The Impact of Public Activity Restriction during COVID-19 to Air Quality in Urban Area of Bandung Measured Using Mobile Monitoring

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ABSTRACT

The COVID-19 outbreak impacted the people’s lives in the world. Lockdown is one way of controlling the spread of the virus. In Indonesia, the government would rather implement public activity restriction than lockdown. The detailed comprehension of the effect of lockdown or similar policies on air pollution is valuable for making future policies about the control of pandemics as well as its effect on air quality. To understand the effect of public activity restriction (PAR) and its correlation with air pollution, mobile monitoring (MM) of particulate matter (PM2.5) was performed in the urban area of Bandung, Indonesia, in July 2021. Based on MM using a bicycle, we found that a PAR had an impact on air pollution. Our result showed that there was a decrease between 20% and 30% in 3 of 6 sub-districts. The advantage of MM was highlighted by the prominent visualization of the concentration of PM2.5 MM data at the level of the road. Localization of polluted roads could be seen clearly through the MM method. The uncovering effect of PAR on air pollution using the MM method will provide important insights for government and policymakers to develop future policy that controls air pollution for better citizen health.

Keywords: PM2.5, Public activity restriction, Air pollution, Partial lockdown, COVID-19

1 INTRODUCTION

Lockdown has been proved to reduce some types of air pollution in several countries (Albayati et al., 2021; Bao and Zhang, 2020; Briz-Redón et al., 2021; Cameletti, 2020). Air pollution in the United States decreased on lockdown (Mendez-Espinosa et al., 2020; Rodríguez-Urrego and Rodríguez-Urrego, 2020). There was a 25.5% decline in the concentration of NO2 and a reduction of PM2.5 because of business closure during lockdown (Berman and Ebisu, 2020). A multicity study in Spain reported that from 11 cities there was an overall reduction of NO2, CO, SO2, and PM10 during lockdown (Briz-Redón et al., 2021). In the Yangtze River delta area, China, primary gaseous pollutants such as SO2, NOx, PM2.5, and VOC have been reduced (Li et al., 2020). It was caused by a reduction in industrial activities, resulting in less emission during the COVID-19 control period. Similar air pollution reduction trends during the COVID-19 controlling policy also happen in Rio de Janeiro (Dantas et al., 2020) and Morocco (Otmani et al., 2020).

In Indonesia, the government has done several measures to reduce and control the spread of the virus. The government has campaigned for social distancing and new normal habits through many mass media. One policy that affects most of the communities is public activity restriction (PAR). As the number of cases increased rapidly at the beginning of July 2021, the government decided...
to do emergency PAR in Indonesia from July 3, 2021, to July 20, 2021, (Lai, 2021; Ministry of Home Affairs, 2021). In general terms, PAR is closely associated with partial lockdown. The main difference between PAR and lockdown was that in PAR, there are no region that was locked completely. The main road that was connected to public places only closed in certain hour to avoid crowd in public places. Nonetheless, this policy extended until July 25, 2021 with some adaptation and relaxation to the regulation based on COVID-19 cases of each province or city. This policy mainly affects the mobility of people and hopefully can control the spread of the virus.

PAR implementation caused limitation of activity from many non-essential sectors. Besides the limitation of work activity, the government also closed some parts of the road to reduce people’s mobility. The purpose of the road closure was to prevent people from going to public places. As a result, traffic was affected by the road closure. The air pollution sources, especially particulate matter (PM) in the urban area were from the vehicle, biomass burning, industries (Lestari and Mauliadi, 2009). The use of vehicle during PAR was generally decreased since most of the office implemented work from home policy. Thus, it is expected that PAR policy is affecting air pollution during the implementation of the policy.

