Developing Strategies for Improving Urban Visual Air Quality

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This study examined the feasibility of adopting various strategies for improving urban air quality using atmospheric visibility as an indicator. Atmospheric visibility was regularly observed twice daily with unaided eyes at two sites since November 1998 in metropolitan Kaohsiung, which was selected as the study area because of having the worst ambient air quality in Taiwan. In addition to regular observation, intensive field monitoring of atmospheric visibility and aerosol particles was conducted in January and March of 2000. Aerosol particles were sampled by using two dichotomous samplers and then analyzed for various metallic constituents, carbon content, and water-soluble ions including major anions (F^-, Cl^-, SO_4^{-2}, and NO_3^-) and cations (NH_4^+, K^+, Na^+, Ca^{+2}, and Mg^{+2}). The apportioning of emission sources to impairing atmospheric visibility was conducted with receptor models based on chemical mass balance (CMB) and principal component factor analysis (PCA). Receptor modeling results were then applied to establish multiple regression models for atmospheric visibility, chemical composition of aerosol particles, and apportioned emission sources. The multiple regression models were further used to determine strategies for improving urban visual air quality in metropolitan Kaohsiung. Receptor modeling results indicated that motor vehicle exhaust and secondary aerosols were major sources of fine particles as well as major contributors to the reduction of atmospheric visibility in metropolitan Kaohsiung. Further investigation of the chemical component of fine particles indicated that ammonium sulfate, ammonium nitrate, and elemental carbon contributed 46%, 17%, and 17%, respectively, of the atmospheric visibility logarithm. Consequently, this study concluded that the most effective strategy for improving visual air quality in metropolitan Kaohsiung is to reduce the formation of secondary aerosols containing ammonium sulfate and ammonium nitrate.

Keywords : visual air quality, atmospheric visibility, source apportionment, receptor modeling

1. Introduction

Air pollution is a major environmental issue owing to its hazardous effects on human health in most large cities. Citizens of metropolitan areas frequently complain about poor ambient air quality, particularly impaired atmospheric visibility. Since atmospheric visibility is the most noticeable manifestation of ambient air pollution and is relatively easily understood by the general public, it is a useful indicator of ambient air quality.

Atmospheric visibility is defined as the greatest distance in a given direction at which an object can be visually identified with unaided eyes (Wark et al., 1981). The object could be a dark object positioned prominently against the sky on the horizon in the daytime or a known, preferably unfocused moderately intense light source at nighttime. Generally, atmospheric visibility varies significantly with regions and seasons (Waggoner et al., 1981). Both stationary and mobile sources are thought to contribute to the impairment of atmospheric visibility (Chang, 1999). Atmospheric visibility impairment is mainly attributed to the scattering and absorption of visible light by gaseous pollutants (e.g. NO_2) as well as to suspended fine particles in the ambient atmosphere (Hodkinson, 1966; Appel et al., 1985; Grobliki et al., 1981). Atmospheric fine particles, generally characterized as secondary pollutants, are formed in an oxidizing atmospheric environment by photochemical and/or catalytic reactions. Fine particles emitted from combustion sources normally contain a higher portion of hazardous species (e.g. heavy metals and PAHs) than coarse

particles do (Brook et al., 1997). Additionally, sulfur dioxide and nitrogen oxides could also react with ammonium and moisture to form ammonium sulfate and ammonium nitrate, thus accounting for the significant impairment of atmospheric visibility.

With the rapid population growth and increasing industrialization over the past three decades, poor ambient air quality became one of the major environmental concerns of the general public in metropolitan Kaohsiung. Kaohsiung has the worst ambient air quality in Taiwan since more than 60% of Taiwan's heavy industries including oil refinery plants, petrochemical plants, iron and steel plants, cement plants, and utility power plants, are located in Kaohsiung itself or its suburbs. The annual percentage of unhealthy days, defined as a Pollutants Standard Index (PSI) value of greater than 100, was 9.34 % and 10.1% in 1999 and 2000, respectively, in metropolitan Kaohsiung (ROCEPA Home Page). Additionally, average atmospheric visibility of 9.2 kilometers with a minimum monthly average of 2.3 km was recorded by Kaohsiung Meteorology Station during 1979-1998, lower than in most large cities (Yuan et al., 1998a).

This study is a report based on a two-year project (1999-2000) sponsored by the Kaohsiung City Government to investigate the influence of ambient aerosol particles on atmospheric visibility. This study attempted to observe the temporal and spatial variation of atmospheric visibility in metropolitan Kaohsiung, correlate atmospheric visibility with the chemical composition of aerosol particles, and determine effective strategies for improving urban visual air quality.

