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Korean National Emissions Inventory System and 2007 Air Pollutant Emissions

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ABSTRACT

Korea has experienced dramatic development and has become highly industrialized and urbanized during the past 40 years, which has resulted in rapid economic growth. Due to the industrialization and urbanization, however, air pollutant emission sources have increased substantially. Rapid increases in emission sources have caused Korea to suffer from serious air pollution. An air pollutant emissions inventory is one set of essential data to help policymakers understand the current status of air pollution levels, to establish air pollution control policies and to analyze the impacts of implementation of policies, as well as for air quality studies. To accurately and realistically estimate administrative district level air pollutant emissions of Korea, we developed a Korean Emissions Inventory System named the Clean Air Policy Support System (CAPSS). In CAPSS, emissions sources are classified into four levels. Emission factors for each classification category are collected from various domestic and international research reports, and the CAPSS utilizes various national, regional and local level statistical data, compiled by approximately 150 Korean organizations. In this paper, we introduced for the first time, a Korean national emissions inventory system and release Korea's official 2007 air pollutant emissions for five regulated air pollutants.

Key words: Emission inventory, Emission estimation method, CAPSS, Air pollutant, SCC

1. INTRODUCTION

South Korea (hereafter Korea) is a country in East Asia, located on the southern part of the Korean Peninsula. It is neighbored by North Korea to the north, Japan to the east and China to the west. Korea has experienced dramatic development and has become highly industrialized and urbanized during the past 40 years, which has resulted in rapid economic growth (for example, the sharp increase in gross domestic product). Due to industrialization and urbanization, however, air pollutant emission sources have increased substantially as well, for example, rapid increases have occurred in the number of vehicles and energy consumption. Because of the small land area (99,720 km^2 as of 2007) and very small habitable area (65% of total land area is forested land), the rapid increase in emission sources has resulted in serious air pollution in Korea. During the last 20 years in Seoul City (the capital of Korea), the ambient concentration of nitrogen dioxides increased from 27 ppb in 1989 to 38 ppb in 2008, and that of ozone soared from 8 ppb in 1989 to 19 ppb in 2008 (NIER, 2009).

An air pollutant emissions inventory is one set of essential data used by policymakers to understand the current status of air pollution levels, to establish air pollution protection policies and to analyze the impacts of the implementation of policies. It is also fundamental data for air quality studies; for example, air quality modelers need national emissions data because atmospheric photochemical dispersion models require accurate and realistic emissions inputs to determine air pollutant concentrations through chemical reactions.

In order to accurately and realistically estimate the administrative district level air pollutant emissions of Korea, we developed a Korean Emissions Inventory System named the Clean Air Policy Support System (CAPSS). In CAPSS, emissions sources are classified into four levels (12 upper levels - 54 intermediate levels - 312 lower levels - 527 detail levels). Although emission factors for each classification category are collected from various domestic and international research reports, in principle, domestic emission factors are utilized preferentially to reflect Korean conditions. For activity data, the CAPSS utilizes various national, regional and local level statistical data, compiled by approximately 150 Korean organizations, such as the

National Institute of Environmental Research (NIER), Ministry of Environment (ME), Ministry of Land, Transport and Maritime Affairs (MLTM), Statistics Korea, Korea Meteorological Administration (KMA), Korea Energy Economics Institute (KEEI), Korea National Oil Corporation (KNOC), Korea Coal Association (KCA), Korea City Gas Association (KCGA), Korea Automobile Manufacturers Association (KAMA), Korea Environment Corporation (EMC), Korea Transportation Safety Authority (TSA) and a large number of private companies.

In this paper, we introduce for the first time a Korean national emissions inventory system and release Korea's official 2007 air pollutant emissions for five regulated air pollutants, carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), fine particulate matter (PM_{10}) and volatile organic compounds (VOCs).

2. METHODOLOGY

2.1 Inventory Domain and Source Classification Categories

The domain of CAPSS covers a total of 248 administrative districts in South Korea, as shown in Fig. 1. The Seoul Metropolitan Area (SMA), which includes Seoul City, Gyeonggi Province and Incheon City, is a highly urbanized area which houses almost half of the Korean population. City-province (7 cities and 9 provinces) level emissions are calculated by summing district emissions in each city or province. When summed, all of the city-province level emissions represent the national level emissions.

We divided the Source Classification Category (SCC) into four levels, based on the European Environment Agency's (EEA) CORe Inventory of AIR emissions (EMEP/CORINAIR), in consideration of the Korean Standard Industrial Classification System (EEA, 2006): (1) the upper level (SCC1): 12 source categories, (2) the intermediate level (SCC2): 54 source categories, (3) the lower level (SCC3): 312 source categories and (4) the detail level (SCC4): 527 source categories. Some categories in the SCC3 are not divided further into SCC4. Although we know that more SCC levels result in higher resolution results, we could not segregate SCC into more than four levels due to the limitation of statistical data at a higher level. Detailed information about the four level SCC categories used in CAPSS is presented in Table 1.

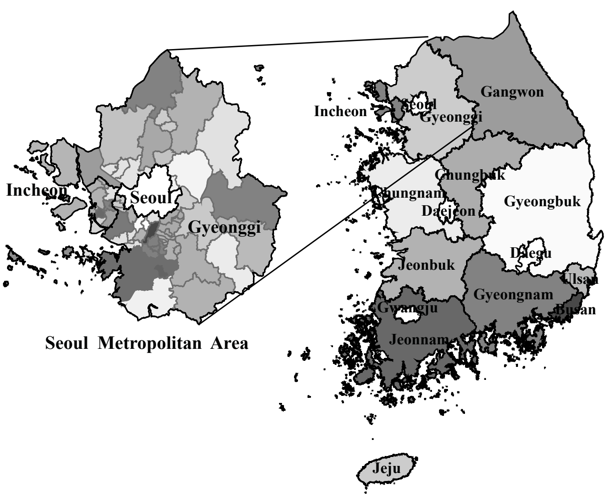

Fig. 1. Korean national emissions inventory domain: 7 cities and 9 provinces (right) and Seoul Metropolitan Area (SMA) with administrative districts (left).

2.2 Emissions Estimation Method for Point and Area Sources

In general, there are two emissions estimation methods for point sources, the direct method and the indirect method. The direct method uses real-time air pollutant emissions released through stacks in industrial sites, whereas the indirect method (also called the emission factor method) utilizes emissions factors and activity data to calculate emissions. We used both the direct and indirect methods for point sources depending on the available real-time emissions data. For the estimation of emissions from area sources, we used the indirect method utilizing various ample data from organizations in Korea.

