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EFFECTS OF GASOLINE, DIESEL, LPG, AND LOW-CARBON FUELS AND VARIOUS CERTIFICATION MODES ON NANOPARTICLE EMISSION CHARACTERISTICS IN LIGHT-DUTY VEHICLES

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ABSTRACT−This study was focused on experimental comparisons of the effects of various vehicle certification modes on particle emission characteristics of light-duty vehicles with gasoline, diesel, LPG, and low-carbon fuels such as bio-diesel, bio-ethanol, and compressed natural gas, respectively. The particulate matter from various fueled vehicles was analyzed with the golden particle measurement system recommended by the particle measurement programme, which consists of CVS, a particle number counter, and particle number diluters. To verify particle number and size distribution characteristics, various vehicle emission certification modes such as NEDC, FTP-75, and HWFET were compared to evaluate particle formation with both CPC and DMS500. The formation of particles was highly dependent on vehicle speed and load conditions for each mode. In particular, the particle numbers of conventional fuels and low-carbon fuels sharply increased during cold start, fast transient acceleration, and high-load operation phases of the vehicle emission tests. A diesel vehicle fitted with a particulate filter showed substantial reduction of particulate matter with a number concentration equivalent to gasoline and LPG fuel. Moreover, bio-fuels and natural gas have the potential to reduce the particulate emissions with the help of clean combustion and low-carbon fuel quality compared to non-DPF diesel-fueled vehicles.

KEY WORDS : Particulate matter, Nanoparticles, Diesel particulate filter, Differential mobility spectrometer, Condensation particle counter, Low-carbon fuels

1. INTRODUCTION

Diesel-powered engines have advantages of increased engine power output, fuel economy, and higher durability than spark ignition engines. In addition, they can reduce emissions such as hydrocarbons and carbon monoxide. Diesel engines are widely used in heavy-duty trucks, buses, engine generators, etc., as they have fewer penalties in performance and emissions. In spite of the many advantages, the emissions of smoke and particulate matter (PM) from heavy-duty engines are a big drawback and are thus the focus of many environmental researchers. From the viewpoint of health, PM emitted from diesel engines causes adverse health effects, and recent studies have announced that PM in the atmosphere is an important factor in mortality and morbidity (Dockery *et al*., 1993; Giechaskiel *et al*., 2007; Hagena *et al*., 2006; Ostro, 1984; Pope *et al*., 1992; Takeda *et al*., 1995; Vaaraslahti *et al*., 2005).

In addition to diesel particles, conventional gasoline and low-carbon fuels such as liquefied petroleum gas (LPG), compressed natural gas (CNG), and various bio-fuels emit a considerable amount of nanoparticles during the cold start phase and at high-speed operating conditions; thus, the particle formation mechanism of spark ignition engines have been investigated (Choi *et al*., 2006; Kayes and Hochgreb, 1999; Ristovski *et al*., 2000).

PM has been emphasized as a toxic air contaminant (TAC) by the California air resources board (CARB). Moreover, the developed countries have been focusing on the effects of a variety of airborne particulates on health risks. Current legislative exhaust emissions standards restrict particle emission in terms of the total mass discharged per kilometer traveled. Regulations based on total mass are an effective way to control large particles; however, fine particles contribute little to the total mass of particulate matter emissions (Andersson *et al*., 2001 and 2004).

In this context, the international particle measurement programme (PMP) has been developing a new particle size measurement technique to complement or replace mass-based PM measurement procedures. Final inter-laboratory correlation exercise (ILCE) results on particle number for LDV showed that particle number concentrations emitted from non-diesel particulate filter (DPF) diesel-fueled vehicles (E+13 particles/km) were much higher than from multi-point injection (MPI) gasoline engines (E+11 particles/km) and slightly higher than from gasoline direct injection engines

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(E+12 particles/km), but particle numbers with DPF fitted vehicles showed results equivalent to gasoline engines (Andersson *et al*., 2007; Lee *et al*., 2008; Roberto *et al*., 2007).

In diesel vehicle emissions, PM consists of tiny solid particles and liquid droplets ranging from a few nanometers to around one micrometer in diameter (below 1,000 nm). PM size distributions are generally classified as tri-modal. The three modes are the nucleation mode, accumulation mode, and coarse mode. The nucleation mode is typically composed of nanoparticles in the 5~50 nm diameter range. This mode consists of volatile organic and sulfur compounds formed during the exhaust dilution and cooling process. The accumulation mode ranges from 50 to 1,000 nm and usually consists of particles that have been deposited on cylinder walls and exhaust system surfaces. Finally, the coarse mode, rarely emitted in internal combustion engines, is composed of particles with diameters greater than 1,000 nm (Kittelson, 1998).

