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On the Effectiveness of Emergency Reduction Measures for Ultrafine Dust Concentration in Seoul, Korea

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ABSTRACT

Since 2018, emergency reduction measures (ERMs) have been implemented by the Seoul Metropolitan Government to address air quality in Seoul, Republic of Korea. ERMs are activated when the concentration of ultrafine dust, particulate matter (PM) with an aerodynamic diameter of less than 2.5μm (PM 2.5), exceeds a certain level. In this study, using the daily time series data from 1 January 2018 to 31 June 2023, the effectiveness of ERMs is empirically analyzed by specifying multiple regression models in which PM 2.5 is explained not only by the days of ERMs but also by many other important factors. The empirical analysis shows that (i) PM 2.5 is influenced by its own past values up to three days; (ii) PM 2.5 is negatively influenced by both rainfall and wind speed, but positively related to temperature, humidity and yellow dust. The effect of PM 2.5 from the neighborhood (Dailan, China) is significantly positive; (iii) the effect of vehicle traffic volume and coal thermal power generation on PM 2.5 is not statistically significant; (iv) the effect of ERMs is not very strong when many important control variables are included in the regression equation. In conclusion, the ERMs do not play an effective role in reducing PM 2.5 over the whole period. However, it can be seen that the effectiveness of the ERMs has been increasing in recent years.

Introduction

Since 2018, emergency reduction measures (ERMs) have been in place to reduce air pollutants from vehicles, factories, and construction sites. The main aim of the measures is to reduce ultrafine and/or fine particulate matter in the short term to protect the health of the citizens. ERMs are active when the concentration of ultrafine particulate matter (PM) with an aerodynamic diameter of less than 2.5μm (PM 2.5) exceeds a certain level. The Seoul Metropolitan Government's air quality information website explains the need for ERMs as follows: "ERMs are short-term strong measures to reduce the concentration of particulate matter when the concentration of particulate matter is high, and it is necessary to reduce domestic sources as much as possible to mitigate the rapid increase of particulate matter even when high concentrations of particulate matter are imported from China and other countries." It is therefore very important to recognize the scope for reducing domestic sources. The greater the scope, the more you can reduce, while the smaller the scope, the less you can reduce. Metropolitan area-wide ERMs are issued when one of the following conditions is met in two or more cities or provinces in the metropolitan area (Seoul, Incheon, and Gyeonggi) as of 17:00 pm on the same day:

The mean PM 2.5 concentration exceeds 50 μg/m^3 between 00:00 and 16:00 on the same day and/or the 24-hour mean concentration is forecast to exceed 50 μg/ m^3 the following day.

PM 2.5 advisory or warning is issued for at least one of the warning zones between 00:00 and 16:00 on the same day, and/or the 24-hour mean concentration is forecast to exceed 50 μg/ m^3 for the next day.

The 24-hour average concentration of PM 2.5 is forecast to exceed 75 μg/ m^3 for the following day.

In response to the challenge of particulate matter pollution, a comprehensive set of measures has been implemented to reduce emissions in various sectors. Table 1 shows measures to reduce particulate matter from transport, workplaces, construction sites, street cleaning, exposure reduction, heating, and others. The measures to reduce particulate matter developed and adopted by the government reflect a multi-faceted approach to reducing air pollution. Notably, these measures include nationwide restrictions on Class 5 vehicles, which coincide with the closure of parking facilities associated with administrative and public institutions in Seoul. These measures aim to reduce vehicle emissions, which are a major contributor to particulate matter in the air. In addition, targeted regulations in the workplace environment - reducing the use of emission equipment - exemplify a nuanced strategy to minimize dust generation. These efforts are complemented by initiatives to improve road cleaning practices, the use of fire engines to spray water on roads, and the introduction of protective measures for sensitive populations, including a ban on outdoor events and the recommendation of temporary closures of educational institutions. These measures are complemented by efforts to conserve energy and the increased enforcement of vehicle emissions and unauthorized parking.