2.2.1 Point Sources by the Direct Method

According to the Air Pollution Prevention Law (Korean Clean Air Act) in Korea, large facilities (for example, power plants and cement kilns) should install a Continuous Emission Monitoring System (CEMS) in stacks to continuously monitor air pollutant emissions and report real-time data to the governmental CEMS management center. We collected officially approved CEMS database (DB) information and utilized this to more accurately and reliably estimate emissions for large point sources. Annual emissions from the CEMS DB were estimated as follows,

$$E=\frac{Conc \times MW \times FR \times OT \times OD}{22.4 \times 10^6} \qquad \text{Eq. (1)}$$

where E is annual emissions (kg), Conc is concentration (ppm), MW is molecular weight, FR is flow rate (m^3), OT is operation time (hour), OD is operation day (day) and 10^6 is used for unit conversion.

2.2.2 Point and Area Sources by the Emission Factor Method

Emissions from point sources with no CEMS or areas sources were basically estimated by the multiplication of emission factors and relevant activity data in consideration of the removal efficiencies of control devices. Air pollutant emission factors for each SCC4 category were compiled from a wide range of published sources, for example, Korean research reports published by the NIER, ME and numerous universities, as well as the EEA's EMEP/CORINAIR and the US Environmental Protection Agency's (EPA) AP-42 (US EPA, 1995). They were then evaluated and approved by the Committee of Air Pollutant Emission Factors before being used in CAPSS. In principle, domestic emission factors were utilized preferentially to estimate air emissions (NIER, 2005a, b).

Activity data for point sources were collected by a web-based source data collection system named the Stack Emission Management System (SEMS). Individual companies input their source information through SEMS such as fuel consumption, amount of products and information about stacks and control devices. After quality assurance and quality control, SEMS information was put into a database and utilized in CAPSS for point source emissions estimation. Activity data for area sources were compiled from a wide range of sources of about 120 organizations in Korea such as Statistics Korea, KMA, KEEI, KNOC, KCA, KCGA and several private companies.

Because methodologies for individual sources in the SCC4 categories are slightly different, we introduce here the fundamental concepts used in CAPSS to calculate the emissions for each source category. Emissions from fuel combustion sources, which include

Table 1. The four Source Classification Categories in CAPSS.

Emission characteristics	SCC1	SCC2	SCC3	SCC4
Point	Combustion in energy industries	5: Public power; District heating plants; Petroleum refining plants; Solid fuel transformation plants; Commercial power	28	–
Point & Area	Non-industrial combustion plants	3: Commercial and institutional plants; Residential plants; Plants in agriculture, forestry and aquaculture	18	–
Point & Area	Combustion in manufacturing industries	3: Combustion in boilers, gas turbines and stationary engines; Process furnace; Other	49	–
Point & Area	Production processes	9: Processes in petroleum industries; Processes in iron and steel industries and collieries; Processes in non-ferrous metal industries; Processes in inorganic chemical industries; Processes in organic chemical industries; Processes in wood, paper and pulp industries; Processes in food and drink industries; Ammonia consumption; Processes in other industries	82	148
Point & Area	Storage and distribution of fuels	1: Liquid fuel distribution	3	–
Area	Solvent use	4: Paint application; Degreasing and electronics; Dry cleaning; Other use of solvents and related activities	17	4
Mobile	Road transport	8: Passenger cars; Taxis; Light-duty vehicles; Buses; Trucks; Special purpose vehicles (SPV); Recreational vehicles (RV); Motorcycles	31	58
Mobile	Other mobile sources and machinery	6: Military; Railways; Ships; Aircrafts; Agricultural machinery; Construction machinery and equipment	22	127
Point	Waste treatment and disposal	2: Waste incineration; Solid waste disposal on land	13	10
Area	Agriculture	2: Cultures with fertilizers; Enteric fermentation	10	28
Area	Other sources & sinks	6: Non-management broadleaf and coniferous forests; Forest and other vegetation fires; Wetland; Waters; Animals; Other	17	92
Mobile & Area	Fugitive dust	5: Re-entrainment road dust; Automobile tire wear; Construction site; Vacant land; Unloading and stored in the open	22	60
Total	12	54	312	527

* Numbers represent the number of caterories

combustion in energy industries, non-industrial combustion plants and combustion in manufacturing industries, were estimated in CAPSS. Emissions of SOx and other species from fuel combustion sources were estimated using equation (a) in Table 2. Uncontrolled emission factors for each species were multiplied by fuel consumptions in consideration of the removal efficiency of air pollutant control devices. Emissions from production processes, storage and distribution of fuels and waste treatment were estimated in CAPSS by multiplying controlled emission factors and amounts of products manufactured, volume of gasoline shipped, distributed or sold and amount of wastes incinerated, respectively (see equation (b) in Table 2). In the case of solvent use, we used controlled emission factors and the amount of solvent used or alternative statistics corresponding to emission factors, for example, number of employees and corresponding emission factors in printing (see equation (c) in Table 3).

Due to the lack of emissions sources and activity data, as well as reliable emission factors, emissions from natural sources (biogenic VOCs), fugitive dust (PM_{10}) and agricultural sources were excluded from this paper. We are currently developing methodologies and will include emissions from theses sources in the future.

2.2.3 Spatial Allocation of Emissions from Point and Area Sources

Emissions from point sources were spatially allocated using information on the locations of point sources, mostly using latitude and longitude data of individual industrial sites. If there was no information on location, emissions were allocated over the districts containing industrial sites. In the case of emissions from area sources, if emissions were estimated utilizing district level activity data, they were accepted as district level emissions without any spatial allocation. However, if city-province level activity data were used, emissions were spatially allocated using a spatial allocation index database such as population data and number of employees.

2.3 Emissions Estimation Method for Mobile Sources

Mobile sources can be subdivided into two categories: on-road mobile sources and non-road mobile sources. On-road mobile sources (named road transport in SCC1) include such vehicles as passenger cars, taxis, buses, trucks, and non-road mobile sources (named other mobile sources and machinery in SCC1) include railways, air traffic, construction machinery and other such means of transport (Table 1). Because the portion of emissions from mobile sources is large, especially in urbanized cities, we present the detailed emissions estimation method for mobile sources in the following sections.

Table 2. The emissions estimation method for point and area sources.

