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A Study on the Energy and Environmental Efficiency of Urban Train System

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Abstract: The urban train system is known as an energy-efficient and environmentally-efficient public transportation system. In this study, we suggest the method of constructing spatially the most realistic CO_2 emission inventory by using a bottom-up approach with actual traffic amounts of urban train. We also developed the energy efficiency and the environmental efficiency of urban trains and we compared them with the other transport system in Seoul. As a result, the urban train system was shown as highly energy-efficient and environmentally-efficient public transportation system. The energy efficiency of the urban trains of Seoul were calculated as 58 ~ 111 kcal/p·km, which was about one-tenth of the level of sedans and one-fourth the level of busses. The environmental efficiency was calculated 12 ~ 22 gCO_2/p·km, which was about one-eighteenth the level of sedans and one-fifth the level of busses.

Keywords: Greenhouse-gas, Emission factor, Urban train, Source inventory, Bottom-up approach

1. Introduction

The total final energy consumption ratio of the transportation sector in South Korea is about 17.6%. The importance of energy consumption in metropolitan area transportation sector is even higher. Approximately 29.2% of energy is used in the transportation sector in the capital, Seoul [1]. Greenhouse-gas emission is also closely related with energy consumption, so we need to consider both the energy efficiency and environmental efficiency of each means of transportation.

The road transportation and the rail transportation are the main form of passenger transportation in the urban area. The modal share rate was surveyed as 23% for sedans, 27% for buses, and 39% for urban train in Seoul [2].

The urban train system is known to be an energy-efficient and environmentally efficient public transportation system. Schafer & Victor (1999) [3] listed the energy efficiency of sedans as 400 ~ 520 kcal/p·km(passenger kilometer), buses as 140 ~ 260 kcal/p·km, and electric rail system as 48 ~ 95 kcal/p·km. Electric rail systems have about 5 ~ 10 times higher energy efficiency per passenger kilometer than sedans [3]. Kim & Lee (2014) [4] calculated the energy consumption units of transportation for South Korea. They showed that the railway transportation mode is more energy efficient in passenger transportation than the road transportation mode [4].

A modal shift that changes the modal share rate to one suitable for urban regional characteristics and efficient structure of transportation is the most effective way for reduction of greenhouse-gas emissions [5]. To actualize the effective modal shift for the city, first of all, a realistic CO_2 emission inventory using a bottom-up approach with actual traffic amounts is required. In addition, the energy efficiency, and environmental efficiency are needed.

The urban train system of Seoul consists of electric locomotives. The energy is used on the actual operated rail. However, in the structure of electricity pricing conditions of South Korea, the electricity consumption is counted for head office buildings of each operator such as KORAIL (National

Line), Seoul Metro (Line 1 - 4), Seoul Metropolitan Rapid Transit Corporation (Line 5 - 8).

Accordingly, greenhouse-gas emission is not counted in the transportation sector, but in the public service sector. This is a factor that can distort the energy consumption and greenhouse-gas emissions, that determine the modal shift in the city.

When calculating the greenhouse-gas emission, a bottom-up approach of greenhouse-gas emission inventory with realistic activity data is the most appropriate method because of the realistic traffic volume data for spatial analysis. Furthermore, the "IPCC 2006 Guide Line" recommended the bottom-up approach with realistic activity data [6]. However, the energy consumption of the urban train system is calculated using a top-down approach through total energy consumption of each head office building in Seoul.

In this study, first of all, we approached the CO_2 emission inventory with the bottom-up method. According to this method, we constructed spatially high-resolution CO_2 emission data by using realistic activity data for urban trains, which is the most important passenger public transportation in Seoul.

Second, we estimated energy efficiency and environmental efficiency of urban trains and we compared these with the other transportation systems in Seoul.

2. Methodology

We analyzed on the energy efficiency of the urban train system (subway system) that operated in Seoul boundary area in this study. The flow chart in Figure 1. shows energy consumption and CO_2 emissions demonstrating the, energy efficiency and environmental efficiency.