Table 1. Fine Dust Reduction Measures

	Fine Dust Reduction Measures
Transportation	Class 5 Vehicle Restrictions (Nationwide) Two-part vehicle system for government administrative and public institutions in Seoul Closure of parking lots of government and public institutions in Seoul and the banning on driving public and employee vehicles
Workplace	Reducing utilization rates for atmospheric emission plants (types 1-3)
Construction Sites	Shorten/adjust construction time at construction sites generating dust scattering
Road Cleaning	Enhancing the cleanliness of major highways and general roads Utilizing fire trucks for street water spraying
Exposure Mitigation	Protecting vulnerable people from fine dust Prohibiting outdoor events Recommendation to close or suspend daycare centers, kindergartens, and schools
Heating	Energy reduction, including compliance with proper heating temperature of buildings
Others	Enforcement of special crackdowns on workplaces and construction sites generating fine dust Strengthen crackdown on automobile emissions and idling Strengthen crackdown on illegal parking Inspection of parking lots

The implementation of ERMs is a positive step for public health, but there is no specific information on how much the measures will reduce PM 2.5. There is also skepticism that domestic measures to reduce PM 2.5 may not have much impact, as most of the PM 2.5 come from neighboring China. On the other hand, there are those who believe that active domestic measures to reduce even a small part of the large increase in particulate matter can be effective in reducing particulate matter.

The purpose of this study is to analyze the effectiveness of emergency reduction measures by using daily data on PM 2.5, meteorological data, traffic volume in Seoul, coal thermal power generation, and PM 2.5 concentrations in Dalian, China, to investigate how much room there is to reduce PM 2.5 on days when emergency reduction measures are implemented through a multiple regression analysis. Using hourly data from days when the emergency measures were taken into action, we will also analyze whether there is a reduction in PM 2.5 from 6am to 9pm, when the measures are actually in place.

Literature Review

It is not very clear whether the main factors responsible for the high concentrations of PM 2.5 in Seoul are from domestic sources or from foreign sources. Previous studies have produced mixed results. The Korea National Institute of Environmental Research (2019) reports that the impact of domestic factors on PM 2.5 in the Seoul metropolitan area is greater than that of foreign factors. The results of the Cooperative Domestic Air Quality Survey (KORUS-AQ) show that domestic, Chinese, and North Korean sources explain 52%, 34%, and 9%, respectively, of ultrafine particulate matter in Korea. However, the survey was conducted in May and June 2016, so the results may be different in winter, when heating demands are higher. There is also a number of other opinions that emphasize China as a source of influence on the high concentration of PM 2.5 in Korea. When high concentrations of particulate matter occur in Korea, the contribution of domestic and foreign sources varies from case to case, and the foreign factor, such as China, is very high at 69-82% in certain periods (Korea National Institute of Environmental Research, 2019).

A number of studies have analyzed the causes of domestic ultrafine particulate matter considering various domestic and foreign factors (Lee et al., 2012; Kim et al., 2016; Oh et al., 2017). Park and Shin (2017) conducted a monthly panel analysis by adding wind direction as an explanatory variable, and found that the concentration of ultrafine particles in the Shandong Province had a significant effect on the concentration of ultrafine particles in South Korea.

On the other hand, Kim and Kim (2019) analyzed that it takes 12 to 30 hours for PM 2.5 particles originating from China to reach Seoul. This makes it difficult to reflect these characteristics in the analysis using monthly data. Therefore, they use daily data to analyze the correlation between particulate matter in Beijing and Tianjin and particulate matter in Seoul, including the variable of wind direction. Kim (2019) discusses the influence of fine dust concentration in China on fine dust in Korea, and shows that the westerly wind direction is the main factor.

In this study, I consider all the variables mentioned in the previous studies mentioned above. In the regression model, westerly wind direction and PM 2.5 concentration level in Dailen, China are considered as Chinese sources. And I also consider many meteorological variables and domestic policy variables such as total traffic volume and coal thermal power generation variables. In addition, this study uses not only monthly data but also hourly data to investigate the effectiveness of ERMs in Seoul, Republic of Korea.

Data

The dataset consists of daily ultrafine particulate matter (pm25), mean temperature (temp, Celsius), precipitation (rain, mm), mean wind speed (wind, m/s), westerly wind direction (wind_dum1), mean humidity (moist, %rh), solar radiation (sun, MJ/m2), sum of observed traffic volume in Seoul (traffic_mil, in millions), daily coal thermal power generation in Incheon (coal_thou, thousand MWh), ultrafine particulate matter concentration in Dalian, China (china), date of ERMs (act_s), yellow dust occurrence (yellowsand) for the period from January 1, 2018 to June 31, 2023. For the traffic_mil and coal_thou series, data beyond 2022 are not available. These provide a total of 2007 and 1642 observations, respectively. The PM data of Seoul and Dailen are obtained from Air Korea (https://www.airkorea.or.kr/web) and Chinese Environmental Protection Administration (https://www.aqistudy.cn/historydata), respectively. All meteorological data is obtained from Korea Meteorological Administration (http://www.climate.go.kr/home/).