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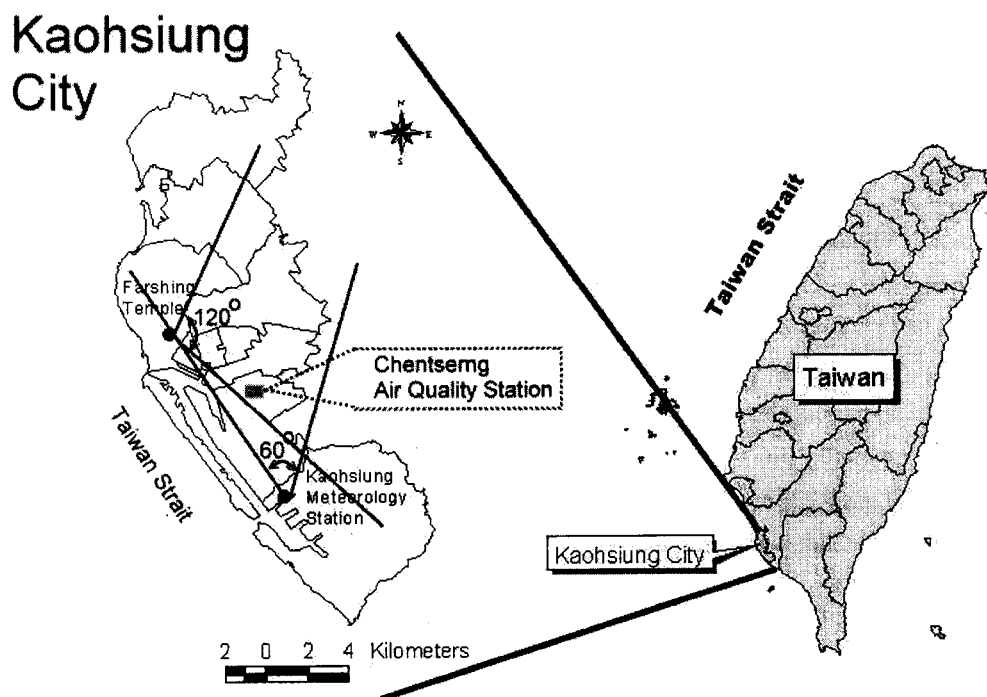E-mail ﹕ycsngi@mail.nsysu.edu.tw

2. Methodologies

Fig. 1. Location of observation sites of atmospheric visibility and sampling site of aerosols in metro Kaohsiung.

2.1 Field Observation of Atmospheric Visibility

To characterize the atmospheric visibility in metropolitan Kaohsiung, this study conducted both regular and intensive observations of atmospheric visibility. Regular observations were made to investigate the seasonal and spatial variation of atmospheric visibility, while intensive observations investigated diurnal variation of atmospheric visibility. Regular observations have been conducted twice daily at 11:00 am and 2:00 pm for almost three years since November 1998. Furthermore, two intensive observation campaigns were conducted during January 8-16 and March 24-30, 2000, and observations were taken every hour from 7:00 am to 5:00 pm during these periods.

The atmospheric visibility was visually observed without visual aids at two sites, Kaohsiung Meteorology Station and Farshing Temple, as illustrated in Fig. 1. Kaohsiung

Meteorology Station faced north with an observation angle of 60°, while Farshing Temple faced east with an observation angle of 120°. Objects were pre-identified at both sites for the observation of atmospheric visibility. The location of each pre-identified object was mapped by a global positioning system (GPS) and this GPS data was used to determine the distance from the observation site to each object with an error of roughly fifty meters. In this observation campaign, Kaohsiung Meteorology Station and Farshing Temple had 11 and 17 objects, respectively.

2.2 Sampling of Atmospheric Aerosols

To realize the influence of aerosol characteristics on atmospheric visibility impairment in metropolitan Kaohsiung, aerosol particles were simultaneously sampled during the intensive observation periods. Atmospheric aerosols were collected at Chentserng Air Quality
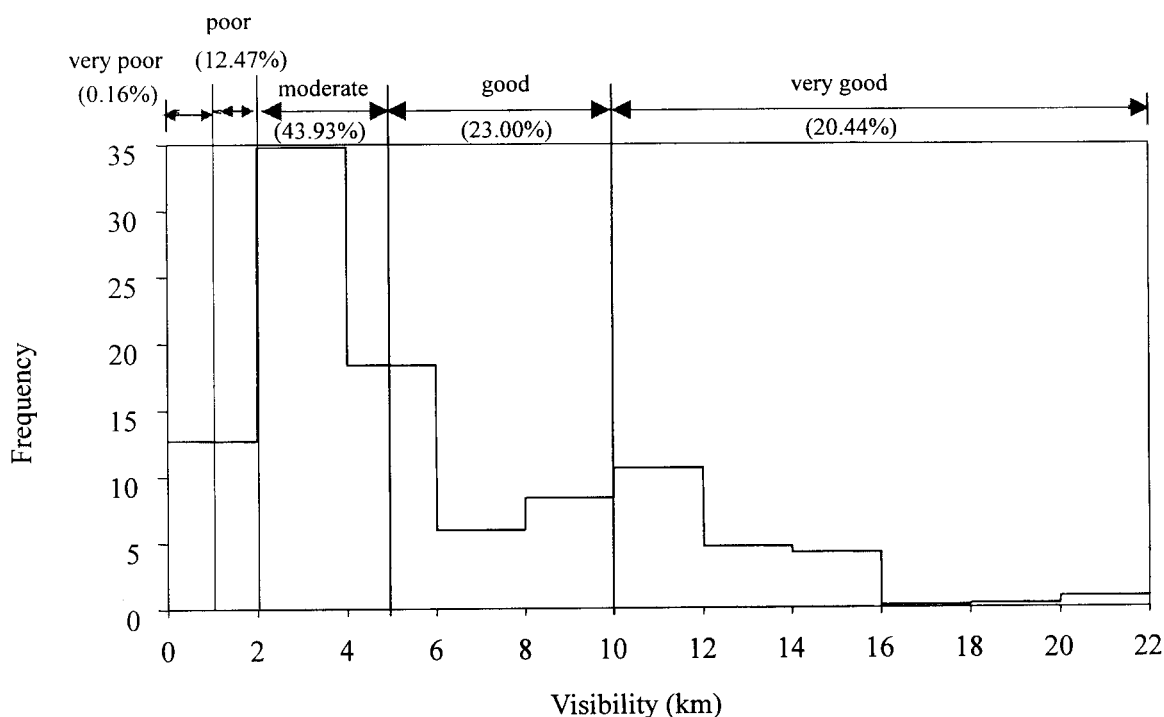
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Fig. 3. Distribution of atmospheric visibility in metro Kaohsiung.

atmospheric visibility and emission sources of aerosol particles (e.g. secondary aerosols, mobile sources, soil dust, and stationary sources) was established and validated. Meanwhile, another regression model derived from atmospheric visibility and aerosol particle chemical composition (i.e. $(NH_4)_2SO_4$, NH_4NO_3, and EC) was also established and validated. These two regression models were applied to investigate the contribution of emission sources and chemical composition to atmospheric visibility, which can then be further used to develop strategies for the improvement of atmospheric visibility in metropolitan Kaohsiung.

