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A Review on the Characteristics of Air Pollutants Emitted from Passenger Cars in Korea

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Abstract

On-road source emissions are major air pollutants and have been associated with serious health effects in Seoul metropolis. Thus, it is of fundamental importance to have an accurate assessment of vehicle emissions in order to implement an effective air quality management policy. As a result, there is a need to overview vehicle emission characteristics of air pollutants. This article discusses vehicle exhaust sampling and chemical analysis, emission characteristics of air pollutants, and emission regulations from passenger cars. The vehicle exhaust sampling and chemical analysis methods were described in particulate matter and gaseous compounds. In this article, chassis dynamometer, measurement instrumentation for nano-particulate matter and carbon compounds analysis device were described. For the gasoline and diesel vehicles, the effective parameters of emissions were average vehicle speed, vehicle mileage and model year. The particle number emissions for diesel nano-particles were sensitive to the sampling conditions. Also, the particle number emissions with a diesel particle filter (DPF) largely reduced rather than those without it. This article also describes different emission characteristics of air pollutants according to biodiesel or bioethanol mixing ratio. The Korean emission standards for passenger cars were compared with those of the US and EU. Finally, the objective is to give an overview of relevant background information on emission characteristics of air pollutants from passenger cars in Korea.

1. Introduction

Motor vehicles are major emitters of gaseous and particulate matter in urban areas, and exposure to particulate matter pollution can have serious health effects, ranging from respiratory and cardiovascular disease to mortality(1). With a growing population and rapid industrialization, the number of road vehicles in Korea has increased over the past several decades. Moreover, most of the road vehicles are concentrated in metropolitan cities. Consequently air quality has deteriorated in metropolitan areas and air pollution has now become a national concern(2).

As of 2011, on-road vehicles in Seoul were believed to be the single largest source for the major atmospheric pollutants, contributing, 81% of the carbon monoxide (CO), 51% of the fine particulate matter ($PM_{2.5}$), and 45% of the nitrogen oxides (NOx) to the Korean national emission inventory(3). Thus, an accurate assessment of emissions from motor vehicles is crucial to understand the air quality in the region(4). In order to improve air quality in the metropolitan areas according to Special Act on Metropolitan Air Quality Improvement, the government has reinforced the emission regulations for cars both in manufacture and in use, supplying low emission vehicles in Korea. Cooper *et al.* (2004)(5) noted that it is of fundamental importance to have an accurate assessment

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of the emission of air pollutants from motor vehicles in order to implement and effective air quality management policy. As a result, it is necessary to overview emission characteristics of air pollutants from motor vehicles.

Emission characteristics of gaseous compounds and particulate matter from gasoline and diesel passenger cars were described for previous studies. To better understand the emission characteristics of diesel and gasoline vehicles, many measurements have been conducted in recent year(6). The portable emission measurement system (PEMS) has been developed as an effective and practical method to quantify vehicle emission levels in real-world situations(7, 8). The chassis dynamometer testing system has been widely used to investigate the characteristics of vehicle exhaust emissions(9). Vehicle emission are strongly related with such factors as driving cycle, fuel quality, and aftertreatment equipment(7, 10-12). Giannelli *et al.* (2002)(13) reported parameters with major, intermediate and minor effects on HC, CO, NOx emissions from light duty gasoline vehicles. The major effect on the emissions is average speed command, min/max temperature command and registration distribution etc. The intermediate effect on the emissions is absolute humidity, air conditioning, altitude, mileage accumulation etc. Ntziachristos and Samaras (2000)(14) presents the emission factors for three-way catalyst (TWC) equipped passenger cars (PCs) with constitute a large proportion of the vehicle fleet at a European level. The emission factors have been the most common approach used in COPERT III and MOBILE6 emission inventorying tools based on large number of tests(15, 16). Over the past few years, diesel exhaust particle size and number distribution have become a focus of attention because of the presence of large numbers of fine and ultrafine particle, which may have adverse effects on health(17). Keogh *et al.*(18) reported that most of current vehicle emission regulations are regarding mass and not particle number-based, this means that a great deal of motor vehicle particle emissions is not controlled or regulated. Also, ultrafine particles (< 100 nm) constitute less than 10% of the total particle mass in the atmosphere(19, 20), however, in number concentration, they overwhelm particles > 100 nm(21). According to Seigneur (2009)(22), the fine PM ($PM_{2.5}$) mass concentration is dominated by the mass of the accumulation mode (with little contribution from ultrafine particulate matter (UFPM)), whereas the UFPM number concentration is dominated by the nuclei mode. The nuclei mode particles are also generated by the homogeneous nucleation of semivolatile organic compounds or sulfuric acid during the dilution and cooling of the vehicle exhaust. Smaller particles contained a larger fraction of semivolatile species(23).

