO	mg/km	1000	1000	1000	1000	500	500	500	500
PM	mg/km	-	5*	4.5*	4.5*	25	5	4.5	4.5
PN#	#/km	-	-	-	TBD**	-	-	6.0E+11	6.0E+11

Status : PN valve for Euro 6 is planned to be adopted in a comitology proposal by the commossion 2nd September 2011.

ultra-fine-particle and nano-particle range, in contrast to the larger particles from diesel engines (Choi *et al*., 2006; Kannapin and Grusk, 2010; Kayes and Hochgreb, 1999; Kunde *et al*., 2010; Price *et al*., 2006; Rofail and Henein, 2011).

New emissions standard Euro 5a, which was enacted in September 2009, regulates the PM mass (g/km) emissions standard for diesel and GDI vehicles. To meet the PN (#/km) regulation for diesel powered vehicles in Euro 5b, DPFs with higher efficiencies will be required (Andersson *et al*., 2007; Kapus and Jansen, 2010; Walter *et al*., 2011). Moreover, the introduction of Euro 6 over the New European Driving Cycle (NEDC) will lead to the implementation of a PN limit for all SI passenger vehicles, as shown in Table 1.

In the case of heavy-duty diesel engines, Euro 6 will specify the PN concentrations for the worldwide heavy-duty transient cycle (WHTC) and the worldwide heavy-duty steady-state cycle (WHSC) as 6.0×10^{11} (#/kWh) and 8.0×10^{11} (#/kWh), respectively (Andersson *et al*., 2007, 2010; Johnson, 2011; May *et al*,. 2008; Myung *et al*., 2011).

Because motor vehicles are a major contributor to both air pollution and greenhouse gas (GHG) emissions, the California Air Resources Board (CARB) is proposing the establishment of new PM emissions standards for light-duty vehicles as part of the Low Emission Vehicle (LEV) III program. These standards propose that, beginning in 2014, all vehicles subject to LEV III-SULEV requirements must comply with at least one of the following two standards: 1) A Federal Test Procedure (FTP)-weighted PM mass emissions limit of 0.006 g/mi by 2014 and of 0.003 g/mi by 2017, 2) A FTP-weighted solid particle number (SPN) emissions limit of 6.0×10^{12} particles/mi by 2014 and of 3.0×10^{12} particles/mi by 2017 (Ayala *et al*., 2008; CARB, 2010; Kunde *et al*., 2010; McMahon *et al*., 2011; Zhang and McMahon, 2010).

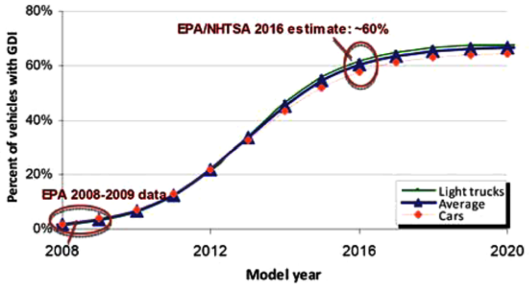


Figure 1. GDI fleet penetration scenario based on a fit to current numbers and on estimates of compliance with federal requirements.

The proposed modification to the current limit for PM mass emissions is expected to encourage the increased penetration of highly efficient GDI vehicles for CO_2 reduction benefits, as shown in Figure 1 (CARB, 2010).

This review provides comprehensive information on techniques for meeting the future particle emissions standards, including particulate formation mechanisms, combustion control strategies and exhaust after-treatment systems for state-of-the-art internal combustion engines such as GDI and CRDI engines.

2. PM OF THE INTERNAL COMBUSTION ENGINE

2.1. Particle Formation Mechanism

PM is defined as all substances, other than unbound water, that are present in exhaust gas in the solid (ash, carbon) or liquid phases. Engine particulates consist of combustion-generated, solid carbon particles, commonly referred to as soot, that result from agglomeration or cracking, and upon which some organic compounds have been adsorbed. The carbon particles become coated with condensed and adsorbed organic compounds, including unburned hydrocarbons and oxygenated hydrocarbons. The condensed matter can be comprised of inorganic compounds such as sulfur dioxide, nitrogen dioxide and sulfuric acid

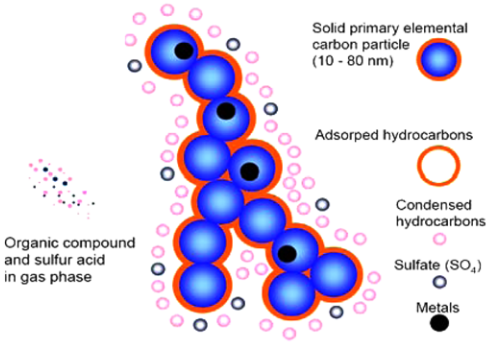


Figure 2. Agglomerated diesel particle.

(Eastwood, 2008; Kayes and Hochgreb, 1998; Kittelson, 1998; Zhao *et al*., 1999). Figure 2 shows the typical diesel particle.

Internal combustion engines have been identified as a significant source of ultrafine PM. A significant proportion of diesel emissions particles have diameters smaller than 100 nm, whereas particles emitted from gasoline-powered engines are generally less than 80 nm in diameter. Particles from engines fueled by compressed natural gas (CNG) or liquefied petroleum gas (LPG) are smaller than those from diesel emissions, with the majority between 20 and 60 nm in diameter. Typically, these particles are a complex mixture of solid and more-volatile particles (Burtscher, 2005; Lee *et al*., 2010; Myung *et al*., 2009a; Ristovski *et al*., 2000; Roberto *et al*., 2007; Zhao *et al*., 1999).

