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Congestion Charging Schemes for Greener Policies

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In Seoul, traffic congestion in Central Business District (CBD) and other roads including urban motorways is one of the biggest issues in the transport sector. These traffic congestions are not only causing delays in travel time but severe environmental problems such as fine dust and exhaust gases. In Seoul, as greenhouse gases and fine dust problems are getting worse, there have been several countermeasures to reduce greenhouse gases and fine dust from the transport sector. But there still needs a fundamental solution to reducing the traffic. In this study, the congestion charge policy on urban motorways in Seoul was applied as a solution for reducing traffic, and the environmental effects of the congestion charge on urban motorways were investigated. First, changes in travel patterns were investigated according to the congestion charge. A traffic simulation was performed to identify travel pattern changes and to calculate environmental and fuel-saving benefits. Next, the environmental benefits of pricing were identified by combining pollutant coefficients with the amount of pollutant decreased. Lastly, fuel-saving benefits were calculated. The result showed that the passenger car share in Seoul metropolitan area decreased by 0.95 % after implementing the congestion charge, while the bus and subway share increased by 0.44 %, and 1.45 % respectively. The environmental benefits of applying the congestion charge were 17,350 million KRW/y and the fuel-saving benefits were 59,260 million KRW/y.

1. Introduction

In many megacities around the world, there are miscellaneous urban-related problems including traffic congestion, air pollution, and housing shortage. Among these problems, traffic congestion is incurring not only travel time delays but waste of energy and air pollution(Barth and Boriboonsomsin, 2009). In 494 cities in the United States, people wasted 4.3 billion h and 6.4 billion L of gasoline annually due to traffic congestion, resulting in 18 billion t of excess greenhouse gas emissions and 101 billion USD of annual congestion cost (Schrank et al., 2021). Because of these negative effects caused by traffic congestion, most of the city authorities introduced various measures to alleviate traffic congestion.

As the interest in the global climate crisis has been increasing, the interest in greenhouse gases caused by urban activities is growing as well. In South Korea, the total greenhouse gas emission in 2020 was 656,222,880 t CO_2-eq and 15.4 % of the total emission was from the transport sector. As 97 % of emissions from the transport sector, which is equivalent to 93,248,220 t CO_2-eq, was from the road transport sector, it could be argued that there is a great need to reduce greenhouse gas emissions from the road transport sector.

In Seoul, people are suffering from severe traffic congestion on the roads. According to the Seoul Metropolitan government, the average speed on roads in the evening peak hour was 20 km/h in 2021, and 17.4 km/h in the Central Business District (CBD).

In Seoul, there are 10 urban motorways that connect regions in Seoul and the outskirts rapidly. Among the 10 urban motorways in Seoul shown in Figure 1, 3 urban motorways(Gangnam beltway, Seobu underground expressway, Sinwol-Yeoui underground road) are toll roads and the other 7 motorways are free roads. The average travel speed of 6 free urban motorways except Bundang-Naegok urban expressway in the evening peak was 35.7 km/h in 2021 and the lowest was 28.9 km/h. Referring to the travel speed of these urban motorways, it could be argued that the urban motorways in Seoul are not functioning well and it is urgent to introduce measures to alleviate congestion as those road congestions are worsening travel time delay, waste of energy, and air pollution.

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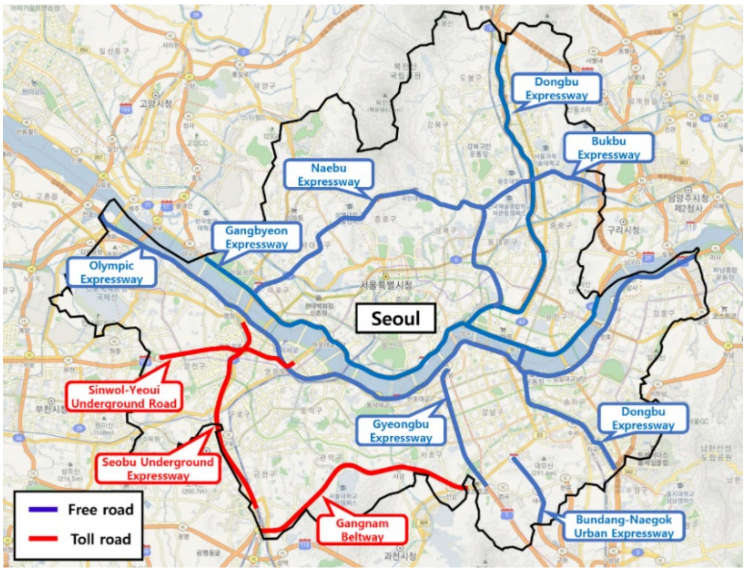