In this study, we reviewed vehicle exhaust sampling, chemical analysis, emission characteristics and vehicle emission regulations of air pollutants from passenger cars which are most dominant type of vehicles in Seoul metropolis. The objective is to provide an overview of relevant background information on emission characteristics of air pollutants from passenger cars in Korea.

2. Vehicle Exhaust Sampling and Test Methods

2.1 Sampling and chemical analysis

Engine exhaust consists primarily of nitrogen, oxygen, water vapor, and CO_2, with minor constituents of CO, hydrocarbons, NOx, and PM. Owing to the high temperature of engine exhaust, 150-300 °C, and the potential for water condensation as it cools, regulatory protocols specify that PM emissions be measured through a dilution tunnel(24). Vehicle load simulations were conducted on the light-duty vehicle chassis dynamometer system (MDD-48-108-200HP, Horiba) which is a device reproducing real world driving cycles such as idle, acceleration, cruising, and deceleration modes. Chassis dynamometer system consists of chassis dynamometer, driver aid, constant volume sampler (CVS-7100), dilute tunnel, and exhaust gas analyzer. The exhaust gas from the tailpipe was collected by the CVS sampler and analyzed after dilution with ambient air. The driver aid displays driving conditions on a monitor screen. The

Fig. 1 Chassis dynamometer facility for measuring motor vehicle emissions

chassis dynamometer system has been used to investigate the characteristics of vehicle exhaust emission(25-26). The chassis dynamometer facility is shown in Fig. 1(27). Table 1(27) lists a variety of sampling media and chemical analyses included in such suites.

2.2 Measurement for nano-particulate matter

Number and mass concentrations of nano-particulate matter were measured using EEPS (Engine Exhaust Particle Sizer, model 3090, TSI Inc.) which is a real time reproducing device (Fig. 2). The EEPS is based on the development of the electric aerosol spectrometer(28, 29). Using multiple electrometers as detectors, EEPS measured particle size from 5.6 to 560 nm with a sizing resolution of total 32 channels. EEPS reads size distribution at a frequency of 10Hz, which makes it an ideal instrument to measure diesel engine particle emissions during transient conditions. An impactor is installed at the inlet of the EEPS to remove particles with aerodynamic diameter larger than 1 μm. Particles passing through the impactor are then charged in a unipolar diffusion charger to a predictable charge state. The charged particles subsequently enter an annular space between two cylinders. Under the electrical field between the two cylinders do not directly relate to specific particle size channels. Particles that enter the EEPS at the same time are detected at different times, on different electrometers, depending upon size and charge(30).

The scanning mobility particle sizer (SMPS, model 3934, TSI, Inc.) was composed of electrostatic classifier (EC, model, 3071A, TSI, Inc.) and condensation particle counter (CPC, model 3010, TSI, Inc.). The electrostatic classifier was equipped with an 808 nm 50% cutoff impactor to remove the larger particles in the sample stream. The CPC was composed of a saturated tube, condenser, particle sensor, flowmeter

Table 1 Vehicle exhaust sampling and chemical analysis methods

Species	Sampling medium	Analysis method
(a) Particulate matter Total mass PM_{10} and $PM_{2.5}$	Teflon or TIGF[a] filter	Gravimetric
Souble organic carbon	Teflon filter of TIGF	Weight loss after extraction with DCM[b] and drying
Elemental/organic carbon	Pre-fired quartz filter	Thermal/optical reflectance (TOR)
Metals and elements (Al, Si, P, S, Cl, K, Ca, …)	Teflon filter	ICP-MS[c], X-ray fluorescence
Inorganic ions and acids (NO_2^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, NH_4^+, HNO_2, HNO_3, H_2SO_4)	Teflon or pre-fired quartz filter and water impingers	Water extraction and ion chromatography
(b) Gaseous compounds VOC(C_1-C_{12}) CO, NO, NO_2, N_2O, SO_2	Tedlar bags, SUMA canisters Tedlar bags or continuous	GC-MS or GC-FID NDIR and/or FTIR

[a] Teflon impregnated glass fiber.