Equations by category	Descriptions
(a) Fuel combustion	
$E=EF\times Fuel \times(1-R)$	Fuel: amount of fuel consumption R: removal efficiency
(b) Production processes/Storage and distribution of fuels/ Waste treatment	
$E=EF\times$ Product/ Gasoline/ Wastes	Product amount of products manufactured Fuel: volume of gasoline shipped, distributed or sold Wastes: amount of wastes incinerated
(c) Solvent use	
$E=EF\times$ Solvent/ Stats	Solvent: amount of solvent used Stats: alternative statistics corresponding to EF

*E=emission, EF=emission factor

2.3.1 On-Road Mobile Sources

In principle, total emissions from on-road mobile sources per vehicle type (or category in SCC3) are estimated by summing emissions from three subcategories as in SCC4: (1) hot engine operation, (2) cold start and (3) fuel evaporation, as suggested by Ntziachristos and Samaras (Ntziachristos and Samaras, 2000). This can be expressed as follows,

$$E_{TOTAL}=E_{HOT}+E_{COLD}+E_{EVAP} \qquad \text{Eq. (2)}$$

where E_{TOTAL} is total emissions from on-road mobile sources, E_{HOT} is emissions during stabilized hot engine operation, E_{COLD} is emissions during a cold start and E_{EVAP} is emissions from fuel evaporation (relevant only to VOCs from gasoline vehicles).

(1) Hot Engine Operation

Emissions from hot engine operation were calculated by equation (a) in Table 3. Total VKT (or mileage) per vehicle type can be calculated by the following equation.

$$\text{Total VKT}=\text{daily mean VKT}\times\text{number of vehicles}\times 365\text{ days} \qquad \text{Eq. (3)}$$

Total VKT values per vehicle type were spatially allocated into road networks using the results of a traffic volume survey. Emissions from hot engine operation were then calculated by multiplying emission factors and deterioration factors. Deterioration factors per vehicle type were used to account for vehicle age impacts on emissions. Because emission factors are a

Table 3. The emissions estimation method for on-road mobile sources.

Equations by category	Descriptions
(a) Hot engine operation	
$E=EF \times VKT \times NV \times DF$	VKT: vehicle kilometers traveled NV: number of vehicles DF: deterioration factor
(b) Cold start	
$E=EF \times VKT \times NV \times \beta \times (e^{COLD}/e^{HOT}-1)$	EF: emission factor for hot engine operation VKT: vehicle kilometers traveled NV: number of vehicles β: fraction of kilometer driven with cold engines or catalyst operated below the light-off temperature e^{COLD}/e^{HOT}: ratio of cold over hot emissions
$\beta=(0.0647-0.025 \times l_{trip})-(0.00974-0.000386 \times l_{trip}) \times T$	l_{trip}: average trip length T: mean temperature
(c) Fuel evaporation	
$E=365 \times NV \times (e^d+S^c+S^{fi})+R$ see Ntziachristos and Samaras[6] for details on e^d, S^c, S^{fi}, and R	365: 365 days NV: number of gasoline vehicles e^d: mean emission factor for diurnal losses of gasoline vehicles S^c: average hot and warm soak emission factor of gasoline vehicles equipped with carburetor S^{fi}: average hot and warm soak emission factor of gasoline vehicle equipped with fuel injection R: hot and warm running losses

* E=emission, EF=emission factor

function of vehicle speed, mean speed per road type (urban, rural and highway) was taken into account. Actual mean speed or 80% of the speed limit for each road was utilized depending on data availability of the traffic speed survey (actual mean speed was utilized when survey data were available). Fig. 2 shows how emissions from hot engine operation were estimated.

(2) Cold Start

Cold start emissions are introduced into the calculation as additional emissions and can be calculated by equation (b) in Table 3. Because the β-parameter is a function of ambient air temperature and average trip length, a mean air temperature of 13.1°C and average trip length of 12.35 km were applied from the KMA automated weather station data and NIER report, respectively (Jang *et al.*, 2007).

(3) Fuel Evaporation

Due to lack of data, evaporative VOCs emissions were only estimated for gasoline vehicles and included three primary sources from diurnal emissions, hot soak emissions and running losses. Emissions from fuel evaporation were calculated by equation (c) in Table 3. More detailed descriptions can be found in the program by Ntziachristos and Samaras (Ntziachristos and Samaras, 2000).

Almost all the emission factors per vehicle type in

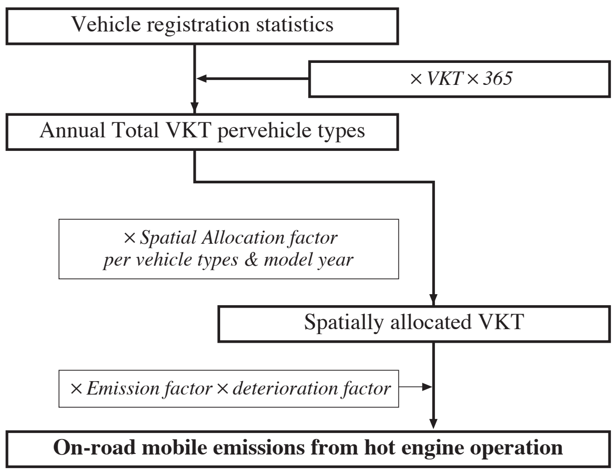

Fig. 2. Schematic diagram of the calculation procedure for on-road mobile emissions.

consideration of model year were developed by NIER (Ryu *et al.*, 2005; Ryu *et al.*, 2004; Ryu *et al.*, 2003). In such cases, no emission factors were calculated, and emission factors of similar vehicle types and model year were adopted and utilized in CAPSS.

We collected a wide range of activity data for vehicle-related information (e.g., number of vehicles, vehicle kilometers traveled (VKT)) and road related information (e.g., highway, urban and rural roads) as well as other information (e.g., Geographic Information System (GIS) database, number of vehicles with exhaust gas reduction devices, surface weather stations data). These data were collected from 10 organizations in Korea, including the MLTM, KAMA, EMC, TSA, Korea Expressway Corporation, Korea Association for National Gas Vehicles (KANGV), and Korea National Joint Conference of Taxi Association.

2. 3. 2 Non-Road Mobile Source

In principle, total emissions from non-road mobiles sources are estimated by summing emissions from five sources: (1) railways, (2) ships, (3) aircrafts, (4) agricultural machinery and (5) construction machinery. This can be expressed as follows,

$$E_{TOTAL}=E_{RAIL}+E_{SHIP}+E_{AIR}+E_{AGRI}+E_{CONS} \quad \text{Eq. (4)}$$

where E_{TOTAL} is total emissions from non-road mobile sources, and E_{RAIL}, E_{SHIP}, E_{AIR}, E_{AGRI} and E_{CONS} are emissions from railways, ships, aircrafts, agricultural machinery and construction machinery, respectively.

