Estimation of Enhancing Improvement for Ambient Air-quality during Street Flushing and Sweeping

Tai-Yi Yu[1*], Yu-Chun Chiang[2], Chung-Shin Yuan[3], Chung-Hsuang Hung[4]

[1] Ming Chuan University, Department of Risk Management and Insurance, 250 Chun Shan N. Rd. Sec. 5, Taipei 111, Taiwan

[2] Yuan Ze University, Department of Mechanical Engineering, 135 Yuan-Tung Rd., Chung-Li, Taoyuan 320, Taiwan

[3] National Sun Yat-Sen University, Graduate Institute of Environmental Engineering, 70 Lien-hai Rd., Kaohsiung 804, Taiwan

[4] National Kaohsiung First University of Science & Tech., Department of Safety Health and Environmental Engineering, 2 Juoyue Rd., Kaohsiung 811, Taiwan

Abstract

This investigation addressed the source apportionment of aerosol particles using both the receptor and dispersion models. Factor analysis and chemical mass balance (CMB) models were two receptor modeling techniques employed to categorize the possible sources in Kaohsiung district. The ISCST3 dispersion model was also used to evaluate improvements in ambient-air quality. Factor analysis revealed that road sweeping resulted in a variation of approximately 10% in the compositions of TSP and PM_{10}. The mass fractions of TSP explained by the CMB model were 60-70% before flushing, 35-37% after flushing, 71-83% before sweeping, and 80-120% after sweeping. The CMB method identified six possible sources of TSP as: combustion sources (53.2 ± 11.1%), street dust (12.4 ± 9.3%), nitrate (4.9 ± 1.2%), sulfate (2.9 ± 0.8%), sea salt (1.0 ± 0.3%), and gasoline cars (0.4 ± 0.6%). The simulation results of ISCST3 model showed that road flushing improved annual PM_{10} from 1.5-2.1% at the 11 monitoring stations operated around Kaohsiung City. After road flushing, the ratios and concentrations of TSP for street dust and combustion sources were reduced. For TSP, road sweeping increased the concentrations of street dust within 30 m downwind of the sampling sites (both sites located downwind at 5 and 30 meters); but reduced it at 200 m downwind. Factor analysis showed rates of street dust for TSP were lower than 28% before street sweeping; lower than 17% after street sweeping. The CMB model revealed that contributed rates of street dust for TSP were lower than 22% before street sweeping, and lower than 34% after street sweeping. The ISCST3 model showed air quality

*****Corresponding author. Tel.: 886-2-28824564 ext. 2328, Fax: 886-2-28809755

E-*mail address*: yutaiyi@gmail.com

improvements for PM_{10} in urban areas were greater than in industrial areas. Moreover, the maximum improvement in the annual mean PM_{10} was around 2 $\mu g/m^3$.

Keywords: Road flushing and sweeping; Factor analysis; Receptor modeling; ISCST3 model.

INTRODUCTION

Based on the monitoring results of ambient air-quality stations of the Taiwan Environmental Protection Administration (TEPA), the two dominant criteria pollutants with PSI > 100 are PM_{10} and O_3. Ozone is the secondary pollutant that undergoes complex chemical reactions and transformation, which is a relatively difficult problem to classify and efficiently control. Some particulate matter includes secondary pollutants, eventually deposited on the ground by dry/wet deposition. Statistical results of the Taiwan Emission Database System (TEDS) (TEPA 2002) demonstrated that street dust emitted from paved and unpaved roads was the largest contributor among all sources, accounting for approximately 41% of suspended particulates (PM_{10}). Hence, suspended particles are the first targets of control measures, based on monitoring results. Meanwhile, re-entrainment of dust generated by vehicles is the largest contributor of PM_{10}, so quantifying the actual effect of street washing and sweeping on PM_{10} and air quality is an important issue for abatement strategies.

According to the TSP experiments in ambient air over northern Taiwan, Chiang and Chang (1996) applied factor analysis, enhanced factor analysis, and the CMB model to separate soil (18-45%), sea salt (4-7%), diesel motors (2-8%), street dust (1-17%) and secondary aerosol (6-9%). The results of sampling $PM_{2.5-10}$ near the coastal area in southern Taiwan indicated that motor vehicles and fugitive sources were the main contributors, and sea salt, the coal-firing industry and photochemical smog were minor sources during daytime. At night, the percentage attributed to steel plants and secondary reactions clearly increased. Su *et al*. (1995) presented a near-source method for estimating various sources of PM_{10} and demonstrated that motor vehicles were responsible for 31-39%, sea salt 12-17%, secondary nitrate 4-8%, secondary sulfate 7-13% and organic carbon 3-7% of PM_{10}. Chow *et al*. (1996) conducted experiments at 10 sites in central California and found that motor vehicle accounted for 30-42%, street dust for 25-27%, and sea salt for 17% of PM_{10}. Chiu *et al*. (2001) applied the CMB7 receptor model and PM_{10} trajectory model to obtain the contributed emission sources for PM_{10} over central Taiwan. Analytic results revealed that motor vehicles and street dust are still the major sources of pollution, accounting for 35-74%; these are followed by secondary aerosol (sulfate and nitrate), accounting for 16-27%, while coal-fired power plants accounted for about 5%. However, results from the PM_{10} trajectory model demonstrated that power plants, steel plants, the fossil industry, and food plants were dominant stationary sources.