The number, size and growth rates of these more-volatile particles depend on variables that affect condensation, such as the dilution rate, temperature, residence time, surface area of pre-existing particles, and humidity (Khalek *et al*., 1998, 1999). Figure 3 shows typical diesel engine exhaust mass- and number-weighted distributions (Bukowiecki *et al*., 2002). The highest PNs are found in the nucleation mode, with particle diameters smaller than 0.1 µm. However, the percentage of the mass represented by this mode is low (1-20%). Most of the particulate mass is found in the accumulation mode, with particle diameters between 0.1 µm and 1.0 µm. The coarse mode, with particle sizes larger than 1.0 µm, represents 5–20% of the particulate mass, but the particle number in this mode is minor (Filippo, 2011; Joshi *et al*., 2011; Kirchner *et al*., 2010).

The number of ultrafine particles in and near the tailpipe is also influenced by the sulfur content of the fuel and the composition of the lubricating oil. A fraction of the sulfur in fuel is oxidized to sulfur trioxide, SO_3. The SO_3 binds with water, forming sulfuric acid, one of the gas-phase species that can nucleate to form new smaller particles (Giechaskiel *et al*., 2005; Kittelson *et al*., 2006).

Many studies (Kittelson *et al*., 2008; Ristovski *et al*., 2000; Sakurai *et al*., 2003) have addressed the influence of the fuel sulfur level on ultrafine particle formation in vehicles. In general, most of these studies suggest that a significant reduction in the number of ultrafine particles emitted occurs when fuel sulfur levels are reduced. Figure 4 shows the effect of the fuel and lube oil sulfur level on the PN of diesel exhaust gas with continuous regenerating trap (CRT) (Kittelson *et al*., 2008).

2.2. PM Emissions from SI Engines

The mass based PM standard for diesel engines has not been considered for SI engines due to more than an order of magnitude lower. However, recent studies report that the PN concentration from SI engines increases significantly with high loads, aggressive acceleration and cold start conditions (Andersson *et al*., 2001; Dimou *et al*., 2011; Iorio *et al*., 2011; Peckham *et al*., 2011a, 2011b).

Much of the research indicates that GDI engines produce significantly more particulates than conventional PFI engines, especially during the cold start phase and during stratified operation (Daniel *et al*., 2011; Kannapin and Guske, 2010; Kapus and Jansen, 2010; Kunde *et al*., 2010; Yamakawa *et al*., 2011). Therefore, for the first time a general reduction in the particulate-matter limit for spark-ignition direct injection engines is being combined with plans to introduce a limit on the particle number for SI engines. Figure 5 presents methods that can be used to

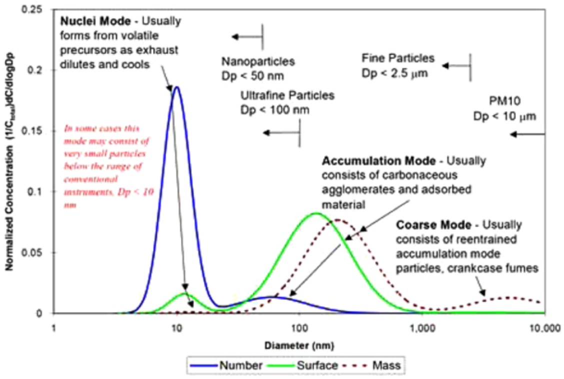


Figure 3. Typical mass and number-weighted size distributions of diesel PM.

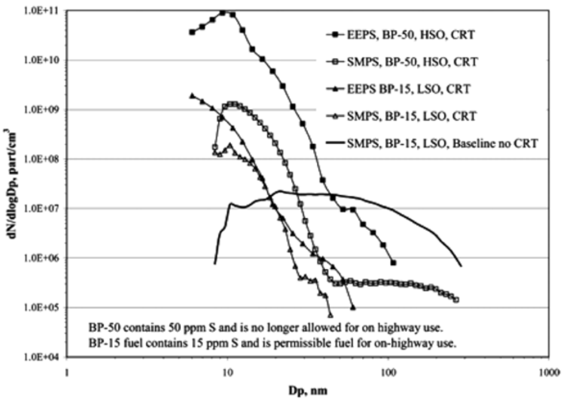


Figure 4. Effect of fuel and lube oil sulfur level on the diesel exhaust PN with a CRT.

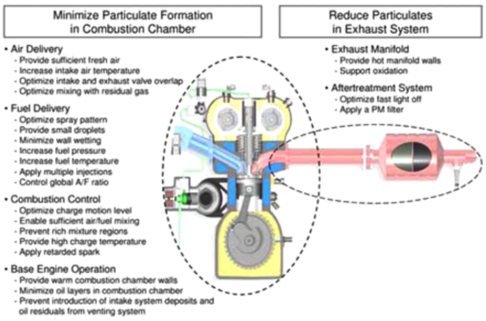


Figure 5. Methods for minimizing particulate emissions from GDI engines.

minimize the tailpipe particulate matter emissions of a GDI engine (Piock *et al*., 2011).

Particles are a result of incomplete combustion and poor mixture formation in the combustion chamber. In particular, fuel wetting of the cylinder wall is responsible for particle formation during the cold start and transient phase in GDI engines. In addition to optimizing combustion chamber and piston bowl shape, the intake flow motion as well as the fuel injection control strategy must be optimized to avoid wall wetting and to enhance mixture preparation (Lee *et al*., 2004; Price *et al*., 2006; Shimizu *et al*., 2011; Yamakawa *et al*., 2011). Influence of engine operating parameters on the reduction of particle emissions is shown in Figure 6 (Kannapin and Guske, 2010).

Each variation in the injection parameters or the fuel requires an adjustment to the start of injection in the engine control unit (ECU) data. Increasing fuel pressure leads to a considerable decrease in the PN. Splitting the quantity of injected fuel into separate injection events while adjusting the timing improves the mixture preparation and reduces the PN emissions (Lohfink *et al*., 2008; Piock *et al*., 2011; Sabathil *et al*., 2011). These measures were shown to produce a positive effect, particularly in the problem areas of cold starting/catalyst heating, drive-off cycles and high vehicle speed. The NEDC revealed a 65% reduction in the PN, as shown in Figure 7 (Kapus and Jansen, 2010; Uchiyama *et al*., 2011).