[b] Dichloromethane.

[c] Inductively coupled plasma mass spectrometry.

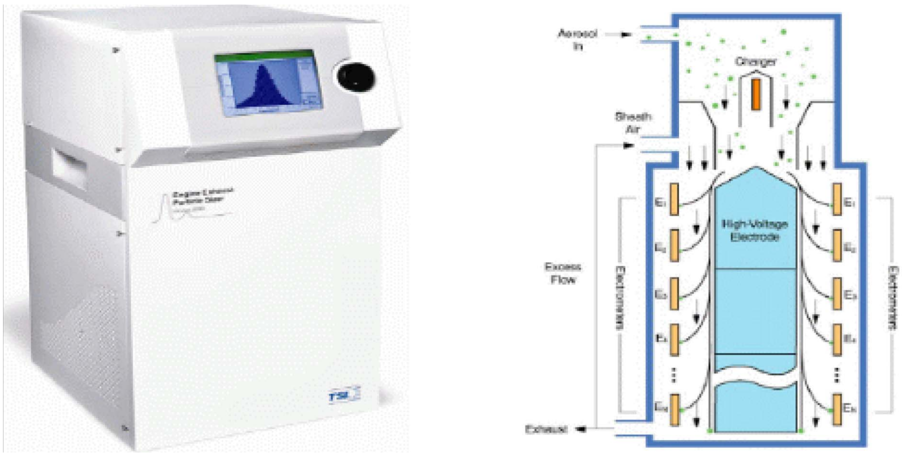

Fig. 2 The photograph and measurement principles of EEPS

and pump. The operational principles of these instruments are described elsewhere(31). The flow rates of aerosol and sheath air were set at 0.3 and 31/min, respectively.

An electrical low pressure impactor (ELPI, Dekati, Ltd.) monitored the number weighted (aerodynamic) size distribution in real time. ELPI operated with oil-soaked sintered plates and a filter stage that extended the lower cutpoint to ~ 7 nm(32). ELPI has 12 stages and the measuring size range is from 30 nm to 10 um. The diesel particles are first charged electrically in a charger and the particles discharge currents when they are trapped in a plate of an impactor. By measuring this current and applying charging efficiency for each particle size, the number of diesel particles is determined. The advantage of ELPI is short measurement time, but it cannot measure particles smaller than 30 nm and suffered from impactor fouling(33).

2.3 Carbon compounds analysis device

Hourly element carbon (EC) and organic carbon (OC) concentrations were measured using semi-continuous OCEC analyzer (Semi-continuous OCEC Instrument, Sunset Labs). This device was programmed to collect aerosol for 47 minutes beginning at the top of each hour with the analysis of carbonaceous aerosols. Sample collection was accomplished at flow rate of 24.0 L/min through an inlet equipped with a sharp-cut $PM_{2.5}$ cyclone and a carbon impregnated parallel plate organics denuder designed to remove gas-phase organic compounds upstream of the collection filter. Calibration of the Sunset Labs field analyzer was accomplished by an internal calibration using 5% methane in helium mixture in a fixed volume loop automatically repeated at the conclusion of each analysis cycle, and an external calibration using sucrose spikes on clean, pre-baked filters.

3. Emission Characteristics of Air Pollutants by Fuel Type

3.1 Gasoline and diesel

In this study, we compared gasoline and diesel fuel. In the case of gasoline engine, mixture of air and fuel is put inside the engine, and the spark plug makes spark for fuel combustion when the piston is compressed. As for diesel engine, however, only air inside the engine at high-pressure compression piston in the state pumps the fuel inside the engine and the fuel will be ignited spontaneously. The exhaust air pollutants have different characteristics due to different internal combustion engines. Generally, the gaseous pollutants such as CO, HC, NOx, CO_2, SO_2, and VOCs etc. from gasoline engine were emitted while particulate pollutants such as PM, Soluble Organic Fraction (SOF), Elemental Carbon (EC)/Organic

Carbon (OC), and smoke etc. as well as the gaseous pollutants from diesel engine were emitted.