The variables wind_dum1, act_s and yellowsand are dummy variables: wind_dum1 equals 1 if the wind is westerly or 0 otherwise; act_s equals 1 if the ERM is implemented on that day or 0 otherwise; yellowsand equals 1 if yellow dust occurs on that day or 0 otherwise.

Table 2 summarizes the descriptive statistics of the variables. The sample mean of PM 2.5 (pm25) is 21.47 µg/m³ with a standard deviation of 14.58 µg/m³. This means that PM 2.5 is highly dispersed, which is also confirmed by its range 133. The sample mean of ERMs (act_s) is about 0.02, which implies that the sum of days for ERMs is less than 40 (0.02*2,007=40.14. Exact number of days is 36). More than half of the average wind direction in Seoul is between southwest and northwest. The PM 2.5 concentration in Dailen (China) is much more variable than in Seoul. This is confirmed by its standard deviation of 25.05 and range of 243.

Table 2. Descriptive Statistics for the Variables.

	pm25	act_s	rain	sun	temp	moist
Mean	21.47	0.02	3.64	14.23	13.19	61.5
Median	18	0	0	13.52	13.8	61.4
Max	135	1	176.2	31.19	33.7	99.3
Min	2	0	0	0	-14.9	17.9
S.D.	14.58	0.13	13.04	7.23	10.49	15.15
Skew	2.05	7.26	5.84	0.21	-0.28	0.08
Kurt	10.41	53.77	46.39	2.14	2.09	2.56
Obs.	2007	2007	2007	2007	2007	2007
	wind	wind_dum1	yellowsand	traffic_mil	coal_thou	china
Mean	2.16	0.51	0.02	8.91	88.61	29.57
Median	2.1	1	0	9.15	92.21	22
Max	6	1	1	10.55	118.32	243
Min	0.6	0	0	0.17	45.99	0
S.D.	0.69	0.5	0.14	1.02	18.34	25.05
Skew	0.98	-0.03	7.06	-1.66	-0.2	2.75
Kurt	4.72	1	50.84	9.85	1.83	14.12
Obs.	2007	2007	2007	1642	1642	2007

Notes: This table presents mean, median, maximum (Max), minimum (Min), standard deviation (S.D.), skewness (Skew), kurtosis (Kurt), and the number of observations (Obs.).

Figure 1 shows the trends and variations of the time series variables. PM 10 is added to Figure 1 for comparison. The PM 10 denotes particulate matter with an aerodynamic diameter of less than 10 µm. As can be seen, although the degree of fluctuation of PM 2.5 and PM 10 is different, they share quite a similar pattern. Almost all meteorological variables have a strong seasonality. Therefore, it is very important to take into account the seasonality when analyzing the influence of ERMs on PM 2.5.

