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Characterizing Particulate Matter 2.5 Concentration Pattern within a Transportation Network: A Case Study in the Port of Houston Region

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Abstract

Particulate matter 2.5 has been identified as an important contributor to the toxicity of air pollutions. Roadways are one of the major sources in an urban area. To protect the public health from the $PM_{2.5}$ pollutions, an effective monitoring system is required. Various methodology and technologies have been developed and designed to measure the $PM_{2.5}$ concentrations, which however also exist some limitations that are not easily overcome. This study is intended to propose a method to estimate and monitor the $PM_{2.5}$ concentrations in a region within a transportation network. A case study was conducted to the Port of Houston region where there are three ambient air quality monitoring stations. The $PM_{2.5}$ concentration pattern and its associated health risk were characterized to develop lookup tables of $PM_{2.5}$ concentration factors. Results showed that the majority of the average daily $PM_{2.5}$ concentrations in the Port of Houston region are lower than 10 μg/m^3, indicating the lowest PM-caused health risk. No significant difference in the trends of the $PM_{2.5}$ emission patterns collected from the three stations was observed. Two lookup tables of generalized $PM_{2.5}$ concentration factors were developed to estimate the average daily concentration in a specific time of a year in the region, which could be easily applied to a similar region for $PM_{2.5}$ monitoring.

Keywords: Average daily concentration; Particulate matter 2.5; Transportation network; Health risk assessment

Introduction

Particulate Matter (PM) is a complex mixture of extremely small particles and liquid droplets suspended in the air. The composition of PM includes various chemical components, such as heavy metals (e.g. Hg, Cd), trace metals, pesticides, sulfur dioxide, nitrogen oxides, and carbon monoxide [1-3]. Most of these chemical components have been identified as contributors to the toxicity of air pollution. What's more, these components could interact with each other, leading to higher uncertainty in assessing the adverse health effects of the PM to human beings.

Further, once inhaled, the smaller particles can penetrate the deeper into the respiratory system of human beings, resulting in more hazardous health effects. For instance, $PM_{2.5}$ can penetrate into lungs and access to bloodstream, thereby impairing lung function [4]. A number of epidemiological studies have analyzed the concentration-response relationship between ambient $PM_{2.5}$ and cardiopulmonary mortality [5-10], which are the solid evidences on its public health impacts. Besides, it can remain airborne for long periods and travel hundreds of miles. Previous epidemiologic and controlled human exposure studies have revealed that the $PM_{2.5}$ from crustal or soil or road dust, traffic, and wood smoke or vegetative burning, could cause cardiovascular mortality effects [11]. In 1987, World Health Organization (WHO) first published Air Quality Guidelines (AQG). The AQG recommends a threshold of 25 μg/m^3 and 10 μg/m^3 for 24-hr (ADC) and annual average $PM_{2.5}$ concentration (AAC), respectively, at outdoor exposure, over which significant adverse health effects may take place [12,13].

To protect the public health from $PM_{2.5}$ pollutions, an effective monitoring system is required. The United States Environmental Protection Agency (USEPA) developed a methodology called AP-42 to estimate emission factors for $PM_{2.5}$ from paved roads [14]. The methodology mainly focuses on the surface loading resulting from material's deposition on travel surface, which requires assumptions and silt-loading data collection, regardless of vehicle speed, frontal area, drag coefficient or silt reservoir depletion. These requirements substantially diminish the accuracy of emissions inventories for road emissions [15]. Besides, two vehicle-based technologies were developed to estimate paved road dust (e.g. $PM_{2.5}$ and PM_{10}), including Testing Re-entrained Aerosol Kinetic Emissions from Roads (TRAKER) and System of Continuous Aerosol Measurements of Particulate Emissions from Roadways (SCAMPER). The two technologies use an instrumented tower system to measure PM horizontal fluxes for the collection of paved road dust as it is aerosolized by driving activities. However, this mobile system measurement is limited to the PM concentrations behind the two front wheels of the test vehicle, which is a function of vehicle speed and silt loading [16].

The objective of this study is to propose a method to estimate and monitor $PM_{2.5}$ concentrations in a region within a transportation network, which is presented in the form of a lookup table of concentration factors. A case study is conducted in the Port of Houston region, the roadways of which are paved with concrete. The $PM_{2.5}$ concentrations in the region are characterized, in terms of its associated health risk level and concentration pattern. In addition, this method takes into account $PM_{2.5}$'s susceptible factors, including temperature, relevant humidity (RH), and wind speed.