Kaiser (1958) noted that the factor analysis offset the disadvantage of principal component analysis. Since then, many studies (Ladd and Driscoll, 1980; Horel, 1981; Walsh and Richman, 1981) have shown that it functions quite well in simplifying complex problems. Eder (1989) and Eder *et al*. (1993) employed factor analysis to examine the concentration data of SO_4^{2-} in the eastern U.S., including data from 40 monitoring stations of the ADS (Acid Deposition System) from 1981 to 1986, and 77 monitoring stations of the Aerometric Information Retrieval System (AIRS) of the U.S. EPA. In separated seven and six sub-areas for 40 and 77 stations, the contributed ratios of concentrations' variance were 74.2% and 64.02%, respectively. Marcazzan *et al*. (2001) applied factor analysis to identify the four sources of elements, gaseous pollutants and mass concentration contributing to PM_{10} and $PM_{2.5}$ composition: vehicle-exhaust emissions, resuspended dust, secondary sulfates, and industrial emissions. The composition data allowed a quantification of two major components of atmospheric particulates: sulphates (mainly of secondary origin) and particles with crustal origin. Manoli *et al*. (2002) also utilized factor analysis on separate fine and coarse aerosol data for source identification and apportionment at a traffic-impacted urban site. Results revealed that the largest contribution to fine-sized aerosol is traffic (38%) followed by road dust (28%), while road dust clearly dominated the coarse size fraction (57%).

CMB model is an efficient multivariate model based on balancing the masses of the source and the receptor. It analyzes the specific composition of receptor sites by balancing the masses of chemical species and further determines the percentages associated with the sources. Used with the correct source fingerprint, the CMB model can estimate the attributed contributions in different source types at the receptor site. The CMB model has been proven to be a useful tool in estimating the attributed ratios of varied sources for airborne pollutants, including particulate matter and VOC (Lin and Milford, 1994; Conner *et al*., 1995; Fujita *et al*., 1998; Xsu and Tsai, 2001). Research studies (Tsai and Cheng, 1999; Tsuang *et al*., 2003a,b) of airborne pollutants over Taiwan using the receptor model has a nearly 15-year history, and most of them addressed aerosol and heavy-metal pollution.

Seung *et al*. (2001) demonstrated the results of $PM_{2.5}$ source apportionment using the CMB7 receptor model that secondary aerosol was, on average, the major contributor to $PM_{2.5}$ particles, followed by nontraffic organic carbon (OC) emission, agricultural waste burning, motor vehicle emission, road dust, waste incineration, marine aerosol, and others. Samara *et al*. (2003) sampled ambient PM_{10} at three sites in an industrialized urban area of northern Greece and analyzed for 17 chemical elements, 5 water-soluble ions and 13 polycyclic aromatic hydrocarbons. Chemical source profiles consisting of the same particulate components were obtained for a number of industrial activities, residential oil burning, non-catalyst and catalyst-equipped passenger cars, diesel-fueled taxis and buses, as well as for geological fugitive sources (paved road dust and soil from open lands). Results of CMB modeling showed that a major source of ambient PM_{10} at all

three sites was diesel-vehicle exhaust. Zhang *et al*. (2004) applied CMB method in Beijing to identify the sources of $PM_{2.5}$ and found that the main sources included fugitive dust, coal burning/industrial processes, traffic emissions, and secondary aerosol produced by atmospheric chemical conversion. Zheng *et al*. (2005) utilized CMB model to analyze $PM_{2.5}$ samples at 6-day intervals at five urban and rural sites simultaneously in Beijing. The major sources of $PM_{2.5}$ mass in Beijing averaged over five sites on an annual basis were determined to be dust (20%), secondary sulfate (17%), secondary nitrate (10%), coal combustion (7%), diesel and gasoline exhaust (7%), secondary ammonium (6%), biomass aerosol (6%), cigarette smoke (1%), and vegetative detritus (1%).