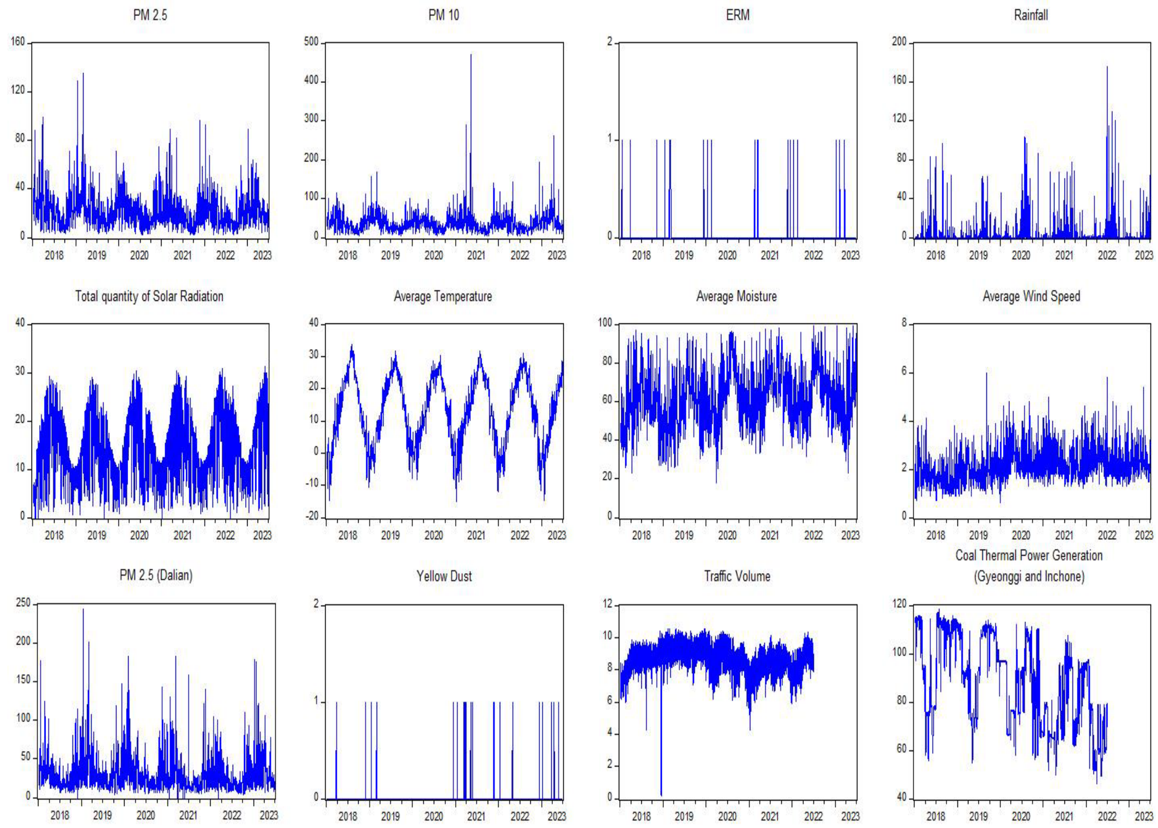
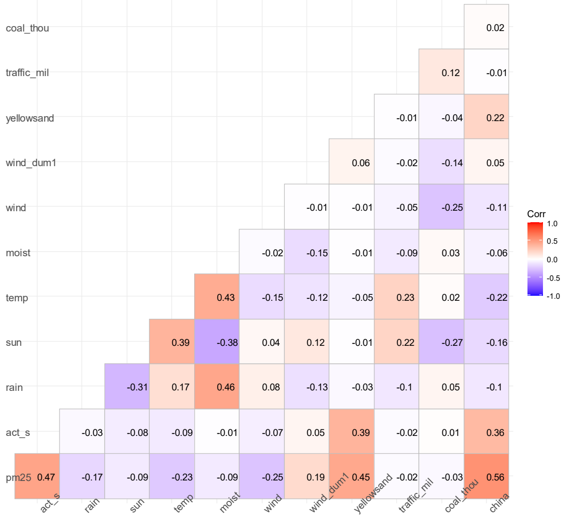


Figure 1. Trends and Fluctuations of the Time-Series Variables



	act_s	rain	sun	temp	moist	wind	wind_dum1	yellowsand	traffic_mil	coal_thou	china
coal_thou											0.02
traffic_mil										0.12	-0.01
yellowsand									-0.01	-0.04	0.22
wind_dum1								0.06	-0.02	-0.14	0.05
wind							-0.01	-0.01	-0.05	-0.25	-0.11
moist						-0.02	-0.15	-0.01	-0.09	0.03	-0.06
temp					0.43	-0.15	-0.12	-0.05	0.23	0.02	-0.22
sun				0.39	-0.38	0.04	0.12	-0.01	0.22	-0.27	-0.16
rain			-0.31	0.17	0.46	0.08	-0.13	-0.03	-0.1	0.05	-0.1
act_s		-0.03	-0.08	-0.09	-0.01	-0.07	0.05	0.39	-0.02	0.01	0.36
pm25	0.47	-0.17	-0.09	-0.23	-0.09	-0.25	0.19	0.45	-0.02	-0.03	0.56

Figure 2. Sample Correlation Estimates

Figure 2 shows the estimated correlation between the variables. The concentration of PM 2.5 in Seoul is strongly and positively correlated with the date of ERM implementation, the occurrence of yellow dust, and the concentration of PM 2.5 in Dailen, China. As can be seen, act_s is positively correlated with yellowsand and china, and their estimated sample correlations are 0.39 and 0.36, respectively. This is quite natural since yellowsand and china are the main factors that can increase the concentration level of PM 2.5 in Seoul. One thing to note is that even though the sample correlation between pm25 and act_s is high, it does not necessarily show the pure correlation between the variables. In order to see the pure correlation between these two variables, the effect of other variables should be controlled.

