Pedestrian exposure to Nitrogen Dioxide (NO$_2$) and Carbon Monoxide (CO): A case study of Surabaya, Indonesia

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Abstract. The increase in motor vehicles used every day also increases the rate of pollution. Motor vehicles are the main source of the nitrogen dioxide (NO$_2$) and carbon monoxide (CO) pollutants that can be dangerous for human health in excessive amounts. This study investigates the patterns of NO$_2$ and CO concentrations in the ambient air, specifically on the sidewalks of two big streets in Surabaya. Measurements were taken over a period of 15 hours using a portable monitoring device. The results indicated that the NO$_2$ concentration would decrease by 0.008 mg/m$^3$ and 0.012 mg/m$^3$, respectively, at peak times during the day and night. Meanwhile, the CO concentration would increase by 1.486 mg/m$^3$ during the peak time at night. The factors that significantly influenced NO$_2$ were day variation (weekday or weekend), morning peak hour, noon peak hour, night peak hour, and temperature. Regression with these factors had an R$^2$ value of 30.7%. For CO, the significant factors were night peak time, temperature, wind direction, and the number of vehicles, with an R$^2$ value of 16.9%.

Keywords: NO$_2$, CO, plants, vehicles

1. Introduction
Surabaya is the biggest city in Indonesia, second only to Jakarta. The city has over 2 million people based on the population census in 2010, which showed at the time that the population had increased significantly (by 0.63%) since the previous census [1]. Consequently, there has been an increase in the use of various transport modes to support daily activities, e.g., motor vehicles. Based on data from the Transportation Agency of Surabaya City, there were 4.5 million vehicles in Surabaya in 2014, and that number was increasing by 17,000 every month.

There are six main pollutants in Surabaya, which are Carbon monoxide (CO), Lead (Pb), Nitrogen dioxide (NO$_2$), Ozone (O$_3$), Particulate matter (PM), and Sulfur dioxide (SO$_2$) [2]. Motor vehicles, especially the old ones, are the main cause of NO$_2$ and CO pollution [2]. Therefore, any increase in vehicles will increase the NO$_2$ and CO gasses in the ambient air. Pedestrians, particularly those who walk along roads with heavy traffic, have been exposed to these gases, especially when they exceed threshold levels.

In Lagos City, Nigeria, pedestrians are exposed to CO at levels of $8.84 \pm 1.40$ ppm during rush hour and $6.80 \pm 1.48$ ppm during normal traffic periods [3]. Meanwhile, pedestrian exposure to NO$_2$ on busy streets is relatively high at an average of 38 mg/m$^3$. These high amounts of pollutants are due to poorly tuned engines and street canyon conditions. The lowest exposure to NO$_2$ was 23 mg/m$^3$. 

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which occurred in places where pedestrians walked alongside low-intensity traffic and pollutants spread well, such as residential neighborhoods [4].

Another study was conducted in Brisbane, Australia. There, CO and NO2 concentrations peaked from 08.00 AM to 09.00 AM on workdays. On the weekend (Sunday), the concentration increased starting at 06.00 PM and kept increasing until the peak night hour in the period 11.00 PM-01.00 AM. These peak concentrations were influenced by the increase in vehicles during these periods. On workdays, most people commute to work in the morning; therefore, the number of vehicle was greatest in the morning, increasing the concentrations of pollutants as well. Meanwhile, during the weekend (Sunday), the usual activity was leisure activities, thus the number of vehicles increased at night [5].

CO can poison humans in the form of COHb (carboxyhemoglobin) in the blood [6]. The affinity for CO is greater than that for oxygen, causing Hb to bond with CO instead of oxygen. This can disrupt the nervous system and slow down reflexes. CO can also cause continuous seizures, leading to unconsciousness and death. Inhaling air with a high concentration of NO2 disrupts the respiratory channel in the human respiratory system. This kind of exposure, even in the short term, can cause respiratory diseases, especially asthma, which, in turn, can lead to other respiratory symptoms (such as coughing and difficulty breathing) [7]. Considering the above facts and also the massive increase in vehicle ownership in Surabaya, which has led to heavy traffic on some roads, the present study determines the concentration patterns of NO2 and CO and their correlations with traffic volume.