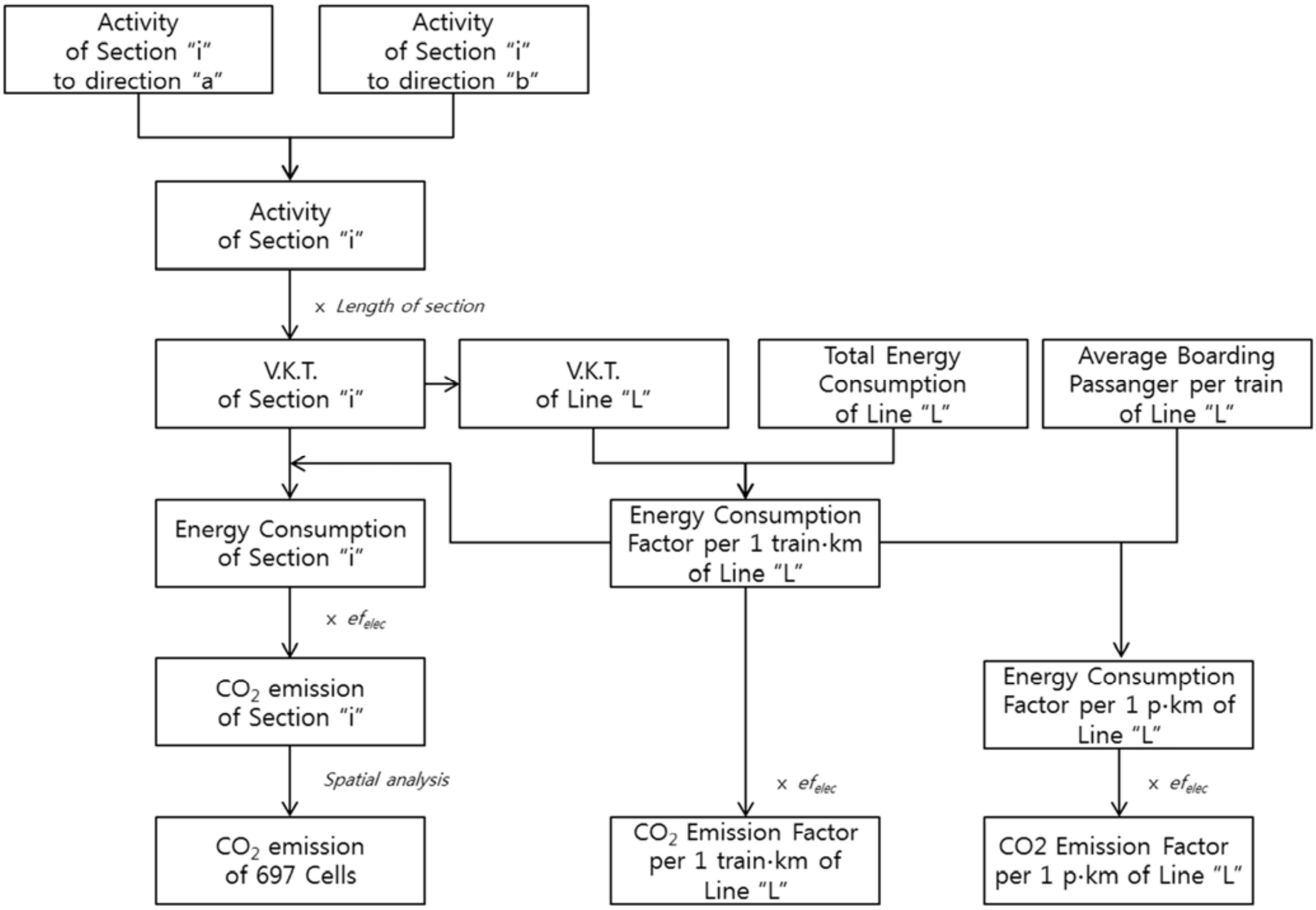


Figure 1. *Calculating flow chart. (I corrected this figure. Please delete these words in ( ) after you checked).*

2.1. Calculation Method of Activity Data and V.K.T.

The electricity consumption of the urban train of each section is based on the urban train schedule. This was constructed on the basis of activity from the starting point to the end point of the train timetable (KORAIL, Seoul Metro, Seoul Metropolitan Rapid Transit Corporation) to estimate a bottom-up approached energy consumption and CO_2 emissions.