The major parameter with effects on emissions was average vehicle speed. CO, HC, NOx, CO_2 and PM have similarly been shown to be dependent on speed regardless of fuel type according to previous studies(2, 34, 15). Giannelli *et al.* (2002)(13) reported that low speed (16.1-24.1 km/h) emissions of CO, HC and NOx increased by 15-40%, 20-80% and 20-50% for gasoline vehicles, respectively, compared with those at higher speeds (24.1-104.6 km/h). The CO, NOx, HC and CO_2 emissions at lower speeds (4.7-10.8 km/h) decreased rapidly with increase in speed while they remained unchanged at higher speeds from 65.4 to 97.3 km/h for gasoline passenger cars(2, 35). Also, CO, HC, NOx and PM emissions from diesel vehicles decreased at lower speeds (4.5-10.5 km/h) rather than higher speeds (65.4-97.3 km/h)(34). Ntziachristos and Samaras (2000)(14) pointed out the effect of driving cycle on the emissions such that higher emissions at low mean speeds was due to high frequency and intensity of speed transients and lower emissions at high mean speeds (> 70 km/h) due to less variation of traveling speed.

The vehicle mileage has been found in previous studies as a factor of intermediate importance, leading to a change in emissions of 5-20%. All vehicle emissions as a function of percent increases in the fraction of older vehicles relative to MOBILE6 default vehicle age fractions(13). The vehicle mileage associated with model year because model year was older as the mileage accumulates. According to previous studies, it was found that for CO, HC, and NOx, the cars of each mileage were over 80,000 km emitted 44-78%, 53-86%, and 72-81% more than those with mileage under 80,000 km, respectively(2). Ntziachristos and Samaras (2000)(14) noted that CO, NOx and HC emissions at ≤ 10,000 km, mileage class decreased 63-66% rather than those at > 90,000 km, mileage class. In addition to aging of catalyst, normal wear of the engine and build-up of deposits on the cylinder walls and head were thought to be responsible for the increase in emissions. The probability of malfunctioning or severely damaged engine parts, which leads to very high emissions, increases with age. An increase of the fraction of such vehicles (high- or ultra-emitters) in the total population leads to an overall elevated level of emissions of the fleet(14).

The U.S. Environmental Protection Agency (EPA) and the European Environment Agency (EEA) ascribed reduced vehicle emissions to better control technologies(15, 16). For gasoline vehicles, the improvement of three-way catalytic converter technologies with fuel control strategy has been a dominant effect to reduce emissions for meeting the stringent emission regulations. The major engine modifications include migration from indirect to direct fuel injection, the use of a high pressure, common rail, fuel system(36), and the use of cooled exhaust gas recirculation (EGR)(37). EGR is employed to regulate the relative concentrations of NOx and PM in the exhaust. Although changes in engine technology may be able to meet certain interim emission regulations, it is widely accepted that diesel vehicles can only meet the circa 2010 tailpipe standards with exhaust aftertreatment(38-40). The overall system, still under development, requires an oxidation catalyst to remove hydrocarbons and CO, a DPF to trap PM, and either an urea SCR (selective catalytic reduction) catalyst or catalyzed NOx trap to remove oxides of nitrogen.

In the case of the diesel engines, it is important to investigate emission characteristics of DEPs (diesel exhaust particles). According to current vehicle emission regulations, the standards for diesel vehicular particulate emission are usually based on total particulate mass emission and smoke levels(41-43). The mass standard trapped on a filter relates to particles. However, the filter measurements are approaching the limit of detectability for modern low emission diesel engines. The sizes and numbers of particles emitted from motor vehicles, as well as mass concentrations, are now commonly measured by researchers in order to understand the characteristics of particle emissions from vehicle engines(44). Diesel engines normally generate higher exhaust particle number concentrations than engines running on gasoline or compressed natural gas(45). Diesel nano-particles are very sensitive to the sampling conditions(46), and their subsequent growth is highly influenced by the dilution condition(47). Therefore, important effect parameters for diesel particulate matter are dilution ratio and dilution temperature. In the previous studies, the measured particle size of diesel emissions can be strongly affected by dilution ratio(48, 49). Also, Abdul-Khalek *et al.* (1999)(47) found that when the dilution temperature increased, it would slow down the nucleation rate considerably and reduce the rate of growth of particles due to the increase in vapor pressure of volatile species. Most volatile particles by the condensation of hydrocarbons or sulfur compounds consist of nucleation mode (D_p < 20 nm)(23).

