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Characteristics of Real-World Gaseous Emissions from Construction Machinery

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Abstract: In Korea's air pollutant inventory, construction machinery is a major emission source in the non-road sector. Since 2004, the Korean government has introduced and reinforced emission regulations to reduce the air pollutants emitted from their diesel engines. Since the engine dynamometer test method used in emission regulations has limitations in reflecting emission characteristics under the diverse working conditions of construction machinery, it is necessary to examine the effectiveness of emission regulations and the validity of the emission factors applied as inputs to the air pollutants inventory. This could be done by evaluating engine operation and emission characteristics under real-world working conditions. In this study, 14 units were selected among the excavators, wheel loaders, and forklifts that represent approximately 90% of the registered construction machines in Korea. They were equipped with a portable emission measurement system (PEMS) to measure gaseous emissions and collect engine data under various real-world working conditions. With the reinforcement of emission regulations for the construction machinery from K-tier3 to K-tier4 in Korea, exhaust after-treatment technologies, such as selective catalytic reduction and diesel oxidation catalyst, were applied. Real world NOx was reduced by approximately 83%, and THC 77% and CO by 73%, respectively. Real world NOx + THC of the K-tier3 machines exceeded the laboratory emission limit, but the K-tier4 machines considerably improved, 20% for excavator (124 kW), 61% for excavator (90 kW), 90% for wheel loader (202 kW) and 21% for Fork-lift (55 kW), despite some differences. The emission factors applied to the air pollutant inventory have been developed using the engine dynamometer test method, but they were considerably underestimated compared with emissions under real-world working conditions. The difference was even larger for the K-tier4 machines. In this study, the possibility of developing emission factor equations that use the engine load factor as a parameter was confirmed by using the engine work 1 g/kW·h segment moving averaging window (MAW) method.

Keywords: construction; machinery; emissions; PEMS

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1. Introduction

In Korea's air pollutants emission inventory—referred to as the Clean Air Policy Support System (CAPSS), NOx and PM2.5 in the non-road sector represent 28.7 and 18.2% in 2019, respectively. Construction machinery is a major source of air pollutant emissions, accounting for 37.3 and 36.4% of non-road NOx and PM2.5 emissions, respectively [1]. Construction machinery is defined in various ways depending on its purpose, and the Clean Air Conservation Act of Korea [2] requires that diesel engines installed in 30 types of construction machinery comply with emission standards at the manufacturing stage. In Korea, approximately 530,000 construction machines are registered and in use, with forklifts (47%), excavators (37%), and wheel loaders (7%) accounting for the majority (90 percent) [3]. Most of these construction machines have diesel engines, and emission reduction technologies are at a lower level compared with on-road vehicles produced at the same time [4].

Since 2004, the Korean government has established and continuously reinforced emission standards for diesel engines installed in newly manufactured construction machinery in order to reduce air pollution [2]. In Korea, emission standards for construction machinery engines have been set by referring to the U.S. federal "tier" regulation for non-road diesel engines [5] and the EU's "Stage" regulation [6]. Emission standards for non-road diesel engines are set differently according to the engine net power. Korea's emission standards for construction machinery engines have been rapidly reinforced within a short period of time. In the case of NOx for the machinery over 56 kW, the K-tier4 standard (0.4 g/kWh) applied in 2015 was approximately 96% lower compared with the K-tier1 standard (9.2 g/kWh) in 2004. For the certification test to verify the compliance of construction machinery engines with emission standards, the emission test method using an engine dynamometer is applied, and the test method in UN Regulation No. 96 [7] has been introduced in Korea. From the K-tier4 stage, the non-road transient cycle (NRTC), a transient test method in which the engine revolution and torque are changed continuously was introduced. However, the laboratory measurement method has limitations in reflecting the diversity of work of construction machinery.

For motor vehicles equipped with diesel engines, there were cases in which NOx emissions complied with emission standards in the laboratory test, but they were excessive in on-road measurements performed using a portable emission measurement system (PEMS) [8,9]. This issue attracted global attention when the U.S. EPA uncovered emission manipulation for Volkswagen diesel vehicles [10]. This NOx deviation problem between laboratories and on-road driving could be resolved only after the introduction of real driving emission (RDE) measurement that uses PEMS for emission regulation [11,12]. In the case of heavy-duty diesel engines to which the transient engine dynamometer emission test method was applied earlier than non-road engines, the excessive NOx emission problem during on-road driving could also only be resolved after the introduction of RDE regulation [13,14]. These cases for on-road diesel vehicles show that evaluation under real-world working conditions is also important for emission regulations with respect to non-road engines. This also indicates that it is necessary to evaluate emission characteristics under real-world working conditions to revise the emission factors applied to construction machinery in Korea's air pollutants emission inventory because they have been developed using the engine dynamometer emission test results.

Although limited compared with on-road vehicles, studies have been conducted to evaluate emissions under the diverse working conditions of non-road machinery with the development of PEMS [15–17]. Another study [18] evaluated 16 non-road mobile machines in the pilot program to apply PEMS to EU non-road emission regulations as a tool for in-service conformity. They could calculate the engine output and brake-specific emissions using electronic control module (ECM) data and compare the real-world emission results with laboratory emission limits. They also presented the work-based moving averaging window (MAW) method as a useful data evaluation method. A previous study [19] measured emissions from 27 construction machines of six types in the US under real-world working conditions using PEMS equipment that met the requirements of 40 CFR part 1065 [20]. A previous study [4] measured real world NOx emissions from 29 non-road mobile machines of nine types operating in London. The NOx was reduced by 78% due to the reinforcement of emission standards from Stage III-A to Stage IV, but 63 to 67% of the equipment exceeded the laboratory emission limit under real-world working conditions according to the emission standards being applied. Another study [21] measured real-world emissions from ten construction machines in Nanjing using PEMS and highlighted that the model applied to the emission inventory considerably underestimates air pollutant emissions from construction machinery. In addition, another study [22] measured real-world emissions from 16 excavators and 19-wheel loaders in China in various working modes and found that the conventional NOx emission factor was underestimated compared with the real-world emissions. These studies showed that it is possible to evaluate emissions from construction machinery under real-world working conditions in an effective manner using PEMS. These findings further highlight that emissions under real-world working conditions may exceed the laboratory emission limits or there may be a considerable difference to the conventional emission factors used for the emission inventory.

To effectively reduce air pollutants emitted from construction machinery and achieve realistic emission inventory, it is necessary to evaluate emissions and develop the emission factor under real-world working conditions in Korea. Given that the Korean government plans to introduce in-service monitoring using PEMS to construction machinery manufacturers by implementing the EU Stage V regulations [23], the importance of evaluating emissions from construction machinery under real-world working conditions is increasing in Korea.