A numerous fixed monitoring station may be needed to map air pollution profiles in high resolution. The mobile monitoring method is a potential approach to measure high spatial resolution data of air quality (Hasenfratz et al., 2015). The study of the lockdown effect during the COVID-19 pandemic using the mobile monitoring method is still limited. Taxi-based mobile monitoring in China was done to measure the change in gaseous pollutants: CO, NO₂, and O₃ (Wang et al., 2021). It is found that the mean concentration of NO₂ and CO decreased by 44–47% as the impact of COVID-19 pandemic. Similar research to measure particle number concentration and black carbon also used the mobile monitoring method by deploying an electric car carrying a TSI condensation particle counter (CPC; Models 3783 and 3775) and Magee Scientific Aethalometer Model AE33 (Hudda et al., 2020). The reduction in traffic volume during the COVID-19 lockdown period resulted in lower black carbon and particle number concentrations. These studies generally, discuss and compare the air pollution condition before, during, and after COVID-19 lockdown. In the previous study, we have implemented the mobile monitoring system to evaluate the air quality of a residential area that located near major road and toll road (Munir et al., 2022). We found that the mobile monitoring system that was designed could show a prominent pollution level between residential and road area which covers an area of around 3 km². In current study, we would like to apply the mobile monitoring system to observe how the PAR policy would affect the pollution level and distribution in larger area and different road condition.

To date, no literature of which we are aware has reported changes of air pollution using low-cost PM sensor and MM method in the urban area (< 5 km²) during the implementation of public activity restriction which is different from lockdown. Previous study by Wang et al. (2021) was done to observe three gaseous pollutants during COVID-19 lockdown in China. The observation was done using a taxi in order to generate high resolution data. The mean concentration of NO₂ and CO were decreased during the lockdown. Another research using mobile monitoring was conducted in Massachusetts (Hudda et al., 2020). Hudda et al. (2020) observed the COVID-19 lockdown effect to the black carbon and particle number concentration using a car to capture the concentration of the pollution in urban area. A significant decrease in the air pollutants, namely black carbon and particle number was observed during the COVID-19 lockdown. In current study, the policy itself was different than lockdown, especially the introduction of uneven road access during the implementation of PAR. The road closure policy as part of PAR is done on such a micro-scale compared to the area of the city. Lockdown and PAR may differ in term of the area and time of which the policy implemented. Lockdown may refer to general restriction on whole area of a city, while in PAR only certain region/roads that was limited during a time period. It is expected to observe a more distinct PM level difference at the level of road segment during PAR rather than lockdown. The uneven road access restrictions will manipulate the traffic flow which could affect the air pollutant in several roads, whereas lockdown generally restricts the activity of the people in the area without road access manipulation. Our objective is to capture PM₂.₅ profiles during PAR time using the mobile monitoring method. The vehicle is prohibited to pass a certain road, which will affect the PM level in the closed road during PAR. The mobile monitoring method offers high spatial resolution as a trade-off to temporal resolution (Wang et al., 2021). Thus, it should be noted that the air dynamic of surrounding microenvironment during observation was
beyond the scope of this study. The profiles of PM$_{2.5}$ will be shown as mapping of each points of measurements during the study. This study mainly analyzes the correlation of PAR on air quality, especially the concentration of PM$_{2.5}$ by using the mobile monitoring system. This study also highlight how PAR policy could cause a localization of PM as the result of uneven road access distribution across the area during PAR.

2 METHODS

2.1 Study Area and Research Design

Bandung City, the provincial capital of West Java, has an area of 167.31 km$^2$ at an altitude of 768 m. The total population of Bandung is 2.4 million with a population density of 14,549.88 per km$^2$. The sampling route in the area of interest is selected from areas around the center of the city. The route passes various roads that either open or closed during PAR. Main places that may be crowded by vehicles and act as a possible source of pollution such as shopping centers and town squares are passed by the vehicle. The route of the research area can be seen in Fig. 1. The area is approximately 1.8 km$^2$ and the route traveled is around 11 km.

The subdistricts in this study generally have similar characteristics. The route passed road with shop, shopping center, public area (garden, town square, etc.), and other places. Several landmarks that could describe the condition in the subdistricts are as follows. A large park, Tegallega, is located on the side of road 4. This park dominated with tree and open spaces for the community to jog or exercise. Road 5 was dominated with shops and offices. The town square is located near road 6, in this area there is also mosque, banks, and tourist attractions. There are 2 big shopping malls that was passed by the route: an electronic shopping center (road 7) and a mall (road 1).