The goal of this research is to verify particle number and size distribution characteristics under various vehicle certification modes such as the new European driving cycle (NEDC), federal test procedure (FTP)-75, and the highway fuel economy test (HWFET) modes using conventional fuels, including low-carbon fuels that are widely used in Korea automotive markets.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1. Test Fuels and Vehicle Descriptions

Figure 1 shows the schematic diagram of the vehicle experimental apparatus used to analyze the particle number concentration and particle mass under the NEDC, FTP-75, and HWFET modes. To minimize fuel variation during test periods, gasoline and diesel fuels were supplied from the same filling station with one-batch preparation. Summer LPG and CNG for urban buses were used for gas-fueled vehicles. In the case of the 2.0 liter diesel engine, advanced DPF meeting the EURO 4 emission regulation was equipped. In addition, a 2.5 liter diesel engine run on 50% of bio-diesel fuel was tested. Additionally, a retrofitted 2.4 liter bi-fueled CNG vehicle that can automatically switch between gasoline and natural gas fuel was also tested. The test procedure for the bi-fueled CNG vehicle was as follows. To assess each fuel effect on particle formation in the CNG vehicle, the gasoline fuel mode was tested first. Then, the natural gas mode was selected using the fuel selection switch. In this condition, natural gas was automatically changed from gasoline during the NEDC mode when the engine coolant temperature reached a target value. In the case of the ethanol flexible fuel vehicle (FFV), the ethanol content was varied from gasoline to E85 (85% ethanol + 15% gasoline). To save time, only the NEDC test mode was used for low-carbon fuels (FFV, bio-diesel). Test fuel properties and vehicle specifications are summarized in Table 1, Table 2, and Table 3.

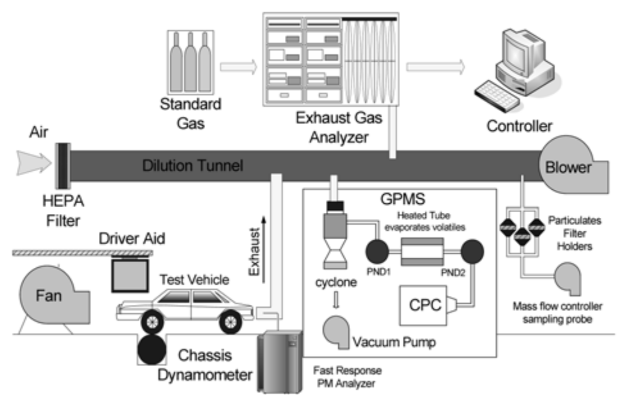

Figure 1. Schematic diagram of vehicle experimental system.

Table 1. Properties of ethanol blended gasoline fuel.

Property items	Gasoline	E85
RON	93.2	> 100
Distillation temperature (ºC)		
10 vol%	51.9	73.9
50 vol%	80.0	78.0
90 vol%	153.9	78.7
Sulfur content (mg/kg)	18.00	0.90
Oxygen (weight%)	1.75	30.00

Table 2. Properties of bio-diesel fuel.

Property items	ULSD	BD50
Cetane number	55.9	55
Density@15ºC (kg/m^3)	826.9	850
Viscosity (mm^2/s)	2.8	3.2
Sulfur content (weight %)	0.022	0.014
Lubrication@60ºC (μm)	336	164

2.2. Particle Analyzer and Sampling System

The flow rate of the diluted exhaust gas through the CVS tunnel was 20 m^3/min at standard reference conditions (i.e., 20ºC and 1 bar). The primary dilution air was passed through a high-efficiency particulate air (HEPA) filter to minimize the particle effect of the background level of an emission facility.

A sample probe for particles was fitted near the center line in the dilution tunnel, and a cyclone was used as a pre-classifier to remove the particles with diameters greater than 2.5 μm in the CVS tunnel. The number of particles emitted from the test vehicle was counted using the golden particle measurement system (GPMS) which is recommended by PMP.

Figure 2 represents the GPMS and particle mass system

Table 3. Specifications of test vehicles.

Vehicle/fuel type	LPG	Gasoline	Diesel	Diesel	FFV (Bio-ethanol)	Bio-diesel	Bi-fuel (Retrofit) (Gasoline+CNG)
Engine type	I4	I4-VVT	I4-VGT	I4-VGT	I4	I4-VGT	I4-VVT
Engine displacement	1,998 cc	1,998 cc	1,991 cc	1,493 cc	1,596 cc	2,497 cc	2,359 cc
Transmission	AT4	AT4	AT4	AT4	MT5	AT4	AT4
After-treatment system	MCC+UCC	MCC+UCC	DOC+DPF	DOC	UCC	DOC	MCC+UCC
Injection type	LPi	MPI	CRDI	CRDI	MPI	CRDI	MPI
Max.power (hp/rpm)	141/6,000	144/6,000	151/3,800	112/4,000	101/6,000	145/3,800	166/5,800
Emission category	ULEV	ULEV	EURO 4	EURO 4	TLEV	EURO 3	ULEV
Model year	2007	2007	2008	2006	2005	2004	2007
Odometer (km)	24,338	24,586	17,114	32,511	25,125	91,624	14,478

