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Article

Study on Charging Method Selection According to Public-Sector Electric Vehicle Operating Environment

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Abstract: South Korea proposed reducing greenhouse gas emissions by 37% compared to the expected emissions by 2030 as the POST-2020 greenhouse gas reduction target. Electric vehicle distribution in the public sector is essential to achieve the carbon dioxide reduction target for transportation. In particular, when buses with internal combustion engines, which travel long distances and contribute substantially to greenhouse gas emissions, are replaced with electric buses, it is expected that greenhouse gas emissions will be significantly reduced. There are three types of electric buses with different power supply systems: a plug-in type in which power is supplied when a plug is inserted, a battery-swapping type in which a battery mounted on top of the vehicle is swapped at a swapping station, and a wireless type in which the battery is wirelessly charged through self-induction at a charging facility installed on the road. Vehicles of each charging type have different advantages and disadvantages. The performance, charging type, battery capacity, and operating environment of electric buses are mutually related parameters that must be considered when introducing such vehicles. Therefore, the optimal charging type must be selected according to the operating environment to enable the widespread use of electric buses. As such, this report proposes the optimal charging type according to the operating environment of public-sector electric vehicles.

Keywords: Public sector, operating environment, electric bus, optimal charging type, charging infrastructure

Nomenclature

B_y^{ene}	Annual electric bus energy-saving benefit compared to compressed natural gas (CNG) bus [$]
$B_y^{ene,cng}$	Annual CNG bus energy-saving benefit [$]
$B_y^{ene,ev}$	Annual electric bus energy-saving benefit [$]
B_y^{om}	Annual maintenance cost saving benefit [$]
B_y^{oper}	Annual electric bus fare benefit [$]
B_y^{total}	Annual electric bus total benefit [$]
C_{bat}	Battery cost [$]
$C_{bat,wear}$	Battery wear cost [$]
$C_y^{bat,exc}$	Battery replacement cost [$]
C_y^{cng}	Annual CNG cost [$/ m^3]
C_y^{ev}	Annual electricity cost [$/kWh]
C_y^{inf}	Electric bus initial infrastructure construction cost [$]

C_y^{om}	Annual electric bus infrastructure maintenance cost [$]
C_y^{oper}	Electric bus fare [$]
C_y^{sub}	Electric bus subsidy [$]
C_y^{total}	Annual electric bus total cost [$]
C_y^{veh}	Electric bus actual purchase cost [$]
$C_y^{veh,ini}$	Electric bus initial purchase cost [$]
E_{bat}	Electric bus battery capacity [kWh]
E_{dis}	Electric bus battery discharge amount [kWh]
E_{out}	Electric bus battery capacity (before considering state of charge (SOC)) [kWh]
N	Number of electric buses
P_{bat}	Electric motor energy consumption [kW]
P_{cha}	Electric bus charging power [kW]
r	Discount rate
$SOC_{\max}$	Battery maximum SOC
SOC_t	Battery SOC at time t
t_{cha}	Electric bus charging time [s]
$t_{interval}$	Electric bus headway [s]
V	Electric bus average velocity [km/h]
S	Bus travel distance [km]
Y	Analysis time [yr]
α_{cng}	CNG bus fuel efficiency [km/m^3]
α_{ev}	Electric bus fuel efficiency [km/kWh]
β_y	Annual number of bus passengers [people]
η_{cha}	Charging efficiency
η_{dis}	Discharge efficiency

1. Introduction

Recently, interest in environmental issues has been increasing owing to CO_2 emission control reinforcement and the greenhouse gas emissions caused by increased fossil fuel use. The transportation sector accounts for a significant proportion of fossil fuel consumption, and global efforts have therefore been made to develop public transportation systems based on electric vehicles to reduce the greenhouse gas emissions of the transportation sector [1–3].

In major Asian and European cities, electric vehicles with CO_2 emissions lower than those of conventional internal combustion engine vehicles have emerged in urban transportation [4–9]. Although the high initial costs of electric vehicles remain a major obstacle to their widespread use, their application will be promoted by European companies and led by Chinese automakers. Currently, China is the top producer and consumer of electric commercial vehicles, such as electric buses, taxis, and trucks, in the world. It is becoming the world leader in terms of the key technologies

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as well as market size. Accordingly, Beijing established a policy that 80% of all buses will be replaced with electric buses by 2019 and is providing purchase subsidies for electric buses and operating subsidies of up to RMB 80,000 per year. In addition to China, the U.S. and Europe are developing and producing electric vehicles with various performance levels, and the penetration of electric vehicles into the public sector is being promoted through government funding and incentive policies [10].

