Technical Note

Emission Characteristics of Hazardous Air Pollutants from Construction Equipment

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ABSTRACT

The emission characteristics of mobile air pollution sources belonging to the non-road sector have yet to be thoroughly investigated, especially when compared to those of on-road vehicles. Hence, the present study employed an engine dynamometer to evaluate the emissions of a diesel engine complying with Tier 3 standards during various driving modes (KC1-8, NRSC, and NRTC) and a portable emissions measurement system (PEMS) to assess those of two excavators, one complying with Tier 3 and the other with Tier 4 standards, during real-world working and driving conditions. The characteristics and chemical composition of the emitted regulated pollutants (carbon monoxide (CO), non-methane hydrocarbon (NMHC), nitrogen oxide (NO_x), and particulate matter (PM)) and hazardous air pollutants (HAPs), e.g., volatile organic compounds (VOCs), aldehydes, and polycyclic aromatic hydrocarbons (PAHs), were then determined. For the regulated pollutants, NRTC mode generated the highest emissions owing to the rapid changes in engine load and speed during transitions. As a result of the after-treatment systems, which utilized a diesel oxidation catalyst (DOC) and selective catalytic reduction (SCR), CO, NMHC, and NO_x emissions from the Tier 4-compliant excavator were lower than those from the Tier 3-compliant diesel engine and excavator. The operating conditions of the diesel engine and construction equipment as well as the after-treatment systems significantly affected the composition of the non-methane volatile organic compound (NMVOC) emissions, which were dominated by alkanes that comprised 23 detected species. Sampling the particle-phase PAHs, we found phenanthrene, fluoranthene, and naphthalene; furthermore, we estimated the concentrations of the gas-phase PAHs with models to obtain the total PAH concentrations. Formaldehyde, which contributed the largest fraction of the aldehydes, was more abundant than the other species. Thus, emissions from non-road sources, including construction equipment, must be controlled because of the considerable health risks from pollutants such as formaldehyde and benzene. Our results will aid in the establishment of a national emission inventory for HAPs.

Keywords: Engine dynamometer; Diesel engine; Portable emissions measurement system; Excavator; Hazardous air pollutants.

INTRODUCTION

Mobile sources of air pollution can be categorized into *on-road transport vehicles*, such as cars, vans, buses, and trucks, and *non-road non-transport vehicles*, such as construction equipment, agricultural machines, vessels, and aircrafts. Several studies have been conducted on on-road sources in Korea as well as abroad; however, studies on non-road sources are insufficient. According to the national air pollutant emissions data of 2016, non-road construction equipment is a major emission source among mobile sources,

with volatile organic compound (VOC) emissions of 17% (highest after vessels and cars) and PM_{2.5} of 23.6% (highest after vessels and freight vehicles) (NIER, 2019a). Moreover, according to the Ministry of Environment's Clean Air Conservation Act, approximately 420,000 units are registered as construction equipment as of 2018, except for dump trucks and concrete mixer trucks. Car emission standards are applied to these units, and these have shown a 4.2% increase in the last 3 years (MLIT, 2019) and require continuous management.

In Korea, pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HCs), and particulate matter (PM), from mobile sources, such as construction equipment, are regulated and managed based on the existing emission standards and inventory setup. However, increasing interest in human health risks in recent years is gradually

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increasing the importance of managing hazardous air pollutants (HAPs), such as VOCs, aldehydes, and PAHs. In particular, among the pollutants emitted from diesel engines used in construction equipment, very small amounts of HAPs are detected; however, their prolonged exposure is extremely hazardous to human health as these entities are toxic, carcinogenic, and bioaccumulative (NIER, 2018a). However, HAP emissions from the exhausts of mobile sources, such as construction equipment, are difficult to manage owing to the lack of control standards.

The HAPs are classified into gaseous and particulate matter. Mobile source emissions are main sources for gaseous and particulate matter in urban air pollution (Jung *et al.*, 2017). Gaseous matter is comprised of aromatic hydrocarbons, such as benzene and toluene, as well as the derivatives, such as VOCs and aldehydes, with a distinctive odor. VOCs have high saturated vapor pressure and are easily evaporated. These are known to be the precursors of photochemical smog, and upon reaction with NO_x (photolytic reaction) contribute to the formation of secondary ozone. Benzene is known to cause leukemia, myeloma, and lymphoma (NIER, 2006, 2017). Aldehydes are a type of organic compounds with the carbonyl group of $-(\text{CH})=\text{O}$ attached (NIER, 2006), and are formed by incomplete combustion of hydrocarbons (Kumar *et al.*, 2011). Among aldehydes, formaldehyde is known to cause emotional instability, memory loss, and attentional disorder upon exposure (Han *et al.*, 2006). Particulate matter includes polycyclic aromatic hydrocarbons (PAHs) that are known to cause bronchitis, lung cancer, dermatitis, and conjunctivitis (Wang *et al.*, 2013; Costagliola *et al.*, 2014; Li *et al.*, 2015); this category also includes heavy metals that are known carcinogens. Particulate matter of diesel engine exhausts comprises high amounts of PAHs; these are likely to be generated via incomplete combustion of fuel. Among PAHs, benzo[a]pyrene has been reported to be carcinogenic (NIER, 2006). In particular, exhausts from diesel engines used in construction equipment have been known to have hazardous effects on health, causing cardiovascular diseases, lung cancer, and asthma (Kagawa, 2002; Hirano *et al.*, 2003; Kadkhoda *et al.*, 2004), and have been designated as Group 1 carcinogens by the International Agency for Research on Cancer (IARC) in 2012.