For CO_2 emission, around 92.5% of the total greenhouse gas(GHG) emissions in USA is corresponding to the on-road CO_2 emission, while around 7.5% is the non-road sector such as construction machinery, agriculture machinery. In particular, around 40% GHG emission from the off-road sector corresponded to the construction machinery [24]. Furthermore, diesel-fueled agriculture machines are significantly dependent on the mode working at the real operation condition such as idle, transport, and harvesting, resulting in the real-operation CO_2 emission from the agriculture machines. Furthermore, the previous study has reported that the amount of CO_2 emission from the agriculture machines can be caused by the real operation modes, which can contribute to increase the impact to the environment [25]. In addition, Savickas et. al. has reported that the global worming potential (GWP), a value enables to compare the amount of energy the emissions of 1 ton of a gas will absorb over a given period of time, is highly related to the exhaust gas content and concentration, the driving speed, the feed rate, and the engine load factor [26].

The load factor is highly associated with the fuel consumption with respect to the real operating condition of construction machines. The gaseous emissions from diesel-fueled construction machines are well-known to be mainly related to fuel consumption, consequently, the load factor can be attributed to the emissions.

In this study, engine operation and gaseous emission characteristics under real-world working conditions were evaluated for excavators, forklifts, and wheel loaders, which comprise the largest proportion of construction machinery in Korea. Seven units were selected for each of the K-tier3 and K-tier4 standards (a total of 14 units), which were applied after 2010 in Korea, and the emissions were measured with PEMS. The results were compared to the emission standards of diesel engines for the non-road equipment and the emission factors applied to CAPSS.

2. Materials and Methods

In this study, fourteen construction machines corresponding to K-tier3 and K-tier4 were selected to evaluate the gas emissions under real-world working conditions of the construction machines. The gas emissions were measured with PEMS to the machine. The measured emissions were compared with the laboratory emission limits and the conventional emission factors used in CAPSS. The possibility of developing emission factor equations based on the real-world emissions was reviewed using the MAW data analysis with 1 kWh engine work segment.

2.1. Construction Machinery Tested

The types and main specifications of the construction machines tested in this study are shown in Table 1. Three excavators, two forklifts, and two-wheel loaders were tested for each of the K-tier3 and K-tier4 emission standards, representing a total of 14 units. The engine net power ranged from 110 to 336 kW for the excavators, from 130 to 405 kW for the wheel loaders, and from 55 to 73.5 kW for the forklifts, which are within the ranges predominantly used at construction sites in Korea. An electronically controlled common rail fuel system was applied to all the engines of the construction machines tested. In relation to emission control technology, additional technology was not applied to three out of the seven K-tier3 construction machines, but exhaust gas recirculation (EGR), a system that thermal NOx reduction by lowering the combustion temperature, EGR was applied to three units and selective catalytic reduction (SCR), a system that NOx reduction by the chemical reaction with urea injected, SCR was applied to one unit. Further reinforced emission control technologies were applied to the K-tier4 construction machines. The diesel oxidation catalyst (DOC), a system that CO, HC reduction through the oxidation reaction in the catalytic filter, DOC was installed in all seven units and EGR and SCR were applied to six units for NOx reduction. The diesel particulate filter (DPF), a system that collects and burns particle mass to remove it, DPF was applied to one unit for particulate matter reduction. Generally, the emission control technologies applied to the construction machinery engines are different according to the severity of the emission regulations being applied.

Table 1. Main specifications of the construction machinery being tested.

Machine ID	Types	Model Year	Engine Net Power and Revolution (kW/rpm)	Engine Volume (L)	Korean Emission Regulation	Emission Control Technologies
T3-Ex-1	Excavator	2013	121/2100	5.9	K-tier3	Non
T3-Ex-2	Excavator	2013	121/2100	5.9	K-tier3	Non
T3-Ex-3	Excavator	2013	210/1800	7.8	K-tier3	EGR
T3-Lo-1	Loader	2010	191/1750	7.6	K-tier3	Non
T3-Lo-2	Loader	2013	405/2100	12.7	K-tier3	SCR
T3-FK-1	Fork-lift	2014	74/2300	3.4	K-tier3	EGR
T3-FK-2	Fork-lift	2014	81/2300	3.4	K-tier3	EGR
T4-Ex-1	Excavator	2017	141/1900	5.9	K-tier4	EGR, SCR, DOC
T4-Ex-2	Excavator	2017	110/2000	4.0	K-tier4	EGR, SCR, DPF, DOC
T4-Ex-3	Excavator	2015	336/1900	12.8	K-tier4	EGR, SCR, DPF, DOC
T4-Lo-1	Loader	2017	213/1800	7.6	K-tier4	EGR, SCR, DOC
T4-Lo-2	Loader	2016	129/2200	4.4	K-tier4	EGR, SCR, DOC
T4-FK-1	Fork-lift	2016	55/2200	3.8	K-tier4	EGR, DOC
T4-FK-2	Fork-lift	2017	73.5/2300	3.4	K-tier4	EGR, SCR, DOC

The emission standards and the emission factors used in CAPSS for each construction machine tested are shown in Table 2. Given that ECM was installed in all the engines of the construction machines tested, the engine output during operation could be calculated by collecting the engine revolution and load rate through SAE J 1939 or the communication protocol of the manufacturer.

All the tests were conducted under the supervision of the Transportation Pollution Research Center of the National Institute of Environmental Research, a certification agency for emissions from on-road vehicles and non-road engines in Korea. The emission tests were conducted at a test site where various tasks could be undertaken by each construction machine under the cooperation of the Korea Construction Equipment Technology Institute and the Korea Automotive Technology Institute.

Table 2. Standard of gaseous emissions and emission factor with concern of construction machines tested.

Machine I.D	Gaseous Emission Standard (g/kWh)				Emission Factors (g/kWh)		
	CO	NMHC	NOx	NMHC + NOx	CO	THC	NOx
T3-Ex-1	5.0	-	-	4.0	1.5	0.13	3.54
T3-Ex-2	5.0	-	-	4.0	1.5	0.13	3.54
T3-Ex-3	3.5	-	-	4.0	1.78	0.18	3.55
T3-Lo-1	3.5	-	-	4.0	2.14	0.16	3.43
T3-Lo-2	3.5	-	-	4.0	2.14	0.16	3.43
T3-FK-1	5.0	-	-	4.7	1.79	0.17	3.69
T3-FK-2	5.0	-	-	4.0	1.36	0.2	3.66
T4-Ex-1	5.0	0.19	0.4	-	0.071	0.017	0.188
T4-Ex-2	5.0	0.19	0.4	-	0.071	0.017	0.188
T4-Ex-3	3.5	0.19	0.4	-	0.106	0.023	0.191
T4-Lo-1	3.5	0.19	0.4	-	0.106	0.023	0.191
T4-Lo-2	5.0	0.19	0.4	-	0.071	0.017	0.188
T4-FK-1	5.0	-	-	4.7	0.391	0.078	3.501
T4-FK-2	5.0	0.19	0.4	-	0.071	0.017	0.188