Many studies on electric vehicles have also been conducted in South Korea. Accordingly, various efforts are being made to increase the utilization of electric vehicles. For instance, plug-in charging-type electric buses were introduced into city bus routes in November 2016 [3]. South Korea has performed small-scale electric bus demonstration projects, and many local governments, including that of Jeju Island, are pursuing the active use of electric buses. In addition, Daegu City has been performing a demonstration project for electric taxi distribution since 2016 with the objective of becoming a leading city for electric vehicles. It has a goal of distributing 2000 electric vehicles by 2020.

According to the International Energy Agency (IEA), the primary obstacles to electric vehicle penetration include their high purchase prices, the shortage of charging infrastructure, and the battery service life. Thus, these factors must be considered to achieve the commercialization and popularization of electric vehicles in the public sector [10]. Accordingly, various studies have been conducted to realize this objective. For instance [11–13] present analyses of charging infrastructure placement cases conducted with the goal of minimizing the total installation costs of electric bus charging stations. However, the techniques proposed therein can only be applied under specific conditions, because all of the electric buses must be of the same charging type. Meanwhile, [14–18] describe analyses conducted using application programs, such as genetic algorithms, to construct the optimal charging infrastructure for electric vehicles. The results of those studies also can only be applied under specific conditions, even though the distance between charging locations was optimized and the charging infrastructure was analyzed for cost minimization. In addition, Chan [19] performed feasibility assessment considering the technical limits of electric buses, but it was assumed that all of the electric buses were charged with the same capacity for the same time period.

Electric buses of each charging type have different advantages and disadvantages. The performance, battery capacity, and operating environment of electric buses are mutually related parameters that must all be considered when introducing such vehicles. Therefore, the optimal charging type must be selected according to the operating environment to enable the widespread use of electric buses in the public sector. As such, the battery capacity was estimated in this study considering the depth of discharge (DOD) range and wear cost of electric buses. In addition, the number of additional electric buses required beyond the number of existing compressed natural gas (CNG) buses was estimated by considering the electric bus charging time by performing energy consumption analysis according to the electric bus operating environment. Based on the results, the optimal charging type was proposed and economic efficiency analysis of the bus routes in Daegu City, South Korea, was performed for verification.

2. Electric Bus Characteristics by Charging Type

Electric buses can be classified into three types according to the charging method: plug-in, battery-swapping, and wireless. For a plug-in bus, the charging facility costs are low and the required facilities are simple because the battery in such a vehicle is charged simply by using a plug at a charging facility. Owing to the battery charging time, however, additional electric buses are required to maintain the existing bus headway.

Meanwhile, a battery-swapping vehicle is operated by driving its electric motor with electrical energy through a detachable battery mounted on the vehicle, and additional electric buses are unnecessary because no extra time is required other than the time for battery replacement. However, the initial infrastructure construction costs associated with this type of vehicle are significantly higher than those associated with vehicles of the other charging types. This drawback can be minimized by

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installing charging stations at the intersections of multiple routes, because the initial infrastructure construction costs can be reduced based on the operation rate of each route.

Finally, a wireless charging vehicle converts the magnetic field generated by the electric wires buried under the road into electrical energy by employing a current collector mounted underneath the vehicle and performs battery charging and driving using this energy. While this method enables battery charging during vehicle operation, the charging efficiencies of such vehicles are lower than those of vehicles of the other charging types, the initial infrastructure construction costs are somewhat higher than those of plug-in vehicles, and additional electric buses are required to maintain the existing bus headway. Table 1 summarizes the characteristics of electric buses based on a battery capacity of 100 kWh according to charging type.

Table 1. Electric bus characteristics by charging type.