Besides receptor models, dispersion model was another tool used to simulate the improvement of air quality. Among the nine preferred models recommended by U.S. Environmental Protection Agency, the ISCST3 (U.S. EPA 1995) model is the most frequently used in all sectors to simulate air-quality problems. This model has been applied in various situations for regulatory modeling and solving problems associated with risk assessment. ISCST3 dispersion model cannot be generally used for particulate matter simulation due to their high gravity-deposition velocity; however, this study applied this model for the preliminary phase of estimating air quality. The ISCST3 model has been used to assess risks associated with dioxin and to evaluate concentrations from specific potential sources for sensitive receptors (Cryer and Wesenbeeck, 2001; Sullivan *et al*., 2004).

Street flushing and sweeping reduced the occurrence of dust re-entrainment by reducing the amount of dust on the road, further diminishing the emission of TSP and PM_{10}. In recent years, the TEPA has cleaned streets using street sweepers and scrubbers, mainly for public health and aesthetic reasons. The local government environmental protection organization still promotes street cleaning work, but actual improvement in air quality from cleaning away street dust is variable. This study integrated experimental and analytical results with other projects (Hung *et al*., 2003; Yuan *et al*., 2003) involved with analyses using receptor and dispersion models, evaluated the contribution of street dust to particulate matter, and quantified the effects of street sweeping and flushing on the control of suspended particles. The major objectives of this investigation were to:

1) Find the contribution ratios of street dust on particulate matter.
2) Evaluate the improved effects of street flushing and sweeping on particulate matter.
3) Quantify the improvement in ambient air-quality by street flushing and sweeping.

METHODS

Yuan *et al*. (2003) examined the influence of operating parameters on the collection efficiency of street dust with a street scrubber. This study was consulted and the improvement in pollution

by particulate matter and in air quality during street flushing and sweeping was evaluated. Street dust was sampled in metropolitan Kaohsiung (Fig. 1) with a vacuum cleaner (SANYO, Model SC-6L), and each sampling run took more than 17 minutes, ensuring at least 98% collection efficiency. The pilot road (Hung *et al*., 2003) was chosen to study the effect of street washing and street sweeping, respectively. Four sampling sites were selected 5 m upwind, and 5, 30 and 200 m downwind of the pilot road during the process of street sweeping. Two sampling sites were chosen at 5 m upwind and 5 m downwind during street flushing. The street scrubbers traveled along the streets at 10 km/hr and the water injection pressure was 2.0 k/gm^2. The air was sampled continuously for eight hours each time. Suspended particles such as TSP (KIMOTO MODEL 121 FT) and PM_{10} (VEREWA F701) were collected on-site. Ion composition, metal composition, and carbon composition analyses were utilized to determine the chemical composition of street dust and suspended particles. The anion and cation compositions were analyzed by ion chromatography (IC, Dionex Series 100).

Ten species were analyzed accordingly: F^-, Cl^-, Br^-, SO_4^{-2}, NO_3^-, NH_4^+, Ca^{+2}, Na^+, K^+ and Mg^{+2}. Inductively Coupled Plasma-Atomic Emission Spectrometry **(**ICP-AES, PERKIN ELMER PLASMA 400 ICP-AES) was used to detect 13 elements: V, Ti, Al, Cu, Ca, Cr, Fe, K, Mg, Mn, Ni. Pb and Zn. The carbon composition was analyzed using an elemental analyzer, which can measure the amount of elemental carbon and total carbon (TC) in suspended particles. The amount of organic carbon can be calculated by subtracting the amount of elemental carbon from the amount of total carbon. The elemental analyzer was a CHNS/O 1108 elemental analyzer (EA), produced by the Carlo Erba Corp., and equipped with an AS 200 pipette and a DP 700 integrator.

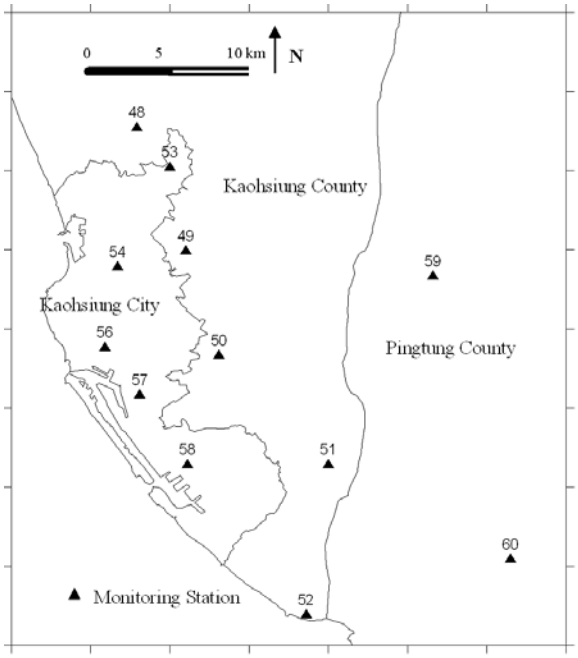

Fig. 1. Location of air-quality stations.