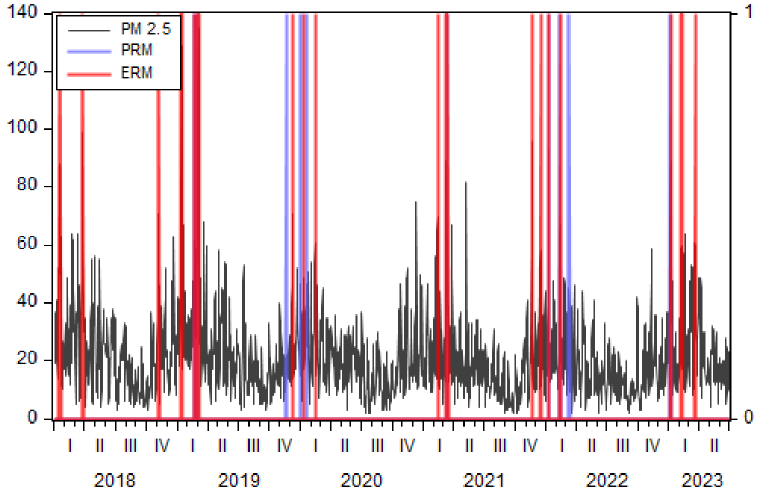


Figure 3. Concentration of Ultrafine Dust and dates of ERM implementation

Figure 3 shows the concentration of ultrafine dust and the dates of ERM implementation. It can be clearly seen that the ERMs were triggered when the PM 2.5 concentration was high. In addition, in some cases the ERMs were in effect for only one day, while in others they were in effect for two or three consecutive days.

Empirical Model and Estimated Results

Linear Multiple Regression Model

The main difficulty in analyzing the effectiveness of the ERMs is that we cannot observe the particulate matter that would have occurred if the ERMs had not been implemented, although we can observe the particulate matter on the day the ERMs were implemented. Technically, it can be analyzed by comparing it with particulate matter in other areas where the ERM was not implemented at that time (for example, Busan and Gwangju). However, the concentration of particulate matter is very localized, so it is difficult to assume that the concentration of PM 2.5 in these areas would be similar to that in Seoul without ERM. Therefore, in this study, we use the following full regression model to examine the extent to which ultrafine dust can be reduced:

$$
\begin{aligned}
pm25_t = \beta_0 + \sum_{i=1}^{4} \rho_i \, pm25_{t-i} + \beta_1 \, act\_s_t + \beta_2 rain_t + \beta_3 sun_t + \beta_4 \, temp_t + \beta_5 \, moist_t + \beta_6 \, wind_t \\
+ \beta_7 wind\_dum1_t + \beta_8 \, yellowsand_t + \beta_9 \, traffic_t + \beta_{10} \, coal_t + \beta_{11} china_t \\
+ \sum_{i=1}^{11} \delta_i D_{it} + u_t,
\end{aligned}
$$

where D_{it} are monthly dummy variables from January to December, with the baseline variable set to July, and u_t is the error term. As can be seen in Figure 1, the inclusion of seasonal dummy variables helps to account for the seasonal effect of PM 2.5. In the above model, the PM at time t can be influenced by the past PM at times $t-1$, $t-2$, $t-3$, and $t-4$. To investigate the scope for reducing PM 2.5 by some domestic policy variables during the period of ERMs, we consider four regression models: (i) M0: This model includes all independent variables except the act_s, so that it explains the behavior of PM 2. 5 without ERMs; (ii) M1: the PM 2.5 is explained only by the variable act_s; (iii) M2: this model includes all independent variables including act_s but important policy variables of ERMs, traffic and coal; (iv) M3: this model is a full model that includes all independent variables with act_s. By comparing the estimation results of these 4 models, one can infer the effectiveness of ERMs in reducing PM 2.5 in Seoul. The models are estimated using the usual least squares estimation method.