2. Methods

2.1 Location selection

The study was done on Gemblongan St. and Embong Malang St., Surabaya, where we measured concentrations on a workday and weekend (Sunday). In each location, we used two difference scenarios, one with vegetation separating traffic and pedestrians, the other without vegetation.

Gemblongan St.: Based on Mayor Decree Number 46, year 2000, concerning the class of roads in Surabaya (Keputusan Walikota Surabaya Nomor 46 Tahun 2000 tentang Kelas Jalan di Kota Surabaya), Gemblongan is a street with a Class 3B designation, a collector street where motor vehicles, including cargo vehicles up to 8 tons, are allowed to pass through. The street goes in one direction, every lane has a width of 2.5 m, and it is divided into five lanes. On both sides of the street, there are sidewalks with widths ± 3 m. This street goes on for 0.74 km. Plants are placed on one side of the road with a distance between plants of ± 6 m.

Embong Malang St.: Embong Malang is a street with a Class 3C designation, meaning that it is a local street where motor vehicles with a cargo width of not more than 2,100 mm can pass through, and the heaviest cargo allowed is 8 tons. The street goes in one direction only, every lane is 2.5 m wide, and it is divided into five lanes. On the right and left sides of the street, there were sidewalks with widths of ± 6 m and ± 2 m, respectively. This street goes on for 1.63 km. Plants were placed along the side of the road with the distance between plants was ± 4 m.

![Figure 1. Gemblongan St.](image1.png)  ![Figure 2. Embong Malang St.](image2.png)
2.2 Sample measurements
When sampling without plants, the tool was placed on a tripod with a ±1.5 m height (as high as the average human respiratory system). The distance between the tool and the road was 1 m. Meanwhile, in an area with plants, the tool was placed 1 m behind the plants at a ±1.5 m height. The distance between plants was ±30 cm. This distance was measured from the outmost plant stem to the next one. The plants were planted so that there would be no gaps in the canopy. The plants used were plants with heights around 1.5 m – 2.0 m, which had a good ability to absorb pollutants, and which were aesthetically pleasing. This study used croton plants (Codiaeum variegatum). Each sampling period was 15 hours long (06.00 AM-09.00 PM West Indonesian Time, WIB) on both Sunday (weekend) and during weekdays (Monday, Tuesday, or Wednesday). In total, measurements were taken four (4) times. To obtain concentrations of CO and NO₂, a factory-calibrated portable Aeroqual S500 was used. Aside from sampling, vehicle counting was done using CCTV footage from the Transportation Agency of Surabaya. CCTV cameras were placed in crossroads above the traffic lights to ensure that they captured the traffic volume in all lanes. Wind direction and wind speed were measured using a Kestrel 5500. Temperature and relative humidity were also measured.

2.3 Data analysis
We identified patterns in NO₂ and CO concentrations, and, with the analysis from the CCTV footage, possible sources were also identified. The possible sources of pollution were divided into groups, which were motorbikes, gas-fueled cars, solar-fuel cars, busses, trucks, and others. The volume in each group was counted. The CCTV footage was also used to identify other pollutant sources; these may include smokers, food sellers, trash burning, and so forth.

To obtain variables that may affect the concentrations, multiple linear regression was employed. This analysis was used to see the significance of influence from meteorological condition (wind speed and wind direction), vehicles, day variations, and plant existence towards NO₂ and CO concentrations. Nine independent variables were tested, and six of them were dummy variables. These were the day variable (weekend = 0; weekday = 1), peak time in the morning (1 = yes), peak time at noon (1 = yes), night peak time (1 = yes), vegetation (with plant = 0, without plant = 1), and wind direction. The other three variables were continuous, i.e., temperature, wind velocity, and traffic volume (total number of vehicles).

3. Results
3.1 NO₂ and CO concentration patterns
Figure 3 displays the NO₂ concentrations on Embong Malang St., showing that the weekend and weekdays do not differ much in terms of there being plants or not. It is noted that concentrations on weekdays were higher than they were during the weekend in both cases.

Whenever vegetation was available, the highest concentration on a weekday on this road was 0.288 mg/m³ at 11.45 AM. During peak concentration, the total number of vehicles was 457 in a span of 5 minutes, of which 268 had motorbikes, 139 were gas-fueled cars, 45 were diesel cars, 4 were trucks, there was 1 other vehicle, and no buses went by. The average concentration was 0.136 mg/m³ and the lowest concentration was 0.085 mg/m³.

