국제학석사학위논문

The Effects of Air Pollution on COVID-19 Death Rate and Its Implications on Urban Development

미세먼지가 코로나-19 사망률에 미치는 영향 및 도시개발 정책에 주는 시사점

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Master's Thesis of International Studies

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Abstract

Looking back at the history of urbanization, cities are a location presenting many opportunities to people but also many disadvantages when it comes to the air pollution and pandemic. Korea has high level of air pollution and some cities of Korea are among the world's worst cities with high level of air pollution resulting in environmental issues and poor health of citizens. Numerous studies observed positive association between exposure to air pollutants such as $PM_{2.5}$ and PM_{10} and lung related diseases in Korea. With the outbreak of the 5th pandemic, COVID-19, studies conducted in other overseas countries suggest positive association between air pollution and mortality of COVID-19 but there is lack of research on the case of Korea. This paper examines the effects of air pollution on the death cases and case fatality rate of COVID-19 across 228 cities, counties and districts in Korea.

A series of analysis were performed to determine whether the exposure to $PM_{2.5}$ and PM_{10} from 2015 to 2019 increased COVID-19 death cases. Previous research papers on COVID-19 examined the fact that some characteristics of cities such as age group, income level of the people had an effect on the outcome of the virus so demographic, socio-economic and health related factors affecting the severity and mortality of COVID-19 were controlled in this paper. It used instrumental variable estimations and OLS estimations to test the robustness of the result. The results of the analyses were found to be robust. Both PM_{10} and $PM_{2.5}$ are positive and statistically significant at 10% and 5% level respectively on COVID-19 death cases per 100,000 people. 1$\mu g/m^3$ increase of PM_{10} concentration is projected to increase COVID-19 death cases per 100,000 people by 1.94~4.63% depending on the model used. Likewise, 1μg/m^3 increase of $PM_{2.5}$ concentration is projected to increase COVID-19 deaths per 100,000 by 3.21~8.72% depending on the estimation. For the case fatality rate of COVID-19, PM_{10} and $PM_{2.5}$ are both positive and statistically significant at 5% level. Other factors such as the number of primary and general hospitals at province level and level of income per capita were negative and statistically significant on the number of deaths per 100,000 population and case fatality rate of COVID-19. The number of beds at nursing hospitals, population density and proportion of elderly resulted to be positive and statistically significant at 1% level both on COVID-19 deaths per 100,000 and case fatality rate.

COVID-19 brought many changes to our lives, shifting priorities of individuals and government to one's health. The importance of public health has grown but both the pandemic and air pollution are threatening our health increasing related diseases and death cases. For an effective reduction on the level of air pollution concentration, it is necessary to strengthen the current air pollution regulations and implement customized measures at urban level as high air pollution occur mostly in urban areas due to increased human activities. Additionally, the results of the paper highlight the importance to consider air quality in the policy making of urban planning and take actions in creating sustainable, resilient, and sustainable city post-COVID.

Keyword : COVID-19, air pollution, $PM_{2.5}$, PM_{10}, urban planning
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List of Abbreviations

2SLS	Two-Stage Least Squares
CDC	US Centers for Disease Control and Prevention
CFR	Case Fatality Rate
COVID-19	Corona Virus 2019
KDCA	Korea Disease Control and Prevention Agency
KOSIS	Korean Statistical Information Service
OECD	Organization for Economic Cooperation and Development
OLS	Ordinary Least Squares
$PM_{2.5}$	Particulate matter with an aerodynamic diameter less than 2.5 microns(μm)
PM_{10}	Particulate matter with an aerodynamic diameter less than 10microns(μm) in diameter
SMA	Seoul Metropolitan Area
WHO	World Health Organization

I. Introduction

1.1 Stylized fact on city and pandemics

Throughout the history, people living with one another were always threatened by evolving diseases especially in cities or urban areas. Due to the crowded nature, strong connectivity, other socio-economic, cultural and demographic factors, cities are a location with many risk factors responsible for the rapid transmission of infectious diseases (Davis, 2022). Since the industrial evolution of the 18^{th} century, people living in urban areas increased as they were offered with many advantages including job opportunities, higher education and security. At the same time, it posed challenges in the aspect of emerging diseases caused by sanitary problems including poor water and waste management as well as close contact between people (Neiderud, 2015). In order to prevent the fast spread of infection and related death cases, improvements were made in the urban environments starting from the spread of Cholera in the early 19^{th} century. Transformations were made in the water sewage system and the Public Health Act of 1848 was established in London requiring urban planning to include public health act (Liu &Wang, 2021). During this time in New York, the demand for urban green spaces grew as cities became polluted, congested and overcrowded leading to the establishment of Central Park in New York and Emerald Necklace in Boston of the United States (Liu &Wang, 2021). In addition, the spread of the tuberculosis in New York required public spaces and housing in the United States to have windows facing to the exterior. Progressively, the pandemics and other public health crises have changed the shape of cities in the sanitation system, public parks, street design, ecology and housing regulations (UN-Habitat, 2021).

With the new pandemic, COVID-19, hitting urban areas faster than other areas, the relationship between urban planning and public health is being discussed. Many researchers propose urban planning to include healthy city in the design to prevent future epidemics and improve one's immune system that can defend over the virus decreasing mortality. Thus, it is essential to explore urban and environmental factors that can affect the health of the citizens within a city and reflect these in the urban planning system for the cities' sustainable development.

According to the report released by UN-Habitat (2021), bad air quality is known to be causing respiratory diseases or aggravating other health conditions. It claims that it is the major factor increasing the risk of dying from COVID-19. This report further mentioned that the response of cities and how they cope with the pandemic are important because cities are a location that geographically link the regions, towns to rural areas. Among the different factors influencing the COVID-19 mortality, this paper explores the relationship between air pollution and the mortality and Case Fatality Rate (hereafter referred as "CFR") of COVID-19 in 228 'si', 'gun', 'gu' (cities, counties and districts) of Korea. The detailed names of each city, county and district are listed in Appendix 1.

1.2 Overview of COVID-19 in Korea

In December 2019, the spread of COVID-19 was first reported by the Wuhan Municipal Health Commission. It was first called the Wuhan pneumonia by the press but with increasing infection and death cases all over the world, it was officially announced as Corona Virus 2019 (hereafter referred to as COVID-19) by the World Health Organization (hereafter referred to as WHO) on February 12th 2020. After being a global threat, the WHO made the decision to characterize COVID-19 as a global pandemic on March 11th, documenting it as the fifth pandemic after the Spanish flu back in 1918 (Liu et al., 2020). The fight with the virus is still on-going, causing numerous infection and death cases all over the world. According to the WHO dashboard, there are 609 million cumulative confirmed cases and 6.5 million death cases as of September 19th 2022.

In Korea, the government has admitted the first COVID-19 confirmed case on January 20th 2020. The reported number of deaths and confirmed cases started to surge ever since. According to the press release by the Korea Disease Control and Prevention Agency (hereafter referred as "KDCA") dated June 22nd 2022, the total cumulative deaths were 24,472 cases with CFR (total death over total confirmed multiplied by 100) of 0.13% and confirmed patients were 18,298,341 people among which 34,106 people were from overseas. The cumulative confirmed cases were 35,453 people per 100,000 population among which 53% were female and 47% were male with the share of elderly, those over 60years old, taking 17.9% of the share. Per province, the total cumulative confirmed rate was highest in Gyeonggi-do with 27.2% followed by Seoul with 20% since 2020. As for the total cumulative death cases of

COVID-19, 51.3% of the deceased were female and 48.7% were male. The proportion of elderly over 60 years old took up 93.7% of the total cumulative deaths among which the share of those over 80 years old took 58.8% with the CFR of 2.69%[1]. Another data revealed by the KDCA analyzed 5,382 death cases of COVID-19, reporting that on average 1.9 underlying conditions were met per each death case. The most identified medical conditions were cardiovascular diseases including heart attack, stroke, myocarditis and high blood pressure followed by metabolic syndrome such as diabetes. Other included diseases were nervous system diseases including dementia, Parkinson's disease or epilepsy and bladder related diseases, cancer including lung, liver cancer and respiratory diseases. The fatality of COVID-19 and the risk of developing severe symptoms are high on the group of people with underlying diseases and elderly possibly because of their low immunity[2].

1.3 Background on Particulate Matter in Korea

Air pollution causes respiratory and other types of diseases affecting the morbidity and mortality. There are many different types of air pollution but those that are major public health concerns are the particulate matter with an aerodynamic diameter less than 2.5 microns(μm) and less than 10microns(μm) in diameter (hereafter referred to as " $PM_{2.5}$" and " PM_{10}" respectively), carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2). These are mainly

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[1] Press Release by KDPA on June 22nd 2022.

[2] More details are on The JoongAng.(2022) "Analysis of 5,382 COVID-19 deaths in Korea... This underlying disease is the most dangerous"

derived from residential energy usage, vehicle traffic, power generation, industrial emissions, and waste or agriculture incineration[3].

Among the different types of air pollutants, this study chose to focus on $PM_{2.5}$ and PM_{10} because they are the most studied types with existing evidences of their negative health effects and COVID-19 CFR (Perone, 2021). They are also the most known to the people in the society as opposed to other air pollutants with government measures. Both types are able to penetrate in the body and affect organs such as the lung. Especially $PM_{2.5}$ is known to be the most dangerous causing the most significant health issues and premature mortality. In 2013, the International Agency for Research on Cancer of the WHO categorized outdoor air pollution and particulate matter as first degree carcinogenic to humans with evidence of increasing risks of lung cancer, bladder cancer and respiratory and heart diseases (Straif et al., 2013). Along with increasing studies on the negative effect of air pollution on people′s health, the WHO global air quality guideline was updated and revised in 2021 adjusting the recommended levels downward for countries to meet the concentration level of 5μg/m^3 for $PM_{2.5}$ and 10 μg/ m^3 for PM_{10} (WHO global air quality guideline, 2021).

Korea is among one the countries likely to face the greatest threat from outdoor air pollution in the future. According to the report by the Organization for Economic Cooperation and Development (hereby ″OECD″) released in 2016, the

[3] The definition and details on air pollution are referred from the WHO.

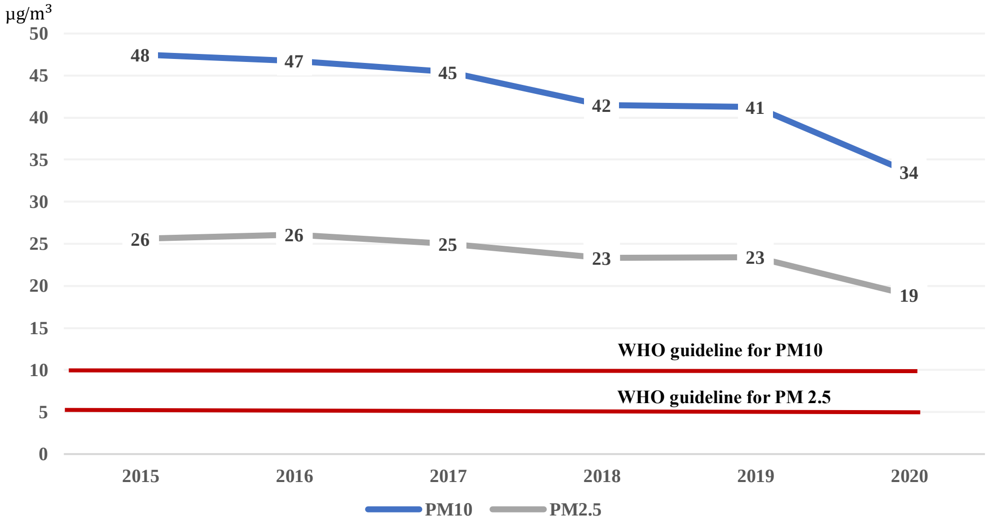
number of premature deaths caused by the high exposure to air pollution is projected to increase most significantly in Japan and Korea by 2060 among the OECD countries. Thus, welfare costs per-capita from the illness due to outdoor air pollution are estimated to be highest in China followed by Korea[4]. The World Air Quality Report of 2019 presented Korea to be ranking the highest in terms of the average $PM_{2.5}$ level among OECD countries with 61 out of top 100 most polluted cities being located within the country.

During the past decades, the Korean government has enacted and revised related laws and regulations to reduce the level of air pollution. The Clean Air Conservation Act of 1990 included standards for emission on air pollutants and regulations on the emission facilities. Over the years, these measures were strengthened and revised several times (OECD working paper No 158, 2020). After starting to take control and collecting data on the concentration level of $PM_{2.5}$ in 2015, the government applied stricter air quality standards and implemented emergency measures since 2017. The average concentration of PM_{10} and $PM_{2.5}$ from 2015 to 2020 of Korea are shown in Figure 1. The detailed data per province for each year are also presented in Appendix 2. The annual concentration of both PM_{10} and $PM_{2.5}$ started to show a decrease after 2017 and this trend dramatically dropped in 2020 due to the spread of COVID-19 that slowed down the economy and reduced traffic with various social distancing measures (Seo et al., 2020; Ju et al., 2021). Despite the government's efforts to reduce the level of air pollution, Korea is

[4] More details can be found also in OECD (2016), "The Economic Consequence of Outdoor Air Pollution".

exposed to around four times higher concentration of PM_{10} and $PM_{2.5}$ than the recommended air quality standard level of the WHO.

Figure 1. Average level of PM_{10} and $PM_{2.5}$ since 2015 in Korea



Source: Data from KOSIS generated by the author

According to Article 7 of the Clean Air Conservation Act, the Minister of Environment is recommended to announce to the public the prediction result of air pollution level in order to minimize its effect on public health, industrial activities and growth of animals and plants[5]. Usually, the data from the monitoring stations in different regions are used for forecasting purpose and notified to the public as either good, moderate, bad and very bad depending on the concentration level of particulate matter as shown below in Table 1.

[5] More details on the Clean Air Conservation Act can be seen on Korean Law Information Center.