2.2. PEMS System

In this study, the Semtech DS plus system (Sensors, Saline, MI, USA) was used as PEMS, and it is compliant with the requirements of UN Regulation No. 49 [27] and U.S. 40 CFR part 1065 [20]. PEMS comprises an exhaust flow meter, exhaust gas analyzers, data logger connected to ECM, and a GPS speed measurement. Semtech DS plus system measures NO and NO2 using a non-dispersed ultra-violet (NDUV) sensor and calculates the NOx by adding the measurements. THC is measured using a flame ionization detector (FID) while CO and CO_2 are measured using the non-dispersive infra-red method [28]. The exhaust gas flow meter uses the Pitot-tube method. Three sizes of flow meters were used for the engine volume of the test construction machinery. A flow meter of 63.5 mm was used for an engine volume of less than 4 L, 76.2 mm was used for engines of less than 6 L, and 101.6 mm was used for engines of more than 6 L in size. The engine revolution and the load ratio information were collected among ECM data through connection with the on-board diagnostic communication port of the construction machine engine being tested. The engine power was calculated by combining the information with the engine full load torque data provided by the engine manufacturer. The PEMS was equipped with a battery pack as a power source so that the gas emissions were not affected by the engine operation. All the gaseous emission concentrations, the exhaust gas flow rate, and the ECM data were measured at 1 Hz. The PEMS equipment used in this study can be also used for on-road vehicles, and its reliability was verified in on-road emission studies conducted at TPRC [9,29]. Before conducting the emission tests, pre-test calibration was performed, including leak check and zero-span calibration. Upon the completion of the tests, post-test zero span calibration was performed. Figure 1 shows the tested construction machines equipped with PEMS. And detailed technical parameters and measurement accuracies have been shown in Table 3.

(**a**) (**b**) (**c**)

Figure 1. Real-operation of construction machinery with PEMS; (**a**) Excavator, (**b**) Wheel loader, (**c**) Fork-lift.

Table 3. Specification of the PEMS (Semtech Ds plus).

Description	Method	Range	Accuracy	Resolution
CO_2	NDIR	0 to 18%	±2% Reading	0.01%
CO	NDIR	0 to 8%		10 ppm
NOx (NO + NO_2)	NDUV	NO: 0 to 3000 ppm NO_2: 0 to 500 ppm		NO: 0.3 ppm NO2: 0.3 ppm
O_2	Paramagnetic	0 to 25%		0.1%
THC	FID	0 to 10,000 ppm	±1% Reading	-
Exhaust flow	Pitot-tube	30.7 to 2137.8 kg/hr	±2% Reading	0.1 SCFM

2.3. Real-World Works Performed with the Tested Construction Machinery

Construction machinery performs various tasks according to its type. In this study, some typical works for each construction machinery type were examined before the tests. Previous studies [30,31] applied the working cycles presented in JCMAS H020 (for excavators) and JCMAS H022 (for wheel loaders) provided by the Japan Construction Mechanization Association (JCMA) to evaluate the energy consumption of excavators and wheel loaders. Another study [32] simulated the energy consumption of fork-lift using the working cycle suggested by the VDI 2198 standard provided by The Association of German Engineers (Verein Deutscher Ingenieure). In this study, a real-world working mode was constructed, and emission test was performed by referring to the working cycles suggested by JCMAS and VDI for each construction machine. The works for excavators include "digging and loading", "leveling ground", and "moving". For "digging and loading", the soil was dug to a depth of approximately 2 m using the bucket, raised to a height of approximately 2.5 m, and unloaded by turning the vehicle body by 90° repeatedly. "Leveling ground" is the work of leveling the ground using the bucket in the range of approximately 4 m, and "moving" is the work of moving on flat ground. The works for wheel loaders were divided into "loading" in which the bucket is filled with soil and then emptied after approximately 15 m of moving and turning, "moving on a hill", and "moving on ground". The works for forklifts include "lifting and carrying" in which a load is lifted, moved by approximately 30 m, and then lowered. Fourteen construction machines were tested to evaluate the engine operation and emission characteristics for each working mode. The emissions were measured while each construction machine performed working modes with some flexibility depending on the situation at the test site.

2.4. Data Analysis

During the operation of the construction machinery, gaseous emissions (NOx, HC, CO, and CO_2) were calculated by integrating the second-by-second values measured through PEMS. To compare the results under consistent conditions, emission data from the engine warm-up state were analyzed. The EU's in-service monitoring regulation [23] excludes cold start emission data from the entire test data and compares the analyzed results with the emission standard. In CAPSS, the on-road and off-road emission inventory calculates the final emission amount by applying the cold-start adjustment factor to the emission calculated using the emission factor in the engine warm-up state. In this study, we focused on comparing laboratory emission standard and conventional emission factor for exhaust gas in engine warm-up state, and meaningful results were obtained. The engine power was calculated using Equation (1) based on the engine revolution and the load data acquired from the ECM of the construction machinery being tested.

$$P_c = \frac{2 \times \pi \times N \times \tau}{60,000} \tag{1}$$

where, P_c the Calculated engine power (kW), and N the Engine speed (rpm), τ the Engine torque (Nm) .

The brake-specific emission (g/kW·h) was calculated using Equation (2) based on the gaseous mass emissions measured through PEMS and the engine power.

$$EF_m = \frac{\sum_{n=i}^{j} ER_{m,n}}{\sum_{n=i}^{j} P_{c,n}} \times 3600 \tag{2}$$

where, EF_m the Measured brake-specific emission factor (g/kW·h), and n the Duration of a certain working mode (s), and i, j the Start and end time of the working mode (s), and $ER_{m,n}$ the Instantaneous emission rate (g/s), and $P_{c,n}$ the Instantaneous engine power (kW).

The conformity factor of the construction machinery was calculated using Equation (3) to evaluate how different the average brake-specific emission value calculated under real-world working conditions is from the laboratory emission limit.

$$CF = \frac{EF_m}{EL_L} \tag{3}$$

where the Conformity factor, and EL the Emission limit for laboratory test (g/kW·h).

The difference from the conventional emission factor applied to the construction machinery emission inventory of CAPSS was evaluated by defining it as the deviation ratio as in Equation (4).

$$DR = \frac{EF_m}{EF_{EI}} \tag{4}$$

where, DR the Deviation ratio, and EF_{EI} the Emission factor used for Korean emission inventory (g/kW·h).