Fan *et al.* (2018) reported that the majority of the carbonyl compounds emitted from non-road diesel engines are formaldehyde and acetaldehyde, followed by acrolein, acetone, propionaldehyde, and crotonaldehyde, which decrease when the engine load increases. According to Jung *et al.* (2019), among the constituents of non-methane hydrocarbon (NMHC) emissions from heavy-duty diesel trucks with after-treatment systems, formaldehyde and acetaldehyde constitute approximately 14–29.9% and 5.7–12.4%, respectively. Moreover, George *et al.* (2014) reported that carbonyls, formaldehyde, and acetaldehyde are the main components of VOCs from heavy-duty diesel vehicles with the latest after-treatment systems, making up at least 72% of all VOCs. According to Nelson *et al.* (2008), among the VOCs emitted from heavy-duty diesel vehicles, formaldehyde showed the highest emission at 29.8 mg km^{-1} , followed by acetaldehyde (13.2 mg km^{-1}), benzene (6.1 mg km^{-1}), and

toluene (3.4 mg km^{-1}). PAHs emitted from heavy-duty diesel vehicles are reduced by at least 90% when a diesel particulate filter (DPF) is installed, whereas the ratio of gaseous PAHs to the total PAHs is reported to be high when it is not installed (Hu *et al.*, 2013). Jin *et al.* (2014) reported that 12 types of particulate PAHs were detected from heavy-duty diesel engines, but they were present in a very low ratio of $0.034 \pm 0.013\%$ of diesel particulate matter (DPM), while phenanthrene and anthracene together comprised 44.8% of PAHs. Research data on emission characteristics and speciation of HAPs for construction equipment compared to heavy-duty diesel vehicles is largely lacking both in Korea as well as in other countries.

Therefore, this study was aimed at investigating the emission characteristics of HAPs, determining the species involved, and selecting priority pollutants. Test modes, based on real work measurement results, were employed for the purpose. A portable emissions measurement system (PEMS) was installed, and an engine dynamometer experiment for the construction equipment (which is a major non-road emission source) was conducted.

METHODS

Test Engine, Models, and Fuel

This study selected one construction equipment engine (conforming to Tier 3 emission standards) and two excavators (conforming to Tier 3 and Tier 4 emission standards) based on the fact that these engines and models formed a large share of the construction equipment registered in Korea (MLIT, 2019). Engines complying with Tier 3 emission standards do not have a reduction device, but engines and excavators complying with Tier 4 emission standards have exhaust gas recirculation (EGR), diesel oxidation catalyst (DOC), and selective catalytic reduction (SCR) systems installed. Specifications of the engines and excavators undertaken for the study are shown in Tables 1 and 2. Test fuel met the diesel fuel standards of the Clean Air Conservation Act in Korea; properties of the tested diesel are presented in Table 3.

Test Modes

Construction equipment engines were tested in various certification modes (KC1-8, NRSC, and NRTC) for an engine dynamometer (DYNAS3 HD 460; Horiba) and are shown in Fig. 1. Excavators were tested by dividing the conditions as follows: (a) driving conditions during actual driving (10-minute round trip to the worksite) and (b) working conditions (real work considering 20 minutes of NRTC, which is the certification mode). Moreover, the test using the engine dynamometer and PEMS were performed at least 3 times each.

Measurement Device and Test Method

Engine Dynamometer Exhaust Gas Measurement System

The engine dynamometer exhaust gas measurement system was used to measure the concentration of pollutants as shown in Fig. 1. The measurement system consists of an engine dynamometer, dilution tunnel, constant volume sampler, and exhaust gas analyzer. In the engine dynamometer, the

Table 1. Specification of test engine for construction equipment.

Engine	Type	Displacement (cc)	Engine power (kW rpm ⁻¹)	After-treatment system	Emission standards
DL06	Excavator, Folk lift, Loader	5,890	107 2000 ⁻¹	None	Tier 3

Table 2. Specification of test construction equipment.

Type	Engine	Displacement (cc)	Engine power (kW rpm ⁻¹)	After-treatment system	Emission standards
Excavator	DL06	5,890	101 2000 ⁻¹	None	Tier 3
Excavator	DL06P	5,890	141 1900 ⁻¹	EGR ^a , DOC ^b , SCR ^c	Tier 4

^a Exhaust Gas Recirculation.^b Diesel Oxidation Catalyst^c Selective Catalytic Reduction.**Table 3.** Properties of the tested diesel.