Figure 1: Urban motorway network in Seoul

As greenhouse gases and fine dust are severe urban related problems in Seoul and the interest in air quality has been growing, the Seoul metropolitan government has introduced policies such as green transportation zone in the CBD, which aims to promote public transport use and manage private car demand as well, and entry regulations of old diesel vehicles into Seoul to reduce air pollution from old diesel vehicles. But there are limitations to these policies, as entry restrictions only apply to older diesel vehicles and Green Transport Zones are limited to the city centre. To decrease the air pollutants from the transport sector, a stronger Transport Demand Management (TDM) policy should be introduced to decrease private car use and promote public transport use not only in CBD but in whole regions in Seoul.

TDM is a measure to manage transport demand using miscellaneous techniques including High Occupancy Vehicle (HOV) lanes, congestion charging, information providing, etc., and it is recently recognised as a significant method to mitigate greenhouse gases by decreasing private car use (Black and Schreffler, 2010). Many cities including Seoul, London, and Stockholm are implementing congestion charges to decrease private car use and promote public transport use, and various studies have shown that the congestion charge has positive effects such as reducing emissions and increasing public transportation use.

Daniel and Bekka (2000) calculated the environmental benefits of congestion charge by calculating the optimal charge and showed that introducing congestion charge to the entire road network is efficient for reducing Carbon Monoxide (CO), Hydrocarbon (HC), and Nitrogen Oxide (NOx). It was also shown that introducing a congestion charge into a partial network could reduce emissions and congestion.

In London, private car use in the zone with congestion charges decreased by 34 % while bus and bicycle use increased by 21 % and 28 % respectively (Leape, 2006). As NOx and Particle Matter 10 (PM10) emissions within the congestion charge area decreased by 12 % and 11.9 % respectively, it was argued that congestion charge is effective for mitigating emissions (Beevers and Carslaw, 2005). In Stockholm, the traffic volume entering the congestion charge zone decreased by 22 % after introducing congestion charges compared to the same period a year ago (Eliasson et al., 2009). Simeonova et al. (2021) examined the effects of congestion charging in central Stockholm and demonstrated that the congestion charge reduced not only air pollution by 5~15 % but the incidence of acute asthma among young children. Wu et al. (2017) examined the effects of the congestion charge in Beijing by constructing scenarios according to the area of charging, public transport service level, and charging method. It was predicted that the congestion charging would increase public transportation use in the charging area by 13 % and decrease CO and HC emissions by 60~70 % and NOx emissions by 35~45 %.

Meanwhile, in Seoul, the congestion charge has been charged at Namsan tunnel 1 and 3, which are the main arterials to Seoul CBD, since 1996. During the first 2 years after charging, the private car volume of these tunnels decreased by 34 % while the taxi and bus volume increased by 211 % and 63 % respectively. The travel speed of these tunnels increased from 22 km/h to 32 km/h as well (Lim and Kim, 2015). Kim and Hwang (2005) analysed the impact of road pricing schemes on urban motorways in Seoul with four pricing schemes: a toll road system, congestion pricing system, etc. The study was conducted by traffic simulation on the Gyeongbu expressway, located in southern Seoul, concluding that the congestion pricing system is the most beneficial pricing scheme in terms of speed gains and trip reductions.

Most of the studies reviewed above have studied the effects of congestion pricing on city centres, and only a few have studied the effects of congestion pricing on urban motorways but have only estimated effects related to traffic volume and speed. This study aims to identify the environmental benefits of expanding congestion charges, which are currently charged only at Namsan tunnel 1 and 3 in the city centre, to 7 urban motorways in Seoul, which are functioning as a main arterial and covering wider regions throughout Seoul.

The 7 urban motorways selected for implementing congestion charges are Gangbyeon Expressway, Olympic Expressway, Dongbu Expressway, Naebu Expressway, Bukbu Expressway, Gyeongbu Expressway, Bundang-Naegok Urban Expressway. One of the reasons for imposing congestion charges on these 7 urban motorways is that these roads have greater mobility, which provides justification for road pricing, as these roads have higher speeds and larger capacities compared to other roads. Another reason is that the effect of charging is expected to be large, as demand on these roads is large because these roads are not only free but provide greater mobility.