Generally, the diesel vehicle and diesel engine emitted the higher amounts of EC than OC emissions in exhaust particulates(50-52). However, Geller *et al.* (2006)(32) pointed out that the emitted OC levels of the catalyzed DPF-equipped diesel vehicle are from 1.5 to 11 times higher than EC concentrations during stead-state and transient operations. Moreover, EC dominated OC for the diesel vehicle without a DPF, whereas OC dominated EC for the gasoline vehicle and the catalyzed DPF-diesel vehicle based on chassis dynamometer examination. Also, EC and OC (g/km) were 12.91 and 4.97, respectively at diesel transient while they were 0.14 and 0.48, respectively at the catalyst DPF transient(32). Also, the particle number concentrations for with a DPF were largely reduced rather than for without a DPF. The particle number emissions for with a DPF decreased 83-86% compared to that for without a DPF(53). The lowest particle number emissions were those of the DPF-equipped vehicle, ranging from 3.2 to 5.1×10^{11} particles/km, thus, almost 100-fold lower than those of the conventional diesel passenger vehicle(32).

3.2 Biodiesel

Biodiesel can be made from alcohol and vegetable oils, which are both agriculturally derived products. Biodiesel made from such renewable resources is safer due to increased flash point, biodegradable, containing little or no sulfur, tending to reduce visible smoke from the exhaust, and an environmentally innocuous nature(54). Biodiesel mixing ratio increases, the overall reduction of particulate matter tends. Especially, as the mixing ratio of 20% or more, reduction increases, but NOx tends to increase with the increase of the mixing ratio. While suppressing the increase of NOx, particulate matter is needs to maximize the order of 20% to 30% biodiesel blend. Also, particle number emissions tend to decrease with the increase of the mixing ratio(23).

The bus fueled by biodiesel shows less particle emissions compare to diesel bus due to the presence of the oxygen in the fuel(55). But the matter is complex because particle number distributions are very sensitive to the level of dilution and heating prior to sampling, engine operating conditions, the type and strength of biofuel blends and the specific vehicles used(56). According to above reasons, other studies have different tendency. Diesel engine fueled with biodiesel blends emits more PM_2 particle number concentrations than those with diesel fuel(54). Also, most of the studies indicate that, irrespective of the type of biofuel (pure or blended) and engine used, particle number emissions are somewhat larger for biofueled vehicles than those for conventionally fuelled vehicles(57). It is difficult to make definitive conclusions about why particulate emissions were higher or lower with the increase of mixing ratio.

3.3 Bioethanol

Bioethanol has the potential to replace gasoline in internal combustion engines; however, the cost of bioethanol production is high compared to petroleum-based fossil fuels(58-59). Currently, large scale fuel ethanol production is mainly based on sugar containing raw materials (i.e. sugarcane) and starch grains (i.e. corn, wheat and cassava) which are not desirable due to their food and feed value(60). Many studies(61-66) reported that more than 30% CO reduction was noticed in higher level ethanol blends. Celik *et al.*(61) found 53% CO reduction for the blend E50 in 1C engine. Schifter *et al.*(62) noticed 52% CO reduction for E6 to E20 blends in 1C engine. Balki and Sayin(63) reported 35% CO reduction for pure ethanol (E100) com- pared to gasoline in 1C engine. Apparently, Liang *et al.*(67) and Liang *et al.*(68) reported a slight increase in CO emissions for E100 and dimethyl ether blends in 4C engine. Moreover, Zhuang and Hong(69) also noticed a slight increase in CO emissions for E0 to E70 in 1C engine.

Among them, some of the literatures(64, 70-73) reported only a slight reduction in NOx emission up to 10%. Ozsezen *et al.*(70) found 1.3% NOx reduction for E5 and E10 in 4C water cooled MPFI engine. Jia *et al.*(74) have noticed 5.9% reduction for E10. Panga *et al.*(75) obtained only 1% reduction for E10. Schifter *et al.*(62) reported 60% increase in NOx emission for up to E20 in 1C engine. Najafi et al.(76) found up to 45% increase in NOx emission for E20 in 4C SOHC engine. Melo *et al.*(77) reported that NOx increased in high speed and decreased in low speed for hydrous ethanol. In case of the NOx, there is no trend for different SI engine fueled with ethanol blending ratio.

