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Did air pollution continue to affect bike share usage in Seoul during the COVID-19 pandemic?

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ABSTRACT

Introduction: The role of cycling has become more important in the urban transport system during the Covid-19 pandemic. As public transport passengers have tried to avoid crowded vehicles due to safety concerns, a rapid surge of cycling activities has been noted in many countries. This implies that more cyclists might be exposed to air pollution, potentially leading to health problems in cities like Seoul where the level of air pollution is high.

Methods: We utilised three years of bike sharing programme (Ddareungi) data in Seoul and time series models to examine the changes in the relationship between particulate concentration (PM$_{2.5}$) and total daily cycling duration before and during the pandemic.

Results: We find that cyclists reacted less to the PM$_{2.5}$ level during the pandemic, potentially due to the lack of covid-secure travel modes. Specifically, our results show significant negative associations between concentrations of PM$_{2.5}$ and total daily cycling duration before the pandemic (year 2018 and 2019). However, this association became insignificant in 2020.

Conclusions: Building comprehensive cycling infrastructure that can reduce air pollution exposure of cyclists and improving air quality alert systems could help build a more resilient city for the future.

1. Introduction

Cycling has played an important role in urban transport systems during the coronavirus pandemic. A rapid surge of cycling activities has been noted in many countries, and several cities have utilised this opportunity to improve their cycling infrastructure (Adkins, 2021; Buehler and Pucher, 2021; Hong et al., 2020). As public transport passengers have tried to avoid crowded vehicles due to concerns over the transmission of the virus, cycling seems to have been a viable alternative to private cars during the pandemic.

Cycling has been a key research topic for several decades due to its substantial health and environment benefits (Oja et al., 2011; Gotschi et al., 2016; Pucher and Buehler, 2008; Unwin, 1995). Increased levels of cycling could reduce car-dependency and improve public health. However, cyclists are vulnerable to traffic collisions and air pollution, potentially reducing the health benefits of cycling. Although several studies have shown that the health benefits of cycling outweigh the negative effects of air pollution exposure or traffic collisions (Tainio et al., 2016; Schepers et al., 2015; Hartog et al., 2010; Mueller et al., 2015), a body of research on the air pollution...
Seoul, South Korea, has suffered from a high level of air pollution for several years, and has adopted various policies and regulations to improve air quality (Kim et al., 2020). For example, the government introduced ambient air quality standards updated in 2015. In addition, an air pollutant emission cap management system was implemented in Seoul in 2008 (Trnka, 2020). Health concerns over air pollution have grown continuously, and have become a key political issue (Mccurry, 2019). During the pandemic, cycling activities have increased while public transport ridership has decreased substantially in Seoul. Car traffic has also decreased but to a much lesser extent.

Other studies have emphasized the importance of information/knowledge for influencing environmental behaviours (Tan and Xu, 2016; Maizlish et al., 2017). Several studies showed the net positive health benefits of cycling despite the air pollution exposure. Some argued that the level of air pollution exposure of cyclists or pedestrians is not as high as that of drivers or public transport passengers (De Nazelle et al., 2012; Cepeda et al., 2017) while other studies showed the opposite results (Vouitis et al., 2014; Wang et al., 2021; Briggs et al., 2008). Importantly, the high inhalation doses of cyclists compared to drivers or public transport passengers (Apparicio et al., 2018; Borghi et al., 2021) were reported in several studies, potentially resulting in relatively worse health effects on cyclists compared to other travellers. Moreover, short and long-term exposure to air pollution causes serious health issues (Kampa and Castanas, 2008), leading to active research on cycling and air pollution exposure (Weichenthal et al., 2011; Lu et al., 2019; Raza et al., 2018; Tran et al., 2020). It is also worth noting that these health effects studies rely heavily on dose-response function assumptions, which could result in substantial variations in results.

A limited number of studies have examined how cyclists change their travel behaviour to mitigate the adverse effects of air pollution. For example, using their own survey, Zhao et al. (2018) investigated the reactions to air pollution (PM$_{2.5}$) across different groups of cyclists. Their result showed that female cyclists are more sensitive to air pollution than males. In addition, income and the perception of safety and comfort are important determinants of cycling in hazy weather. Anowar et al. (2017) examined the extent to which cyclists are willing to trade-off air pollution exposure with other factors such as travel time. Their results indicated that cyclists would change to routes with a low level of air pollution if it added only a small amount of time (less than 4 min). Other studies also provide evidence of behavioural changes (e.g., reduction in outdoor activities) in response to high levels of air pollution (An et al., 2017; Roberts et al., 2014; Cole-Hunter et al., 2015). These studies imply that cyclists are likely to change their behaviour (e.g., shift to other transport modes) to avoid or reduce their exposure to air pollution. Some research also showed that the behavioural response may be stronger in highly polluted areas such as Seoul (Jun and Min, 2019).