Basic equations for each non-road mobile source are summarized in Table 4. For emissions from railways, we used emission factors per train type developed by the Korea Railroad Research Institute (KRRI) (Jung *et al.*, 1997) and activity data (fuel consumption per train type and railroad line) collected from Korea Railroad. In the case of emissions from ships, the US EPA emission factors per sailing mode were utilized, and activity data (port entry and departure per ship tonnage, fuel consumption, etc.) were compiled from the MLTM, Korea Maritime and Port Administration and KEEI. For aircraft emissions, an Emission and Dispersion Modeling System (EDMS) for emission factors per aircraft type, developed by the US Federal Aviation Administration, was used (Anderson *et al.*, 1997), and activity data such as Landing-TakeOff (LTO) cycles were collected from the Korea Airports Corporation (KAC) and Incheon International Airport (IIAC). Emissions from ground support equipment (e.g., baggage tractor, belt loader, catering truck, etc.) during landing and takeoff were also taken into account. For emissions from agricultural and construction machineries, emission factors and average rated horsepower developed by NIER were utilized (Eom *et al.*, 1999; Chung *et al.*, 1997), and activity data (number of machineries) were collected from the MLTM.

2. 3. 3 Spatial Allocation of Emissions from Mobile Sources

Emissions from on-road mobile sources were spatially allocated using information from a traffic volume survey for each road network. For roads with no available survey data, emissions were allocated over the districts using city-province level estimated VKT data, which were calculated by subtracting actual VKT from total VKT. Using estimated VKT, we computed a city-province level spatial allocation index to allocate emissions. Emissions from railways were spatially allocated using the information of length ratio of railroads in districts. Emissions from ships and aircrafts were allocated utilizing information on sailing routes and the location of runways in airports, respectively. For emissions from agricultural and construction machineries, we first estimated city-provincial level emissions using the number of registered machines in the city or province and then spatially allocated emissions over the districts. We utilized the ratio between urban and agricultural areas in the district to allocate emissions from agricultural machineries over districts and used groundbreaking construction areas in the district for spatial allocation of construction machineries (NIER, 2010).

Table 4. The emissions estimation method for non-road mobile sources.

Equations by category	Descriptions
(a) Railways	
E=EF×Fuel	Fuel: fuel consumption of each railroad tracks
(b) Ships	
E=EF×(FuelA +FuelM)	FuelA: fuel consumption at anchoring FuelM: fuel consumption at maneuvering
(c) Aircrafts	
E=EF×LTO	LTO: landing-takeoff cycles per aircraft types
(d) Agricultural and construction machineries	
E=EF×NM ×HP×LF	NM: number of machines HP: average rated horsepower LF: typical load factor (value used in CAPSS=0.48)

* E=emission, EF=emission factor

3. RESULTS

3. 1 Overall 2007 Air Pollutant Emissions in Korea

Total 2007 air pollutant emissions for CO, NOx, SOx, PM_{10} and VOCs in Korea were estimated as 3,372,151 tons, excluding biogenic VOCs, fugitive dust, as well as emissions from agricultural sources. As shown in Table 5, NOx emissions occupied the largest share with

1,188 thousand tons (35.2%), followed by VOCs emissions with 875 thousand tons (25.9%) and CO emissions with 809 thousand tons (24.0%).

Mobile sources (road transport + other mobile sources and machinery), which emitted 1,582 thousand tons (46.9%) of the five air pollutants during 2007, were the largest sources of pollution in Korea. The next largest sources were combustion sources (combustion in energy industries + non-industrial combustion plants + combustion in manufacturing industries) contributing 860 thousand tons (25.5%) of the five air pollutant emissions, followed by solvent use sources, which emitted 531 thousand tons (15.8%) of VOC emissions.

For the mobile sources, NOx and CO were dominant air pollutants with 732 (46.3%) and 642 (40.6%) thousand tons of emissions, respectively. In the case of combustion sources, NOx, SOx and CO were the main air pollutants with 394 (45.8%), 261 (30.3%) and 136 (15.8%) thousand tons of emissions, respectively. VOCs were unique air pollutants emitted from solvent use sources.

3. 2 Sectoral Contribution of Emissions

Table 5 summarizes the 2007 national air pollutant emissions in terms of SCC1 sectors, and Fig. 3 shows the sectoral contribution of emissions for the five air pollutants CO, NOx, SOx, PM_{10} and VOCs.

3. 2. 1 CO

Total CO emissions in Korea during 2007 were 809 thousand tons. The road transport sector was the dominant source, with 546 thousand tons of emissions and a 67.6% contribution rate to total emissions. In the road transport subsectors, passenger cars were the primary sources with 305 thousand tons of emissions. The second largest sector for CO emissions was other mobile sources and the machinery sector, which emitted 96 thousand tons of CO emissions with an 11.8% contribution rate. In this sector, emissions from construction machinery and equipment were the major contributor (74 thousand tons). The third largest sector was the non-industrial combustion plants sector, with 80 thousand tons of emissions and a 9.9% contribution rate.

3. 2. 2 NOx

Total NOx emissions in Korea during 2007 were 1,188 thousand tons. The road transport sector was the dominant source with 495 thousand tons of emissions and a 41.7% contribution rate to total emissions. In the road transport subsectors, trucks were the primary sources with 299 thousand tons of emissions. The second largest sector for NOx emissions was other mobile sources and the machinery sector, which emitted 237 thousand tons of NOx emissions with a 20.0% contribution rate. In this sector, emissions from construction machinery and equipment were the major contributor (152 thousand tons). The third largest sector was combustion in the energy industries sector with 156 thousand tons of emissions and a 13.2% contribution rate. Emissions from public powers were the main contributor (123 thousand tons). The fourth largest sector was combustion in manufacturing industries (155 thousand tons, 13.1%).

3. 2. 3 SOx

Total SOx emissions in Korea during 2007 were 403 thousand tons. Combustion in the manufacturing industries sector was the primary source with 102 thousand tons of emissions and a 25.4% contribution rate to total emissions. For combustion in manufacturing industries subsectors, other sectors were primary sources with 62 thousand tons of emissions. The second largest sector for SOx emissions was combustion in the energy indus-

Table 5. Sectoral air pollutant emissions in 2007 (unit: ton/year).