The following three steps were implemented to evaluate the effect of street dust on air-quality with the ISCST3 model.

1) Analyze the amount of street dust as a percentage of the amount of suspended particles. Factor analysis was used to interpret data on the composition of 26 substances collected on-site, so the contribution of different sources to suspended particles could be explained by qualitative analysis and the reference value in the CMB method.
2) Quantify the contribution of street dust to the suspended particles. The CMB model and the statistical test method enable the data on the composition of air pollutants to be used more effectively to determine the contribution of various sources to suspended particles.
3) Analyze the contribution of suspended particles to air quality. TEPA uses PSI value as an index in air-quality management plans, so it can also be used as a performance index in street flushing and sweeping. This investigation used the ISCST3 dispersion model, meteorological data, ambient air-quality data and emission data of TEDS5, to simulate the background and improvement of air quality in 2001. Yuan (2003) analyzed four samples to evaluate the reduction in the amount of suspended particles in an urban area caused by street flushing and sweeping. Results demonstrated that street washing was responsible for 11% (± 9.2) of the reduction in TSP, but 6% (± 0.48) in PM_{10}. Therefore, the reduction in PM_{10} due to street flushing is set to 6%. Accordingly, the ISCST3 model was applied to recalculate the air-quality index over 11 stations.

Factor Analysis

Principle component analysis was the alternative method used to determine the initial conditions for solving multi-variable problems. Although principle component analysis can simplify the dimensions of complex variables, it cannot always reasonably explain physical phenomena of complex principal components. Kaiser (1958) introduced the orthogonal rotation method, factor analysis, to effectively interpret the physical meaning of components. Factor analysis maximized the variance of the squared correlation coefficient of every rotating principle component, whereas the goal of the principle component method maximized the sum of the squared correlation coefficients. If the second-order moment (variance) is maximized, then the correlation coefficients will exhibit a so-called wide distribution, such that every rotating principle component has a few variables with high factor loading; whereas most variables have a factor loading of zero, such that the relationship between the rotating principle components and variables is easy to explain. The trace elements of possible sources attributing to particulate matters were another key factor in identifying the physical meaning of unknown rotated components. According to analytical results of past studies (Gordon 1988; Yaaqub *et al*., 1991; Gertler *et al*., 1995; Kubilay and Saydam, 1995; Seidl, 1998; Abonyi *et al*., 2003; Zhang *et al*.,

2004), source-caused trace elements were specified as: combustion source for As, Ni, Se and V; mobile source for Pb; secondary aerosol for sulfate and nitrate; street dust or soil for Fe, Ti, Mn and Mg; diesel vehicle for Ni; agriculture waste combustion for K, and; sea salt for Cl^- and Na^+.

Chemical mass balance method

The CMB receptor model comprises a group of solutions to a linear equation. The equation states that the concentration of chemical substances at the receptor site equals the sum of the products associated with the possible sources. The data input to the CMB model were the composition of the specific sources and the concentration at the receptor site; the output was the contribution of the sources to the overall mass. CMB is suitable for analyzing multi-species data, which most commonly involves the analysis of PM_{10}, $PM_{2.5}$ and VOC. The relationship among the concentrations of air pollutants from the various sources and receptors can be represented as Eq. (1).

$$C_i = \sum_{j=1}^{J} \alpha_{ij} F_{ij} S_j \tag{1}$$

Here, C_i represents the concentration of the i_{th} element at the receptor site; α_{ij} represents the coefficient of the synthesis or removal of the i_{th} element during the transfer; F_{ij} represents the mass ratio of the i_{th} element emitted by the j_{th} pollution source, and S_j is the contribution of the j_{th} pollution source.

Evaluating the influence of street washing and sweeping on the air quality using the dispersion model

ISCST3 is one of the preferred models that the U.S. EPA recommends. Based on the steady state Gaussian plume, it can be used in simulating regulations that govern primary or inert gas pollutants. In this research project, it was also a useful preliminary model to quantify improvements in PM_{10} concentration. The ground-level concentration at a receptor for area sources can be presented as Eq. (2), and the steps for evaluating the influence of street washing and sweeping are as follows.

$$C(x,y) = \frac{QK}{2\pi U_s} \int_x \frac{\mathrm{VD}}{\sigma_y \sigma_z} \left[\int_y \exp\left(-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right) dy \right] dx \tag{2}$$

C(x,y): concentration of pollutant downwind of position X, Y

Q: emission intensity of pollutants (mass per unit time)

K: unit conversion coefficient

V: vertical item (source's height, receptor's height or other)

D: decay term

$\sigma_x\sigma_y\sigma_z$: standard deviation in the x, y and z directions

U_s: average wind speed (m/s)