Whenever there was no vegetation, the highest concentration was slightly lower than with vegetation, at 0.24 mg/m³. The total number of vehicles was 452, with 289 motorbikes, 110 gasoline cars, 50 diesel-cars, 2 buses, 1 truck, and no other vehicles. The peak occurred at 16.20 WIB. However, the lowest and average concentrations were the same or higher than they were with vegetation. The concentrations were 0.136 mg/m³ and 0.178 mg/m³, respectively. This suggests the possibility that there was a surge in pollutants when no plants were present, probably due to rapid traffic increases within a short time or other possible causes, such as smoking activities on the part of the pedestrians.

During the weekend, on the same street, the highest concentrations of NO₂ without plants was 0.195 mg/m³, higher than when vegetation was present, which was 0.167 mg/m³, possibly due to a
significant traffic volume difference. The highest concentrations occurred at 03.35 PM (without vegetation) and 10.00 AM (with vegetation). Traffic during no-plant measurements was at 533 units, significantly higher than during the plant scenario. On average, the concentration was higher whenever vegetation was not present. The average and lowest concentrations were 0.154 mg/m³ and 0.097 mg/m³ (without plants), respectively, compared with 0.119 mg/m³ and 0.076 mg/m³ (with plants), respectively.

Based on Figure 4, it can be inferred that the NO₂ concentrations on Gemblongan St. showed results similar to those for Embong Malang St., where the weekend and weekday concentrations did not differ by much, even though, generally, the NO₂ concentration on weekdays was higher than it was on the weekend.

The highest concentration with plants on the weekend on this road was 0.244 mg/m³ at 09.40 AM. At this peak concentration, there were 412 vehicles on the road. The average concentration was 0.163 mg/m³, and the lowest concentration was 0.141 mg/m³. On the weekdays, the highest concentration was 0.244 mg/m³ at 05.50 PM. At this peak concentration, the number of vehicles was 423. The lowest concentration was 0.142 mg/m³, and the average concentration was 0.175 mg/m³.

In comparison when vegetation was not available, during the weekend, the highest concentration was 0.168 mg/m³, the lowest concentration was 0.077 mg/m³, and the average concentration was 0.118 mg/m³. Unsurprisingly, these values were lower than found on weekdays, where the highest concentration was 0.199 mg/m³ at noon when there were 489 vehicles on the road. The average concentration was 0.129 mg/m³, and the lowest concentration was 0.092 mg/m³.

**Figure 3.** Concentration patterns for NO₂ on Embong Malang St.

**Figure 4.** Concentration patterns for NO₂ on Gemblongan St.
Figure 5 displays that CO concentration on weekdays was higher than on the weekend. The highest concentration on the weekend happened in a location without plants and was 13.11 mg/m³ at 10.40 WIB. At this peak concentration, there were 273 vehicles present. The average concentration was 1.73 mg/m³. For an area with plants, on the weekend, the highest concentration was 4.09 mg/m³. The number of vehicles passing by was 395.

During weekdays, the highest concentration was 14.18 mg/m³ in the area with plants. This happened at 11.30 WIB when 373 vehicles were passing by. The average concentration was 1.54 mg/m³, and the lowest concentration was 0.00 mg/m³. The highest concentration in the location without plants was 14.05 mg/m³, occurring in the afternoon with 583 vehicles passing by. The average concentration was 3.03 mg/m³, and the lowest concentration was 0.00 mg/m³.

Based on Figure 6, it can be inferred that the highest concentration on a weekday in Gemblongan St. were there were plants was 21.71 mg/m³ at 17.15 WIB and with 462 vehicles present. The vehicles included 307 motorbikes, 135 gas-fueled car, 15 solar-fueled cars, 1 bus, 3 trucks, and 1 other vehicle. The highest concentration without plants was 6.96 mg/m³ at 09.40 WIB. The number of vehicles then was 459 with 315 motorbikes, 117 gas-fueled cars, 15 solar-fueled cars, 1 bus, 8 trucks, and 3 other vehicles. The average concentration with plants was 1.73 mg/m³, and without plants it was 1.64 mg/m³. The lowest concentration was 0.00 mg/m³.