The timetable of urban train is divided into weekdays and Saturdays, Sundays. Traffic volume for each day of the week varies in Seoul. Because the staring points to the end points of each trains are different (a, b in Figure 2.), the activities of section that were split by stations are different.

Therefore, yearly activity was calculated in both directions by each section with operations timetables.

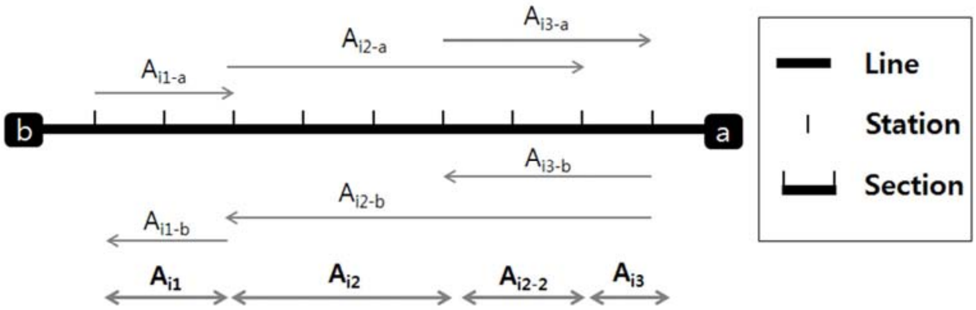


Figure 2. *Calculating method of activity data.*

The actual activity data of the section is the sum of the traffic volume to 'a' direction ($A_{L,i-a}$) and traffic volume of 'b' direction ($A_{L,i-b}$). The actual activity was calculated using equation (1).

$$A_{L,i} = A_{L,i-a} + A_{L,i-b} \quad (1)$$

Afterwards, the length of all sections was calculated with a spatial analysis tool (ArcGIS10.1 in this study). The total Vehicle Kilometers Traveled (V.K.T.) is the product of calculated activity data of each section by timetables and the length of each section, as in equation (2).

$$V.K.T._{\cdot L,i} = A_{L,i} \times l_{L,I} \quad (2)$$

2.2. Calculation of Per Train·km Factors of Urban Trains

The energy consumption factor per 1 train·km ($f_{energy}*_L$) was calculated with the total energy consumption of each line divided by Vehicle Kilometer Traveled of each line ($V.K.T_L$), equation (3). The electricity energy consumption contributed indirect CO_2 emissions because that was not emitted on the urban train operated line but at the electric power generator locations. We considered this indirect CO_2 emission with the CO_2 emission factor of electricity generation (ef_{elec}). CO_2 emission factors per 1 train·km($f_{CO2}*_L$) were calculated from the product of energy consumption factor per 1 train·km ($f_{energy}*_L$) and emission factor of electricity use (ef_{elec}=0.198 gCO_2/kcal, KEPCO), equation (4).

$$f_{energy} *_L = \frac{E_L}{V.K.T._{\cdot L}} \quad (3)$$

$$f_{CO2} *_L = f_{energy} *_L \times ef_{elec} \quad (4)$$

The energy consumption of each section ($E_{L,i}$), was calculated from the product of Vehicle Kilometer Traveled of each section ($V.K.T._{L,i}$) and the energy consumption factor per 1 train·km ($f_{energy}*_L$), equation (5).

The CO_2 emission of each section ($C_{L,i}$) was calculated using equation (6), the product of the energy consumption of each section ($E_{L,i}$) and the emission factor of electricity (ef_{elec}).

$$E_{L,i} = V.K.T._{\cdot i} \times f_{energy}*_L \quad (5)$$

$$C_{L,i} = E_{L,i} \times ef_{elec} \quad (6)$$

2.3. Making Cell Data of CO_2 Emissions by Urban Trains

The National Institute of Environmental Research (NIER) provides 1km by 1km spatial resolution data for a greenhouse-gas emission inventory called GHG-CAPSS (Green House Gas – Clean Air Policy Support System). The CO_2 emissions of each section ($C_{L,i}$) were calculated in this study was summed up by each 1 km by 1 km divided cell. So, the CO_2 emission inventory of urban train system can be provided as same resolution of GHG-CAPSS. Lee et al. (2012) [7] created the same format of the greenhouse-gas emission inventory of road transportation sector by each 1 km by 1 km divided cell in Seoul [7]. The CO_2 emission for the urban train system was calculated for each cell, Figure 3. This can be utilized with GHG-CAPSS of NIER.

