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IMPACT OF FUEL, INJECTION TYPE AND AFTER-TREATMENT SYSTEM ON PARTICULATE EMISSIONS OF LIGHT-DUTY VEHICLES USING DIFFERENT FUELS ON FTP-75 AND HWFET TEST CYCLES

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ABSTRACT−The characteristics of particulate emission, in relation to factors such as fuel, injection type, after-treatment system and test cycle, were investigated. Five light-duty vehicles with different fuel, injection types and after-treatment systems - Compressed Natural Gas (CNG), Gasoline (Port Injection/Direct injection), and Diesel (with/without Diesel Particulate Filter (DPF)) - were tested on Federal Test Procedure (FTP) -75 and Highway Fuel Economy Test (HWFET) cycles. Particulate emissions were measured using a TSI 3090 Engine Exhaust Particle Sizer (EEPS) and Horiba Solid Particulate Counting system (SPCS). For the FTP-75 cycle, the DPF-equipped diesel vehicle showed the lowest particulate emission for the EEPS system, while CNG showed the lowest emission for the SPCS system due to the difference between the two measurement systems. However, the DPF-equipped diesel showed the least PN emission for both EEPS and SPCS method on the HWFET test cycle. Except for the DPF-equipped diesel, fuels with lighter molecular weight generated fewer particulates. Aside from fuel-type, the status of the engine was the most important factor determining particulate emission. When the engine was cold, a large number of particulates is formed regardless of engine-operating conditions. In contrast, warm engines form particulates only if the load on the engine is high enough, and the absolute magnitude is also lower than during the cold-start condition.

KEY WORDS : Particulate matter, Particulate number, Condensation particle counting, Different mobility analysis

1. INTRODUCTION

In recent decades, the targets imposed by emission regulations affecting vehicles including fuel economy, have become stricter by more than an order of magnitude, requiring significant effort from automobile manufacturers. Although various solutions have been proposed and adopted to meet these regulations, further improvements are still necessary to meet future regulations. Particulates, often called particulate matter (PM), are one of the major hazardous emissions from vehicles. Particulates are formed as by-product of combustion, and exhausted into the atmosphere as aerosols. Due to their harmful effect on human health, the World Health Organization designates particulates as a Group 1 carcinogen. Compare to the Euro 1 regulation applied in 1992, Euro 6 regulation (to be applied in late 2014), requires less than 1/30th the current level of PM emission for light duty vehicles (decreased from 0.14 to 0.0045 g/km). Starting with the Euro 5+ regulation, PM emission targets at the same level have also been applied for gasoline direct-injection vehicles.

Even though various technical improvements have been done in particulates reduction such as fuel injection optimization (Piock *et al*., 2011) or adoption of particulate filter, there are still several answered fundamental questions, including how to define "particulate emissions" beyond the traditional mass based method. Traditionally, particulate emission was defined by the total mass of particulates collected in a dilution tunnel. However, after it has been known that nano-particles (particles of diameter < 50 nm) can be more harmful to human health, although their contribution to the total particulate mass is not significant (Myung and Park, 2012), Particulate Number (PN) has been suggested as a complementary measurement method. With the effort of working group on Particulate Measurement Protocol (PMP), a new method to measure PN emission has been proposed and it is going to be introduced in European regulation, except for vehicles equipped with port-fuel gasoline-injection engines. However, there are debates ongoing with regard to PN emission, such as the suitability of setting 23 nm as a cut-off diameter of particles, and about the difficulty of achieving good repeatability and reproducibility (Giechaskiel *et al*., 2010). Because of these unresolved issues, the results from studies on particulate emissions have large variances related to specific test methods, experimental apparatus and injection types (Choi *et al*., 2012; Kim *et al*., 2013).

