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Role of passenger cars and taxies in air pollution of Tehran, Iran

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ABSTRACT

Air Pollution is one of the significant problems in Tehran. Understanding the role of different sources can result in better decision-making. Some pollutions are not emitted directly from sources and are present in the atmosphere due to chemical reactions. Therefore, using air quality modeling can be beneficial to our understanding of these phenomena. An air quality modeling system was used first to model the base case of ambient pollution. Then, the emissions of passenger cars and taxis were omitted separately to determine the role of their contribution to air pollution. The modeling results showed an acceptable performance with the index of agreement of 0.84 and 0.61 for ozone and particle matter (PM), respectively. The accumulated contribution of passenger cars and taxis to PM AQI was 14 units. However, their role in ozone formation was complex.

1) Introduction

Particulate Matters smaller than 2.5 µm ($PM_{2.5}$) have been known as a major wintertime pollutant in Tehran, Iran [1-2]. Also, in recent years, Ozone (O_3) has become the dominant pollutant in the summertime. Although the number of polluted days, due to $PM_{2.5}$, decreased over the past eight years, the number of polluted days due to O_3 has increased significantly (Figure 1).

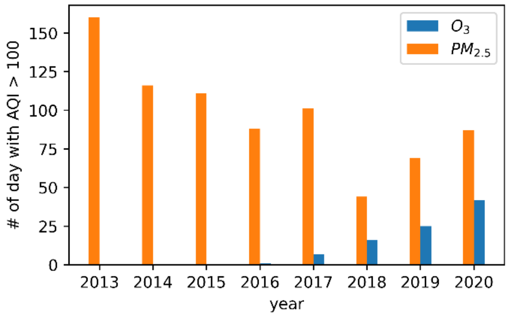

Figure1: Number of days with AQI higher than 100 due to O_3 and $PM_{2.5}$ over the past eight years

High $PM_{2.5}$ concentration would result in adverse health problems and economic costs [3-4]. A study showed that reducing annual PM2.5 concentrations to 10 µg/m3 could have had economic benefits up to USD 1.9 billion [3]. Health costs due to global O_3 pollution are estimated to be USD 580 billion by 2050, and its related mortalities will exceed 2 million, a study showed [5]. Regional contribution to O_3 increased from 2017 to 2018. However, this contribution decreased in 2019. Also, high O3 concentrations were not observed in 2019, while this phenomenon was observed in 2017 and 2018. A study showed that this abnormality in the observations was linked to the change in the O3 production regime [6].

$PM_{2.5}$ primary sources have been known to be vehicles [7]. However, studies showed that other sources, such as mineral PM, contribute to Tehran's pollution even during the wintertime [8]. On the other hand, O_3 is a secondary pollutant that forms from atmospheric reactions under the required conditions[9].

O_3 precursor species are mainly Nitrogen oxides (NO_x) and Volatile Organic Compounds (VOC, which are part of Hydrocarbons). Due to high reactivity under high temperatures during summer, a series of complex atmospheric reactions lead to the formation of tropospheric O_3 alongside smog [9]. It should be noted that some part of the $PM_{2.5}$ air pollution results from atmospheric reactions, known as secondary organic aerosols (SOA). NO_x and sulfur oxides (SO_x) are part of the SOA precursor species. As a result, $PM_{2.5}$ was not mainly emitted directly from the sources [10].

Air quality modeling is an effective method to be conducted before any controlling action to avoid unnecessary costs. This study is aimed to find the contribution of passenger cars and taxis to Tehran's air pollution. To do so, Tehran's emission inventory alongside state-of-the-art atmospheric models was used to determine their role in Tehran's $PM_{2.5}$ and O_3 pollution.

2) Main Body

2-1) Study domain

Tehran is the capital of Iran, located in the south of the Alborz mountains, and faces the flat plain from the south. (Figure 2).