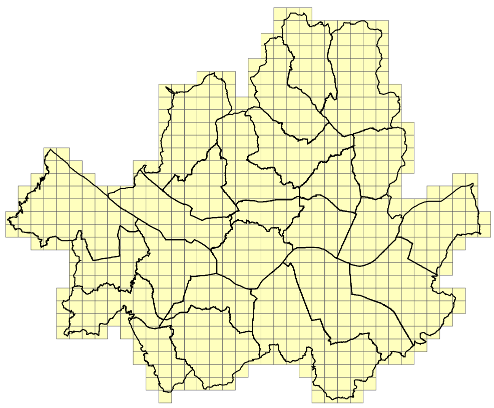


Figure 3. *697 Cells (1 km^2) of Seoul.*

2.4. Calculation of Energy Efficiency and Environmental Efficiency of Urban Trains

The urban train system can simultaneously transport a high volume of passengers. So, we calculated the energy consumption per 1 passenger·km(energy efficiency) and CO_2 emission per 1 passenger·km(environmental efficiency) to discuss the energy and environmental effectiveness.

The average boarding passenger per train (B_L) data was required for calculating these efficiencies. The data was collected from each urban train operator to calculate these efficiencies. Table 1 shows the average boarding passenger per train (B_L) data.

Table 1. *Average number of boarding passengers per train.*

Operator	Line	Average boarding passenger per train (B_L) (passenger/train)
KORAIL	National Line	652
Seoul Metro	Line 1	
	Line 2	653
	Line 3	530
	Line 4	552
Seoul Metropolitan Rapid Transit Corporation	Line 5	444
	Line 6	389
	Line 7	571
	Line 8	356

The energy consumption per 1 passenger·km ($I_{energy}*_L$) was calculated from the energy consumption factors per 1 train·km ($f_{energy}*_L$) divided by the average boarding passenger per train (B_L), equation (7). The CO_2 emission per 1 passenger· km ($I_{CO2}*_L$) was calculated from the product of the $I_{energy}*_L$ and ef_{elec}, equation (8)

$$I_{energy}*_L = \frac{f_{energy}*_L}{B_L} \quad (7)$$

$$I_{CO2}*_L = I_{energy}*_L \times ef_{elec} \quad (8)$$

3. Results

3.1. Total Energy Consumption & CO_2 Emissions of Urban Train

In this study, the Vehicle Kilometer Traveled of each section (V.K.T.$_{L,i}$), the energy consumption of each section ($E_{L,i}$), and the CO_2 Emission of each section ($C_{L,i}$) were calculated for all urban train lines in Seoul. We totaled the values within its line. Table 2 shows the result.

The total V.K.T. of each urban train line was calculated at 47,836,302 train·km /year in Seoul. Line 2 was the highest at 9,297,359 train·km /year, and Line 8 was the lowest at 1,877,325 train·km/year.

The total energy consumption of each urban train line was calculated as 2,443,210 Giga-cal/year in Seoul. Line 2 was the highest at 615,220 Giga-cal/year, and the Line 8 was the lowest at 59,779 Giga-cal/year.

Table 2. *Total energy consumption & CO_2 emissions for each urban train line.*

Line	*V.K.T.$_L$* (train • km/year)	*E_L* (Giga cal/year)	*C_L* (tonCO_2/year)
National Line	7,133,903	474,207	93,739
Line 1	2,103,737	111,904	22,121
Line 2	9,297,359	615,220	121,613
Line 3	5,279,836	309,408	61,162
Line 4	5,632,301	262,722	51,933
Line 5	6,803,802	261,157	51,624
Line 6	3,508,906	142,637	28,196
Line 7	6,199,133	206,176	40,756
Line 8	1,877,325	59,779	11,817
Total	47,836,302	2,443,210	482,960

The total CO_2 emission of each urban train line was calculated at 482,960 tonCO_2/year in Seoul. Line 2 was the highest at 121,613 tonCO_2/year, and Line 8 was the lowest at 11,817 tonCO_2/year.