In this paper, we examined how the total volume of trips on shared bicycles changes in response to the level of particulate matter (PM$_{2.5}$) before and during the pandemic. Specifically, we investigated the relationship between the level of PM$_{2.5}$ and total daily cycling duration between 2018 and 2020 by utilising bike sharing programme (Ddareungi) data from Seoul, South Korea and time series regression models. The results will provide empirical evidence for environmental and transport planners for making better plans in the future.

### Table 1

Changes in vehicles and public transport usage.

|                      | 2019 | 2020 | Reduction |
|----------------------|------|------|-----------|
| Motorised vehicles$^a$ | 10,586 | 10,091 | −495 (−4.7%) |
| Public transport passengers$^b$ | 10,445 | 7767 | −2678 (−34.5%) |

Unit: thousand vehicles/people per day.

$^a$ Daily average (0–24hr) traffic collected at 135 common points in 2019 and 2020 (https://topis.seoul.go.kr/refRoom/openRefRoom_2.do).

$^b$ Passengers of mass public transport modes (subway lines 1–9 and Wui New Line, local buses, and community buses (https://news.seoul.go.kr/traffic/archives/31616.).

It is worth noting that cycling activities have increased as shown in Fig. 2.
Some acknowledged that disseminating information on air pollution through smartphone apps or other air pollution alert systems could be an effective way to promote behaviour change. Saberian et al. (2017), for instance, evaluated the effectiveness of air pollution alert programmes on the reduction of cycling volumes, and found a reduction of between 14% and 35% when an alert was issued.

A body of research has examined the relationship between the built environment and air pollution exposure for active travel users (Hankey et al., 2012; Farrell et al., 2016). Air pollution dispersal depends on various factors such as meteorological conditions, geographic features and the characteristics of sources. Built environments and traffic conditions are also important factors, leading to variations in the level of air pollution exposure within a city (Zhou et al., 2018; Miskell et al., 2015). Jarjour et al. (2013) showed that cyclists could reduce traffic-related air pollution exposure by choosing low-traffic bicycle boulevards. Weichenthal et al. (2014) argued that traffic conditions and built environment factors are the most important determinants of ultrafine particles and black carbon concentrations in a city. Gilliland et al. (2018) also showed the substantial variations in the air pollution exposure level within routes, and land use factors are closely associated with air pollution exposure. Interestingly, street trees and high residential land use have negative relationships with PM$_{2.5}$ concentrations.

In sum, previous studies provide evidence that travellers will adapt their travel behaviour to lower their exposure to air pollution although there are still limited empirical studies, especially for developing countries (Zhao et al., 2018). This trend can be reinforced through information/knowledge dissemination strategies. In South Korea, air pollution issues have been a key political issue, and the effect of making real-time air quality information available on outdoor activities has already been evaluated (Yoo, 2021). However, there is a lack of empirical studies about how cyclists react to high levels of air pollution in South Korea, and how this relationship changed before and during the pandemic. In this study, we utilised three years of bike sharing programme data and time series models to examine the relationship between PM$_{2.5}$ concentrations and total daily cycling duration before and during the pandemic. It is worth noting that the intention of this study is to investigate the overall relationship between PM$_{2.5}$ concentrations and total daily cycling duration rather than examining individual level behaviour with detailed characteristics of cyclists. The overall relationship represents the sum of individual relationships. This approach does not require information of individual characteristics and these are not included in the bike sharing programme data. In addition, the chosen approach is appropriate to answer our key research question (i.e., how did the overall relationship between PM$_{2.5}$ concentration and total daily cycling duration change before and during the pandemic?).

3. Data and analytical model

Seoul is the capital of South Korea with a population of approximately 10 million inhabitants. It is considered as a global city and has a comprehensive public transport network. For example, the subway system has 9 lines, 302 stations and about 327 km of track...
More than 10 million passengers per day have used the public transport system in Seoul since 2013 except in 2020 (about a 34% reduction due to COVID-19). Total modal shares of buses and subway in 2019 were about 24% and 41.6%, respectively. During the pandemic, several government interventions (e.g., social distancing, reduction of public transport services, work/study from home for some government workers and university students) were introduced although there was no lockdown in Seoul. The government also urged companies to adopt flexible work hours and to facilitate working from home to reduce the transmission rate of the virus at the workplace (Cha, 2020). These interventions reduced total traffic volumes. However, public transport ridership reduced significantly (Cho and Yoon, 2020) while coping with these new interventions. In addition, the frequency of public transport services dropped for certain times of day (e.g., after 10pm), potentially increasing the use of other transport modes (e.g., cars or bicycles).