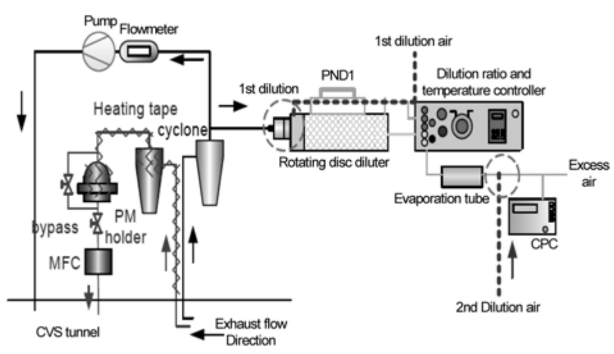

Figure 2. Schematic diagram of GPMS and mass measurement system.

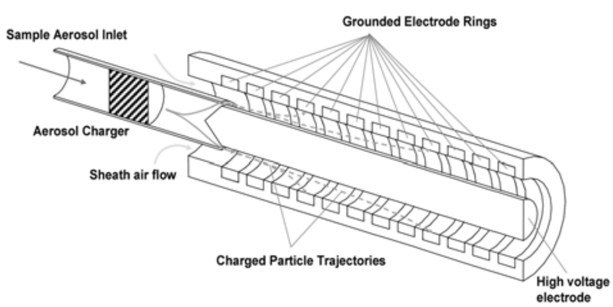

Figure 3. Principle of DMS500 fast particulate spectrometer.

components. The volatile particle remover (VPR) comprises the first particle number diluter (PND_1), an evaporation tube (ET), and a PND_2. The PND_1 is a rotating disc diluter (MD19-2E) with the hot dilution set at 150°C and HEPA filtered dilution air. After the first diluter, the sample was further divided into two flows. The flow was conducted to the ET held at a constant temperature of 300°C. A 3010D condensation particle counter (CPC) manufactured by TSI was used to measure the time-resolved particle emission number concentrations at NEDC, FTP-75, and HWFET modes.

As well as a CPC, a fast particulate spectrometer (DMS500) was installed at the tailpipe location to analyze the particle size distribution of gasoline, diesel with or without DPF, LPG, and bio-diesel-fueled vehicles at a high-speed driving condition (120 km/h).

Figure 3 shows the principle of the DMS500, which provides particle number and size distributions between 5 nm and 1,000 nm. The particles were charged as they passed through charger, and the charged particles landed in a ring as function of charge and aerodynamic drag (Fast Particulate Spectrometer user manual, 2008). The response time of the fast particle analyzer was on the order of 100 ms.

2.3. Calculation Procedure of Total Particle Numbers in Vehicle Tests

Total particle number (N) emissions for vehicle driving mode were calculated by means of the following equation by particle number measurement procedure of regulation No. 83 (TRANS-WP29-GRPE-48, 2004).

$$N = \frac{V_{mix} \times C_{avg} \times DR_{tot} \times 10^3}{d} \tag{1}$$

In equation 1, N (particles/km) is particle number emission expressed in particles per kilometer, V_{mix} is the volume of the diluted exhaust gas in liters per test, C_{avg} is the average concentration of particles in diluted exhaust gas in particles per cubic centimeter, DR_{tot} is the total dilution factor of the diluter in the VPR, and d is the distance corresponding to test mode in kilometers.

3. VEHICLE EXPERIMENTAL RESULTS

3.1. Particle Size Distribution during High Speed Driving Condition

In order to understand particle formation characteristics during steady vehicle speed (120 km/h) of LPG, diesel, gasoline, and bio-diesel vehicles, each vehicle was driven on a chassis dynamometer after reaching the fully warmed-up condition. The size distribution was measured with the DMS500. The sampling probe was positioned between the

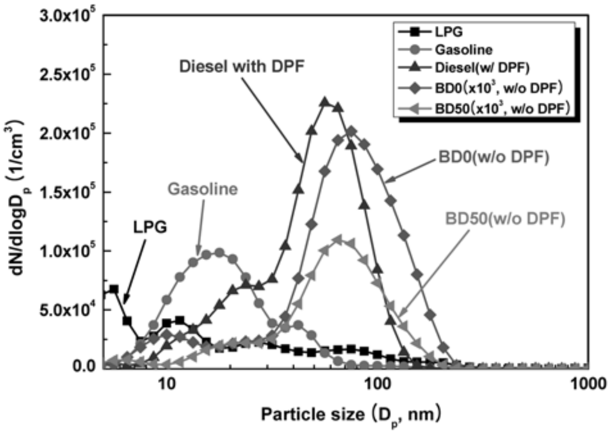

Figure 4. Particle size distribution and number concentration characteristics with different fuels at high speed driving condition (120 km/h).

tailpipe and the CVS inlet point.