In relation to the analysis of the PEMS data, the MAW method using reference engine work has been applied to heavy-duty vehicle emission regulations [27]. The method is a moving averaging process, based on reference engine work achieved at type approval test procedure. The measured real-world second-by-second emissions are integrated and averaged over the durations that match the performed the real-world engine work with the value of a reference engine work. The calculation is then moving with a time increment equal to the data sampling frequency, i.e., 1 Hz. A previous study [18] showed that this MAW method can also be used for the analysis of PEMS data from non-road machinery. Although the quantity at type approval test should be used as a reference value for the verifying the compliance to emission regulation, other quantity can be applied as a reference value for the purpose of evaluating emission characteristics. Previous studies [12,33] applied 1 km-segment MAW to the analysis of the data of a light-duty vehicle to evaluate emission characteristics according to the driving dynamics. In this work, because all the engine works at type approval tests of the selected machinery have not been published by manufacturers, engine work 1 kWh-segment is applied to MAW analysis for evaluating emission characteristics according to engine load factor and examining the possibility of developing an emission factor equation. With the l kWh-segmented MAW method, the average values of emissions, power and load factor were calculated by real time data, in consequence, the highly fluctuated real time curve can be transformed to the stabilized curve, as depicted in Figure 2. Figure 3 represents the emission with concern of the work, which is used by Equations (5) and (6). To compare the results, the MAW method was applied to the tested construction machines with the number of power ranges.

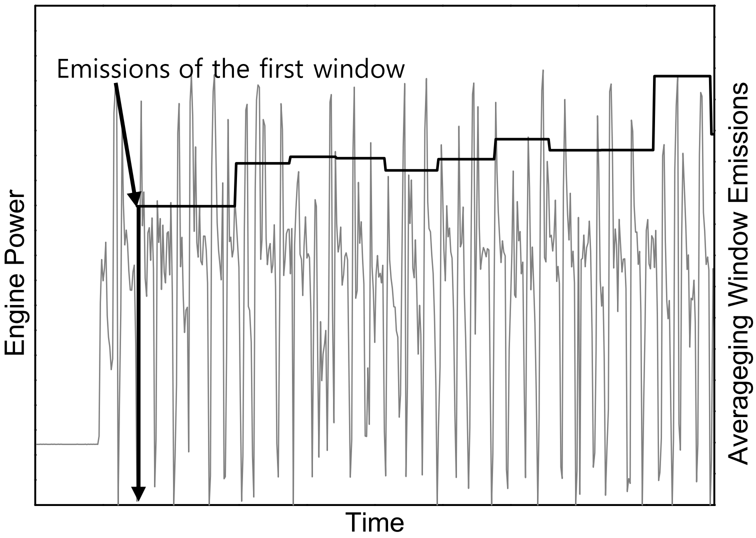


Figure 2. Engine power, time, and averaging window gaseous emissions, starting from the first averaging window.

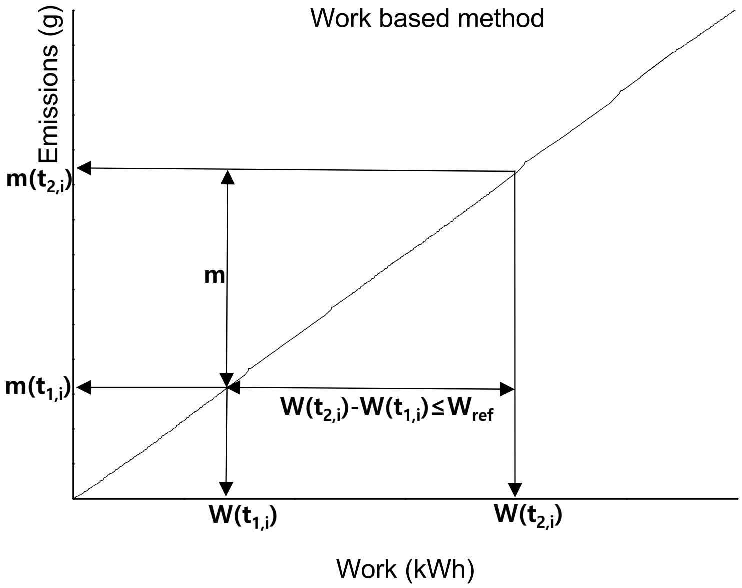


Figure 3. Schematic diagram for the emission with concern of the work with 1 kWh based moving average window (MAW) method.

The duration ($t_{2,i}$–$t_{1,i}$) of the *i*th averaging window is determined Equation (5)

$$W(t_{2,i}) - W(t_{1,i}) \le W_{ref} \tag{5}$$

where, $W(t_{1,i})$ is the engine work (kWh) measured from the start time $t_{1,I}$ to the certain time arriving at 1 kWh (the reference engine work, W_{ref}), $W(t_{2,i})$ is the engine work (kWh) from time $t_{2,i}$ following the certain time arriving at W_{ref} for calculating $W(t_{1,i})$ to the certain time arriving at the next 1 kWh, the maximum value to satisfy Equation (5).

The brake specific gaseous emissions e_{gas} (g/kWh) can be calculated for each averaging window and each gaseous in the following Equation (6)

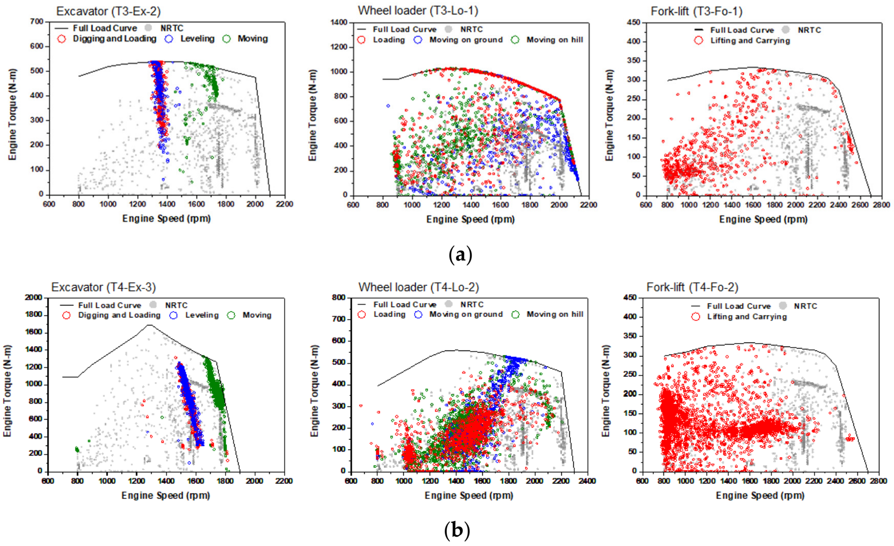
$$e_{gas} = \frac{m}{W(t_{2,i}) - W(t_{1,i})} \tag{6}$$

where, m is the mass emission of the gaseous emissions (mg/averaging window), the value for $W(t_{2,i}) - W(t_{1,i})$ is the engine work during the ith averaging window (kWh).