	Plug-in	Battery-swapping	Wireless
Charging power	200 kW		
Charging time	20–30 min	40 sec	30–40 min
Charging efficiency	0.95%	0.95%	0.75%
Installation location	Route origin and end	Intersections	5%–15% of the operating route
Cost	1.1×10^6 \$	32×10^6 \$	4×10^6 \$
Case			

3. Public-Sector Bus Battery Capacity Estimation

3.1 Battery DOD Range Estimation

According to the IEA, battery service life is a major obstacle to the distribution of electric vehicles and therefore must be considered to commercialize and popularize electric buses. Thus, the battery capacity that can be used during the service life according to the DOD selection must be calculated, and the DOD that provides the largest total usable capacity must be selected. Figure 1 shows the dependence of the service life a lithium-ion battery on the DOD, demonstrating that the DOD is inversely proportional to the service life. However, when the DOD is reduced to extend the service life using this relationship, the battery cannot be used efficiently because its total usable capacity is decreased. Therefore, the battery degradation cost should be calculated according to the DOD from the DOD-cycle curve so that the battery can be operated in the interval in which the degradation cost is minimized. The battery degradation cost can be calculated according to the DOD as follows [21]:

$$ {}_{\text{deg}} \quad \times \quad \times \quad \times \quad \times \quad . \tag{1}$$

Figure 2 depicts the battery degradation cost for battery cycling within a specific state of charge (SOC) range. The degradation cost of a 100 kWh battery was analyzed using the DOD-cycle graph in Figure 1. It was assumed that the battery price was 273 \$/kWh and the discharge efficiency was 0.97. The appropriate DOD was found to be 75% considering battery degradation [22, 23].

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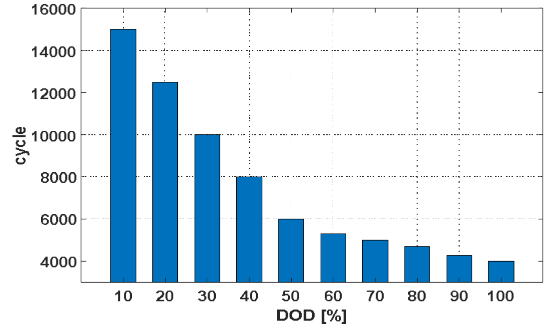

Figure 1. Lithium-ion DOD cycle life model.

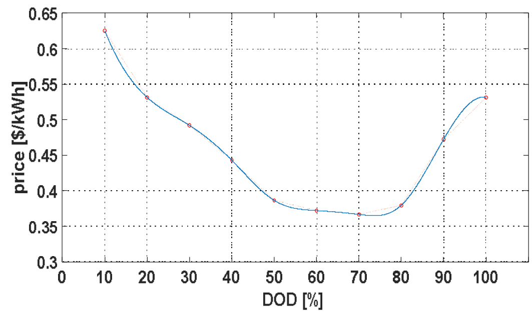

Figure 2. Battery degradation cost by DOD.

3.2 Battery Capacity Estimation

In this section, battery capacity estimation considering the all-electric range (AER), battery DOD, and vehicle specifications is presented. The battery capacity can be estimated using Equation (2), and the energy consumption can be calculated based on the power consumed by the electric motor, as shown in Equation (3) [20]:

(2)

and

. (3)

The vehicle parameters in Equation (3) are defined as shown in Table 2.

Table 2. Vehicle parameters.

Symbol	Property	Unit	Value
	Motor drive efficiencies	-	0.91
	Vehicle mass	kg	16,236
	Gravity	m/s^2	9.81
	Rolling resistance coefficient	-	0.01
	Air density	kg/m^3	1.23
	Aerodynamic drag coefficient	-	0.7
	Frontal area	m^2	7.8965
	Mass factor	-	0.04

The battery capacity was analyzed according to the electric bus AER using the MATLAB-based vehicle simulation program ADVISOR. The Orange County bus cycle (OCC) test was performed based on actual bus operating data, and the results are presented in Figure 3.

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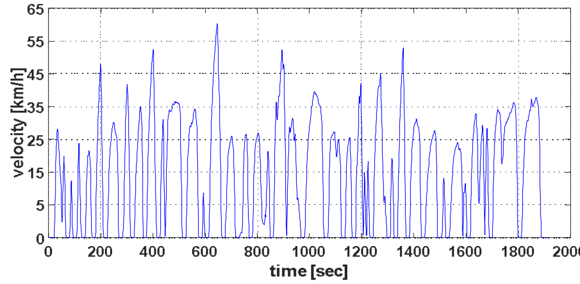
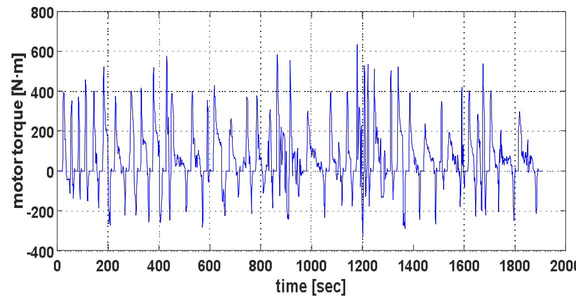
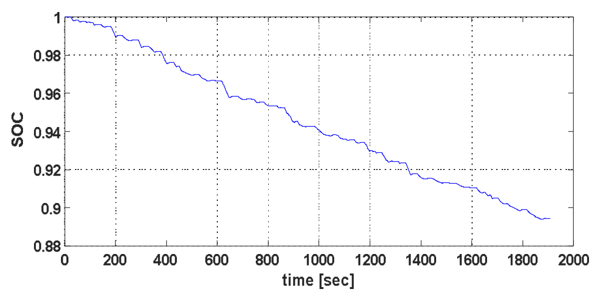
For the electric bus AER, 80 km was used, as specified by the Ministry of Environment. Table 3 summarizes the battery capacity results obtained from the simulation.