This study focuses on the time when the road closure is implemented. The schedule of road closure is on 08:00–11:00, 13:00–16:30, and 18:00–05:00 (UTC+07:00). It is expected to have at least two datasets from the same route during road closure conditions and normal road conditions at different times of the day. The investigation was not done during bad weather. Table S1 shows the weather and data collection time for 23 days.

The bicycle is chosen as the mode of transportation in this study since it is only possible to pass the road closure using a bicycle rather than other vehicles such as motorcycles or cars. Each collection of datasets along the route takes between 50 and 120 minutes. The device is placed on the front of the rider's chest at a height of about 1.25 m from the ground. Every 10 seconds the
position, temperature, humidity, and concentration of PM$_{2.5}$ data were measured and sent to the server. After each run of data collection, the weather conditions were recorded on a logbook.

We group the data based on the condition during the measurement. The condition is explained as the condition of the road and implementation of PAR. “Closed” means that the measurement is on the location in which part of the road is closed while “Open” means the measurement is on the part of the road which is opened. PAR implementation is indicated by “Yes” and “No” conditions. During the implementation of PAR (“Yes”), the closed road could not be passed by the vehicle. The part of the closed road could be passed in “No” condition. The condition of the open road means that the road could be passed by the vehicle in both “Yes” and “No” condition. For example, Closed-No condition means that the data is measured on the part of the closed road when there is no implementation of PAR. After the implementation of emergency PAR was ended (after July 20, 2021) all the data is categorized as “No” condition. The detailed part of the road that is opened and closed during the implementation of PAR is depicted in Fig. 1.

2.2 Data Collection

The device used in this study consists of a low-cost PM sensor HPMA (Model HPMA115S0, Honeywell, United States of America) and a temperature-humidity sensor Asair (Model AM2301, Guangzhou Aosong Electronics Co., Ltd., China). The HPMA sensor and the system has been calibrated which has been explained elsewhere (Hapidin et al., 2019; Munir et al., 2022). This device is connected to an Android phone through a Wi-Fi connection. The smartphone GPS is used to determine each coordinate of measurement. An Android application is made to do this task and send the data to the cloud server. Later, the data can be downloaded from the website for further analysis.

In the other hand, meteorological data on daily average temperature, relative humidity, and wind speed in this study is obtained from the Meteorological, Climatological, and Geophysical Agency website (BMKG, 2021). Since there is only one meteorological station in Bandung, the meteorological data for each sub-district is considered the same. The data from meteorological station is used to do correlation analysis between meteorological and PM concentration. The mobile device also included a temperature and humidity sensor to provide more relevant data for PM reading correction.

2.3 Data Processing

The data is processed using some software which are Microsoft Excel, RStudio (R Core Team, 2021; RStudio Team, 2023), and QGIS (QGIS Development Team, 2021). Excel and RStudio are mainly used to do data preprocessing and descriptive statistics in this study. We did a Kruskal-Wallis and Wilcoxon rank test to analyze the difference between the data by its subdistrict. The test was initially done based on the condition of PAR then by its subdistrict. The result of this test could determine which pair of subdistricts that had significant PM concentration difference. QGIS was used to visualize the data on the map.

The reading of low-cost PM sensor may be affected by several factors such as the difference of PM refractive index, environmental change such as moisture that lead to reading failure (Wang et al., 2015), scattering of LED or laser of the PM sensor by moisture on high relative humidity environment (Jayaratne et al., 2018), and hygroscopic growth affecting the size of PM (Crilley et al., 2018). As weather especially the humidity is varying in time of observation, correction to the data is needed to get corrected PM concentration. The PM concentration is corrected using Eq. (1) based on $\kappa$-Köhler theory (Crilley et al., 2018).

\[
\text{PM}_{\text{corrected}} = \frac{\text{PM}_{\text{raw}}}{C}
\]  

\[
C = 1 + \frac{1.65}{1 - 1 + \frac{\kappa}{\sigma_w}}
\]
The term $\alpha_w$ is water activity (ambient RH/100) and $\kappa$ is hygroscopicity parameter. To correct PM$_{2.5}$ data, we choose $\kappa$ to be 0.4. Crilley et al. (2018) found that $\kappa$ value is between 0.38 to 0.41 for PM$_{2.5}$ (Crilley et al., 2018). We decided to correct all the PM$_{2.5}$ data using this method as the RH in all data sets is quite large. We discarded measurement data with RH more than 95%.