To reduce water condensation in the sampling probe and delivery pipe, which can critically influence particle counting, electrically controlled heating tape was applied to maintain a constant temperature above 150°C. For stable particle analysis, the dilution ratio of the DMS500 was experimentally selected and set to 4:1 (dilution air:exhaust gas) in gasoline, LPG, and DPF diesel vehicles and 200 to 1,000:1 in non-DPF diesel vehicles to evaluate particle formation on the optimization condition and to prevent saturation.

Figure 4 shows the particle size and number distributions during constant vehicle speeds for the LPG-, gasoline-, diesel-, and bio-diesel-fueled vehicles. PM size distributions in an internal combustion engine are generally classified into the nucleation and accumulation modes which are distinguished by the particle diameter. The nucleation and accumulation mode have particles of diameters less than about 50 nm and from 50 nm to 1,000 nm, respectively; however, the boundary between nucleation and accumulation mode is variable. In the case of LPG, nucleation mode below $d_p < 10$ nm was mostly observed, and the maximum particle number concentration was 7.0E+4 particles/cm³.

The particle sizes were mainly distributed in the 10 nm < d_p < 50 nm range in the case of gasoline, and the number concentration slightly increased compared to the LPG vehicle. An especially high particle number was measured in non-DPF diesel vehicles, with an order of magnitude of about E+8 particles/cm³, while the particle sizes were distributed in accumulation mode around 100 nm in size.

Comparing BD0 with BD50, as the bio-diesel contents increased, particle number concentration levels were reduced. Moreover, the particle size distribution of the DPF-equipped diesel vehicle showed a similar tendency to the non-DPF diesel vehicle. The particle emission level drastically decreased to E+5 particles/cm³, an order of magnitude equivalent to those of the advanced LPG and gasoline vehicles. The large concentration of the diesel DPF vehicle at 120 km/h could be explained by noting that the high temperature inside the particulate trap caused the natural regeneration of particles during the high-speed operating condition.

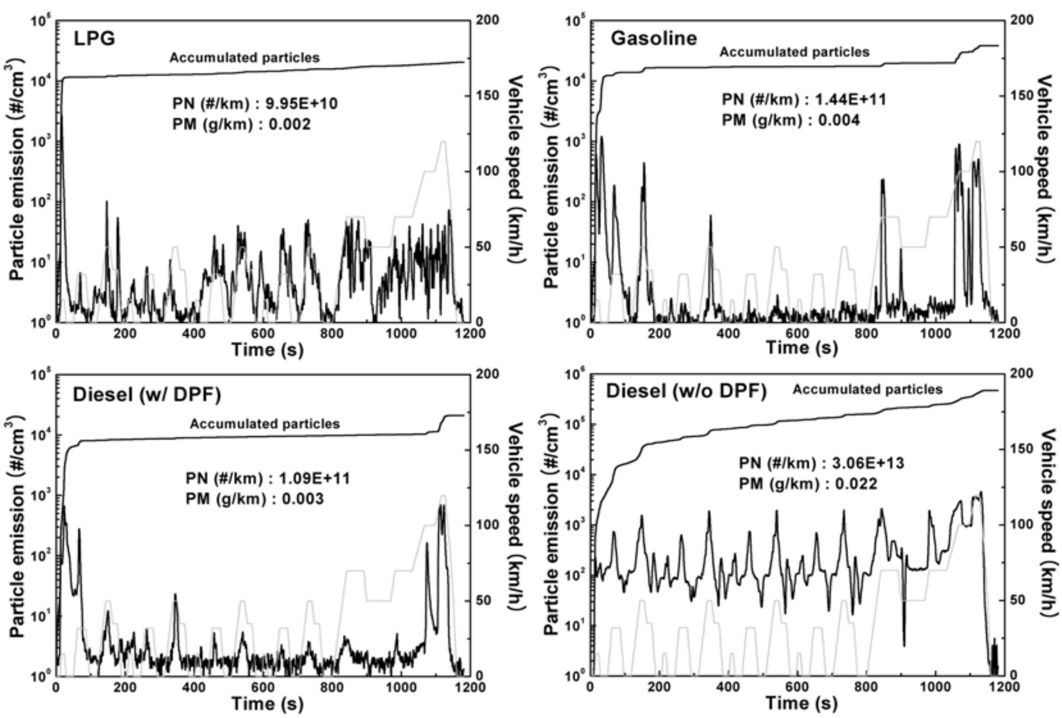

Figure 5. Time-resolved particle number concentrations of NEDC mode.