1) Simulation of background PM_{10} concentrations. The daily PM_{10} concentrations of the selected 11 air quality stations were simulated from the meteorological data and emission inventory in 2001. The PM_{10} concentrations resulting from point, mobile, and fugitive sources were calculated.
2) Correction of background air quality. The simulated values were compared to the monitored yearly mean PM_{10} concentrations at 11 measuring stations; the emission intensity of area sources was then adjusted and the total variance of the difference between the measured and simulated values was minimized for the 11 air-quality stations.
3) Analyze the contribution of street dust to PM_{10} emission with street flushing and sweeping conditions. The reduction of street dust, through street washing and sweeping, was evaluated for the improvement of the air-quality index at the monitoring stations with ISCST3 model.

RESULTS

Factor analysis (Table 1) revealed eigenvalues and explained variances for TSP and PM_{10} during street sweeping on the pilot road. The total accounted variances of the first rotated component are 50 and 51% for TSP and PM_{10} before street sweeping; 69 and 44% for TSP and PM_{10} after street sweeping. With respect to the trace elements, factor analysis could be a useful tool to yield the compositional changes of the suspended matter, PM_{10} and TSP. In this research, one rotated principal could combine several different sources identified with trace elements. If one rotated component was significantly positive correlated to specific trace element, the source identified with specific trace elements possibly could be attributed to this rotated component. According to the analytical results of TSP before street sweeping, the first principal component presented high positive loadings for Ti, K, Mg, Zn; second principal component was highly loaded on Al, TC, OC and Ca^{2+}; the third principal component was highly loaded on Ni, Na^{+}. Similarly, the results of TSP after street sweeping showed the first principal component had high positive loadings for Ti, Pb, TC, EC, OC and Ca^{2+}; second principal component was highly loaded on Al, Mn, Na^{+}, NH^{4+}, K, Mg^{2+}, SO_4^{-}; third principal component was highly loaded on Ca, Cr, K and Ni.

The factor that most strongly affected TSP before street sweeping (Table 2) was soil re-entrainment and agricultural waste combustion, which accounted for 50% of TSP. Street dust and mobile vehicles accounted for 28%, and fuel combustion and sea salt for 22%. After street sweeping, soil re-entrainment and mobile sources accounted for 69%; street dust, sea salt and secondary aerosol accounted for 17%, and fuel combustion and agricultural waste combustion accounted for 14%. These results showed that the rates of street dust accounted for were lower

than 28 and 17% before and after street sweeping, respectively.

Table 1. The factor loading of rotated principal for TSP during street sweeping.

	Before			After		
Item/component	**1**	2	3	**1**	2	3
Eigenvalues	11.6	6.5	5.0	15.3	3.7	3.0
Explained variances (%)	50.6	28.0	21.7	69.4	16.8	13.9
Ti	**0.98**	0.18	0.04	**0.97**	-0.24	-0.05
Al	0.45	**0.85**	0.27	-0.58	**0.79**	0.20
Cu	0.83	0.29	-0.49	-	-	-
Ca	0.56	0.62	0.55	-0.33	-0.02	**0.94**
Cr	-0.98	0.00	0.21	-0.45	0.25	**0.86**
Fe	-0.97	-0.06	0.25	-0.63	0.23	0.74
K	**0.90**	-0.32	0.28	-0.30	0.52	**0.80**
Mg	**0.92**	-0.11	0.38	-0.87	0.40	0.29
Mn	-0.06	-0.11	-0.99	-0.31	**0.86**	0.41
Ni	0.11	0.30	**0.95**	0.40	0.06	**0.91**
Pb	0.63	-0.77	-0.07	**0.90**	-0.24	-0.36
Zn	**0.95**	0.31	-0.06	-0.45	0.45	0.77
TC	-0.07	**0.97**	-0.23	**0.96**	-0.18	-0.20
EC	-0.05	-0.99	-0.15	**0.94**	-0.21	-0.28
OC	-0.02	**1.00**	-0.08	**0.98**	-0.16	-0.14
Na^+	-0.27	-0.42	**0.87**	-0.10	**0.98**	0.17
NH_4^+	-0.87	-0.37	-0.33	-0.43	**0.89**	0.17
K^+	-0.13	-0.76	0.64	-0.35	**0.94**	0.04
Mg^{2+}	0.77	0.03	0.64	0.07	**0.99**	0.11
Ca^{2+}	0.37	**0.92**	0.12	**0.94**	-0.33	-0.11
Cl^-	-0.70	-0.06	-0.71	-0.55	0.64	0.55
NO_3^-	-0.95	-0.05	-0.32	-0.41	0.78	0.48
SO_4^-	-0.77	-0.37	0.52	-0.24	**0.97**	0.06
Sources	AWC SR	SD MV	FC SS	SR MV	SD SS, SA	FC AWC

λ: eigenvalue, v: explained variance (%)

AWC: Agriculture Waste Combustion, FC: Fuel Combustion, SS: Sea Salt

MV: Mobile Vehicles, SD: Street Dust, SR: Soil Re-entrainment, DV: Diesel Vehicle

SA: Secondary Aerosol

Table 2. The factor loading of rotated principal for PM_{10} during street sweeping.