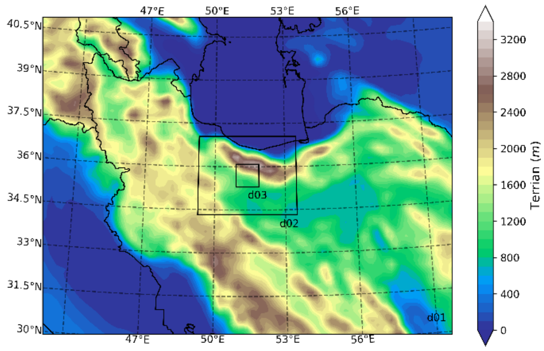

Figure 2: Three nested domain topographies

2-2) Model Configuration

The state-of-the-art (WRF3.9.1), the non-hydrostatic, Eulerian numerical weather prediction (NWP) model [11], was used to provide meteorological fields to drive the chemical transform model (CTM). The US EPA's CMAQ5.3.2 model was used, which simulates different pollutants' chemistry, transport, and deposition processes [12]. The US EPA's SMOKE model was used to convert Tehran's emission inventory to hourly speciated emissions with spatial and temporal patterns [13]. The WRF-SMOKE-CMAQ modeling system is applied in an offline paradigm.

The topography of used three nested domains is shown in Figure 2. The physic parameterization of the WRF model was summarized in Tables 1-2 for wintertime and summertime, respectively.

The WRF domain configuration is summarized in Table 3. Aerosol module v6 (AE06) and regional atmospheric chemistry mechanism v2 (RACM2) were used for the CMAQ model configuration.

Figure 3: The study domain. Mehrabad station is shown as a placemark without any mark. Air monitoring stations are shown as placemarks with marks

Table 1: Wintertime WRF configuration

Microphysics	New Thompson [14]
Radiation	(Short-wave) RRTMG [15] (Long-wave) RRTMG
PBL	MYJ [16]
Surface layer	Eta
Land surface	Noah [17]
Urban physic	SLUCM [18]
Cumulus	Tiedtke [19]

Table 2: Summertime WRF configuration

Microphysics	New Thompson
Radiation	(Short-wave) Dudhia [20] (Long-wave) RRTM
PBL	YSU [21]
Surface layer	MM5 [21]
Land surface	Noah
Urban physic	SLUCM
Cumulus	Grell-Devenyi [22]

Table 3: WRF domain configuration

Horizontal Spacing	d01: 18km (90×70) d02: 6km (64×52) d03: 2km (46×46)
Time Step	d01:108s, d02:36s, d03:12s
BC & IC	GFS (0.5° every 6 hour)

CMAQ's initial condition (IC) and boundary condition (BC) of the second domain were used from the Mozart model's outputs [23]. The EDGAR emission inventory [24] was used for the second domain as an input for the SMOKE model. CMAQ's IC and BC of the third domain (Tehran) were extracted from CMAQ's output of the second domain. Tehran Emission inventory (provided by the Iran Department of Environment) was used for the third domain and processed into the SMOKE model. Emission inventory of vehicle fleets was updated using the IVE model. A total of 24 hours of spin-up was used to simulate the pollutants. The system model was run for 3 days in summer and 3 days in winter, so the effect of different weather conditions can be investigated.

2-3) Observation datasets

Temperature and wind speed were extracted from Mehrabad synoptic station for the WRF model validation. Seventeen air quality monitoring stations were selected to validate the performance of the CMAQ model. Mehrabad synoptic station and air quality monitoring stations are shown in Figure 3.

2-4) Base case and scenarios

The default configuration, as mentioned previously, was used as the base model (BASE). For First Scenario (SE1), the emissions of passenger cars were eliminated from the hourly emissions input, and for Second Scenario (SE2), the emissions of Taxis were eliminated from the hourly emissions input.