3. Results and Discussion

3.1. Engine Driving Characteristics for Construction Machinery

Emissions from construction machinery are affected by the operational characteristics of internal combustion engines. As shown in Figure 4, engine operation characteristics are significantly different depending on the type and working mode of the construction machinery. In the case of the "digging and loading" and "leveling ground" working modes of the excavators, the engine torque values were distributed in the narrow area in specific engine speed ranges because the diesel engine of excavator drives a hydraulic pump in certain engine speed ranges controlled. In the excavator "moving" mode, the engine speed slightly changed, but the range was narrow compared with the wheel loader or forklift, with the torque generally being 50% or more of the full load. In the case of the wheel loader, the engine speed and torque were widely distributed, similar to those of the on-road vehicles. The forklift operated at relatively low engine speed and torque. This is likely because the movement range is narrow due to the nature of work and stopping and operation are repeatedly performed. As shown in Figure 2 the NRTC, which is the engine dynamometer emission certification test cycle, has limitation to cover the very wide engine driving ranges in real-world working conditions for various construction machines. The difference in the engine operation characteristics between the certification test and real-world working conditions seems to be a factor causing a difference in the emissions. Considering the differences in the engine operation among the construction machines, the emissions should be analyzed for each construction machinery type.



(a)

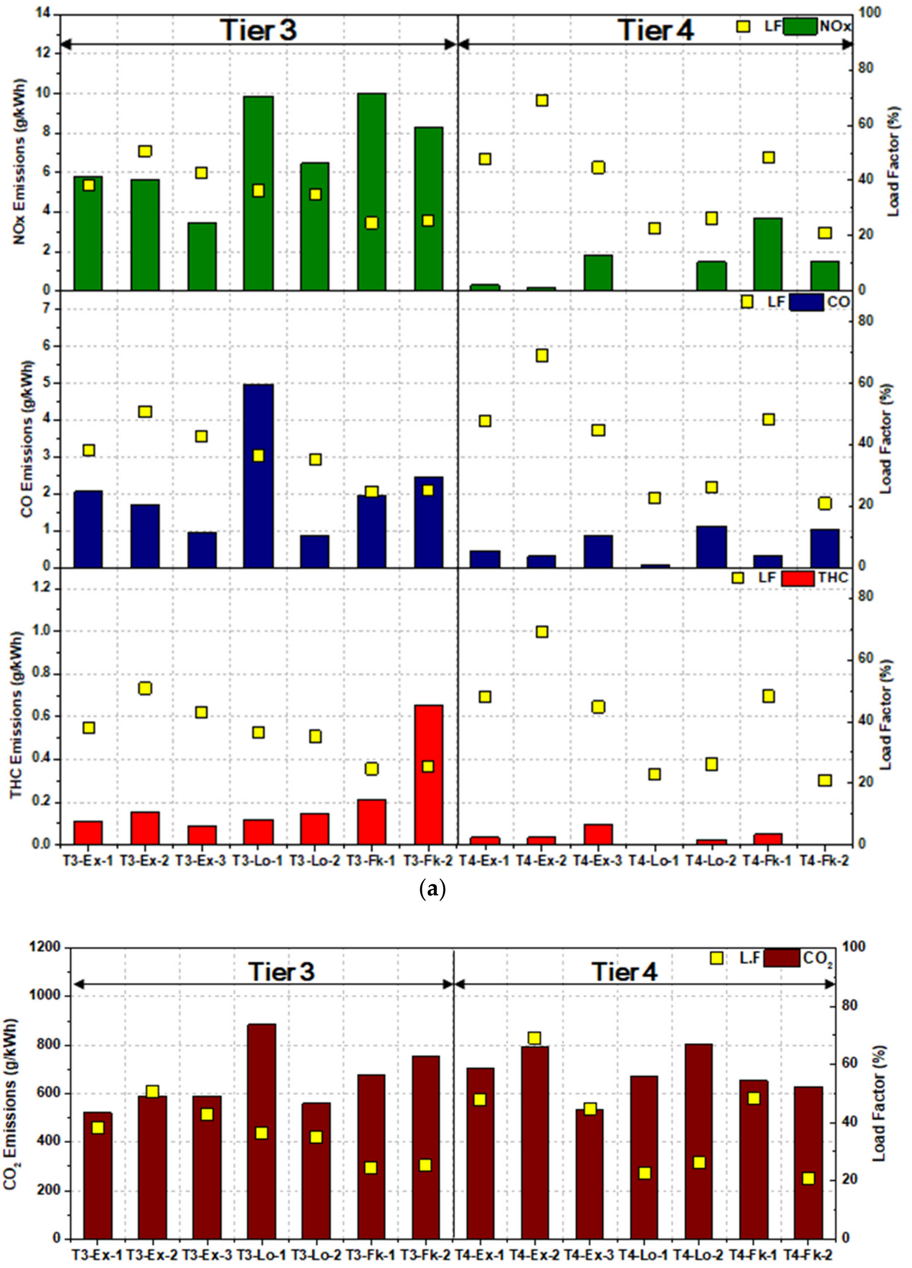
(b)

Figure 4. Engine torque with concern of engine speed for three difference construction machines operating the test conditions. (**a**) Tier 3; (**b**) Tier 4.

3.2. Average Brake-Specific Emissions

Figure 5 shows the average brake-specific emissions and engine load factor of the construction machinery being tested according to the construction machinery type and the emission regulations being applied. The engine load factor is the ratio of the average engine power during operation to the rated engine power. The engine load factor is different even for the same construction machinery type. Due to the feature of real-world working conditions for construction machinery, it is impossible to conduct tests by controlling the work and the way that it is driven in the same manner. In this study, the engine load factor ranged from 24 to 51% for the K-tier3 machinery and from 19 to 69% for the K-tier4 machinery, which were in line with the results of previous studies [17,27] as shown in Figure 5a. The average brake-specific emissions were NOx 7.27 g/kWh, THC 0.21 g/kWh, and CO 2.06 g/kWh for the K-tier3 machinery and NOx 1.21 g/kWh, THC 0.05 g/kWh, and CO 0.55 g/kWh for the K-tier4 machines. Given that the emission standards of the engine were reinforced, averaged NOx was reduced by approximately 83%, THC by 77% and CO by 73%, respectively, under real-world working conditions. In a study by [19], given that the US Federal emission regulations were reinforced from Tier3 to Tier4, NOx was reduced by approximately 51%, THC by 71%, and CO by 78%. A previous study [4] found that NOx was reduced by approximately 78% when the EU emission regulations were strengthened from Stage III to Stage IV. The results of this study were in line with the results of previous studies considering the variation in PEMS test results for construction machinery. The improved real-world gaseous emissions as the reinforced emission standard from K-tier3 to K-tier4 show the emission reduction effects of exhaust gas after-treatment systems, such as SCR and DOC, installed in most K-tier4 construction machinery. The effect of emission reduction technology was also shown in construction equipment to which the same emission regulations were applied. T3-Ex-3 with EGR applied in K-tier3 excavators emitted 43% and 39% lower NOx than T3-Ex-1 and T3-Ex-2 without EGR, and T3-Lo-2, with SCR applied in wheel loaders was 42% lower in NOx than T3-Lo-1, which was not. In K-tier4 Fork-lift, T4-FK-2 with EGR and SCR applied together had 59% lower NOx than T4-FK-1 with EGR only. The average CO_2 emissions were 654.8 g/kWh for the K-tier3 machinery and 683.8 g/kWh for the K-tier4 machinery. Although the K-tier4 machinery had approximately 4% larger emissions, it seems inappropriate to judge these changes in CO_2 due to significant differences in the specifications and working conditions of the construction machinery being tested as shown in Figure 3b. CO_2 emission is normally dependent on the amount of fuel used, and the telematics data from CHs shows the high dependence on the CH driving speed during harvesting and Load factor [25,26]. To reduce CO_2 emission from the construction machinery. Advanced modes and technology, various eco-modes and highly energy efficient hydraulic pump systems, have been developed worldwide to improve the fuel efficiency [34].