Table 1. Category of Particulate Matter prediction level in Korea (㎍/㎥)

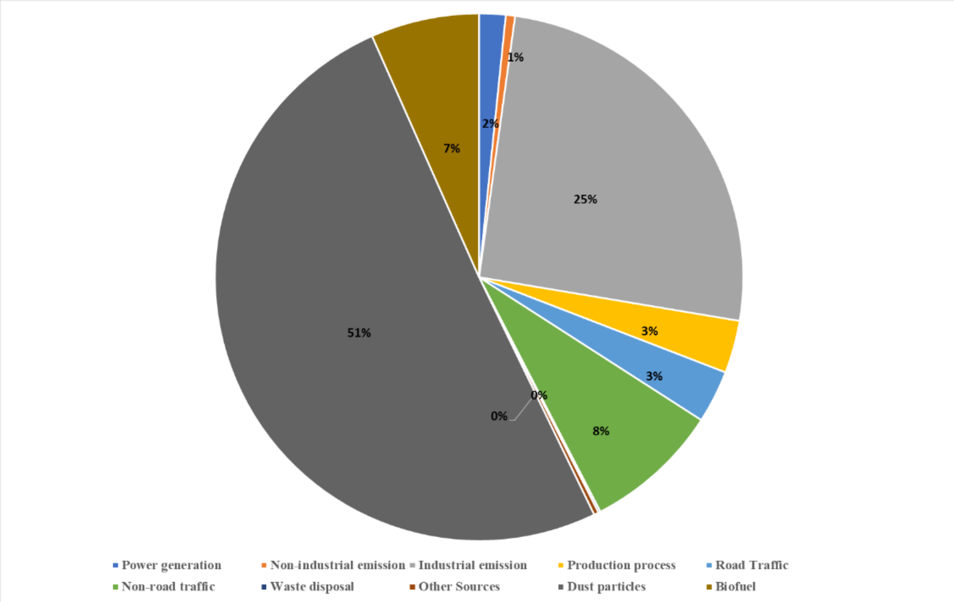
	Good	Moderate	Bad	Very bad
PM_{10}	0-30	31-80	81-150	<151
$PM_{2.5}$	0-15	16-35	36-75	<76

Source: Air Korea, Korea Environment Corporation

In general, the particulate matters are originated by fuel combustion in the manufacturing, traffic, industry, household, agriculture and power generation sectors. As illustrated in Figure 2 and 3, the main sources of domestic particulate matter are fugitive dust mainly from roads and construction sites, followed by industrial emission and traffic related sectors for both $PM_{2.5}$ and PM_{10}. According to the result of joint study with NASA announced by the Ministry of Environment in 2016, 48% of Korea's air pollution resulted to be flown from overseas countries among which 38% was from China. While the rest, 52% of the share was expected to be produced locally. However, this result cannot be generalized as the measure was only analyzed in one location of Korea, at the Olympic Park in Seoul[6].

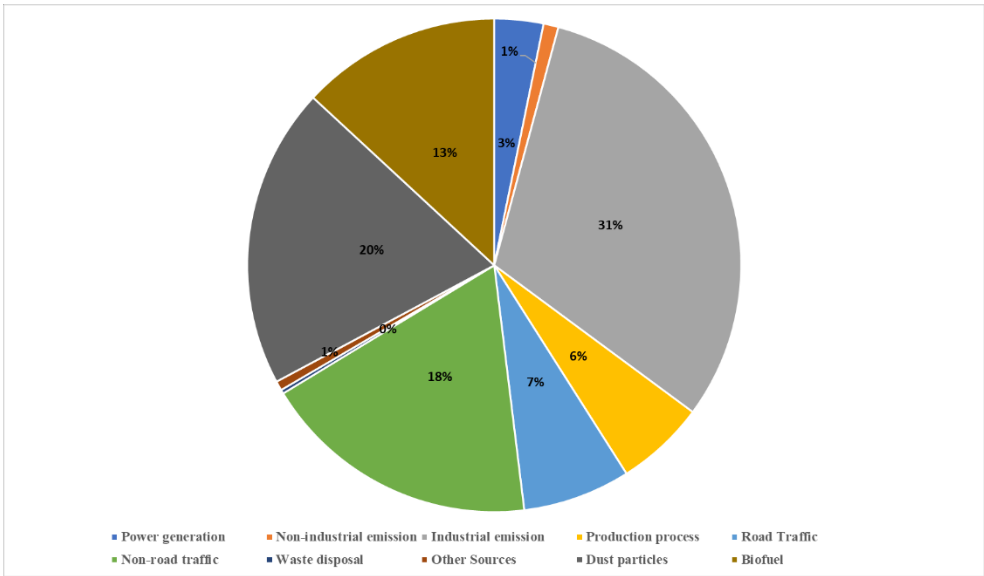
[6] Chon & Chung (2019) "Environment Ministry, NASA to check dust", Korea JoongAng Daily

Figure 2. Sources of PM_{10} in 2019



Source: Data from KOSIS generated by the author

Figure 3. Sources of $PM_{2.5}$ in 2019



Source: Data from KOSIS generated by the author

1.4 Purpose of the research

Now in the 21st century, we are faced with challenges arising from COVID-19. This time, the spread of the virus is faster, threatening not only those living in cities but also in any other regions as the World is more connected to one another. At this stage, I believe it is important to identify and have an understanding on the different factors affecting COVID-19 death cases and CFR in order to provide appropriate implications.

There are numerous research papers that study the relation between the mortality and lethality of COVID-19 and long-term air pollution. Studies have found that the exposure to air pollution or particulate matter brings higher risk of cardiovascular and respiratory comorbidities and weakens the immune system which can then lead to poor prognosis increasing death cases among COVID-19 patients (Semczuk-Kaczmarek et al., 2022). Many other studies have proven that the COVID-19 infection can be significant if a person's lung function has weakened through the past exposure to air pollution because COVID-19 is regarded as a respiratory disease (Zhang et al., 2020). The epidemiological mechanism behind this is that through the exposure of air pollution, angiotensin-converting enzyme 2(ACE-2), an important entry receptor for severe acute respiratory syndrome corona virus 2(SARS-CoV-2), increases. The overexpressed ACE-2 facilitates the infection of COVID-19 (Wang et al.2020).

For the above reasons mentioned, this study hypothesizes that the past exposure to air pollution specifically PM_{10} and $PM_{2.5}$ worsen the chance of recovery from COVID-19 leading to higher mortality. This paper aims to explore whether the high level of long-term average air pollution increases the death and CFR of COVID-19.

Although Korea is one of the countries with the highest air pollution level, there is lack of research that investigates the effects of long-term air pollution on the mortality and CFR of COVID-19. In the first part of the analysis, the paper plans to explore whether the long-term air pollution concentration level during 2015 to 2019, before COVID-19, in every "Si", "Gun" or "Gu"[7](hereafter referred to as city, county and district respectively) of Korea have an effect on the mortality and CFR of COVID-19. After reviewing the results, the paper would like to analyze whether the current urban planning projects and policies in terms of air pollution are effective measures considering the results of the regression. Lastly, the paper aims to contribute to the environment sector in urban development hoping that human can build resilience with the pandemic.

[7] Korea is subdivided into smaller administrative level. "Si" are cities over 150,000 people, "Gun" are counties with less than 150,000 people and "Gu" is more densely populated than "Gun".

II. Literature Review

Existing data on global basis and within Korea proved that the exposure of particulate matter increases mortality in general and also results in higher rate of hospitalization because of lung or cardiovascular disease. Also, elderly population are more affected by the concentration of pollutants (Gu & Jun, 2021; Bae Hyun Joo, 2014; Wu et al., 2020). Recently, many have researched the effects of air pollution on the infection and mortality rates of COVID-19 using the data of different countries in the World. Yu et al., (2021) conducted a study on the relationship between $PM_{2.5}$ and COVID-19 confirmed cases and death per million population of 251 countries and regions using the multi-variate linear regression. The results showed to be positive and statistically significant between COVID-19 confirmed cases, death cases and $PM_{2.5}$ concentration, GDP per capita, population density. Other country-specific studies suggested that air pollutants significantly and positively correlate with the spread and mortality of COVID-19. However, these results vary depending on the region and period of study. Wu et al. (2020) examined the exposure of air pollution in the United States using the average $PM_{2.5}$ from 2000 to 2016 with COVID-19 mortality cases on county level. Negative binomial mixed models were used, resulting to be statistically significant at 5% level, estimating that an increase of 1 μg/m^3 of $PM_{2.5}$ increases COVID-19 death rate by 8%. Marquès et al. (2022) found that long-term exposure to PM_{10} above the WHO guideline level increases the number of severe COVID-19 cases and deaths. It used the observational study on 2,112 patients suffering from COVID-19 infection in Catalonia, Spain. The severity of patients increases by 3.06% with an increase of 1μg/m3 in PM_{10}

concentration. The study on the effects of air pollution on COVID-19 related mortality in Northern Italy by Coker et al. (2020) used the aggregated $PM_{2.5}$ concentration data from 2015 to 2019 and number of excess deaths from January to April 2020 in comparison to the average deaths of the past five years. It found positive association between $PM_{2.5}$ and COVID-19 related mortality using negative binomial regression. The study observed one unit increase in $PM_{2.5}$ concentration increases the mortality rate by 9% to 14% due to COVID-19. Perone (2022) used three different types of models including binominal regression, OLS and spatial autoregressible models to investigate the association between air quality of 107 provinces in Italy and the spread and mortality in such areas. Both $PM_{2.5}$ and PM_{10} were positive and statistically significantly related to the spread and mortality of COVID-19. Also, Becchetti et al. (2022) used the difference between daily deaths during the pandemic and five-year average deaths between 2015-2019 of different regions in Italy. It concluded that the effects of particulate matter in Italian municipalities were positive and statistically significant using pooled and fixed-effect instrumental variable estimates. It concluded that an additional 1μg/m^3 of $PM_{2.5}$ is estimated to increase mortality rate by 2.9% to 5.59%. Leirião et al. (2021) used linear regressions to investigate the relation between $PM_{2.5}, PM_{10}$ and NO_2 and COVID-19 mortality, fatality rates in the municipalities of São Paulo in Brazil using the air pollution data from 2015 to 2019. Positive and statistically significant results were found between COVID-19 mortality rate and $PM_{2.5}$ and PM_{10}.

The influence of air pollution on COVID-19 infection and mortality rates can be measured either in the short-term, using the data of air pollution during the period of COVID-19, or long-term exposure, using the data before COVID-19. In Korea, there are only studies that investigate the relation of short-term exposure to air pollution on the transmission of COVID-19. Hoang et al (2021) examined the effects of six air pollutants seven days prior to the research period on the daily confirmed cases between February and September 2020 in two clusters Seoul-Gyeonggi and Daegu-Gyeongbuk. The study applied a generalized additive model (GAM) and found positive association between NO_2 concentration with daily COVID-19 confirmed cases in both clusters. Whereas $PM_{2.5}$ was found to be only associated in Daegu-Gyeongbuk cluster. Lym & Kim (2021) investigated the effect of $PM_{2.5}$ and temperature on the transmission of COVID-19 during the second and third wave of the pandemic, August to December 2020, across districts in Seoul using the Bayesian generalized linear mixed model. It resulted that there was a positive correlation between seven days lagged effect of $PM_{2.5}$ concentration and the number of COVID-19 confirmed cases. Whereas, the temperature showed to have a negative correlation between with the number of COVID-19 confirmed cases. To sum up, the short-term effects of air pollution on the transmission of COVID-19 in Korea during the period of pandemic were investigated but there was no research analyzing the long-term effects of air pollution on COVID-19 mortality rate and CFR.

There were various attempts in order to understand the characteristics of COVID-19 in Korea from different perspectives. Kim et al. (2020) used the number of confirmed and death cases between February 19th to April 30th in Gyeongsangbuk-do area to find that age group and underlying disease were statistically significant at 1% level and resident type was statistically significant at 5% level. Jo et al. (2021) analyzed that both density and connectivity are important factors in the proliferation of the COVID-19 but connectivity is more positively correlated to COVID-19 infection rate in the case of Korea. Kim et al. (2020) used the data of 5,628 COVID-19 patients provided from Korea Disease Control and Prevention Agency to find that older age, dementia, high lymphocyte, cancer, dyspnea, COPD, change of consciousness, heart disease, high platelets, abnormal diastolic pressure and fever were the factors having an impact on COVID-19 deaths. Similarly, Byeon et al. (2021) presented that older age, men and chronic diseases including malignant neoplasms of respiratory and others had lower survival rate of COVID-19 among patients. Kim et al. (2021) analyzed the risk factors of COVID-19 death using regional data to derive that age, population density and lower medical facilities per person were the statistically significant factors affecting COVID-19 death rate. There was also a study on the effect of income level on the infection and mortality rates of COVID-19 using the data of those diagnosed with COVID-19 from January until June 2020. This study found no relation between income level and COVID-19 mortality but negative association was detected with COVID-19 infection rate.

Overall, overseas literatures showed that different types of air pollution can be positively associated with COVID-19 infection and mortality rates. Existing studies demonstrated that $PM_{2.5}$ and PM_{10} both could be positively associated with the death, fatality and transmission rates of COVID-19. Other studies also highlighted that age, male, underlying disease, and population density of the living area can be the risk factors affecting COVID-19 deaths. This paper can be differentiated from the other papers as it is the first study that provides evidence whether the long-term concentration level of air pollution in Korea can affect COVID-19 mortality and severity. Moreover, it will control other regional and geographical factors such as health related, socio-economic, demographic variables to deal with the problem of omitted variable bias. Based on the results, the current government's air pollution reduction policies will be analyzed and new measures will be suggested in order to transform cities and urban areas and take actions for the post COVID-19 era.

III. Methodology

3.1 Base Model & Data

The administrative divisions of Korea consist of metropolitan cities, special cities and provinces. These are further divided into cities(si), counties(gun), districts (gu), towns(eup), township(myeon), neighborhoods(dong) and villages(ri). This study considers city, county and district levels as the unit of data collection. The detailed lists of the region are presented in Appendix 1. To test the hypothesis, the study uses Two-Stage Least Squares(2SLS) for potential unmeasured confounding effect between COVID-19 confirmed and death cases per 100,000 people and to keep out the influence of other extraneous components. The robustness of the results was tested through various sensitivity analyses using different types of independent variables applying Ordinary Least Squares (OLS) models. The effects of PM_{10} and $PM_{2.5}$ were examined separately because their concentrations are highly correlated.

As for the control variables, the paper tried to take into account the factors identified by the US Centers for Disease Control and Prevention (CDC) related to the severe COVID-19 symptoms. The available data such as age, ethnicity, income level, and crowding degree were first collected and categorized as either demographic, socio-economic or heath related variables. The details are presented in Table 2 and included in the models to capture the effects that may affect the results of the study.

The 2SLS regression models used low education rate as the instrumental variable of COVID-19 confirmed cases per 100,000 people. The predicted value of the instrument in the 1st stage estimation was then used in the 2nd stage estimation.