	Before			After		
Item/component	**1**	2	3	**1**	2	3
Eigenvalues	11.2	7.2	3.7	9.3	6.4	5.3
Explained variances (%)	50.7	32.6	16.6	44.3	30.6	25.1
Ti	-0.46	0.85	0.27	-0.90	0.17	-0.40
Al	**0.98**	0.16	-0.10	-0.39	-0.88	-0.27
Cu	-	-	-	-	-	-
Ca	0.11	**0.98**	0.19	-	-	-
Cr	-0.12	0.20	**0.97**	**0.83**	0.48	-0.30
Fe	0.19	0.74	0.65	**0.95**	0.31	0.06
K	0.72	0.35	-0.60	-0.41	-0.52	**0.75**
Mg	**1.00**	0.04	-0.04	**0.97**	-0.24	-0.03
Mn	**1.00**	-0.07	0.01	-0.40	**0.78**	0.48
Ni	**0.93**	-0.18	0.31	**0.82**	0.50	-0.27
Pb	-0.52	**0.85**	0.13	-0.84	0.48	0.24
Zn	1.00	-0.04	0.04	-0.75	0.10	-0.66
TC	0.07	1.00	0.04	**0.86**	0.46	0.22
EC	-0.80	-0.01	-0.61	-0.75	0.11	0.65
OC	0.28	**0.94**	0.20	**0.94**	0.33	-0.07
Na^+	-0.77	0.55	0.32	0.13	0.13	**0.98**
NH_4^+	0.26	-0.45	-0.85	0.31	0.04	**0.95**
K^+	-0.22	0.67	-0.71	0.16	**0.94**	-0.32
Mg^{2+}	-0.55	0.79	0.27	-0.54	0.10	-0.84
Ca^{2+}	-0.37	**0.93**	-0.07	-0.02	**0.98**	-0.22
Cl^-	0.21	**0.94**	-0.27	-0.41	0.00	**0.91**
NO_3^-	-0.95	0.06	0.30	-0.08	-0.08	**0.99**
SO_4^-	-0.83	0.52	0.21	-0.02	**0.91**	-0.41
Sources	FC, SD AWC, SR	SS MV,SR	-	FC	SA MV	SS AWC

λ: eigenvalue,ν: explained variance (%)

AWC: Agriculture Waste Combustion, FC: Fuel Combustion, SS: Sea Salt

MV: Mobile Vehicles, SD: Street Dust, SR: Soil Re-entrainment, DV: Diesel Vehicle

SA: Secondary Aerosol

The PM_{10} results (Table 3) before street sweeping demonstrated that: the first principal component presented high positive loadings for Al, Mg, Mn, Ni; second principal component was highly loaded on Ca, Pb, Ca^{+2} and Cl^{-}; third principal component was highly loaded on Cr. Similarly, the results of PM_{10} after street sweeping showed that: the first principal component was high positive loadings for Cr, Fe, Mg, Mn, TC and OC; second principal component was highly loaded on Mn, K^{+}, Ca^{+2} and SO_4^{-2}; third principal component was highly loaded on NH_4^{+}, Na^{+} and Cl^{-}. The first factor that most strongly affected PM_{10} before street sweeping, was the effect of street dust and agricultural waste combustion, which accounted for 51% of PM_{10}; sea salt, mobile vehicles and soil re-entrainment for 33%; after street sweeping, soil re-entrainment and mobile sources accounted for 69%; street dust, sea salt and secondary aerosol accounted for 17%; fuel combustion and agricultural waste combustion accounted for 14%. These results revealed that the explained rates of street dust for PM_{10} were lower than 51 and 17% before and after street sweeping, respectively. The concentrations of three substances (F^{-}, Br^{-} and V) were under detection limits, so only 23 compositions are presented in Tables 2 and 3.