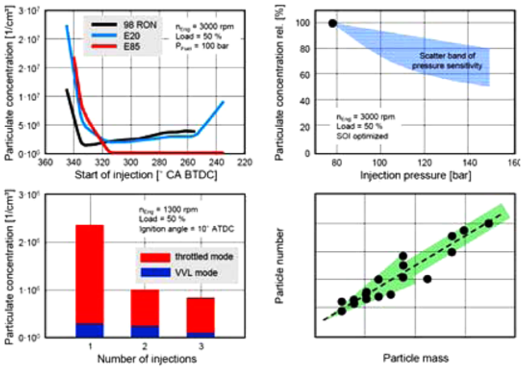


Figure 6. Parametric study results for reducing the particles from a GDI engine.

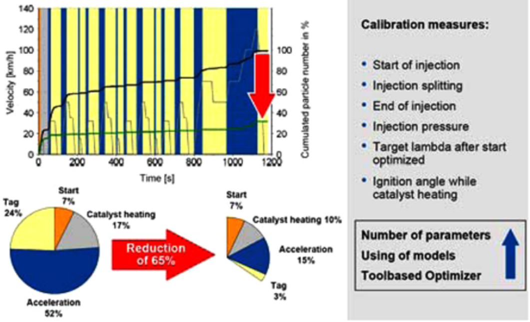


Figure 7. Overall parametric study results for reducing the particles from a GDI vehicle in NEDC mode.

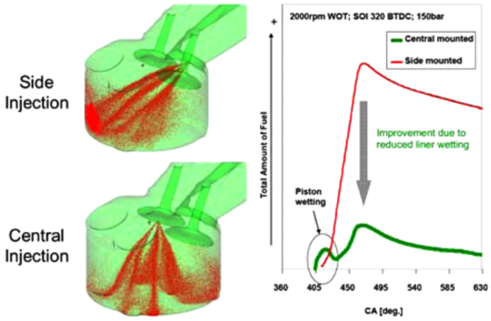


Figure 8. Spray distribution and liner wetting under full load conditions at 2000 rpm.

The effects on liner wetting are significantly different for each injector location. A side mounted injector causes liner wetting primarily at low engine speeds with the spray only gradually deflected downward by the tumble, whereas the central injector causes more liner wetting at high engine speeds because of stronger spray deflection (Kunde *et al*., 2010). Figure 8 shows an example of the liner wetting intensity under a full load at 2000 rpm.

Figure 9 shows the particulate emissions at steady state engine temperatures (coolant and oil) of 60ºC and 90ºC and at injection timings of 300ºCA and 260ºCA for low load point operation. An increased engine temperature strongly reduces the particulate emissions. The engine tests show that the optimum injection timing is independent of engine temperature. Therefore, particulate emissions are best optimized at a cold temperature and during the warm-up phase, with a focus on injection system control (Piock *et al*., 2011).

Various gasoline engine combustion systems were used to identify the impact of advanced engine technologies on PN distributions (Eastwood, 2008; Maricq *et al*., 1999; Ntziachristos *et al*., 2004; Sogawa *et al*., 2007). Among GDI vehicles, particle numbers from the lean burn GDI vehicle were larger than those from the stoichiometric GDI vehicle. Compared to a DI diesel vehicle without an after-treatment system (Vehicle D), the lean burn GDI vehicle showed a total particle number approximately one tenth of

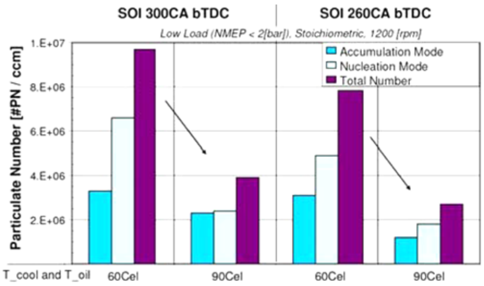


Figure 9. Influence of engine temperature and injection timing on PN emission from a GDI engine.

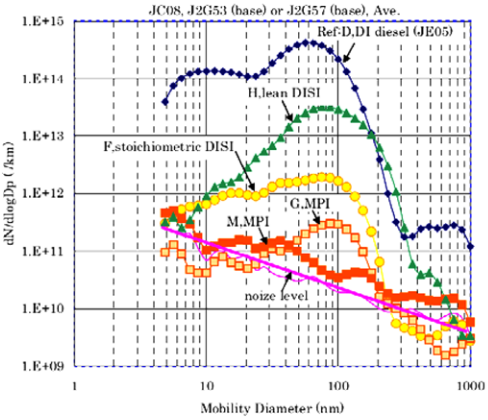


Figure 10. Comparison of particle number size distributions in the JC08 mode driving cycle or typical gasoline combustion systems with DMS500.

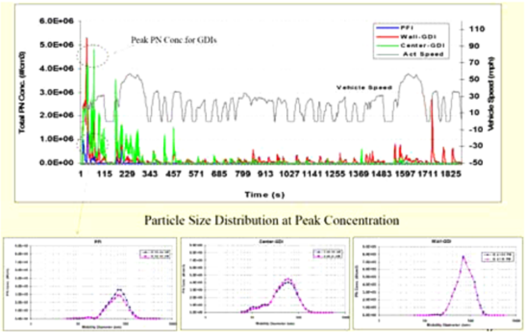


Figure 11. Comparison of real-time total PN concentrations from the FTP mode with various injection control schemes.