The formulas are as follows:

1st stage:

$$\ln\,(Crate_i) = \beta_0 + \beta_1 EDU_i + \beta_2 PM_i + \beta_3 dem_i + \beta_4 socio_i + \ \beta_5 health_{i\,+}\ \varepsilon_i$$

2nd stage:

$$ln(Drate_i) = \beta_6 + \beta_7 \ln\widehat{(Crate_i)} + \beta_8 PM_i + \beta_9 dem_i + \beta_{10} socio_i + \beta_{11} health_i + \varepsilon_i$$

The equation for OLS regression model using interaction variable as the independent variable(Y) is as below:

$$\begin{aligned}\mathrm{Ln}(Drate_i) = \beta_0 + \beta_1 PM_i + \beta_2 ln(Crate_i) + \beta_3 PM_i X ln(Crate_i) + \beta_4 dem_i \\ + \beta_5 socio_i + \beta_6 health_i + \varepsilon_i\end{aligned}$$

The equation for OLS regression model with CFR as the dependent variable (X) used the following equation:

$$\mathrm{Ln}\,(CFR_i) = \beta_0 + \beta_1 PM_i + \beta_2 dem_i + \beta_3 socio_i + \beta_4 health_i + \varepsilon_i$$

Where,

$\ln\,(Crate_i)$= Log of COVID-19 confirmed cases per 100,000 people in city *i*;

$\ln\,(Drate_i)$ = Log of COVID-19 death cases per 100,000 people in city *i*;

$\ln\,(CFR_i)$ = Log of COVID-19 CFR in city *i*;

EDU_i = % over 15 years old with primary school education or less in city *i*;

PM_i = Mean concentration of PM_{10} and $PM_{2.5}$ (2015 – 2019) in city *i*;

dem_i = Set of democratic factors incl. ratio of elderly, foreigner… in city *i*;

$socio_i$= Socio-economic factors such as income per capita in *i*;

$health_i$ = Set of health-related variables in city *i*;

Table 2. Description on variables

Category	Variable	Name in Stata	Description	Source
Dependent Variable	COVID -19 death rate	Drate	Number of cumulative death cases per 100,000 people from January 2020 to 16th May 2022	COVID-19 website by MOHW
	Case Fatality Rate	CFR	Number of cumulative of deaths divided by cumulative number of confirmed multiplied by 100	
Independent Variable	PM_{10}	pm10	Average level of concentration from 2015 to 2019	KOSIS
	$PM_{2.5}$	pm25		
Demographic Variable	Elderly rate	elderlyrate	Share of population older than 65 years old in 2019	
	Ratio of foreigner	foreignshare	Ratio of registered foreigners in each city or county in 2018	
	Population density	popdenst	Total number of inhabitants over the total area (person per 100 km^2) in 2019	
Socio-economic variable	Income	income	Reported year-end settlement of earned income (million won) by city or county per capita in 2020	
	Low educated rate	lowedurate	Over 15years old with primary school or no school attainment in 2020	
Health variable	COVID-19 confirmed rate	Crate	Cumulative number of confirmed cases per 100,000 people from January 2020 to 16th May	COVID-19 website by MOHW
	COVID-19 full vaccinated rate (%)	Vrate2	Cumulative number of persons vaccinated with 2nd shot up to June 28th over the number of populations living in the area in 2020	COVID-19 Vaccination website by KDCA
	Number of general hospitals	Generalhosprate	Total number of general hospitals of each province per 10,000 population in 2019	KOSIS
	Number of beds in nursing hospital	nursingbedrate	Total number of beds in nursing care facilities per 10,000 population in 2018	
	Obesity rate (%)	obesityrate	Average percentage of people with a body mass index (kg/m2) of 25 or higher in 2020 & 2021	
	Smoking rate (%)	smokingrate	Percentage of current smokers that "smoke daily" or "smoke occasionally" in 2021	

The main dependent variable is the cumulative COVID-19 death cases per 100,000 population in 228 cities, counties or districts within 17 provinces of Korea. In Korea, COVID-19 death cases are reported based on the location of residence of the deceased during COVID-19 quarantine period or with the proof from medical doctors in the case of death after being released from the quarantine. The total cumulative number of death cases are then divided by the population of each city, county and district then multiplied by 100,000. Similarly, COVID-19 confirmed rate, used as a control variable, is the cumulative number of COVID-19 confirmed cases divided by the population of the region then multiplied by 100,000 people. The data was extracted from the Korea Disease Control and Preventive Agency system from January 2020 to 16th May 2022. CFR was calculated dividing the total cumulative death cases by the total cumulative confirmed cases multiplied by 100. As for our main independent variables, the average annual mean of $PM_{2.5}$ and PM_{10} concentration levels between 2015 to 2019 in each 228 cities, counties and districts were considered to account for the air pollution level before COVID-19. The data on $PM_{2.5}$ was not available before 2015 because the Korean government officially began to pay attention to $PM_{2.5}$ from 2015. However, the study period is in line with existing literatures that examined the long-term effect of air pollution such as Coker et al. (2020). The data on air pollution was supplied by KOSIS (Korean Statistical Information Service). In order to eliminate potential endogeneity issue, the air quality data during the pandemic was eliminated and not considered as COVID-19 outbreak significantly reduced air pollution level due to social distancing measures (Ju et al. 2021). The pollution values for eight cities, counties and districts being Mungyeong, Seongju Yeongyang, Yecheon, Uiseong, Cheongdo, Cheongsong, Gunwi were missing due to the lack of monitoring stations in Gyeongsangbuk-do province for the year 2015. For these regions, the data on the average concentration of PM_{10} and $PM_{2.5}$ on the province level are used.

For the demographic variables, the share of population over 65 years old in 2019 was retrieved from KOSIS. This data was used as one the control variables as older people are relatively more vulnerable to the virus. According to data by the Ministry of Health and Welfare on Coronavirus, those over 60 years old take up 18% of the total cumulative confirmed patients and 93.59% of deceased respectively. As shown, the share of the elderly in the region is an important factor affecting COVID-19 deaths. The percent of foreign resident[8] was included as some studies suggested these factors relate to different pandemic outcome. According to KDCA, the infection of foreign residents in the 20s to 30s from Asian countries greatly increased since May 2021 taking the share of 11% of the total new cases between 1st to 7th August, 2021[9]. The associations of racial minorities and COVID-19 deaths was proven not to be statistically significant according to the study by Chauvin (2021). As for the population density, there is a positive correlation with the lethality of COVID-19 according to Chauvin, J.P. (2021) and Kim et al. (2021). City, county and district levels data on population density (per people per $100km^2$) of 2019 was used in the regression. Population density is an important factor on COVID-19

[8] Overseas researches (Desmet & Wacziarg, 2021, Knittel 2020) mention the presence of racial minorities.

[9] The confirmation of foreigners living in the country increased since early May then July 2021. Most were from big cities like Seoul, Incheon and Gyeonggi Province. Kim, H.J., (2021) "1 in 10 new COVID-19 cases were foreign residents in past 2 weeks: KDCA". Yonhap News Agency.

transmission and there is evidence that the proportion of COVID-19 death rate in dense areas such as New Delhi, Mumbai, Sao Paolo or even in New York City and Miami are relatively high because of the people's living conditions including poor sanitation (Upadhyaya., 2020).

On the socio-economic side, the year-end settlement of earned income (million won) per capita of the year 2020 reported to the National Tax Statistics was used to distinguish the effect of income on COVID-19 confirmed and mortality rates. There is evidence of positive relation between lower income level patients and higher susceptibility to COVID-19 infection (Kim et al.,2021) and mortality (Wu et al. 2020). However, some studies did not find any association between COVID-19 death rate and poverty rate (Knittel et al.,2020). Low education rate, the share of those over 15years old with primary school or no school attainment in 2020 was retrieved from KOSIS, to capture the risk of human-human contact. Low education rate represents those with less than primary school education with difficulty to enter the labor market leading to low frequency of contact with people thereby reducing the risk of infection compared to those with higher education level. The direct association with COVID-19 confirmation is likely to be strong but rather weak with COVID-19 death because people have to be confirmed first. The paper by Chauvin (2021) found no association between local education level and COVID-19 deaths per capita in Brazil. The general effect of education on mortality rate is mixed. Some argue that it has inverse relation with mortality whereas others such as Albouy and Lequien (2009) observed that education reforms in France had insignificant effect on the mortality.

Within the health status category of the region, the total number of primary and general hospitals in 2019 per 10,000 population was included at province level to consider the accessibility of treatment locations for patients with critical and severe symptoms. In Korea, the regional COVID-19 management team assigns the patient to the hospitals, community facility or home quarantine depending on the availability of the bed and severity of symptoms once a patient is confirmed with COVID-19 (Her, 2020). The data was extracted from KOSIS at province level because the hospitalized COVID-19 patients were most likely to be considered for treatments at general or primary hospitals nearest to their residents. Previous overseas studies highlighted that better medical system may be interpreted as better recovery from the virus. Additionally, the number of nursing hospital beds per 10,000 population were considered as infected and death rates soared in such facilities with aged patients being severely hit and having tougher recovery from the virus[10]. The data of COVID-19 full vaccination(second dose) rate was obtained through COVID-19 vaccination website by KDCA which showed the cumulative number of people vaccinated until June 28th 2022 over the number of populations living in the area of each public health center. COVID-19 vaccination is the only mean that can prevent the proliferation and reduce the severity and mortality from the virus. It was used as a proxy to account that higher vaccine coverage can help to prevent the risk of infection and mortality from COVID-19. However, Korea only introduced vaccination against COVID-19 since February 2021 so there is a time gap in the data as people living in Korea were not protected from the virus for a year and a month

[10] Using the data from 13th to 17th March 2022, 62.5% of the deceased were located at the hospital and 35.3% died from the nursing facilities. Kyunghyan Shinmun(2022) "Rapid increase in COVID-19 deaths and measures for vulnerable facilities urgently needed", Accessed on 9th of September.

since the beginning of the outbreak of the pandemic[11]. Lastly, obesity (Sattar et al., 2020) and smoking (Rosoff et al., 2021) are the factors that can weaken the immune system which can help the body to fight back the disease.

[11] BBC news Korea.(2022) . “COVID-19 Vaccination Starts...It took a year and 37 days”

3.2 Preliminary Data Analysis

The summary statistics of the variables are shown in Table 3. As the distribution of data for death, confirmed cases and CFR were skewed to one side, the variables were log-transformed to bring them closer to the normal distribution. The distributions graph of the main variables are illustrated in Appendix 3. The independent variables PM_{10} and $PM_{2.5}$ are obtained using the average concentration of PM_{10} and $PM_{2.5}$ during the period of 2015 to 2019.

Table 3. Summary of statistics

Variables	N	Mean	SD	Min	Max
Drate	228	47.79	29.49	3	204
CFR	228	0.156	0.094	0.0094	0.628
Crate	228	32102	6783	14433	72408
lDrate	228	3.692	0.624	1.099	5.318
lCFR	228	-6.638	0.634	-9.274	-5.070
lCrate	228	10.36	0.208	9.577	11.19
pm10	228	41.38	6.279	19.75	58.93
pm25	228	23.09	3.618	12.60	33.22
elderlyrate	228	20.06	8.017	7.258	38.87
popdenst	228	3870.4	6078	19.53	26662
income	228	35.56	6.653	25.81	74.69
Vrate2	228	0.873	0.0396	0.634	1.042
smokingrate	228	19.06	2.927	10.50	27.70
obesityrate	228	31.82	2.998	23.4	40.45
foreignshare	228	2.329	1.815	0.315	9.740
Generalhosprate	228	72.5	56.17	0	435.4
lowedurate	228	14.16	8.340	2.218	33.93
nursingbedrate	228	59.95	54.52	0	360.61

The mean cumulative death cases per 100,000 population was 47.8 during the period. The highest COVID-19 death cases occurred in Seo-Gu, Busan (204 deaths per 100,000 population) and lowest in Bosong-Gun (3deaths per 100,000 population) in South Jeolla Province. The mean value for CFR was 0.156%. The region with the lowest CFR was in Boseonggun, Jeonnam province (0.0094%) and highest in Sunchanggun, Jeonbuk province (0.628%). The detailed regions for COVID-19 death cases per 100,000 population and CFR are analyzed on Appendix 4 and 5.

The mean of the long-term concentration level for PM_{10} was 41.38μg/m^3. The highest was in Pyeongtaek-si (58.90μg/m^3), an industrial area located in Gyeonggi-do province. The lowest average concentration of PM_{10} was in Bonghwa-gun (19.8 μg/m^3) in North Gyeongsang Province. The average level of concentration for $PM_{2.5}$ during the period was 23.10 μg/m^3. It was highest in Iksan-si (33.2μg/m^3) in North Jeolla Province. It is lowest in Ulleungdo(12.6 μg/m^3) and Bonghwa-gun(12.6 μg/m^3) both located in Gyeongsangbuk-do province, of South Korea. The details on the average concentration levels of PM_{10} and $PM_{2.5}$ are shown in Appendix 6 and 7. Accordingly, the level of the particulate matters tends to be higher in metropolitan cities, industrial areas and urban regions as air pollution is deeply related to human activities.

IV. Results

4.1 Analysis on COVID-19 Death Rate

The instrumental variable approach was used to reduce the unmeasured confounding effect and mitigate the possible issues regarding endogeneity between COVID-19 confirmation and mortality. Low education rate was used as the instrumental variable and the analyses in Appendix 8 indicate that it is strongly associated with COVID-19 confirmation but not with death cases per 100,000 population. First, low education level can be interpreted as the difficulty to obtain a job which will then reduce human contact and social interaction within the society lowering COVID-19 confirmed cases. The OLS regression results in Appendix 8 also specify that low education has negative and statistically significant association with COVID-19 confirmed cases but not death cases 100,000 population. Additionally, the results of the first-stage estimation in model 1 and 3 of Table 4 prove that low education rate is negative and statistically significant at 1% level on COVID-19 confirmed cases per 100,000 people. This instrument only affects COVID-19 deaths only through the infection of COVID-19 satisfying one of three conditions for a valid instrument, to be uncorrelated with all other factors besides COVID-19 confirmed cases. The joint significance of the instrument was tested and the F-statistics indicated to be 43.69 for PM_{10} and 61.14 for $PM_{2.5}$. However, due to the possible association between low education rate and income level, a separate estimation model without income per capita was regressed and shown in Appendix 9 to prove that the results of the main variables PM_{10} and $PM_{2.5}$ remain unchanged.