Table 3. The accounted contribution of TSP sources during street flushing process via CMB method.

	position	TSP μg/m³ (%)	R^2	K^2	Sources concentration (μg/m³)					
					Sea salt	Street dust	Gasoline car	Fuel combustion	Sulfate	Nitrate
Before flushing	UW	391 (62.8)	0.99	1.65	3 (0.6)	63 (16.1)	—	150 (38.5)	11 (2.8)	19 (4.8)
	DW	418 (69.1)	0.99	1.43	4 (0.9)	73 (17.5)	—	193 (46.2)	7 (1.7)	12 (2.8)
After flushing	UW	422 (37.9)	1.00	0.93	4 (0.9)	19 (4.4)	6 (1.3)	108 (25.7)	10 (2.3)	14 (3.3)
	DW	424 (35.8)	1.00	1.14	5 (1.1)	18 (4.3)	7 (1.6)	98 (23.1)	9 (2.2)	14 (3.4)

UW: upwind; DW: downwind; R^2: R square; K^2: chi square; the number in the parenthesis presented the percentage of total mass

According to the factor analysis results, the exact explained contribution of street dust was not precisely recognized; however, the principal component containing street dust was separated and the maximum rate for street dust was decided. The process of street sweeping decreased the rate of the specific principal component containing street dust from 28 to 17% for TSP; from 51 to 17% for PM_{10}. The CMB method was applied to quantify the contribution of six possible sources (Chiang *et al*., 1993) for TSP through the process of street flushing and sweeping. The six

sources of particulate matter were recognized as gasoline vehicles, fuel combustion, sulfate, nitrate, street dust and sea salt. Before street flushing, the rate of TSP mass concentrations accounted for was about 1% for sea salt, 17% for street dust, 42% for fuel combustion, 2% for sulfate, and 4% for nitrate at the upwind and downwind sites. The mass proportion determined by CMB analysis (Table 4), was from 60 to 70% before street flushing, and from 35 to 38% after street flushing, revealing that the process of street flushing may affect the physical and chemical characteristics of suspended particles.

Table 4. The contribution of TSP sources accounted for during street sweeping process via CMB approach.

	Position	TSP	R^2	K^2	Source concentration (μ/gm^3)					
		μ/gm^3 (%)			Sea salt	Street dust	Gasoline car	Fuel combustion	Sulfate	Nitrate
Before sweeping	UW	152 (81.4)	0.99	1.13	2 (1.1)	27 (17.8)	1 (0.6)	79 (52.1)	6 (4.1)	9 (6.0)
	DW 5 m	171 (81.7)	0.99	0.97	2 (1.2)	2 (1.2)	3 (1.5)	120 (70.2)	5 (2.7)	8 (4.9)
	DW 30 m	171. (71.8)	0.99	1.34	2 (1.4)	0.3 (0.2)	—	104 (60.9)	6 (3.3)	10 (6.1)
	DW 200 m	172 (82.4)	0.99	1.11	2 (1.0)	38 (22.1)	—	88 (51.4)	5 (2.8)	9 (5.1)
After sweeping	UW	145 (109.3)	0.98	1.96	3 (1.9)	28 (19.6)	—	116 (79.8)	5 (3.7)	6 (4.3)
	DW 5 m	152 (80.3)	0.97	1.99	2 (1.3)	30 (19.8)	—	80 (52.8)	4 (2.6)	5 (3.6)
	DW 30 m	146.4 (95.2)	0.96	3.34	3 (1.7)	50 (33.8)	—	76 (52.2)	5 (3.2)	6 (4.3)
	DW 200 m	141.1 (33.8)	0.98	2.23	1 (0.7)	5 (3.3)	16 (11.3)	18 (12.8)	3 (2.0)	5 (3.6)

UW: upwind; DW: downwind; R^2: R square; K^2: chi square; the number in the parenthesis presents the percentage of total mass.

For TSP, CMB method explained six possible sources: combustion sources (53.2 ± 11.1%), street dust (12.4 ± 9.3%), nitrate (4.9 ± 1.2%), sulfate (2.9 ± 0.8%), sea salt (1.0 ± 0.3%) and gasoline cars (0.4 ± 0.6%). Based on the CMB approach, street dust and fuel combustion were two dominant sources of six possible contributors, from which a certain amount of TSP concentration was reduced through street flushing. Street flushing reduced the contribution of

street dust both at the upwind (63 to 19 μg/m^3) and downwind (73 to 18 μg/m^3) sites. Moreover, street flushing also decreased the amount of fuel combustion at the upwind (150 to 108 μg/m^3) and downwind (193 to 92 μg/m^3) sites. The process of street flushing decreased TSP concentration for street dust and fuel combustion 70% and 28% at upwind site, respectively; 75% and 49% at downwind site.

Table 5. Air quality improvement after street flushing.