Most of the researches(61, 62, 67, 70, 72) found unburned hydrocarbon(HC) emission decrease with ethanol fuel blends in SI engine compared to gasoline. Celik(61) obtained 12% HC reduction for E25-E100. Ozsezen *et al.*(70) noticed 14% reduction in HC for E5 and E10 in 4C engine. Schifter *et al.*(62) obtained 19% HC reduction for E6-E20 on 1C engine. Most of the studies(61, 62, 70, 72, 78) reported that HC reduction is from 10% to 40% for the blends E5-E100.

4. Comparison with Exhaust Emission Standards

4.1 United State

The US emission standards are shown in Table 2. After amended by the 1992 Clean Air Act, the US has enforced stricter NOx and HC emission standards since 1994. In addition, the exhaust emission durability was strengthened from 80,000 km and 5 years to 160,000 km and 10 years since 1994(79). In the case of US, the definition of gasoline and diesel passenger cars was ≤ 12 passengers. The test cycle was US Federal Test Procedure (FTP). National Low Emission Vehicle (NLEV) will be in place until Model Year (MY) 2004, at which time Tier 2 standards will take effect. Fleet Average System (FAS) was applied at Tier 2 which had 0.044 g/km NOx fleet average at 193,000 km/10 year phased-in 25/50/75/100%(80).

California in the US where LA smog accident occurred had vehicle emission regulations for the first time in the world. The Transitional Low Emission Vehicle (TLEV), Low Emission Vehicle (LEV), Ultra Low Emission Vehicle (ULEV) and Zero Emission Vehicle (ZEV) depending on vehicle emission regulation levels were divided in California since 1995. Also, Fleet Average Standards (FAS) were carried out step by step(79). The LEV 1 and LEV 2 emis-

Table 2 US Federal emission standards of gasoline and diesel passenger cars

Emissions (g/km)	Durability (km)	MY91 → Tier 0	MY94 → Tier 1	MY01 → NLEV	Test Cycle
HC	80,000	0.25	0.25	0.25	US FTP
NMHC	80,000 160,000	0.25 0.25	0.16 0.19	0.047[c] 0.056[c]	
CO	80,000 160,000	2.1 2.1	2.1 2.6	2.1 2.6	
NOx[a, b]	80,000 160,000	0.62 0.62	0.25 0.37	0.124 0.186	
PM	80,000 160,000	0.124 0.124	0.05 0.06	0.05 0.05	

[a] Emission diesel vehicles were allowed 1.0/1.25 g/mi NOx until MY2003.

[b] NOx (highway)-standard : 1.33×NOx (city) - standard as listed above.

[c] NMOG measurement instead of NMHC.

Table 3 Tier 2 Phase-in schedule in % for passenger cars

Standard	‘01	‘02	‘03	‘04	‘05	‘06	‘07	‘08
NLEV, 0.186 NOx	100	100	100	–	–	–	–	–
Tier 2, 0.044 NOx	–	–	–	25	50	75	100	100

Table 4 California LEV 1 emission standards of passenger cars

Emissions (g/km)	Durability (km)	TLEV[a]1	LEV[b]1	ULEV[c]1	ZEV[d]1	Test Cycle
NMOG	80,000 160,000	0.078 0.097	0.047 0.056	0.025 0.034	0 0	US FTP
CO	80,000 160,000	2.1 2.6	2.1 2.6	1.1 1.3	0 0	
NOx	80,000 160,000	0.25 0.37	0.124 0.186	0.124 0.186	0 0	
PM	80,000 160,000	– 0.050	– 0.050	– 0.025	0 0	

[a] Transitional Low Emission Vehicle.
[b] Low Emission Vehicle.
[c] Ultra Low Emission Vehicle.
[d] Zero Emission Vehicle.