Properties	Result	Standards ^b
Residual carbon content/10% residual oil (wt %)	0.02	≤ 0.15
Density (15°C, kg m ⁻³)	825	815–835
Sulfur content (ppm)	6	≤ 10
PAHs ^a (wt %)	2	≤ 5
Lubrication (μm)	294	≤ 400
Aromatic compounds (wt %)	20	≤ 30
Cetane index (or Cetane number)	54	≥ 52

^a Polycyclic aromatic hydrocarbons.^b Korea Ministry of Environment, Air quality conservation law (KME, 2019).

mechanical setting load was applied to reflect the actual driving state, such as acceleration, deceleration, and constant speed. When the engine is driven according to the test mode that was set up, the gas emitted from the exhaust pipe is mixed with dilution air in the dilution tunnel and then flows into the constant volume sampler (CVS 7400T; Horiba). In the constant volume sampler, the mixed gas is collected in a sampling bag and analyzed using the exhaust gas analyzer (MEXA 7200D; Horiba); emissions are calculated by converting the results into grams per kilowatt-hour (g kWh⁻¹). Among the exhaust gases, CO and CO₂ were analyzed using nondispersive infrared (NDIR) spectroscopy, THC and CH₄ using a heated flame ionization detector (HFID), and NO_x using a chemiluminescence detector (CLD). Table 4 and Fig. 2 show the specifications of the devices and test processes used in the analyses.

For particulate matter, the exhaust gas in the dilution tunnel is diluted with air to a certain ratio when the engine dynamometer is driven in test mode and the particulate matter is collected. The devices used captured particulate matter on a quartz filter after collecting some of the exhaust gas from the dilution tunnel and diluting it with external air. A microbalance (CP2P-F; Sartorius) is used to weigh the particulate matter captured on the filter paper, and to ensure an accurate measurement it was measured in a weighing chamber with a temperature and relative humidity maintained at 20 ± 5°C and 47 ± 5%, respectively.

Portable Emissions Measurement System (PEMS)

We installed the PEMS (SEMTECH DS+; Sensors) on the

construction equipment and measured the concentration of exhaust gas pollutants in real time, while actual work was performed. The measurement system consists of an exhaust gas analyzer, a flowmeter, sampling system, and power supply. The real work conditions reflected in the analyses of the construction equipment were excavation and movement under conditions in which excavators actually work. Engine revolutions per minute (r min⁻¹) and load factor data for the construction equipment were obtained from the electronic control unit (ECU), and flow data was obtained using a separate exhaust flowmeter with a pitot tube. In the PEMS, mixed gas was collected in a sampling bag and analyzed with the exhaust gas analyzer; emissions were calculated by converting the results into grams per kilowatt-hour. Among the exhaust gases, CO and CO₂ were analyzed using NDIR spectroscopy, THC using a FID, NO_x using nondispersive ultraviolet (NDUV) spectroscopy, and PM using ion mobility and gravimetric methods. Table 5 shows the specifications of the devices used in the analyses.

Hazardous Air Pollutants (HAPs) Analysis Method

To collect VOCs, the pollutants emitted when construction equipment engines and excavators were driven were collected in sampling bags and the exhaust gases were analyzed. Afterwards, the samples were collected in a 5 L Tedlar bag through the purge line of the engine dynamometer and pitot tube of the PEMS. VOCs were analyzed using the EPA TO-14A standard (U.S EPA, 1999a) and the sample concentration and pre-treatment process were analyzed using the following thermal desorption system. The sample underwent purging

and trapping, and the moisture was removed using the Nafion dryer. The VOCs were then concentrated at a low temperature and absorbed at -15°C in a UNITY cold trap.

The concentrated samples were next heated at 300°C and detached before being injected in a gas chromatography-mass spectrometer (GC-MS) and analyzed. For a standard

Fig. 1. Driving pattern of in (a) KCI-8, (b) NRSC, and (c) NRTC modes.

Table 4. Specification of exhaust gas analyzer for engine dynamometer.

Pollutant	Measuring Method	Measuring Conc. range
CO	NDIR ^b	50, 100, 300, 3000 ppm
THC ^a	HFID ^c	20, 50, 100, 200 ppmC
NO _x	CLD ^d	20, 50, 100, 1000 ppm
CO ₂	NDIR ^b	1, 2, 3, 6 %
CH ₄	HFID ^c	10, 20, 50 ppm

^a Total hydrocarbons.

^b Non Dispersive Infrared.

^c Heated Flame Ionization Detector.

^d Chemiluminescence Detector.

Fig. 2. Schematic diagram of engine emission test system.

Table 5. Specification of exhaust gas analyzer for PEMS.

Pollutant	Measuring Method	Measuring Conc. range
CO	NDIR ^b	0 to 8%
NO _x	NDUV ^c	0 to 300–900 ppm
CO ₂	NDIR ^b	0 to 20%
THC ^a	FID ^d	0 to 100–30,000 ppmC
PM	Ion mobility & gravimetric PM	1 to 250 mg m ⁻³
Flow-meter	Delta pressure	30.7–2137.8 kg h ⁻¹ @ 100°C

^a Total hydrocarbons.

^b Non Dispersive Infrared.

^c Non Dispersive Ultra Violet Spectroscopy.

^d Flame Ionization Detector.

substance (56 Component VOC Mix; Supelco Inc.), 100 ppb standard gas with a mixture of 56 components including ozone precursor was used and the calibration curve was checked at 2, 5, 10, 20, 50 ppb. The coefficient of determination (R^2) for the area and concentration was 0.998. Table 6 shows the analytical conditions.