Methodology

Sample collection

The Port of Houston is a 25-mile-long complex of diversified public and private facilities, which is located a few hours' sailing time from the Gulf of Mexico. There are three official $PM_{2.5}$ monitoring stations within the transportation network of the region, which are shown in Figure 1.

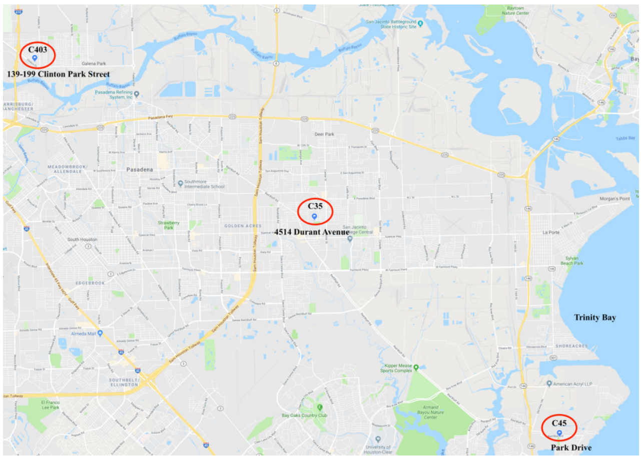

Figure 1: $PM_{2.5}$ monitoring stations in the port of Houston (Source: google map).

The three stations include Clinton C403 (Latitude: 29° 44' 1.00" North, Longitude: 95° 15' 27.00" West), Hou.DeerPrk2 C35 (Latitude: 29° 40' 12.09" North, Longitude: 95° 07' 42.63" West), and Seabrook Friendship Park C45 (Latitude: 29° 34' 58.97" North, Longitude: 95° 00' 55.96" West) in Harris county in Texas, which are maintained by the City of Houston, TMSI for the Texas Commission on Environmental Quality (TCEQ), and TCEQ Houston regional office, respectively. As shown in Figure 1, the three stations are close to the highways with varied traffic capacities. Specifically, the C403 is next to the freeway of Interstate 610 (I610), the C35 lies in the heart of the region on Clinton Park Street, and the C45 is adjacent to the Texas State Highway 146 (SH 146) and the water body of Trinity Bay. The average annual daily traffic (AADT) data for the three highways are listed in Table 1. Obviously, the traffic in C403 is the heavier, followed by C45, and then C35.

The dispersion of $PM_{2.5}$ is sensitive to metrological variables, such as wind speeds, relative humidity (RH), and temperature. The wind speeds during the measuring period in the three stations are shown in Table 1.

Comparatively, the wind speeds in station C403 is slightly higher than other two stations, and the wind speed changes in stations C35 and C45 are relatively similar to each other. Besides, the correlation coefficient R for every two sets of wind speeds for each station ranges from 0.67 to 0.75, which mean their wind speed patterns are highly positively correlated to each other.

Stations	C403	C35	C45
Minimum	0.90	0.30	0.30
Maximum	11.40	8.90	12.70
Average	3.32	2.15	2.83
Variance	4.42	2.76	4.27
Ambient Highways	I 610	Clinton Park Street	SH 146
AADT*	37,799	9,940	16,568

*Interactive Traffic Counts Search/Report [17] and Houston Regional Traffic Count Map [18]

Table 1: Wind speeds during the monitoring period at the three stations (Mil/h).

Table 2 lists the average monthly temperature and RH in Houston throughout a year, where the temperature and RH in the summer are higher than in the winter, except the stable RH level recorded in the afternoon.

Parameter	Temperature (°F)		Relative Humidity (%)	
Month	High	Low	Morning	Afternoon
Jan	17	6	85	58
Feb	19	8	86	55
Mar	23	11	87	54
Apr	26	15	89	54
May	30	20	91	57
Jun	33	23	92	56
Jul	34	24	93	55
Aug	35	24	93	55
Sep	32	21	93	57
Oct	28	16	91	53
Nov	23	11	89	55
Dec	18	7	87	57

Table 2: Average temperature and relative humidity in Houston in 2017 (Source: Current Results weather and science facts [19-20]).

The three stations monitor every five minute $PM_{2.5}$ concentrations. The average of hourly $PM_{2.5}$ concentrations in $\mu g/m^3$ is downloadable on the website of the TCEQ [21]. In this study, the $PM_{2.5}$ hourly concentrations were collected from the first of January to the fifth of December in 2017, which were preprocessed to remove invalid data, such as measure instrument errors.

