Estimating the contribution of traffic flow to pollutant concentrations

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Abstract. The rapid increase in vehicular use due to human activities in urban areas has been leading to a worsening in air quality, thus negatively affect the exposure of inhabitants to polluted air and also harms the environment. This work studies the contribution of traffic flow on CO and NO2 concentration. The field measurement of both pollutants was considered in a roughly isolated street canyon. In addition, the meteorological parameters of the studied location were collected parallel with traffic flow data. There have been days in which the study location was affected by traffic flow and some others were not affected. In particular, statistical tests and data analysis were applied to the collected dataset after splitting it into two groups. One with zero traffic flow and the other with a significant variation in traffic flow. Also, the effect of meteorological parameters such as wind speed, wind direction, ambient temperature, and relative humidity on pollutant concentrations was considered. Moreover, the multivariate linear regression models were developed for both pollutants to address the contribution of each factor. As a result, the positive effect of traffic flow and the negative effect of the wind directions highly improves the prediction of the near-road traffic-related pollutant concentration.

1. Introduction

Outdoor air pollution is one of the most challenging issues that adversely affect human health, fauna, flora, and climate change. In 2016, the World Health Organization (WHO) declared that 91% of the world’s population was living in places where, according to WHO air quality guidelines, acceptable levels for ambient air quality are not met. In addition, the same report stated that the death rate caused by air pollution is 4.2 million premature deaths worldwide per year with a considerable proportion (91%) of those premature deaths occurred in low and middle-income countries [1]. Moreover, according to the International Council on Clean Transportation (ICCT) for the year 2017, about 3.5 million premature deaths from stroke, ischemic heart disease, chronic obstructive pulmonary disease, lung cancer, lower respiratory infections, and diabetes are the outcome of global ambient air pollution. The global transportation sector is considered to be one of the main sources of this health burden through its contribution to increasing the concentration of particulate matter particles with aerodynamic diameter < 2.5 µm (PM2.5), ozone (O3), and nitrogen dioxide (NO2) [2]. A previous study [3] demonstrated high correlation between exposure to air pollution and traffic flows, which led to
negative health effects for people living in urban areas, and emphasized the importance of planning and placing the highly congested roads away from vital areas like schools and hospitals.

Despite the high interrelation between air pollution and traffic flow, this relation is not clear and leads researchers to investigate the many aspects that can improve or deteriorate the ambient air quality [4]. Many previous studies were conducted to clarify the correlation between air pollution and different aspects. Firstly, the pollutant concentration measures in urban areas are generated by many sources other than traffic (e.g., commercial and industrial sectors), these different sources can disorganize the background concentration of some pollutants like particulate matter [5,6]. In addition, the distance between the pollutant source and air quality monitoring stations significantly affects the pollutant concentration level, especially for stations far away from the roadway. Venkatram et al. [7] found that the concentration of a certain pollutant varies depending on the receptor location, wind direction, and pollutant type, where one pollutant has a significant concentration 100 m away from the pollutant source, in contrast, another pollutant concentration with a short lifetime fade in 17 m from the pollutant source. Another study evaluated the effect of positioning the emission receptor inside and outside a tunnel where a significant variation was noticed [8]. Moreover, the street geometry and urban terrain with wind direction affect the pollutant concentration [9,10].

On the other hand, research has shown a consequential contribution of meteorological parameters, such as precipitation level, wind speed, temperature, relative humidity, and thermal inversions on pollutant formation and transport [11–13]. Last but not least, Yuval et al. [14] introduced an important factor that highly confuses the correlation between traffic flow and pollutant concentration, this factor is weather stability, which can lead to high pollutant concentration at night-time, in spite of the much lower traffic volumes than daytime due to the conversion from stable to convective conditions.

Overall, many factors affect pollutant concentration. So it is difficult to examine all these factors and other related to traffic composition and fuel type [15], which brought many researchers to include some of them and ignore others which may lead to biased relationship between traffic flow and air quality.

On the flip side, the literature review showed that the concentration levels of traffic-related gaseous emissions (e.g., CO and NO\textsubscript{2}) near roadway were poorly investigated in Egypt. There is a paucity of studies that have been observed despite the increased population exposure in different regions in Egypt to traffic-related air pollution. In 2015, ICCT declared that Transportation Attributable (TA) deaths for the most polluted 100 urban areas over the world, and three Egyptian cities were listed (Cairo, Alexandria, and Sohag) [16]. Furthermore, poor air quality in Egypt has been adversely affecting inhabitants' health to place Egypt at the forefront countries with high disability-adjusted life years (DALYs) caused by disease which influenced more than 1.2 million individuals for the year 2012 [1].