Table 4. IV estimates for PM_{10} & $PM_{2.5}$

VARIABLES	(1) First stage lCrate	(2) Second Stage lDrate	(3) First-stage lCrate	(4) Second-stage lDrate
pm10	0.00610***	**0.0194***		
	(0.00217)	**(0.0110)**		
pm25			0.00885***	**0.0321****
			(0.00316)	**(0.0147)**
lCrate		-0.903		-0.764
		(0.597)		(0.497)
Vrate2	-0.230	-2.195	-0.229	-2.270
	(0.376)	(1.550)	(0.376)	(1.515)
Generalhosprate	1.168**	-5.390**	0.896*	-6.161***
	(0.504)	(2.210)	(0.468)	(1.873)
nursingbedrate	0.000325*	0.00347***	0.000316*	0.00336***
	(0.000187)	(0.000759)	(0.000187)	(0.000742)
obesityrate	0.0105***	0.00931	0.00990**	0.00578
	(0.00396)	(0.0172)	(0.00396)	(0.0164)
smokingrate	-0.00456	0.0197	-0.00498	0.0190
	(0.00406)	(0.0162)	(0.00406)	(0.0160)
foreignshare	0.0153**	0.00525	0.0147*	0.00187
	(0.00747)	(0.0338)	(0.00745)	(0.0323)
income	0.00281	-0.0160*	0.00234	-0.0176**
	(0.00205)	(0.00881)	(0.00203)	(0.00832)
popdenst	0.000467**	0.00404***	0.000404**	0.00379***
	(0.000194)	(0.000904)	(0.000193)	(0.000835)
lowedurate	-0.0134***		-0.0144***	
	(0.00203)		(0.00185)	
Constant	9.984***	14.09**	10.12***	13.04**
	(0.362)	(6.197)	(0.354)	(5.411)
Observations	228	228	228	228
R-squared	0.566	0.208	0.566	0.233
F-stat	43.691		61.142	

Notes: 1) Standard errors are in parentheses
*2) *** p<0.01, ** p<0.05, * p<0.1*

The empirical findings in Table 4 show that both types of air pollution are positive and significantly associated with higher percentage increase in COVID-19 death cases per 100,000 population. PM_{10} is positive and statistically significant at 10% level. $PM_{2.5}$ is positive and statistically significant at 5% level on COVID-19 death cases per 100,000 people. The magnitude is greater for $PM_{2.5}$ than PM_{10}. The main results are similar to the findings conducted in overseas countries by Perone (2022), Leirião et al. (2021) and other papers listed in the literature reviews. In model 2 of Table 4, an additional 1μg/m^3 concentration of PM_{10} is estimated to increase 1.94% of COVID-19 death cases per 100,000 population. In model 4 of Table 4, 1μg/m^3 increase of $PM_{2.5}$ is estimated to increase COVID-19 death cases per 100,000 people by 3.21%.

Three different groups of control variables in the demographics, socio-economic, health related sectors were considered to explain the differences in COVID-19 death cases across cities, counties and districts. The number of primary and general hospitals in each province is negative and statistically significant at 5% for PM_{10} in model 2 and 1% level for $PM_{2.5}$ in model 4 of Table 4 indicating that COVID-19 mortality can be reduced with access to the healthcare system. On the other hand, the number of beds per 10,000 people at nursing hospitals have positive and statistically significant effect at 1% level on COVID-19 deaths in both models as expected because these are vulnerable facilities that take care of elderly with comorbidities with high risk of death. Already, high proportion of COVID-19 death cases continued to increase throughout the pandemic in nursing care facilities and many highlighted the need to pay more attention to these types of facilities. The study by Kim et al. (2020) that investigated the factors related to COVID-19 infection and deaths in Gyeongsangbuk-do area of Korea, mentioned the type of residence such as in care facility was positively associated with COVID-19 mortality. In the socio-economic sector, income per capita is negative and statistically significant at 10% level for model 2 and 5% level for model 4 of Table 4. This can be interpreted because people take care of their health as income level increases by eating healthier food and going to the gym to exercise which might have led to higher immunity thus reducing COVID-19 mortality. Becchetti et al. (2022) also observed negative and statistically significant relation between income and COVID-19 excess deaths in Italian municipalities. The result for population density is consistent with previous studies, suggesting positive and statistically significant at 1% level on COVID-19 death cases per 100,000 population in both model 2 and model 4 of Table 4. The study of Brazil conducted by Chauvin (2021) noticed that stronger correlation was detected between population density and COVID-19 deaths as the pandemic period progressed. Overall, these results are similar to many other research papers that investigated the factors affecting COVID-19 mortality rate in which population density, proportion of population over 65 years old were found to have positive and statistical significance whereas per capita income had negative and statistically significant effect on COVID-19 death rate (Upadhyaya et al., 2020). Lastly, we did not find much evidence on the relationship between COVID-19 mortality and full vaccination rate, obesity rate, smoking rate and share of foreign residents living in the cities, counties and districts.

4.2 Sensitivity Analysis

To check the robustness of the regression models, an interaction variable (air pollution level multiplied by infection rate of the region) was used as the independent variable. The OLS estimation was conducted to find that the results were similar to those obtained in 2SLS models, and shown in model 2 and model 4 of Table 5. The interaction variable of PM_{10} (lCratepm10) is positive and statistically significant at 10% level in model 2 of Table 5 and statistically significant at 5% level for $PM_{2.5}$ in model 4 of Table 5. The results of other factors are similar to the previous empirical results except for smoking rate which is positive and statistically significant at 10% in both models of Table 5. In model 2 and 4 of Table 5, PM_{10} and $PM_{2.5}$ are negative and statistically significant at 10% level with the use of interaction variable probably because air pollution in Korea is higher in metropolitan cities with higher share of working population and COVID-19 confirmed rate but lower death rate compared to other regions because of younger population has stronger immunity to fight back the virus. COVID-19 full vaccination rate of each city, county and district resulted to be negative and statistically significant at 5% level which is in line with our prediction that vaccine will provide protection in the immune system preventing death. Elderly rate is an important factor on COVID-19 death cases per 100,000 people and showed to be statistically significant at 1% level. This is because older population are more vulnerable to the virus increasing its lethality because of their low immune systems and comorbidities. This falls in line with the result of the study by Coker et al. (2020) which found bigger impact in municipalities with higher share of aged population in Northern Italy.

Table 5. OLS estimates for PM_{10} & $PM_{2.5}$

VARIABLES	(1) log Death rate	(2) log Death rate	(3) log Death rate	(4) log Death rate
lCratepm10		**0.0463***		
		(0.0247)		
lCratepm25				**0.0872****
				(0.0413)
pm10	0.0179**	-0.458*		
	(0.00800)	(0.254)		
pm25			0.0280**	-0.869**
			(0.0117)	(0.425)
lCrate	0.720***	-1.073	0.720***	-1.171
	(0.246)	(0.988)	(0.245)	(0.928)
Vrate2	-3.119**	-3.209**	-3.178**	-3.256**
	(1.379)	(1.372)	(1.379)	(1.368)
Generalhosprate	-6.463***	-5.929***	-7.199***	-6.961***
	(1.874)	(1.885)	(1.723)	(1.713)
nursingbedrate	0.00278***	0.00288***	0.00275***	0.00287***
	(0.000691)	(0.000690)	(0.000691)	(0.000688)
obesityrate	-0.00197	-0.00172	-0.00403	-0.00221
	(0.0147)	(0.0147)	(0.0147)	(0.0146)
smokingrate	0.0278*	0.0284*	0.0265*	0.0255*
	(0.0149)	(0.0148)	(0.0149)	(0.0148)
foreignshare	0.000746	-0.00448	-0.000587	-0.00830
	(0.0277)	(0.0276)	(0.0275)	(0.0276)
income	-0.0168**	-0.0173**	-0.0179**	-0.0180**
	(0.00747)	(0.00743)	(0.00739)	(0.00733)
popdenst	0.00313***	0.00309***	0.00300***	0.00291***
	(0.000699)	(0.000696)	(0.000697)	(0.000693)
elderlyrate	3.520***	3.607***	3.301***	3.365***
	(0.755)	(0.752)	(0.715)	(0.710)
Constant	-2.181	16.24	-1.802	17.62*
	(2.803)	(10.22)	(2.813)	(9.618)
Observations	228	228	228	228
R-squared	0.354	0.365	0.356	0.369

Notes: 1) Standard errors are in parentheses
*2) *** p<0.01, ** p<0.05, * p<0.1*

Then, we also replaced the variable lDrate to lCFR. The effects of average concentration level of $PM_{2.5}$ and PM_{10} on CFR was evaluated using OLS regression and the estimated results are shown in Table 6 below.

Table 6. OLS estimates using Case Fatality Rate(CFR)

VARIABLES	(1) log CFR	(2) log CFR
pm10	**0.0158****	
	(0.00802)	
pm25		**0.0249****
		(0.0118)
Vrate2	-2.886**	-2.938**
	(1.414)	(1.414)
Generalhosprate	-7.090***	-7.742***
	(1.902)	(1.758)
nursingbedrate	0.00266***	0.00264***
	(0.000704)	(0.000704)
obesityrate	-0.00110	-0.00293
	(0.0149)	(0.0149)
smokingrate	0.0272*	0.0260*
	(0.0153)	(0.0152)
foreignshare	-0.00649	-0.00766
	(0.0281)	(0.0280)
income	-0.0167**	-0.0177**
	(0.00761)	(0.00755)
popdenst	0.00299***	0.00287***
	(0.000694)	(0.000695)
elderlyrate	3.744***	3.550***
	(0.715)	(0.658)
Constant	-0.577	-0.236
	(1.358)	(1.322)
Observations	228	228
R-squared	0.344	0.345

Notes: 1) Standard errors are in parentheses
*2) *** p<0.01, ** p<0.05, * p<0.1*

The estimation results in Table 6 show that PM_{10} is positive and statistically significant at 5% level. An average of 1μg/m^3 increases of PM_{10} increases COVID-19 CFR by 1.58%. $PM_{2.5}$ was also found to be positive and statistically significant at 5% level. An increase of 1μg/m^3 in the average concentration level of $PM_{2.5}$ increases CFR by 2.49%. Both PM_{10} and $PM_{2.5}$ have positive impact on the CFR of COVID-19 and this finding is in line with other overseas studies by Travaglio et al. (2021) and Leirião et al. (2021). In order to avoid any biased estimation results due to the collinearities issues among the variables, the variance inflation factors (VIF) was calculated to detect the multicollinearity degree. As a result, the VIF values of the variables range from 1 to 2.65 in both models of Table 6, with the mean VIF of 1.89 for model 1 and mean VIF of 1.77 for model 2 of Table 6. Accordingly, there is no issue of multicollinearity between the independent variables in the estimated models above.

Our empirical findings suggest that public health is at risk especially during the time of the pandemic COVID-19. Air pollution is increasing COVID-19 deaths and CFR worsening the impact to the society. As a consequence, the government and related agencies should strategically plan and develop technologies related to the reduction of air pollution and increase efficient energy consumption in order to achieve clean air environment. In the following chapter, the current government policies and planning post COVID-19 shall be examined with some suggestions related to the result of the analysis.

V. Policy Implications

Currently, the Ministry of Land, Infrastructure and Transport (MOLIT) is the national urban planning authority in charge of long-term policies under the Comprehensive National Territorial Plan (CNTP) since 1972. The Fifth Comprehensive National Territorial Plan applicable from 2020 to 2040 is the current urban policy that covers sectors such as spatial structure, human development, climate resilience, environmental sustainability and others. It tackles issues of decreasing populations, economic growth, land environment and quality of life. Among the six main strategies, the fourth strategy is about measures related to climate change and air pollution with actions aiming to create an environment-friendly territory. The urban policy measures on climate change and air pollution from Space & Environment (2020) are summarized in Table7 below.

Table 7. Strategies on the Fifth Comprehensive National Territorial Plan

Sector	Strategies
Climate Change & air pollution	- Set greenhouse reduction goal according to the Paris Agreement - Optimize the structure of urban space to reduce fine-particle dust - Engage in international collaboration and aid-systems - Increase green areas within the living area of the citizens - Implement green infrastructure to lower energy consumption

Reference: The Fifth Comprehensive National Territorial Plan (2020~ 2040)

Additionally, there is the Comprehensive Plan on Fine Dust Management by the Ministry of Environment along with twenty different ministries that deals with the overall domestic and international air pollution policies of Korea. The detailed measures for the period of 2020 to 2024 are summarized and listed below in Table 8.

Table 8. Summary of the Comprehensive Planning per sector for 2020-2024

Main Sector	Main Strategies
Air Quality Standard	$PM_{2.5}$: Daily av. of 35μg/㎥ or less, yearly av. of 15μg/㎥ or less PM_{10}: Daily av. of 100μg/㎥ or less, yearly av. of 50μg/㎥ or less
Power Generation	- Close down 10 old coal-fired power plants by 2025 - Replace to power efficient turbines to reduce emission - Increase the share of renewable energy
Industries	-Total Suspended Particles Emission Cap setting max. allowable level - Impose emission charges and mandates - Increase number of facilities with TMS measurement
Transportation	- Subsidies provided for buying electric or hydrogen cars - Fuel regulations on diesel to contain less than 0.1% sulphur content - Stricter permissible emission standards in line with U.S.A and EU - Increase network of bus subway, train to reduce car usage - Control air pollution of ports, construction sites, airports and farms
Daily surroundings	-Fugitive dust producing construction business and facilities required to report to the government, get inspected learn preventive practice
Urban	- Support the replacement of boiler over 10 years to an eco-boiler - Increase the supply of dust cleaning vehicles and switch them to environment friendly cleaning vehicles - Restore natural environment in damaged regions - Expand urban wind road in each of the 17 regions - Fine dust forest(90ha) in industrial areas + 10 forests in living areas.
Vulnerable group	- Install air purifier in the facilities used by vulnerable groups - Increase air pollution monitoring stations and monitoring vehicles - Educate teachers to provide info, requiring behavioral changes
Public	-Provide guideline on air pollution discouraging outdoor activities
Seasonal Measures (Dec-Mar)	- Inspect business facilities & implement voluntary reduction system - Stop running coal-based power plant and set max. permissible level - Limit the operation of group 5 vehicles in Metropolitan areas - Limit the usage of old construction machine - Require lower speed of ships in port - Stricter inspection of fugitive dust in construction sites and road
Emergency Measures	- Reduce school hours or adjust outdoor activities at school - Provide health guideline to the sensitive group
International measures	- Discuss details on air pollution in high-level meeting with China - Sign MOU with China to share info, joint-research and measures - North East Asia Clean Air Partnership established in 2018 to share scientific evidence, technologies, policies on air pollution. - Elaborate joint research to analyze the cause of air pollution with China, Japan on Long-range Transboundary Air Pollutant

Reference: The Comprehensive Plan for fine dust Management (2020~2024)

After reviewing the current government's air pollution policies including its urban measures, I noticed that these are mostly passive methods likely to take a long time to achieve successful results. Although the government is trying to share related information with the citizens, there is lack of measures requiring their active participations. According to the demographics data of Statistics Korea, 91.8% of the total population are found to be living in urban area in 2021[12], so it is necessary to elaborate air pollution measures on urban level that can bring immediate reduction in its level of concentration.