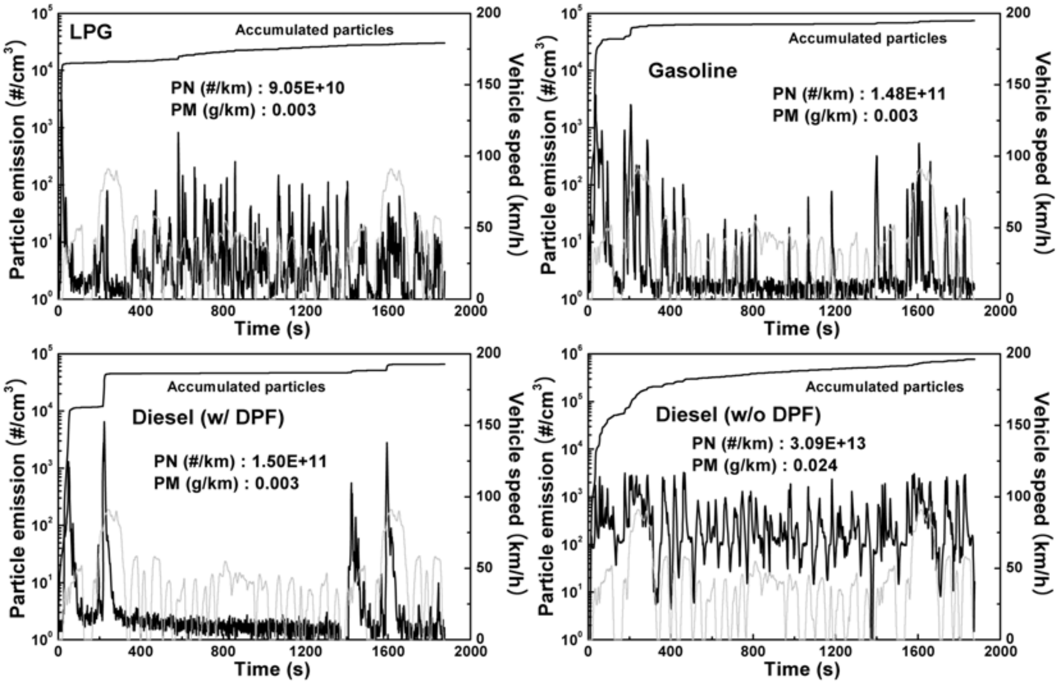

Figure 6. Time-resolved particle number concentrations of FTP-75 mode.

3.2. Comparison of Time-Resolved Particle Number Concentrations in NEDC, FTP-75, and HWFET Modes

Figure 5 shows the time-resolved particle emission traces of LPG, gasoline, and diesel vehicles measured by the CPC for the NEDC mode. The levels of PM number emissions showed a close relationship to the driving condition of the vehicle testing modes and the fuels used. Particle number concentrations of LPG, gasoline, and DPF diesel vehicles were the highest during the cold start phase, on the order of E+3 particles/cm^3. Particle emissions gradually decreased after the first transient and remained below 10 particles/cm^3 except at the 120 km/h accelerating condition.

The particle numbers and masses were, respectively, 9.95E+10 particles/km and 0.002 g/km for LPG, 1.44E+11 particles/km and 0.004 g/km for gasoline, and 1.09E+11 particles/km and 0.003 g/km for DPF-diesel. However, the non-DPF diesel vehicle showed higher particle mass and number concentration, with values of 3.06E+13 particles/km and 0.022 g/km, respectively. These levels do not meet the EURO 5 proposed number and mass regulation standards of 6.0E+11 particles/km and 0.0045 g/km, respectively. In the case of diesel fuel, the DPF after-treatment system has the potential to greatly reduce particle numbers and mass emissions.

Figure 6 presents the time-resolved particle emission behaviors of FTP-75 mode for LPG, gasoline, and diesel vehicles. Particle formation increased similarly to the NEDC mode during vehicle speed-up; however, the concentrations were primarily emitted during the cold start phase because the vehicle speed gradient was steeper than in the NEDC mode. The total particle number and mass of the FTP-75 mode showed similar levels compared to NEDC. To verify the effect of vehicle speed on particle formation, HWFET mode was also tested.

Figure 7 shows the time-resolved particle size distribution spectra of LPG, gasoline, and diesel-fueled vehicles during HWFET mode using the DMS500. From the particle spectra of HWFET mode, the nucleation mode was mostly emitted by the LPG and gasoline-fueled vehicles, while the accumulation mode was observed in diesel-fueled vehicles. The order of particle number emissions was gasoline, LPG, DPF diesel, and non-DPF diesel.

3.3. Evaluation of Particle Emissions for Low-Carbon Fuels

Low-carbon fuels such as bio-ethanol, bio-diesel, and natural gas have the potential to reduce regulated emissions and carbon dioxide in automotive fuels.