For a weekend on Gemblongan St., the CO concentration showed 0.00 mg/m³ for all the highest, average, and lowest concentrations. For the location with plants, the highest concentration on the weekend was 6.71 mg/m³ at 09.35 AM when there were 380 vehicles passing by which consisted of 332 motorbikes, 29 gas-fueled cars, 1 solar car, 8 trucks and no busses or other vehicle. The average concentration was 0.54 mg/m³, and the lowest concentration was 0.00 mg/m³.

Based on Figure 5, it can be inferred that the highest concentration on a weekday in Embong Malang Street was 21.71 mg/m³ at 17.15 WIB and with 462 vehicles present. The vehicles included 307 motorbikes, 135 gas-fueled car, 15 solar-fueled cars, 1 bus, 3 trucks, and 1 other vehicle. The highest concentration without plants was 6.96 mg/m³ at 09.40 WIB. The number of vehicles then was 459 with 315 motorbikes, 117 gas-fueled cars, 15 solar-fueled cars, 1 bus, 8 trucks, and 3 other vehicles. The average concentration with plants was 1.73 mg/m³, and without plants it was 1.64 mg/m³. The lowest concentration was 0.00 mg/m³.

For a weekend on Gemblongan St., the CO concentration showed 0.00 mg/m³ for all the highest, average, and lowest concentrations. For the location with plants, the highest concentration on the weekend was 6.71 mg/m³ at 09.35 AM when there were 380 vehicles passing by which consisted of 332 motorbikes, 29 gas-fueled cars, 1 solar car, 8 trucks and no busses or other vehicle. The average concentration was 0.54 mg/m³, and the lowest concentration was 0.00 mg/m³.
3.2 Variables affecting concentrations of the pollutants

Table 1 shows the result of multiple linear regression for NO$_2$. Based on the results, it can be inferred that the existence of plants, wind direction, wind velocity, and the number of vehicles did not influence the NO$_2$ concentration significantly. The NO$_2$ concentration was affected significantly by the day variable, morning peak hour, noon peak hour, night peak hour, and temperature. The morning peak hour could increase the NO$_2$ concentration by 0.013 mg/m$^3$, while the noon and night peak hours could decrease the NO$_2$ concentration by 0.008 mg/m$^3$ and 0.012 mg/m$^3$, respectively. It can also be inferred that the NO$_2$ concentration was bigger on weekdays compared to the weekend, indicated by the day variable coefficient of 0.016. Everyone degree increase in temperature increased the NO$_2$ concentration by 0.005 mg/m$^3$. As shown in the R$^2$ value of 0.307, the influence of the existing variables (day variable, morning peak hour, noon peak hour, night peak hour, and temperature) can explain 30.7% of the variation in NO$_2$ concentration.

Table 1. Coefficients of variables affecting the concentration of NO$_2$

| Variable                                      | Coeff.  | Std. Error Coeff | p-value | Model R$^2$ |
|-----------------------------------------------|---------|-----------------|---------|-------------|
| Constant                                      | -0.030  | 0.008           | 0.000   | 0.307       |
| Day variable (dummy variable, weekend = 0, weekday = 1) | 0.016   | 0.002           | 0.000   |             |
| Morning peak (dummy variable, peak time = 1)  | 0.013   | 0.003           | 0.000   |             |
| Noon peak (dummy variable, peak time = 1)    | -0.008  | 0.003           | 0.011   |             |
| Night peak time (peak time = 1)              | -0.012  | 0.003           | 0.000   |             |
| Plant (without plant = 1)                    | 0.002   | 0.001           | 0.145   |             |
| Temperature                                   | 0.005   | 0.000           | 0.000   |             |
| Wind direction                                | 0.003   | 0.002           | 0.161   |             |
| Wind velocity                                 | -0.002  | 0.001           | 0.258   |             |
| Volume of Vehicles                            | 4.28E-6 | 0.000           | 0.513   |             |