Table 5 California LEV 2 emission standards of passenger cars

Emissions (g/km)	Durability (km)	LEV[a]2	ULEV[b]2	SULEV[c]2	ZEV[d]2	Test Cycle
NMOG	80,000 193,000	0.047 0.056	0.025 0.034	– 0.006	0 0	US FTP
CO	80,000 193,000	2.1 2.6	1.1 1.3	– 0.6	0 0	
NOx	80,000 193,000	0.031 0.044	0.031 0.044	– 0.012	0 0	
PM	80,000 193,000	– 0.006	– 0.006	– 0.006	0 0	

[a] Low Emission Vehicle.
[b] Ultra Low Emission Vehicle.
[c] Super Low Emission Vehicle.
[d] Zero Emission Vehicle.

sion standards are shown in Table 4 and 5. In the case of LEV 2, new stringent NOx and PM limits plus additional Super Ultra Low Emission Vehicle (SULEV) category. The LEV 1 emissions categories phased out 2004-2007 while the LEV 2 standards were phased in 25/50/75/100% from 2004-2007. The Non Methane Hydrocarbons (NMHC) to Non Methane Organics (NMOG) certification factor of 1.04 was allowed. Mandatory phase-out of TLEV limits by MY2004(80). From 2001, NMOG fleet average emissions should be satisfied with emission standards according to year (Table 6).

4.2 EU

In the beginning of EU emission standards (Euro 1) of gasoline and diesel for passenger cars were the

Table 6 NMOG fleet average for passenger cars

Emissions (g/km)	‘01	‘02	‘03	‘04	‘05	‘06	‘07	‘08	‘09	‘10+
NMOG	0.044	0.042	0.039	0.033	0.030	0.029	0.027	0.025	0.024	0.022

Table 7 EU emission standards of passenger cars for Euro 1-Euro 4

Emissions (g/km)	Euro 1/EC93	Euro 2/EC96		Euro 3/EC2000		Euro 4/EC2005		Test Cycle
	Gasoline = Diesel	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel	
HC	-	-	-	0.20	-	0.10	-	NEDC
NOx	-	-	-	0.15	0.50	0.08	0.25	
HC+NOx	0.97	0.5	0.7	-	0.56	-	0.30	
CO	2.72	2.2	1.0	2.3	0.64	1.0	0.50	
PM	0.14	-	0.08	-	0.05	-	0.025	

Table 8 EU emission standards of gasoline passenger cars for Euro 5 and Euro 6

Emissions	Unit	Euro 5a (2009)	Euro 5b/b+ (2011)	Euro 6 (2014)	Test Cycle
THC[a]	g/km	0.100	0.100	0.100	NEDC
NMHC[b]		0.068	0.068	0.068	
NOx		0.060	0.060	0.060	
CO		1.0	1.0	1.0	
PM		0.005	0.0045	0.0045	
PN#	Nb/km	-	-	6.0×E11	

[a] Total Hydrocarbons.

[b] Non Methane Hydrocarbons.

Table 9 EU emission standards of diesel passenger cars for Euro 5 and Euro 6

Emissions	Unit	Euro 5a (2009)	Euro 5b/b+ (2011)	Euro 6 (2014)	Test Cycle
NOx	g/km	0.180	0.180	0.080	NEDC
HC+NOx		0.230	0.230	0.170	
CO		0.500	0.500	0.500	
PM		0.005	0.0045	0.0045	
PN#	Nb/km	-	6.0×E11	6.0×E11	

same in 1993. In the case of EU, the passenger cars were ≤ 2.5 ton Gross Vehicle Weight (GVW) and ≤ 6 seats. The test cycle for Euro 1-Euro 4 was New European Driving Cycle (NEDC). Gasoline and diesel were divided from Euro 2 standard. But PM emission standards were applied to only diesel vehicles. The separation of HC and NOx standards for gasoline vehicles implied more stringent exhaust emission regulations from Euro 3. The deterioration factors were 80,000 km or 5 years for Euro 3 while those were 100,000 km or 5 years for Euro 4. Stricter in-use durability was required from Euro 4(80). The

Table 10 Korean emission standards of gasoline passenger cars

Model year	Useful life[a]	CO	NOx	NMHC[b]/NMOG[c]	US standards
≤ 1999	5 yrs/80,000 km	2.11	0.62	0.25[b]	US Tier 0
2000-2002.6	5 yrs/80,000 km 10 yrs/160,000 km	2.11 2.61	0.25 0.37	0.16[b] 0.19[b]	US Tier 1
2002.7-2005	5 yrs/80,000 km 10 yrs/160,000 km	2.11 2.61	0.12 0.19	0.047[b] 0.056[b]	US NLEV
2006-2013	5 yrs/80,000 km 10 yrs/160,000 km	1.06 1.31	0.031 0.044	0.025[c] 0.034[c]	CARB ULEV

[a] For automobile components.
[b] Non Methane Hydrocarbons.
[c] Non Methane Organic Gases.