	Monitoring				Simulation results after street flushing				Reducing percentage (%)			
Station	A	B	C	D	A	B	C	D	A	B	C	D
49	55.9	1	1	21	54.8	1	1	21	-2.1	0	0	0
50	76.8	15	13	34	75.2	14	12	32	-2.1	7	8	6
51	83.3	25	24	48	81.6	24	23	47	-2.0	4	4	2
52	86.0	28	24	53	84.3	28	24	53	-2.1	0	0	0
53	79.4	15	15	40	77.9	14	14	40	-2.0	7	7	0
54	69.4	3	3	18	68.0	2	1	17	-2.1	33	67	6
56	75.8	10	9	38	74.7	10	9	38	-1.5	0	0	0
57	69.3	20	20	41	68.1	17	17	38	-1.7	15	15	7
58	77.8	15	12	28	76.4	13	10	26	-1.7	13	17	7
59	74.5	7	6	43	73.2	6	5	42	-1.8	14	17	2
60	84.7	14	13	48	82.9	12	11	46	-2.1	14	15	4
Summary		153	140	412		141	127	400		8*	9*	3*

A: annual mean value of PM_{10} concentrations (μ/gm^3)

B: numbers of days with ratios of sub-PSI was greater than 100 for PM_{10}

C: numbers of days with ratios of PSI was greater than 100 and dominant pollutant was PM_{10}

D: numbers of days with ratios of PSI was greater than 100

* presented the average reducing percentages of all air-quality stations

The mass proportion explained by CMB method (Table 5) for cases before and after street sweeping ranged from 80 to 120%. Street sweeping decreased the TSP concentrations for all sampling sites: upwind (152 to 145 μg/m^3); 5 m downwind (171 to 152 μg/m^3); 30 m downwind (171 to 146 μg/m^3), and; 200 m downwind (172 to 141 μg/m^3). Before street sweeping, the explained rate of TSP mass concentrations at the four sampling sites was about 1-2% for sea salt, 0-22% for street dust, 13-80% for fuel combustion, 0-2% for gasoline car, 3-4% for sulfate, and 5-6% for nitrate. The sampling results from the four sites demonstrated that fuel combustion was the largest contributor of six sources, for conditions both before and after street sweeping. Through the process of street sweeping, the TSP concentrations from fuel combustion declined at

the downwind sites 5 m (120 to 80 μg/m^3), 30 m (104 to 76 μg/m^3), and 200 m (88 to 18 μg/m^3)., Street sweeping especially increased the mass contribution of sea salt and street dust at the sampling sites for the three upwind sites, and the 5-m and 30-m downwind sites. Perhaps street sweeping caused the effect of dust re-entrainment. However, street sweeping reduced the contribution of street dust (from 22% to 3%) at the sampling site 200 m downwind. The other four sources revealed irregular trends for the mass contribution of TSP associated with street sweeping.

The ISC3 model was employed to simulate the improvement in PM_{10} and air quality by street flushing over Kaohsiung City. This study calculated four indicators (Table 6) to assess the improvement of air-quality: annual mean value of PM_{10} concentrations, number of days with ratios of sub-PSI greater than 100 for $PM_{10,}$ number of days with ratios of PSI greater than 100 and dominant pollutant was PM_{10}, and number of days with ratios of PSI greater than 100. The improvement ratios of annual mean concentration for PM_{10} were from 1.5 to 2.1% over the 11 air-quality stations; the ratios at the monitoring station around the city center were less. The largest and smallest decreased value of TSP concentrations were located at stations 60 (84.7 to 82.9 μg/m^3) and 56 (75.8 to 74.7 μg/m^3) (see Fig. 1).

The other three indicators revealed that the monitoring stations around the industrial districts (stations 49, 52 and 53) exhibited less improvement than the city center (stations 54, 57 and 58). The industrial-area stations 49 and 52 showed 0% improvement for the three indicators. The process of street flushing reduced the total number of days for which PSI >100 fell by 3% (from 412 to 400), and the total number of days for which sub-PSI >100 over PM_{10} fell by 9% (from 140 to 127). This consequence demonstrated the effects of street flushing between industrial districts and city center. The improvement of air-quality by street flushing was more effective in city center than industrial regions.

CONCLUSION

This work analyzed the compositions of street dust and roughly evaluated the improvement in air quality due to street flushing and sweeping using three tools: factor analysis, CMB model, and the ISC3 dispersion model. With the assistance of factor analysis, the accounted rates of street dust on TSP were lower than 28% before street sweeping, and 17% after street sweeping. Analytical results of CMB model explained six sources and revealed that the explained rates of street dust for PM_{10} were lower than 51% before street sweeping, and 17% after street sweeping. Simulation of ISCST3 model showed that improvements in PM_{10} at the air-quality stations in urban areas were greater than in industrial areas. Moreover, the maximum improvement in the annual mean PM_{10} was around 2 μg/m^3. The combination of three analytical methods could be a useful measure to assess the improvement of air quality during road sweeping and flushing.

Therefore, the reduction effect elucidated here can be utilized as a preliminary reference. More accurate data on these reductions can be obtained by conducting further experiments on the speciation of particulate matter.

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