(a) Velocity



(b) Motor torque



(c) SOC

Figure 3. OCC test driving cycle.

Table 3. ADVISOR simulation results.

AER [km]	Battery capacity [kWh]	Fuel efficiency [km/kWh]	Operating time [sec]
80	108	0.74	13,744

As stated in Table 3, the battery capacity appropriate for the chosen electric bus AER is 108 kWh. In this case, the fuel efficiency is approximately 0.74 km/kWh. Using Equation (4), the battery capacity in Table 3 was recalculated considering the DOD and was found to be 144 kWh when a DOD of 75% was applied, as shown in Figure 2:

$$_{max} \quad _{min}. \tag{4}$$

4. Public-Sector Electric Bus Operating Environment Analysis

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The operating environment of electric buses is the same as that of the existing CNG buses, but battery charging time is required owing to the energy consumption during operation. Therefore, the number of additional buses required to compensate for the battery charging time must be estimated to maintain the same headway as that of the existing CNG buses. In this section, analyses of the charging time and number of additional buses required according to the battery energy consumption, which depends on the electric bus operating environment, are presented.

4.1 Energy Consumption Dependence on Electric Bus Operating Environment

The electrical energy consumed internally during electric bus operation can be obtained based on the amount of battery discharge, as shown in Equation (5):

. (5)

In this case, the fuel efficiency accounts for the passenger and cooling/heating ratios at time t.

4.2 Electric Bus Charging Time

The electric bus charging time is defined as the time it takes to replace the electrical energy consumed internally during operation and can be calculated based on the SOC at time t after operation, as shown in Equation (6):

max . (6)

4.3 Number of Additional Electrical Buses Required Considering Charging Time

When the electric bus charging time is longer than the headway, additional electric buses are required to maintain the same operating environment as that of the existing CNG buses. The number of additional electric buses required can be calculated using Equation (7):

. (7)

5. Public-Sector Electric Bus Economic Efficiency Analysis

5.1 Analysis Method

Economic efficiency analysis is employed to determine the feasibility of an investment project by measuring its costs and benefits and calculating the resulting economic return. The quantities employed in economic efficiency analysis include the benefit-cost ratio (B/C ratio), net present value (NPV), and internal rate of return (IRR). Both the NPV and IRR are used to assess a project in which costs and benefits occur in each time slot and have extremely similar ranges of use. Since the IRR cannot provide theoretical background appropriate for making the final selection of an alternative while providing results corresponding to various alternatives to the analyzer, the NPV is regarded as more appropriate than the IRR in terms of project assessment. In this study, the economic efficiency of electric bus operation was analyzed using the NPV, as shown in Equation (8):

. (8)

5.2 Cost Item Calculation

The cost for the economic efficiency assessment was calculated as follows:

. (9)

The total cost is given by the sum of the actual vehicle purchase and infrastructure construction costs, which are the initial costs, and the maintenance and battery replacement costs, which are the operating costs. As shown in Equations (10) and (11), the actual vehicle purchase cost can be determined by subtracting the vehicle subsidy from the vehicle purchase cost, and the maintenance cost can be obtained by taking 8% of the infrastructure construction cost from the third year:

(10)eks159

and

. (11)

The overhead costs were assumed to be 18×10^3 \$ per year in this study. The battery replacement cost was determined according to the economic efficiency analysis period after the battery service life was calculated using Figures 2 and 3.