Table 2 shows the linear regression results for CO, which differ from those of NO$_2$. Based on Table 2, it can be inferred that there were five variables with a significant influence on CO concentration; these are: the day variable, night peak hour, temperature, wind direction, and number of vehicles. The night peak hour saw an increase in CO concentration of 1.486 mg/m$^3$. From the coefficient for the day variable, it can be inferred that the CO concentration was higher on a weekday compared to the weekend by 1.65 mg/m$^3$. Wind direction and the number of vehicles increased the CO concentration by 0.397 mg/m$^3$ and 0.001 mg/m$^3$, respectively. Everyone degree increase in temperature decreased the CO concentration by 0.067 mg/m$^3$. The other variables, i.e., the morning peak hour, noon peak hour, existence of plants, and wind velocity, did not have a significant influence on CO concentration. Table 2 also shows an R$^2$ value of 0.169. This means that the day variable, night peak hour, temperature, wind direction, and amount of vehicle can explain 16.9% of the variability in CO concentration.

Table 2. Coefficients of the variables affecting the concentration of CO

| Variable                                      | Coeff.  | Std. Error Coeff | p-value | Model R$^2$ |
|-----------------------------------------------|---------|-----------------|---------|-------------|
| Constant                                      | 2.063   | 0.705           | 0.004   | 0.169       |
| Day variable (dummy variable, weekend = 0, weekday = 1) | 1.650   | 0.132           | 0.000   |             |
| Morning peak (dummy variable, peak time = 1)  | 0.175   | 0.241           | 0.466   |             |
The NO$_2$ concentration shows a bimodal pattern, as it increases in the morning, decreases in the day, and increases again in the evening. Apart from the traffic contribution, the decrease of NO$_2$ in the day is caused by the NO$_2$ photolytic cycle [8]. The photolytic cycle phase with a direct interaction between sunlight and NO$_2$ causes NO$_2$ to absorb energy in the form of ultraviolet rays and sunlight. The absorbed energy breaks NO$_2$ molecules down into NO molecules and oxygen (O) atoms. The oxygen atoms formed are very reactive and react with atmospheric oxygen (O$_2$), forming ozone (O$_3$) which is another pollutant [9]. The CO concentration in an open location increases when an atmosphere inversion occurs. This phenomenon occurs when colder air is trapped below a warmer layer of air. An inversion acts like a cover, preventing pollution from mixing in the atmosphere and trapping it on the surface. High CO concentration also occur during the morning and evening rush hours [10].

The day variable has a positive influence on both NO$_2$ and CO concentrations. The influence is relatively similar, i.e., a higher concentration on a weekday compared to the weekend, and the p-value indicates that the increase during a weekday is significant. This result is comparable to the research showing that the NO$_2$ concentration was higher by 16% on workday compared to the weekend (Sunday) in Brisbane, Australia [5]. This finding also corresponds to the number of vehicles on the road, as the number was 48% higher on weekdays compared to weekends (Sunday). For CO, the research result was similar to the study that found that the average CO decreased every hour from 06.00 AM to 03.00 PM on Sunday compared to Wednesday on Gemblongan St. [11]. After taking measurements for 9 hours (06.00 AM-03.00 PM), the results of this study are in agreement with other studies, i.e., the CO decreases by 28% from weekday to weekend. The CO concentration on a workday was higher by 21% compared to the weekend (Sunday), which is proportional to the increase in vehicles on workdays [5]. From the research of Blanchard and Tanenbaum, In Southern California, the average CO was more or less 0-17% lower on Saturday and about 12-32% lower on Sunday compared to workdays [12]. Overall, the results show that vegetation reduces both NO$_2$ and CO concentrations.

The results for the NO$_2$ concentration at noon fit the above statement where the NO$_2$ concentration would decrease when the noon peak hour occurred. This is caused by the photolytic cycle. The increasing CO concentration at night was potentially caused by other pollutant sources aside from vehicles. Since the sample measurement was taken from a pedestrian point of view, during the measurement session, most of the time during the afternoon and night, often people, some smoking, would pass the location, get close to the sampling device and even linger. This could have led to a surge in concentration.

Differently, during the night peak hour, the NO$_2$ decreased because the number of vehicles continued to decrease the later the hour became. Based on Figures 1-4, it can be inferred that the trend line for the number of vehicles in the night generally decreased. Therefore, the NO$_2$ concentration also decreased, unlike the CO concentration, which increased due to other factors, such as smokers.