Estimation Results

Table 3 summarizes the estimation results of the linear regression models. The t-values are calculated using the robust standard errors proposed by Newey and West (1987). The results of M0 show that PM 2.5 in Seoul is determined by meteorological variables, policy variables, and seasonality. First, PM 2.5 is found to be serially correlated in the sense that the lagged values of PM 2.5 significantly affect the current PM 2.5. As rainfall and wind speed increase, PM 2.5 decreases significantly, which is not surprising. In addition, PM 2.5 is positively influenced by solar radiation, humidity and yellow dust. The westerly wind direction and the concentration of PM 2.5 in Dalian have statistically significant positive effects on the concentration of PM 2.5 in Seoul. This confirms the results of Kim et al. (2018) and Oh et al. (2020) that China's contribution to PM 2.5 in Seoul is very large. An important and unusual observation is that the amount of total observed traffic in Seoul and the amount of coal-fired power generation in the Incheon-Gyeonggi region have no significant effect on PM 2.5 in Seoul. There are very strong monthly effects on PM concentration. In particular, the effects of February and January are very pronounced compared to those of other months. It turns out that the model fits the data relatively well, as R2 is 0.718, which means that 71.8% of the variation of PM 2.5 in Seoul is explained by the independent variables.

The estimation results of M1 show that the ERM variable has a statistically significant positive effect on PM 2.5 (51.74). This means that the average difference between days with and without ERM is 51.74. From this result, we can see that the ERMs are implemented when the concentration of PM 2.5 is high. At the same time, this difference suggests that there is a lot of room for further reduction of PM 2.5 in Seoul. The results of M1 can be compared with those of M2, which includes all independent variables except policy variables (controllable policy variables: total observed traffic volume in Seoul and coal power generation). It shows that the results of M2 are very different from those of M1. When all variables except domestic variables (controllable policy variables) are set under control, the estimated regression coefficient of ERMs decreased to 7.15. This means that when meteorological variables, China-related variables, and seasonality are considered to be control variables, the coefficient estimate of ERMs is reduced to 7.15, which is small given that the difference in M1 is 51. This implies that the variables of these three categories explain a large part of the difference in PM 2.5 between days with and without ERMs (51.74).

M3 is a full model that includes all the independent variables of M2 with the domestic variables (controllable policy variables: total observed traffic in Seoul and coal power generation). From the estimation results, we can see that the inclusion of these two variables increases the explanatory power of the model by only 0.1%, and they are statistically significant at all. In addition, it can be seen that there are limitations in trying to reduce PM 2.5 using domestic variables through ERMs, since the estimated coefficient of ERMs is 7.23, which is very close to that of M2, 7.15. Thus, from these results we can say that policies to reduce PM 2.5 by reducing traffic or coal thermal power generation are less effective.

Table 3. Estimation Results of the Multiple Regression Models

	M0		M1		M2		M3	
Variables	Coef.	t-value	Coef.	t-value	Coef.	t-value	Coef.	t-value
Constant	-7.09*	-2.02	20.90**	63.55	-1.67	-0.70	-6.92*	-1.98
act_s			51.74**	21.61	7.15**	3.98	7.23**	4.02
PM 2.5(-1)	0.58**	25.73			0.55**	23.83	0.55**	23.79
PM 2.5(-2)	-0.27**	-10.45			-0.27**	-10.57	-0.27**	-10.60
PM 2.5(-3)	0.11**	4.41			0.11**	4.38	0.11**	4.33
PM 2.5(-4)	-0.04	-1.91			-0.04	-1.89	-0.04*	-1.99
rain	-0.11**	-5.41			-0.11**	-5.43	-0.10**	-5.39
sun	0.14**	2.99			0.12**	2.74	0.14**	2.97
temp	0.26**	4.08			0.28**	4.38	0.27**	4.32
moist	0.14**	6.83			0.13**	6.45	0.14**	6.75
wind	-4.46**	-14.44			-4.48**	-14.81	-4.40**	-14.28
wind_dum1	1.52**	3.63			1.53**	3.68	1.58**	3.80
yellowsand	25.07**	15.28			23.36**	13.87	23.42**	13.91
traffic	0.26	1.19					0.25	1.17
coal	0.02	1.27					0.02	1.40
china	0.11**	11.92			0.11**	11.32	0.11**	11.14
January	16.29**	7.80			16.28**	7.89	16.84**	8.08
February	17.17**	8.71			17.15**	8.87	17.78**	9.03
March	13.44**	8.10			13.11**	8.32	13.89**	8.39
April	9.74**	6.97			9.51**	7.30	10.15**	7.28
May	6.35**	5.39			6.19**	5.57	6.71**	5.70
June	3.69**	3.49			3.43**	3.42	3.86**	3.67
August	-0.60	-0.58			-0.60	-0.59	-0.69	-0.67
September	-0.75	-0.70			-1.01	-0.94	-0.91	-0.86
October	2.79*	2.19			2.74*	2.18	2.95*	2.33
November	9.59**	6.01			9.93**	6.27	10.12**	6.35
December	14.25**	7.16			14.32**	7.31	14.82**	7.46
R^2	0.718		0.222		0.720		0.721	
$\bar{R}^2$	0.714		0.221		0.716		0.716	