3.2. Energy & Environmental Efficiencies of Urban Trains

Table 3 is the result of calculated values of the energy consumption factors per tarin·km ($f_{Energy}*_L$), the CO_2 emission factors per tarin·km ($f_{CO2}*_L$), the energy consumption per passenger·km ($I_{Energy}*_L$), and the CO_2 emission per passenger·km ($I_{CO2}*_L$).

The average energy consumption factor per train·km of all line was calculated as 46,093 kcal/train·km. The National Line was the highest at 66,472 kcal/train·km, and Line 8 was the lowest at 31,842 kcal/train·km.

The average CO_2 emission factors per train·km of all line was calculated as 9,111 gCO_2/train·km. The National Line was the highest at 13,080 gCO_2/train·km, and Line 8 was lowest at 6,294 gCO_2/train·km.

The average energy consumption per passenger·km of all line was calculated at 90 kcal/p·km. Line 3 was highest at 111 kcal/p·km, and Line 7 was lowest at 58 kcal/p·km.

The average CO_2 emission per passenger·km of all line was calculated at 18 gCO_2/p·km. Line 3 was highest at 22 gCO_2/p·km, and Line 7 was lowest at 12 gCO_2/p·km.

Table 3. *Energy consumption factor, CO_2 emission factor, energy efficiency and environmental efficiency for each urban train line in Seoul.*

Line	$f_{Energy}*_L$ (kcal/train·km)	$f_{CO2}*_L$ (gCO_2/train·km)	$I_{Energy}*_L$ (kcal/p·km)	$I_{CO2}*_L$ (gCO_2/p·km)
National Line	66,472	13,140	102	20
Line 1	53,193	10,515	82	16
Line 2	66,172	13,080	101	20
Line 3	58,602	11,584	111	22
Line 4	46,646	9,221	85	17
Line 5	38,384	7,588	87	17
Line 6	40,650	8,035	104	21
Line 7	33,259	6,574	58	12
Line 8	31,842	6,294	90	18
Average	46,093	9,111	90	18

4. Discussion

4.1. Spatial Analysis of CO_2

The actual activity-based CO_2 emission of each section ($C_{L,i}$) calculated in this study was calculated using a 1 km by 1km grid cell format, the same as GHG-CAPSS format used by The National Institute of Environmental Research. The Figure 4 is the spatial distribution map of the CO_2 emissions of urban train in Seoul.

The map developed in this study is impossible to implement with existing statistical data. There are large CO_2 emissions in downtown area near the district of Jongno-Gu and Jung-Gu, and the circle line of Line 2 also has high activity. The spatially realistic inventory of the CO_2 emission distribution map that we developed can be utilized as important data in a CO_2 emission reduction plan.