To sample the aldehydes, we connected the front and rear of the dinitrophenylhydrazine (DNPH) cartridge and Waters ozone scrubber, sampled the exhaust gas flowing at 2 L min⁻¹ through the dilution tunnel of the engine dynamometer and pitot tube of the PEMS, and stored it in a freezer below 4°C until pre-treatment. For the solvent, we filtered acetonitrile with a GHP filter (47 mm, 0.2 µm) before use and then extracted the cartridge with the extraction amount set at 5 mL. We divided the samples into 2 mL vials and analyzed

them using the EPA TO-11A standard (U.S. EPA, 1999b) via ultra-performance liquid chromatography (UPLC). For the standard substance, we diluted and used the 40 µg mL⁻¹ standard solution that is a mixture of 13 components (Carbonyl-DNPH Mix 1; Supelco Inc.) and checked the calibration curve at 100, 200, 500, 800, and 1000 ng mL⁻¹. The coefficient of determination (R^2) for the area and concentration was 0.996. Table 7 shows the analytical conditions.

For PAHs, we collected particulate matter on a quartz filter, put the filter with material collected from front and rear of the engine in the 11 mL extraction cell in an accelerated solvent extraction system, and filled the empty space in the cell with diatomite to prevent extraction errors. The system extracted samples at a high temperature and pressure, and approximately 20 mL of dichloromethane was extracted for

Table 6. Analytical conditions of TD and GC/MS

Method		EPA TO-14A			
Thermal desorber	Model	Markes International / Unity2			
	Purge	Prepurge time (mL min ⁻¹)			
		1			
		Trap prepurge time (mL min ⁻¹)			
		1			
	Sample	Sampling time (min)			
		10			
		Sample flow rate (mL min ⁻¹)			
		20			
	Trap desorber	Trap low temp. (°C)			
GC/MS		–15			
		Trap high temp. (°C)			
		300			
		Trap hold time (min)			
		5			
		Split flow (mL min ⁻¹)			
		30			
	Model	Agilent 7890B / Almsco BenchTOF-Select			
	Column	DB-1 (60 m × 0.32 mm × 3.00 µm)			
	Column temp.	Temp. (°C)	Rate (°C min ⁻¹)	Hold time (min)	Total time (min)
		30	0.0	30.00	30.00
		150	5.0	10.00	64.00
		200	15.0	10.00	77.33
	Transfer line temp.	200			
	Ion source temp.	200			
	Electron energy	70 eV			
	Ionization mode	EI			
	MS scan range	35–350 amu			

Table 7. Analytical conditions of UPLC.

Method	EPA TO-11A			
Model	Waters US / ACQUITY UPLC			
Detector	TUV, 360 nm			
Column	ACQUITY UPLC™ BEH C18 1.7 μm, 2.1 × 100 mm			
Mobile phase	Solvent A: 90% Water + 10% TetraHydro Furan (THF)			
	Solvent B: 100% Acetonitrile (ACN)			
Gradient	Time (min)	Flow (mL min ⁻¹)	A(%)	B(%)
	Initial	0.3	60	40
	5.0	0.3	60	40
	10.0	0.3	0	100
	12.0	0.3	60	40
	15.0	0.3	60	40
Flow rate	0.3 mL min ⁻¹			
Injection volume	2 μL			

15 min at 100°C and 2000 psi. To analyze the PAHs, we used a standard substance and followed the EPA TO-13A standard (U.S. EPA, 1999c). For the standard substance, we diluted and used the 100 µg mL⁻¹ standard solution with a mixture of 16 components (PAHs Mix; Supelco Inc.), and checked the calibration curve at 0.1, 0.25, 0.5, 1, and 2 µg mL⁻¹. The coefficient of determination (R^2) for the area and concentration was 0.994. Table 8 shows the analytical conditions.

RESULTS AND DISCUSSION

Emission Characteristics of Regulated Pollutants

We provided measurements in various test modes using the engine dynamometer and PEMS of the construction equipment. As shown in Fig. 3, construction equipment Tier 3 engine showed higher emission in the NRTC mode with high engine load and speed variations than the KC1-8 and NRSC modes with little change. In the engine and PEMS

mode, 1.1–3.3 and 1.1–1.5 times more CO and NMHC were respectively emitted during cold start due to incomplete combustion and lower catalytic activity than the hot start (NIER, 2017; Hong *et al.*, 2018b; NIER, 2018). Moreover, NMHC is also known to be formed during the chemical reaction of unburned hydrocarbons due to low combustion temperature (Heywood, 1988; Kennedy, 2015). CO and NMHC emissions are affected by the diesel oxidation catalyst, while NO_x emissions are affected by selective catalytic reduction. Thus, Tier 4 PEMS showed 41–42% lower CO, 91–94% lower NMHC, and 90–92% lower NO_x than Tier 3 engine and PEMS. NO_x showed higher emissions in hot start than cold start in the engine and PEMS mode, which is a combustion characteristic wherein thermal NO_x increases (Jung *et al.*, 2019). As shown in Fig. 3, PM emissions of construction equipment ranged between 0.02–0.08 g kWh⁻¹ in Tier 3 engine and PEMS and 0.01–0.03 g kWh⁻¹ in Tier 4 PEMS, indicating that it was lower in Tier 4 than Tier 3.

Table 8. Analytical conditions of GC-MS.