The objective of this study was to investigate the relationship between particulates emission (mainly focused

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on the number and size distribution of particulates) and various factors such as engine operation parameters such as fuel, fuel injection type, and after-treatment system. To obtain realistic data, the official test methods used in the United States and South Korea (Federal Test Procedure (FTP) 75 and Highway Fuel Economy Test (HWFET) of the US EPA) were used. The test vehicles included two gasoline vehicles (with different fuel injection types) and two diesel vehicles (with different after-treatment systems). A vehicle fueled by Compressed Natural Gas (CNG) was also tested for comparison. Aside from hydrogen, CNG is the fuel with the lowest carbon content and the best evaporation property, thereby generating the least amount of particulate matter in general cases (Ristovski *et al*., 2000). Other exhaust emissions, such as total hydrocarbon (THC), carbon monoxide (CO), and carbon dioxide (CO2) were also measured to assess any difference caused by the characteristics of the fuels and test vehicles.

2. EXPERIMENTAL CONDITION

2.1. Test Cycle and Experimental Apparatus

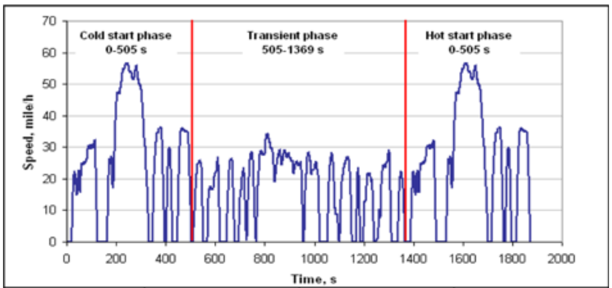
The velocity profiles and characteristics of the FTP-75 and HWFET cycles are given in Figure 1. For the FTP-75 cycle, a 10-minute soaking time between the transient phase and the hot-start phase were omitted. Both FTP-75 and HWFET cycles have similar levels of maximum acceleration (5.3 kph/s), but only FTP-75 cycle contains cold-start and idle operation. For each test condition, the tests were performed at least three times to verify repeatability Before the test, all test vehicles were soaked under the same conditions (25°C and 50% relative humidity) during 24-hour period of testing.

Figure 2 shows a schematic diagram of the experimental setup. The tests were performed on a 2WD roller-type chassis dynamometer (BEP 380 hp), and exhaust emission gases were collected and measured using an integrated gas analyzer (Horiba MEXA 7200H). All these test measurements were performed according to the official procedure of the corresponding test cycle.

For particulate emissions, two different devices were used. The measure of total PN and particle-size distribution was done using a TSI 3090i Engine Exhaust Particle Size Spectrometer (EEPS), which is based on Differential Mobility Analysis. The sampling tube for the EEPS was installed in the middle of the dilution tunnel, where it measured particle number and size distribution with a resolution of 1 sec. In addition, a Horiba MEXA 2000-Solid Particle Counting System (SPCS), which uses a laser-based solid-particle counting method officially approved by PMP, was also installed to measure the total particulate number. The differences between the two measurement systems are illustrated in Table 1. In general, PN results from the EEPS system are higher than those from the SPCS system because EEPS has a lower limit of detection, and can also detect molecules of volatile hydrocarbons.

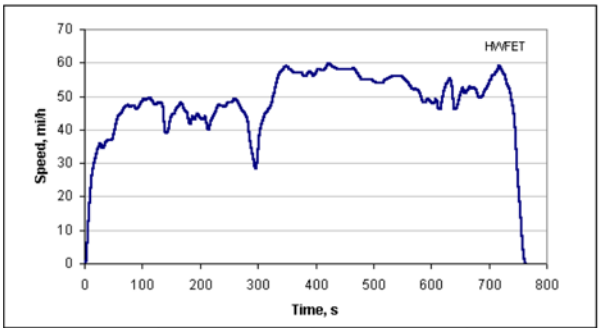
2.2. Test Vehicle and Fuel

The technical specifications of the five test vehicles are summarized in Table 2. Spark ignition vehicles (Vehicle 1, 2 and 3) were equipped with a close-coupled three-way catalyst (TWC). However, they did not have a special after-treatment system for particulate emissions such as Exhaust Gas Recirculation (EGR) or particulate filter. Vehicles 2



Distance	17.77 km	Time	1874 sec.
Max. Speed	91.3 km/h	Avg. Speed	34.1 km/h

(a) FTP-75 cycle



Distance	16.45 km	Time	765 sec.
Max. Speed	96.4 km/h	Avg. Speed	77.7 km/h

(b) HWFET cycle

Figure 1. Test cycles for experiment.