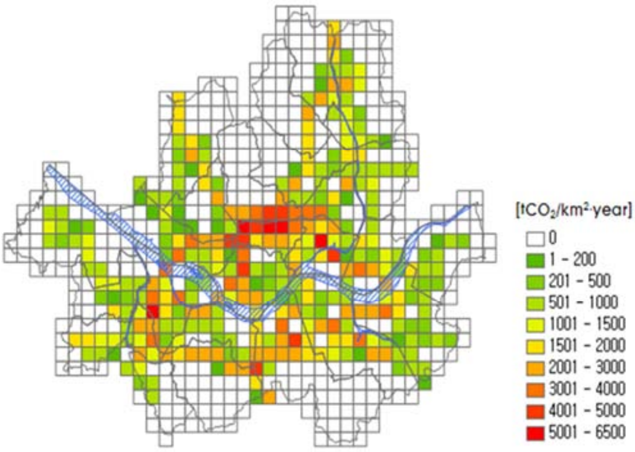


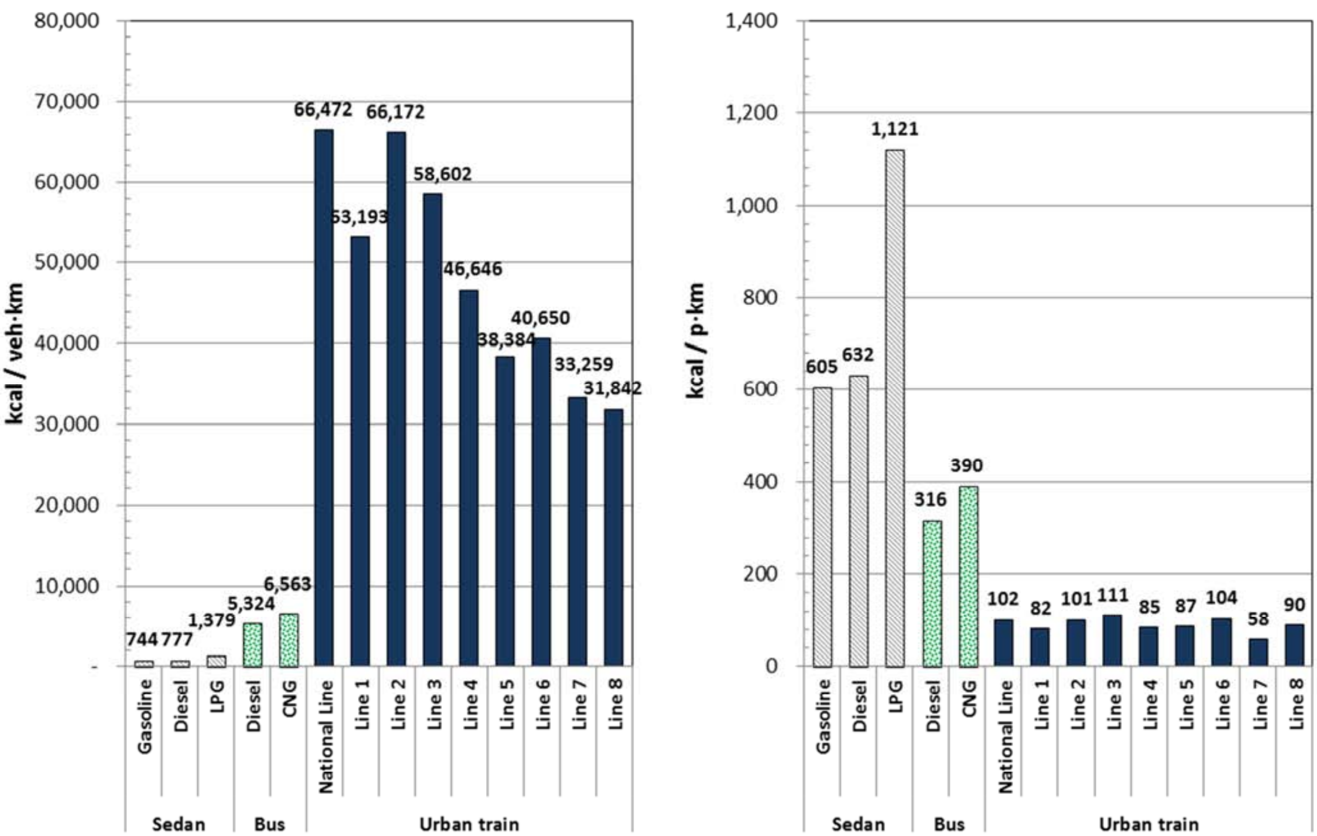
Figure 4. *Distribution map of CO_2 emissions per km^2 by urban train.*

4.2. Comparison of Efficiency: Other Transportation

We compared the energy efficiency of passenger transportation such as sedan, bus, urban train. Energy consumption factor such as energy consumption per vehicle·km (f_{energy}*, Figure 5-(a)), and the Energy efficiency such as energy consumption per passenger·km (I_{energy}*, Figure 5-(b)) were utilized in the analysis.