Method	EPA TO-13A			
Model	Agilent 7890A / Almsco Bench TOF-dx			
Column	HP-5MS (30 m × 0.25 mm × 0.25 μm)			
Column temp.	Temp (°C)	Rate (°C min ⁻¹)	Hold time (min)	Total time (min)
	50		1	1
	180	8	0	17.25
	240	5	0	29.25
	300	10	10	45.25
Column flow	1 mL min ⁻¹			
Inlet heater	300°C			
Split ratio	10:1			
Injection volume	1 μL			
Transfer line	300°C			
Ion source	250°C			
MS scan range	100–300 amu			

Emission Characteristics of HAPs

Fig. 4 shows the composition of NMVOCs. In both engine and PEMS, alkanes were highest at 40.3–57.0% because there are 23 individual alkane components, accounting for the highest ratio among NMVOCs. The ratio of PEMS for alkanes was higher in Tier 4 than Tier 3 because alkanes have lower reactivity with DOC than others (Bohac *et al.*, 2006; Knafl *et al.*, 2006). According to Knafl *et al.* (2006), the VOCs had different conversion efficiencies through diesel oxidation catalysts, corresponding to 63–80%, 74–83%, and 92–99%, for alkanes, aromatics, and alkenes, respectively. In addition, similar results from heavy-duty diesel trucks and buses have been reported in the literature (NIER, 2017), with alkane, aromatic, and alkene emissions of 46.1–48.5%, 24.2–25.8%, and 22.3–25.1%, respectively. Next, aromatics were 26.8–52.8%, with the major harmful substance, BTEX, accounting for approximately 60–80%; it is generated by incomplete combustion and partial oxidation (Myung *et al.*, 2020). Furthermore, alkenes took up 1.0–26.5%, while cycloalkanes ranged between 1.3–17.0%. The difference in component ratios in NMVOCs due to the test mode is affected by engine driving and starting conditions or the reduction device (Jung *et al.*, 2019).

As shown in Fig. 5, for BTEX, the NRTC mode with high engine load and speed variations showed 1.2–1.3 times higher emission than the KC1-8 and NRSC modes. In engine and PEMS, benzene and toluene were higher in cold start than hot start, whereas ethylbenzene and xylene were emitted in similar or higher amounts in hot start than cold start. According to NIER (2019b), this is because benzene and toluene with low molecular weight have relatively high combustibility in hot start; the molecular weights of benzene, toluene, ethylbenzene, and xylene were 78.11, 92.14, 106.17, and 106.14–106.17 g mol⁻¹, respectively.

As shown in Fig. 6, aldehyde emissions in the engine and PEMS test mode were generally in the order of formaldehyde (1.6–26.2 mg km⁻¹) > acetaldehyde (0.5–9.1 mg km⁻¹) > acrolein (0.1–3.1 mg km⁻¹). Formaldehyde was 40–80%, while acetaldehyde was 17–44%, accounting for a higher ratio at 62–97% of all aldehydes and showing lower emissions in PEMS than engine. This was also the case for heavy-duty

diesel trucks with 48% formaldehyde and 21% acetaldehyde (Yao *et al.*, 2015). George *et al.* (2014) noted that formaldehyde and acetaldehyde are the major components, comprising about 72% of all VOCs from heavy-duty diesel vehicles with the latest reduction devices. Aldehydes are formed by incomplete combustion of hydrocarbons (Sasi *et al.*, 2011), and formaldehyde (HCHO) with relatively low molecular weight and high volatility shows high emissions.

In this study, 16 particle-phase PAHs in PM were analyzed, while gas-phase PAHs were not sampled. In the atmosphere, PAHs are semi-volatile compounds in both gas and particle phases (Akyüz and Çabuk, 2010). For total PAH concentrations, gas-phase PAHs were estimated using the gas-particle partition coefficient (K_p) calculated for five low-molecular-weight PAH compounds (Akyüz and Çabuk, 2010), based on previously established models (Yamasaki *et al.*, 1982; Pankow, 1987; Pankow and Bidleman, 1991, 1992), via the following equation:

$$K_p = (F/TSP)/A \quad (1)$$

where K_p is the gas-particle partition coefficient (m³ μg⁻¹), TSP is the concentration of total suspended particulate material (μg m⁻³), F is the particle-phase concentration of PAHs (μg m⁻³), and A is the gaseous-phase concentration of PAHs (μg m⁻³).

Fig. 7 shows the total PAH emissions (gas + particle phase) estimated in this study. For the Tier 3 engine, 10.3–24.0 μg kWh⁻¹ of phenanthrene and 0–8.2 μg kWh⁻¹ of fluoranthene were estimated, while for Tier 3 and Tier 4 PEMS, 0–1148 μg kWh⁻¹ of naphthalene and 0–1020 μg kWh⁻¹ of phenanthrene were estimated, respectively. The results show that 83.4–87.9% of the total PAHs were in the gas phase. For gas-particle partitioning at a traffic site, approximately 90% were gaseous PAHs (Tasdemir and Esen, 2007). According to Akyüz and Çabuk (2010), low-molecular-weight PAHs (2–3 rings) are mainly associated with the gas phase. When $K_p \cdot TSP$ is bigger than 1, the compound partitions dominantly to the particle phase; a $K_p \cdot TSP$ smaller than 1 indicates partitioning dominantly to the gaseous phase (Volckens and Leith, 2003). Σ PAHs was less than 0.5% of PM, a minute

Fig. 3. Emission characteristics of (a) CO, (b) NMHC, (c) NO_x, and (d) PM from test engine and PEMS for construction equipment according to driving modes.

Fig. 4. Composition of NMVOCs from test engine and PEMS for construction equipment according to driving modes.