3. Results and Discussion

3.1 Temporal and Spatial Variation of Atmospheric Visibility

Regular observation indicated that the atmospheric visibility observed at 11:00 am and 2:00 pm in metropolitan Kaohsiung ranged from 0.7 to 20.6 km. Meanwhile, the most frequently observed atmospheric visibility ranged from 2.0 to 5.0 km and accounted for approximately 44% of the time. However, the atmospheric visibility observed in this study was lower than the previously reported monthly average of 9.2 km with a range of 2.3-23.1 km, during 1979-1998 (Yuan et al., 1998b). Generally, the atmospheric visibility observed at Kaohsiung Meteorology Station (observed along a north-south axis) was approximately 0.2-1.0 km higher than that at Farshing Temple (observed along an east-west axis). Figure 2 illustrates the monthly variation of atmospheric visibility during the investigation period from November 1998 to June 2001. A seasonal variation of atmospheric visibility was observed in metropolitan Kaohsiung. The atmospheric visibility was best in summer and worst in late autumn and winter. Furthermore, the seasonal average atmospheric visibilities in spring, summer, autumn, and winter were 5.4,

Monitoring Station, at ten-meter height on the roof of a three-story building located in center of metropolitan Kaohsiung (Fig.1). Both fine and coarse particles (i.e. $PM_{2.5}$ and $PM_{2.5-10}$) were collected by two dichotomous samplers (Anderson Model 241) with Teflon and quartz fiber filters separately. The filters were conditioned at $23\pm2°C$ and $40\pm5\%$ relative humidity for twenty-four hours before sampling. Aerosol particles were collected for a consecutive five-hour period in both the morning (7:00 am - 12:00 am) and afternoon (12:00 am - 5:00 pm) during the intensive sampling periods.

2.3 Chemical Analysis of Aerosol Particles

The chemical composition of aerosol particles collected on the sampling filters was further analyzed. Teflon filters were used to analyze metallic constituents, while quartz fiber filters were used to analyze ionic species and carbon contents. Metallic constituents of aerosol particles including Al, Ca, Cr, Cu, Fe, K, Mg, Mn, Ni, Pb, S, Si, V, and Zn were determined using X-ray fluorescence (XRF; Rigaku RIX 2000). Meanwhile, the quartz fiber filters were cut into three identical parts before analysis. Among these parts, one third of the quartz filter was extracted for analyzing water-soluble ions, while the remaining two thirds of the filter was analyzed for carbonaceous contents. Water-soluble ionic species including major anions (Cl^-, NO_3^-, and SO_4^{-2}) and cations (NH_4^+, K^+, Na^+, Ca^{+2}, and Mg^{+2}) were determined using ion chromatography (IC; Dionex Model DX100). Meanwhile, the carbonaceous contents of the aerosol particles were measured with an elemental analyzer (EA; Carlo Erba Model 1108). Before the collection of carbon samples, the quartz fiber filters were pre-heated at $900°C$ for 1.5 hours to remove impurities. This preheating

minimized background carbon in the quartz fiber filter and matrix, which can interfere with the analytical results and overestimate the carbonaceous contents of aerosol particles. The elemental analyzer was operated using the procedure of oxidation at $1020°C$ and reduction at $500°C$, with heating for fifteen minutes. Additionally, one third of the quartz fiber filters were heated in advance by hot nitrogen gas ($340-345°C$) for ten minutes to expel organic carbon fraction, after which elemental carbon (EC) was determined. Another one third of the quartz fiber filters were analyzed without heating and the carbon obtained was characterized as total carbon (TC). Organic carbon (OC) can then be estimated by extracting elemental carbon from total carbon.

2.4 Source Apportionment of Aerosol Particles

A receptor model based on principal component factor analysis (PCA) and chemical mass balance (CMB) was used to identify the probable emission sources and their apportionment of fine particles. PCA has been widely applied in previous air quality studies to explore the relationships among measured parameters (Roscoe et al., 1982), and is also employed in the source apportionment of particulate matter sampled at receptor sites (Harrison et al., 1997). This study also evaluated the experimental data set acquired during the intensive sampling periods to describe corresponding pollutant concentrations and compositions of aerosol particles in metropolitan Kaohsiung. The chemical speciated data were calculated via principal components (PCs) from the correlation matrix of chemical species concentrations of aerosol particles. The principal components are the orthogonal projections of the original inter-correlated
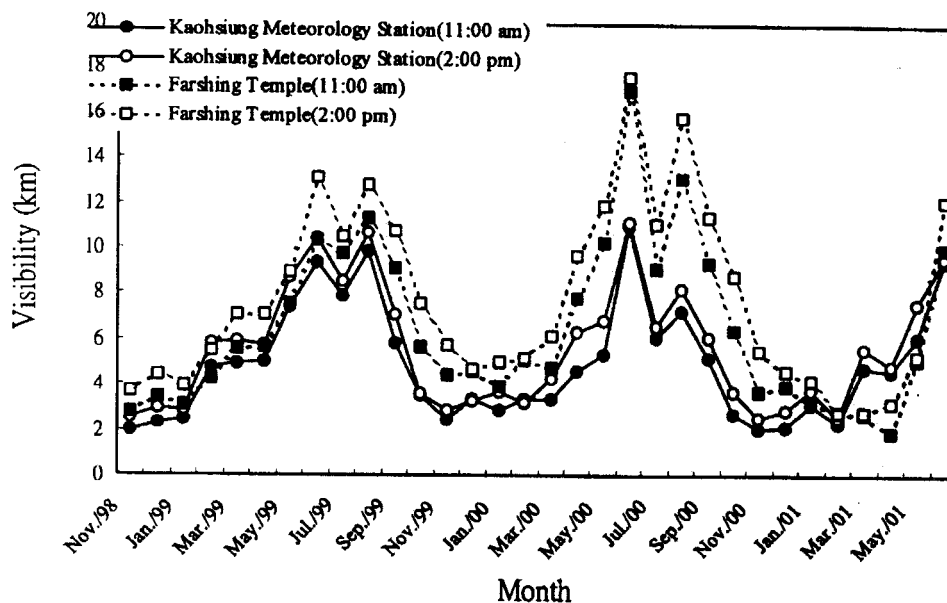
Fig. 2.   Seasonal variation of atmospueric visibility in metro Kaohsiung.