The energy consumption of each transportation method was calculated. The sedan used between 744 and 1,379 kcal/car·km, Bus used between 5,324 and 6,563 kcal/car·km. The urban train system is much larger form of transportation, and its energy consumption factors were between 31,842 and 66,472 kcal/train·km; this was 50 to 100 times higher than the sedan. However, the number of boarding passenger on an urban train usually ranges from 444 to 653, much larger than that of sedan (1.23 passengers) or bus (16.83 passengers). Therefore, energy consumption per passenger·km (I_{energy}*) is needed to fully compare the energy efficiency of these forms of transportation.

The Figure 5-(b) shows that the I_{energy}* of a sedan is between 605 and 1,121 kcal/p·km, a bus is between 316 and 390 kcal/p·km. The urban train is between 58 and 111 kcal/p·km, about one-tenth of the level of a sedan and one-fourth the level of a bus. In conclusion, the urban train is a very energy-efficient transportation system.

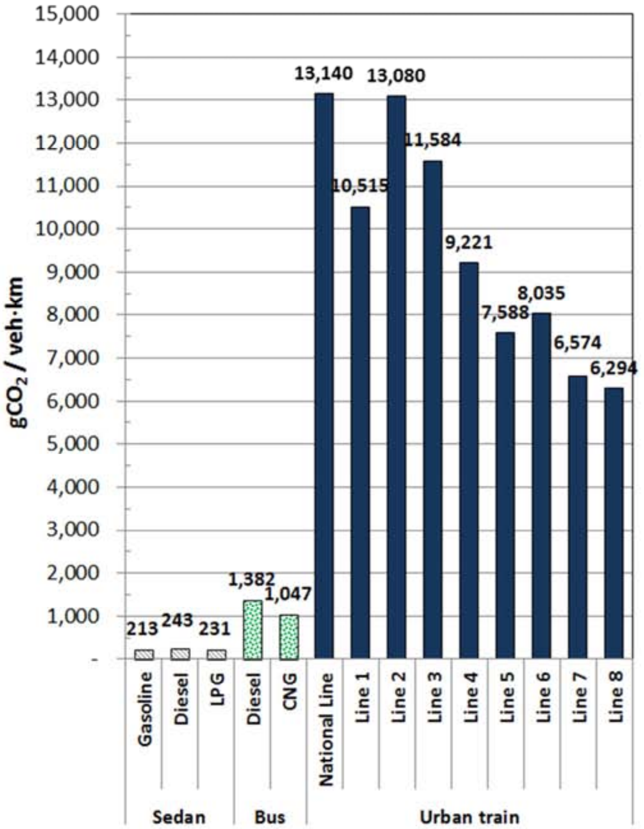


(a) Energy consumption factors per 1 vehicle·km (b) Energy efficiency per 1 p·km

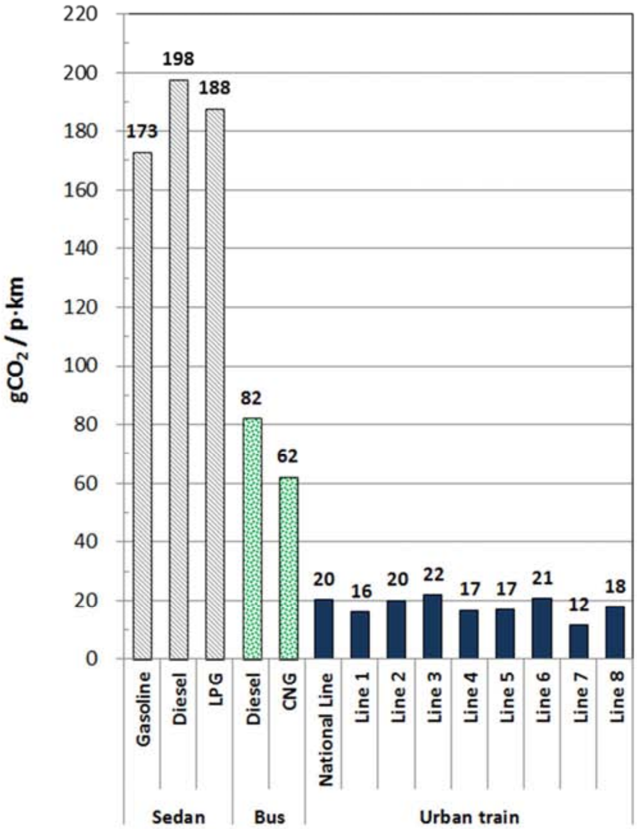
Figure 5. *Energy consumption factors and energy efficiencies by vehicle type.*

Because of the urban train using electricity as an energy source that has low CO_2 emissions per 1 kcal, the urban train is more predominant in the environmental efficiency (Figure 6-(b)).