Fig. 5. Emission characteristics of BTEX from (a) test engine and (b) PEMS for construction equipment according to driving modes.

amount. PAH emissions including high-quality diesel fuel standards were lowered (Nelson *et al.*, 2008). In this study, the tested diesel fuel was satisfied within high-quality diesel fuel standards for the sulfur, PAHs, lubrication, and aromatic

compounds, etc. shown in Table 3.

HAPs speciation was derived based on the NMHC emissions measured in the engine and PEMS test mode of construction equipment. As shown in Table 9, both

Fig. 6. Emission characteristics of aldehydes from (a) test engine and (b) PEMS for construction equipment according to driving modes.

construction equipment engine and PEMS showed the highest component ratios of carcinogen formaldehyde at 10.7–36.6%, followed by acetaldehyde accounting for 3.7–12.4%. For heavy-duty diesel trucks with the same capacity as construction equipment, speciation of formaldehyde was 25.1% and acetaldehyde was 10.4%, showing a similar tendency (NIER, 2017). Since the emission tendency of major substances by test mode is similar in engine and PEMS but varies according to individual substances, speciation development in various conditions of engine and PEMS is important. In addition to formaldehyde and benzene defined as carcinogens by the IARC, probable carcinogens, such as acetaldehyde and ethylbenzene, also require preferential management through constant monitoring.

CONCLUSIONS

This study investigated the characteristics of regulated pollutants (CO, NMHC, NO_x, and PM) and HAPs (VOCs, aldehydes, and PAHs), emitted by a diesel engine, which complied with Tier 3 standards, and two excavators, one of which complied with Tier 3 standards and the other, with Tier 4 standards, by using an engine dynamometer and PEMS. For the regulated pollutants, the diesel engine generated the

largest emissions during NRTC mode because of the high engine load and variable speed. The DOC and SCR systems reduced the CO and NMHC, and NO_x, respectively, released by the Tier 4-compliant excavator; hence, fewer emissions, including of PM, were observed for this machinery than the Tier 3-compliant diesel engine and excavator.

The emitted NMVOCs primarily consisted of alkanes, which comprised 23 individual species, but the proportions of the components varied according to the driving and starting conditions as well as the after-treatment systems. Furthermore, the toxic substance BTEX contributed more than 60% of the measured aromatics. The greatest contributors among the aldehydes, in descending order, were formaldehyde, acetaldehyde, and acrolein, and the percentage of the first, which possesses a relatively low molecular weight and high volatility, peaked during the test mode for both the diesel engine and the excavators. We detected phenanthrene, fluoranthene, and naphthalene upon sampling the particle-phase PAHs; furthermore, we estimated the concentrations of the gas-phase PAHs with models to obtain the total PAH concentrations.

We found the most abundant HAP to be formaldehyde, a carcinogen, followed by acetaldehyde, a probable carcinogen. Hence, harmful compounds emanating from construction

Fig. 7. Emission characteristics of total PAHs from (a) test engine and (b) PEMS for construction equipment according to driving modes.

Table 9. Hazardous air pollutants speciation for construction equipment (unit: %).

Compounds	Engine(Tier 3)				PEMS(Tier 3)			PEMS(Tier 4)		
	KC1-8	NRSC	NRTC (Cold)	NRTC (Hot)	Work	Drive (Cold)	Drive (Hot)	Work	Drive (Cold)	Drive (Hot)
Benzene	2.07	2.89	3.07	2.39	5.90	6.61	5.62	1.14	2.26	0.88
Toluene	1.53	1.86	2.74	1.76	6.60	6.88	4.28	7.37	7.72	6.88
Ethylbenzene	0.45	0.50	0.64	0.48	2.36	2.51	1.99	1.52	1.84	2.27
Xylene	2.69	3.77	4.33	3.91	8.60	11.18	9.37	4.26	4.69	5.07
Formaldehyde	21.90	30.07	26.74	30.41	15.96	10.68	14.04	35.43	23.63	36.58
Acetaldehyde	12.09	11.26	8.82	10.25	3.73	9.04	9.13	5.47	9.48	12.38
Acrolein	3.66	2.92	3.22	2.11	0.72	1.17	2.10	0.33	8.26	4.52

equipment, which also include the carcinogen benzene and the probable carcinogen ethylbenzene, require preferential management through constant monitoring. This study provides basic data for policies aiming to reduce such emissions from non-road sources in Korea and for a prospective national emission inventory containing HAP species.