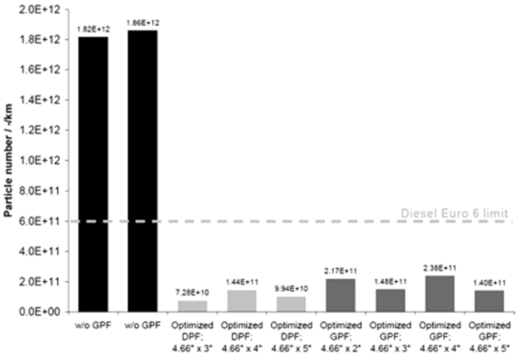


Figure 12. Particle number tailpipe emissions in NEDC mode with various particle filters from Audi A5 Coupe 2L TFSI GDI vehicle.

that of the DI diesel vehicle, whereas the PN of the stoichiometric GDI vehicle was approximately one hundredth of the DI diesel vehicle value. Figure 10 shows the particle size distributions in JC08 mode from various gasoline combustion systems (Sogawa *et al*., 2007).

To support the proposed California LEV III PM regulations, particulate emissions measurements, including PM mass, PN emissions and PM composition for PFI and GDI vehicles were evaluated by CARB (Ayala *et al*., 2008; CARB, 2010; McMahon *et al*., 2011). For all three vehicles, total PN emissions in phase 1 during an engine cold start are significantly higher than in phase 2 and 3 after the engines are warmed up. The phase 1 total PN emissions for the center-guided GDI is the highest of the three vehicles. This phase 1 result is three times higher than for the PFI and 40% higher than for the wall-guided GDI vehicle. For the FTP-weighted total PN emissions, the percentage of sub-23 nm total particles ranges from 28% for the center-guided GDI to 24% for the PFI vehicle and 19% for the wall-guided GDI vehicle. Figure 11 shows the real-time total PN concentrations from the FTP mode for PFI and GDI engines with injection control schemes (Zhang and McMahon, 2010).

Recent measurements of tailpipe PN emissions show that conventional GDI light-duty passenger engines cannot comply with a limitation of 6×10^{11} #/km. To achieve compliance, two different approaches are feasible: 1) Engine hardware modification and EMS improvement, 2) Exhaust after-treatment with a gasoline particulate filter (GPF) (Daniel *et al*., 2011; Kapus and Jansen, 2010; Kannapin and Gusken, 2010; Walter *et al*., 2011). Figure 12 shows the NEDC test results for a vehicle with or without particulate filters in the exhaust system. All of the filter solutions provide excellent filtration performance. The optimized DPF honeycombs show efficiencies that are higher than 90%, and the optimized GPF honeycombs show efficiencies of approximately 90% (Mikulic *et al*., 2010).

2.3. PM Emission from Diesel Engines

The sale of diesel cars in Europe has increased significantly during the last decade. A combination of many different factors has most likely contributed to this development. Diesel is the most efficient internal combustion engine fuel, providing more power and fuel efficiency than gasoline, CNG, or LPG (Arcoumanis *et al*., 2008; Myung *et al*., 2009a, 2009b; Ristovski *et al*., 2005). Ristovski *et al*., 2005). Diesel engines perform well with respect to low CO, HC, and CO_2 emissions, but diesel combustion tends

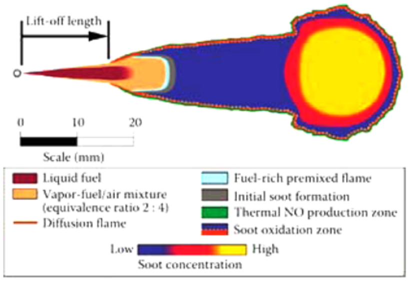


Figure 13. Conceptual model of mixing-controlled and a diffusion flame in diesel engine combustion.

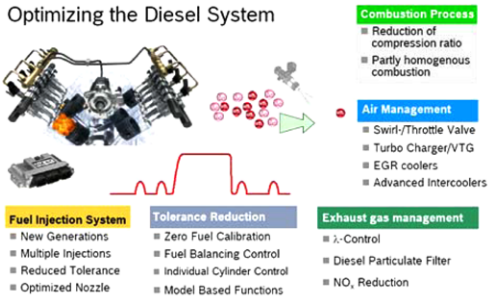


Figure 14. Advanced diesel engine fuel injection equipment, control strategies and after-treatment systems.

to produce significant amounts of PM that is caused by incomplete combustion around individual fuel droplets in the combustion zone, which is shown in Figure 13 (Eastwood, 2008; Rakopolous and Giakoumis, 2009).

Figure 14 shows measures that can be used to reduce particle emissions from diesel engines, including electronic engine control, high pressure injection systems, combustion chamber design, and exhaust after-treatment systems such as a diesel oxidation catalyst (DOC) or a DPF (Johnson, 2009, 2010, 2011; Heywood and Welling, 2009; Ntziachristos *et al*., 2006; Surenhalli *et al*., 2011). The development of fuel injection equipment for direct injection diesel engines has focused on reducing the droplet size and the air entrainment in the spray. Corresponding developments for combustion chambers have involved increasing the diameter and making the chamber shallower.

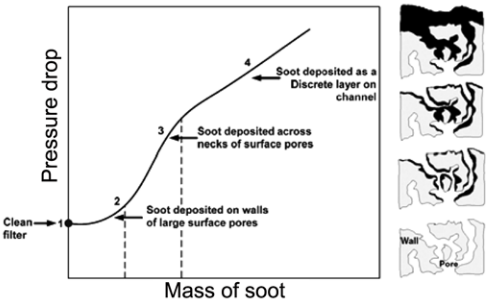


Figure 15. Particulate filling process inside the DPF.

These measures have decreased PM formation in diesel engines, whereas other methods of modifying combustion have decreased NO_X formation (Benajes *et al*., 2010; Di-Penta *et al*., 2011; Kobayashi *et al*., 2011).