5.3 Benefit Item Calculation

The total benefit is given by the sum of the energy and maintenance cost savings compared to those of CNG buses and the profit from the fare, as shown in Equation (12):

. (12)

The benefit obtained from electric bus operation compared to CNG bus operation was calculated as the energy cost saved, and the amount saved on periodic maintenance supplies, such as oil, was calculated as the maintenance cost saved:

, (13)

, (14)

and

. (15)

The annual profit from the electric bus fare can be expressed as shown in Equation (16):

. (16)

6. Case Study

In this study, the battery capacity was calculated considering the battery DOD range and degradation cost of public-sector electric buses. In addition, the number of additional electric buses required beyond the number of existing CNG buses was analyzed considering the electric bus charging time by performing energy consumption analysis according to the electric bus operating environment. The optimal charging type was proposed based on the results, and economic efficiency analysis of bus routes 518, 708, and Express 5 in Daegu City, South Korea, was performed for verification. The economic efficiency analysis was conducted for plug-in, battery-swapping, and wireless charging vehicles. The discount rate was set to 5.5%, and the analysis period was set to 20 years. As described in Section 3, the battery capacity was 144 kWh and the battery charging power was 200 kW. In addition, the target electric buses achieved the average city bus velocity of 20 km/h. Figure 4 provides a map of the three investigated bus routes, and Table 4 describes the operating environment of each route. The analysis of the numbers of additional electric buses required beyond the numbers of existing CNG buses considering the electric bus charging time based on these operating environments indicated that routes 518 and Express 5 each required two additional vehicles to maintain the same operating environment as that of the current CNG buses.

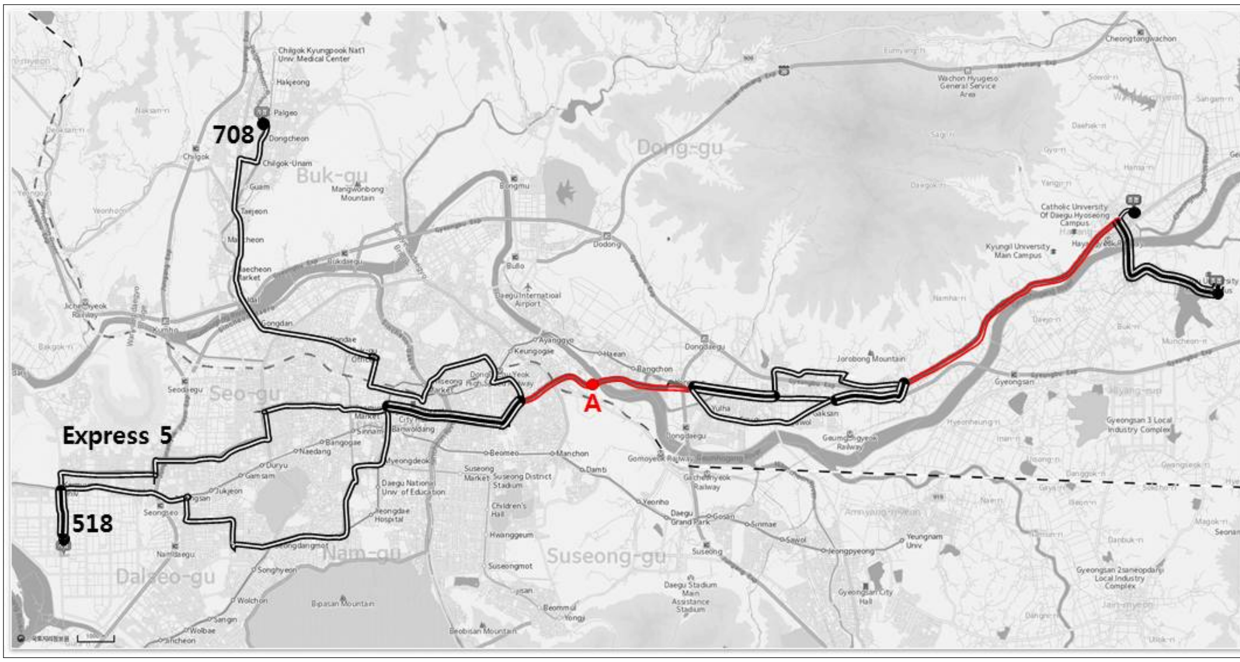

Figure 4. Map of routes 518, 708, and Express 5 in Daegu City, South Korea.

Table 4. Existing CNG bus operating environment by route.

