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Particulate Matter (PM_{10} and $PM_{2.5}$) in Subway Systems: Health-Based Economic Assessment

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Received: 18 October 2017; Accepted: 16 November 2017; Published: 20 November 2017

Abstract: Particulate matter (PM) is implicated in severely negative health effects, and subway-system PM is potentially more genotoxic than several other particle types. However, there are insufficient studies on subway-system PM-pollution reduction and control and the potential economic benefits thereof. Thus, the present study undertakes to assess the potential economic benefits resulting from a 10 μg/m^3 reduction in PM_{10} and $PM_{2.5}$ concentrations in a subway system, and to evaluate the importance of prevention and management of PM generally and subway-system PM specifically. Socioeconomic benefits such as medical expense curtailment, the precautionary effect on premature death, and the precautionary effect on productivity loss among subway passengers and workers were estimated by the cost-of-illness (COI) method. The health endpoints included two categories of disease: all lung cancer and cardiovascular diseases. The results showed that the total annual economic value in cost savings was 328.2 million KRW: 124.2 million KRW in direct costs, 186.4 million KRW in premature mortality costs, and 17.6 million KRW in productivity loss costs, respectively. These findings suggest that the control of PM_{10} and $PM_{2.5}$ levels in subway systems should be promoted, as such effort certainly can produce significant economic benefits.

Keywords: economic analysis; particulate matter; subway; economic assessment

1. Introduction

In today's society, the subway, with its high speed, comfort, environmental friendliness, and large transport capacity, is a lifeline of urban development [1]. It is a highly promoted alternative means of public transportation that relieves traffic congestion in city centers and reduces environmental pollution. The confined and underground spaces of underground subway systems, however, can accumulate pollutants from various sources. In particular, high levels of particulate matter (PM) have been detected in the underground subway systems of London, Helsinki, Berlin, Stockholm, Rome, Cairo, Beijing, and Seoul [2–8].

PM is composed of several compounds, including carbon-centered combustion particles, secondary inorganics, and crustal-derived particles [9]. In addition to particles entering from the outside environment, subway aerosol particles are generated by the mechanical abrasion of rail tracks, wheels, catenary chains and brake pads, while passenger movement mixes and suspends them [10].

Inhalation of PM can affect the heart and lungs, resulting in serious health problems. The most dangerous particles in this regard are PM_{10} and $PM_{2.5}$, which are smaller than or equal to 10 μm and 2.5 μm in aerodynamic diameter, respectively [11]. These particles have been reported to increase the risk of respiratory-related diseases such as lung cancer, chronic obstructive pulmonary disease, asthma exacerbation, and cardiovascular-related diseases including irregular heartbeat, vascular dysfunction, and arrhythmia. Global studies also have significantly associated them with acute and chronic premature death [12,13]. Karlsson et al. (2005) reported that subway particles are more genotoxic than street particles, tire-road-wear particles, and particles from diesel and wood combustion [14]. Therefore, a great concern of governments and health organisations worldwide is the adverse health effects of such PM on subway passengers and employees, especially considering the potentially high concentrations of PM combined with prolonged exposure times [15–17].

In a study of pollutants monitored in subway lines in Seoul (Korea), the concentrations of PM_{10} and $PM_{2.5}$ inside trains were notably higher than those measured on platforms and in ambient air. PM_{10} concentrations inside subway lines 1, 2 and 4 exceeded the Korea indoor air quality standard of 150 $\mu g/m^3$. The average percentage exceeding the PM_{10} standard was 83.3% on line 1, 37.9% on line 2 and 63.1% on line 4, respectively. Besides, $PM_{2.5}$ accounted for most of PM_{10} and polluted subway air, and $PM_{2.5}$ level ranged from 77.7 $\mu g/m^3$ to 158.2 $\mu g/m^3$, which were much higher than the ambient air $PM_{2.5}$ standard published by United States Environmental Protection Agency (24 h arithmetic mean: 65 $\mu g/m^3$) [5]. Sohn et al. (2008) reported that in case of 24 h measurement, the mean levels of PM_{10} of platform and waiting room were 156.18 $\mu g/m^3$ and 111.00 $\mu g/m^3$ [7]. A study showed that the average PM_{10} and $PM_{2.5}$ concentrations in subway cabins of line 2 were 132.8 $\mu g/m^3$ and 81.4 $\mu g/m^3$, meanwhile those figures of line 5 were 154.4 $\mu g/m^3$ and 73.1 $\mu g/m^3$, respectively [18]. In Korea, efforts to improve air quality in subway cabins and tunnels along with the effects of PM-level reduction by different technologies have been reported [18–21]. The goals of such studies are to protect public health and to curtail the inevitable economic losses associated with the health problems caused by PM exposure.

In order to determine the amount of benefit associated with PM pollution control, a cost-of-illness (COI) study can be used. The COI model, one of the earliest economic evaluation methods utilized in the healthcare field, estimates the economic burden of illness in a society in terms of healthcare-resources consumption and the productivity loss [22].