This paper aims to investigate the relationship between traffic flow and air quality in the face of multiple surrounding factors. This aim will be achieved by selecting a roughly isolated street, which has limited sources of pollutants, and stable traffic conditions in order to focus on studying the most affecting factors on the correlation between traffic flow and pollutant concentration using statistical analysis methods.

This research starts by collecting a substantial range of data for studied factors in a street located in Alexandria, Egypt. Then, a correlation analysis is performed to understand the relationship between the reduced traffic flow and pollutants concentration in urban areas. In addition, the effect of meteorological parameters on decreasing polluting concentrations is clearly discussed. Finally, a multivariate linear regression model is performed to identify the contribution of the studied factors on pollutant concentration.

2. Case study and data collection
The challenge in studying the correlation between pollutant concentration and traffic-related emissions lies in measuring and interpreting the influencing factors on pollutant concentration such as average traffic speed and traffic composition, other pollutant sources, and other meteorological factors [17]. As mentioned in the introduction above, some studies focused on measuring pollutants concentration in
congested places where all traffic-related data has been considered, but the other weather-related factors were ignored. While other studies had to measure the traffic-related pollutant concentration inside a tunnel to avoid weather-related effects which leads to a problematic generalization of these outcomes on the open-air roads. All these factors have been taken into account in selecting a study location in order to focus on the reduced vehicle flows effects.

To ensure that the selected street is isolated from other congested roads and away from industrial and commercial zones, a university campus in Abu Qir, Alexandria, Egypt is selected for this investigation. In particular, the Arab Academy for Science, Technology and Maritime Transport (AASTMT), a major trip generator located 15 km away from downtown of Alexandria city, is considered. Monitoring devices of pollutants and vehicles were placed on the main exit street of the campus, where this street consists of two traffic lanes and is distinguished by being surrounded by three-meter fences on both sides. Figure 1 shows the study location and the distribution of devices on the main exit street canyon. Data was collected between September and December 2020. This time of the year was selected in order to collect a wide range of data to be analysed subsequently as it is characterized by variation in weather conditions such as temperature, wind speed, and direction.

2.1. Air pollution data
Two major pollutants emitted from vehicles with severe consequences were measured. Nitrogen Dioxide and Carbon Monoxide (NO$_2$ and CO). Moreover, WHO declared that Concentrations of NO$_2$ are often strongly correlated with those of other toxic pollutants. It is often used as a surrogate for the pollutant mixture as a whole. In consequence, achieving guideline concentrations for individual pollutants such as NO$_2$ may therefore bring public health benefits that cover the effect of other toxic emissions [18,19].

The ETL3000 monitoring station (UniTec, Italy) is used to measure NO$_2$ and CO concentration in the study location, where these gases were measured through proprietary Thick Film Metal Oxide Semiconductor Technology (TFMOS). Thick film sensors are used to convert chemical-physical information into an electrical signal. The average one-hour data of NO$_2$ (in µg/m$^3$) and CO (in mg/m$^3$) concentration were measured for most of the study period. The instrument was installed at an elevation of 2.2 m above ground level on the street canyon sidewalk.

**Figure 1.** Study location. The black markers denote locations of (1) traffic detector; (2) air quality monitoring station; (3) surveillance camera; (4) temporary weather station.
2.2. Meteorological data
In this study, the air meteorological data for September–December 2020 for Alexandria were obtained from El-Nouzha International Airport (31.2°N, 29.92°E) weather station at an elevation of 10 m through Meteoblue website [20]. Moreover, a temporary weather station was used in the study location for two weeks period to validate the Meteoblue weather data, where the matching of data was observed with a 0.91 Pearson correlation coefficient. The following parameters were collected on an hourly basis: ambient air temperature (°C), wind direction and average speed (m/s), and relative humidity R.H (%). These parameters are considered to be the most influential meteorological parameters in the near road pollutant concentrations [11] in addition to the amount of precipitation. However, there are insufficient data to study this factor due to the lack of rainy days during the study period.