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REFERENCES

- Akyüz, M. and Ç abuk, H. (2010). Gas-particle partitioning and seasonal variation of polycyclic aromatic hydrocarbons in the atmosphere of Zonguldak, Turkey. *Sci. Total Environ.* 408: 5550–5558. <https://doi.org/10.1016/j.scitotenv.2010.07.063>
- Bohac, S.V., Han, M., Jacobs, T.J., Lopez, A.J. and Assanis, D.N. (2006). Speciated hydrocarbon emissions from and automotive diesel engine and DOC utilizing conventional and PCI combustion. *SAE Technical Paper* 2006-01-0201. <https://doi.org/10.4271/2006-01-0201>
- Costagliola, M.A., Murena, F. and Prati, M.V. (2014). Exhaust emissions of volatile organic compounds of powered two-wheelers: Effect of cold start and vehicle speed. Contribution to greenhouse effect and tropospheric ozone formation. *Sci. Total Environ.* 468–469: 1043–1049. <https://doi.org/10.1016/j.scitotenv.2013.09.025>
- Environmental Protection Agency (U.S. EPA) (1999a). *Determination of volatile organic compounds (VOCs) in ambient air using specially prepared canisters with subsequent analysis by gas chromatography, Method TO-14A*. Environmental Protection Agency, Washington DC, USA.
- Environmental Protection Agency (U.S. EPA) (1999b). *Determination of formaldehyde in ambient air using adsorbent cartridge followed by high performance liquid chromatography (HPLC), Method TO-11A*. Environmental Protection Agency, Washington DC, USA.
- Environmental Protection Agency (U.S. EPA) (1999c). *Determination of polycyclic aromatic hydrocarbons (PAHs) in ambient air using gas chromatography/mass spectrometry (GC/MS), Method TO-13A*. Environmental Protection Agency, Washington DC, USA.
- Fan C., Song C., Lv, G., Wang, G., Zhou, H. and Jing X. (2018). Evaluation of carbonyl compound emissions from a non-road machinery diesel engine fueled with a methanol/diesel blend. *Appl. Therm. Eng.* 129: 1382–1391. <https://doi.org/10.1016/j.applthermaleng.2017.10.086>
- George, I.J., Hays, M.D., Snow, R., Faircloth, J., George, B.J., Long, T. and Baldauf, R.W. (2014). Cold temperature and biodiesel fuel emissions of volatile organic compounds from diesel trucks. *Environ. Sci. Technol.* 48: 14782–14789. <https://doi.org/10.1021/es502949a>
- Han, J.S., Lee, M.D., Lim, Y.J., Lee, S.U., Kim, Y.M., Kong, B.J., An, J.Y. and Hong, Y.D. (2006). Study on the distributions of VOCs, aldehydes, PAHs concentration in Seoul metropolitan area. *J. Korean Soc. Atmos. Environ.* 22: 574–589. (in Korean with English Abstract) <https://www.koreascience.or.kr/article/JAKO200604623601730.page>
- Heywood, J.B. (1988). *Internal combustion engine fundamentals*. McGraw-Hill Press, New York, USA.
- Hong, H., Mun, S., Chung, T., Kim, S., Seo, S., Kim, J., Jung, S. and Hong, Y. (2018). Emission characteristics of hazardous air pollutants from diesel heavy duty buses for Euro 5 according to after-treatment systems. *J. ILASS Korea* 23: 74–80. (in Korean with English Abstract) <https://doi.org/10.15435/JILASSKR.2018.23.4.175>
- Hu, S., Herner, J.D., Robertson, W., Kobayashi, R., Chang, M.-C., Huang, S., Zielinska, B., Kado, N., Collins, J.F., Rieger, P., Huai, T. and Ayala, A. (2013). Emissions of polycyclic aromatic hydrocarbons (PAHs) and nitro-PAHs from heavy-duty diesel vehicles with DPF with SCR. *J. Air Waste Manage. Assoc.* 63: 984–996. <https://doi.org/10.1080/10962247.2013.795202>
- Jin, T., Qu, Liang, Liu, S., Gao, J., Wang, J., Wang, F., Zhang, P., Bai, Z. and Xu, X. (2014). Chemical characteristics of particulate matter emitted from a heavy duty diesel engine and correlation among inorganic and PAH components. *Fuel* 116: 655–661. <https://doi.org/10.1016/j.fuel.2013.08.074>
- Jung, S., Lim, J., Kwon, S., Jeon, S., Kim, J., Lee, J. and Kim, S. (2017). Characterization of particulate matter from diesel passenger cars tested on chassis dynamometers. *J. Environ. Sci.* 54: 21–32. <https://doi.org/10.1016/j.jes.2016.01.035>
- Jung, S., Mun, S., Chung, T., Kim, S., Seo, S., Kim, I., Hong, H., Chong, H., Sung, K., Kim, J. and Hong, Y. (2019). Emission characteristics of regulated and unregulated air pollutants from heavy duty diesel trucks and buses. *Aerosol Air Qual. Res.* 19: 431–442. <https://doi.org/10.4209/aaqr.2018.05.0195>
- Kadkhoda, K., Pourpak, Z., Pourfathallah, A.A. and Kazemnihad, A. (2004). The ex vivo study of synergistic effects of polycyclic aromatic hydrocarbon benzo(a)pyrene with ovalbumin on systemic immune response by oral route. *Toxicology* 199: 261–265. <https://doi.org/10.1016/j.tox.2004.02.029>
- Kagawa, J. (2002). Health effects of diesel exhaust emissions—A mixture of air pollutants of worldwide concern. *Toxicology* 181–182: 349–353. [https://doi.org/10.1016/S0300-483X\(02\)00461-4](https://doi.org/10.1016/S0300-483X(02)00461-4)
- Kennedy, J., Lee, W.J., Chang, Y.C., Chen, C.Y. and Wang, L.C. (2015). An overview: Energy saving and pollution reduction by using green fuel blends in diesel engines. *Appl. Energy* 159: 214–236. <https://doi.org/10.1016/j.apenergy.2015.08.084>
- Knafl, A., Busch, S.B., Han, M., Bohac, S.V. and Assanis, D.N. (2006). Characterizing light-off behavior and species-resolved conversion efficiencies during in-situ diesel oxidation catalyst degreening. *SAE Technical Paper* 2006-01-0209. <https://doi.org/10.4271/2006-01-0209>
- Kumar, S., Nayek, M., Kumar, A., Tandon, A., Mondal, P., Vijay, P., Bhangale, U.D. and Tyagi, D. (2011). Aldehyde, ketone and methane emissions from motor vehicle exhaust: A critical review. *Am. Chem. Sci. J.* 1: 1–27. <https://doi.org/10.9734/acsj/2011/214>
- Li, L., Ge, Y., Wang, M., Li, J. Peng, J. and Song, Y. (2015). Effect of gasoline/methanol blends on motorcycle emissions: Exhaust and evaporative emissions. *Atmos. Environ.* 102: 79–85. <https://doi.org/10.1016/j.atmosenv.2014.11.044>
- Ministry of Land, Infrastructure and Transport (MLIT) (2019). Construction equipment registration statistics (2018). Ministry of Land, Infrastructure and Transport, Sejong, Republic of Korea.
- Myung, C., Choi, K., Cho, J., Kim, K., Baek, S., Lim, Y. and