Since the model had some uncertainties due to BC, considered emissions, meteorology field, etc., we used the observed daily air quality index (AQI) as the base condition (Equation 1). Then by using Equation 2, we determined the contribution of taxis and passenger cars to the air pollution of Tehran.

$$AQI(\bar{C}) = AQI_{\min} + \frac{\bar{C} - C_{\min}}{C_{\max} - C_{\min}} \times \Delta AQI \quad (1)$$

$$AQI_{SE} = AQI[\bar{C}_{observe} - (\overline{BASE - SE})] \quad (2)$$

Where C_{min}, C_{max}, and AQI_{min} are, according to Table 4, $\bar{C}_{observe}$ is the daily average concentration of air quality monitoring station, $\overline{BASE - SE}$ is the daily average concentration of base model minus scenario model.

Table 4: Required parameters to calculate AQI

AQI	$PM_{2.5}$	O_3 (1 hr)	O_3 (8 hr)
0 - 50	0-12	-	0-54
51 - 100	12.1-35.4	-	55-70
101- 150	35.5-55.4	125-164	71-85
151-200	55.5-150.4	165-204	86-105
201-300	150.5-250.5	205-404	106-200
301-400	250.5-350.5	405-504	-

3) Results and Discussion

3-1) Model validation

The WRF model showed acceptable performance during both the summer and winter seasons. The model captured the diurnal temperature patterns at 2 meters (T_2) in both summer and winter times with the Pearson correlation of 0.92 and 0.96, respectively. However, the model underestimated the T_2 during the summer with a mean squared error (MSE) of 2.7°C. In comparison, the T_2 MSE of the WRF model during the winter was 1.5 °C. The Pearson correlation of wind speed at 10 meters ($Wind_{10}$) for summer and winter seasons were 0.36 and 0.26, respectively. The reason that the Mehrabad station reports the wind speed rounded could be the reason for this result. Also, observational $Wind_{10}$ below two ms^{-1} is reported with 0 ms^{-1} (Figure 4). Overall performance of the WRF was acceptable.

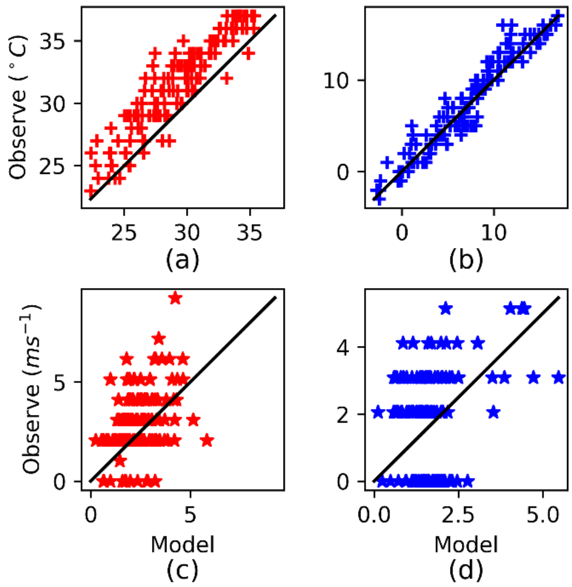

Figure 4: WRF performance of (a) summer T_2, (b) winter T_2 (c) summer $Wind_{10}$ (d) winter $Wind_{10}$

The CMAQ model was validated via all twenty air quality monitoring stations. The model could not predict the $PM_{2.5}$ correctly, mainly in the summertime, since the dust emissions were not introduced into the model. The O_3 also was overestimated during wintertime since O_3 formation was mainly calibrated over summer. O_3 was simulated with acceptable performance over the summertime, although it slightly underestimates the peak at noon concentration. $PM_{2.5}$ is also slightly underestimated in some stations by the model during the winter since dust and biogenic emissions were not introduced into the model.

Also, the bias in the meteorology parameters and boundary conditions can contribute to the pollutant's prediction by the model. The index of the agreement for $PM_{2.5}$ and O_3 were 0.61 and 0.84, respectively. Their root means squared errors were 37.6 μgm^{-3} and 22.2 ppb, respectively.

Since O_3 is the dominant pollutant in summers and $PM_{2.5}$ is the dominant pollutant in winters, $PM_{2.5}$ and O_3 during winter and summer were validated and discussed in this paper, respectively (Figure 5).