SCC1	CO	NOx	SOx	PM_{10}	VOCs	Total
Combustion in energy industries	40,360	156,304	94,317	2,951	5,870	299,802
Non-industrial combustion plants	80,155	82,396	64,083	2,208	2,910	231,752
Combustion in manufacturing industries	15,424	155,053	102,172	53,144	2,941	328,733
Production processes	21,771	48,725	85,709	6,074	140,357	302,635
Storage and distribution of fuels	0	0	0	0	29,752	29,752
Solvent use	0	0	0	0	531,282	531,282
Road transport	546,493	495,084	856	22,694	95,404	1,160,531
Other mobile sources and machinery	95,559	237,101	52,814	10,477	25,206	421,157
Waste treatment and disposal	2,231	13,097	2,574	302	40,379	58,583
Other sources & sinks	6,870	163	0	294	597	7,924
Combustion total	135,939	393,753	260,573	58,302	11,721	860,288
Mobile total	642,052	732,185	53,670	33,171	120,610	1,581,688
Total	808,862	1,187,923	402,525	98,143	874,699	3,372,151

* Exclusive of fugitive dust and biogenic VOCs

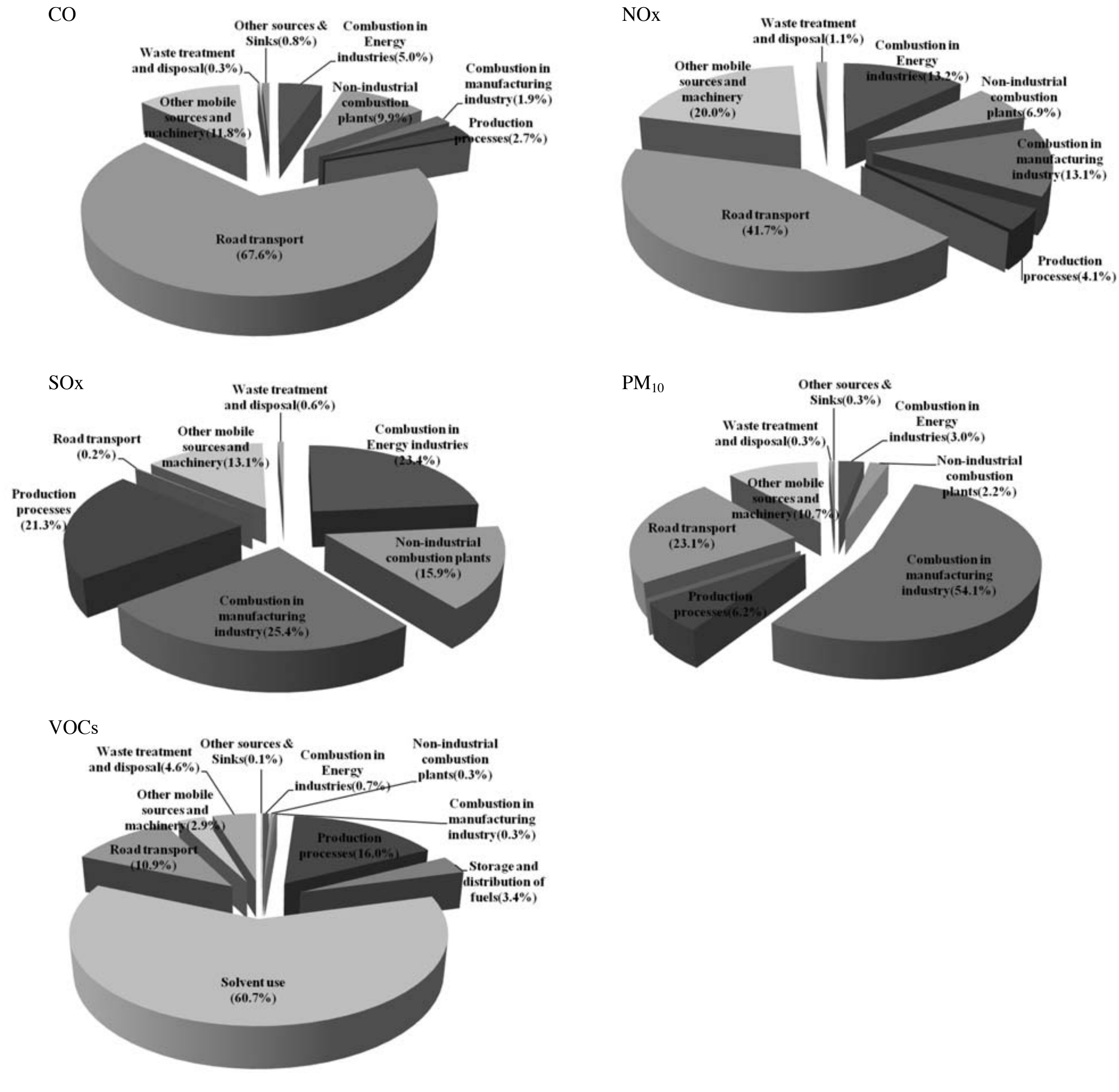

Fig. 3. Contribution rate by source category for CO, NOx, SOx, PM_{10} and VOCs.

tries sector, which emitted 94 thousand tons of SOx emissions with a 23.4% contribution rate. In this sector, emissions from public powers were primary sources (71 thousand tons). The third largest sector was the production processes sector with 86 thousand tons of emissions and a 21.3% contribution rate. Emissions from processes in petroleum industries and processes in iron and steel industries and collieries were the main contributors (36 and 33 thousand tons, respectively). The fourth largest sector was non-industrial combustion plants (64 thousand tons, 15.9%).

3.2.4 PM_{10}

Total PM_{10} emissions in Korea during 2007 were 98 thousand tons. Combustion in the manufacturing industries sector was the dominant source with 53 thousand tons of emissions and a 54.1% contribution rate to total emissions. For the combustion in manufacturing industries subsectors, other sectors were primary sources with 50 thousand tons of emissions. The second largest sector for PM_{10} emissions was the road transport sector, which emitted 23 thousand tons of PM_{10} emissions with a 23.1% contribution rate. In this sector, emissions from trucks were the major contributor (15 thousand tons). The third largest sector was other mobile sources and the machinery sector with 11 thousand tons of emissions and a 10.7% contribution rate.

3.2.5 VOCs

Total VOCs emissions in Korea during 2007 were 875 thousand tons. The solvent use sector was the dominant source with 531 thousand tons of emissions and a 60.7% contribution rate to total emissions. In the solvent use subsectors, the paint application sector was the primary source with 348 thousand tons of emissions. The second largest sector for VOC emissions was the production processes sector, which emitted 140 thousand tons of VOC emissions with a 16.0% contribution rate. In this sector, emissions from processes in petroleum industries were major contributors (52 thousand tons). The third largest sector was the road transport sector with 95 thousand tons of emissions and a 10.9% contribution rate.