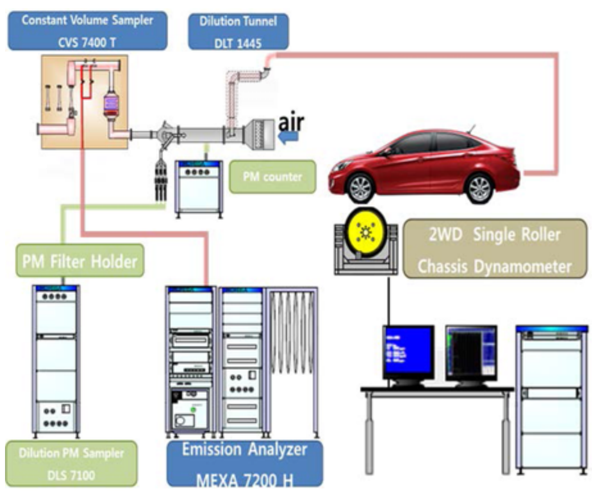


Figure 2. Schematic diagram of experimental setup.

Table 1. Technical specifications for particle counter.

Test device	SPCS	EEPS
Basic principle	Laser scattering of solid particle	Difference in electric mobility of particles
Detection range (nm)	23 ~ 1000	5.6 ~ 560
Particle counting	Solid particles only	Solid + Volatile
Output data	Total particle number (#/km)	Particle concentration (#/cc), Size distribution
Note	Official method by PMP	

Table 2. Technical specifications for test vehicles.

Test vehicle	#1	#2	#3	#4	#5
Fuel	CNG	Gasoline		Diesel	
Displacement volume (cc)	→	1,998	2,996	1,685	1,991
Compression ratio	→:	10.5:1	10.7:1	17.0:1	17.7:1
Maximum power (hp)	N/A	165	245	140	126
Fuel injection	Port injection		Direct injection		
Injector type	Port fuel injector		Out-ward	Multi-hole	
Piston	Flat with valve relief			Bowl	
Fuel injection pressure (bar)	N/A	4.5	200	1800	1400
After treatment	Closed Coupled TWC @ downstream of exhaust			DOC + DPF	DOC
Emission level	Tier 2 Bin 5			Euro 5	Euro 3

and 3 were fueled by gasoline but they have different injection systems. Vehicle 3 was equipped with an outwardly opening center-mounted direct-injection system, while Vehicle 2 used a conventional port-fuel-injection system. For the compression-ignition vehicles, Vehicle 4 met EURO 5 regulations by using Diesel Oxidation Catalyst (DOC) and Diesel-Particulate Filter (DPF), but Vehicle 5 did not have a particulate filter, so it only met the EURO 3 regulation. Both diesel vehicles are equipped with EGR system. The engine of Vehicle 1 was a modification of the engine of Vehicle 2, enabling the assumption that the difference in results between the two was due to the fuel characteristics.

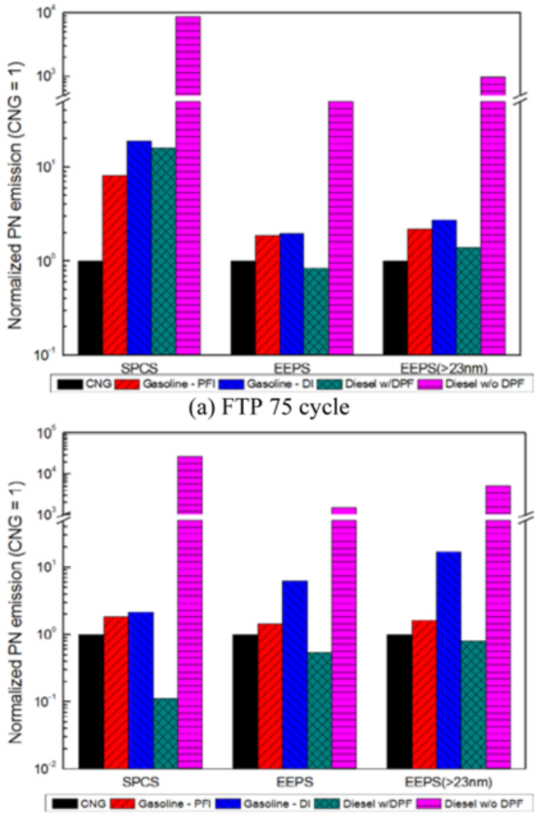
Table 3. Physical properties of test fuel.