variable data matrix onto new axes in the variable-dimensional data space. PCA combines correlated variables into a common variable (or namely a component). The standardized concentrations of the chemical species can thus be expressed as a linear combination of the PC loadings and the PC scores. PC loadings denote corrections between the extracted PCs and variables. These factor loadings represent the relative influence of each parameter in determining a given component. An eigenvalue is associated with each component, and is proportional to the variance in the experimental data set accounted for by the principal component or eigenvector. This study selected principal components with eigenvalues exceeding 1.0 as probable pollution sources (Tsai et al., 1998).

The chemical mass balance based receptor model (CMB8) comprises a least-square solution to a set of linear equations. The solution expresses each receptor concentration of a chemical species as a linear sum of the products of the source profile species and source contributions. Meanwhile, the source profiles (the fraction of each species in the emissions

from each source type) and receptor concentrations, each with realistic uncertainty estimates, are used as input data for the CMB model. The model output comprises the contributions from each source type to total ambient aerosol mass and to individual chemical species concentrations (Watson et al., 1997). By referring to the previous PCA results, appropriate source profiles of fine particles were selected for this study. Most of the source profiles were originally obtained from previous studies on Taiwan (Wang, 1994; Yang, 1998), and the remainders were obtained from related researches conducted in the USA. (Watson et al., 1994; Gray et al., 1988; Chow et al., 1995) This study used 19 different source types, which can be summarized into five categories: (1) motor vehicle exhaust, (2) combustion source, (3) industrial process, (4) geological material, and (5) secondary particles.

2.5 Correlation Analysis of Atmospheric Visibility and Aerosol Particles

A multiple regression model derived from

Table 1. Comparison of aerosol compositions measured for various studies.

	Chemical compositions of aerosols in Kaohsiung ($\mu g/m^3$)					
	1st intensive (this study) (18 samples)		2nd intensive (this study) (14 samples)		Chen et at., 2001 (16 samples)	
	$PM_{2.5}$		$PM_{2.5}$		$PM_{2.5}$	
Species	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
Mass conc.	85.59	31.83	60.73	27.10	53.68	21.51
Cl^-	2.50	1.05	1.05	0.41	1.19	0.55
NO_3^-	10.41	5.39	8.75	8.24	4.88	4.39
SO_4^{2-}	12.60	6.56	11.61	4.37	6.46	2.38
Na^+	1.07	0.60	0.96	0.31	0.28	0.07
NH_4^+	13.90	7.69	7.14	3.21	3.58	1.66
K^+	0.70	0.46	0.97	0.30	0.22	0.11
Mg^{2+}	0.09	0.16	0.19	0.06	ND	
Ca^{2+}	2.10	1.20	1.46	0.64	0.24	0.03
EC	10.65	3.61	6.66	2.65	3.40	0.55
OC	11.88	3.74	8.10	3.35	6.75	2.30
Mg	0.23	0.08	0.50	0.51	NA	
Al	0.58	0.22	2.74	3.14	0.67	0.17
Si	0.95	0.34	4.71	5.09	2.91	1.30
S	10.03	3.49	6.88	6.15	NA	
Cl	1.89	1.36	0.59	1.11	NA	
K	0.76	0.27	1.42	1.33	NA	
Ca	0.35	0.15	0.85	1.21	0.55	0.39
V	0.16	0.12	0.08	0.11	0.01	0.00
Cr	0.26	0.12	0.25	0.24	NA	
Mn	0.17	0.08	0.17	0.17	ND	
Fe	0.41	0.21	1.47	1.15	0.02	0.01
Ni	0.00	0.00	0.01	0.01	0.00	0.00
Cu	0.28	0.09	0.30	0.47	NA	
Zn	0.61	0.55	0.33	0.59	0.00	0.00
Pb	0.08	0.05	0.12	0.15	0.00	0.00
Ti	NA		NA		0.20	0.06

Note: ND= not detectable

NA= not available

Table 2. Major components contributed to ambient fine particles obtained from principal component factor analysis.

Species	Component I	Component II
Cl^-	**0.80**	-0.27
NO_3^-	**0.79**	-0.12
SO_4^{-2}	**0.84**	0.06
NH_4^+	**0.91**	-0.12
K^+	-0.33	-0.11
Na^+	-0.05	-0.06
Mg^{+2}	0.01	-0.15
Ca^{+2}	-0.15	-0.21
EC	**0.81**	-0.15
OC	0.67	0.03
Al	-0.31	**0.72**
Si	-0.39	0.58
S	**0.88**	-0.04
V	0.38	-0.22
Cr	0.02	-0.10
Mn	0.13	0.25
Fe	-0.28	0.53
Ni	-0.15	**0.84**
Cu	-0.05	**0.86**
Zn	0.11	0.16
Pb	0.09	**0.80**
Eigenvalue	5.35	3.59
Percentage of variance	25.46 %	17.12 %
Probable emission sources	Secondary aerosols or crude oil boilers	Motor vehicle exhaust or soil dust

9.1, 8.2, and 3.4 km, respectively.