- Park, S. (2020). Evaluation of regulated, particulate, and BTEX emissions inventories from a gasoline direct injection passenger car with various ethanol blended fuels under urban and rural driving cycles in Korea. *Fuel* 262: 116406. <https://doi.org/10.1016/j.fuel.2019.116406>
- National Institute of Environmental Research (NIER) (2006). A Study on the estimation of the HAPs emission factors for the mobile source (III). National Institute of Environmental Research, Incheon, Republic of Korea.
- National Institute of Environmental Research (NIER) (2017). The emission characteristics of mobile source air toxics and management strategy (IV). National Institute of Environmental Research, Incheon, Republic of Korea.
- National Institute of Environmental Research (NIER) (2018a). Study on emission characteristics of hazardous air pollutants in vehicle. National Institute of Environmental Research, Incheon, Republic of Korea.
- National Institute of Environmental Research (NIER) (2018b). The emission characteristics of mobile source air toxics and management strategy (V). National Institute of Environmental Research, Incheon, Republic of Korea.
- National Institute of Environmental Research (NIER) (2019a). National air pollutants emission service (2016). National Institute of Environmental Research, Incheon, Republic of Korea.
- National Institute of Environmental Research (NIER) (2019b). The emission characteristics of mobile source air toxics and management strategy (VI). National Institute of Environmental Research, Incheon, Republic of Korea.
- Nelson, P.F., Tibbett, A.R. and Day, S.J. (2008). Effect of vehicle type and fuel quality on real world toxic emissions from diesel vehicles. *Atmos. Environ.* 42: 5291–5303. <https://doi.org/10.1016/j.atmosenv.2008.02.049>
- Pankow, J.F. (1987). Review and comparative analysis of the theories on partitioning between the gas and aerosol particulate phases in the atmosphere. *Atmos. Environ.* 21: 2275–2283. [https://doi.org/10.1016/0004-6981\(87\)90363-5](https://doi.org/10.1016/0004-6981(87)90363-5)
- Pankow, J.F. and Bidleman, T.F. (1991). Effects of temperature, TSP and per cent non-exchangeable material in determining the gas-particle partitioning of organic compounds. *Atmos. Environ.* 25: 2241–2249. [https://doi.org/10.1016/0960-1686\(91\)90099-S](https://doi.org/10.1016/0960-1686(91)90099-S)
- Pankow, J.F. and Bidleman, T.F. (1992). Interdependence of the slopes and intercepts from log-log correlations of measured gas-particle partitioning and vapor pressure-I. Theory and analysis of available data. *Atmos. Environ.* 26: 1071–1080. [https://doi.org/10.1016/0960-1686\(92\)90039-N](https://doi.org/10.1016/0960-1686(92)90039-N)
- Tasdemir, Y. and Esen, F. (2007). Urban air PAH: Concentrations, temporal changes and gas/particle partitioning at a traffic site in Turkey. *Atmos. Res.* 84: 1–12. <https://doi.org/10.1016/j.atmosres.2006.04.003>
- Volckens, J. and Leith, D. (2003). Comparison of methods for measuring gas-particle partitioning of semivolatile compounds. *Atmos. Environ.* 37: 3177–3188. [https://doi.org/10.1016/S1352-2310\(03\)00352-2](https://doi.org/10.1016/S1352-2310(03)00352-2)
- Wang, J., Jin, L., Gao, J., Shi, J., Zhao, Y., Liu, S., Jin, T., Bai, Z. and Wu, C.Y. (2013). Investigation of speciated VOC in gasoline vehicular exhaust under ECE and EUDC test cycles. *Sci. Total Environ.* 445–446: 110–116. <https://doi.org/10.1016/j.scitotenv.2012.12.044>
- Yamasaki, H., Kuwata, K. and Miyamoto, H. (1982). Effects of ambient temperature on aspects of airborne polycyclic aromatic hydrocarbons. *Environ. Sci. Technol.* 16: 189–194. <https://doi.org/10.1021/es00098a003>
- Yao, Z., Jiang, X., Shen, X., Ye, Y., Cao, X., Zhang, Y. and He, K. (2015). On-road emission characteristics of carbonyl compounds for heavy-duty diesel trucks. *Aerosol Air Qual. Res.* 15: 915–925. <https://doi.org/10.4209/aaqr.2014.10.0261>

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