Table 4 shows the conformity factors that compares the average emissions under real-world working conditions with the laboratory engine emission standards and the deviation ratios that performs comparisons with the conventional emission factors applied to CAPSS in Korea. As described in this table, the conformity factor can be obtained by a/b, where a is real working emission (cf. Table 4) and b is gaseous emission standard (cf. Table 2) The regulated air pollutants and the emission standards for construction machinery engines are different depending on the regulation stage and engine net power. The K-tier3 machinery being tested was regulated with NOx + THC. Only one excavator (T3-Ex-3) had lower real-world NOx + THC than the laboratory emission limit, and the conformity factors ranged from 1.44 to 2.5 for six units. The six K-tier4 machines being tested were regulated with NOx. The NOx conformity factors were less than 1 (from 0.04 to 0.8) for three machines but ranged from 3.7 to 4.58 for the remaining three machines. K-tier4 machines showed considerable differences in NOx conformity factors and EU Stage IV machines also showed similar trend in a previous study [4] that the NOx conformity factors of stage IV excavators ranged from 0.48 to 10.42. This previous study [4] highlighted that a failure of SCR can only be diagnosed through the PEMS test in the no warning state, such as the exhaust gas temperature control problem, in Stage IV machinery. A similar issue also happened in diesel vehicles. On-road NOx emissions from Euro 6b diesel vehicles equipped with SCR were much deviated as vehicles and exceeded laboratory emission limit in considerable number of vehicles. The Euro 6b vehicles were not subjected to real driving emission(RDE) regulation [12,35,36]. Theses studies indicated that the NOx reduction performance of SCR in pre-RDE vehicles were not sufficient for on-road NOx to be controlled under the laboratory emission limit. The results of this study also showed the unstable NOx reduction efficiency of SCR for K-tier4 construction machines which real-world emission regulation was not implemented.



(**a**)

(**b**)

Figure 5. Average brake-specific emissions, engine load factors and power for tested construction machinery. (**a**) Real-world emissions and Load Factor; (**b**) CO_2 emission and Load Factor.

Table 4. Real working emissions, conformity factors and deviation ratios for the test construction machinery.

ID of Test Machine	Real Working Emission (g/kWh)			Conformity Factor			Deviation Ratio		
	CO	NOx	THC	CO	NOx	THC	CO	NOx	THC
T3-EX-1	2.06	5.80	0.11	0.41	1.48		1.37	1.64	0.84
T3-EX-2	1.71	5.60	0.15	0.34	1.44		1.14	1.58	1.19
T3-EX-3	0.95	3.45	0.09	0.27	0.88		0.53	0.97	0.51
T3-Lo-1	4.96	9.88	0.12	1.42	2.50		2.32	2.88	0.75
T3-Lo-2	0.87	6.45	0.14	0.25	1.65		0.41	1.88	0.90
T3-Fo-1	1.94	10.01	0.22	0.39	2.18		1.08	2.71	1.27
T3-Fo-1	2.44	8.27	0.65	0.49	2.23		1.80	2.26	3.26
T4-EX-1	0.46	0.32	0.03	0.09	0.80	0.18	6.50	1.71	2.05
T4-EX-2	0.31	0.15	0.03	0.06	0.39	0.18	4.30	0.82	2.05
T4-EX-3	0.87	1.83	0.10	0.25	4.58	0.51	8.25	9.60	4.25
T4-Lo-1	0.06	0.02	-	0.02	0.04	-	0.54	0.09	-
T4-Lo-2	1.14	1.48	0.02	0.23	3.70	0.13	16.04	7.87	1.44
T4-Fo-1	0.34	3.73	0.05	0.07	0.80		0.88	1.06	0.64
T4-Fo-2	1.02	1.53	-	0.20	3.83	-	14.35	8.14	-

For the four K-tier4 machines regulated with THC, the conformity factors were less than 1 (ranged from 0.13 to 0.51). In the case of CO, the conformity factors were less than 0.5 for the 13 machines being tested except for 1 K-tier3 wheel loader, showing that the laboratory emission limit was generally met under real-world working conditions. The deviation ratios, which perform comparisons with the emission factors of CAPSS, were found to be higher than the conformity factors for most of the machines. This is likely because the emission factors used in CAPSS were developed using the engine dynamometer test results, including the engine emission certification test. Given that engine manufacturers must pass the emission certification test to produce and sell engines, the engine dynamometer test results are usually lower than the emission standards. In this study, however, emissions from the construction machinery under real-world working conditions were considerably higher than the engine dynamometer test results, and the K-tier4 machinery with reinforced emission standards showed substantial differences. Previous studies [4,22] showed that the emission factors of construction machinery applied to the air pollutant inventory is substantially different from emissions under real-world working conditions, indicating that it is necessary to reflect the emission characteristics under real-world working conditions to improve the accuracy of the air pollutant inventory of construction machinery.