A DPF removes particulate matter from diesel exhaust by physical filtration. The most common type is a ceramic (cordierite or silicon carbide) honeycomb monolith housed in a steel container that has excellent thermal shock resistance and thermal conductivity properties. The structure is similar to an emissions catalyst substrate, but with the channels blocked at alternate ends. The exhaust gases must therefore flow through the walls between the channels, and the particulate matter is deposited on the walls (Andrew *et al*., 2009; Furuta *et al*., 2009; Margraf *et al*., 2011; Mizutani *et al*., 2010). Figure 15 shows a general overview of the filtration mechanism in a DPF (Rakopolous and Giakoumis, 2009).

The soot emitted by a diesel engine is the result of incomplete combustion of the diesel fuel. It consists of nonvolatile black carbon (BC) and relatively volatile organic carbon (OC), where the OC component includes primarily polycyclic aromatic hydrocarbons (PAHs) and aliphatic hydrocarbons (AL). There are two stages of PM oxidation. In the first step, the catalyst oxidizes the NO in the exhaust gas into NO_2 in a non-porous flow-through filter. In the next step, the NO_2 reacts with soot to produce CO and CO_2 in a wall-flow filter. It has been shown that NO_2 is much more reactive for soot oxidation (Eastwood, 2008; Kittelson, 1998; Rakopolous and Giakoumis, 2009; Zinola and Lavy, 2009).

Figure 16 shows the computational simulations used to predict the filtration efficiency, pressure drop, and thermal effects during regeneration of the DPF. Because a heat release occurs as a result of soot combustion, the maximum

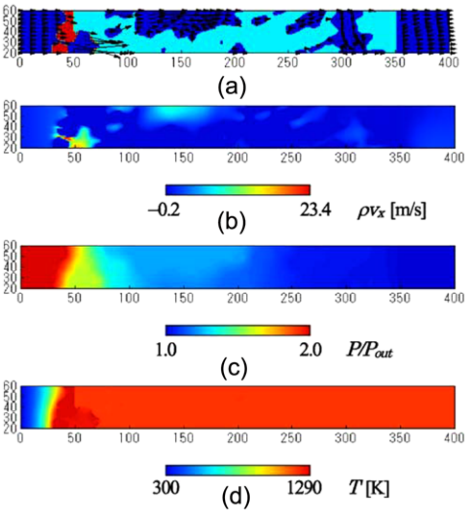
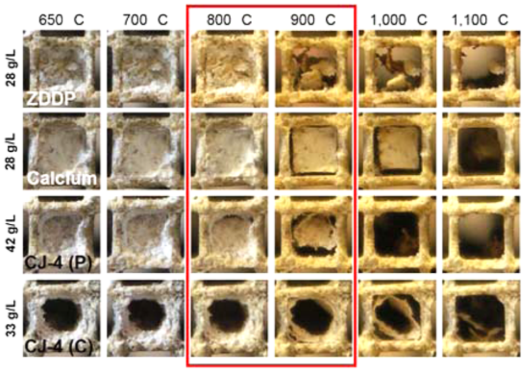


Figure 16. Combustion field in the x–y plane of (a) filter region and deposited soot layer with velocity vector, (b) mass flux in the x-direction, (c) pressure and (d) temperature; t = 4 ms.



DPF	Ash Level	Lubricant	Regeneration
Cordierite Catalyzed 200/12	12.5	Commercial CJ-4	Periodic
	42		
	33		Continuous
	28	Base Oil + ZDDP	Periodic
	29	Base Oil + Ca	

Figure 17. Reduction in ash volume at elevated temperatures.

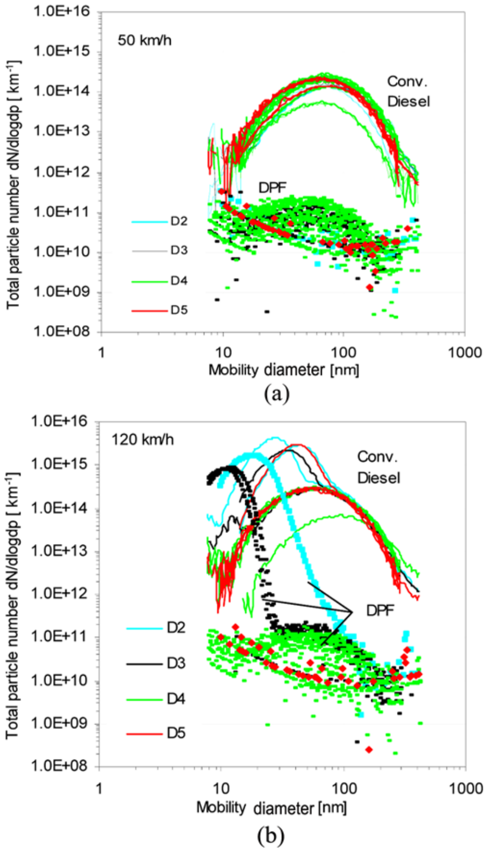


Figure 18. Particulate matter size distributions of conventional diesel and DPF vehicles over (a) 50 km/h and (b) 120 km/h.

temperature is higher than the initial soot layer temperature by 90 K. As expected, when NO_2 is added the soot oxidation rate becomes larger to burn more soot in the filter. The effectiveness of the regeneration process using NO_2 is confirmed through a simulation of a real DPF system. This is useful information for the development of future NOx–soot regenerating DPF systems for the after-treatment of exhaust gas (Piscaglia and Ferrairi, 2009; Yamamoto *et al*., 2009).

