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 (NOx), 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 NOx 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 PM1.5 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 (NOx), 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...
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 (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; Kadhkhoda 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 formicdehyde 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, formicdehyde 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 ± 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
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 NOₓ 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, such as acceleration, deceleration, and constant speed. When the engine is driven according to the test mode, 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 NOₓ 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, NOₓ 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

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### 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              | EGR⁴, DOC⁵, SCR⁶       | Tier 4            |

⁴ Exhaust Gas Recirculation.
⁵ Diesel Oxidation Catalyst.
⁶ Selective Catalytic Reduction.

### Table 3. Properties of the tested diesel.

| Properties                             | Result | Standards⁵ |
|----------------------------------------|--------|------------|
| 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 (wt %)                            | 2      | ≤ 5        |
| Lubrication (µm)                        | 294    | ≤ 400      |
| Aromatic compounds (wt %)               | 20     | ≤ 30       |
| Cetane index (or Cetane number)         | 54     | ≥ 52       |

⁴ Polycyclic aromatic hydrocarbons.
⁵ Korea Ministry of Environment, Air quality conservation law (KME, 2019).
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

![Graphs showing driving patterns](image)

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

| Pollutant | Measuring Method | Measuring Conc. range |
|-----------|------------------|-----------------------|
| CO        | NDIR            | 50, 100, 300, 3000 ppm |
| THC\(^a\) | HFID\(^c\)      | 20, 50, 100, 200 ppmC |
| NO\(_x\)  | CLD\(^d\)       | 20, 50, 100, 1000 ppmC|
| 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.
to 8%)
- NOx: 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\(^\circ\)C)

\(^a\)Total hydrocarbons.
\(^b\)Non Dispersive Infrared.
\(^c\)Non Dispersive Ultra Violet Spectroscopy.
\(^d\)Flame Ionization Detector.

Table 5. Specification of exhaust gas analyzer for PEMS.

| Pollutant | Measuring Method | Measuring Conc. range |
|-----------|------------------|----------------------|
| CO        | NDIR\(^b\)       | 0 to 8%              |
| NOx       | 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\(^\circ\)C |

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

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

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Table 6. Analytical conditions of TD and GC/MS

| Method            | EPA TO-14A          |
|-------------------|---------------------|
| **Thermal desorber** | Markes International / Unity2 |
| Purge             |                     |
| Prepurge time (mL min⁻¹) | 1                   |
| Trap purprege time (mL min⁻¹) | 1                   |
| Sample            |                     |
| Sampling time (min) | 10                  |
| Sample flow rate (mL min⁻¹) | 20                  |
| Trap desorber     |                     |
| Trap low temp. (°C) | –15                 |
| Trap high temp. (°C) | 300                 |
| Trap hold time (min) | 5                   |
| Split flow (mL min⁻¹) | 30                  |
| **GC/MS**         |                     |
| Model             | Agilent 7890B / Almso BenchTOF-Select |
| Column            | DB-1 (60 m × 0.32 mm × 3.00 μm) |
| Column temp.      |                     |
| Temp. (°C)        | Rate (°C min⁻¹)     |
| 30                | 0.0                 |
| 150               | 5.0                 |
| 200               | 15.0                |
| 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 (R²) 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 NOₓ emissions are affected by selective catalytic reduction. Thus, Tier 4 PEMS showed 41–42% lower CO, 91–94% lower NMHC, and 90–92% lower NOₓ than Tier 3 engine and PEMS. NOₓ showed higher emissions in hot start than cold start in the engine and PEMS mode, which is a combustion characteristic wherein thermal NOₓ 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.
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 106.17–106.17 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 (Kponge) 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:

\[ K_{p} = (F/TSP)/A \]

where \( K_{p} \) is the gas-particle partition coefficient (m³ µg⁻¹), \( F/TSP \) is the concentration of total suspended particulate material (µg m⁻³), \( F \) is the gas-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 \( K_{p} \) TSP is bigger than 1, the compound partitions dominantly to the particle phase; a \( K_{p} \) TSP smaller than 1 indicates partitioning dominantly to the gaseous phase (Volckens and Leith, 2003). ∑PAHs was less than 0.5% of PM, a minute

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              | 80                     | 8                       | 0                   | 17.25               |
| 180             | 8                      | 0                       | 0                   | 29.25               |
| 240             | 5                      | 10                      | 10                  | 45.25               |
| 300             | 10                     | 10                      | 10                  |                    |
| 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            |
Fig. 3. Emission characteristics of (a) CO, (b) NMHC, (c) NO\textsubscript{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 trend 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, NOx, 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 NOx, 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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