Ddareungi is the official bike rental service provided by the Seoul metropolitan government since 2015. In 2021, there were 3040 bike stations in Seoul, and they are well connected with the public transport system. Fig. 1 shows a map of Ddareungi stations and the subway system in Seoul. We can easily see that most Ddareungi stations are located along the subway lines and near stations. The number of registered users has increased substantially. During the pandemic, rentals increased by about 24% compared to 2019. For the analysis, we utilised three-years of Ddareungi data (2018–2020). Data are publicly available (http://data.seoul.go.kr/dataList/OA-15246/F/1/datasetView.do). Since there is only one bike rental service in Seoul, the data include all rental cycling activities in Seoul. In addition, three years of data allow us to consider a time trend in rental cycling activities while examining the changes caused by the COVID-19 pandemic with a time series model. Data include aggregated information on total rentals, distances, and durations according to date, station, age, gender and membership. After processing, we have total 1092 observations (2018: 363 days; 2019: 363 days; and 2020: 366 days). For the main analysis, we calculated total daily cycling duration (the daily sum of the time each bike was rented for) and used it as a dependent variable since it is the most relevant measure for air pollution exposure. We took a square-root transformation due to the skewed distribution of total daily cycling durations. It is worth noting that the characteristics of bikeshare users may be different from general cyclists. For example, Buck et al. (2013) compared personal and travel characteristics of bikeshare users in Washington D.C. (from two bikeshare member surveys) with those of area cyclists (from the regional travel survey). Their results showed that bikeshare users are more likely to be female, younger and have fewer bicycles than general cyclists. In addition, they tend to cycle for utilitarian purposes more than general cyclists. Therefore, our results should be interpreted with care.

Fig. 2. Average total daily rental cases and durations across the day of week.

https://news.seoul.go.kr/traffic/archives/31616.
https://news.seoul.go.kr/traffic/archives/285.
https://news.seoul.go.kr/traffic/archives/504919. About 900 new bike stations were installed in 2021.

It is worth noting that square-root transformation seems to perform better than log-transformation based on residual analyses.
Fig. 2 shows the average total daily total number of bicycle rentals and trip durations across the days of week between 2018 and 2020. We can see the substantial increases in total rentals and durations since 2018. Average total rentals show that people used Ddareungi more on weekdays compared to weekends. This implies that Ddareungi served as an effective travel mode for daily activities and potentially first-last mile connection based on its excellent connections to the public transport system. Interestingly, people spent more time cycling during the weekend than weekdays even though the number of rentals is lower. This could be due to leisure and exercise activities during the weekend, and most weekdays trips (e.g., first-last mile of commute or connection) are short ones.

The seven-day moving averages of total daily cycling durations are shown in Fig. 3. The cycling durations increased in spring and autumn but decreased rapidly during the middle of summer. This could be due to the high temperatures and typhoons in summer in Seoul. This indicates that seasonal effects and weather conditions should be controlled for in the main analyses.

We chose to quantify air pollution using the concentration of fine particulates (PM$_{2.5}$ i.e., particles with a diameter of 2.5 μm or less). PM$_{2.5}$ data for Seoul can be downloaded from the Seoul government website (https://cleanair.seoul.go.kr/statistics/dayAverage). Data provide the PM$_{2.5}$ level of 25 Gu (administrative districts) in Seoul. We calculated daily average PM$_{2.5}$ levels across 25 districts from 2018 to 2020, and used it as the key independent variable. Fig. 4 shows the average levels of PM$_{2.5}$ varied across years. There were significantly higher levels of PM$_{2.5}$ in winter in 2019. In general, PM$_{2.5}$ levels are high during winter and spring. Although the average level of PM$_{2.5}$ in 2020 is lower than that of 2019 (possibly due to the Covid-19 effects), a significant number of days in 2020 has much higher level of PM$_{2.5}$ against global standards (i.e., 35 μg/m$^3$ and 25 μg/m$^3$). It implies that cyclists in Seoul, as in other developing countries, are more at risk of being affected by the harmful air pollutants than those in developed countries. Weather information was obtained from the NOAA Integrated Surface Database by using the worldmet package in R.