The CO_2 emission per passenger·km of a sedan is between 173 and 198 gCO_2/p·km and a bus is between 62 and 82 gCO_2/p·km. The urban train is between 12 and 22 gCO_2/p·km, that is about one-eighteenth the level of a sedan and one-fifth of a bus.



(a) CO_2 emission factors per 1 vehicle·km



(b) Environmental efficiency per 1 p·km

Figure 6. *CO_2 emission factors and environmental efficiencies by each vehicle type.*

4.3. Comparison: Other Study

We compared calculated energy efficiency and environmental efficiency with other results.

Table 4. *Energy efficiency and environmental efficiency of other results.*

Researcher	Energy efficiency (kcal/ p·km)	Environmental efficiency (gCO_2/ p·km)	Rail transportation type	Studied region
This Study	58 ~ 111	16.1 ~ 21.9	Subway	South Korea (Seoul)
MOTIE[a]	60		Subway	South Korea
Schafer & Victor	72		Light rail system	World
Kim et al.	51	28	Metropolitan subway	South Korea
KOTI[b]	98		Subway	South Korea
	36	17	Railway	World
	96	34	Railway	Europe 28 countries
	172	62	Railway	USA
IEA & UIC[c]	33	21	Railway	Japan
	61	28	Railway	Russia
	18	10	Railway	India
	25	16	Railway	China

a MOTIE: Ministry of Trade, Industry and Energy (South Korea)
b KOTI: The Korea Transport Institute (South Korea)
c IEA & UIC: International Energy Agency & International Union of Railways

The energy consumption per passenger·km of an urban train that calculated in this study were between 58 and 111 kcal/p·km. Ministry of Trade, Industry and Energy (MOTIE, 2015) listed the energy efficiency of subway as 60 kcal/p·km in South Korea [8]. Schafer & Victor (1999) listed the energy efficiency of light rail system as 72 kcal/p·km [3]. Kim & Lee (2014) listed the energy efficiency as 51 kcal/p·km and environmental efficiency as 28 gCO_2/p·km in South Korea [4]. The Korea Transport Institute (KOTI, 2005) listed energy efficiency of subway as 98 kcal/p·km in South Korea [9]. International Energy Agency & International Union of Railways (IEA & UIC, 2015) listed energy efficiency of rail way as 18 – 172 kcal/p·km, and environmental efficiency as 10 – 62 gCO_2/p·km[10].

5. Conclusion

The actual activity data is required to calculate the bottom-up approach CO_2 emission inventory of urban train system. In this study, we calculated the bottom-up approach CO_2 emission by realistic activity data of urban train system in Seoul. We can provide much more spatially realistic CO_2 emission inventory data than the existing method that uses the electricity consumption counted for head office building of each operator.

And, when we look through the energy efficiency and the environmental efficiency we calculated, the urban train is much more energy-effective and environmentally-effective transportation than the others in Seoul.

Nomenclature

A	Activity(Traffic volume)
V.K.T	Vehicle Kilometer Traveled (km·train/year)
l	Length of section "i" (km)
f_{energy}*	Energy consumption factor per 1 train·km (kcal/train·km)
f_{CO2}*	CO_2 emission factor per 1 train·km (kcal/train·km)
E	Total energy consumption of Line (kcal)
C	CO_2 emission ($kgCO_2$)
ef_{elec}	emission factor of electricity use ($kgCO_2$/kcal)
B	Average boarding passenger per train (passenger /train)
I_{energy}*	Energy consumption efficiency (kcal/p·km)
I_{CO2}*	Environmental efficiency (gCO_2/p·km)
Subscript "L"	Urban train Line
Subscript "i"	Section(segment) of Line

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