In order to identify the environmental benefits, the travel pattern change and modal share change after the congestion charge were identified first. Then, the amount of air pollutants and fuel use decreased after the congestion charge was calculated using the volume of traffic decreased. Lastly, the environmental benefits of introducing congestion charge to 7 urban motorways were calculated by converting the amount of air pollutants decreased and fuel consumption saved into monetary value.

2. Methodology

2.1 Construction of charging points on urban motorways

In this paper, congestion charging was implemented in 7 urban motorways mentioned above to identify the travel pattern changes according to congestion charging. It was assumed that the congestion charging is implemented after 2030, when the planned roads and railways are completed. The congestion charge was charged only for passenger cars and only when entering the motorways.

The congestion charge in these motorways was set at 2,000 KRW, the same price currently charged for regular passenger cars at Namsan tunnel no. 1 and 3. Unlike the Namsan tunnels, which collect the congestion charges only from 7 am to 9 pm on weekdays, it was assumed that the charge in the motorways is collected 24 hours every day.

The road network and Origin-Destination (OD) matrix for Seoul metropolitan area were acquired from the Korea Transport DataBase (KTDB) to secure reliability.

The congestion charge was collected at every entry link of the 7 motorways and the main road link at the boundaries of Seoul. To collect congestion charges at these links, a Volume Delay Function (VDF) was used and the VDF was modified by adding toll road weight to the Bureau of Public Roads (BPR) function. The BPR function is a function that calculates the travel cost according to the travel time of a link using the traffic volume and capacity of a link (Spiess, 1990).

The toll road weight used for charging was constructed in a generalised cost form, which transformed the congestion charge into additional travel time, and was calculated by dividing the charge by the time value of a passenger car. The VDF used to calculate link travel cost is shown in Eq(1).

$$T = T_0(1 + \alpha(v/c)^{\beta}) + \frac{C}{VOT/60} \times \epsilon \tag{1}$$

where, T : Travel time (min)
T_0 : Free flow travel time (min)
v : Traffic volume of link
c : Link capacity
α, β : Coefficient
C : Congestion charge (KRW)
VOT : Time value for passenger cars (KRW/1h)
ϵ : Dummy variable (1: passenger cars, 0: other vehicle types)

2.2 Identification of travel pattern changes

After charging every entry ramp of the 7 urban motorways on the network, the travel pattern change according to the congestion charge was identified. In this study, the travel pattern changes including changes in traffic volume in the 7 urban motorways and modal share according to congestion charge were identified by simulating travels before and after the congestion charge using EMME/4, a traffic simulation software. To identify these changes, the modal split step, which splits trips between each zone by each transport mode, of a 4-step model of traffic demand forecasting, which consists of trip generation, trip distribution, modal split, and trip assignment steps, was conducted. The gradual logit model, which calculates modal share by calculating the utilities of each mode, was used for the modal split. The gradual logit model used in the study is shown in Eq(2).

$$P_i^* = \frac{P_i * \exp\Delta U_i}{\Sigma P_i * \exp\Delta U_i} \tag{2}$$

Where, P_i^* : Revised share of mode i after implementation
P_i : Original share of mode i before implementation
ΔU_i : Change in the utility of mode i

2.3 Calculation of environmental benefits and fuel saving benefits

When the traffic volume decreases according to the congestion charge, the greenhouse gases and fine dusts from cars also decrease (Barth and Boriboonsomsin, 2009). After calculating the traffic volume change before and after introducing the congestion charge, environmental benefits caused by the decrease of air pollutants from cars were calculated. To calculate the environmental benefits, the method of calculating environmental benefits of the Korea Development Institute (KDI) was applied and the amount of emissions from each vehicle class (passenger cars, buses, freight vehicles) before and after implementing the congestion charge was calculated. The amount of emission was calculated by multiplying the coefficients of each pollutant classified by vehicle class and speed by Vehicle Kilometre Travelled (VKT) of each vehicle class. Next, the amount of emissions per year before and after the congestion charge was converted into monetary value using Eq(3), and the annual environmental benefits was calculated by identifying the difference between these monetary value using Eq(4).
After calculating the environmental benefits, the benefits of fuel savings and the amount of fuel saved according to the decreased traffic volume were calculated in the same way as the environmental benefits. The expression used for calculating the amount of fuel consumed annually is shown in Eq(5) and the expression for calculating the annual benefits of fuel savings is shown in Eq(6).