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Analytical Methods

Short-term and long term particulate matter concentration analysis

Align with WHO AQG, hourly $PM_{2.5}$ concentrations were converted to an Average Daily Concentration (ADC) and Annual Average Concentration (AAC), expressed in Equation (1) and (2).

$$ADC_i = \frac{1}{24}\sum_{j=1}^{24} CONC_j \quad (1)$$

$$AAC_k = \frac{1}{24*n}\sum_{1}^{n}\sum_{j=1}^{24} CONC_j \quad (2)$$

Where

i = the i^{th} day in a year.

j = the j^{th} hour of a day.

k = the k^{th} monitoring station.

$CONC_j$ = the concentration of the j^{th} hour in a day, $\mu g/m^3$

n = number of measuring period in a year, days.

The WHO AQG, 25 $\mu g/m^3$ for ADC and 10 $\mu g/m^3$ for AAC, are adopted as the threshold for the short-and long-term $PM_{2.5}$ exposures, respectively. Exposed to the $PM_{2.5}$ at the level below the threshold, the health risk is the lowest, in terms of cardiopulmonary and lung cancer mortality. Adverse health effects can be expected, when exposed to the level greater than the thresholds.

Emission factor analysis

To investigate the trend of the $PM_{2.5}$ concentrations throughout a year in a region, a concentration factor is introduced, which is the result of real-time hourly concentration divided by its average concentration. The variation of the time series $PM_{2.5}$ concentrations is measured by Monthly (MCF), Day of Week (DWF), and Hourly Concentration Factors (HCF), which are computed by Equations (3-5).

$$MCF = \frac{1}{24*m}\sum_{1}^{m}\sum_{j=1}^{24} CONC_j / AAC \quad (3)$$

Where,

MCF = Monthly Concentration Factor.

m = number of days in a month, e.g. 31 days in January.

$$DWF = \frac{1}{24*d}\sum_{1}^{d}\sum_{j=1}^{24} CONC_j / AAC \quad (4)$$

where

DWF = Day of Week Concentration Factor

d = number of day of week in a year, e.g. 48 Tuesdays in a year.

$$HCF = \frac{1}{h}\sum_{1}^{h} CONC_j / AAC \quad (5)$$

Where,

HCF = Hourly Concentration Factor.

h = number of the particular hour in a year, e.g. 365 times of 13:00 hour in a year.

A generalized concentration factor can be calculated for the day of week in the month for an entire region, expressed by Equation (6).

$$GCF = \frac{1}{p}\sum_{k=1}^{p}\left(\frac{1}{24*\ell}\sum_{1}^{\ell}\sum_{j=1}^{24} CONC_{j,k} / AAC_k\right) \quad (6)$$

Where,

GCF = Generalized Concentration Factor.

$CONC_{j,k}$ = the j^{th} hourly concentration for the k^{th} monitoring station.

p = number of test sites in the target location, p is 3 in this case study.

ℓ =number of the day of week in the month, for example, 4 times of Tuesdays in February in 2017, ℓ is 4.

Correlation analysis

Pearson correlation coefficient can be chosen to measure the linear correlation between the ADC measured from every two stations for the year of 2017, which is signified by R, expressed by Equation (7).

$$R = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (7)$$

Where,

n = the sample size, namely the number of days collected $PM_{2.5}$ concentrations.

x_i, y_i = the single sample indexed with i.

$\bar{x}, \bar{y}$ = the sample mean of the data collected from every two stations.

The R ranges from -1 to +1 for negative and positive correlation relationship, respectively. The R closer to zero presents the lower correlation with each other.

Results and Discussion

$PM_{2.5}$ concentration distribution

$PM_{2.5}$ concentrations are susceptible for temperature, wind speed, and RH. While the wind speeds in the three stations are within a close range, the temperature and RH could slightly vary from month to month. Figure 2 illustrates the $PM_{2.5}$ concentration distribution in the three monitoring stations across twelve months in the year of 2017.