Fuel	CNG	LPG	Gasoline	Diesel
Chemical composition	CH_4	C_4H_{10}	C_4-C_{12}	C_{12}-C_{25}
H/C ratio	3.8:1	2.52:1	1.95–2.05:1	1.9:1
LHV (MJ/kg)	50.0	45.7	41.0	42.5
State	Gas	Liquid		
Injection	Port	Port	Port/Direct	Direct
Ignition	SI			CI

The physical properties of the test fuels are summarized in Table 2. Unlike for Compressed Natural Gas (CNG), which is mainly composed of methane, gasoline and diesel do not have uniform physical properties because they are actually composed of hundreds of different hydrocarbon species. The gasoline used in this study contained approximately 11 vol% methyl tert-butyl ether (MTBE) as oxygenate, resulting in a higher H/C ratio and lower heating value, compared to non-reformulated gasoline.

3. TEST RESULT

Figure 3 shows the total PN emission result for each test vehicle for the FTP-75 and HWFET cycles. For the EEPS system results, emission data for particulates with diameter larger than 23 nm (same detection limit as for SPCS) were also juxtaposed in the figure, in order to compare the measurement characteristics of the two different test devices. All the other exhaust emissions are given in Tables 4 and 5. Because the SPCS and EEPS systems use different units of measure − SPCS measures total PN per unit distance driven (#/km), while EEPS gives information on PN concentration (#/cc) − experimental results were normalized using the PN-emission value of the CNG vehicle in each test cycle.



(a) FTP 75 cycle

(b) HWFET cycle

Figure 3. Total PN emission for each fuel.

Table 4. Exhaust emissions for FTP-75 cycle.

Emission (g/km)	THC	CO	NOx	CO_2	Fuel economy (km/L)
Vehicle #1	0.0155	0.1775	0.0313	164.2	-
Vehicle #2	0.0171	0.2754	0.0308	183.1	12.75
Vehicle #3	0.0086	0.0903	0.0098	215.7	10.85
Vehicle #4	0.0072	0.0388	0.4832	166.9	16.07
Vehicle #5	0.0508	0.0986	0.5852	209.8	12.77

For SPCS, the PN numbers were also normalized by the engine displacement volume of the CNG vehicle because engines with larger displacement volume have a disadvantage in total PN.

For SPCS system, PN emissions of CNG vehicle before normzlized were 9.4×10^9 and 2.4×10^{10} particles/km for FTP-75 and HWFET cycle, respectively.

According to Figure 3, the diesel vehicle without DPF (Vehicle 5) showed an order-of-magnitude higher emission compare to other types of vehicles, for all test cases. For other vehicles, the DPF-equipped vehicle (Vehicle 4) showed the lowest PN emission for the HWFET cycle, regardless of the measurement device used. During the FTP-75 cycle, this vehicle showed the lowest PN emission by EEPS measurement, but showed almost 10 times higher PN emission than that of the CNG vehicle measured using the SPCS device. The difference between the two systems became small when the lower limit of particulate detection was equated; even so, the PN emission from the diesel engines measured much less by the EEPS method than by the SPCS method. This discrepancy can be explained by the particulate detection mechanisms of the two systems. For the SPCS method, only solid particles are measured because a super-condensation process that occurs during the measurement process removes all volatile carbon particles, which are mainly hydrocarbons. However, for the EEPS system, both volatile and solid carbons are measured without removal, generating differences in PN emission due to inclusion of the volatile fraction. As indirect evidence, during the FTP-75 cycle, it was observed that the diesel vehicles showed much lower hydrocarbon emission than the other test vehicles, which infers the advantage (recorded less) of PN measurement using the EEPS system. Another factor which may cause this difference is the characteristics of the two test cycles. The FTP-75 cycle includes a cold-start condition while the HWFET test cycle has a warm-up period only. Diesel-fueled vehicles are more sensitive to engine condition (cold/warm) than are CNG or gasoline engines because diesel evaporates poorly, and generates more of the liquid droplets that may become large particulates.