The fixed monitoring station could provide all-day pollution level in a certain area; however, it would need numerous of fixed monitoring station to get higher spatial resolution. High spatial resolution data from mobile monitoring is presented in this study to map the PM concentration in higher spatial resolution in the specific time period. Although both fixed and mobile monitoring method has their own advantages and disadvantages, the mobile monitoring method is more favorable in this study.

3 RESULTS AND DISCUSSION

Statistical analyses of the data showed interesting results from the measurement of the concentration of PM$_{2.5}$. As we expected, there were specific areas with a lower concentration of PM$_{2.5}$ than other areas. The area with a low concentration of PM$_{2.5}$ is on a closed road during the implementation of PAR.

3.1 Meteorological Condition Pollution Levels

The daily temperature and RH were shown in Fig. 2. During the test there was a variation of weather which was documented by visual observation (Table S1). We could calculate the average and coefficient of variance (CV) of temperature and RH. The average daily temperature and RH are $23.24 \pm 0.73^\circ C$ and $72.95 \pm 7.47\%$, respectively. The CVs are 3.1% for temperature and 10.2% for RH. The variation of temperature and RH was relatively small during the study periods. Some extreme changes may happen due to different weather condition of each day. In addition, we calculated the Spearman correlation between meteorological and PM concentration which was explained in the supplementary content (Fig. S3).

The heatmap of several pollution PM$_{2.5}$, SO$_2$, NO$_2$, and CO from a fixed monitoring station was presented in Fig. S6. In general, the gaseous pollution level was lower at midnight to morning time which means that the traffic activity was at its lowest. However, even though the PAR policy implemented almost in the entire July 2021, the changes of pollutant level did not happen every day. PM$_{2.5}$, SO$_2$, and NO$_2$ level generally reach the lowest level at 8:00–18:00 (UTC+7). The CO level

![Fig. 2. Daily temperature and RH during study period.](https://example.com/fig2.png)
was also affected by a slight decrease at 12:00–18:00 (UTC+7). The pattern of NO is different from previous study that was conducted in China in 2015–2018 (Kuerban et al., 2020). In our study we found that the NO level generally low in the morning until afternoon and start to rise at the night. In contrast, pollution level in previous study is at peak around 8:00–9:00 in the morning since it is the peak hour for commuting (Han et al., 2011; Kuerban et al., 2020). During PAR implementation, many offices implemented work from home thus reducing the use of transportation in the morning.

3.2 The Concentration of PM$_{2.5}$ by Sub-district in Different Cases

The descriptive statistics on PM$_{2.5}$ measurement using MM were categorized into different cases. Based on each measurement location, the sub-district of measurement can be determined. The data were grouped by the condition of the road (Open/Closed) and implementation of PAR (Yes/No). Next, based on the time and date of measurement we determine which data were measured when the PAR was implemented. The average PM concentration presented in Fig. 3 was calculated from all days of observation. However, if the results were compared on the same day, there was difference PM concentration for some road segments. For the record, the route that passed the sub-district of R is only on the open road since the road closure policy was mainly implemented in areas that were close to the center of the city.