Studies of engine-out soot and ash emissions revealed that lubricant-derived ash-related species compose between 0.5% and 1.0% of the total PM emitted by a diesel engine. A microscopic analysis of individual soot particles showed that the lubricant-derived ash precursors (Ca, MG, Zn, S and P compounds) were intimately bound to the carbonaceous PM (Kittelson *et al*., 2006, 2008; Sakurai *et al*., 2003). Ash significantly affects the sensitivity of the DPF pressure drop to soot and ash that were deposited along the DPF channels and form a physical barrier or membrane that prevents soot depth filtration. Therefore, ash that accumulates in a filter that is regenerated periodically leads to increased ash plug formation at the back of the channels (Austin *et al*., 2010; Lee *et al*., 2011; Wei *et al*., 2010; Zhang *et al*., 2011). Investigations of the effects of exhaust temperature on ash composition and ash layer properties showed that an elevated temperature of over 700°C resulted in ash decomposition, as shown in Figure 17 (Sappok *et al*., 2010).

From the "Particulates" project, Ntziachristos *et al.* (2004) reported particle size distributions measured by a scan mobility particle sizer (SMPS), including volatile particles for steady-state operations. The vehicles met Euro 1 to Euro 3 certification levels and were operated with four diesel fuels that were doped with sulfur to different concentrations (D2=280, D3=38, D4=8, and D5=3 ppm-S). The SMPS measurements for the diesel vehicles are presented in Figure 18. The SMPS particle size distributions show that the diesel vehicle emissions are affected by driving conditions and fuel sulfur content, with a distinct nucleation mode appearing for the higher speed and the fuel with a higher sulfur concentration.

A similar evaluation was performed using a variety of

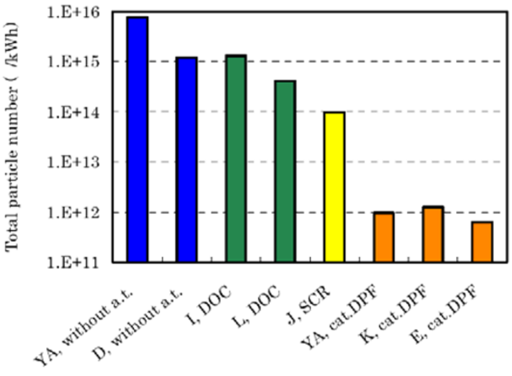


Figure 19. Comparison of total particle numbers in JE05 mode driving cycle in terms of typical diesel after-treatment systems.

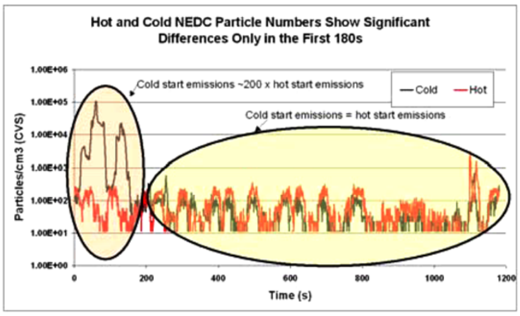


Figure 20. Effect of cold start on particle number emissions in the NEDC for the ILCE golden vehicle (diesel DPF).

diesel vehicles and diesel engines equipped with typical after-treatment systems to identify the effects of diesel after-treatment systems on particle number size distributions. Results obtained in JE05 mode are shown in Figure 19 (Sogawa *et al*., 2007). Compared to the diesel vehicles without after-treatment systems, every diesel after-treatment system, especially the catalyzed DPF systems, was verified to effectively reduce the particle numbers. Total particle numbers ranging from around $1x10^{11}$ to $5x10^{11}$ #/kWh were observed for the particle number distributions of vehicles/engines with catalyzed DPF systems (Engine YA, Vehicles K and E).

Cold start effects were observed for the golden vehicle (diesel DPF) (Andersson *et al*., 2007), with increased particle number emissions in the first 200 s of the NEDC that are not observed for the same cycle with a hot engine start, as shown in Figure 20. This observation is consistent with the results of several studies investigating different vehicles that were performed in accordance with the Particle Measurement Programme (PMP) method. They found that all of the DI diesel DPF vehicles emitted approximately 90% of their total PN emissions within the cold start and warm-up operation stages of the vehicle emission test cycles. Particle emissions decreased drastically once the vehicle and the DPF system reached operating temperature (Andersson *et al*., 2001, 2004, 2007; Ayala *et al*., 2008; Lee *et al*., 2008; Myung *et al*., 2009b; Ristimaki *et al*., 2005; Rocher *et al*., 2011). Heavy-duty diesel engine advancements are primarily aimed at improving fuel economy, reliability, cost, and durability. Continued concern about exhaust emissions from heavy-duty diesel engines, such as the PM and NOx components, has led to the implementation of progressively tighter regulations in the European Union (Brück *et al*., 2009; Czerwinski *et al*., 2011; Heywood and Welling, 2009; Johnson, 2011; Theis *et al*., 2011). Figure 21 shows the medium and heavy-duty DPF-SCR system that is used to meet Euro 6 emissions regulations.

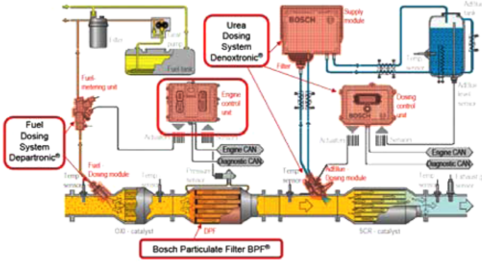


Figure 21. Layout of a modern medium- or heavy-duty DPF-SCR system.

The international PMP has been developing a new particle number measurement technique through the ILCE (Inter-Laboratory Correlation Exercise) for heavy-duty engines that will comply with EURO 6 standards and will complement or replace mass-based PM measurement procedures (Andersson and Clarke, 2008; Andersson *et al*., 2010; Giechaskiel *et al*., 2008a, 2008b).