Notes: This table presents coefficients (Coef.), t-value. *, **, and *** denote significance at 10%, 5%, and 1%, respectively. The standard errors for calculating t-value are robust standard errors of Newey and West (1987).

Trends in Ultrafine Particulate Matter Using Hourly Data

The above regression analysis is based on monthly data. Monthly data do not allow us to observe the effect of ERMs within a day. In order to see the hourly impact of ERMs within a day, we use hourly data in this subsection.

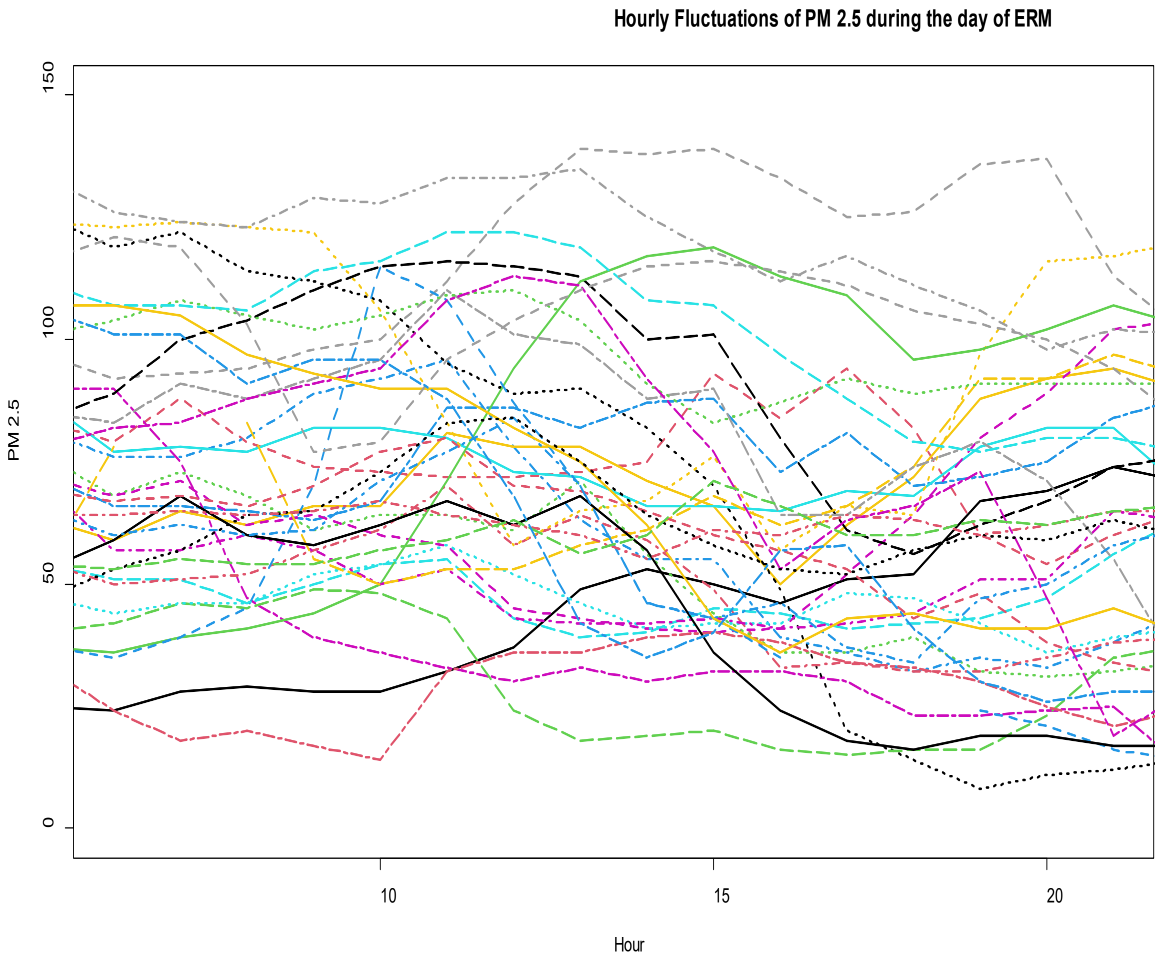


Figure 4. Hourly trend of PM 2.5 on the day of the ERM

Figure 4 shows the hourly (18:00 - 21:00) trend of PM 2.5 concentration levels on 36 emergency mitigation action days from January 1, 2018 to June 30, 2023. We can see a slight downward trend in some of the PM 2.5 concentrations, but overall there is not a very clear downward trend.