The economic valuation of the health effects of environmental pollution using the COI approach has been reported worldwide [23–25]. COI model was applied to assess the economic benefits of reducing particulate air pollution in Lebanese urban areas [23]. A monetary valuation of PM_{10}-related health risks in 16 districts and 4 functional zones in Beijing (China) was performed, in which COI method was used in integration with an epidemiological exposure-response model and another economic valuation method [24]. Not many studies have evaluated the economic benefit specifically of decreased subway-PM concentrations. Thus, the present study has been undertaken with the aims of assessing the potential economic benefits associated with 10 $\mu g/m^3$ reduction in PM_{10} and $PM_{2.5}$ concentrations in subway systems and of providing basic data for improved public awareness of the importance of prevention and management of PM, especially subway-system PM. In addition, estimation framework, methods, and basic data in this study can provide basic information and reference for the estimation of economic benefit in correspondence with particulate pollution control. In this paper, social benefits resulting from the reduction of PM_{10} and $PM_{2.5}$ levels in a subway system, specifically medical expense curtailment, the precautionary effect on premature death, and the precautionary effect on productivity loss of subway passengers and workers, are considered. Population-based data were collected and computed to obtain the theoretical annual economic values due to decreased levels of PM_{10} and $PM_{2.5}$ in nine subway lines in Seoul, Korea. The results propose that the economic benefits of PM_{10} and $PM_{2.5}$ concentration reduction in subway systems can be significant.

The remaining of the paper is organized as follows. In section "Materials and Methods", estimation framework and economic benefit estimation methods are presented. Estimation framework includes selection of health endpoints, cost-of-illness (COI) model, and exposed population. Subsection "Economic benefit estimation methods" describes methods of mortality and morbidity characterization and economic benefit estimation. Next, estimation results are mentioned in section "Results". This is followed by section "Discussion", in which discussion about results together with strengths and limitations of the study is presented. Finally, several conclusions are given in section “Conclusions”.

2. Materials and Methods

2.1. Estimation Framework

2.1.1. Selection of Health Endpoints

In this study, the background data on the social costs of PM_{10} and $PM_{2.5}$ were obtained using the conditional valuation model, which calculates the probability that these particles can cause human health problems, especially respiratory and cardiovascular diseases. For selection of health endpoints of particulate pollution, the following principles were taken into account:

- health endpoints reported with a robust characterization of exposure-response relationships;
- health endpoints provided by reliable statistics, such as those based on the International Classification of Diseases (ICD).

According to these principles, two disease categories, namely malignant neoplasm of trachea, bronchus and lung cancer (hereafter: “all lung cancer”) and cardiovascular diseases were selected as representative PM-induced diseases (Table 1), and the total socioeconomic benefits associated with 10 $\mu g/m^3$ PM_{10} and $PM_{2.5}$ decrements in subway tunnels and train cabins were estimated.

Table 1. Categories of targeted diseases [a].

Types of Disease	Sub-Types of Disease	ICD-10 Codes
All lung cancer	Malignant neoplasm of trachea	C33
	Malignant neoplasm of bronchus and lung	C34
Cardiovascular diseases	Acute rheumatic fever	I00–I02
	Chronic rheumatic heart diseases	I05–I09
	Essential (primary) hyper tension	I10
	Other hypertensive diseases	I11–I15
	Acute myocardial infarction	I21–I22
	Other ischemic heart diseases	I20, I23–I25
	Pulmonary embolism	I26
	Conduction disorders and cardiac arrhythmias	I44–I49
	Heart failure	I50
	Other heart diseases	I27–I43, I51–I52
	Intracranial hemorrhage	I60–I62
	Cerebral infarction	I63
	Stroke (not specified as hemorrhage or infarction)	I64
	Other cerebrovascular diseases	I65–I69
	Atherosclerosis	I70
	Other peripheral vascular diseases	I73
	Arterial embolism and thrombosis	I74
	Other diseases of arteries, arterioles and capillaries	I71–I72, I77–I79
	Phlebitis, thrombophlebitis, venous embolism and thrombosis	I80–I82
	Varicose veins of lower extremities	I83
	Hemorrhoids	I84
	Other diseases of circulatory system	I85–I99

[a] Abbreviation: ICD, International Classification of Diseases.

2.1.2. Cost-of-Illness (COI) Model

COI studies has been reported in a number of papers published since the 1960s [26–28]. Generally, to determine the economic costs of any illness, three types of costs should be considered: direct costs, indirect costs, and intangible costs. Intangible costs reflect the patient’s level of pain and suffering as well as the limitations imposed by the pain and suffering on his quality of life [29]. As intangible costs have seldom been estimated in COI studies (due to measurement difficulties and related controversies [30]), we quantified the socioeconomic benefits in terms of direct and indirect costs only.

We calculated the cost savings by identifying several institutions' information sources that contain population-based data on resource utilization by patients with all lung cancer and cardiovascular diseases. The major indexes for calculation of each cost item and the sources of those indexes are summarized in Table 2.

Table 2. Categories related to all lung cancer and cardiovascular diseases, with data sources.