Euro 5 and Euro 6 regulations show Table 8 and 9. In the case of Euro 5, Total Hydrocarbons (THC) and Non Methane Hydrocarbons (NMHC) were divided. The test cycle was NEDC. Especially, PM number regulations were applied ≥ 2011 years for diesel and ≥ 2014 years for gasoline(80).

4.3 Korea

In the case of the gasoline passenger cars, stricter emission standards went into effect in 2000 based on 1994 US emission regulations. The Korean emission standards are shown in Table 10. Korean vehicle manufacturers were compelled to achieve these emission regulations with better control technologies. In particular, the improvement in three-way catalytic converter technology for gasoline cars has been an important parameter in reducing emissions. Generally the passenger cars were equipped with engine displacement ≥ 1000cc, < 3.5 ton GVW and ≤ 8 seats. The test cycle was US Federal Test Procedure (FTP). The NMHC to NMOG certification factor of 1.04 was allowed in Korea from 2009(81).

Table 11 Korean emission standards of diesel passenger cars for 1999-2005

Model year	CO	NOx	NMHC[a]	PM
≤ 1999	1.50	1.12	0.25	0.14
2000	1.20	1.02	0.25	0.11
2001-2002.6	1.10	0.95	0.22	0.11
2002.7-2005	0.95	0.65	0.08	0.07

[a] Non Methane Hydrocarbons.

Korean emission standards for diesel passenger cars are shown in Table 11 and 12. Although US FTP mode was used for diesel passenger cars until 2005, pollutants reduction technology levels could follow emission standards in Korea. Generally, Korea government applied the EU emission regulations for diesel passenger cars to Korean technology standardization in 2006. The test cycle has been NEDC since 2006. Also, PM number concentration has been regulated since 2012.

Table 12 Korean emission standards of diesel passenger cars for 2006-2014

Model year	CO	NOx	NMHC[a]+NOx	PM	PN#	EU standards
2006-2009.8	0.63	0.33	0.39	0.04	-	Euro 4
2009.9-2013	0.63	0.235	0.295	0.005	6×10^{11}[b]	Euro 5
≥ 2014	0.63	0.105	0.195	0.0045	6×10^{11}	Euro 6

[a] Non Methane Hydrocarbons.
[b] Applied by 2012.

5. Summary

In this paper, vehicle sampling and measurement, emission characteristics and emission regulations of air pollutants from passenger cars were reviewed.

Vehicle load simulations were conducted using chassis dynamometer system which is a device reproducing real driving conditions such as idle, acceleration, crusing, and deceleration modes. The vehicle exhaust sampling and chemical analysis methods were described in particulate matter and gaseous compounds. Also, main measurement instrumentation for nano-particulate matter was introduced in three devices (EEPS, SMPS and ELPI). Hourly element carbon (EC) and organic carbon (OC) concentrations were measured using semi-continuous OCEC analyzer.

Generally, gaseous compounds (CO, HC, NOx, CO_2, SO_2, VOCs, etc.) from gasoline engine were emitted while particulate matter (PM, SOF, EC/OC etc.) as well as gaseous pollutants from diesel engine was emitted. The parameters with effects on emissions were average vehicle speed, vehicle mileage, and model year. The particle number emissions for diesel nano-particles were sensitive to the sampling conditions (dilution temperature and ratio). Also, particle number emissions with a DPF were largely reduced rather than those without it. Biodiesel mixing ratio increased, the overall reduction of particulate matter tendency. But it was difficult to identify the reason why diesel exhaust emissions changed according to the increase in mixing ratio. In the case of bioethanol, the CO and unburned hydrocarbons showed reduction. However NOx showed different emissions according to various SI engines and bioethanol blending ratio.

The Korean emission standards for passenger cars were compared with those for the US and EU. In Korea, vehicle emission standards for gasoline passenger cars were implemented based on the US regulations, while the EU regulations have been applied for diesel passenger cars since 2006.

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