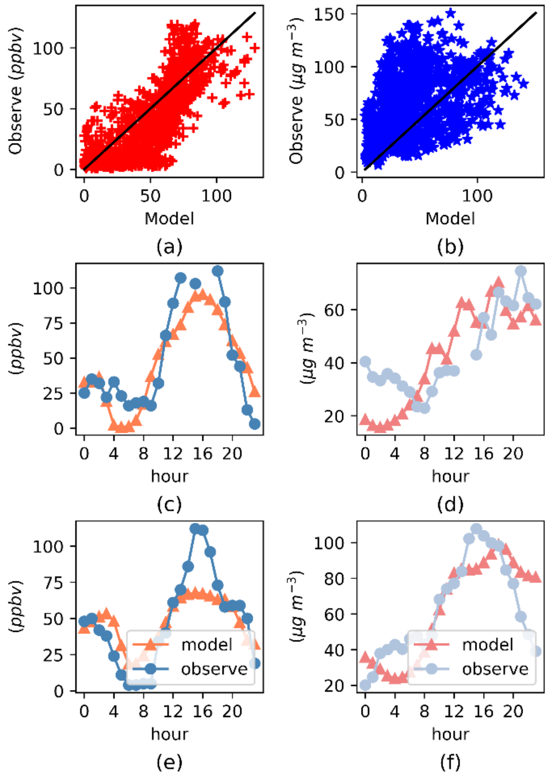

Figure 5: CMAQ model validation. Scatter plot of (a) summertime O_3, and (b) wintertime $PM_{2.5}$. A daily diurnal plot of (c) summertime O_3, and (d) wintertime $PM_{2.5}$ in Golbarg station. A diurnal time series of (e) summertime O_3, and (f) wintertime $PM_{2.5}$ in Modarres station.

The model sometimes overestimated the O_3 during the nights during the summer. NO Miss-presentation in the emissions and underestimation in planetary boundary layer height calculation by the WRF model is mentioned as the depletion of nighttime O_3. It was noted that sometimes regional O_3 could contribute to the O_3 concentration resulting in some abnormality in CMAQ's O_3 predictions since there were some uncertainties in the boundary conditions. Sometimes the model overestimated the O_3 at peak times. This could be due to O_3 formation in the RACM2 mechanism.

$PM_{2.5}$ is mainly underestimated by the model during the summer. Uncertainty in the meteorology field calculated by the WRF model, the boundary conditions, dust, and biogenic emissions are known as reasons for this $PM_{2.5}$ underestimations by the model. Also, changes in the land-use type and desertification could be linked to the result since these phenomena were not considered in the model. However, under a high-pressure system with a stable atmosphere and low wind speeds, where most pollutants are considered local, the model presented an acceptable performance in capturing $PM_{2.5}$ concentrations.

3-2) Scenarios

For SE1 and SE2, the emissions of passenger cars and taxis were omitted from the emission inventory in the SMOKE model, respectively. As expected, the $PM_{2.5}$ concentrations decreased significantly, slightly higher in SE1 than in SE2. These improvements in the AQI are due to both primary and secondary aerosol reduction. Since passenger cars have emitted a great amount of NOx and PMs, the majority of $PM_{2.5}$ might be due to SOA. In the worst case, passenger cars contributed 8% of air pollution of wintertime $PM_{2.5}$, and their elimination from the city could improve the AQI by 12.84 (from 152 to 139). The average contribution of passenger cars to AQI on three selected days was 4% (Figure 6).

Since taxies take a small portion of the vehicle fleet of Tehran, even with their high-rate emissions and age, according to emission inventory, they did not contribute to the improvement of AQI. However, their elimination reduced the average PM peak by 0.17 μgm^{-3} (Figure 7).