Types of Cost	Categories		Estimation Variables	Data Sources
Direct costs	Direct medical costs	Benefit sector	Treatment amount of hospitalization and outpatient	National Health Insurance Statistical Yearbook [31]
		Non-benefit sector	Treatment amount and non-benefit rate of hospitalization and outpatient	
	Direct non-medical costs	Transportation	Outpatient-visit days, Round-trip transportation cost	National Health Insurance Statistical Yearbook [31], The Third Korea National Health and Nutrition Estimation Survey [32]
		Caregiver	Hospitalization days, Average daily care-giver cost	National Health Insurance Statistical Yearbook [31], The Korea Patient Helper Society [33]
Indirect costs	Future income loss due to premature death		Number of deaths, Number of years , Employment rate, Average annual real wage, Discount rate	Cause of Death Statistics [34], Economically Active Population Survey [35], Survey Report on Labor Conditions by Employment Type [36]
	Productivity loss resulting from absence from work		Hospitalization days, Outpatient visit days, Employment rate, Average daily wage	National Health Insurance Statistical Yearbook [31], Economically Active Population Survey [35], Survey Report on Labor Conditions by Employment Type [36]

A. Direct Costs

In this study, the direct costs included direct medical costs (medical expenditures) and direct non-medical costs (transportation costs, caregiver costs). The direct medical costs indicated the sum of medical expenses paid by outpatients and inpatients at medical institutions for treatment of diseases. The direct non-medical costs included transportation costs for visits to medical institutions and caregiver costs for inpatients. The round-trip transportation costs included those for outpatient visits and admission. Caregiver costs were estimated as the opportunity costs for guardians or the personnel expenses for paid caregivers to care inpatients.

The direct cost was calculated by Equation (1):

$$\sum_a \sum_i \sum_j \left(\frac{E^a_{ij}}{1-a} + \frac{OE^a_{ij}}{1-\beta}\right) + \sum_a \sum_i \sum_j (O^a_{ij} \times OM) + \sum_a \sum_i \sum_j \{N^a_{ij} \times (M+I)\} \quad (1)$$

where

$a = 1, 2, \ldots, n$ diseases;

$i = 1, 2$ genders;

$j = 0, 1, \ldots, n$ age;

E^a_{ij} is the total treatment amount of inpatients for a, i and j in the health insurance data;

OE^a_{ij} is the total treatment amount of outpatients for a, i and j in the health insurance data;

α is the percentage of hospitalization expenses borne by the patient;

β is the percentage of outpatient expenses borne by the patient;

O^a_{ij} is the number of outpatient-visit days for a, i and j;

OM is the average round-trip transportation costs per outpatient visit;

N^a_{ij} is the number of hospitalization days for a, i and j;

M is the average round-trip transportation costs of admission, and
I is the daily average costs of caregivers for inpatients.

B. Indirect Costs

Indirect costs included the loss of income related to premature death and the cost associated with productivity loss. For estimation of indirect costs, the human capital approach, by which productivity loss due to disease is calculated, is almost unanimously used [37].

Future income loss due to premature death was estimated according to the number of deaths related to the targeted diseases by gender and age (in Appendix A) [34], the annual expected income of a person if he does not die early, the labor force participation rate by gender and age (in Appendix A) [35], the employment rate by gender and age (in Appendix A) [35], and the discount rate.

The future income loss due to premature death was calculated by Equation (2):

$$\sum_a \sum_j \sum_i \{F_{ij}^a \times \frac{Y_j^{t+\tau} \times p_{ij} \times e_{ij}}{(1+r)^i}\} \tag{2}$$

where

$a = 1, 2, \ldots, n$ diseases;
$i = 1, 2$ genders;
$j = 0, 1, \ldots, n$ age;
t is the age at time of death;
τ is the number of years;
F_{ij}^a is the number of deaths;
$Y_j^{t+\tau}$ is the annual expected income at $t + \tau$;
p_{ij} is the labor force participation rate;
e_{ij} is the employment rate, and
r is the discount rate.

The cost of productivity loss is defined as the cost of workday loss due to hospitalization and work-time loss due to outpatient care [38]. The productivity loss cost was calculated by Equation (3):

$$\sum_a \sum_j \sum_i \{(N_{ij}^a + \delta \times O_{ij}^a) \times p_{ij} \times e_{ij} \times y_{ij}\} \tag{3}$$

where

$a = 1, 2, \ldots, n$ diseases;
$i = 1, 2$ genders;
$j = 0, 1, \ldots, n$ age;
N_{ij}^a is the number of hospitalization days for a, i and j;
δ is the non-production rate for an outpatient vs. a hospitalized patient;
O_{ij}^a is the number of outpatient-visit days for a, i and j;
p_{ij} is the labor force participation rate;
e_{ij} is the employment rate, and
y_{ij} is patients' daily average income.

2.1.3. Exposed Population

In the subway, exposure targets of hazardous substances are passengers and workers in subway tunnels. In the present study, the average number of passengers per cabin was set as 262, the average boarding time per person as 1 h, the average number of people exposed to hazardous substances as 13,000 people per day, the average number of workers in a tunnel as 10, and the average total number of workers in the Seoul metropolitan area, considering the entire history of lines 1–9, as 5060 people. The daily exposure time of the workers in subway tunnels was set to 3 h [21].

2.2. Economic Benefit Estimation Methods

In consideration of the data that have been acquired thus far in studies worldwide, the present assessment process entailed the following assumptions:

- there is no exposure threshold below which PM_{10} and $PM_{2.5}$ are not a cause of morbidity or mortality;
- there are no differences in exposure or susceptibility among different populations;
- differences in methodology or sample size among epidemiological studies are ignored;
- the data for all age groups will be applied to the estimations in cases where the data for a particular age is unavailable [23].