2.3. Traffic data
This study location is characterized by a minimal impact of traffic data on pollutant concentration. This feature appears due to the almost zero variation on traffic composition, fuel type, and average traffic speed. To confirm that, the traffic speed detector is placed in the next column to the air quality monitoring station, where the average mean speed per hour ranged from 14 km/h to 17 km/h. Furthermore, a fixed camera was used during the whole study period to check the traffic composition for each hour, where the average proportions of the traffic composition for the study period were as follows: 94% passenger car, 1.9% microbus, 2.5% bus, and 1.6% truck.

As the study area is located inside an enclosed space (university campus), traffic was concentrated during the working hours. As traffic begins to increase at 8:00 am until it reaches its peak at 1:00 pm or 3:00 pm depending on summer or winter time, and gradually decreases around 7:00 pm (traffic is almost zero on weekends and holidays). These traffic variations help to interpret the reduction in pollutant concentration due to the absence of traffic flow effect, hence knowing the effect of other factors. Figure 2A shows the average hourly traffic volume for the entire study period.

2.4. Data Preparation
The collected on-site monitoring data includes: traffic volume, NO\textsubscript{2} and CO concentration, wind speed, wind direction, ambient temperature, and relative humidity. Then, the hourly data was averaged over all days for the entire study period. More than 1,750 readings were separately recorded for each factor, where the average hourly records have been prepared for all factors for each hour of the day. After that, the outliers for all records were eliminated using Mahalanobis distance, which can be used to determine the presence of outliers in the dataset, whether a process is in control, or whether a sample is a member of a group or not [21]. These omitted outliers occurred due to other non-considered factors such as weather stability which can cause pollutant concentration disturbance [14]. In order to provide a preliminary picture of the data distribution, Table 1 shows descriptive statistics of pollutant concentrations, meteorological parameters, and traffic flows for the period in question, in particular, it presents the number of observations (N), minimum value, maximum value, mean, standard deviation (Std. Dev.), median, and interquartile range (IQR) for the average hourly values for each of the dependant and independent factors.

Table 1. Descriptive statistics for the measured and observed data, where A) data associated with zero traffic flow; B) data associated with the presence of traffic flow.

|                | N  | Minimum | Maximum | Mean | Std. Dev. | Median | IQR   |
|----------------|----|---------|---------|------|-----------|--------|-------|
| A) Without traffic effect |    |         |         |      |           |        |       |
| CO (mg/m\textsuperscript{3}) | 712 | 0.6     | 2.1     | 0.74 | 0.30      | 0.60   | 0.10  |
| NO\textsubscript{2} (ug/m\textsuperscript{3}) | 712 | 2.1     | 208.8   | 45.59| 48.41     | 26.90  | 42.35 |
| Wind speed (m/s) | 712 | 0.1     | 8.5     | 3.44 | 1.50      | 3.30   | 1.63  |
3. Data analysis
To study the relationship between traffic flow and air quality, other factors that affect the pollutant concentration must be analysed. Most of the meteorological parameters have an opposite effect to the effect of traffic on pollutant concentration [11]. Therefore, it is not necessary to observe the maximum values of pollutant concentration with the maximum value of traffic flow, especially when the time of occurring the maximum weather conditions matches the time of reaching the maximum values of the traffic flow. The analysis shows that the maximum concentration of pollutants (shaded by red colour) was observed between 8:00 am and 10:00 am, whereas maximum traffic flow occurs between 1:00 pm and 3:00 pm, as shown in Figure 2 E-F. The reason for this is that the maximum values of most influencing meteorological parameters (Figure 2 B-D) on reducing pollutant concentration occur at the same time as traffic flow values. However, the maximum pollutant concentration was measured at the time of occurrence of average: traffic flow, ambient temperature, relative humidity, and minimum wind speed. On the other hand, the minimum values of pollutant concentrations appear at the same time as the minimum traffic flow values with the appearance of relatively moderate variation in pollutant concentration due to the effect of meteorological parameters. In particular, the correlation between a certain factor and pollutant concentration can be examined by studying this factor at a time of the day when there is a variation in this factor while other factors are in minimal variation.
3.1. The contribution of traffic flow in the face of wind speed and ambient temperature