The case when the measurement was done on the closed road and PAR was implemented (Closed-Yes) was presumed as the possible lowest concentration of PM$_{2.5}$ as there was almost no source from vehicle on the closed road during the implementation of PAR. The average concentration of PM$_{2.5}$, in this case, were 16.3 μg m$^{-3}$, 15.9 μg m$^{-3}$, 15.5 μg m$^{-3}$, 19.3 μg m$^{-3}$, and 20.1 μg m$^{-3}$ for sub-district A, AA, BW, C, and S, respectively. On contrary, we could compare those averages to the case when we measured the concentration of PM$_{2.5}$ on the open road and the time when PAR was not implemented (Open-No). The average concentration of PM$_{2.5}$ for such case was 23.2 μg m$^{-3}$, 23.2 μg m$^{-3}$, 20.1 μg m$^{-3}$, 19.6 μg m$^{-3}$, 21 μg m$^{-3}$, and 19.4 μg m$^{-3}$ for sub-district A, AA, BW, C, R, and S, respectively. The concentration of PM$_{2.5}$ was reduced by about 20–30% for sub-districts A, AA, and BW. This could suggest that the road closure policy was an example of controlling air pollution as well as reducing people's mobility.

![Fig. 3. The average concentration of PM$_{2.5}$ by sub-districts. The data were grouped into the condition of the road and implementation of PAR.](https://aaqr.org)
3.3 Effect of Road Closure to Concentration of \( \text{PM}_{2.5} \)

During emergency PAR, the city needed to close several roads in the city. The reason for this closure of the road was to reduce people’s activities especially visiting public places such as parks and shopping malls. As a result, a vehicle such as a motorcycle, car, and public transportation cannot pass several roads. Our observation showed that the closure of the road affected the concentration of \( \text{PM}_{2.5} \) in some areas while there was no effect on other areas.

The Kruskal-Wallis (KW) and Wilcoxon rank test was done to evaluate the mean of PM concentration between the group by the condition of PAR. The KW-test showed a \( p \)-value of \( 1.5 \times 10^{-6} \) which tell that there is a significant difference between PM measurement of “Yes” and “No” condition. Then, we did KW-test based on Subdistrict group and condition of PAR. The summary of KW-test could be seen in Figs. S4–S5. The PM concentration of between subdistrict A, AA, BW, and R are all significantly different during no implementation of PAR. We could see that when the PAR is not implemented, the PM concentration in every subdistrict is various. This could happen due to variation of traffic condition in each subdistrict. In contrary, in “Yes” condition of PAR, there was only some groups that have significant difference. The group that were significantly different were A-AA, A-BW, AA-C, AA-R, AA-S, BW-R, BW-S, BW-C, and C-R. We could see that there were several subdistricts that contain route with only open road, only closed road, or both conditions. The pair of groups that showed \( p \)-value > 0.05 could be interpreted that the PM level during implementation of PAR are not significantly different between each subdistrict. However, subdistrict BW and C showed significant differences since it only has closed road and open road, respectively. In addition, the subdistrict BW (only closed road) also showed significant difference with subdistrict R (only open road) and S (mixed open and closed road).

We compared our measurement during the pandemic with other literature that measured the concentration of \( \text{PM}_{2.5} \) in Bandung. Snider et al. (2016) measured the concentration of \( \text{PM}_{2.5} \) in several cities using filter-based measurement. The two years (2014–2015) average concentration of \( \text{PM}_{2.5} \) in Bandung is 31 \( \mu \text{g m}^{-3} \). Sinaga et al. (2020) did the latest measurement of \( \text{PM}_{2.5} \) in Bandung which daily average result for the dry season period (July–September 2019) is 39.2 ± 13.5 \( \mu \text{g m}^{-3} \). Our results (Fig. 2 and Table S2) in all sub-districts, condition of PAR, and condition of the road, the concentration of PM was generally lower than the previous measurement by Sinaga et al. (2020). This implementation of PAR may have mostly affected the reduction of \( \text{PM}_{2.5} \).