Table 5. Exhaust emissions for HWFET cycle.

Emission (g/km)	THC	CO	NOx	CO_2	Fuel economy (km/L)
Vehicle #1	0.004	0.072	0.006	96.25	-
Vehicle #2	0.001	0.018	0.006	114.9	20.25
Vehicle #3	0.001	0.010	0.001	125.6	18.53
Vehicle #4	0.003	0.004	0.132	110.8	24.08
Vehicle #5	0.028	0.017	0.396	139.9	19.04

Information on the size distribution of particulates, with respect to test fuel, is given in Figure 4. For the FTP-75 cycle, gasoline direct-injection vehicles showed two peaks in particulate size: one near 10 nm, and the other around 50 nm. The first peak was mainly due to the particulates in nuclear-mode (diameter approximately 5 ~ 30 nm), while the second peak was caused by particulates in accumulation-mode (diameter approximately 30 ~ 200 nm). The gasoline port-fuel-injection vehicle also showed two peaks, but the mean diameter of the second peak was half that of particulates from the direct-injection vehicle. This was because the mixture preparation is much better in port-fuel-injection engines. Although the absolute magnitudes are very different, both diesel-fueled vehicles showed one peak

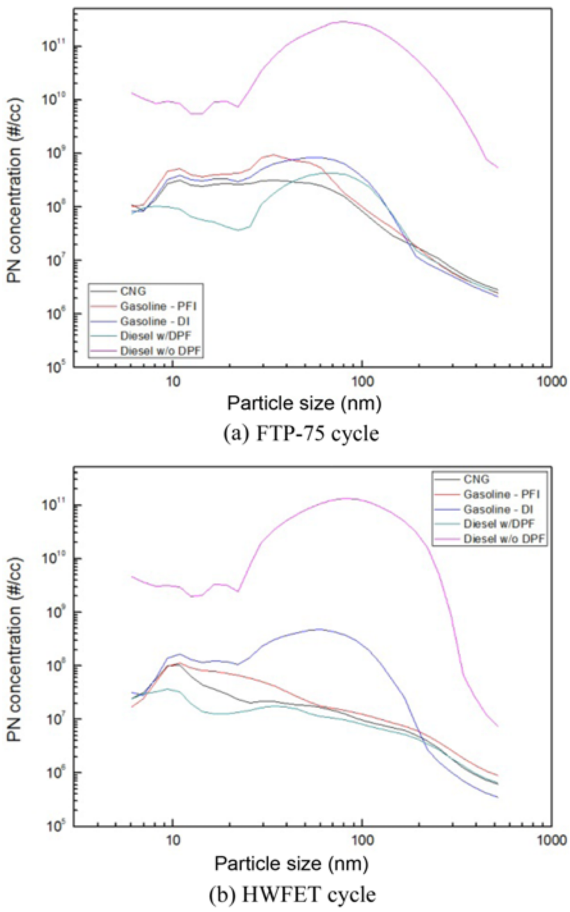


Figure 4. Particulates size distribution for each fuel.