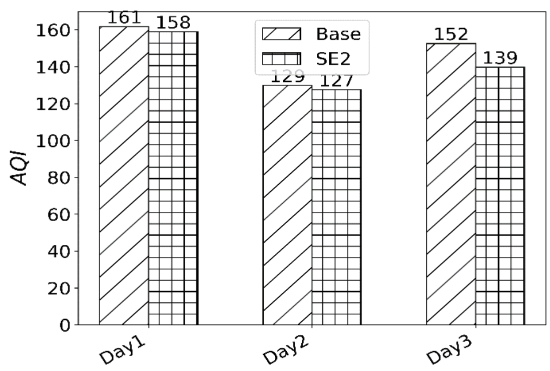

Figure 6: SE1 AQI corresponds with $PM_{2.5}$ during wintertime

However, O_3 concentrations were not decreased on all days. As shown in Figure 8 and Figure 9, O_3's AQI could be increased or reduced by reducing precursor pollutants emissions. This abnormality could be due to changes in the O_3 formation regime. This means that O3 formation is susceptible to incoming pollutants from boundaries on some days. On some other days, the O_3 formation is susceptible to local precursor pollutants emissions. Also, the location in which precursor pollutants are emitted could be essential. As local meteorology conditions change, based on where the precursor pollutants are emitted, it affects the O_3 formation regime in different parts of the city.

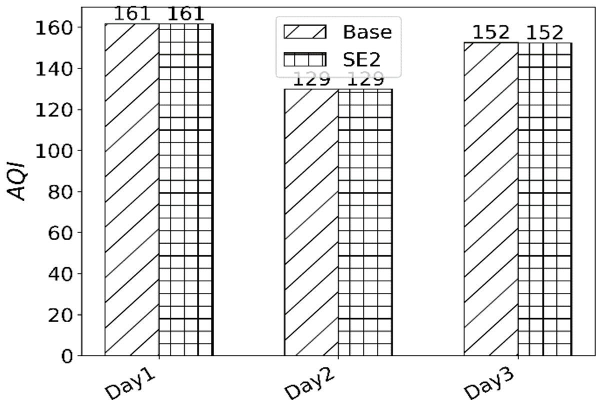

Figure 7: SE2 AQI corresponds with $PM_{2.5}$ during wintertime

Removing passenger car emissions could improve the O_3 AQI by 8, and in the worst case, it worsens the AQI by 9 units. Also, on some days, the effect of passenger cars on the O_3 pollution is negligible and could be related to high ambient temperature. However, it needs more investigations to be proven (Figure 8). As mentioned before, this is probably due to incoming precursor pollutants from the modeling boundaries.

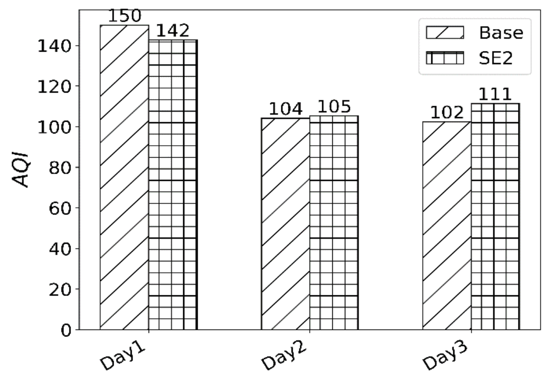

Figure 8: SE1 AQI corresponds with O_3 during summertime

In contrast with removing passenger car emissions, removing taxies emissions did have the same result in O_3 formation and behavior. Where removal of passenger cars could Improve the AQI related to O_3 in one day (Day 1), taxies emissions removal harmed the AQI. In the worst case in the modeling days, the removal of taxies emissions worsens the AQI by 2 units. As mentioned before, this behavior in O_3 formation is due to the location of emissions in the city. Since taxies only travel in specific parts of the city, according to the Tehran emission inventory, alongside the meteorology condition, their contribution to O_3 is more complicated. It could not affect air pollution.