Route	No. of buses	Operating distance [km]	Operating time [min]
518	22	39.87	128
708	13	41.98	124
Express 5	28	40.81	114

The fuel efficiencies employed to determine the internal electrical energy consumption during operation were recalculated considering the passenger and cooling/heating ratios at time t, as shown in Table 5.

Table 5. Use rate and fuel efficiency by time slot.

Time	Use rate	Fuel efficiency [km/kWh]	Time	Use rate	Fuel efficiency [km/kWh]
5:00	0.009	0.8822	14:00	0.053	0.5556
6:00	0.028	0.7722	15:00	0.062	0.4949
7:00	0.065	0.4735	16:00	0.072	0.4399
8:00	0.079	0.4071	17:00	0.077	0.4141
9:00	0.060	0.5065	18:00	0.090	0.3692
10:00	0.050	0.5821	19:00	0.060	0.5025
11:00	0.050	0.5878	20:00	0.045	0.6385
12:00	0.055	0.5458	21:00	0.047	0.6183
13:00	0.056	0.5364	22:00	0.038	0.7379

The energy consumption due to electric bus operation was calculated using Equation (5) and Table

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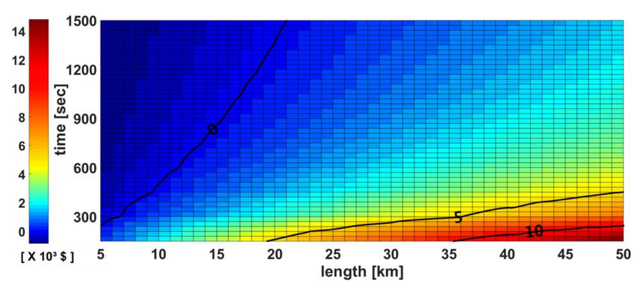
5. Economic efficiency analysis was performed by determining the energy consumption, charging time, and number of additional electric buses required according to the electric bus operating distance and headway. The cost items by bus were defined as shown in Table 5. The annual benefit of each bus due to the fare was found to be 2,880×10³ $, and the annual energy and maintenance cost savings due to electric bus operation were determined to amount to 473×10³ $. The fare in Daegu City was then calculated by reflecting the annual discount rate of 5.5%, as shown in Table 6.

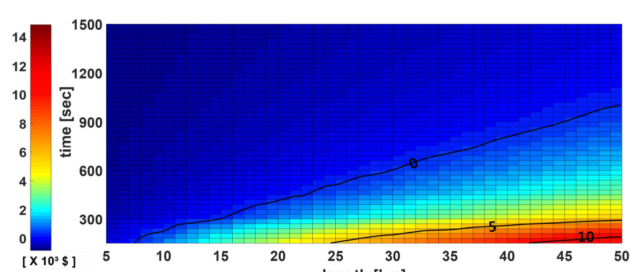
Table 6. Cost items per bus by electric bus charging type.

		CNG	Plug-in	Battery-swapping	Wireless
Vehicle cost [×10³ $]	Vehicle cost	220	450		480
	Vehicle subsidy	120	200		
	Actual vehicle purchase cost	120	250		280
Infrastructure construction cost [×10⁶ $]		7	1.10	32	4
Operating cost [$/km]	Fuel cost	0.46	0.13		
	Engine oil cost	0.01	-		
	Tire wear cost	0.01			
	Maintenance cost	0.02	0.01		

The analysis was conducted according to the driving distance and headway based on the parameters suggested Table 4, Table 5. Additional electric buses were required depending on the operating environment, and Figure 5 presents the NPV analysis results obtained considering this factor. As shown in Figure 5(d), each charging type exhibits different NPV analysis results. The charging types are not all economically efficient in operating environments in which the operating distance is short and the headway is long.



(a) Plug-in



(b) Battery-swapping

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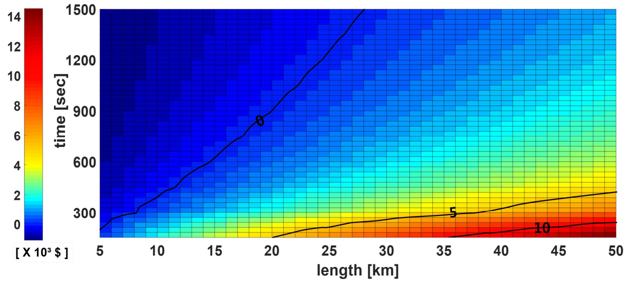
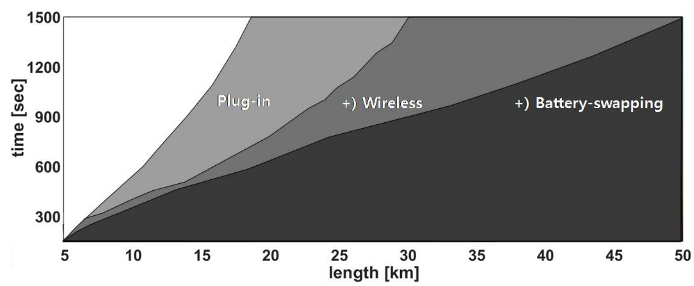