The social benefits of decreased PM_{10} and $PM_{2.5}$ levels were set up, and the economic values were calculated using the COI analytical model. Generally, the average value for each cost category was estimated, and the economic value was calculated by multiplying that average cost by the number of cases theoretically decreased by each 10 $\mu g/m^3$ reduction in PM_{10} and $PM_{2.5}$ levels.

2.2.1. Mortality and Morbidity Characterization

The theoretical decreases in morbidity cases were obtained by multiplying the prevention rate by the total number of patients and calculating the ratio of the exposed population size to the nationwide population size. The decreases in mortality cases, meanwhile, were estimated by multiplying the prevention rate by the total number of deaths and calculating the ratio of the exposed population size to the nationwide population size.

- Table 3 summarizes the data used in the calculations of the per-year reductions in morbidity and mortality cases due to 10 $\mu g/m^3$ decrement of PM_{10} and $PM_{2.5}$ levels. Generally, country-specific or local epidemiological studies are the most proper indicators for the assessment of associations between environmental pollution and health outcome in a given region. Nevertheless, given that such studies require time and cost investments as well as there are inadequate domestic data, epidemiological studies established in other countries can be adopted assuming that human reaction is similar in different regions [21,23]. In this study, analytical epidemiological studies used as data sources of the prevention rates in correspondence with 10 $\mu g/m^3$ PM_{10} and $PM_{2.5}$ decrements were considered based on some essential criteria, including: studies assess the association between the change in concentration of PM_{10} or $PM_{2.5}$ and one of health endpoints;
- the range of change in concentration of PM_{10} or $PM_{2.5}$ in health assessment is 10 $\mu g/m^3$;
- some approaches are applied to handle potential confoundings or uncertainties.

Extended inclusion criteria were used for further consideration, including sample size, number of studies examined in meta-analyses, and the age groups of participants or subjects in studies. For identification of eligible articles, an initial screen of titles or abstracts was performed, followed by a full-text review and finally a recordation of the reasons of exclusion. Six analytical epidemiological studies in the period 2000–2015 were selected (Table A1).

Table 3. Data used to calculate per-year reductions in morbidity and mortality cases due to 10 $\mu g/m^3$ decrement of PM_{10} and $PM_{2.5}$ levels.

Types of Data	PM Decreased by 10 $\mu g/m^3$	Data Values
Prevention rate for all lung cancer morbidity (%)	PM_{10}	8 [39]
	$PM_{2.5}$	9 [39]
Prevention rate for cardiovascular morbidity (%)	PM_{10}	1.27 [40]
	$PM_{2.5}$	0.51 [41]
Prevention rate for all lung cancer mortality (%)	PM_{10}	5 [42]
	$PM_{2.5}$	9 [42]

Table 3. *Cont.*

Types of Data	PM Decreased by 10 μg/m^3	Data Values
Prevention rate for cardiovascular mortality (%)	PM_{10}	0.76 [43]
	$PM_{2.5}$	6 [44]
Total number of all-lung-cancer patients (persons)	-	106,296 [31]
Total number of cardiovascular patients (persons)	-	10,076,495 [31]
Total number of deaths related to all lung cancer (deaths)	-	3719 [a] [34]
Total number of deaths related to cardiovascular diseases (deaths)	-	15,709 [a] [34]
Number of passengers exposed to PM_{10} and $PM_{2.5}$ (persons)	-	13,000 [21]
Number of workers exposed to PM_{10} and $PM_{2.5}$ (persons)	-	5060 [21]
Nationwide population (persons)		51,069,375 [45]

[a] Data are calculated for people between the ages of 15 and 74.

2.2.2. Economic Benefit Estimation

A. Economic Benefit from Direct Cost Curtailment

Given the lack of sufficient data on patients who are subway passengers and employees, this study estimated the benefit from direct cost savings by multiplying the average direct cost for a specific targeted disease by the total number of patients that could be saved by each 10 μg/m^3 decrement of PM_{10} and $PM_{2.5}$ levels in the subway system. The total scale of the direct costs of the two categories of health endpoint was calculated based on Equation (1). The average direct costs per capita were then calculated by dividing the total direct cost by the nationwide number of patients.

Data from the National Health Insurance Statistical Yearbook of 2015 [31] were used in the estimations of outpatient and inpatient medical expenditures (Tables A2 and A3). The average ratio of non-benefit cost to treatment cost in terms of disease (Table A4) was computed from the total medical expense and the insurance benefit for inpatients and outpatients, again using the National Health Insurance Statistical Yearbook of 2015 [31]. The average round-trip transportation cost per visit was 8607 Korean Won (KRW, the currency of South Korea) for outpatients and 21,334 KRW for admission in 2005 [32]. These estimations were adjusted, according to the 2017 traffic price index [46], to an average round-trip transportation cost of 10,411 KRW for outpatients and 25,805 KRW for admission. The average daily expense for paid caregivers suggested by The Korea Patient Helper Society (75,000 KRW) [33] was input as the opportunity costs for guardians or personnel expenses for caregivers.