3.2 Establishment of Visual Air Quality Index (VAQI)

This study established a visual air quality index (VAQI) for purposes of comparison with the traditional Pollutants Standard Index (PSI) of ambient air quality in metropolitan Kaohsiung. This visual air quality index uses atmospheric visibility as a sole indicator, while the Pollutants Standard Index considers five criteria air pollutants (i.e. PM_{10}, O_3, SO_2, NO_2, and CO). Comparing atmospheric visibility observed in the field with PSI values revealed a moderate correlation between the two. Ambient air quality with a PSI value of 100 was equivalent to atmospheric visibility of approximately 4.0 km in metropolitan Kaohsiung. This study established a specific five-level visual air quality index to describe ambient air quality in metropolitan Kaohsiung. Atmospheric visibility levels ranges of <1.0 km, 1.0-2.0 km, 2.0-5.0 km, 5.0-10.0 km, and >10 km were characterized as very poor, poor, moderate, good, and very good air quality, respectively (Fig. 3). The cumulative percentage frequencies of atmospheric visibility being less than 1.0 km, 2.0 km, 5.0 km, and 10.0 km were approximately 0.16%, 14.63%, 56.56%, and 79.56%, respectively. This distribution agreed with the suggestions of previous investigator that atmospheric visibility could be used as a tentative indicator of ambient air
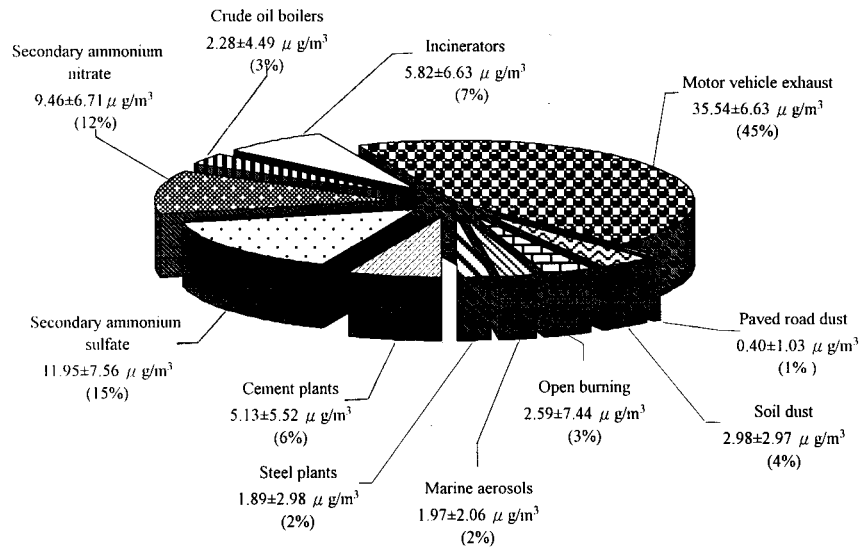
Fig. 4a. Source apportionment of fine particles sampled during the first intensive sampling period.
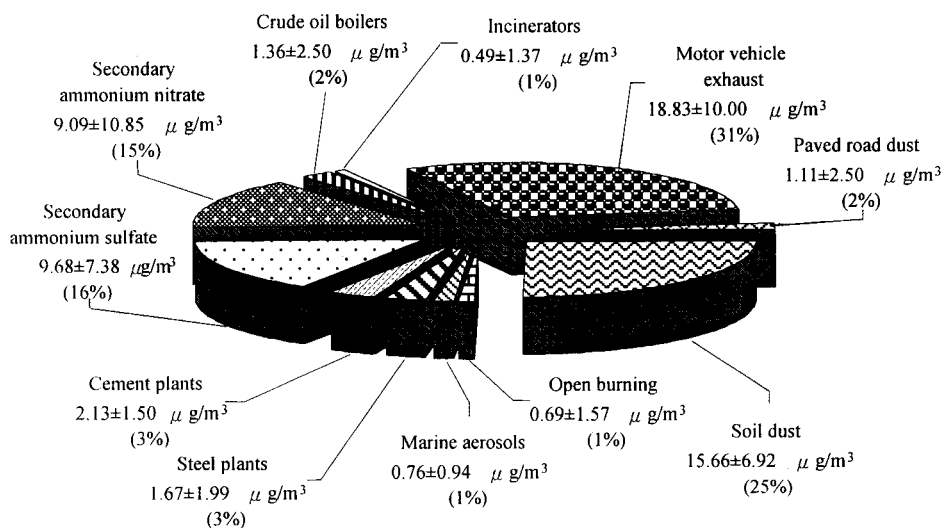

Fig. 4b. Source apportionment of fine particles sampled during the second intensive sampling period.

quality in urban areas (Jeng, 1996). The above results suggested that the ambient air quality, measured in terms of atmospheric visibility, was significantly worse in metropolitan Kaohsiung than in most large cities.

3.3 Source Apportionment of Aerosol Particles

Table 1 lists aerosol composition measurements in Kaohsiung during the two intensive sampling periods, and also compares the measurement results from this study with

those from previous studies. These data sets were then used to identify the major sources of aerosol particles using a statistic approach.

First, the results of principal component factor analysis indicated two major contributors to fine atmosphere particles in metropolitan Kaohsiung (Table 2). Among them, component I accounted for 25.46% of the variance and included Cl^-, NO_3^-, SO_4^{-2}, NH_4^+, EC, and S (factor loading > 0.7). The probable contributors to component I were secondary aerosols and crude oil boilers. Meanwhile, component II accounted for 17.12% of the variance and included Al, Ni, Cu, and Pb.