The Joint Research Centre (JRC) presented the results of a study of a Euro 3 IVECO Cursor 8 heavy-duty engine equipped with a CRT, with a partial flow deep bed filter from EMITEC and without any after-treatment devices. The PM from the secondary tunnel of the full flow dilution system and the PN emissions from the SPCS connected at the dilution tunnel can be seen in Figure 22 (Giechaskiel *et al*., 2008b; May *et al*., 2007, 2008). The major findings are that the efficiency of the EMITEC was approximately 65% for PM and 58% for PN (non-volatiles >23 nm), and that the efficiency of the CRT was approximately 95% for PM and 100% for PN (non-volatiles >23 nm). Both systems exhibited a lower efficiency for the PN of the cold WHTC. The lower efficiency of the CRT in the cold WHTC is related to the high particle emissions at the beginning of the cycle.

The Korea PMP also reported the results of an experimental evaluation of the particle numbers and mass concentrations, the particle size distribution, and the filtration efficiency of a DPF with a turbocharged Euro 3-compliant Daimler OM501 heavy-duty golden diesel

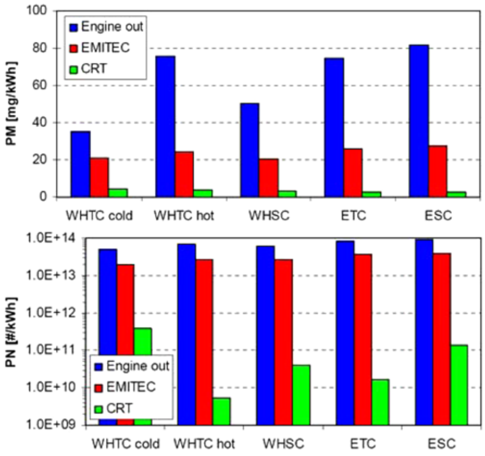


Figure 22. Comparison of PM and PN emissions of after-treatment devices.

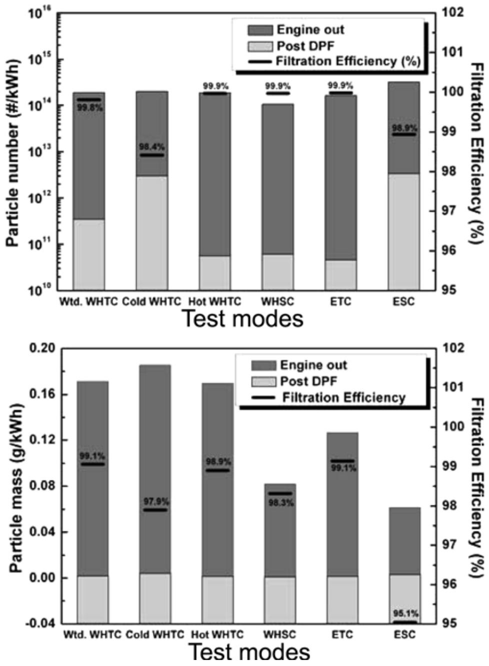


Figure 23. Average particle number and mass emissions for various test modes.

engine as part of the UN/ECE PMP ILCE. The PN and PM results from various engine operation cycles showed a weighted WHTC of 4.783E+11 #/kWh (2.0 mg/kWh), a WHSC of 6.087E+10 #/kWh (1.1 mg/kWh), an ETC of 4.596E+10 #/kWh (1.5 mg/kWh), and an ESC of 3.389E+12 #/kWh (3.1 mg/kWh). The filtration efficiency of the particle number concentration and mass reached approximately 99%, except for an ESC mass efficiency of 95% that occurred because of passive regeneration during the # 8 to #10 modes. The results are shown in Figure 23 (Myung *et al*., 2011).

3. PARTICLE EMISSIONS FROM VEHICLES

External factors such as driving patterns (load and speed of the engine) and environmental conditions such as ambient temperature have a large influence on particle emissions. Higher vehicle speeds are normally associated with higher emissions of particles and changes in the size distribution (Dimou *et al*., 2011; Joshi *et al*., 2011; Heywood and Welling, 2009; Kittelson *et al*., 2006; Maricq, 1999; Ristmaki *et al*., 2005; Samuel *et al*., 2010).

In the PMP-ILCE for light-duty vehicles, participating laboratories measured the PN and PM mass concentrations of a common diesel DPF car, the "golden vehicle". In addition to the golden vehicle, each laboratory performed measurements on a car of their choice; the selected cars included diesel-DPF, diesel non-DPF, direct injected petrol cars and one PPI-petrol. The results of the ILCE PM measurements are presented in Figure 24. The direct-injected petrol cars show PN emissions that are between the diesels with DPF and the diesels without DPF. The mean emissions from the DPF-equipped diesels were lower than 10^{11} #/km, and the emissions from the MPI were statistically similar to the golden vehicle, whereas the GDI emissions levels were 40 to 140 times higher. Conventional diesel vehicle emissions were greater than 2 x 10^{13} #/km in NEDC mode (Andersson *et al*., 2001, 2007; Giechaskiel *et al*., 2007).

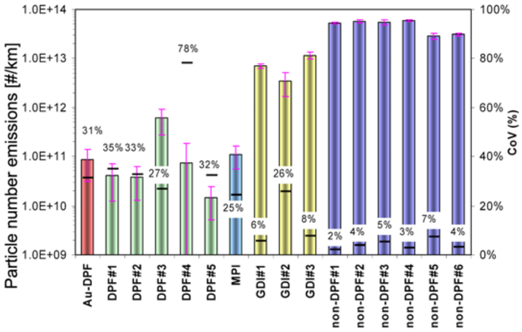


Figure 24. Total particle number emissions and repeatability data for all vehicles in the ILCE.

Figure 25 presents a collection of data found in the published literature and from CARB tests. The figure shows typical ranges of the particle number emissions for various classes of vehicles and driving cycles. Careful control of fuel/air mixing and enhancement of the after-treatment systems can result in very low particle emissions (CARB, 2010).