B. Economic Benefit from Indirect Cost Curtailment

The future income loss due to premature death resulting from diseases related to PM_{10} and $PM_{2.5}$ was estimated by applying the human capital approach following Equation (2). It was assumed that productive activity is not performed from age 0 to 14 years and after age 74 in the life cycle. The annual expected income was computed by multiplying the average monthly wage of "all-workers" group [36] by 12 (months) and the expected number of years of productive activity. The discount rate (r) applied to convert future income to present value was 0% for convenience in calculation [30]. Because all passengers cannot be considered to participate in economic activities, the labor force participation rate and employment rate were determined for gender and age (Table A5) [35]. These rates for the workers were assumed to be 100%. The average human capital loss per capita was then determined by dividing the total human loss by the nationwide number of premature death cases of people between the ages of 15 and 74 (Table A6) [34]. By multiplying the average premature death costs by the number of mortality cases avoided by each 10 μg/m^3 reduction of PM_{10} and $PM_{2.5}$ levels, the economic benefit of preventing unexpected death could be obtained.

The costs of productivity loss were calculated based on Equation (3). According to the assumption that the productivity loss for one day of hospitalization is similar to that for three outpatient visits, the number of non-productive days was calculated by adding the number of hospitalization days and one-third of the outpatient-visit days [47]. The average labor force participation rate and employment rate (Table A5) [35] were used as inputs to estimate the productivity loss. The daily average income was calculated by dividing the average monthly wage by 21, which is the average number of working days in a month for all workers [36]. The average productivity loss cost per capita was then estimated by dividing the total productivity loss cost by the nationwide number of patients. The annual economic value of the precautionary effect on productivity loss was computed from the average productivity loss costs and the theoretical number of morbidity cases reduced due to each 10 μg/m^3 decrement in the PM_{10} and $PM_{2.5}$ concentrations, respectively.

3. Results

According to the predicted values of mortality and morbidity effects (Table 4), the economic benefits associated with the reduction of PM_{10} and $PM_{2.5}$ levels in subway systems were estimated by the COI method. It was determined that medical cost savings of 124.2 million KRW per year would be obtained for each 10-μg/m^3 decrement in PM_{10} and $PM_{2.5}$ concentrations (Table 5). As for the indirect costs, the economic value of the precautionary effect on premature mortality was estimated to be 186.4 million KRW per year (Table 6), while that of the precautionary effect on productivity loss was 17.6 million KRW per year (Table 7). Given the assumed 13,000 passengers and 5060 workers in tunnels, the total annual economic benefit due to each 10 μg/m^3 decrement in PM_{10} and $PM_{2.5}$ concentrations was calculated to be 328.2 million KRW.

Table 4. Morbidity and mortality cases avoided per year due to 10 μg/m^3 decrement of PM_{10} and $PM_{2.5}$ concentrations.

Exposed Target	Exposed PM	Types of Disease	Morbidity Cases Avoided/Year	Mortality Cases Avoided/Year
Passenger	PM_{10}	All lung cancer	2.16	0.05
		Cardiovascular diseases	32.58	0.03
	$PM_{2.5}$	All lung cancer	2.44	0.09
		Cardiovascular diseases	13.08	0.24
Worker	PM_{10}	All lung cancer	0.84	0.02
		Cardiovascular diseases	12.68	0.01
	$PM_{2.5}$	All lung cancer	0.95	0.03
		Cardiovascular diseases	5.09	0.09

Table 5. Annual economic value by medical expense curtailment (unit: 1,000,000 KRW).

Exposed Target	Exposed PM	Types of Disease	Economic Value	Total Economic Value
Passenger	PM_{10}	All lung cancer	14.6	89.4
		Cardiovascular diseases	41.6	
	$PM_{2.5}$	All lung cancer	16.5	
		Cardiovascular diseases	16.7	
Worker	PM_{10}	All lung cancer	5.7	34.8
		Cardiovascular diseases	16.2	
	$PM_{2.5}$	All lung cancer	6.4	
		Cardiovascular diseases	6.5	
Total				124.2

Table 6. Annual economic value of precautionary effect on unexpected death (unit: 1,000,000 KRW).

Exposed Target	Exposed PM	Types of Disease	Economic Value	Total Economic Value
Passenger	PM_{10}	All lung cancer	19.9	136.6
		Cardiovascular diseases	9.0	
	$PM_{2.5}$	All lung cancer	35.7	
		Cardiovascular diseases	72.0	
Worker	PM_{10}	All lung cancer	7.9	49.8
		Cardiovascular diseases	3.0	
	$PM_{2.5}$	All lung cancer	11.9	
		Cardiovascular diseases	27.0	
Total				186.4

Table 7. Annual economic value of precautionary effect on productivity loss (unit: 1,000,000 KRW).

Exposed Target	Exposed PM	Types of Disease	Economic Value	Total Economic Value
Passenger	PM_{10}	All lung cancer	1.6	12.7
		Cardiovascular diseases	6.6	
	$PM_{2.5}$	All lung cancer	1.8	
		Cardiovascular diseases	2.7	
Worker	PM_{10}	All lung cancer	0.6	4.9
		Cardiovascular diseases	2.6	
	$PM_{2.5}$	All lung cancer	0.7	
		Cardiovascular diseases	1.0	
Total				17.6

4. Discussion

In health economics, it is rather common to use the COI framework to quantify the costs of different health risk factors in monetary terms [29]. Besides, figures for COI analysis may be obtained from official statistics, and may be easier and less expensive to obtain than some other methods [25]. As a result, this model was applied in the present study.