In addition, the oxygen component in bio-fuels improved combustion characteristics and enhanced the reduction of harmful emissions. In this section, NEDC mode was selected to compare the particle emissions from these fuels.

Figure 8 shows a comparison of particle number concentrations of the bio-fueled vehicles. From the figure, the particle number concentration of E85 fuel was substantially reduced from 2.14E+11 particles/km for gasoline to 1.35E+11 particles/km. Moreover, particle emission during the last 400 seconds from the NEDC cycle was very low in E85 fuel, ascribed to the clean combustion characteristics of ethanol fuel.

Similarly, particle reduction was observed in a bio-diesel-fueled vehicle. As the bio-diesel content was varied to 50%, the particle number in NEDC mode decreased

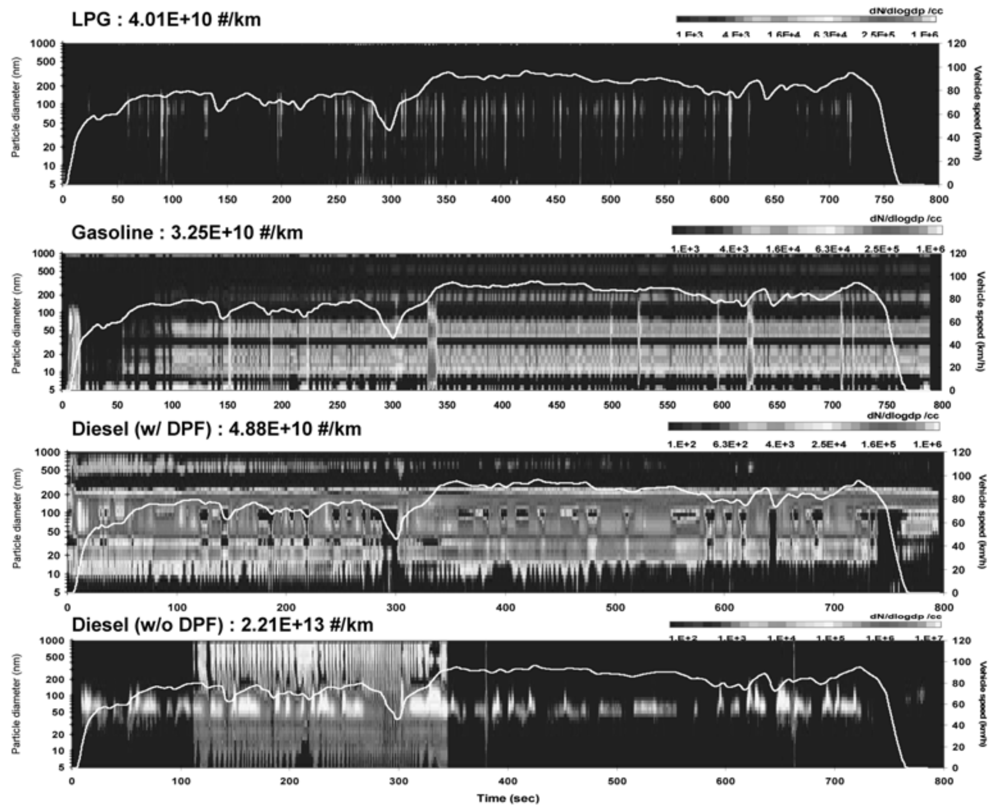

Figure 7. Time-resolved particle size distribution spectra of various vehicles in HWFET mode.