For the main analyses, we utilised a linear regression model with an auto regressive moving average (ARMA) error term. The lag
structure was selected using the auto.arima function from the forecast package in R \cite{Hyndman2008}. It searches for the best ARIMA model based on several measures of model fit such as AIC and BIC. First, we examined how PM levels are related to the total daily total cycling duration with an interaction term of Year and PM$_{2.5}$. The year variable ($X_{\text{year}.t}$) represents the pandemic period (2020), and the interaction term ($X_{\text{year}.t} \times X_{\text{PM2.5}.t}$) indicates how the relationship between total daily cycling duration and PM$_{2.5}$ varies before and during the pandemic.

\[
\sqrt{Y_{\text{total daily cycling duration}.t}} = F(X_{\text{day of week}.t}, X_{\text{season}.t}, X_{\text{weather}.t}, X_{\text{year}.t}, X_{\text{PM2.5}.t})^t = 1, \ldots, 1092 \text{ days} \tag{1}
\]

where, $X_{\text{day of week}.t}$, $X_{\text{season}.t}$, $X_{\text{weather}.t}$, $X_{\text{year}.t}$ and $X_{\text{PM2.5}.t}$ represents day of the week (i.e., Monday to Sunday), season (i.e., spring, summer, autumn and winter), weather (i.e., max wind speed (m/s), average temperature ($^\circ$C) and total precipitation (mm)), year of 2020 and PM$_{2.5}$ level, respectively.

Secondly, we modelled the relationship between PM$_{2.5}$ levels and total daily cycling duration for each year while controlling for day of week, season, and weather factors. The results will confirm how people reacted to the PM$_{2.5}$ level for each year, and how this relationship changed before and during the pandemic.

4. Results

Table 2 shows the empirical results for the relationship between PM$_{2.5}$ levels and total daily cycling duration with an interaction of Year and PM$_{2.5}$. It shows that more time was spent cycling during weekends compared to Monday. This confirms what we saw in Fig. 2. Although there are fewer rentals during the weekends compared to weekdays, people might use Ddareungi for leisure or exercise purposes during the weekends, resulting in longer trips. In addition, shorter duration trips on weekdays compared to weekends supports the hypothesis that Ddareungi was used as a feeder transport mode. Seasonal variables show that people used Ddareungi for more time in autumn compared to winter while controlling for other factors including weather conditions. In addition, all three weather variables are statistically significant at the 0.05 level of significance, and results are consistent with previous studies. As maximum wind speed or total precipitation increases, total daily cycling duration decreases significantly. On the other hand, total daily cycling duration increases as average temperature increases.

Year was not statistically significant. This is not a surprising result. Our testing procedure suggested that the dependent variable should be differenced to induce stationarity. This has the effect of removing a trend from the data. After this procedure, and controlling for our other variables, it seems 2020 was not different from previous years. PM$_{2.5}$ shows a negative and statistically significant association with daily total cycling duration before the year of 2020 (i.e., the reference group). It implies that cyclists adopted behavioural changes to mitigate harmful effects of air pollution exposure before the pandemic. Interestingly, the coefficient of interaction between Year and PM$_{2.5}$ is positive and statistically significant at the 0.05 level of significance. It means that cyclists did not react to the PM$_{2.5}$ level to the same extent during the pandemic compared to pre-pandemic periods (i.e., 2018 and 2019) while all other factors were constant.

We modelled each year separately to examine the changes in the relationship between PM$_{2.5}$ level and total daily cycling duration

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Table 2
Result of the relationship between PM$_{2.5}$ level and total daily cycling duration with the full sample (ARIMA (1,1,2)).

| Day of week (ref: Monday) | Estimate | Standard errors | p-value |
|---------------------------|----------|-----------------|---------|
| Tuesday                   | 9.312    | 17.792          | 0.589   |
| Wednesday                 | -6.682   | 18.522          | 0.704   |
| Thursday                  | -3.676   | 18.313          | 0.824   |
| Friday                    | 5.132    | 18.396          | 0.765   |
| Saturday                  | 87.340   | 18.581          | 0.000** |
| Sunday                    | 60.648   | 17.825          | 0.001** |

| Season (ref: Winter)     |        |                 |         |
|--------------------------|--------|-----------------|---------|
| Spring                   | 49.221 | 50.404          | 0.322   |
| Summer                   | 15.937 | 58.539          | 0.770   |
| Autumn                   | 96.097 | 50.501          | 0.056   |

| Pandemic (Year, 2020)    |        |                 |         |
|--------------------------|--------|-----------------|---------|
| Max wind speed (m/s)     | -13.151| 5.533           | 0.017*  |
| Total precipitation (mm) | -11.970| 0.510           | 0.000** |
| Avg. temperature (°C)    | 24.098 | 1.921           | 0.000** |