$$VOPC = \sum_l \sum_{k=1}^{3} (D_{lk} \times VT_k \times 365) \tag{3}$$

$$VOPCS = VOPC_{Before} - VOPC_{After} \tag{4}$$

Where, $VOPCS$: Environmental benefits (KRW/y)
$VOPC$: Total air pollution cost (KRW/y)
D_{lk} : Vehicle-kilometre by road link (l) and vehicle type (k),
VT_k : Air pollution cost per distance by speed and vehicle type (k)
k : Vehicle type (1: passenger car, 2: bus, 3: freight)

$$VOC = \sum_l \sum_{k=1}^{3} (D_{lk} \times VT_k \times 365) \tag{5}$$

$$VOCS = VOC_{Before} - VOC_{After} \tag{6}$$

Where, $VOCS$: Fuel cost saving benefits (KRW/y)
VOC : Total vehicle fuel cost (KRW/y)
D_{lk} : Vehicle-kilometre by road link (l) and vehicle type (k),
VT_k : Fuel cost per kilometre by speed and vehicle type (k)
k : Vehicle type (1: passenger car, 2: bus, 3: freight)

3. Result

3.1 Travel pattern change

In this study, the congestion charge was introduced in 7 urban motorways in Seoul, and the changes in entry volume of each urban motorway and modal share according to the congestion charge were identified. As shown in Table 1, It was identified that the entry volume of all 7 urban motorways decreased and the total entry volume of 7 urban motorways decreased by 43.8 % from 1,890,115 veh/day to 1,061,665 veh/day after the congestion charge. The Olympic expressway showed the highest decrease rate of 47.8 % followed by the Gangbyeon expressway. The modal share change result shown in Table 2 indicates that passenger car travel decreased after the congestion charge by 0.95 % while the share of buses and metro increased by 0.44 % and 1.45 % respectively.

Table 1: Entry volume of each urban motorway in Seoul (veh/day)

Road	Without charge	With charge	Difference	Increase rate
Gangbyeon Expressway	479,885	251,089	-228,796	-47.7 %
Olympic Expressway	432,025	225,570	-206,454	-47.8 %
Dongbu Expressway	346,531	213,854	-132,678	-38.3 %
Naebu Expressway	153,918	89,942	-63,976	-41.6 %
Bukbu Expressway	120,523	63,836	-56,686	-47%
Gyeongbu Expressway	209,341	120,070	-89,271	-42.6 %
Bundang-Naegok Urban Expressway	147,893	97,303	-50,590	-34.2 %
Total	1,890,115	1,061,665	-828,450	-43.8 %

Table 2: Number of trips and share for each travel mode (trips/day)

	Without charge		With charge		Difference	
	Number of trips	Share	Number of trips	Share	Number of trips	Increase rate
Car	20,937,060	47.89 %	20,738,510	47.44 %	-198,550	-0.95 %
Taxi	3,216,361	7.36 %	3,220,742	7.37 %	4,381	0.14 %
Bus	8,901,226	20.36 %	8,940,795	20.45 %	39,569	0.44 %
Metro	10,661,170	24.39 %	10,815,770	24.74 %	154,600	1.45 %
Total	43,715,817	100.00 %	43,715,817	100.00 %		

3.2 Environmental benefits and fuel cost saving benefits

The amount of emission was calculated by multiplying the coefficients of each pollutant classified by vehicle class and speed by the VKT of each vehicle class. The amount of emissions including Carbon Dioxide (CO_2), Volatile Organic Compounds (VOC) and Particle Matter 2.5 (PM2.5) decreased after implementing the congestion charge as shown in Table 3. The air pollution cost, which converted the amount of emissions into monetary value, was calculated by identifying the difference between the air pollution cost before and after introducing the congestion charge. As shown in Table 4, it was identified that implementing the congestion charge on 7 urban motorways generates annual environmental benefits of 17,350 million KRW.

Table 3: Emissions before and after congestion charge (t/y)

	CO	NOx	VOC	PM2.5	CO_2
Without charge	121,039	292,676	23,577	10,014	44,804,948
With charge	120,580	292,403	23,556	9,997	44,625,258
Difference	-460	-273	-21	-17	-179,689

Table 4: Air pollution cost before and after congestion charge (million KRW/y)

	CO	NOx	VOC	PM2.5	CO_2	Total
Without charge	13,978	2,158,540	31,313	2,151,393	1,630,203	5,985,426
With charge	13,911	2,154,528	31,272	2,146,394	1,621,971	5,968,076
Difference	-67	-4,012	-41	-4,999	-8,232	-17,350

The amount of fuel used was calculated by multiplying the coefficients of fuel consumption classified by vehicle class and speed by the VKT of each vehicle class. The fuel saving benefits were calculated by identifying the difference between the fuel cost before and after the congestion charge. As shown in Table 5, the amount of annual fuel saved according to the congestion charge was 66 million L, which decreased from 19,326 million KRW before the congestion charge to 19,259 million L after the congestion charge. The annual fuel cost saved according to the congestion charge was 59,260 million KRW, which decreased from 18,050,505 million KRW before the congestion charge to 17,991,246 million KRW after the congestion charge.