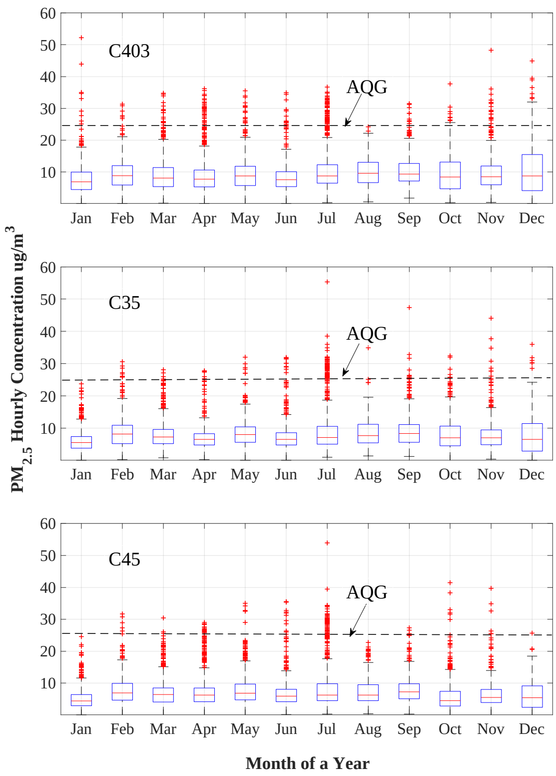

Figure 2: $PM_{2.5}$ hourly concentration distribution per month in 2017.

Though the temperature and RH could fluctuate throughout a year, the fluctuation is rarely reflected in the $PM_{2.5}$ concentration distribution in Figure 2. Monthly concentration factor analysis was conducted to further investigate the impacts of the temperature and RH on the fluctuation and presented in next section.

Besides, the majority of the $PM_{2.5}$ concentrations are distributed to 10 μg/m^3 below, and there are few samples above the AQG of 2.5 μg/m^3. Relatively, more outliers are apparent in station C403, which could be attributed to the slight higher wind speed. The heavier AADT for I610 with the highest traffic capacity next to the C403 could be one of reasons for the outliers.

Further, the hourly concentrations were converted to time series of ADC throughout the year of 2017, and plotted in Figure 3.

The three lines in Figure 3 represent the ADC trends for the three monitoring sites. Visually, the ADC trends are similar to each other. Statistically, they are highly correlated to each other for their higher correlation coefficients R (C403 vs. C45: 0.88; C403 vs. C35: 0.91; C35 vs .C45: 0.95).

Importantly, there are only three days that the ADC is higher than the AQG of 25 μg/m^3, which means the health risk is considerably low in this region for short-term exposure. Meanwhile, the AAC was estimated for the three sites as well. The AAC for the three sites are all lower than the AQG of 10 μg/m^3 for long-term exposure. The highest AAC is 9.4 μg/m^3 for C403, followed by 8.1 μg/m^3 for C35 and 7.1 for C45, which order is consistent to the AADT order for the three sites shown in Table 1. The AAC in C403 almost reaches the threshold, which implies that the wind speed and road traffic can make great contribution to the $PM_{2.5}$ concentrations in the air and its health risk levels for the population in the region.

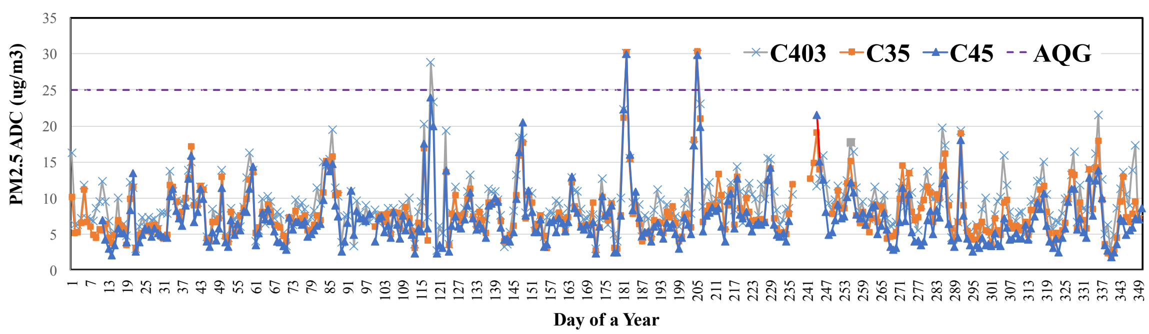

Figure 3: $PM_{2.5}$ average daily concentration (ADC) throughout a year.

$PM_{2.5}$ concentration factor analysis

Monthly concentration factor: Figure 4 shows the monthly $PM_{2.5}$ concentration factors (MCF) throughout the year of 2017 for the three monitoring sites.