3.3. Average Emissions in Real-World Working Modes for Construction Machinery

In this study, emission tests were conducted in the typical working modes as construction machinery for four excavators, three-wheel loaders, and four forklifts. Figures 6 and 7 show the average brake-specific gas emissions according to the average load factor in the typical working modes of the K-tier3 and K-tier4 construction machinery. The engine load factor ranged from 55 to 67% in the "digging and loading", "leveling ground", and "moving" working modes of the excavators, which was higher compared with the working modes of the wheel loaders and forklifts. It ranged widely from 22 to 46% in the "loading", "moving on a hill", and "moving on ground" working modes of the wheel loaders, and there were also significant differences among the two-wheel loaders being tested. During operation, the wheel loaders operated at engine driving points in a significantly wide range compared with the excavators and the forklifts. This is likely because there were significant differences in the engine operation range and the load factor depending on the work of the driver. The "lifting and carrying" work of the forklifts was performed in a low engine power range (22 to 25%). The results showed that the difference in the load factor depending on the work of the construction machinery also affects the emissions. For the "lifting and carrying" work of the K-tier3 forklifts, the engine load factor was low (approximately 22%) but the NOx emissions were approximately 2.6 times higher compared with the "leveling ground" excavator (K-tier3) work whose load factor is approximately 60%. For the K-tier3 construction machinery, the average brake-specific NOx generally increased as the engine load factor decreased, which is a trend also confirmed by the findings of Bonnel et. al. [18]. NOx emissions from the K-tier4 construction machinery were reduced compared with K-tier3 in all the machinery working modes. No clear NOx tendency was observed according to the engine load factor in contrast with the K-tier3 machinery. This is likely because the NOx reduction effect due to the application of the SCR system to the K-tier4 machinery was different for each machine type. The NOx reduction rate by the application of the SCR was highest (90%) in the "moving on hill" wheel loader work mode and lowest (39%) in the "moving" excavator work mode. Although these results have limitations in quite a small number of tests these results can demonstrate that the type and working modes of construction machinery have a considerable influence on the gas emissions. Therefore, it is necessary to develop an emission factor that can reflect the work characteristics for each type of construction machinery to more accurately calculate the air pollutant emission inventory of construction machinery.

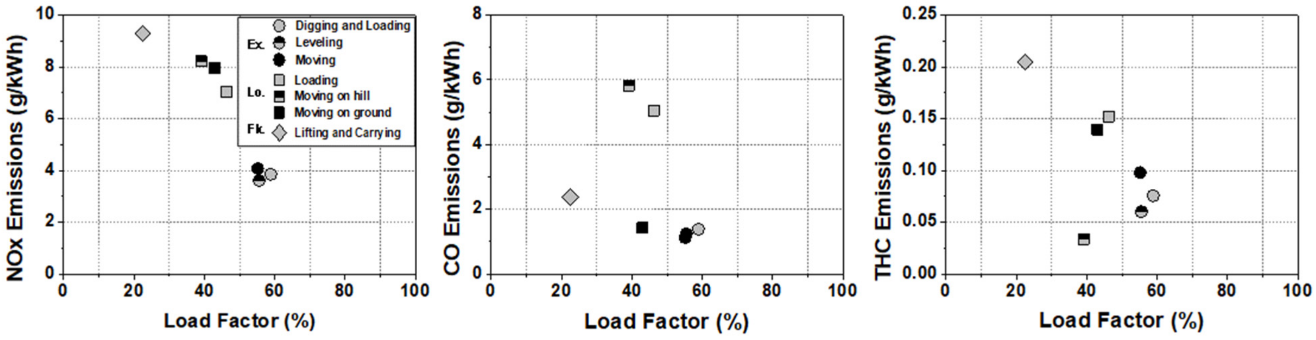


Figure 6. Average brake-specific emissions in according to load factor as real-world working modes of tested for K-tier3 construction machinery.

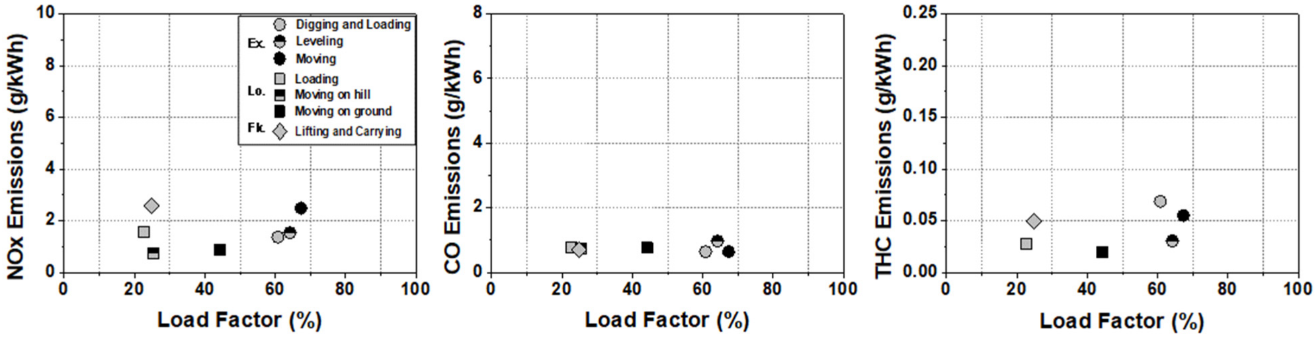
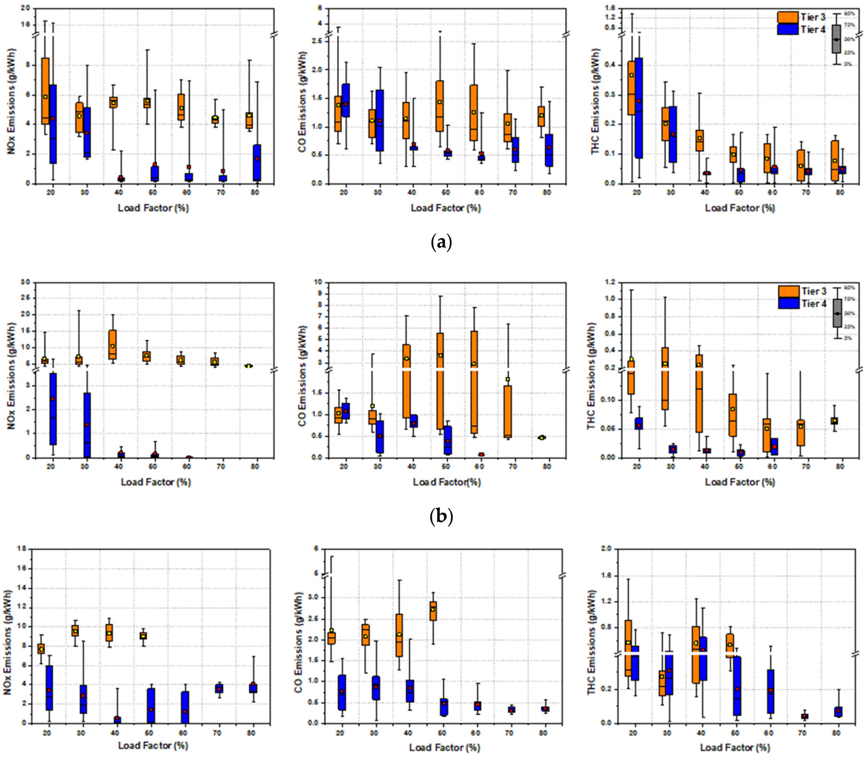


Figure 7. Average brake-specific emissions in according to load factor as real-world working modes of tested for K-tier4 construction machinery.