The probable contributors to component II were soil dust and motor vehicle exhaust.

Moreover, results of chemical mass balance based receptor modeling revealed that the percentage of contributors to the fine particles sampled during the first intensive sampling period were motor vehicle exhaust (35.5±6.63 µg/m³; 45%), secondary ammonium sulfate (11.95±7.65 µg/m³; 15%), secondary ammonium nitrate (9.46±6.71 µg/m³; 12%), municipal solid waste incinerators (5.82±6.63 µg/m³; 7%), cement plants (5.13±5.52 µg/m³; 6%), soil dust (2.98±2.97 µg/m³; 3.7%), open burning (2.59±7.44 µg/m³; 3%), crude oil boilers (2.28±4.49 µg/m³; 3%), and marine aerosols (1.97±2.06 µg/m³; 2%), as illustrated in Fig. 4a. The percentage of contributors to fine particles sampled during the second intensive sampling period were motor vehicle exhaust (18.83±10.00 µg/m³; 31%), soil dust (15.66±6.92 µg/m³; 25%), secondary ammonium sulfate (9.68±7.38 µg/m³; 16%), secondary ammonium nitrate (9.09±10.85 µg/m³; 15%), cement plants (2.13±1.50 µg/m³; 3%), steel plants (1.67±1.99 µg/m³; 3%), and crude oil boilers (1.36±2.50 µg/m³; 2%), as illustrated in Fig. 4b.

In summary, motor vehicle exhaust was the largest contributor to fine particles suspended in the atmosphere of metropolitan Kaohsiung, while secondary aerosols containing ammonium sulfate and ammonium nitrate were the second largest contributor. The ratio of organic carbon to elemental carbon (OC/EC) ranged from 1.33 to 3.92 for fine particles, suggesting that secondary aerosols could be formed in metropolitan Kaohsiung (Wolff, et al., 1982). Furthermore, soil dust was the third largest contributor to fine particles during the second intensive sampling period, owing to a strong continental dust storm blown from Mainland China and Mongolia in late March 2000. Soil dust contributed approximately 25.5% of fine particles during the second

intensive sampling period, compared to just 3.7% during the first intensive sampling period. The high percentage of soil dust contribution to fine particles during the second intensive sampling period indicated that soil dust blown from Northern China and Mongolia could be transported across the Yellow Sea and East China Sea and deposited in metropolitan Kaohsiung.

3.3 Emission Sources Based Improvement Strategy

A linear least-squares regression statistical approach was adopted to investigate the relationship between atmospheric visibility and major emission sources impairing visibility. Meanwhile, the STATISTICA software was used to implement this statistical approach. The multiple regression model based on the correlation among measured atmospheric visibility and likely emission sources is shown as follows,

$$L_v = -0.1249[INCIN] - 0.036[MOBIL] - 0.041[DUST] - 0.081[SOIL]$$
$$- 0.094[OPBN] - 0.152[IRON] - 0.141[CEMT] - 0.103[AMSUL]$$
$$- 0.055[AMNIT] - 0.112[BOILER] - 0.0382[SEA] + 10.239$$

(R=0.88)   (1)

where L_v denotes atmospheric visibility (km); [INCIN] represents the concentration of aerosol particles emitted from municipal solid waste incinerators (µg/m³); [MOBIL] represents the concentration of aerosol particles emitted from mobile sources (µg/m³); [DUST] denotes the concentration of aerosol particles emitted from fugitive road dusts (µg/m³); [SOIL] represents the concentration of soil dusts (µg/m³); [OPBN] is the concentration of aerosol particles emitted from open burning of agricultural wastes (µg/m³); [IRON] denotes the concentration of aerosol particles emitted from iron and steel plants (µg/m³); [CEMT] represents the concentration of aerosol particles emitted from cement plants

Seondary
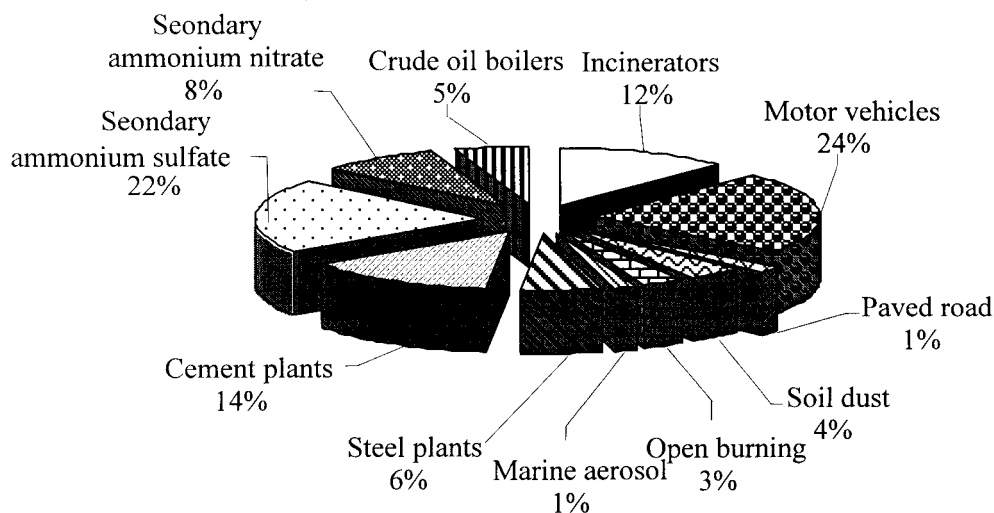ammonium nitrate   Crude oil boilers Incinerators
8%   5%   12%
Seondary   Motor vehicles
ammonium sulfate   24%
22%

                                            Paved road
                                               1%

Cement plants   Soil dust
14%   4%

        Steel plants   Open burning
          6%   Marine aerosol   3%
                    1%

Fig. 5a. The percentage of contributors to atmospheric visibility during the first intensive sampling period.