The decline of air pollution also happened in various countries implementing lockdown as a controlling policy of COVID-19 (Anugerah et al., 2021; Berman and Ebisu, 2020; Brit-Redón et al., 2021; Dantas et al., 2020; Li et al., 2020; Morales-Solís et al., 2021; Otmani et al., 2020; Rendana, 2021). Some studies in Jakarta, the capital city of Indonesia showed improvement of overall air quality based on reduction of \( \text{SO}_2 \), \( \text{NO}_2 \), \( \text{CO} \), and PM during large scale social restriction (LSSR) (Anugerah et al., 2021; Pardamean et al., 2021; Pramana et al., 2020; Santoso et al., 2021). A study in South Sumatra, Indonesia also showed a decrease in air pollution during the LSSR period (Rendana, 2021). Our research gave a similar result on the reduction of air pollution during PAR in several sub-districts. Nevertheless, there was still a possibility that the PAR did not affect air quality such as in Jakarta that showed an increasing concentration of \( \text{PM}_{10} \) due to the southwest monsoon (Anugerah et al., 2021). After all, we could show the PAR effect in reducing the concentration of \( \text{PM}_{2.5} \) in some areas while there was no effect on other areas.

The fossils fueled (gasoline, diesel) vehicles, motorcycle, industries emission, and biomass burning were the main source of \( \text{PM}_{2.5} \) in Bandung (Lestari and Mauliadi, 2009). Since there was almost no vehicle passing the closed road, the \( \text{PM}_{2.5} \) around the closed road was less than the opened road. The variation concentration of \( \text{PM}_{2.5} \) in the level of the segment of the road could be seen clearly. Nevertheless, this prominent variation between closed and opened roads was not always happened on all days of observation. During the closure of the road, we could see a prominent variation between closed and opened roads (Fig. S1). The difference between closed and opened road was various in each day between 25–100%. The observation time could be the factor that caused this prominent effect of road closure to the concentration of \( \text{PM}_{2.5} \). When the road has just closed, there may still many particles from the vehicle in the air. As time goes by, the concentration of \( \text{PM}_{2.5} \) will decay especially on the closed road which was not passed by any vehicles.
vehicle. Decay of concentration of PM also occurred after cooking in indoor cases (Kim et al., 2018). The effect of wind speed, which was discussed in the previous section, also may have contributed to the dispersion of air pollutants in the urban area.

On the other hand, the variation (Fig. S1) between the closed road and normal road did not seem prominent at the normal time (“No” condition). After the emergency PAR ended (see Fig. S2), variation between road segments was reduced especially after the road closure was not implemented anymore. This could happen due to less variation in traffic condition in “No” condition since all road could be passed by vehicle. A study about car free day area policy in Bandung found that it impacts the traffic network (Farda and Balijepalli, 2018). Car free day area is implemented on only some roads in a specific time. This policy has been implemented before COVID-19 PAR. The study found that the car free day tend to divert the vehicle to alternative route, and it could result in lower emission around car free day area but could increase the pollution or causing congestion elsewhere. The condition of car free day was analogous to the condition of “Closed” road. We have shown that there was a difference of PM level between “Closed” and “Open” road during the implementation of PAR. This study showed one benefit of the mobile monitoring method which was its ability to map the concentration of particulate matter in high spatial resolution. As depicted in Fig. 4, it can be seen the localization of a relatively high concentration of PM2.5 on the open road compared to the closed road.

4 CONCLUSIONS

This study presents the effect of public activity restriction (PAR) as an adaptation of partial lockdown in the context of the COVID-19 pandemic on the concentration of PM2.5 in Bandung, Indonesia. Road closure policy as a part of PAR implementation has not automatically reduced air pollutants in all areas. The dispersion of PM2.5 could be affected by other meteorological factors such as wind speed. Nonetheless, 3 of 6 sub-districts show a 20–30% reduction in the concentration of PM2.5 during PAR in a closed road.

The maximum wind speed correlated with higher PM2.5. This could happen since low wind speed prevents PM2.5 dispersion in urban areas. Therefore, the usage of mobile monitoring is needed to provide high spatial resolution data of PM2.5 levels. Our result is proved to be able to visualize the prominent variation of PM2.5 levels on the level of the road segment, especially during the PAR implementation period. In sum, the result of this study could help policymakers and the government to make the best decision regarding air pollution control.
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ADDITIONAL INFORMATION AND DECLARATIONS

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Declaration of Competing Interest

The authors declare no competing interests.

Supplementary Material

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