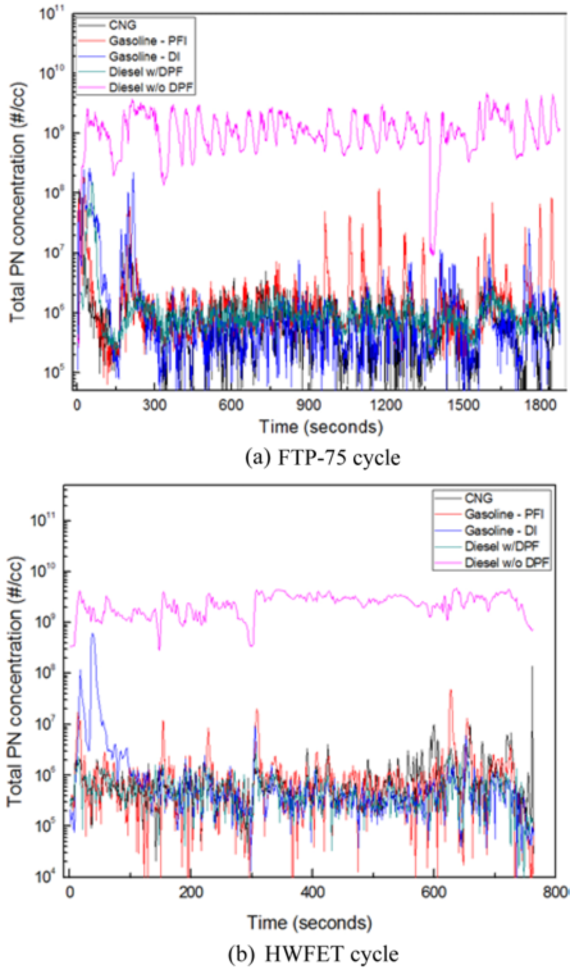
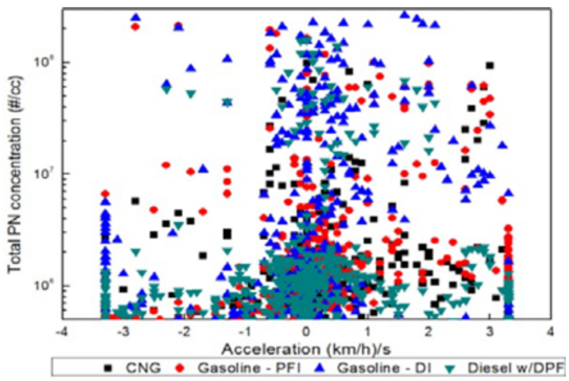


Figure 5. Total PN emission concentration for each cycle as a function of time.

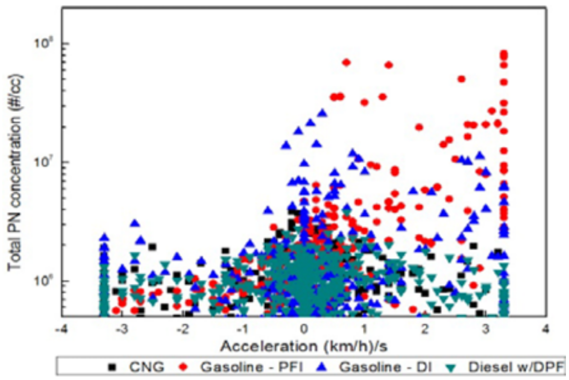
in their accumulation-mode regions, while the CNG vehicle showed only one small peak in the nuclear-mode region. This trend implies that particulates from CNG vehicles are mainly of the volatile fraction, while those from diesel vehicles mainly consist of accumulation-mode particulates.

Figure 5 shows total PN emission as a function of time for each cycle. For FTP-75 cycle, high peaks were observed in first 100 s regardless of which test vehicle was involved. These peaks may have occurred due to the low temperature in the combustion chamber, which inhibits fast evaporation of fuel. In addition, a rich air-to-fuel ratio until heat-up could be the reason for these peaks for test vehicles which use three-way catalyst (Giechaskiel *et al*., 2012). Similar trends were observed during the HWFET cycle, but the stabilization time was much faster since the engine was already warmed-up. After engine warm-up, the PN emission level dropped to 1/100th the peak levels, except for the diesel vehicle without DPF. During warm-up operation, the gasoline vehicle with the direct-fuel-injection system showed less PN emission than that with port-fuel injection, but it is hard to generalize the emission characteristics of gasoline engines from this trend since many previous studies have shown that particulate emissions from gasoline-direct-injection engines during warm-up may differ according to injection type (Choi *et al*., 2012) or to the level of combustion optimization (Oh and Cha, 2013).