(c) Wireless

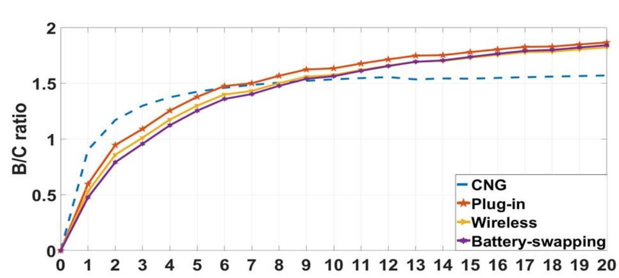


(d) Charging type depending on operating environment

Figure 5. NPV analysis according to operating distance and headway.

6.1 Economic Efficiency Analysis by Operating Route Based on Single Routes

Based on the actually operating single routes in Daegu City, South Korea, that are shown in Figure 4, the economic efficiency of electric buses was analyzed according to the operating distance and headway for each route by charging type, as shown in Figure 6. The CNT buses exhibit the highest B/C ratios initially because only the infrastructure maintenance cost was considered upon completion of infrastructure construction, unlike in the electric bus cases. However, with the total analysis period of 20 years, the economic efficiency increases in the order of plug-in, battery-swapping, and wireless vehicles for route 518. For route 708, the economic efficiency increases in the order of plug-in, wireless, and battery-swapping vehicles. For route Express 5, which has more buses and a shorter headway than route 708, the plug-in and battery-swapping vehicles show the same B/C ratio, and the wireless charging vehicles exhibit high economic efficiency. As demonstrated by the analysis results, plug-in vehicles are advantageous in operating environments with long headways, while battery-swapping vehicles are preferable in operating environments with short headways. However, the results confirm that electric buses are not economically efficient owing to the high initial infrastructure construction costs for routes with short operating distances and long headways. Therefore, the appropriate charging type differs even for the same electric bus operating environment depending on various characteristics, such as the charging time, operating distance, and initial infrastructure investment cost.



(a) Route 518

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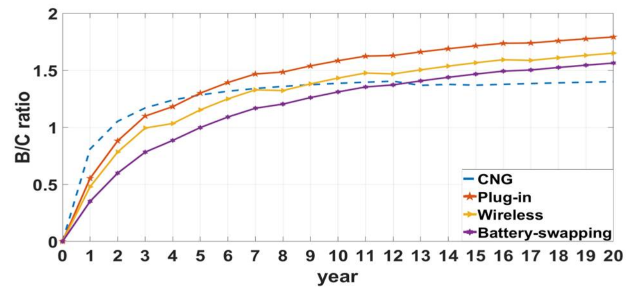
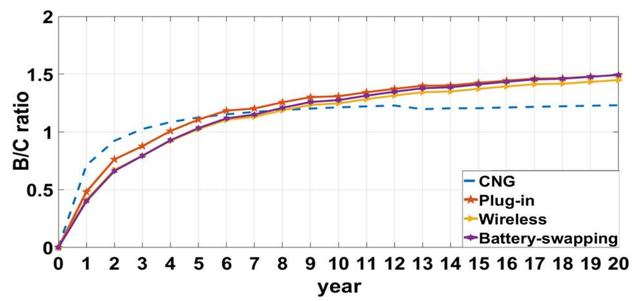


(b) Route 708



(c) Route Express 5

Figure 6. B/C ratio analysis per route.

6.2 Economic Efficiency Analysis by Operating Route Based on Composite Routes

This section presents the economic efficiency analysis conducted based on the actually operating routes in Daegu City, for all of the routes operating at stop A in Figure 4. In this case, the operating ratio is that of each route at stop A, and the characteristics of the routes operating at stop A are summarized in Table 7.

Table 7. Operating environment by existing CNG bus route at stop A.