The estimation outcomes demonstrate that an enormous socioeconomic burden could result from PM pollution, but equally, that a vast economic value could be associated with the control of PM_{10} and $PM_{2.5}$ levels. In correspondence with every 10 μg/m^3 decrement in PM_{10} and $PM_{2.5}$ levels, the direct cost and cost of premature death related to $PM_{2.5}$ and PM_{10} decreased substantially, compared with productivity loss. According to the cost items, the benefit of saving future income loss accounted for the largest proportion of the total benefit, or 56.8%, and the benefits of direct cost saving (37.8%) and saving productivity loss (5.4%) followed in order. The subway is a highly promoted mode of public transport, and a large number of people could be exposed to PM pollution in subway systems every day. In different sampling locations, PM_{10} levels were higher than 150 μg/m^3, and even a high concentration of 480.1 μg/m^3 was reported [5,7,8]. Studies also indicated high levels of $PM_{2.5}$ more than 65 μg/m^3 in ground and underground sampling sites among subway systems [8]. Considering that subway PM_{10} and $PM_{2.5}$ levels notably exceed air quality standards in numerous locations, efforts to decrease PM_{10} and $PM_{2.5}$ concentrations in subway cabins and tunnels promise high economic returns.

In this study, the total scale of healthcare utilization (excepting uninsured items) can be grasped when patients with targeted diseases utilize medical institutions, since all citizens in Korea have been mandatorily insured within a single insurance claim system [48]. In addition, as this study utilized health insurance data along with other nationwide-scale data to estimate direct medical costs, direct non-medical costs (transportation costs, caregiver costs), future income loss due to premature mortality, and the loss of productivity following absence from work, it is expected that the reliability and validity and of its estimation outcomes will be strengthened.

Nonetheless, this study has some limitations that are inevitable or controllable. First, the health insurance data on targeted diseases as additional diagnoses were excluded, so the directs costs and productivity loss could have been underestimated. Second, uninsured medical costs were determined only by estimating the ratio of non-benefit cost to treatment cost based on the data in the National Health Insurance Statistical Yearbook [31], since data on actual uninsured medical costs were not available. Third, given the unavailability of data on the rate of in-home care-giving and the correlation between the rate of care-giving service demand and disease severity, caregiver costs were calculated only for inpatients. However, to limit the underestimation when excluding in-home caregiver costs, we assumed that inpatients needed full-time care-giving. Fourth and finally, due to the insufficiency of data on the sick leave of patients who have neither inpatient nor outpatient visits, the calculation of productivity loss related to absence from work could have been underestimated. A variety of uncertainties arise, since economic benefits were predicted on the basis of epidemiological studies reviewed in the literature, including uncertainty in selection of studies and statistical uncertainty from referenced studies.

By applying COI model, it is difficult to compare findings across COI studies due to the use of different data and methods. Moreover, a number of limitations and uncertainties in economic benefit estimation are recorded in the present study. These shortcomings, however, should not delay the development of PM control measures in subway systems. Furthermore, the present study is valuable, since it can identify some gaps in the data which would be required for a full accounting of costs [29]. This leads to a suggestion that data collections and further analyses should be conducted aimed at improving estimations. Additionally, estimation framework, methods, and basic data of the present study are expected to provide basic information and reference for the estimation of economic benefit in correspondence with particulate pollution control.

5. Conclusions

In this study, the COI method was utilized to assess the economic value of a 10 $\mu g/m^3$ decrement in PM_{10} and $PM_{2.5}$ concentrations. The economic benefit analysis was conducted by setting the benefits of medical expense curtailment, of the precautionary effect on premature death and of the precautionary effect on productivity loss in terms of subway passengers and workers and their respective numbers. As for the results, the total annual economic benefit was calculated to be 328.2 million KRW for each 10 $\mu g/m^3$ decrement in PM_{10} and $PM_{2.5}$ concentrations. For each 10-$\mu g/m^3$ decrement in PM_{10} and $PM_{2.5}$ concentrations, it was determined that the annual savings of medical cost, premature mortality and productivity loss would be 124.2 million KRW, 186.4 million KRW and 17.6 million KRW per year, respectively. In light of these significant economic dividends, it is considered that PM_{10}- and $PM_{2.5}$-level reductions in subway systems should be promoted. Also, the results of this study are considered to be useful in providing basic information and reference for the estimation of economic benefit in correspondence with particulate pollution control.

Acknowledgments: This work was supported by research grants for the Railway Technology Research Project from the Ministry of Land, Infrastructure and Transport, Republic of Korea (17RTRP-B082486-04) and the Gachon University research fund of 2017 (GCU-2017-0181).

Author Contributions: Young-Chul Lee planned the study and contributed the main ideas; Thanh Ngoc Nguyen collected the data and Thanh Ngoc Nguyen and Young-Chul Lee were principally responsible for the writing of the manuscript; Young-Chul Lee, Duckshin Park and Yongil Lee commented on and revised the manuscript.

Conflicts of Interest: The authors declare that they have no competing interests.

Appendix A

Table A1. Summary of studies referenced as data sources of morbidity and mortality prevention rates associated with 10 $\mu g/m^3$ PM_{10} and $PM_{2.5}$ decrements.