The traffic flow effect (TFE) on pollutant concentrations was varied throughout the daytime according to the effect of meteorological parameters. Therefore, the pollutant concentration values were separated for each hour of the day. Then, the effect of the meteorological parameters on pollutant concentrations is analysed either by excluding the TFE by considering the measures of weekends and holidays or by including the TFE of other measures. Therefore, the line inclination between the two values for each hour, with and without traffic flow, represents the effect of traffic on pollutant concentration with the associated meteorological parameters during this hour. Figure 3 A-B shows the variation of CO and NO$_2$ concentration from 4:00 am to 7:00 pm, where the pollutant concentration increases in low-temperature hours and decreases in high-temperature daytime (Figure 2 D). Also, the inclination of the lines is gradually increasing from (4:00-9:00) am due to the increasing traffic flow with the corresponding low wind speed and temperature Figure 2 B-D. Afterward, the lines remain at the same angle of inclination from 10:00 am to 3:00 pm, despite the increase in traffic flow, due to the increase in wind speed and temperature values during this time period. Last but not least, the inclination of the lines begins to decrease from (4:00-7:00) pm, where the traffic flow was declining.

To clearly understand the contribution of wind speed and ambient temperature, both of them are divided into two groups, where the wind speed values ranging from 0.0 m/s to 5 m/s were placed in a group and from 5 m/s to 10 m/s in another group and the ambient temperature was split into two groups, one less and one more than 20 °C. Figure 3 (C to F) shows the significant variation in CO and NO$_2$ concentration between the two groups of both factors. It is also evident that for wind speed groups, the lower TFE has a higher effect on (CO) and equal effect on (NO$_2$) to the effect of the higher
TFE due to the dispersion effect of wind speed [22]. It was also observed that no appreciable variation for the ambient temperature groups for both pollutants due to the large difference in TFE.

3.2. The contribution of wind direction

The effect of urban canyon geometry on wind direction at near street levels is an effect that must be considered, and in general, for the urban street canyon wind patterns perpendicular to the street axis, ground-level winds tend to be opposite to those above the urban canopy [23]. Wind direction (WD) above the urban canopy is defined as $110^\circ \leq WD \leq 200^\circ$ and $WD \geq 290^\circ$ or $WD \leq 20^\circ$ for downwind and upwind conditions, respectively, where the other WD is considered to be parallel to the street. Figure 4 shows a satellite image of the site with these respective quadrant definitions, along with a histogram of the mean CO and NO$_2$ concentrations as a function of wind direction (grouped by 20° intervals for each bar). The concentration for both CO and NO$_2$ varies with wind angle and increases to reach maximum values of pollutant concentration when the wind direction is close to the case of perfect downwind condition. In contrast, the pollutant concentration values gradually decrease until they reach the minimum value at the perfect wind direction angle of upwind conditions. This is due to the formation of eddies inside the street canyon, which causes an increase in pollutant concentrations on the leeward side [9].
Figure 3. The contribution of traffic flow on CO and NO₂ concentration in the case: (A and B) each hour of the day; (C and D) two wind speed groups; (E and F) wind direction groups; (G and H) two ambient temperature group. The TFE refers to Traffic Flow Effect.
All of the above-mentioned analysis of field measurement of this study confirmed that by what has been mentioned in previous studies, there is evidence that supports studying the effect of wind direction by creating a new factor. This factor can be named as (WDE) wind direction effect, where the values of this factor are varied from zero to 180° for the perfect wind direction angle of downwind and upwind conditions, respectively. However, the maximum and minimum contributions of WDE on pollutant concentration occur when the WDE equal to 0 and 180°, respectively. Figure 5 shows the distribution of WDE and the angle of maximum and minimum values. Also, Figure 3 G-H shows the variation in CO and NO₂ concentration in the face of wind direction and traffic flow.

![Figure 4](image1.png)

**Figure 4.** Satellite image of the studied site, along with downwind (red), upwind (green), and parallel to the street (blue), where the histograms of the mean values of CO and NO₂ concentration as a function of wind direction, are on the left side.

![Figure 5](image2.png)

**Figure 5.** Illustration of WDE with respect to the studied street canyon
4. Multivariate linear regression models

As a result of the previous section, it was concluded that the values of pollutant concentrations increase with traffic flow and decrease with the increase of wind speed, ambient temperature, relative humidity, and WDE. Therefore, the multivariate linear regression models are now presented as it is necessary to determine the contribution of each factor in the performance of pollutant concentrations. In particular, Table 2 shows the estimated coefficients, associated statistical tests, and model performances for the hourly concentrations of CO and NO\textsubscript{2} for the entire studied period.