The emission sources of air pollution are all deeply related to human activities from transportation, industry and power plants sectors. These sources differ depending on the types of human activities of that region. For example, the main sources of local emissions in Seoul Metropolitan Area (SMA) are diesel vehicles associating 22% (11% ratio on country level), followed by construction machinery with 20% of the share (16% ratio on country level) according to the Korea Environmental Policy Bulletin No.46. (2018). Whereas, the main source of emission was from the business facilities taking 38% of the share (16% of SMA) when looking at the country as a whole (Korea Environmental Policy Bulletin No.46, 2018). Considering all of these, the level and source of air pollution emission vary in every region but the current regulations on fine dusts emissions are planned and managed only on country level with the exception of Seoul. Apart from the Special Measures for Air Quality in Seoul, other regions do not have any other special measures. It

[12] The definition of urban area is residential, commercial, or industrial area according to Statistics Korea. The urban population was 47.4 million and rural population counted to be 4.24 million in 2021.

would be effective if the country-level regulations were to be extended to the regional and urban level taking account of the main sources of emission of the region based on scientific studies. Eum & Kim (2020) are also in support of the view that fine dust reduction policy should be based on regional level as local characteristics can influence the level of emission.

Similarly, there are only country level measures regarding Korea's energy transition in the power generation sector of Table 8, which can be summarized as planning to close down coal and nuclear power stations gradually and increasing renewable energy sources. In 2017, the emissions from fossil fuels power generating sectors accounted for 36% of the country's total greenhouse emissions (Myllyvirta, 2021). Based on the characteristics of the region, detailed measures on the implementation of the renewable energy should be developed and strengthened to bring changes to the city and to its environment. In order to effectively increase the share of renewable energy, it would be the role of urban planning to bring customized measures and build renewable energy sources on the regional level requiring active participation of citizens, businesses and industries with the objective of energy independence. To sum up, a customized fine dust management and planning for renewable energy are needed on the regional level.

In line with the evidence that both types of particulate matter cause serious health effects worsening the current situation with COVID-19, the government must prioritize its tasks on the reduction of air pollution by strengthening the allowable level. Currently, the Ministry of Environment is controlling $PM_{2.5}$ to be less than $35\mu g/m^3$ on daily level and a yearly average of $15\mu g/m^3$, as for PM_{10} to be less than daily average of 100μg/㎥ and yearly average of 50μg/㎥. It is aiming to decrease $PM_{2.5}$ by 35% compared to the average concentration level of 2016, from 26μg/m^3 to 16μg/m^3 by 2024. However, these standards are higher than WHO's recommendation level which is 5μg/m^3 for $PM_{2.5}$ and 10μg/m^3 for PM_{10}. The current allowable standard must be tightened and the government should separately set up an air quality standard on city level for different types of air pollution. For an effective control on the emission of air pollution, it is necessary to impose higher sanctions to the industry violating the limits. According to OECD working paper No 158 (2020), criminal sanctions for violating environmental laws are often not applied in Korea. Even in the situation in which the permissible emission standards were not met, the government often imposed higher taxes instead of sanctions, making it easier for the violator to get away. We should refer to cases of countries such as Japan, Europe and United States where the regulations on Environment are strongly applied.

According to the empirical results of this paper, population density and proportion of elderly are the other factors having positive association with COVID-19 deaths, worsening the prognosis of COVID-19. Currently, there are many studies and urban policies that suggest accessible urban greenspace in a way to deal with the pandemic. According to the report by WHO, green space in urban area can achieve multiple health benefits including physical and mental health, lowering air pollution, heat island effect and exposure to noise (WHO, 2016 Urban green spaces and health). Even the urban development policies of Korea shown previously in Table 7 and Table

8, include the restoration of natural environment in damaged regions, expansion of urban wind road in 17 regions and building fine dust forests in industrial areas and 10 forests in living areas. Korea's national average of urban green space was 11.51㎡ per capita in 2019 and the Korea Forest Service department is planning to increase to 15㎡ by 2027[13]. In order to bring positive results not only in terms of air pollution but also to the elderly population and dense regions, the government should elaborate the implementation of urban forests and green environment according to the density of the population in each region. Increasing the implementation of such forests and green spaces in the urban area will reduce both the level of air pollution and bring positive effects to the vulnerable group and others living in the crowded cities. Hopefully, such public green area will contribute to lowering COVID-19 deaths and help to fight with other future pandemics.

[13]Urban green space means the area that can easily be accessed by those living in the urban area. Cho, H.P (2022). The Solution to Climate Disaster is 'Urban Forest'. *Maeil Business News Korea*. July 28. URL: https://www.mk.co.kr/news/special-edition/view/2022/07/663597/

VI. Conclusion

6.1 Summary

I believe putting forward air pollution reduction measures at urban level could be the most effective strategy to solve the current the air pollution issues and reduce the number of COVID-19 deaths of South Korea. Korea is one of the countries that is highly dependent on coal and other types of fossil fuel contributing to high domestic air pollution. The major sources of power generation in South Korea are fossil fuels especially coal. Because of the high usage in urban regions, cities have high emission level of air pollution but the current air pollution reduction strategies are rather passive methods limited to restoring natural environment or increasing green areas including fine dust forests. This paper would like to emphasize that the issues of the pandemic and air pollution must be dealt with greater responsibilities in urban planning sector.

The main findings of the study are that it quantified not only the effects of long-term air pollution but also other factors affecting the mortality of COVID-19 in Korea. The results of 2SLS and OLS show that PM_{10} is positive and statistically significant at 10% level on COVID-19 deaths per 100,000 people. $1\mu g/m^3$ increase of PM_{10} concentration is projected to increase COVID-19 death cases per 100,000 people by 1.94%~4.63% depending on the model used. $PM_{2.5}$ is positive and statistically significant at 5% level on COVID-19 deaths per 100,000 people. $1\mu g/m^3$ increase of $PM_{2.5}$ concentration is projected to increase COVID-19 deaths per 100,000 people by 3.21%~8.72%. The sensitivity analyses used CFR as the dependent variable to find that PM_{10} and $PM_{2.5}$ are positive and statistically significant at 5% level. Other factors such as COVID-19 full vaccination rate, the number of primary and general hospitals per 10,000 population at province level and income per capita showed to be negatively associated with COVID-19 deaths. Positive and statistically significant results were found for the number beds at the nursing hospitals per 10,000 population, proportion of elderly and population density on COVID-19 death cases per 100,000 population.

With the threat of the pandemic along with high level of air pollution, the government and policy makers need to re-evaluate the recent air pollution and urban policies. In order to effectively reduce the concentration of air pollution, urban planning should step in and implement customized air pollution measures depending on the sources of emission in each region based on scientific evidence. It should also develop measures on renewable energy requiring citizens to be more responsible and actively participate in such transition. The government must prioritize its tasks on the reduction of air pollution by tightening controls and setting allowable maximum air pollution level at city level to meet the recommended level of the WHO. Furthermore, urban policy should prioritize not only air quality but also find measures that can promote active lifestyle for the health of the citizen within the urban system by expanding urban green space and forests.

In conclusion, the findings show evidence that we need to be protected against air pollution, specifically $PM_{2.5}$ and PM_{10}. The environment of cities must be carefully developed and planned in order to bring air pollution and COVID-19 deaths to the lowest level. We should utilize learning lessons and effectively plan a healthy and sustainable city aiming to achieve long-term clean air quality, sustainable economic development and prevent future epidemics.

6.2 Limitations of the study

First of all, individual data and more specific data including the number of COVID-19 death and confirmed population on daily basis were not available. The data available was only the cumulative number of death and infection cases at a given date so it was impossible to consider time series of data with the number of COVID-19 death cases in each city, county or district. Second, there might be some discrepancy coming from the data as the death cases from COVID-19 is based on the resident registration standards but some people might be exposed to air pollution or vice versa in their working region. However, this discrepancy is expected to be small as most of the deceased are found to be older population. The period of study starts from the year 2015 because of the availability of the data on $PM_{2.5}$. The reliability of the study could increase if longer term data was used and analyzed on the concentration level of particulate matter. Lastly, there are different types of air pollutions such as SO_2, NO_2 and O_3 that are fatal to COVID-19 patients but this paper only discusses about the effect of particulate matter, PM_{10} and $PM_{2.5}$. I believe elaborating this study on other types of air pollution would make the paper more complete.

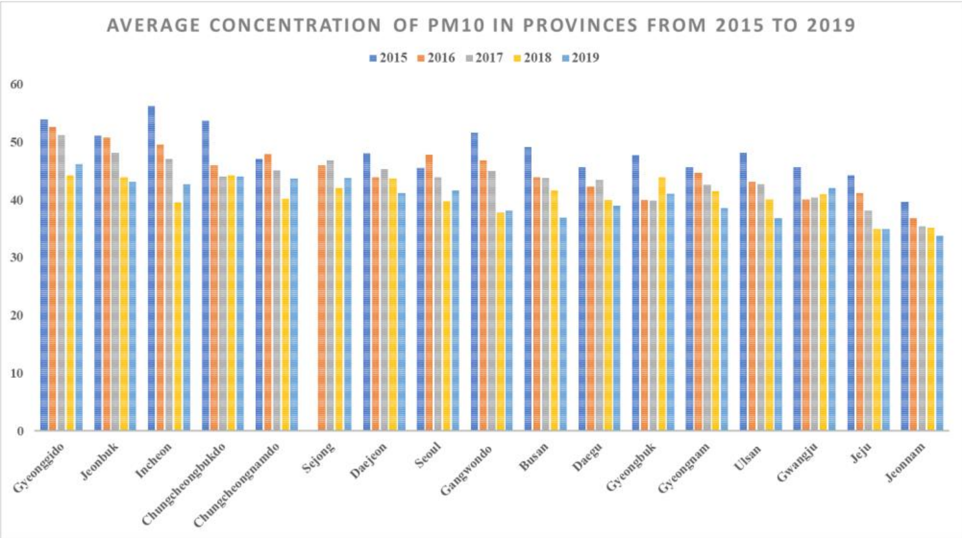
Appendix

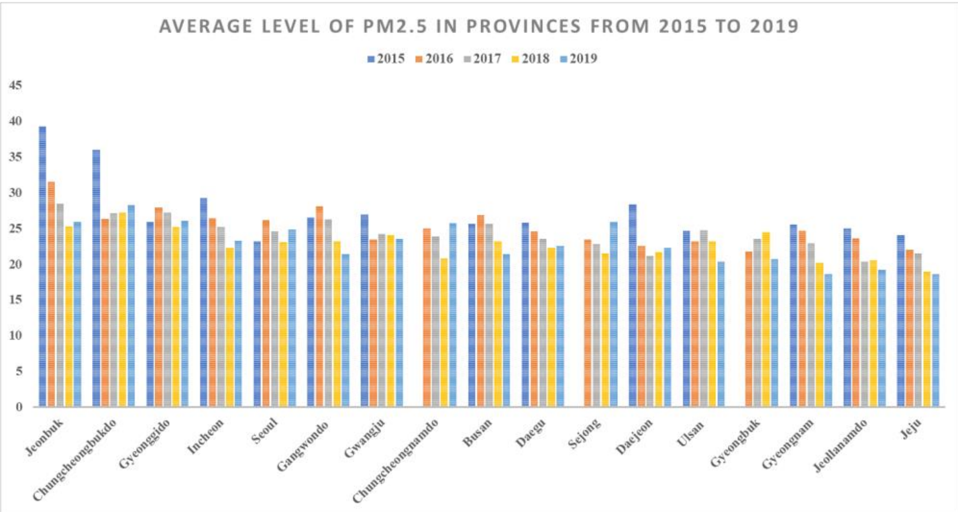
Appendix 1. List of cities, counties and districts per province

Seoul	Seongpagu	Seongdonggu	Jonrogu	Eunpyeonggu
	Gangnamgu	Seodaemungu	Yongsangu	Gwanakgu
	Dongdaemungu	Gangbukgu	Gangseogu	Yangcheongu
	Nowongu	Geumcheongu	Jungnanggu	Gurogu
	Gangdonggu	Junggu	Gwanjingu	Seongbukgu
	Yeongdeungpogu	Seochogu	Dongjakgu	Mapogu
	Dobonggu			
Busan	Jingu	Sahagu	Namgu	HaeunDaegu
	Yeonjegu	Dongnaegu	Gijanggun	Seogu
	Donggu	Geumjeonggu	Sasanggu	Junggu
	Yeongdogu	Gangseogu	Bukgu	Suyeonggu
Ulsan	Bukgu	Junggu	Namgu	Uljugun
	Donggu			
Chungcheongbukdo	Jeungpyeonggun	Chungjusi	Jecheonsi	Jincheongun
	Eumseonggun	Cheonjusi	Okcheongun	Yeongdonggun
	Goesangun	Boeungun	Danyanggun	
Chungcheongnamdo	Cheonansi	Asansi	Dangjinsi	Seosansi
	Hongseonggun	Nonsansi	Gonjusi	Boryeongsi
	Cheongyanggun	Buyeogun	Taeangun	Gyeryongsi
	Geumsangun	Seocheongun	Yesangun	
Sejong	Sejongsi			
Daegu	Dalseogu	Junggu	Namgu	Seogu
	Bukgu	Dalseonggun	Donggu	Suseonggu
Daejeon	Seogu	Daedeokgu	Donggu	Yuseonggu
	Junggu			
Gangwondo	Cheorwongun	Chuncheonsi	Gangneungsisi	Donghaesi
	Samcheoksi	Taebaeksi	Sokchosi	Hwacheongun
	Pyeongchanggun	Injegun	Yeongwolgun	Yanggugun
	Hoengseonggun	Goseonggun	Jeonseongun	Yangyanggun
	Hongcheongun	Wonjusi		
Gwangju	Gwangsangu	Donggu	Namgu	Bukgu
	Seogu			