3.4. Emission Factor Development Based on Moving Averaging Window Analysis

Analyzing PEMS test data with MAW is known to be useful in evaluating emission characteristics according to operation parameters using a relatively small number of test data [12,18,33]. Another study [37] analyzed the on-road NOx emission data measured through PEMS for light-duty diesel trucks with 1 km segment MAW. Emission factor equations were developed according to the average vehicle speed, and a method was proposed for applying it to the emission inventory. MAW analysis could be used in this study for analyzing the emission characteristics of construction machinery under real-world working conditions. In this study, emissions were measured for 14 construction machines, but there were significant differences in the emission characteristics depending on the type of construction machinery and the emission regulations being applied. Therefore, it was necessary to subdivide the machines and then review the emission characteristics. When they were subdivided based on the type of construction machinery and the emission regulations, two or three machines were included per category. Despite this problem, MAW could be used effectively to evaluate the emission characteristics according to the engine load factor. Figure 8 shows the emission characteristics according to the engine load factor by analyzing the test data for each construction machine with 1 kWh engine-work segment MAW. The engine load factor is likely to be a significant variable in developing the emission factor for construction machinery. For the excavators, the K-tier3 machinery had relatively high NOx emissions regardless of the load factor. However, the K-tier4 machinery exhibited a significant reduction in NOx at a load factor of 40% or higher. This is likely because SCR showed high efficiency under operating conditions in sufficiently high exhaust gas temperature with high engine load. In the cases of CO and THC, the emission reduction effect was also observed at an engine load factor of 30% or higher. For the wheel loaders, K-tier3 had the highest NOx and CO emissions when the engine load factor was between 40 and 60% which had instantaneous full load operations. The K-tier4 wheel loaders showed an emission reduction effect in the entire engine load factor range. For the forklifts, emissions were generally reduced due to the introduction of the K-tier4 regulation, but NOx was at a considerably higher level compared with the excavators and wheel loaders. The emission factors for the air pollutant emission inventory for motor vehicles are expressed as polynomial equations that use the average vehicle speed as a parameter [1,38]. These emission factor equations make it possible to calculate emissions inventory in an effective way with a combination of the average vehicle speed activity data in the road traffic statistics. The MAW analysis results of this study show that the air pollutant emission factors of construction machinery can be developed with polynomial equations that use the engine load factor as a parameter. Table 5 shows the regression equations developed with average emissions at engine load factor bins in Figure 6 and the coefficients of determinations. The results confirm the possibility of developing the emission factor equations for construction machinery with a parameter of engine load. Given that the construction machinery engines are equipped with ECM after K-tier3, it is also possible to collect activity data for the engine load factor using SAE J 1939 or the communication protocol of the manufacturer. Combining the regression equations according to the engine load factor of the construction machinery with the activity data collected as ECM data can considerably improve the emission calculation method used in Korea. To officially use the equations developed in this study for CAPSS, additional test data are required to improve the regression equations for specific types of construction machinery and the emission regulations.



(**a**)

(**b**)

(**c**)

Figure 8. Three gaseous emissions with concern of load factor for the difference types of construction machines. (**a**) Excavators; (**b**) Wheel Loaders; (**c**) Fork-lift.

Table 5. Results of regression equations for the different type of construction machines.

Types of Construction Machinery	Emission Standard	Emissions	Regression Equations (L: Load Factor)
Excavators	K-tier3	NOx	$8.3741L^{-0.189}$
		CO	$1.5896L^{-0.07}$
		THC	$15.164L^{-1.26}$
	K-tier4	NOx	$0.0024L^{2}--0.2899L + 9.3168$
		CO	$0.0005L^{2}--0.0615L + 2.4447$
		THC	$0.00014L^{2}--0.01746L + 0.55904$
Wheel-loaders	K-tier3	NOx	$-0.003L^{2} + 0.2454L + 3.3855$
		CO	$-0.0031L^{2} + 0.3019L--4.1919$
		THC	$32.833L^{-1.48}$
	K-tier4	NOx	$2 \times 10^{6}\ L^{-4.309}$
		CO	$379.22L^{-1.881}$
		THC	$7 \times 10^{-5}L^{2}--0.0064L + 0.1516$
Fork-lifts	K-tier3	NOx	$-0.0054L^{2} + 0.4154L + 1.6221$
		CO	$0.0019L^{2}--0.1161L + 3.8195$
		THC	$0.0007L^{2}--0.0455L + 1.1659$
	K-tier4	NOx	$0.0031L^{2}--0.2992L + 8.3535$
		CO	$9.1017L^{-0.737}$
		THC	$1 \times 10^{-5}L^{2}--0.0005L + 0.0392$

4. Conclusions

In this study, a portable emission measurement system (PEMS) was installed in 14 units of excavators, wheel loaders, and forklifts, which comprise the largest proportion among the construction machinery types in Korea, and engine operation characteristics and emissions were measured under real-world working conditions. The non-road transient cycle (NRTC) applied to the emission certification test for construction machinery engines could not reflect the diverse operation ranges of the construction machinery. Given that the emission standards for construction machinery in Korea were reinforced from K-tier3 (equivalent to U.S tier3 or EU Stage III) to K-tier4 (equivalent to U.S tier4 or EU Stage IV), NOx were reduced by approximately 83% and THC by 77% and CO by 73%. This shows that the exhaust after-treatment technologies applied to respond to the reinforced emission regulations operate effectively even under real-world working conditions. For most of the K-tier3 machines, real-world NOx + THC emissions exceeded the laboratory emission limit. The K-tier4 machines showed considerable improvement in terms of conformity, but the real-world NOx emissions from approximately 50% of the construction machines being tested still exceeded the laboratory emission limit. This is likely because the operation of selective catalytic reduction (SCR) was unstable depending on the K-tier4 construction machine likely as Euro6b diesel vehicles which were not subjected to real driving emission regulation. This issue needs to be examined thoroughly in the in-service monitoring of construction machinery using PEMS to be implemented by the Korean government. The emission factors of construction machinery developed from the engine dynamometer emission test results have been applied to CAPSS, but the real-world emission results of construction machinery measured in this study were found to be considerably higher. The difference was even higher for the construction machinery with the K-tier4 regulation applied. This may cause the problem of air pollutant emissions being underestimated for construction machinery. This study highlights the possibility of developing emission factor equations that use the engine load factor as a parameter by conducting engine work-based moving averaging window (MAW) analysis for the PEMS data. This is expected to contribute to improving the construction machinery emission factor by securing additional data.

The construction machinery types, and the number of units being tested for each emission regulation being applied were not sufficient to develop emission factor equations to use for CAPSS. In addition, emission characteristics for particulate matter could not be evaluated due to the uncertainty of the measuring equipment. They will be examined in future research.

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