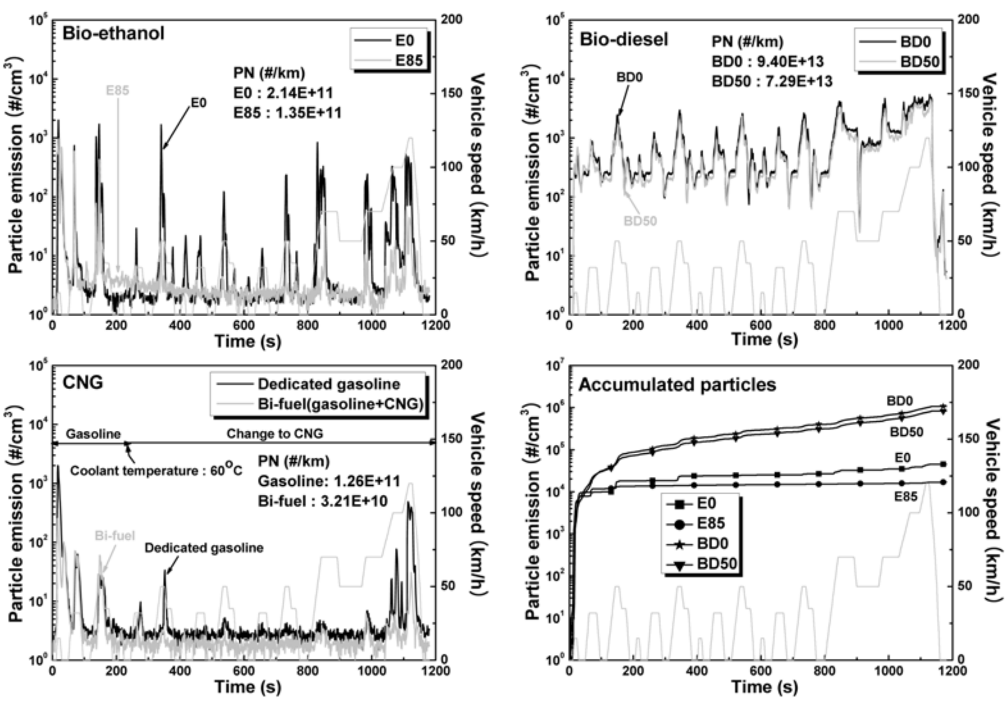

Figure 8. Time-resolved particle number concentrations of NEDC mode for bio-fueled and CNG vehicles.

from 9.40E+13 particles/km for BD0 to 7.29E+13 particles/km for BD50 fuel. Although a significant reduction was observed in bio-diesel fuels, DPF was required to meet the particle number regulation of 6.0E+11 particles/km enacted by EURO 5.

In Korea, natural gas fuel is primarily used in city buses

Table 4. Comparison of particle numbers and mass concentrations in vehicle test modes.

Fuel type		Test modes and particle emissions				
		NEDC		FTP-75		HWFET
		Number (particles/km)	Mass (g/km)	Number (particles/km)	Mass (g/km)	Number (particles/km)
LPG		9.95E+10	0.002	9.05E+10	0.003	4.01E+10
Gasoline		1.44E+11	0.004	1.48E+11	0.003	3.25E+10
DPF diesel		1.09E+11	0.003	1.50E+11	0.003	4.88E+10
Non-DPF diesel		3.06E+13	0.022	3.09E+13	0.024	2.21E+13
Bio-ethanol (FFV)	E0	2.14E+11	0.002	–	–	–
	E85	1.35E+11	0.003	–	–	–
Bio-diesel	BD0	9.40E+13	0.055	–	–	–
	BD50	7.29E+13	0.042	–	–	–
Bi-fuel (CNG)	Gasoline	1.26E+11	0.005	8.99E+10	0.002	1.06E+10
	Bi-fuel	3.21E+10	0.005	1.59E+11	0.002	5.41E+11

to improve air quality in urban areas. Natural gas fuel is mainly composed of methane, which can enhance clean combustion. The bi-fueled CNG vehicle described in Section 2.1 was tested.

From the test result, CNG mode emitted very few particles, about 3.21E+10 particles/km. Moreover, the high particle concentration in gasoline mode was not observed during the last acceleration mode with natural gas operation. Finally, considering gasoline operation during the start transient phase, about 250 seconds, the particle number concentration of the CNG vehicle can be reduced significantly. Total particle emissions were decreased by an order of magnitude when bi-fuel was used.

Table 4 summarizes the test results of particle numbers and mass concentrations for various vehicle test modes and fuel types used in this research. From the table, non-DPF diesel and bio-diesel-fueled vehicles have difficulty in meeting the particle number and mass standards of EURO 5 emission regulations with current after-treatment systems.

It should be noted that advanced LPG and MPI gasoline-fueled vehicles showed PM emissions similar to those of DPF diesel and had enough tolerance for future emission regulations.

Finally, CNG is the cleanest fuel for particle emissions in terms of the fuel characteristics of gaseous natural gas.

4. CONCLUSIONS

The objective of this research was to verify the particle number and size distribution characteristics under various vehicle certification modes such as NEDC, FTP-75, and HWFET with conventional fuels and low-carbon fuels, which are widely used in Korean automotive markets. Based on these analyses, the following major conclusions can be drawn:

(1) Particle emission characteristics during constant vehicle speed show that the particle number of non-DPF diesel reached the orders of E+7 particles/cm^3 to E+8 particles/cm^3, while LPG, gasoline, and diesel vehicles with DPF reached the orders of E+4 particles/cm^3 to E+5 particles/cm^3. In case of gasoline- and LPG-fueled vehicles, nucleation mode ($d_p < 50$ nm) was the main component of particulate matter. However, accumulation mode ($d_p > 50$ nm) was mostly emitted from diesel-fueled vehicles.

(2) All the test fuels emit PM during transient vehicle operation, including cold start, heavy acceleration phase, and high speed. The diesel non-DPF vehicle shows higher particle mass and number concentration; however, the diesel DPF vehicle shows a particle level comparable to gasoline- and LPG-fueled vehicles.