Authors	Year Published	Description	Types of Data
Hamra et al. [39]	2014	Meta-analyses of studies examining the relationship of exposure to $PM_{2.5}$ and PM_{10} with lung cancer incidence and mortality were conducted. In total, 18 studies met authors' inclusion criteria and provided the information necessary to estimate the change in lung cancer risk per 10 $\mu g/m^3$ increase in exposure to PM. Random-effects analyses were used to allow between-study variability to contribute to meta-estimates. Estimates were robust to restriction to studies that considered potential confounders, as well as subanalyses by exposure assessment method.	Prevention rate for all lung cancer morbidity associated with each 10 $\mu g/m^3$ decrement in PM_{10} concentration; Prevention rate for all lung cancer morbidity associated with each 10 $\mu g/m^3$ decrement in $PM_{2.5}$ concentration

Table A1. *Cont.*

Authors	Year Published	Description	Types of Data
Zanobetti et al. [40]	2000	The association between PM_{10} and hospital admission for heart and lung disease in ten United States cities was examined. A Poisson regression model in each city was fit to allow for city-specific differences and then the city-specific results were combined. Potential confounding was examined by a meta-regression of the city-specific results. The results were stable when controlling for confounding by sulfur dioxide, ozone, and carbon monoxide.	Prevention rate for cardiovascular morbidity associated with each 10 $\mu g/m^3$ decrement in PM_{10} concentration
Stafoggia et al. [41]	2013	City-specific Poisson models were fitted to estimate associations of daily concentrations of $PM_{2.5}$, PM_{10} and $PM_{2.5–10}$ with daily counts of emergency hospitalizations for cardiovascular and respiratory diseases in eight Southern European cities, within the MED-PARTICLES project. Pooled estimates were derived from random-effects meta-analysis and the robustness of results to co-pollutant exposure adjustment and model specification was evaluated. Pooled concentration—response curves were estimated using a meta-smoothing approach.	Prevention rate for cardiovascular morbidity associated with each 10 $\mu g/m^3$ decrement in $PM_{2.5}$ concentration
Cui et al. [42]	2015	PUBMED and EMBASE databases were utilized to search for prospective cohort studies that evaluated the association between $PM_{2.5}$, PM_{10} and lung cancer incidence and mortality. Relative risks and 95% confidence interval were calculated using fixed-effect or random-effects models when appropriate.	Prevention rate for all lung cancer mortality associated with each 10 $\mu g/m^3$ decrement in PM_{10} concentration; Prevention rate for all lung cancer mortality associated with each 10 $\mu g/m^3$ decrement in $PM_{2.5}$ concentration
Analitis et al. [43]	2006	The estimated effects of ambient particle concentrations (black smoke and PM_{10}) on cardiovascular and respiratory mortality, from 29 European cities, within the Air Pollution and Health: a European Approach (APHEA2) project, were reported. A 2-stage hierarchical modeling approach assessing city-specific effects first and then overall effects was applied. City characteristics were considered as potential effect modifiers.	Prevention rate for cardiovascular mortality associated with each 10 $\mu g/m^3$ decrement in PM_{10} concentration
Pope et al. [44]	2002	Vital status and cause of death data were collected by the American Cancer Society as part of the Cancer Prevention II study, an on-going prospective mortality study, which enrolled approximately 1.2 million adults in 1982. Participants completed a questionnaire detailing individual risk factor data. The risk factor data for approximately 500,000 adults were linked with air pollution data for metropolitan areas throughout the United States and combined with vital status and cause of death data through 31 December 1998.	Prevention rate for cardiovascular mortality associated with each 10 $\mu g/m^3$ decrement in $PM_{2.5}$ concentration

Table A2. Numbers of in- and outpatients, and corresponding costs of treatment related to lung cancer and cardiovascular diseases (unit: person; 1000 KRW) [a].

ICD-10 Codes	Numbers of Patients		Costs of Treatment	
	Inpatient	Outpatient	Inpatient	Outpatient
C33–C34	38,581	67,715	334,299,667	208,118,814
I00–I02	47	2608	116,783	1,669,552
I05–I09	2065	22,467	24,953,117	8,812,322
I10	43,036	5,441,082	143,089,704	2,519,175,578
I11–I15	7317	365,159	19,725,153	167,941,670
I21–I22	25,733	80,968	211,588,391	70,228,942
I20, I23–I25	105,212	719,564	388,519,479	435,165,181
I26	4335	10,913	19,794,763	5,766,361
I44–I49	35,458	321,855	183,208,643	120,725,083
I50	21,383	110,872	81,249,269	46,900,788
I27–I43, I51–I52	16,112	110,810	146,047,446	53,766,890
I60–I62	35,061	69,961	492,407,437	48,315,017
I63	95,876	402,872	794,037,741	324,810,885
I64	3222	18,943	17,277,939	8,606,552
I65–I69	69,486	374,877	537,458,460	180,360,429
I70	5736	83,279	37,061,120	31,090,296
I73	2092	182,660	8,762,639	26,780,384
I74	1580	8463	9,811,723	2,968,997
I71–I72, I77–I79	7119	46,068	90,497,721	18,350,586
I80–I82	3317	26,474	11,850,703	7,213,287
I83	39,273	145,276	24,240,327	13,473,489
I84	183,732	633,098	171,306,439	64,124,463
I85–I99	16,263	174,771	26,318,701	19,886,521

[a] Source: National Health Insurance Corporation (NHIC); Health Insurance Review & Assessment Service. National Health Insurance Statistical Yearbook of 2015 [31].