Table 5: Annual fuel consumption amount and fuel cost before and after congestion charge

	Annual fuel consumption (million L/y)	Annual fuel cost (million KRW/y)
Without charge	19,326	18,050,505
With charge	19,259	17,991,246
Difference	-66	-59,260

4. Conclusion

Every day in Seoul, people suffer from severe road congestion, which causes travel time delays and waste of energy and air pollution. To mitigate this traffic congestion and air pollution from cars, reducing private car travel and promoting public transport use is urgent. As a solution for reducing private car use, this study suggests congestion charges on urban motorways in Seoul. A traffic simulation was conducted to identify changes in travel patterns according to the congestion charge and it was shown that the congestion charge on 7 urban motorways reduced private car use by 0.95 % while the public transport such as bus and metro increased by 0.44 % and 1.45 % respectively. In terms of the environment, it was shown that the congestion charge is effective for reducing greenhouse gas emissions and PM2.5 from cars as the annual CO_2 emissions decreased by 179,689 t and CO, NOx, VOC, PM2.5 decreased as well after the congestion charge in traffic simulation. According to these results, it was estimated that the annual environmental benefits of the congestion charge on 7 urban motorways are 17,350 million KRW. In addition, this congestion charge policy is effective in saving fuel consumption as the annual fuel consumption decreased by 66 million L after the congestion charge.
Summing up the results, it could be argued that expanding congestion charge to 7 urban motorways have not only environmental benefits but fuel saving benefits. The result of this study could support implementing congestion charges to urban motorways and will help policymakers decide whether to expand congestion charges to urban motorways. Further research could be conducted to identify the optimal stages of implementing congestion charges to those 7 urban motorways considered above.

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References

Barth M., Boriboonsomsin K., 2009, Traffic Congestion and Greenhouse Gases, ACCESS Magazine, 1(35).
Beevers S. D., Carslaw D. C., 2005, The impact of congestion charging on vehicle emissions in London. Atmospheric Environment, 39(1), 1–5.
Black C. S., Schreffler E. N., 2010, Understanding transport demand management and its role in delivery of sustainable urban transport, Transportation Research Record, 2163, 81–88.
Choi, M., Ku, D., Lee S., Lee, S., 2021, Environmental Impact of Personal Mobility in Road Managements, Chemical Engineering Transactions, 89, 331-336.
Daniel J. I., Bekka K., 2000, The Environmental Impact of Highway Congestion Pricing, Journal of Urban Economics, 47(2), 180–215.
Eliasson J., Hultkrantz L., Nerhagen L., Rosqvist L. S., 2009, The Stockholm congestion - charging trial 2006: Overview of effects, Transportation Research Part A: Policy and Practice, 43(3), 240–250.
Saw K., Katti B. K., Joshi G., 2015, Literature Review of Traffic Assignment: Static and Dynamic, International Journal of Transportation Engineering, 2(4), 339-347.
Kim K. S., Hwang K., 2005, An application of road pricing schemes to urban expressways in Seoul, Cities, 22(1), 43–53.
Kumar A., 1980, Use of Incremental Form of Logit Models in Demand Analysis, Transportation Research Record, 775, 21-27.
Leape J., 2006, The London Congestion Charge, Journal of Economic Perspectives, 20(4), 157-176.
Lim K. K., Kim S., 2015, An Evaluation of Urban Congestion Charging in Seoul, Journal of the Eastern Asia Society for Transportation Studies, 11. 141-154.
Schrank D., Albert L., Eisele B., and Lomax T., 2021, 2021 Urban Mobility Report, Texas A&M Transportation Institute with cooperation from INRIX, College Station, TX, United States.
Simeonova E., Currie J., Nilsson P., Walker R., 2021, Congestion Pricing, Air Pollution and Children's Health, Journal of Human Resources, 56(4), 971-996.
Spiess H., 1990, Conical volume-delay functions, Transportation Science, 24(2), 153–158.
Wu K., Chen Y., Ma J., Bai S., Tang X., 2017, Traffic and emissions impact of congestion charging in the central Beijing urban area: A simulation analysis, Transportation Research Part D: Transport and Environment, 51, 203–215.