| Pandemic (Year, 2020)    |        |                 |         |
|--------------------------|--------|-----------------|---------|
| Year (ref: 2018 + 2019)  | -76.144| 105.057         | 0.459   |
| Air pollution            |        |                 |         |
| PM$_{2.5}$ (µg/m$^3$)    | -1.844 | 0.506           | 0.000** |
| Interaction of Year and PM$_{2.5}$ | 2.507 | 1.009 | 0.013* |
| ar1                      | -0.760 | 0.089           | 0.000** |
| ma1                      | 0.006  | 0.079           | 0.918   |
| ma2                      | -0.692 | 0.061           | 0.000** |

| Sample size              | 1092   |                 |         |

significant at the 0.1 level; * significant at the 0.05 level; ** significant at the 0.01 level.
more explicitly. The results are presented in Table 3. Although there are some variations, results are consistent. Weather conditions are important determinants of total daily cycling duration. Statistically significant relationships between PM$_{2.5}$ level and total daily cycling duration are found in pre-pandemic periods (2018 and 2019). However, it becomes insignificant in 2020. This implies that cyclists’ reactions to air pollution changed during the pandemic. As shown in Table 1, a significant reduction in public transport ridership compared to car trips implies the potential impacts of the fear of virus on people’s travel choices towards safer private transport modes. It is also supported by the increased use of cycling. Although overall travel demand reduced due to government policies (e.g., work/study from home for some government workers and university students), most people still travelled for various activities in South Korea during the pandemic. Therefore, the result implies that people cycle more during the pandemic to reduce the risk of Covid-19 virus exposure for their daily activities even on days when the air quality is not good.

| Day of week (ref: Monday) | 2018 | 2019 | 2020 |
|---------------------------|------|------|------|
| Tuesday                   | 35.634 | 0.122 | −0.450 | 0.967 | −15.934 | 0.667 |
| Wednesday                 | 23.348 | 0.340 | −25.140 | 0.370 | −28.808 | 0.452 |
| Thursday                  | −10.962 | 0.641 | −6.353 | 0.808 | −5.791 | 0.865 |
| Friday                    | 15.313 | 0.516 | −21.686 | 0.443 | 7.664 | 0.829 |
| Saturday                  | 88.181 | 0.000** | 46.485 | 0.103 | 108.476 | 0.006** |
| Sunday                    | 67.307 | 0.004** | 24.228 | 0.360 | 90.444 | 0.019* |

| Season (ref: Winter) | 2018 | 2019 | 2020 |
|----------------------|------|------|------|
| Spring               | 15.450 | 0.793 | 95.592 | 0.213 | 85.867 | 0.376 |
| Summer               | 3.802 | 0.940 | 198.987 | 0.027* | −146.144 | 0.197 |
| Autumn               | 185.239 | 0.005** | 117.310 | 0.159 | 97.978 | 0.315 |
| Max wind speed (m/s) | 0.428 | 0.935 | 2.333 | 0.795 | −35.270 | 0.001** |
| Total precipitation (mm) | −10.585 | 0.000** | −15.602 | 0.000** | −11.652 | 0.000** |
| Avg. temperature (°C) | 20.657 | 0.000** | 24.626 | 0.000** | 30.548 | 0.000** |
| PM$_{2.5}$ (μg/ m$^3$) | −1.655 | 0.006** | −1.637 | 0.011* | −0.783 | 0.504 |
| ar1                   | 0.237 | 0.074 | 0.972 | 0.000** | −0.858 | 0.000** |
| ar2                   | 0.711 | 0.000** | −0.707 | 0.000** | 0.069 | 0.273 |
| ma1                   | 0.046 | 0.679 | −0.088 | 0.101 | −0.786 | 0.000** |
| ma2                   | −0.689 | 0.000** | 0.101 | 0.101 | 0.069 | 0.273 |
| Model                 | ARIMA (2,0,2) | ARIMA (1,0,2) | ARIMA (1,1,2) |
| Sample size           | 363 | 363 | 366 |

Table 3

Result of the relationship between PM$_{2.5}$ level and daily total cycling duration for each year.

5. Conclusions

Air pollution has become one of the key life concerns in South Korea. Various policies, including the deployment of an air quality forecasting system, have been implemented, and people have changed their behaviour to minimise harmful effects of air pollution. For instance, people limit their outdoor activities when the level of air pollution is high. This also applies to the use of active travel modes.

Cycling has become more popular during the pandemic in part because the transmission of the virus is less likely outdoors compared to on crowded public transport. People were reluctant to use public transport (e.g., bus and subway) during the pandemic, and cycling became a feasible option that could compete with private cars. Considering the health benefits of cycling through the increased level of physical activity, this is potentially beneficial for society. However, cyclists are often exposed to air pollution that will result in negative health outcomes, especially in developing countries like South Korea where the level of air pollution is high. The lack of covid-secure travel options for daily activities during the pandemic limits the scope for people to change their travel behaviour. People might cycle even when the air quality is bad in Seoul during the pandemic because it is preferable to the alternatives. In this study, we examined how cyclists reacted to the PM$_{2.5}$ level and total daily cycling duration increases as average temperature increases while it decreases as the level of precipitation increases. Seoul has a very hot and humid summer with a high level of precipitation. This is the reason why the cycling activities reduced during the middle of summer. Recently, several abnormal weather events were recorded in Seoul. Planners may need to consider that such events will become more frequent due to climate change and adopt appropriate mitigation measures where possible.