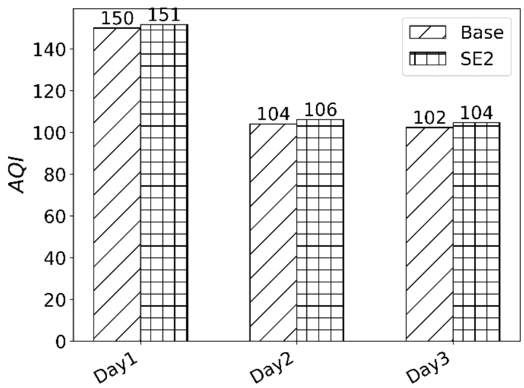

Figure 9: SE2 AQI correspond with O_3 during summertime

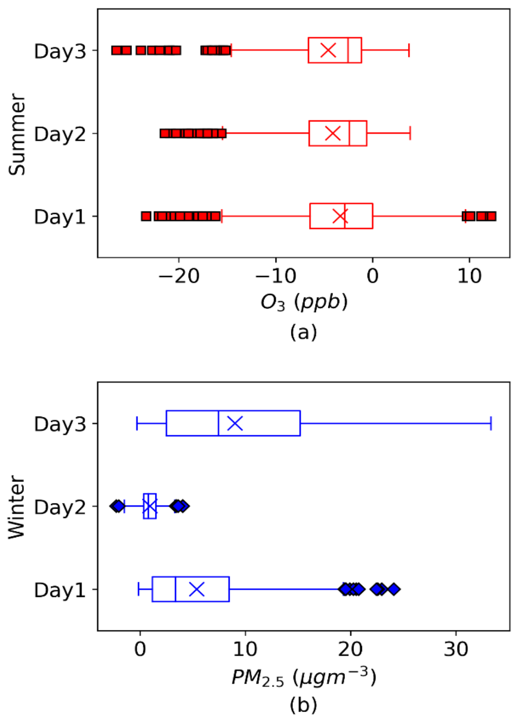

Figure 10: SE1 statistical analysis of (a) O_3 and (b) $PM_{2.5}$ concentrations

Statistical analysis of pollutants concentration could widen our understanding of how these emissions contribute to atmospheric air pollution. Figure 10 shows statistical wintertime $PM_{2.5}$ and summertime O_3 analyses of SE1 between base and scenario models, whereas Figure 11 shows the same analyses for SE2. Summertime O_3 concentration reduced in some hours when passenger cars were removed by higher than 10 ppb, although its concentration is elevated most of the time by about 30 ppb (Figure 10-a). By removing passenger car emissions (SE1), although wintertime $PM_{2.5}$ concentrations could reduce by 12, during the peak of polluted episode, passenger car's contribution could be as high as 30 μgm^{-3}. It should be noted this reduction in $PM_{2.5}$ concentrations could be slighter or more severe than on other days (Figure10-b).

Summertime O_3 concentration reduced in some hours when taxies were removed by 1 ppb, although its concentration is worsening most of the time by about 5 ppb (Figure 11-a). By removing taxies emissions (SE2), although wintertime $PM_{2.5}$ AQI had no significant change during the peak of polluted episodes, the taxies contribution could be as high as 1.5 μgm^{-3}. It should be noted this reduction in $PM_{2.5}$ concentrations could be slighter or more severe than on other days (Figure11-b).