**Table 2.** Multivariate linear regression for CO and NO\textsubscript{2} concentrations.

| Factors       | Coeff.\textsuperscript{a} | Std. Error | Standardized Coeff.\textsuperscript{a} | t-value | Sig.*** | Model Summary |
|---------------|---------------------------|------------|----------------------------------------|---------|---------|---------------|
| **CO concentration** |                           |            |                                        |         |         |               |
| Intercept     | 2.508                     | 0.057      | 44.37                                  | 0.000   | N       | 1765          |
| Traffic flow  | 0.001                     | 0.000      | 0.12                                   | 5.64    | 0.000   | Std. Error 0.244 |
| Wind speed    | 0.050                     | 0.004      | -0.25                                  | -12.62  | 0.000   | Sig.*** 0.000 |
| WDE           | 0.003                     | 0.000      | -0.41                                  | -20.17  | 0.000   | R\textsuperscript{2} 0.514 |
| Temperature   | 0.023                     | 0.002      | -0.31                                  | -13.75  | 0.000   | Adj. R\textsuperscript{2} 0.513 |
| R.H.          | 0.008                     | 0.000      | -0.37                                  | -16.29  | 0.000   |               |
| **NO\textsubscript{2} concentration** |                           |            |                                        |         |         |               |
| Intercept     | 315.37                    | 8.097      | 38.95                                  | 0.000   | N       | 1765          |
| Traffic flow  | 0.138                     | 0.018      | 0.16                                   | 7.77    | 0.000   | Std. Error 34.885 |
| Wind speed    | -8.557                    | 0.564      | -0.29                                  | -15.18  | 0.000   | Sig.*** 0.000 |
| WDE           | -0.480                    | 0.024      | -0.40                                  | -20.30  | 0.000   | R\textsuperscript{2} 0.547 |
| Temperature   | -3.470                    | 0.243      | -0.31                                  | -14.30  | 0.000   | Adj. R\textsuperscript{2} 0.546 |
| R.H.          | -1.238                    | 0.070      | -0.38                                  | -17.61  | 0.000   |               |

*** All statistical significance (p-value) < 0.001
\textsuperscript{a} Coefficient

Table 2 shows that the coefficients of variables related to traffic flows are all significant and positive, clearly indicating that traffic flows lead to increased concentrations of CO and NO\textsubscript{2}. On the other hand, all-weather factors had an opposite contribution to the traffic flow. In particular, concerning the standardized coefficient, the newly created factor (WDE) had the most contribution among the other factors on the values of both pollutant concentrations with a high significant level of confidence. As a result, wind direction can be considered as the highest factor that affects the dispersion of traffic-related pollutants in the urban street canyons. Additionally, despite the relatively small value of the standardized coefficient for traffic flow comparing with the other factors, but in most cases, traffic flow has the most significant influence on the pollutant concentration especially at peak hours because the traffic flow values may increase to reach times the values of the rest of the factors. In consequence, the good value of R\textsuperscript{2} of both models is greater than that in other models that studied pollutant concentration without considering traffic flow and wind direction effect [11].
5. Conclusion
The main focus of this study is to see the overall effect of traffic flow and meteorological parameters on pollutant concentration. The variation of CO and NO\textsubscript{2} concentrations basically present the same behaviour among all studied factors. As a result, it was found that the CO and NO\textsubscript{2} concentration values significantly increased with traffic flow. Coherently, a significant decrease in CO and NO\textsubscript{2} levels was observed when switching from downwind to upwind conditions. Moreover, the field measures show the moderate variation in CO and NO\textsubscript{2} concentration when wind direction is parallel to the street canyon. Also, the measures data of pollutant concentrations and other weather data highlights a strong coupling between them.

Even though the results presented here are specific to limited traffic speed, they serve as an example of model results that can be used to formulate strategies for sampling air quality next to roadways. For example, previously specify certain weather conditions if the needs of determining the contribution of other traffic data (such as traffic speed and composition) on pollutant concentration. Moreover, this study also provides a framework for researchers in developing countries to easily quantify and evaluate their own dataset to address the influence of other factors on pollutant concentration without the need for large budgets and resources. Thus, in order to improve air quality in these countries through taking corrective actions to stop the inflation in mortality and diseases caused by traffic-related air pollution.

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