Particulate emissions measurements for PFI and GDI vehicles, including PM mass and PN concentration and composition, are evaluated and the results are used to support the proposed California LEV III PM regulations for reducing particle emissions. The main objectives of this research are to study the particle size distribution during a transient cycle and evaluation of sub-23 nm particles; these results are measured from the EEPS for PFI and GDI vehicles. The major findings are that the fraction of sub-23 nm particles varied with the adoption of a PFI, a center-guided GDI or a wall-guided GDI for FTP-weighted total

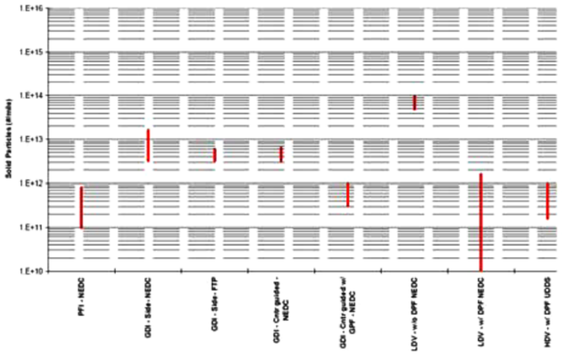


Figure 25. Solid particle number emission rates for various types of vehicles during various driving cycles.

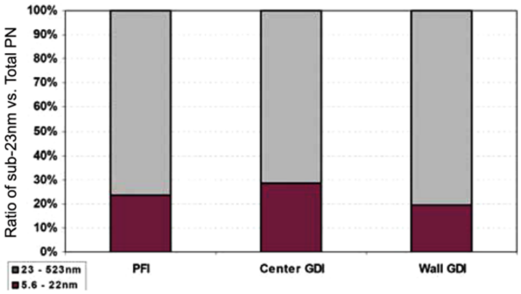


Figure 26. FTP weighted total PN emission fraction.

PN emissions, as shown in Figure 26 (Ayala *et al*., 2008; Zhang and MeMahon, 2010; McMahon *et al*., 2011).

In the case of alternative fuels, synthetic diesel fuels, such as GTL and BTL, and hydrogenated bio-fuels have lower PM emissions than conventional diesel fuel. In particular, bio-fuels and CNG have the potential to reduce particulate emissions with the help of clean combustion and low-carbon fuels (Dimou *et al*., 2011; Iorio *et al*., 2011; Lee *et al*., 2009; Moon *et al*., 2009; Nuszkowski *et al*., 2011; Sogawa *et al*., 2007).

LPG has been widely adopted as an automotive fuel because of its potential for reducing harmful exhaust emissions, its relatively low price, and advantage of lower GHG emissions.

The nano-particle concentration of the port fuel LPG injection engine, which is classified as a gaseous and liquid phase LPG injection type, is much lower than that of the PFI gasoline engine (Agostinelli *et al*., 2011; Gong *et al*., 2011; Lee *et al*., 2010; Li *et al*., 2010; Rajamani *et al*., 2010). In an LPG-DI engine, as the liquid LPG fuel vaporizes in a very short time during the intake stroke, the amount of homogeneous mixture in the combustion chamber is substantially increased, and nano-particle emissions can be effectively reduced (Oh *et al*., 2010; Hwang *et al*., 2011). Figure 27 shows a comparison of the PN concentrations in NEDC mode for vehicles using various fuels (Myung *et al*., 2009b).

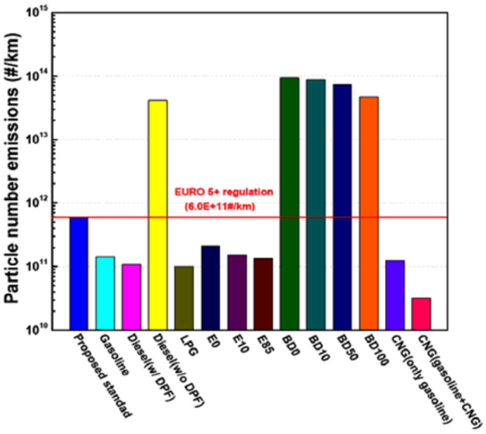


Figure 27. Comparison of the total PN in NEDC mode for various fueled vehicles.

4. CONCLUSIONS

Many scientific studies have linked breathing in PM to a series of significant health problems, including aggravated asthma and an increase in respiratory symptoms. PM emissions can be reduced in a number of ways, including more stringent emissions standards for internal combustion engines and fuels. The introduction of direct fuel injection, an increase in system pressure and advances in engine management systems has significantly improved the performance, fuel economy and exhaust emissions of state-of-the-art SI and CRDI engines.

The major advantages of a GDI engine are higher specific power, increased fuel efficiency and lower emissions because fuel can be sprayed directly into the combustion chamber. However, the GDI combustion mechanism produces excessive particle emissions during the cold start phase and during transient operation. Therefore, many parametric studies focusing on reducing the particulate emissions from the GDI engine were conducted in conjunction with the optimization of engine control strategy, mixture preparation with a high injection pressure, the modification of the combustion chamber, and the implementation of a particulate filter.

Similarly, measures to reduce particle emissions from diesel engines include electronic engine control, high pressure injection systems, combustion chamber design, and exhaust after-treatment systems. Although DPF have been in commercial production for many years, optimization activity on DPF regeneration is ongoing. The filtration efficiency is strongly dependent on the soot loading status because of the build-up of heat.

PM emissions from state-of-the-art passenger vehicles and heavy-duty diesel engines indicate that driving patterns and environmental conditions are closely related to particle emissions. Particle emissions standards for internal combustion engines are being widely adopted in worldwide automotive sectors, and more consideration will be required to develop environmentally friendly vehicles for improving urban air quality.

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