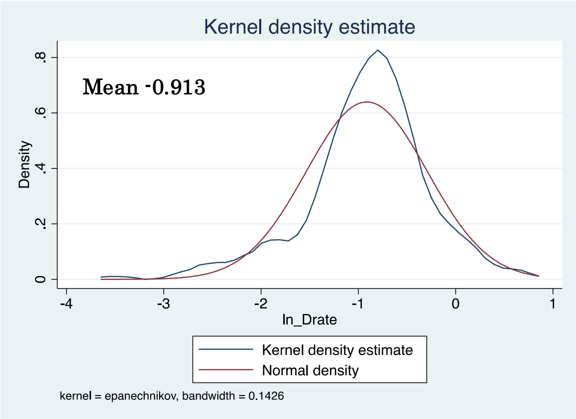
Gyeongbuk	Yeongyanggun Ulleunggun Cheongsonggun Cheongdogun Mungyeongsi Goryeonggun	Gumisi Yeongjusi Pohangsi Uiseonggun Sangjusi Gimcheonsi	Gyeonsansisi Gunwigun Seongjugun Uljingun Yeongcheonsi Andongsi	Gyeongjusi Bonghwagun Yeongdeokgun Yecheongun Chilgokgun
Gyeonggido	Yonginsi Yeoncheongun Gapyeonggun Dongducheonsi Yangpyeonggun Gwangmyeongsi Gimposi Pyeongtaeksi	Hwaseongsi Gwacheonsi Anseongsi Osansi Gunposi Hanamsi Siheungsi Bucheonsi	Goyangsi Yeojusi Uiwangsi Icheonsi Anyangsi Gwangjusi Ansansi Namyangjusi	Seongnamsi Pocheonsi Gurisi Yangjusi Suwonsi Uijeongbusi Pajusi
Gyeongnam	Changwonsi Sancheonggun Namhaegun Hapcheongun Changnyeonggun	Hamyanggun Uiryeonggun Goseonggun Hadonggun Tongyeongsi	Yangsansi Geochanggun Sacheonsi Jinjusi	Gimhaesi Miryangsi Hamangun Geojesi
Incheon	Seogu Michuholgu Junggu	Namdonggu Gyeyanggu	Bupyeonggu Donggu	Yeonsugu Ganghwagun
Jeonbuk	Jeonjusi Buangun Jeongeupsi Sunchanggun	Jangsugun Imsilgun Gimjesi Iksansi	Jinangun Gochanggun Wanjugun	Mujugun Namwonsi Gunsansisi
Jeonnam	Damyanggun Hwasungun Yeonggwanggun Yeongamgun Gokseonggun Hampyeonggun	Yeosusisi Muangun Haenamgun Boseonggun Jindogun Jangheunggu n	Gwangyangsi Suncheonsi Gangjingun Goheunggun Guryegun	Mokposi Jangseonggun Najusi Wandogun Sinangun
Jeju	Jejusi	Seogwiposi		

Appendix 2. *Average concentration of PM10 & PM2.5 per year*

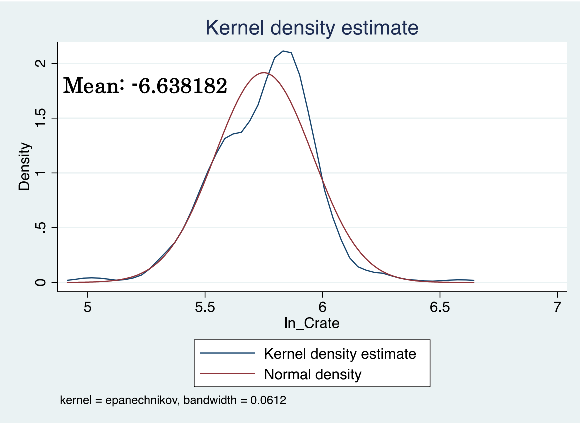




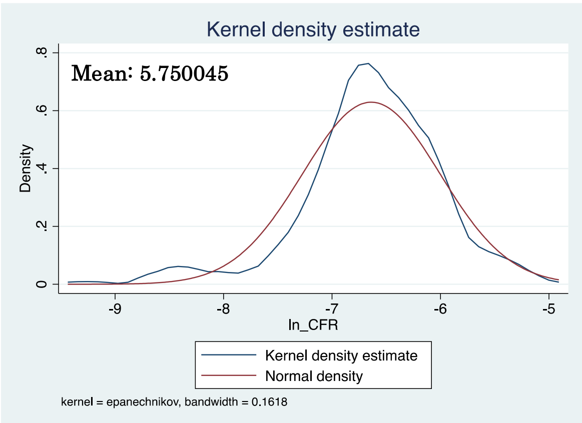
Appendix 3. *Distribution of main variables*



Log Death Rate(lDrate)

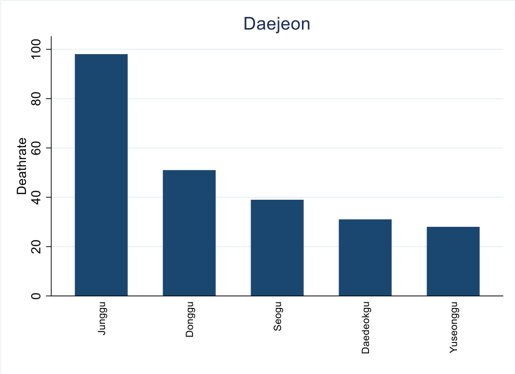


Log Confirmed Rate (lCrate)



Log Case Fatality Rate (lCFR)

Appendix 4. *COVID-19 Death Rate of city, county and district*


Daejeon
Deathrate
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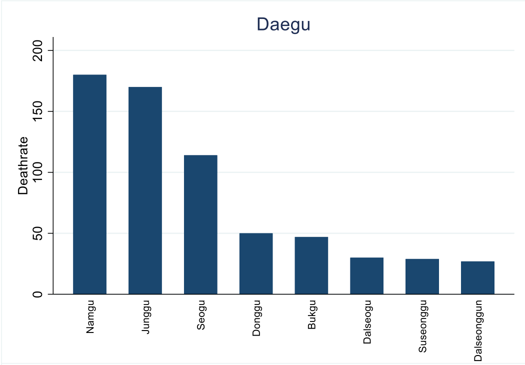
20
40
60
80
100
Junggu
Donggu
Seogu
Daedeokgu
Yuseonggu


Daegu
Deathrate
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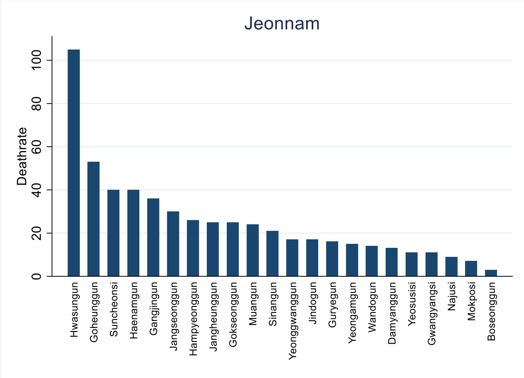
50
100
150
200
Namgu
Junggu
Seogu
Donggu
Bukgu
Dalseogu
Suseonggu
Dalseonggun


Jeonnam
Deathrate
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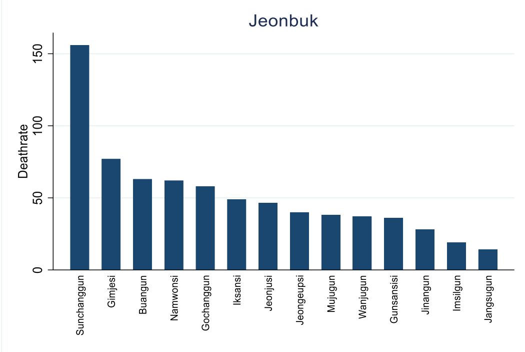
20
40
60
80
100
Hwasungun
Goheunggun
Suncheonsi
Haenamgun
Gangjingun
Jangseonggun
Hampyeonggun
Jangheunggun
Gokseonggun
Muangun
Sinangun
Yeonggwanggun
Jindogun
Guryegun
Yeongamgun
Wandogun
Damyanggun
Yeosusisi
Gwangyangsi
Najusi
Mokposi
Boseonggun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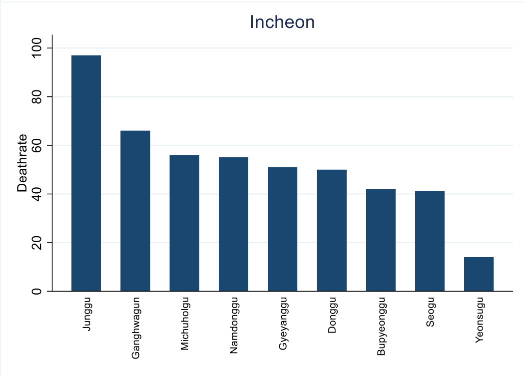
Deathrate
0
50
100
150
Sunchanggun
Gimjesi
Buangun
Namwonsi
Gochanggun
Iksansi
Jeonjusi
Jeongeupsi
Mujugun
Wanjugun
Gunsansisi
Jinangun
Imsilgun
Jangsugun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Deathrate
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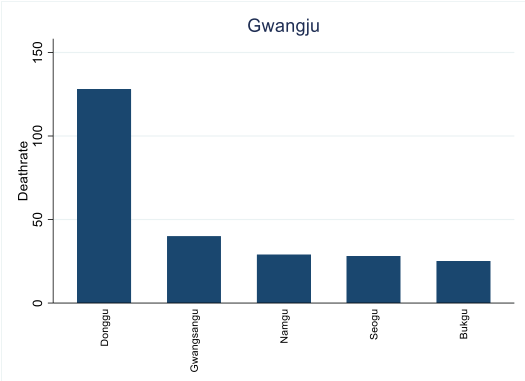
20
40
60
80
100
Junggu
Ganghwagun
Michuholgu
Namdonggu
Gyeyanggu
Donggu
Bupyeonggu
Seogu
Yeonsugu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Deathrate
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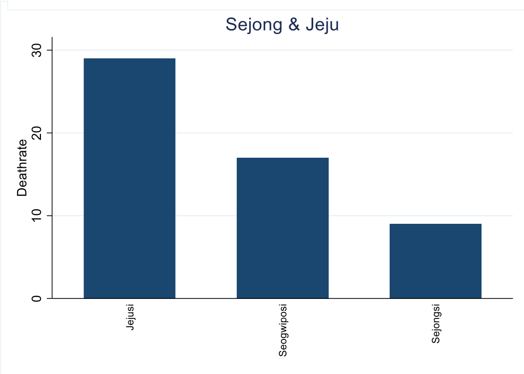
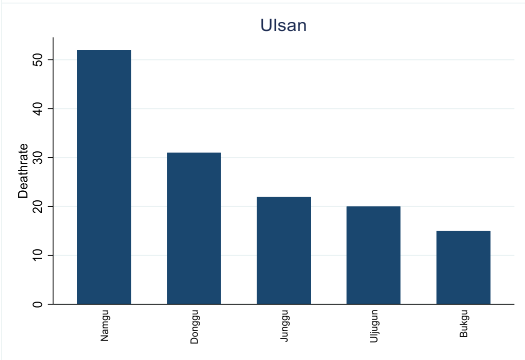
100
150
Donggu
Gwangsangu
Namgu
Seogu
Bukgu


Sejong & Jeju
Deathrate
0
10
20
30
Jejusi
Seogwiposi
Sejongsi


Ulsan
Deathrate
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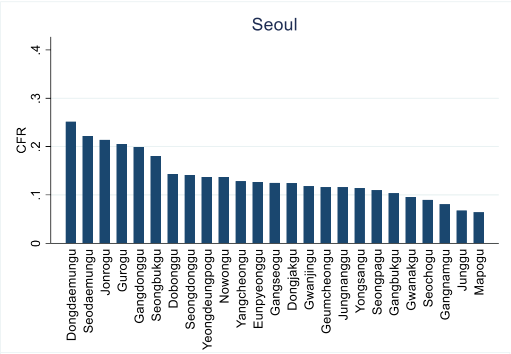
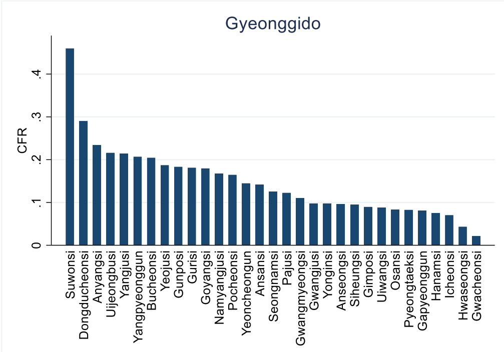
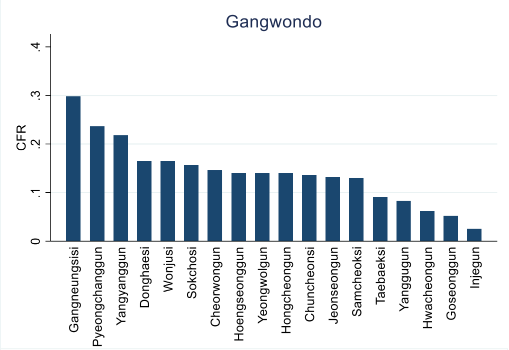
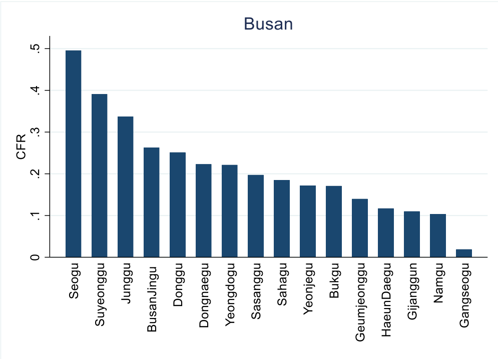
Namgu
Donggu
Junggu
Uljugun
Bukgu

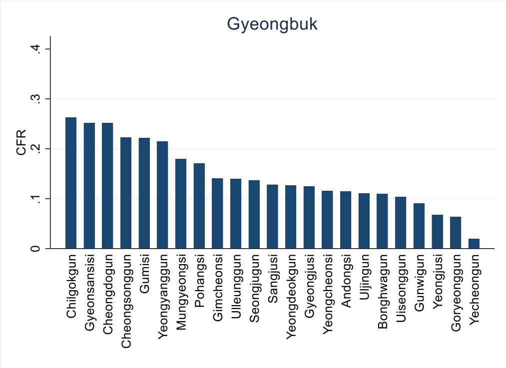
Appendix 5. *Case Fatality Rate of each city, county and district*