3.3 Regional Air Pollutants Emissions

Table 6 summarizes city-provincial level air pollutant emissions, and Fig. 4 shows the spatial distribution of emissions for the five regulated air pollutants, CO, NOx, SOx, PM_{10} and VOCs.

3.3.1 Emissions from Seoul Metropolitan Area

Although SMA (Seoul, Gyeonggi and Incheon) covers only around 12% of the total Korean area (11,745 out of 99,720 km^2 as of 2007) (see Fig. 1), it is a highly urbanized area housing around 49% of the Korean population (23,963 out of 49,269 thousand persons as of 2007) and 46% of the registered vehicles in Korea (7,579 out of 16,428 thousand cars as of 2007).

In terms of air pollutant emissions, as expected, SMA is responsible for 33.0% (1,113 thousand tons) of total Korean air emissions (3,372 thousand tons); in particular, 43.2% (349 thousand tons) of CO emissions, 32.4 % (385 thousand tons) of NOx emissions and 35.6% (311 thousand tons) of VOCs emissions, mostly due to mobile sources (especially from the road transport sector). Detailed SCC1 sectoral emissions from SMA and other selected regions for the five air pollutants are presented in Table 7.

3.3.2 CO

Because road transport was the dominant sector for CO emissions, regional CO emissions depended highly on the number of registered vehicles in the cities or provinces. Gyeonggi Province, with 3,792 thousand vehicles, was the primary region for emissions, with 148 thousand tons of emissions, contributing 18.3% to total emissions. Seoul City (2,933 thousand vehicles) was the second largest source region for CO emissions with 143 thousand tons of emissions and a 17.7% contribution rate. In other regions, except for SMA, Gyeongbuk and Gyeongnam Provinces were major source regions with 59 and 51 thousand tons of emissions, respectively.

3.3.3 NOx

The mobile sector and combustion from the energy industries sector were the main sources for NOx emissions in Korea, as described in the previous section. Gyeonggi Province was the highest source region with 207 thousand tons of emissions and a 17.5% contribu-

Table 6. Regional air pollutant emissions in 2007 (unit: ton/year).

City or Province	CO	NOx	SOx	PM_{10}	VOC	Total
Seoul	143,110	113,086	7,835	3,920	91,459	359,410
Gyeonggi	148,019	207,461	27,342	8,475	161,614	552,911
Incheon	58,041	64,851	17,300	2,466	58,285	200,942
SMA total	349,170	385,398	52,477	14,860	311,358	1,113,263
Busan	52,421	62,959	32,879	2,959	40,411	191,629
Daegu	38,272	35,210	5,465	1,993	31,056	111,996
Gwangju	15,401	14,243	1,072	652	14,788	46,156
Daejeon	22,653	19,917	2,382	820	16,238	62,009
Ulsan	34,615	64,198	63,110	9,797	96,851	268,572
Gangwon	32,468	81,099	23,652	9,485	23,418	170,121
Chungbuk	34,188	63,761	15,525	5,097	33,226	151,798
Chungnam	44,293	105,296	51,904	3,814	56,044	261,352
Jeonbuk	29,595	42,383	10,739	1,923	32,450	117,091
Jeonnam	36,225	98,207	71,892	25,352	77,137	308,814
Gyeongbuk	58,730	99,822	39,690	16,923	52,904	268,069
Gyeongnam	51,175	104,159	28,768	4,006	82,355	270,462
Jeju	9,656	11,270	2,968	462	6,463	30,820
Total	808,862	1,187,923	402,525	98,143	874,699	3,372,151

* Exclusive of fugitive dust and biogenic VOCs

Fig. 4. Spatial distributions of emissions for CO, NOx, SOx, PM_{10} and VOCs.

tion rate to total Korean NOx emissions. In Gyeonggi Province, the road transport sector was the primary source (113 thousand tons, 54.7%), and other mobile sources and the machinery sector were the secondary sources (46 thousand tons, 22.3%). The second highest source region was Seoul City, with 113 thousand tons of emissions (9.5%). Like Gyeonggi Province, in Seoul City, road transport and other mobile sources and machinery sectors were major sources for NOx emissions, contributing 46.0% (52 thousand tons) and 33.8% (38 thousand tons) to total Seoul NOx emissions, respectively. The third highest source region was Chungnam Province, with 105 thousand tons of emissions (8.9%). Unlike Gyeonggi and Seoul, due to four coal-fired power plants, combustion in the energy industries sector was the primary source in this region (51 thousand tons, 48.3%).

3.3.4 SOx

The combustion sector (in particular, combustion in manufacturing industries and combustion in energy industries) and production processes sector were the main sources for SOx emissions in Korea, as described in the previous section. Jeonnam Province, housing a large-scale complex for the petrochemical industry and steel manufacturing industry, was the highest source region with 72 thousand tons of emissions and a 17.9% contribution rate to total Korean SOx emissions. In

Table 7. Regional air pollutant emissions by SCC1 in 2007 for eight selected regions (unit: ton/year).

City or Province	SCC1	CO	NOx	SOx	PM_{10}	VOC
Seoul	01	809	789	5	13	109
	02	3,022	19,625	6,549	278	872
	03	428	1,393	170	5	64
	05	–	–	–	–	3,829
	06	–	–	–	–	63,978
	07	108,789	52,010	152	1,911	17,548
	08	18,846	38,234	583	1,652	4,751
	09	283	1,014	376	22	229
	11	933	22	–	38	77
Gyeonggi	01	5,056	14,612	7,035	206	771
	02	7,574	14,905	3,707	210	607
	03	2,099	11,026	9,609	853	353
	04	97	3,331	2,442	119	4,791
	05	–	–	–	–	7,673
	06	–	–	–	–	113,997
	07	110,009	113,385	176	4,872	18,791
	08	21,030	46,334	3,535	2,066	5,510
	09	673	3,833	838	87	8,996
	11	1,482	35	–	61	123
Incheon	01	9,987	11,192	3,255	367	1,347
	02	740	4,326	4,453	55	178
	03	906	3,066	1,112	100	128
	04	1,012	2,852	3,791	293	13,999
	05	–	–	–	–	1,628
	06	–	–	–	–	28,687
	07	36,855	25,364	49	988	6,947
	08	8,045	17,013	4,397	629	1,713
	09	179	1,031	242	20	3,631
	11	317	7	–	13	27
Ulsan	01	3,315	17,346	11,734	205	637
	02	390	1,979	3,041	41	68
	03	2,471	17,637	13,231	7,486	498
	04	11,276	1,206	28,018	928	42,280
	05	–	–	–	–	2,013
	06	–	–	–	–	45,201
	07	13,531	12,735	21	599	2,527
	08	3,312	12,617	6,947	509	971
	09	93	673	118	20	2,636
	11	226	5	–	10	20
Chungnam	01	8,919	50,907	37,728	1,236	1,207
	02	4,336	3,316	2,373	121	89
	03	1,149	4,822	2,664	144	187
	04	1,521	1,698	5,983	130	18,729
	05	–	–	–	–	1,710
	06	–	–	–	–	27,309
	07	22,460	30,031	40	1,473	4,072
	08	5,402	14,061	2,999	683	1,534
	09	99	451	118	10	1,172
	11	407	10	–	17	35
Jeonnam	01	1,690	14,674	8,633	178	271
	02	2,158	2,938	5,765	119	73
	03	1,695	17,819	20,137	20,682	447
	04	4,899	16,282	27,244	2,150	36,656
	05	–	–	–	–	1,920
	06	–	–	–	–	28,945
	07	20,493	27,230	35	1,364	3,797
	08	4,828	18,681	10,030	826	1,455
	09	51	574	49	13	3,533
	11	411	10	–	20	41