Lastly, we found that people reacted more to the PM$_{2.5}$ level prior to the pandemic. That is, total daily cycling duration decreases...
significantly as the PM$_{2.5}$ level increases. However, this significant association became insignificant in 2020. This could be due to the lack of covid-secure travel modes during the pandemic, possibly leading to harmful health effects. As shown in the literature, the level of air pollutant concentration varies across roads. This indicates that planners should consider air pollution levels when they build new cycling infrastructure. For example, they can avoid building cycling lanes along roads with heavy traffic (Cole-Hunter et al., 2012) and plant trees on the roads. More example could be done to reduce the overall level of car use in the city. Some health experts have argued that we are highly likely to face more outbreaks in the future (Whiting, 2020). Building comprehensive cycling infrastructure that can reduce air pollution exposure of cyclists could help build a more resilient city for the future.

For future work, it will be important to evaluate the net health benefits of cycling in the highly polluted mega cities during this unexpected time with more detailed cycling and air quality data. In addition, more detailed analyses about the spatial variations in the air quality across different areas (e.g., residential areas, sidewalk trees, park, etc.) would be useful for planners. Finally, robust analyses of cycling behaviour depending on individual characteristics (e.g., travel habit, attitudes, socio-demographic factors, etc.) could complement our study to provide more useful information to planners. For example, future studies could examine how the reaction to the level of air pollutants varies according to individual attitudes or habits by using disaggregated data (e.g., surveys). The results can be useful for making more effective policies (e.g., public information campaigns, free bikes rentals, etc.).

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**Author statement**

Jinhyun Hong: Conceptualization; Formal analysis; Writing-original draft.  
David McArthur: Conceptualization; Formal analysis; Writing-critically reviewing and editing.  
Jaehun Sim: Conceptualization; Data processing; Writing-critically reviewing and editing.  
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**References**

Adkins, P., 2021. Can the city cycling boom survive the end of the Covid-19 pandemic? The Conversation.

An, R., Zhang, S., Ji, M., Guan, C., 2017. Impact of ambient air pollution on physical activity among adults: a systematic review and meta-analysis. Perspect. Publ. Health 138, 111–121.

Anowar, S., Eluru, N., Hatzopoulou, M., 2017. Quantifying the value of a clean ride: how far would you bicycle to avoid exposure to traffic-related air pollution? Transport. Res. Pol. Pract. 105, 66–78.

Apparicio, P., Gelb, J., Carrier, M., Mathieu, M.-É., Kingham, S., 2018. Exposure to noise and air pollution by mode of transportation during rush hours in Montreal. J. Transport Geogr. 70, 182–192.

Bergmann, M.-L., Andersen, Z.J., Amini, H., Ellermann, T., Hertel, O., Lim, Y.H., Loft, S., Mehta, A., Westendorp, R.G., Cole-Hunter, T., 2021. Exposure to ultrafine particles while walking or bicycling during Covid-19 closures: a repeated measures study in Copenhagen, Denmark. Sci. Total Environ. 791, 148301.

Blondiau, T., Van Zeebroeck, B., Haubold, H., 2016. Economic benefits of increased cycling. Transport. Res. Procedia 14, 2306–2313.

Borgh, F., Spinuzzi, A., Mandaglio, S., Fanti, G., Campagnolo, D., Rovelli, S., Keller, M., Cattaneo, A., Cavallio, D.M., 2021. Estimation of the inhaled dose of pollutants in different micro-environments: a systematic review of the literature. Toxics 9, 140.

Briggs, D.J., De Hoogh, K., Morris, C., Gulliver, J., 2008. Effects of travel mode on exposures to particulate air pollution. Environ. Int. 34, 12–15.

Buck, D., Buethler, R., Hass, P., Rawls, B., Chung, P., Borecki, N., 2013. Are bikeshare users different from regular cyclists?: a first look at short-term users, annual members, and area cyclists in the Washington, D.C., region. Transport. Res. Rec. 2387, 112–119.

Buethler, R., Pucher, J., 2021. Covid-19 impacts on cycling. 2019–2020. Transport Rev. 41, 393–406.