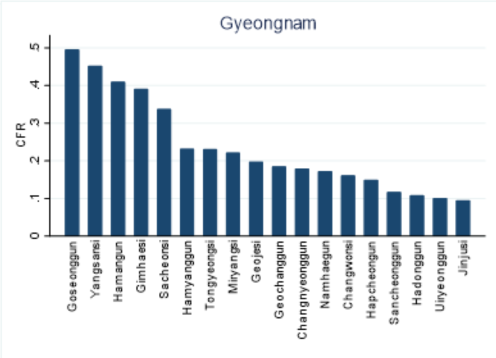


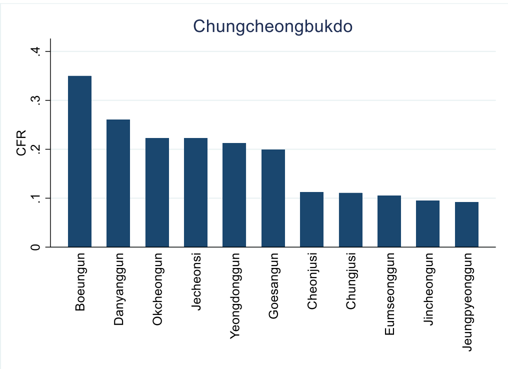


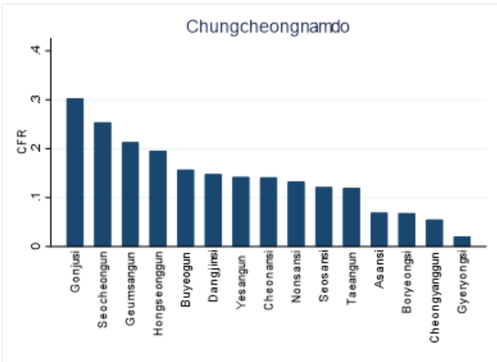


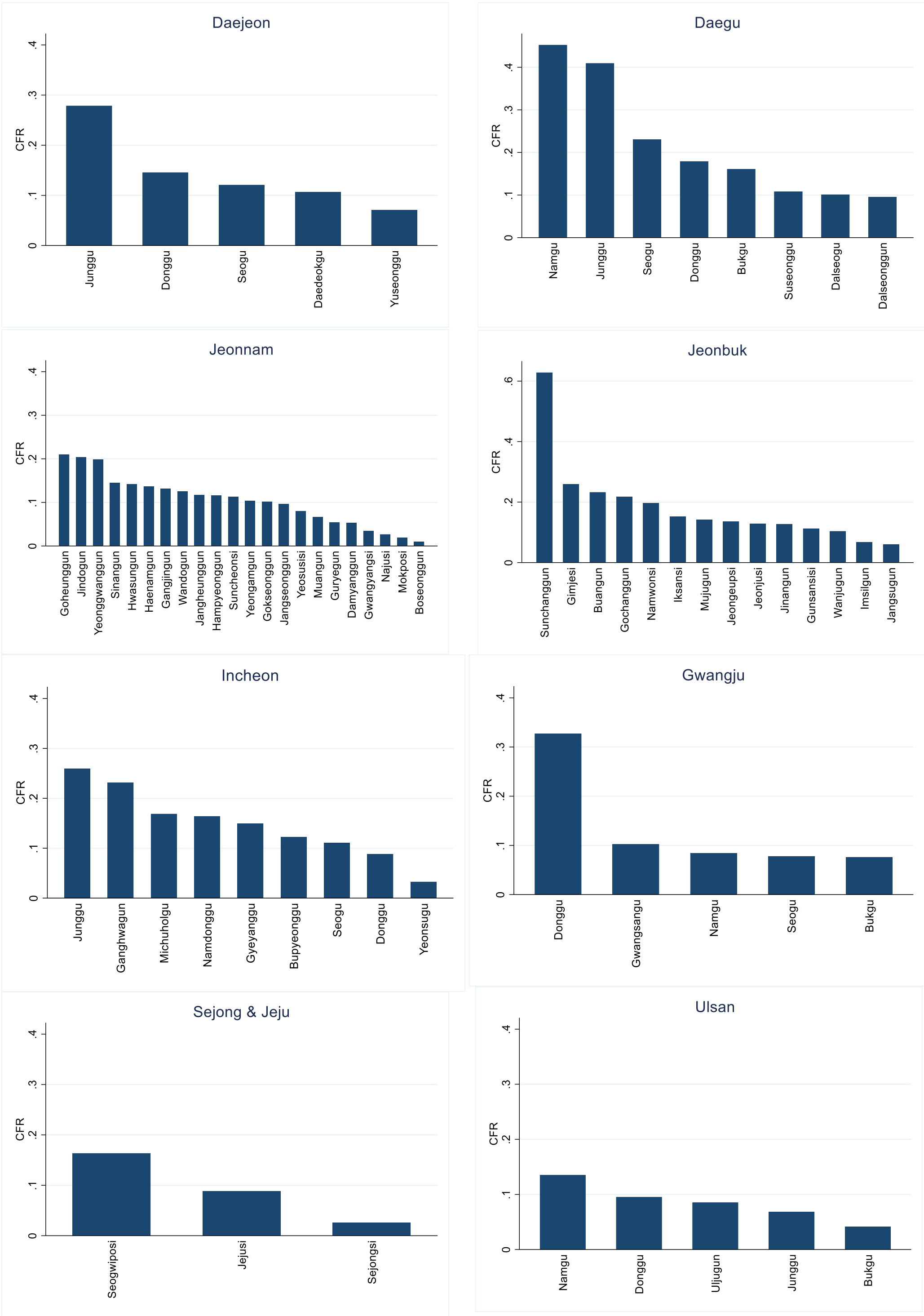








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CFR
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Donggu
Seogu
Daedeokgu
Yuseonggu
Daegu
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Namgu
Junggu
Seogu
Donggu
Bukgu
Suseonggu
Dalseogu
Dalseonggun
Jeonnam
CFR
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Jindogun
Yeonggwanggun
Sinangun
Hwasungun
Haenamgun
Gangjingun
Wandogun
Jangheunggun
Hampyeonggun
Suncheonsi
Yeongamgun
Gokseonggun
Jangseonggun
Yeosusisi
Muangun
Guryegun
Damyanggun
Gwangyangsi
Najusi
Mokposi
Boseonggun
Jeonbuk
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Gochanggun
Namwonsi
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Jeonjusi
Jinangun
Gunsansisi
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Imsilgun
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Seogwiposi
Jejusi
Sejongsi
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CFR
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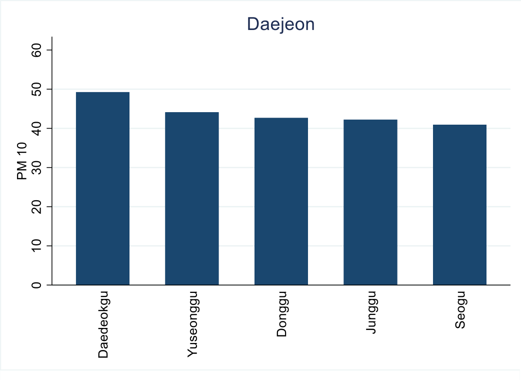
Donggu
Uljugun
Junggu
Bukgu

Appendix 6. *Mean concentration level of PM10 per province*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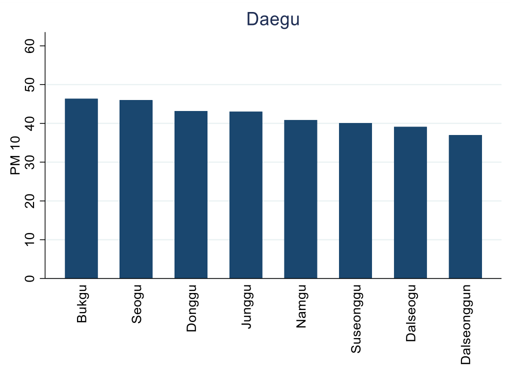
Yuseonggu
Donggu
Junggu
Seogu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PM 10
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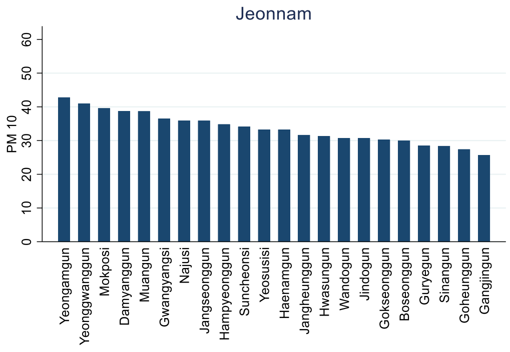
Bukgu
Seogu
Donggu
Junggu
Namgu
Suseonggu
Dalseogu
Dalseonggun


Jeonnam
PM 10
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50
60
Yeongamgun
Yeonggwanggun
Mokposi
Damyanggun
Muangun
Gwangyangsi
Najusi
Jangseonggun
Hampyeonggun
Suncheonsi
Yeosusisi
Haenamgun
Jangheunggun
Hwasungun
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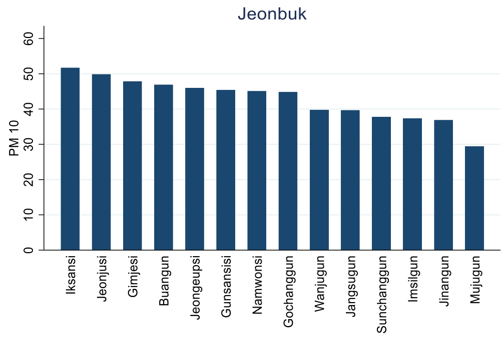
Jindogun
Gokseonggun
Boseonggun
Guryegun
Sinangun
Goheunggun
Gangjingun


Jeonbuk
PM 10
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Iksansi
Jeonjusi
Gimjesi
Buangun
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Namwonsi
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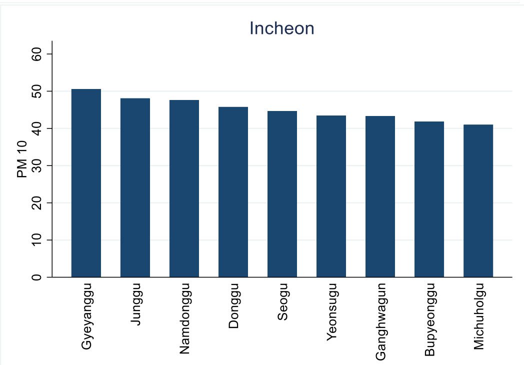
Jinangun
Mujugun


Incheon
PM 10
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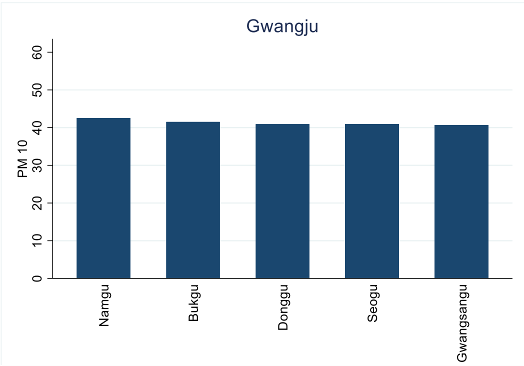
Gyeyanggu
Junggu
Namdonggu
Donggu
Seogu
Yeonsugu
Ganghwagun
Bupyeonggu
Michuholgu


Gwangju
PM 10
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50
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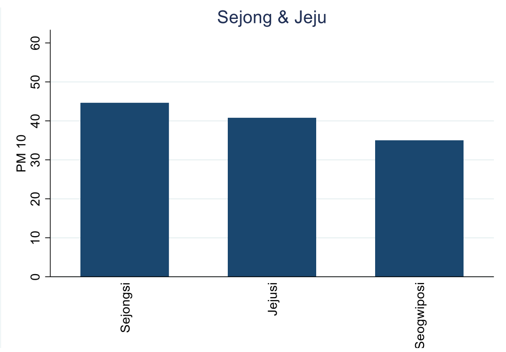
Namgu
Bukgu
Donggu
Seogu
Gwangsangu


Sejong & Jeju
PM 10
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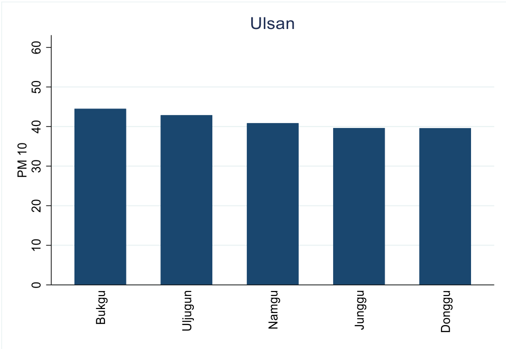
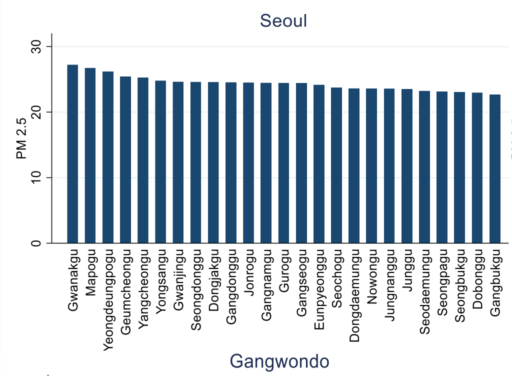
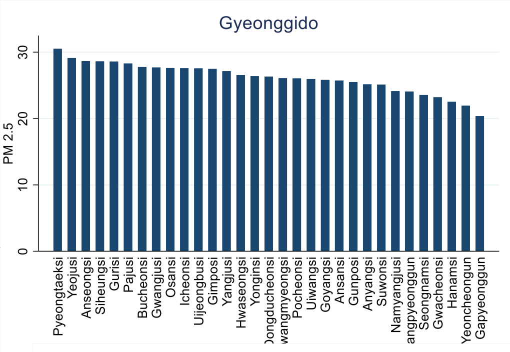
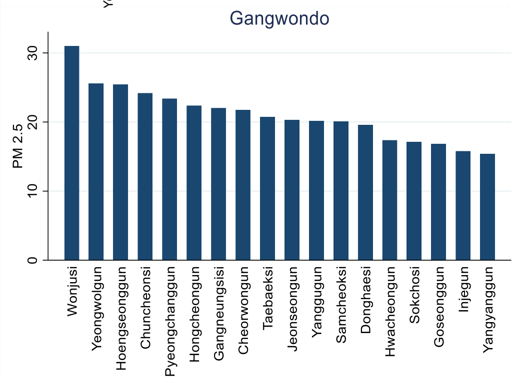
30
40
50
60
Sejongsi
Jejusi
Seogwiposi

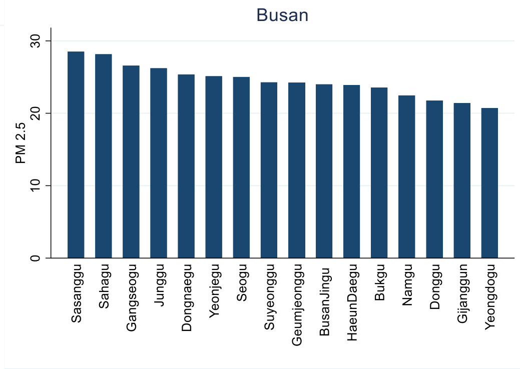

Ulsan
PM 10
0
10
20
30
40
50
60
Bukgu
Uljugun
Namgu
Junggu
Donggu

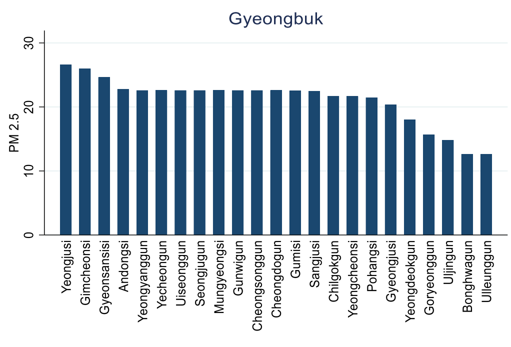
Appendix 7. *Mean concentration level of PM2.5 per province*