The R$^2$ values obtained for the regression models are relatively small, i.e., 30.7% for NO$_2$ and 16.9% for CO. The small R$^2$ values are caused by other variables influencing the result, such as traffic.

| Variable                        | Coeff. | Std. Error Coeff. | p-value | Model R$^2$ |
|---------------------------------|--------|-------------------|---------|-------------|
| peak time = 1)                  |        |                   |         |             |
| Noon peak (dummy variable, peak | 0.226  | 0.247             | 0.360   |             |
| time = 1)                       |        |                   |         |             |
| Night peak time (peak time = 1) | 1.486  | 0.245             | 0.000   |             |
| Plant (without plant = 1)       | 0.136  | 0.125             | 0.277   |             |
| Temperature                     | -0.067 | 0.019             | 0.001   |             |
| Wind direction                  | 0.397  | 0.169             | 0.19    |             |
| Wind velocity                   | -0.116 | 0.115             | 0.314   |             |
| Volume of Vehicles              | 0.001  | 0.001             | 0.035   |             |
jams, surrounding activities, and other factors not accounted for in this research. Therefore, to increase the R² value, other variables could be added that could probably affect the NO₂ and CO concentrations.

4. Conclusion
Pedestrians are susceptible to exposure to pollutants, especially that coming from traffic activities. Emissions from large and small vehicles have a potentially dangerous impact on health. Despite high concentrations of pollutants during the morning and evening, exposure will be less whenever the sidewalks are lined with vegetation, which acts as natural barrier for pollutants. The wind direction and temperature both influence concentrations of pollutants. It is also noted that traffic volume plays a great role in the ambient concentration.

Considering these facts, regulations should be enacted to protect pedestrians from long exposures to pollutants. The least that policy makers could do is to plant ample vegetation along the sidewalks. This will reduce pedestrian exposure and reduce the health impact, especially during the morning peak times.

5. References
[1] Badan Pusat Statistik 2017 Surabaya dalam Angka. BPS Kota Surabaya, Surabaya
[2] Tugaswati, A.T. 2007. Emisi Gas Buang Kendaraan Bermotor dan Dampaknya terhadap Kesehatan http://www.kpbb.org/makalah_ind/Emisi%20Gas%20Buang%20Bermotor%20&%20Dampaknya%20Terhadap%20Kesehatan.pdf Accessed 27 Oktober 2017
[3] Odekanle E L, Fakinle B S, Jimoda L A, Okedere O B, Akeredolu F A, Sonibare, J A 2017 In-Vehicle and Pedestrian Exposure to Carbon Monoxide and Volatile Organic Compounds in A Mega City Urban Climate 21: 173-182
[4] Zak M, Wolny E M, Widziewicz K 2016 The Exposure of Pedestrian, Drivers and Road Transport Passengers to Nitrogen Dioxide Atmospheric Pollution Research 8(4): 781-790
[5] Morawska L, Jayaratne E R, Mengersen K, Jamriska M, Thomas S 2002 Differences in Airborne Particle and Gaseous Concentration in Urban Air between Weekdays and Weekends Atmospheric Environment 36: 4375-4383
[6] Soedomo M 1999 Kumpulan Karya Ilmiah Mengenai Pencemaran Udara ITB, Bandung
[7] US EPA 2014 Integrated Review Plan for the Primary National Ambient Air Quality Standards for Nitrogen Dioxide. Research Triangle Park, North Carolina
[8] New Jersey Department of Environmental Protection 2017 2016 Nitrogen Dioxide Summary
[9] Damayasa I G O 2013 Dampak NOx terhadap Lingkungan Jurnal Ilmiah Kurva Teknik
[10] New Jersey Department of Environmental Protection 2017 2016 Carbon Monoxide Summary
[11] Blanchard C L, Tanenbaum, S J, Lawson D R 2008 Differences between Weekday and Weekend Air Pollutant Levels in Atlanta, Baltimore, Chicago, Dallas-Fort Worth, Denver, Houston, New York, Phoenix, Washington, DC, and Surrounding Areas Journal of the Air and Waste Management Association 58 (12): 1598-1615
[12] Blanchard C L dan Tanenbaum, S J 2003 Differences between Weekday and Weekend Air Pollutant Levels in Southern California Journal of the Air and Waste Management Association 53 (7): 816-828