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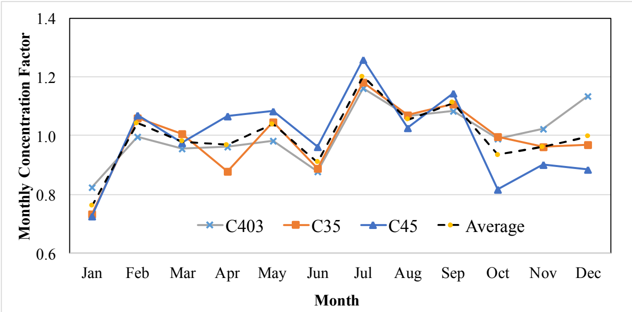

Figure 4: Monthly concentration factor (MCF) distribution.

Generally speaking, the trends of the MCFs are similar to each other. The black dash line shows the average level of MCFs for the three sites, on which the lower levels are observed in the winter, January and December, and the higher levels are apparent in the summer, July – September.

$PM_{2.5}$ concentrations are strongly correlated to ambient temperature and RH [22]. The higher temperature can promote the photochemical reaction between precursors, such as Volatile organic compound (VOC) and NO_x. Meanwhile, the RH in the three sites is proportional to the temperature shown in Table 2. Therefore, it is convinced that the higher $PM_{2.5}$ concentrations in the summer are due to the higher temperature and RH.

Day of week concentration factor: Figure 5 illustrates the day of week concentration factor (DWF) distribution throughout a week, which ranges from 0.9 to 1.10. The lowest DWF is on Monday and Tuesday, while the highest DWF is observed on Wednesday, Friday and Saturday. The DWF varieties from the AAC with only 10%, which is not considered as significant variation.

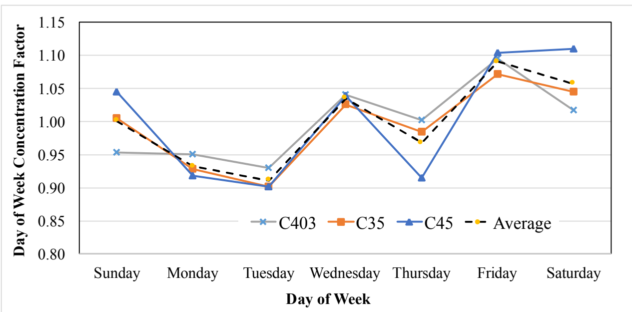

Figure 5: Day of week concentration factor (DWF) distribution.

Hourly factor analysis: The hourly concentration factors (HCF) during a day in 2017 are plotted in Figure 6 for the three monitoring stations and its average level.

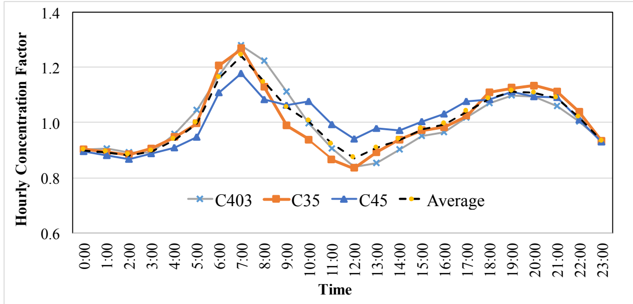

Figure 6: Hourly concentration factor (HCF) distribution.

Apparently, there are two peaks of HCF, namely between 6:00 and 9:00, and 17:00 and 21:00, the pattern of which is consistent with a typical traffic pattern for morning and afternoon peak hours. Further, the HCF in station C403 with crowded traffic drop slower than the ones with lower traffic volumes in stations C35 and C45 after the first peak. This further proves that the traffic is a determinative source of $PM_{2.5}$ concentrations in the port of Houston region.

Application of $PM_{2.5}$ concentration factors

As the $PM_{2.5}$ hourly concentration distribution and its concentration factor analysis results shown in the previous sections, there is no significant difference in the $PM_{2.5}$ concentration patterns measured from the three monitoring stations, in terms of ADC, MCF, and HCF. Therefore, a generalized concentration factor (GCF) for the Port of Houston region could be estimated by combining the ADC and MCF for the three stations, using Equation (6). As a result, seasonal and day of week concentration factors are developed and illustrated in Table 3.