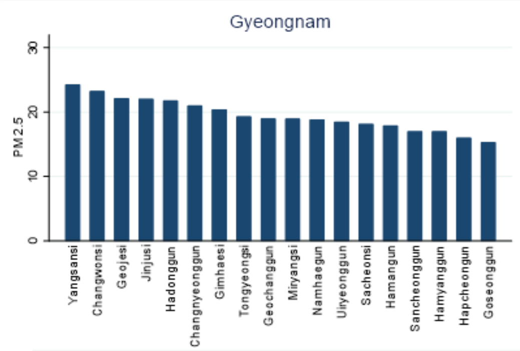


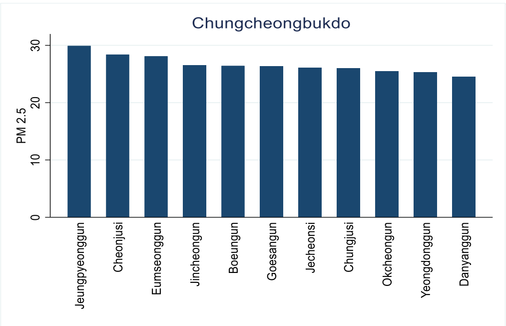


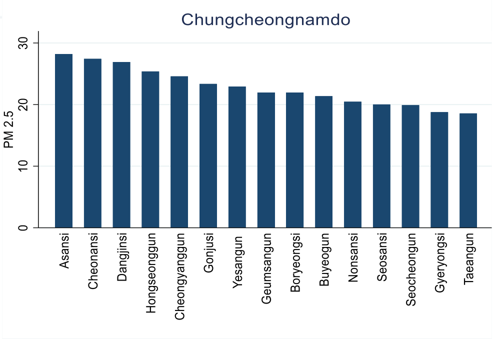


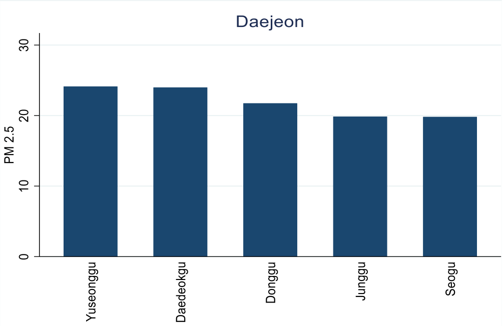


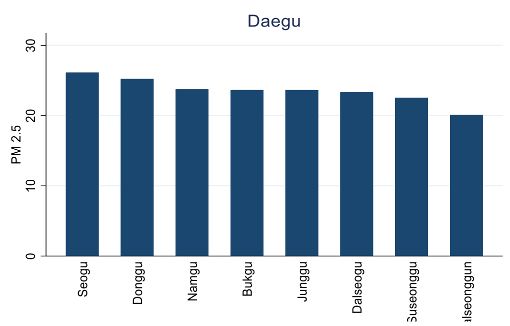


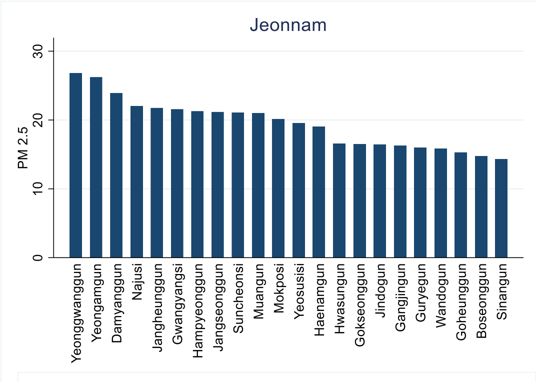


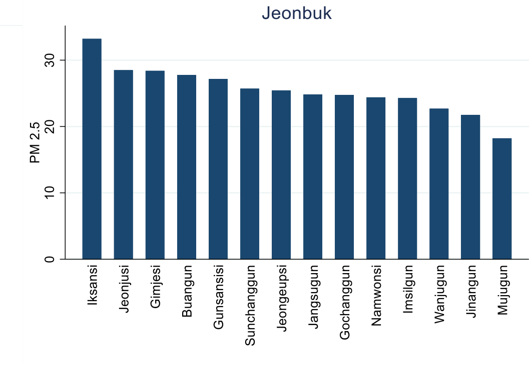


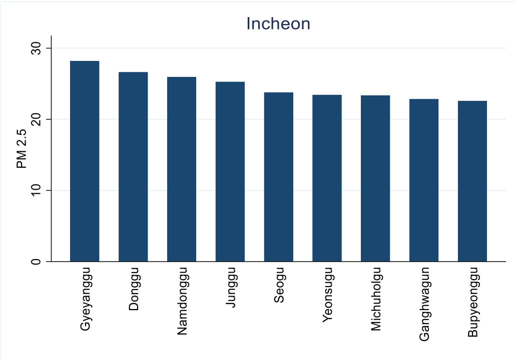


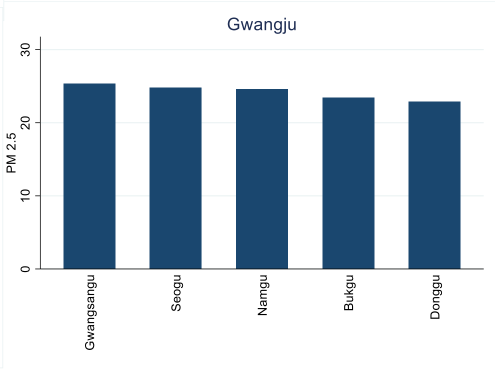

Daejeon
PM 2.5
0
10
20
30
Yuseonggu
Daedeokgu
Donggu
Junggu
Seogu

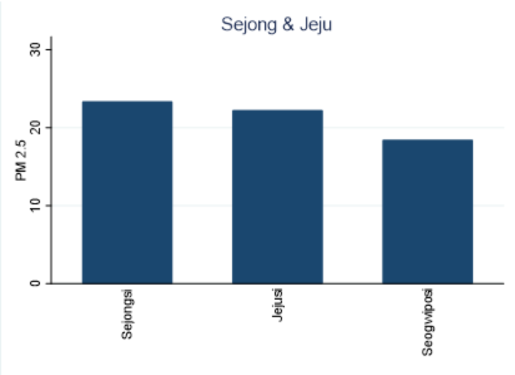

Daegu
PM 2.5
0
10
20
30
Seogu
Donggu
Namgu
Bukgu
Junggu
Dalseogu
useonggu
lseonggun

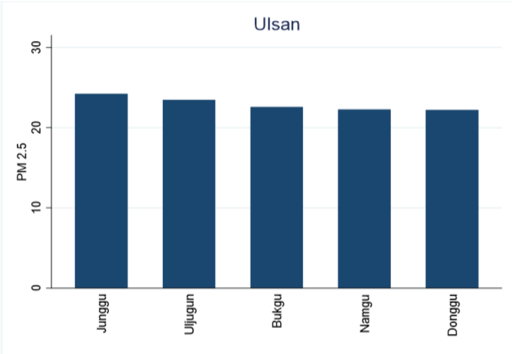

Jeonnam
PM 2.5
0
10
20
30
Yeonggwanggun
Yeongamgun
Damyanggun
Najusi
Jangheungun
Gwangyangsi
Hampyeonggun
Jangseonggun
Suncheonsi
Muangun
Mokposi
Yeosusisi
Haenamgun
Hwasungun
Gokseonggun
Jindogun
Gangjingun
Guryegun
Wandogun
Goheunggun
Boseonggun
Sinangun


Jeonbuk
PM 2.5
0
10
20
30
Iksansi
Jeonjusi
Gimjesi
Buangun
Gunsansisi
Sunchanggun
Jeongeupsi
Jangsugun
Gochanggun
Namwonsi
Imsilgun
Wanjugun
Jinangun
Mujugun


Incheon
PM 2.5
0
10
20
30
Gyeyanggu
Donggu
Namdonggu
Junggu
Seogu
Yeonsugu
Michuholgu
Ganghwagun
Bupyeonggu


Gwangju
PM 2.5
0
10
20
30
Gwangsangu
Seogu
Namgu
Bukgu
Donggu


Sejong & Jeju
PM 2.5
0
10
20
30
Sejongsi
Jejusi
Seogwiposi


Ulsan
PM 2.5
0
10
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30
Junggu
Uljugun
Bukgu
Namgu
Donggu

Appendix 8: *Analysis of the instrumental variable(lowedurate)*

Correlation analysis

VARIABLES	lCrate	lDrate	lowedurate
lCrate	1.0000		
lDrate	0.1416	1.0000	
lowedurate	-0.7139	-0.0488	1.0000

OLS regression of lowedurate

	(1)	(2)
VARIABLES	lCrate	lDrate
lowedurate	-0.0178***	-0.00365
	(0.00116)	(0.00497)
Constant	10.61***	3.743***
	(0.0191)	(0.0816)
Observations	228	228
R-squared	0.510	0.002

Notes: 1) Standard errors in parentheses
2) *** p<0.01, ** p<0.05, * p<0.1

Appendix 9: *Results of 2SLS without income variable*

VARIABLES	(1) Second-Stage log Death Rate	(2) Second-Stage log Death Rate
lCrate	-1.277**	-1.089**
	(0.548)	(0.470)
pm25		0.0372**
		(0.0148)
pm10	0.0243**	
	(0.0108)	
Vrate2	-2.018	-1.997
	(1.624)	(1.578)
Generalhosprate	-4.857**	-5.985***
	(2.262)	(1.940)
nursingbedrate	0.00398***	0.00393***
	(0.000731)	(0.000717)
obesityrate	0.0222	0.0191
	(0.0160)	(0.0155)
smokingrate	0.0278*	0.0284*
	(0.0166)	(0.0161)
foreignshare	0.00671	0.00111
	(0.0352)	(0.0335)
popdenst	0.00445***	0.00416***
	(0.000891)	(0.000837)
Constant	16.38***	14.76***
	(6.104)	(5.446)
Observations	228	228
R-squared	0.138	0.173

Notes: 1) Standard errors in parentheses

2) *** p<0.01, ** p<0.05, * p<0.1

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국문초록

코로나-19 팬더믹은 일상을 다각도로 변화시켰다. 많은 사람들의 생명을 빼앗아 갔고, 국경이 통제되고 물류 이동이 제한되면서 경제적으로 큰 피해를 일으키기도 하였다. 감염은 인구밀도가 높은 도시를 중심으로 빠르게 확산되었으나, 사망률은 도시별로 차이를 보였다. 도시는 삶의 질을 높일 수 있는 많은 기회가 있는 곳이지만, 대기오염이나 전염병이라는 측면에서는 위험이 큰 곳이기도 하다.

전세계적으로 한국은 높은 수준의 대기오염이 있는 지역으로 조사되고 있다. 미세먼지는 환경 및 건강에 심각한 위험을 초래할 수 있기 때문에 세계보건기구(WHO)는 이에 대한 권고 수준을 강화해 나가고 있다. 일반적으로 1000분의 10mm보다 작은 먼지는 미세먼지(PM10), 1000분의 2.5mm보다 작은 먼지는 초미세먼지(PM2.5)로 구분이 된다. 국내 연구에 의하면 미세먼지는 인체에 유해한 영향을 끼쳐 심혈관 질환 및 호흡기나 폐 관련 질환 등으로 인한 사망 위험도를 증가시킨다. 미세먼지가 코로나-19 사망률에 미치는 영향에 대한 연구는 해외를 중심으로 이루어지고 있는데, 아직 국내에 대한 연구는 부족한 상황이다. 본 연구는 2015년부터 2019년까지 전국 228개 시군구별 국내 미세먼지와 초미세먼지의 평균 농도가 코로나-19 사망률과 치명률에 미치는 영향에 대해 분석하고, 이를 토대로 도시개발 관점에서의 시사점을 도출하는 것을 목적으로 수행되었다.

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5월 16일까지 인구 10만명당 코로나-19 누적 사망률과 전체 확진자 수를 사망자 수로 나눈 값인 치명률을 종속변수로 설정하였고, 지난 4년간 각 시군구별 평균 미세먼지와 초미세먼지의 농도를 독립변수로 설정하여 회귀분석을 수행하였다. 분석 기법으로는 도구변수를 사용하여 2단계 도구변수(2SLS) 분석방법과 최소자승법(OLS)으로 회귀모형을 추정하였다. 통제변수로는 인구 밀도, 고령화 비율, 백신접종율, 평균 인당 소득 등 선행 연구에서 유의미한 관계가 나타난 인구, 사회・경제 및 보건 관련 변수로 설정하였다. 강건(robust)한 결과를 위해 도구변수를 변경하여 추정하였고, 독립변수로 치명률을 넣거나 상호작용(interaction term) 변수도 대입하여 분석을 시행하였다.

분석 결과 미세먼지에 대한 노출은 코로나-19로 인한 사망률과 치명률에 통계적으로 유의한 양의 관계가 있는 것으로 나타났다. 이는 미세먼지와 초미세먼지 농도가 증가할수록 코로나-19 감염으로 인한 사망자 수가 높아진다는 것을 뜻한다. 그 외에도 만명당 요양병원 병상수, 고령화 비율, 인구밀도도 통계적으로 유의한 양의 관계로 나타났고, 만명당 종합병원 수, 백신 2차 접종률, 인당 급여는 통계적으로 유의한 음의 관계로 확인되었다.

도시 거주 인구는 앞으로 지속적으로 늘어날 것으로 전망된다. 인구밀도가 높은 도시는 전염병에 취약하고, 미세먼지 농도도 높을 수밖에 없다. 이를 고려하여 정부는 미세먼지 대응 정책을 수립함에 있어 각 도시별 미세먼지 발생 원인을 구체적으로 반영할 필요가 있다. 미세먼지로 인한 건강상 피해를 줄이기 위해서는 지역별 맞춤형 미세먼지 저감 대책을 수립하고, 일반 시민의 능동적 참여를 지원하고,

미세먼지 허용 기준을 WHO 등 국제기구에서 제시한 가이드라인을 고려하여 더 엄격하게 관리할 필요가 있다.

장기화되는 코로나-19 또는 이와 유사한 장래 팬더믹에 대응하기 위해서는 미세먼지에 대한 대책을 다시 면밀히 살펴보아야 한다. 효과적이고 신속한 대응을 위해서는 도시개발 정책에 미세먼지 저감에 관한 장기적 계획뿐만 아니라 단기적인 전략도 포함시켜야 한다. 지속가능한 미래 도시를 위해서는 질병과 환경으로부터 오는 위기를 극복하고 변화할 방향을 모색하여야 한다.

키워드: 미세먼지, 초미세먼지, 코로나-19 사망률, 코로나-19 치명률, 도시개발
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