(3) The orders of magnitude of the total particle number concentrations under various test modes for gasoline, LPG, and diesel (w/DPF) were similar. However, the particle concentration of non-DPF diesel is E+13 particles/km, a level that has difficulty in meeting the particle number emission regulations enacted by EURO 5 and 6.

(4) Alternative fuels such as bio-ethanol, bio-diesel, and natural gas have the potential to reduce particulate number emissions due to their oxygen content and low-carbon fuel characteristics. The particle number concentration of E85 fuel was reduced by 37% compared to gasoline. Moreover, as the bio-diesel content was varied to 50%, the particle number level was reduced by 22%. Finally, the CNG-fueled vehicle emitted the lowest particle number of 3.21E+10 particles/km among the various fuels tested.

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REFERENCES

Andersson, J., Wedekind, B., Hall, D., Stradling, R. and Barnes, C. (2001). DERT/SMMT/CONCAWE Particle Research Programme: Light-duty results. *SAE Paper No.* 2001-01-3577.

Andersson, J., Clarke, D. and Watson, J. A. (2004). UK Particulate Measurement Programme (PMP): A near US 2007 approach to heavy duty diesel particulate measurements - comparison with the standard European method. *SAE Paper No*. 2004-01-1990.

Andersson, J., Giechaskiel, B., Munoz-Bueno, R., Sandbach, E. and Dilara, P. (2007). Particle Measurement Programme (PMP) light-duty inter-laboratory correlation exercise (ILCE-LD) final report.

Choi, B. C., Yoon, Y. B., Kang, H. Y. and Lim, M. T. (2006). Oxidation characteristics of particulate matter on diesel warm-up catalytic converter. *Int. J. Automotive Technology* **7**, **5**, 527−534.

Dockery, D., Pope, C. and Wu, X. (1993). An association between air pollution and mortality in six US cities. *New England J. Med.* **329**, **24**, 1753−1759.

Fast Particulate Spectrometer User Manual (2008). http://www.cambustion.co.uk.

Giechaskiel, B., Munoz-Bueno, R., Rubino, L., Manfredi, U., Dilara, P., Santi, G. D. and Andersson, J. (2007). Particle size and number emissions before, during and after regeneration events of a Euro 4 DPF equipped light-duty diesel vehicle. *SAE Paper No*. 2007-01-1944.

Hagena, J. R., Filipi, Z. S. and Assanis, D. N. (2006). Transient diesel emission, analysis of engine operation during a tip-in. *SAE Paper No*. 2006-01-1151.

Kayes, D. and Hochgreb, S. (1999). Mechanism of particulate matter formation in spark-ignition engines. *Environ. Sci. Technol.*, **33**, 3957−3967.

Kittelson, D. B. (1998). Engines and nanoparticles: A review. *J. Aerosol Sci.* **29**, **5/6**, 575−588.

Lee, J. W., Jung, Y. I., Jung, M. W., Cha, K. O., Kwon, S. I., Kim, J. C. and Park, S. (2008). Experimental investigation and comparison of nano-particle emission characteristics in light-duty vehicles for two different fuels. *Int. J. Automotive Technology* **9**, **4**, 397−403.

Ostro, B. (1984). A research for a threshold in the relationship of air pollution to mortality: A reanalysis of London winters. *Environ*. *Health Perspect*, **58**, 397−399.

Pope, C., Schwartz, J. and Ransom, M. (1992). Daily mortality and PM_{10} pollution in Utah Valey. *Arch*. *Environ*. *Health* **47**, **3**, 211−217.

Ristovski, Z. D., Morawska, L., Hitchins, J., Thomas, S., Greenaway, C. and Gilbert, D. (2000). Particle emissions from compressed natural gas engines. *J. Aerosol Sci.* **31**, **4**, 403−413.

Roberto, C., Volker, S., Rainer, V. and Thorsten, B. (2007). Measurement of nucleation and soot mode particle emission from a diesel passenger car in real world and laboratory in situ dilution. *Atmo*. *Environ.*, **41**, 2125−2135.

Takeda, K., Yaegashi, T., Sekiguchi, K., Saito, K. and Imatake, N. (1995). Mixture preparation and HC emission of a 4-valve engine during cold start and warm-up. *SAE Paper No*. 950074.

TRANS-WP29-GRPE-48 (2004). Conclusions on Improving Particulate Mass Measurement and New Particle Number Measurement Procedures of R83. http://www.unece.org/trans/wp29grpe.

Vaaraslahti, K., Keskinen, J., Giechaskiel, B., Murtonen, T. and Solla, A. (2005). Effect of lubricant on the formation of heavy-duty diesel exhaust nanoparticles. *Environ. Sci. Technol.*, **39**, 8497−8504.