Various analyses have been performed in order to find relationships between the PN-emission pattern and engine-operation parameters such as vehicle speed, engine status, and engine load. Among these, the acceleration (kph/s), which represents engine load, is the most reliable variable connecting PN-emission to engine-operation conditions. Figures 6 and 7 display PN emission on the y-axis, and vehicle acceleration in the third phase of the FTP-75 cycle on the x-axis, with a time resolution of 1 second (The data from Vehicle 5 are omitted due to its consistently high PN emission, regardless of conditions). From Figures 6 (b) and 7, it is possible to observe that symbols indicating high PN-emission points (high y-values) are mostly on the right side (vehicles are accelerating) along the x-axis, which means higher engine load. However this correlation is only variable during warm-up, and cannot be implied for cold-start conditions. Figure 6 (a) is a similar graph for the first phase of the FTP-75 cycle. For this graph, PN emission is



(a) Phase 1 (cold start)



(b) Phase 3 (warmed-up)

Figure 6. PN emission as a function of engine load in FTP-75 cycle.

not a function of engine load in the cold-start condition, although the driving pattern is exactly the same as for the hot-start condition in FTP-75 (Figure 6 (b)). It is guessed that poor fuel evaporation due to the low engine temperature caused high levels of particulate emission regardless of the engine operating conditions. Because of this, vehicles burning diesel – the fuel with the worst evaporation property – showed the largest difference between the data presented in Figure 6 (a) and (b).

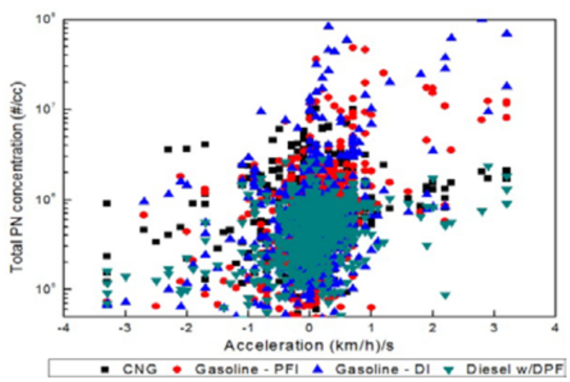


Figure 7. PN emission as a function of engine load in HWFET cycle.

4. CONCLUSION

In this study, the influence of various factors on particulate emission of vehicle was investigated. Five light-duty vehicles using different fuels and with different injection types were tested on a chassis dynamometer following official protocols (FTP-75 and HWFET), to see the effect of each factor. From the experimental results, the following conclusions have been drawn.

(1) For the SPCS system, the CNG-fueled vehicle produced the lowest PN emission, and the total number of particulates increased as the molecular weight of the fuel increased. However, the diesel engine with DPF produced the lowest particulate emission measured by the EEPS system, while the diesel engine without DPF produced 1,000 ~ 10,000 times higher particulate emission levels for all test cases.

(2) For gasoline-fueled vehicles, direct-injection vehicle generated more particulates than port-fuel injection vehicle. This is mainly due to poor vaporization of the fuel during cold-start conditions. When engines are fully warmed up, the total number of particulates produced by the two injection types is not much different.

(3) According to the size distribution obtained from EEPS, it was observed that particulates from CNG vehicles are mainly nuclear-mode particulates, while accumulation-mode particulates are predominant in the emissions of diesel-fueled vehicles.

(4) Among the various factors that affects particulate number, engine status – whether it is cold or warmed-up – is the most important. This impact becomes significant when the average molecular weight of the fuel is high. For the FTP-75 cycle, most of the particulates were emitted during the cold-start condition. After engines were warmed up, particulates mainly formed when vehicles accelerated.

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