Motor vehicles
Crude oil boilers   15%
Secondary   Secondary   5%
ammonium   ammonium nitrate   Incinerators
sulfate 21%   9%   1%

Cement plants
7%

Steel plants
7%   Open burning Soil dust   Paved road
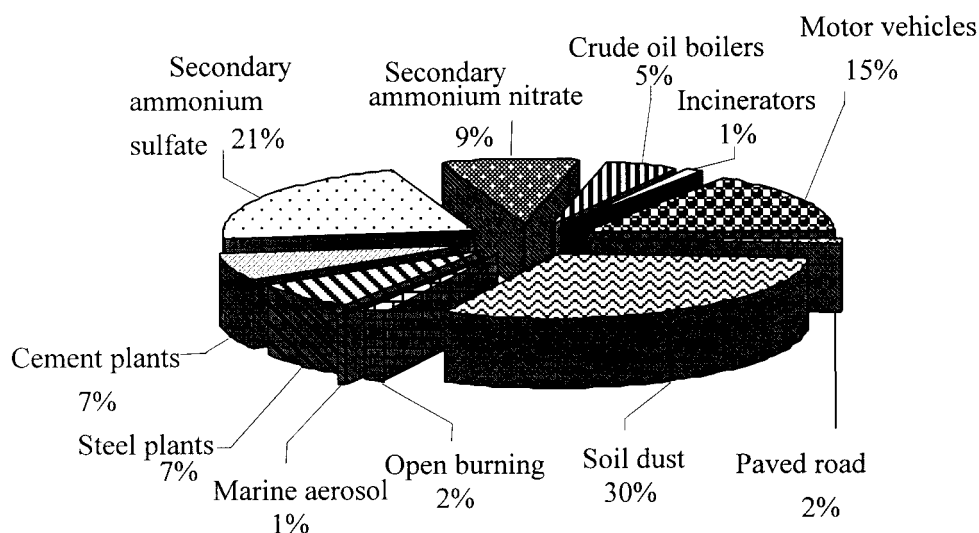Marine aerosol   2%   30%   2%
1%

Fig. 5b. The percentage of contributors to atmospheric visibility during the second intensive sampling period.

($\mu g/m^3$); [*AMSUL*] is the concentration of sulfate-containing secondary aerosols ($\mu g/m^3$); [*AMNIT*] denotes the concentration of nitrate-containing secondary aerosols ($\mu g/m^3$); [*BOILER*] represents the concentration of aerosol particles emitted from industrial boilers ($\mu g/m^3$); and [*SEA*] represents the concentration of aerosol particles emitted from sea salt spray ($\mu g/m^3$).

The multiple regression model can be further applied to determine major emission sources and

their contribution to the impairment of atmospheric visibility during the intensive observation periods. Regression modeling results indicated that, during the first intensive observation period, the major emission sources impairing atmospheric visibility were secondary aerosols (30%), mobile sources (24%), cement plants (14%), municipal solid waste incinerators (12%), steel plants (6%), boilers (5%), soil dust (4%), open burning (3%), and marine aerosols
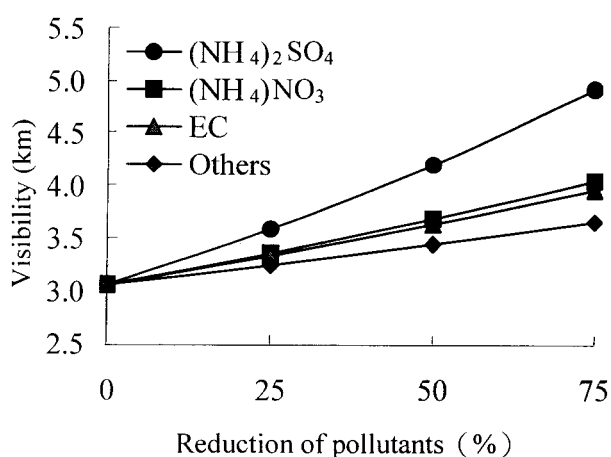
Fig. 6a. The improvement of atmospheric visibility by the reduction of chemical species during the first intensive sampling period.

Fig. 6b. The improvement of atmospheric visibility by the reduction of chemical species during the second intensive sampling period.

(1%) (Fig. 5a). During the second intensive observation period, the major emission sources were secondary aerosols (30%), soil dust (30%), mobile sources (15%), cement plants (7%), steel plants (7%), boilers (5%), open burning (2%), municipal solid waste incinerators (1%), and sea salt (1%) (Fig. 5b). The significant contribution of soil dust to poor atmospheric visibility during the second intensive observation period was attributed to the strong continental dust storm blown from Northern China and Mongolia in late March 2000. The concentration of aerosol particles increased by an average of approximately 2-3 times during the continental dust storm period.