Cepeda, M., Schoufour, J., Fothergill, P., Koohsaad, C.M., Dhanu, K., Kramer, W.M., Franco, O.H., 2017. Levels of ambient air pollution according to mode of transport: a systematic review. Lancet Public Health 2, e23–e34.

Cha, S., 2020. South Korea Urges Work from Home as Country Reports Most Daily Cases since March. Reuters.

Cho, H., Yoon, S., 2020. Changes in Travel Patterns Due to Covid-19 and the Direction of Future Transport Policies in Seoul. Seoul Institute of Technology.

Dons, E., Laeremans, M., Orjuela, J.P., Avila-Palencia, I., De Nazelle, A., Nieuwenhuijsen, M., Van Poppel, M., Carrasco-Turigas, G., Standaert, A., De Boever, P., Nawrot, T., Int Panis, L., 2019. Transport most likely to cause air pollution peak exposures in everyday life: evidence from over 2000 days of personal monitoring. Atmos. Environ. 213, 424–432.

Farrell, W., Weichenthal, S., Goldberg, M., Valois, M.-F., Shekarrizfard, M., Hatzopoulou, M., 2016. Near roadway air pollution across a spatially extensive road and cycling network. Environ. Pollut. 212, 498–507.

Fishman, E., Scheppers, P., Kalmann, C.B.M., 2015. Dutch cycling: quantifying the health and related economic benefits. Am. J. Publ. Health 105, e13–e15.
Gilliland, J., Malyth, M., Xu, X., Luginina, L., Shah, T., 2018. Influence of the natural and built environment on personal exposure to fine particulate matter (PM2.5) in cyclists using city designated bicycle routes. Urban. Sci. 2, 120.

Götschi, T., Garrard, J., Giles-Corti, B., 2016. Cycling as a part of daily life: a review of health perspectives. Transport Rev. 36, 45–71.

Haney, S., Marshall Julian, D., Brauer, M., 2012. Health impacts of the built environment: within-urban variability in physical inactivity, air pollution, and ischemic heart disease mortality. Environ. Health Perspect. 120, 247–253.

Hartog, J.J.D., Boogaard, H., Nijland, H., Hoek, G., 2010. Do the health benefits of cycling outweigh the risks? Environ. Health Perspect. 118, 1109–1116.

Hong, J., Mearuth, D., Raturi, V., 2020. Did safe cycling infrastructure still matter during a covid-19 lockdown? Sustainability 12, 8672.

Hyndman, R.J., Khandakar, Y., 2008. Automatic Time Series Forecasting: the Forecast Package for R. 2008, vol. 27, p. 22.

Jarjour, S., Jerrett, M., Akyildiz, D., De Nazelle, A., Hanning, C., Daly, L., Lipsett, J., Balmes, J., 2013. Cyclist route choice, traffic-related air pollution, and lung function: a scripted exposure study. Environ. Health 12, 14.

Jun, T., Min, I.-S., 2019. Air pollution, respiratory illness and behavioral adaptation: evidence from South Korea. PLoS One 14, e0221098.

Kampa, M., Castanas, E., 2008. Human health effects of air pollution. Environ. Pollut. 151, 362–367.

Kim, D., Choi, H.-E., Gal, W.-M., Seo, S., 2020. Five year trends of particulate matter concentrations in Korean regions (2015-2019): when to ventilate? Int. J. Environ. Res. Public Health 17, 5764.

Kim, S.R., Choi, S., Kim, K., Chang, J., Kim, S.M., Cho, Y., Oh, Y.H., Lee, G., Son, J.S., Kim, K.H., Park, S.M., 2021. Association of the combined effects of air pollution and changes in physical activity with cardiovascular disease in young adults. Eur. Heart J. 42, 2487–2497.

Kim, W., Kim, S.Y., Lee, J.Y., Kim, S.K., Lee, K.Y., 2009. Comparison of commuters’ PM10 exposure using different transportation modes of bus and bicycle. Kor. J. Environm. Health Sci. 35, 447–453.

Kreel, P., Filopoli, Y.A., Tardif, A.C., Castro, L.B., Gidhagen, L., Malucelli, F., Wolf, A., 2020. Cyclists’ exposure to air pollution under different traffic management strategies. Sci. Total Environ. 723, 138043.

Lu, M., Schmitz, O., Vaartjes, I., Karsenberg, D., 2019. Activity-based air pollution exposure assessment: differences between homemakers and cycling commuters. Health Place 60, 102233.

Maizlish, N., Linesch, N.J., Woodcock, J., 2017. Health and greenhouse gas mitigation benefits of ambitious expansion of cycling, walking, and transit in California. J. Transport Health 6, 490–500.