Table A3. Visit days related to lung cancer and cardiovascular diseases (unit: days) [a].

ICD-10 Codes	Visit Days	
	Inpatient	Outpatient
C33–C34	1,274,169	743,627
I00–I02	1270	12,365
I05–I09	35,777	95,769
I10	2,024,940	41,110,659
I11–I15	196,580	1,837,922
I21–I22	266,695	299,949
I20, I23–I25	715,308	2,807,472
I26	87,656	45,975
I44–I49	357,476	1,146,368
I50	486,385	428,545
I27–I43, I51–I52	303,881	389,758
I60–I62	2,902,925	376,549
I63	6,652,417	2,058,337
I64	192,008	58,811
I65–I69	4,859,746	1,563,194
I70	102,666	261,618
I73	46,398	445,746
I74	32,867	26,545
I71–I72, I77–I79	130,265	139,906
I80–I82	48,735	77,906
I83	78,269	350,942
I84	541,883	1,536,758
I85–I99	111,001	359,372

[a] Source: National Health Insurance Corporation (NHIC); Health Insurance Review & Assessment Service. National Health Insurance Statistical Yearbook of 2015 [31].

Table A4. Ratio of non-benefit cost to treatment cost (unit: %) [a].

ICD-10 Code(s)	Ratio of Non-Benefit Cost to Treatment Cost	
	Inpatient	Outpatient
C33–C34	7.63	5.98
I00–I02	23.33	24.70
I05–I09	9.35	38.55
I10	27.24	29.00
I11–I15	24.14	31.48
I21–I22	6.97	33.31
I20, I23–I25	10.15	34.31
I26	19.94	38.18
I44–I49	10.73	37.72
I50	20.38	33.79
I27–I43, I51–I52	11.23	23.91
I60–I62	15.92	36.11
I63	23.32	33.61
I64	25.44	37.29
I65–I69	20.96	34.92
I70	20.25	35.04
I73	18.31	30.44
I74	21.07	35.44
I71–I72, I77–I79	10.49	39.89
I80–I82	21.84	38.19
I83	20.52	36.66
I84	18.77	33.44
I85–I99	20.82	38.20

[a] The data was calculated based on data collected from the National Health Insurance Statistical Yearbook of 2015 [31].

Table A5. Labor force participation rate and employment rate by gender and age [a].

Gender	Age	Participation Rate (%)	Employment Rate (%)
Male	15–19	9.6	8.5
	20–29	64.7	57.6
	30–39	93.3	90.6
	40–49	94.8	93.0
	50–59	90.0	88.1
	60+	54.4	52.9
Female	15–19	12.0	10.9
	20–29	65.6	60.7
	30–39	61.4	59.5
	40–49	67.7	66.4
	50–59	64.6	63.2
	60+	32.7	32.2
Total		63.7	61.5

[a] Source: Statistics Korea, Korean Statistical Information Service. Economically Active Population Survey [35].

Table A6. Deaths related to all lung cancer and cardiovascular diseases (units: persons) [a].

Age	ICD-10 Code(s)															
	C33–C34		I00–I09		I10–I13		I20–I25		I26–I51		I60–I69		I70		I71–I99	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
0	0	0	0	0	0	0	0	0	12	7	1	1	0	0	0	0
1–4	0	0	0	0	0	0	0	0	8	4	2	0	0	0	0	1
5–9	0	0	0	0	0	0	0	0	4	5	3	2	0	0	0	0
10–14	0	0	0	0	0	0	0	0	5	0	4	5	0	0	1	0
15–19	0	2	0	0	0	0	2	0	16	7	7	4	0	0	0	0
20–24	0	1	1	0	1	0	7	2	27	5	7	11	0	0	1	2
25–29	4	6	0	0	1	0	11	2	30	10	20	12	0	0	3	1
30–34	12	11	0	1	3	1	30	6	56	18	38	23	0	0	8	2
35–39	32	26	1	0	6	1	90	10	89	31	89	47	0	0	3	5
40–44	83	64	0	2	10	0	188	30	141	57	212	93	2	0	17	4
45–49	170	107	2	3	17	3	337	44	230	71	385	177	0	0	25	6
50–54	427	208	1	2	33	9	475	66	341	86	579	215	2	0	34	6
55–59	815	289	3	3	45	12	606	100	430	134	716	284	4	1	45	17
60–64	1,239	358	5	7	55	21	675	174	499	143	761	371	2	0	48	21
65–69	1,825	426	4	9	99	49	762	227	551	256	933	507	4	3	59	34
70–74	2,618	678	9	15	162	155	1056	533	730	568	1705	1110	15	4	111	75
75–79	2,737	856	9	17	288	411	1331	1139	995	1055	2335	2191	35	6	146	103
80–84	1,779	894	9	26	321	739	1078	1580	958	1618	2085	2987	23	27	120	117
85–89	714	536	5	20	273	1054	797	1649	655	1767	1234	2796	19	22	78	126
90+	222	260	4	8	191	1090	382	1334	395	1586	676	1825	12	30	31	86

[a] Source: Statistics Korea, Korean Statistical Information Service. Cause of Death Statistics [34].

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