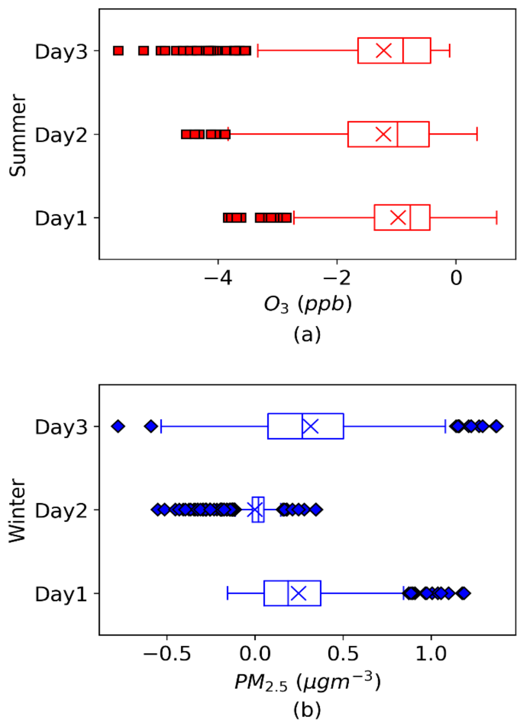

Figure 11: SE2 statistical analysis of (a) O_3 and (b) $PM_{2.5}$ concentrations

Moreover, the average peak of daily summertime O_3 was reduced by 5.351, 1.295, and -1.211 ppb on Day 1, Day 2, and Day 3, respectively, when the passenger cars' emissions were removed from emission files. The average peak of daily summertime O_3 was reduced by -0.535, -0.472, and -0.509 ppb on Day 1, Day 2, and Day 3, respectively, when the taxies emissions were removed from emission files. The average peak of daily wintertime $PM_{2.5}$ was reduced by 13.533, 1.662, and 18.090 μgm^{-3} on Day 1, Day 2, and Day 3, respectively, when the passenger cars' emissions were removed from emission files. The average peak of daily wintertime $PM_{2.5}$ was reduced by 0.654, 0.031, and 0.795 μgm^{-3} on Day 1, Day 2, and Day 3, respectively, when the taxies emissions were removed from emission files.

4) Conclusions

In this study, a WRF-SMOKE-CMAQ system was set up in the Tehran domain using global and local datasets. The model showed acceptable performance in modeling the dominant pollutants. The prepared model was used to investigate the contribution of passenger cars and taxis to air pollution of summertime O_3 and wintertime $PM_{2.5}$.

Based on the studied days using mentioned modeling system, the accumulated role of passenger cars and taxis was about 13 units in $PM_{2.5}$ AQI in three studies days. However, passenger cars and taxis' role in the O_3 pollution of Tehran is more complicated. Removing their emissions can improve O_3 AQI by 5% or worsen it by 9%.

It should be noted that the emission inventory used in this study was based on Tehran's 2016 emission inventory. Also, some uncertainties in the traffic dataset could not reflect real traffic and emissions. As a result, the contribution of passenger cars could be underestimated. Moreover, studies showed that secondary aerosols are underestimated by the model. Therefore, their contribution to air pollution might be higher than those estimated in this study.

It should be noted that different pollution episode type has different source contribution. It means that in some polluted episodes, various polluting sources have different contributions. Also, each day has its governing atmospheric conditions, which have an essential role in pollutants formation, dispersion, and transportation. Therefore, we would like to address other researchers and scholars to mention the impact of their studying scenarios on the study episode. As a result, their study scenario might have a different effect on other days under different circumstances. Also, this study addresses that the role of various sources during the highly polluted episodes could become more dominant due to atmospheric and boundary conditions. This means that although passenger cars' contribution to air pollution was found to be as high as 12 units, their role on other days can be higher than those found in this study.

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چکیده

آلودگی هوا یکی از مشکلات اصلی شهر تهران است. شناسایی نقش عوامل مؤثر در مدیریت آلودگی هوا بسیار مهم است. از نکات مهم اینکه تمام آلودگی موجود در هوای شهری ناشی از انتشار مستقیم از منابع نیست و در اثر واکنش‌های جوی تشکیل می‌شوند. استفاده از الگوهای آلودگی هوا در شناخت عوامل مؤثر در آلودگی هوای شهری به ما کمک می‌کند. از سامانۀ الگوی آلودگی هوا استفاده شد تا ابتدا الگویی مناسب تولید شود. سپس با حذف انتشار منابع انتشار تاکسی‌ها و وسایل نقلیۀ شخصی، سهم این دسته از منابع آلاینده با توجه به تحلیل‌های آماری بررسی می‌شوند. سامانۀ الگوی استفاده شده از عملکرد قابل‌قبولی برای بررسی طرح‌های مورد نظر با ضریب تطابق ۰٫۸۴ و ۰٫۶۱ بترتیب برای آلاینده‌های ازن و ذرات معلق برخوردار بود. مجموع سهم این دو منبع در شاخص کیفیت ذرات معلق ۱۴ واحد بود. اما نقش این منابع در آلودگی ازن بسیار پیچیده شناسایی شد.

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