Table 7. Continued.

City or Province	SCC1	CO	NOx	SOx	PM_{10}	VOC
Gyeongbuk	01	129	2,351	2,374	12	16
	02	14,142	5,631	5,141	262	127
	03	1,736	14,414	16,580	11,646	408
	04	2,818	20,266	13,053	2,174	9,435
	05	–	–	–	–	1,746
	06	–	–	–	–	31,079
	07	33,601	42,229	55	2,042	6,051
	08	5,751	14,459	2,441	751	1,683
	09	63	460	45	12	2,311
	11	489	12	–	24	49
Gyeongnam	01	4,902	34,928	16,893	517	594
	02	2,591	3,531	3,137	121	115
	03	812	3,947	2,846	397	136
	04	1	775	1,120	85	3,460
	05	–	–	–	–	1,803
	06	–	–	–	–	65,090
	07	36,187	43,717	62	2,098	6,562
	08	5,842	16,005	4,493	732	1,610
	09	201	1,241	217	29	2,930
	11	639	15	–	27	55

*Exclusive of fugitive dust and biogenic VOCs
*In SCC1, 01=Combustion in energy industries; 02=Non−industrial combustion plants; 03=Combustion in manufacturing industries; 04=Production processes; 05=Storage and distribution of fuels; 06=Solvent use; 07=Road transport; 08=Other mobile sources and machinery; 09=Waste treatment and disposal; 11=Other sources & sinks

Jeonnam Province, the production processes sector was the primary source (27 thousand tons, 37.9%), and combustion in the manufacturing industries sector was the secondary source (20 thousand tons, 28.0%). The second highest source region was Ulsan City, with 63 thousand tons of emissions (15.7%). In Ulsan City, where the largest petrochemical industry complex is located, production processes and combustion in the manufacturing industries sectors were major sources for SOx emissions, contributing 44.4% (28 thousand tons) and 21.0% (13 thousand tons) to total Ulsan SOx emissions, respectively, followed by combustion in the energy industries (12 thousand tons, 18.6%). The third highest source region was Chungnam Province, with 52 thousand tons of emissions (12.9%). Due to coal-fired power plants, combustion in the energy industries sector was the dominant source in this region (38 thousand tons, 72.7%).

3. 3. 5 PM_{10}

Combustion in the manufacturing industries was the dominant source for PM_{10} emissions in Korea, as described in the previous section. Jeonnam Province, due to its petrochemical and steel manufacturing industry, was the highest source region with 25 thousand tons of emissions and a 25.8% contribution rate to total Korean PM_{10} emissions. In Jeonnam Province, combustion in the manufacturing industries sector was the dominant source (21 thousand tons, 81.6%). The second highest source region was Gyeongbuk Province City, with 17 thousand tons of emissions (17.2%). Like Jeonnam Province, in Gyeongbuk Province, where one of the largest steel manufacturing industry complexes is located, combustion in the manufacturing industries sector was the dominant source of PM_{10} emissions, contributing 68.8% (12 thousand tons) to total Gyeongbuk PM_{10} emissions, followed by production processes (2 thousand tons, 12.8%). The third highest source region was Ulsan City, with 10 thousand tons of emissions (10.0%). Due to the petrochemical industry complex in Ulsan, combustion in the manufacturing industries sector was also the dominant source for PM_{10} emissions in this region (7 thousand tons, 76.4%).

3. 3. 6 VOCs

Solvent use was the dominant source for VOCs emissions in Korea, as described in the previous section. Gyeonggi and Seoul in SMA were the primary and secondary source regions with 162 and 91 thousand tons of emission and an 18.5 and 10.5% contribution rate to total Korean VOCs emissions, respectively. In both the Gyeonggi and Seoul areas, the solvent use sector was the dominant source (114 and 64 thousand tons; 70.5% and 70.0%, respectively), and the paint application sector was the primary source in the solvent use subsectors. In other regions, Ulsan and Gyeongnam were major VOCs source regions with 97 (11.1%) and 82 (9.4%) thousand tons of emissions, respectively. The solvent use sector was the primary source for VOCs emissions in these regions as well. The next highest VOCs source region was Jeonnam Province, with 77 (8.8%) thousand tons of emissions. Unlike the other regions, the production processes sector was the primary source with a 47.5% contribution rate to total Jeonnam VOCs emissions, followed by the solvent use sector (37.5%).

4. CONCLUSIONS

We developed CAPSS, a Korean emissions inventory system, with administrative district resolution and presented 2007 national air pollutant emissions for CO, NOx, SOx, PM_{10} and VOCs in Korea. In CAPSS, emission sources were classified into four levels. Emission factors for each classification category were collected from various domestic and international research reports, and CAPSS utilized various statistical data, compiled by around 150 organizations in Korea.

We used both direct and indirect methods for point sources depending on the available real-time emissions data (CEMS database). For the estimation of emissions from area sources, we used an indirect method utilizing various data from organizations in Korea. Total emissions from on-road mobiles sources per vehicle type were estimated by summing emissions from three subcategories, hot engine operation, cold start and fuel evaporation. Total emissions from non-road mobiles sources were estimated by summing emissions from the five sources of railways, ships, aircrafts, agricultural machinery and construction machinery.