Month	Day of Week						
	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Jan	0.67	0.71	0.70	0.80	0.78	0.81	0.88
Feb	1.24	1.01	0.94	0.93	1.23	0.99	0.95
Mar	0.93	1.19	0.95	1.13	0.71	0.89	1.08
Apr	0.76	0.76	0.84	1.30	0.80	1.32	0.97
May	1.24	0.73	0.81	1.20	0.95	1.10	1.29
Jun	0.71	0.84	0.97	0.66	0.88	1.32	0.86
Jul	1.34	1.53	1.33	0.82	0.82	0.96	1.43
Aug	1.05	0.93	0.88	1.13	1.38	1.09	0.84
Sep	0.99	0.97	1.08	1.06	1.01	1.38	1.17
Oct	0.92	0.73	0.76	1.21	1.14	1.03	0.83
Nov	0.91	0.89	0.97	1.18	1.00	0.96	0.77
Dec	1.32	0.69	0.65	0.68	0.87	1.09	1.64

Table 3: Seasonal and day of week generalized $PM_{2.5}$ concentration factors (GCF) for the Port of Houston region.

Time	GHCF	Month	GMCF	Day of Week	GDWF
0:00	0.90	Jan	0.76	Sunday	1.00
1:00	0.89	Feb	1.04	Monday	0.93
2:00	0.88	Mar	0.98	Tuesday	0.91
3:00	0.89	Apr	0.97	Wednesday	1.03
4:00	0.94	May	1.04	Thursday	0.97
5:00	1.00	Jun	0.91	Friday	1.09
6:00	1.16	Jul	1.20	Saturday	1.06
7:00	1.24	Aug	1.05		
8:00	1.15	Sep	1.11		
9:00	1.05	Oct	0.93		
10:00	1.00	Nov	0.96		
11:00	0.92	Dec	1.00		
12:00	0.87				
13:00	0.91				
14:00	0.94				
15:00	0.98				
16:00	0.99				
17:00	1.04				
18:00	1.09				
19:00	1.11				
20:00	1.11				
21:00	1.09				
22:00	1.02				
23:00	0.93				

Table 4: GHCF, GMCF and GDWF for the Port of Houston region.

Likewise, a generalized annual average $PM_{2.5}$ concentration (GAAC) can be obtained by averaging the AACs in the three sites, namely 8.2 μg/m^3 ((9.4+8.1+7.1) × 1/3= 8.2), which can be combined with the GCFs in Table 3 to estimate the ADC on a specific day of week in a month (e.g. Sunday of April) for a similar region. For instance, the ADC of a Tuesday in the January of 2017 is 0.7 × 8.2 = 5.74 μg/m^3.

In like manner, a generalized hourly concentration factor (GHCF), monthly concentration factor (GMCF), and day of week concentration factor (GDWF) for the three monitoring stations in the port of Houston region were calculated and shown in Table 4. The ADC for a specific day of week in a year (e.g. Tuesday of 2017), a specific time in a day (e.g. ADC at 15:00), and a specific month (e.g. ADC of March) is a result of the GAAC times the corresponding factor listed on Table 4.

Conclusion

In this study, the $PM_{2.5}$ concentrations of 2017 collected from the three monitoring stations in the Port of Houston region were characterized, in terms of its associated health risk level and concentration pattern throughout the year of 2017. The three monitoring stations are located next to the highways with varied traffic capacities in the transportation network, namely I610, Clinton Park Street, and SH146, in which the wind speeds range from 0.30 mil/h to 12.70 mil/h, and the average temperature (6-35) and RH (53% - 93%) in the summer are higher than in the winter.

In 2017, the ADCs collected from the three stations are highly correlated to each other (R ranges from 0.88 to 0.95). There are only three days that the ADC is higher than the AQG of 25 μg/m^3, and the AACs for the three stations are lower than the AQG of 10 μg/m^3. Due to the higher wind speed in station C403 next to I610, its AAC almost reach the threshold. As a whole, the $PM_{2.5}$-caused health risk in the Port of Houston region is the lowest.

Regarding concentration pattern, no significant difference in the trends of ADC, MCF, DWF, and HCF from the three stations were observed. The higher $PM_{2.5}$ concentrations were found in the summer and during traffic morning and afternoon peak hours. During a week, the concentration fluctuates slightly with 10%.

Based on the characterization results, two lookup tables of generalized $PM_{2.5}$ concentration factors were developed to estimate the ADC on a specific day of week in a month, a day of week in a year, time in a day, and a specific month. The two lookup tables could be applied to a similar region for $PM_{2.5}$ monitoring.

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