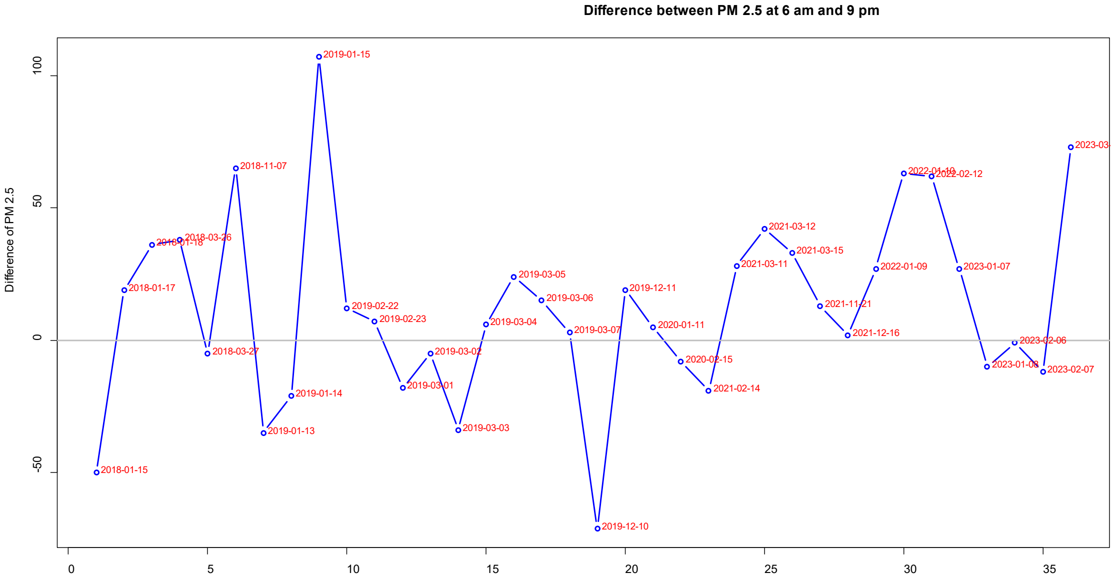


Figure 5. Difference in PM 2.5 on 36 ERM days

Figure 5 shows the difference in PM 2.5 concentration from 18:00 (start time) to 21:00 (end time) on the 36 days of emergency reduction measures. Since this is a simple difference without controlling for any variables, we believe that the reduction due to the ERMs is likely to be smaller than the difference shown above. For the ninth measure (January 15, 2019), the difference is over 100, which may be influenced by the fact that this is the third day of the measure. The sample mean of these differences is 12.14. While this is probably an overestimate of the actual effectiveness of the emergency measures, it still does not show a significant reduction in PM 2.5. However, the difference has been increasing in recent years, suggesting that it is becoming more effective.

Conclusion

Using daily data, it is found that the concentration of PM 2.5 in Seoul is found to be influenced by its own past values up to three days. It is negatively influenced by rainfall and wind speed and positively influenced by insolation, temperature, humidity, and yellow dust. It is also strongly influenced by the westerly wind direction and PM 2.5 from Dalian, China. Yet, the effects of domestic traffic and thermal coal power generation are not statistically significant.

When none of the variables were under control, the difference between the concentration of PM 2.5 on days when ERMs were in place and days when they were not is approximately 51. However, when the meteorological, Chinese, and seasonal factors were placed under control, the difference drops to 7. This suggests that reducing domestic traffic and coal-fired power generation with ERMs has little potential to reduce PM 2.5 in Seoul, Korea.

Using hourly data from 36 ERM days, we found that the reduction of PM 2.5 is not very significant. This magnitude is expected to be smaller under controlled circumstances. However, it is evident that the effectiveness of ERMs has increased in recent years.

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