Total 2007 air pollutant emissions for CO, NOx, SOx, PM_{10} and VOCs in Korea were estimated as 3,372,151 tons, exclusive of biogenic VOCs, fugitive dust and emissions from agricultural sources. NOx emissions occupied the largest share with 1,188 thousand tons, followed by VOCs emissions with 875 thousand tons and CO emissions with 809 thousand tons. Mobile sources, which emitted 1,582 thousand tons of the five air pollutants during 2007, were the largest sources in Korea. The next largest sources were combustion sources with 860 thousand tons of the five air pollutant emissions, followed by solvent use sources, which emitted 531 thousand tons of VOCs emissions.

Total CO emissions were 809 thousand tons, and the road transport sector was the dominant source with a 67.6% contribution rate to total emissions. Total NOx emissions were 1,188 thousand tons, and the road transport sector was the dominant source with a 41.7% contribution rate. Total SOx emissions were 403 thousand tons, and combustion in the manufacturing industries sector was the primary source with a 25.4% contribution rate. Total PM_{10} emissions were 98 thousand tons, and combustion in the manufacturing industries sector was the dominant source with a 54.1% of contribution rate. Total VOCs emissions were 875 thousand tons, and the solvent use sector was the dominant source with a 60.7% contribution rate.

Due to urbanization, SMA was responsible for 33.0% of total Korean air emissions, with 43.2% of CO emissions, 32.4% of NOx emissions and 35.6% of VOCs emissions. In regions other than SMA, the Ulsan, Chungnam, Jeonnam, Gyeongbuk and Gyeongnam areas were primary source regions for air pollutants due to power plants, petrochemical and steel industries in the region.

Although we presented 2007 national air pollutant emissions in this paper, it is important to estimate past or historical emissions to analyze emissions trends. For this, we are currently collecting relevant yearly activity data to calculate past emissions from 2000. We will apply the same methodology introduced in this paper and publish results in the near future. We have also realized that CAPSS should be improved by reflecting the emissions from biomass burning sources (e.g., open burning, charcoal kiln, charcoal broiling, etc.) and adding fugitive dust from unpaved road sources. Emissions from these sources will be included one by one through step-by-step studies in the future.

REFERENCES

Anderson, C., Augustine, S., Embt, D., Thrasher, T., Plante, J. (1997) Emission and Dispersion Modeling System (EDMS) reference manual. U.S Federal Aviation Administration, A170083, Washington, DC.

Chung, I.R., Kim, J.C., Kim, S.Y., Hwang, S.H., Lim, C.S., Lee, H.Y., Kim, K.H., Han, Y.C., Song, B.Y. (1997) A Study on the Reduction of Air pollutant Emission by Diesel Engine (I). Report of National Institute of Environmental Research, Korea 19, 333-343.

Eom, M.D., Kim, T.S., Hwang, D.J., Hong, Y.D., Kim, T. C., You, J.H., Park, Y.H., Seo, C.Y., Lee, J.T., Hwang, S.H., Jeong, I.Y., Kim, D.S., Jang, E.S., Kim, S.M., Lim, C.S., Shin, Y.H., Kim, G.H., Shin, W.G., Jung, S.Y., Kim, M.H., Jung, C.S. (1999) A Study on the Reduction of Air pollutant Emission by Diesel Engine (III). Report of National Institute of Environmental Research, Korea 21, 378-388.

European Environment Agency (EEA) (2006) EMEP/CORINAIR Emission Inventory Guidebook 2006. Technical report No 11/2006, Copenhagen K, Denmark.

Jang, Y.K., Cho, K.L., Kim, K., Kim, H.J., Kim, J. (2007) Development of methodology for esimation of air pollutants emissions and future emissions from on-road mobile sources. National Institute of Environmental Research, Incheon, Korea.

Jung, W.S., Nam, J.S., Han, S.Y., Kim, Y.K., Kwon, S.T., Park, D.S., Seo, J.W., Kim, M.H., Song, S., Oh, B.J., Pyo, Y.D., Gang, S.I., Yang, J.S., Bae, H.M. (1997) A study on the emission factors and reducing methods of air pollutants on the diesel. Korea Railroad Research Institute, Gyeonggi, Korea.

National Institute of Environmental Research (NIER) (2005a) A Study on Atmospheric Emission Inventory Development and the Estimation of Air Pollutant Emission Factors and Quantity VOLME I. Final report No 07/2005, Incheon, Korea.

National Institute of Environmental Research (NIER) (2005b) A Study on Atmospheric Emission Inventory Development and the Estimation of Air Pollutant Emission Factors and Quantity VOLME II. Final report No 07/2005, Incheon, Korea.

National Institute of Environmental Research (NIER) (2009) Annual Report of Ambient Air Quality in Korea. Incheon, Korea.

National Institute of Environmental Research (NIER) (2010) National Air Pollutant Emission Calculation Method Manual (II). Report of National Institute of Environmental Research, Korea, pp. 162-171.

Ntziachristos, L., Samaras, Z. (2000) COPERT III Computer programme to calculate emissions from road transport. European Environment Agency, Copenhagen, Denmark.

Ryu, J.H., Han, J.S., Lim, C.S., Eom, M.D., Hwang, J.W., Yu, S.H., Lee, T.W., Yu, Y.S., Kim, G.H. (2003) The Study on the Estimation of Air Pollutants from Automobiles (I) - Emission Factor of Air Pollutants from Middle and Full sized Buses. Transportation Pollution Research Center, National Institute of Environmental Research, Incheon, Korea.

Ryu, J.H., Lim, C.S., Yu, Y.S., Han, J.S., Kim, S.M., Hwang, J.W., Eom, M.D., Kim, G.Y., Jeon, M.S., Kim, Y.H., Lee, J.T., Lim, Y.S. (2004) The Study on the Estimation of Air Pollutants from Automobiles (II) - Emission Factor of Air Pollutants from Diesel Truck. Transportation Pollution Research Center, National Institute of Environmental Research, Incheon, Korea.

Ryu, J.H., Yu, Y.S., Lim, C.S., Kim, S.M., Kim, J.C., Gwon, S.I., Jeong, S.W., Kim, D.W. (2005) The Study on the Estimation of Air Pollutants from Automobiles (III) - Emission Factor of Air Pollutants from Small sized Light-duty Vehicles. Transportation Pollution Research Center, National Institute of Environmental Research, Korea.

U.S. Environmental Protection Agency (U.S. EPA) (1995) Compilation of Air Pollutant Emission Factors, Volume 1: Sationary Point and Area sources. AP-42 Fifth Edition, Research Triangle Park, NC 27711, USA.

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