3.4 Chemical Compositions Based Improvement Strategy

According to the correlation matrix results (Table 3), ammonium sulfate, ammonium nitrate, total carbon, and the 'remainder' are the major components that can be selected and employed as independent variables for regression analysis. The 'remainders' refers to the chemical species other than ammonium sulfate, ammonium nitrate and total carbon in fine particles. Meanwhile, the
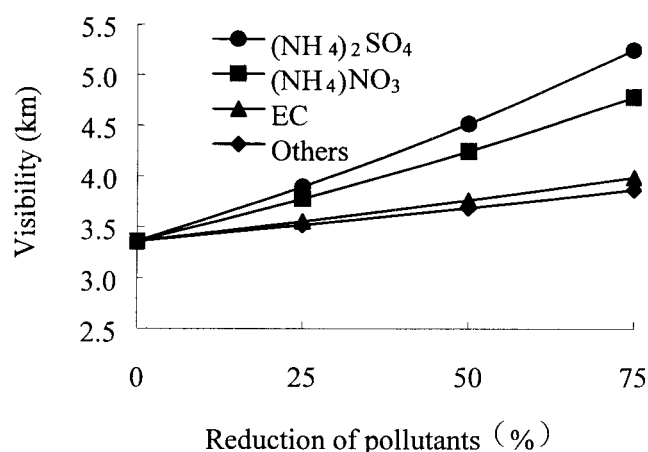
logarithm transformed visibility (logL$_v$) data is considered the dependent variable in a linear least-squares regression. The following equation can then be used to reconstruct atmospheric visibility:

$$\log L_v = \sum_i C_i M_i, \quad i = 1 \sim 4 \qquad (2)$$

where C$_i$ denotes the constant to be estimated by the regression coefficients for component i, and M$_i$ represents the total mass of component i. (NH$_4$)$_2$SO$_4$ and NH$_4$NO$_3$ are calculated by multiplying the $[SO_4^{-2}]$ and $[NO_3^-]$ by 1.3, respectively (Cass,1985). The following equation was proposed as the empirical regression model for this study:

$$\log L_v = -0.020[(NH_4)_2SO_4] -$$
$$0.0074[NH_4NO_3] - 0.0093[EC] \qquad (3)$$
$$- 0.028[Remainders] + 1.1722$$

$$(R=0.91)$$

where [(NH$_4$)$_2$SO$_4$] denotes the concentration of ammonium sulfate (=1.3x[SO$_4^{-2}$]) (μg/m^3), [NH$_4$NO$_3$] represents the concentration of ammonium sulfate (=1.3x[NO$_3^-$]) (μg/m^3), [EC]

Table 3. Correlation coefficients of determination for chemical species in ambient fine particles.

	Cl-	NO$_3$-	SO$_4$-2	Na+	NH$_4$+	K+	Ca+2	EC	OC
Cl-	1.00								
NO$_3$-	0.42	1.00							
SO$_4$-2	0.46	0.67	1.00						
Na+	0.25	-0.21	-0.07	1.00					
NH$_4$+	0.50	**0.87**	**0.94**	-0.14	1.00				
K+	0.76	0.54	0.56	-0.07	0.59	1.00			
Ca+2	0.79	0.37	0.47	0.04	0.47	**0.82**	1.00		
EC	0.61	**0.83**	0.74	-0.32	**0.84**	0.76	0.64	1.00	
OC	0.63	0.71	0.68	-0.37	0.74	0.74	0.68	**0.95**	1.00

is the concentration of elemental carbons ($\mu g/m^3$).

According to the above empirical regression model, ammonium sulfate contributed approximately 46% of the atmospheric visibility logarithm, while the 'remainders', ammonium nitrate, and elemental carbons contributed about 20%, 17%, and 17%, respectively. During the first intensive sampling period, the most effective strategy for improving atmospheric visibility was to prevent the formation of secondary aerosols containing ammonium sulfate (Fig. 6a).

Atmospheric visibility could be increased from 3.1 km to 5.0 km by reducing the concentration of secondary aerosols containing ammonium sulfate by approximately 75%. However, during the second intensive sampling period, the best strategy for improving atmospheric visibility was to prevent the formation of aerosol particles containing ammonium sulfate and ammonium nitrate (Fig. 6b). In this case, a 75% reduction of secondary aerosols containing ammonium sulfate and ammonium nitrate could increase atmospheric visibility from 3.4 km to 5.3 km. Other strategies for improving atmospheric visibility include reducing emissions from mobile and stationary sources by establishing more stringent emission standards, and establishing a network for regularly sampling and monitoring ambient fine particles and atmospheric visibility.

4. Conclusions

Source apportionment results indicated that the major contributors to fine particles were motor vehicle exhaust and secondary aerosols. Motor vehicle exhaust was the largest contributor during the intensive sampling periods, averaging 44.4% and 30.6% in Winter and Spring, respectively. Meanwhile, the second largest contributor was secondary aerosols containing ammonium sulfate and ammonium nitrate, representing 26.7% and 31.4% of fine particles in Winter and Spring, respectively. With the exception of soil dust, the relative contribution of different emission sources did not differ significantly between the two intensive sampling periods. Soil dust accounted for only 4% of fine particles during the first intensive sampling period, but increased markedly to 25% during the second intensive sampling period. The high percentage contribution of soil dust during the second intensive sampling period was mainly attributed

to a large continental dust storm. The results strongly indicated that soil dust blown from the desert areas of Northern China could be transported across the Yellow Sea and the East China Sea and evidently deposited in metropolitan Kaohsiung.

Results of multiple regression modeling based on the correlation between atmospheric visibility and emission sources revealed a similarity between the source contribution pattern for visibility impairment and the source apportionment of fine particles. With the exception of soil dust during second intensive sampling period, the major contributors to visibility impairment were secondary aerosols and mobile sources during the intensive sampling periods. According to the multiple regression model based on the correlation between atmospheric visibility and chemical composition, ammonium sulfate contributed approximately 46% of the atmospheric visibility logarithm, while 'remainders', ammonium nitrate, and elemental carbons contributed about 20%, 17%, and 17%, respectively. Based on the above discussion, this study concluded that the most effective strategy for improving atmospheric visibility in metropolitan Kaohsiung was to prevent the formation of fine particles containing ammonium sulfate and ammonium nitrate.

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