Mccurry, J., 2019. ‘social disaster’: South Korea Brings in Emergency Laws to Tackle Dust Pollution. The Guardian.

Miskell, G., Salmond, J., Dirks, K.N., 2015. A novel approach in quantifying the effect of urban design features on local-scale Air pollution in central urban areas. Environ. Sci. Technol. 49, 9004–9011.

Mueller, N., Rojas-Rueda, D., Cole-Hunter, T., De Nazelle, A., Dons, E., Gerike, R., Götschi, T., Int Panis, L., Kahlmeier, S., Nieuwenhuijsen, M., 2015. Health impact assessment of active transportation: a systematic review. Prev. Med. 76, 103–114.

Oja, P., Titze, S., Bauman, A., De Geus, J., Krenn, P., Kohlberger, T., 2011. Health benefits of cycling: a systematic review. Scand. J. Med. Sci. Sports 21, 496–509.

Pucher, J., Buehler, R., 2008. Cycling for Everyone: Lessons from Europe, vol. 2074. Transportation Research Record, pp. 58–65.

Radon, S., Newbold, K.B., Egan, J., Williams, A., 2016. Factors influencing health behaviours in response to the air quality health index: a cross-sectional study in Hamilton, Canada. Environ. Health. Environ. Health Rev. 59, 17–29.

Railway Technology 2020, Seoul Metropolitan Subway [Online]. (Accessed 23 June 2021).

Raza, W., Vora, B., Johansson, C., Sommar, J.N., 2018. Air pollution as a risk factor in health impact assessments of a travel mode shift towards cycling. Glob. Health Action 11, 429081.

Roberts, J.D., Voss, J.J., Knifft, B., 2014. The association of ambient air pollution and physical inactivity in the United States. PLoS One 9, e90143.

Roberts, J.D., Voss, J.J., Knight, B., 2014. The association of ambient air pollution and physical inactivity in the United States. PLoS One 9, e90143.

Sabierian, S., Heyes, A., Rivers, N., 2017. Alerts work! Air quality warnings and cycling. Resour. Energy Econ. 49, 165.

Saberian, S., Heyes, A., Rivers, N., 2017. Alerts work! Air quality warnings and cycling. Resour. Energy Econ. 49, 165.

Schepers, P., Fishman, E., Beelen, R., Heinen, E., Wijnen, W., Parkin, J., 2015. The mortality impact of bicycle paths and lanes related to physical activity, air pollution exposure and road safety. J. Transport Health 2, 460–473.

Tainio, M., De Nazelle, A., Gotschi, T., Kahlmeier, S., Rojas-Rueda, D., Nieuwenhuijsen, M.J., De Sá, T.H., Kelly, P., Woodcock, J., 2016. Can air pollution negate the health benefits of cycling and walking? Prev. Med. 87, 233–236.

Tan, H., Xu, J., 2019. Differentiated effects of risk perception and causal attribution on public behavioral responses to air pollution: a segmentation analysis. J. Environ. Psychol. 65, 101335.

Tran, P.T.M., Zhao, M., Yamamoto, K., Minet, L., Nguyen, T., Balasubramanian, R., 2020. Cyclists’ personal exposure to traffic-related air pollution and its influence on bikeability. Transport. Res. Transport Environ. 88, 102563.

Trmal, D., 2020. Policies, Regulatory Framework and Enforcement for Air Quality Management: the Case of Korea – Environment Working. Oecd. Paper No. 158, Unwin, N.C., 1995. Promoting the public health benefits of cycling. Publ. Health 109, 41–46.

Voultsis, I., Taimisto, P., Kelessis, A., Samaras, Z., 2014. Microenvironment particle measurements in Thessaloniki, Greece. Urban Clim. 10, 608–620.

Wang, C.-Y., Lim, B.-S., Wang, Y.-H., Huang, Y.-C.T., 2021. Identification of high personal Pm2.5 exposure during real time commuting in the Taipei metropolitan area. Atmosphere 12, 396.

Weichenthal, S., Int Panis, L., Kahlmeier, S., Nieuwenhuijsen, M., 2015. Health impact assessment of active transportation: a systematic review. Prev. Med. 76, 103–114.

Yoo, G., 2021. Real-time information on air pollution and avoidance behavior: evidence from South Korea. Popul. Environ. 42, 406–424.

Zhao, P., Li, S., Li, P., Liu, J., Long, K., 2018. How does air pollution influence cycling behaviour? Evidence from Beijing. Transport. Res. Transport Environ. 63, 828–838.

Zhou, C., Li, S., Wang, S., 2018. Examining the impacts of urban form on air pollution in developing countries: a case study of China’s megacities. Int. J. Environ. Res. Publ. Health 15, 1565.