Route	No. of buses	Operating distance [km]	Operating time [min]	Operating ratio
156	19	25.58	96	0.1188
518	22	39.87	128	0.1375
651	19	32.73	114	0.1188
708	13	41.98	124	0.0813
808	12	35.73	106	0.0750
814	29	34.10	103	0.1813
849	5	13.12	85	0.0313
Express 5	28	40.81	114	0.1750
Bukgu 3	13	24.13	90	0.0813

Using the operating ratios in Table 7, the economic efficiency of electric buses for 20 years was analyzed based on composite routes according to the operating distance and headway for each route by charging type. Figure 7 presents the results. Battery-swapping vehicles minimize the initial infrastructure construction cost because the necessary infrastructure can be installed at the intersections of the composite routes. Therefore, $32{\times}10^6$ \$, which was the initial infrastructure

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construction cost of the battery-swapping vehicles, was applied to the operating ratio of each route at stop A, and economic efficiency analysis was conducted for the composite routes. The battery-swapping vehicles exhibit the highest economic efficiency for all of the routes at stop A. However, for routes 651, 708, 808, and Bukgu 3, which have relatively lower operating ratios at stop A, the B/C ratios of the battery-swapping vehicles are not significantly different from those of the plug-in vehicles in spite of their high economic efficiency, as shown in Table 8.

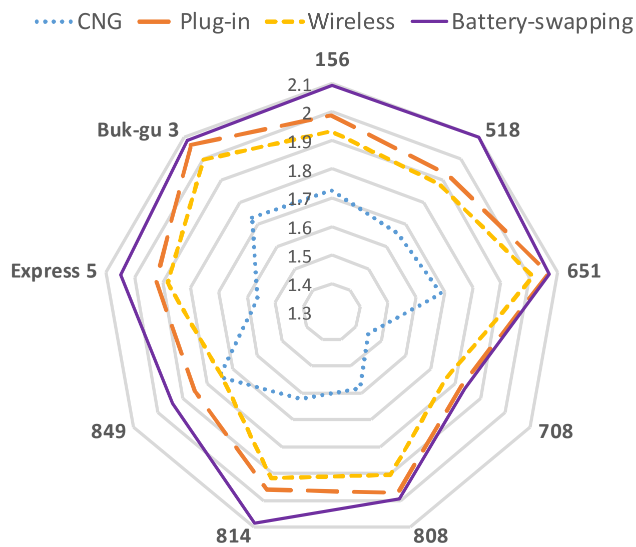

Figure 7. B/C ratio analysis by composite route.

Table 8. B/C ratio analysis by composite route.

Route	CNG	Plug-in	Wireless	Battery-swapping
156	1.7280	1.9868	1.9336	2.0914
518	1.6606	1.9308	1.8841	2.0995
651	1.6859	2.0683	2.0122	2.0730
708	1.4487	1.8204	1.7623	1.8382
808	1.5816	1.9701	1.9043	1.9934
814	1.6212	1.9612	1.9184	2.0852
849	1.7540	1.8523	1.7432	1.9428
Express 5	1.5644	1.9222	1.8802	2.0491
Bukgu 3	1.7300	2.0624	1.9946	2.0832

In this section, the economic efficiency analysis of each route by charging type is presented for single and composite routes. For the single routes, the plug-in vehicles with relatively lower initial infrastructure construction costs provided the highest economic efficiencies. However, for Express 5, which has a high operating ratio, the plug-in and battery-swapping vehicles yielded similar B/C ratios. For the composite routes, the battery-swapping vehicles provided the highest economic efficiencies for all of the routes, as determined by conducting economic efficiency analysis for 20 years, because the initial infrastructure costs could be reduced according to the operating ratio of each route by installing battery-swapping facilities at the intersections of multiple routes.

The charging type to be adopted differs depending on the operating environment of the route in question, confirming that it is necessary to consider the electric bus operation routes when designing electric bus charging infrastructure.

6. Conclusion

For the distribution of electric vehicles in the public sector, it is necessary to select appropriate charging types and develop charging infrastructure according to the operating environment. For electric buses, each charging type has different advantages and disadvantages, and the performance, battery capacity, and operating environment of electric buses are mutually related parameters that must be considered when introducing such vehicles. Accordingly, the operating environment must be accounted for to determine the optimal charging type and thereby to enable the widespread use of electric buses. Therefore, in this study, optimal charging type analysis was performed and charging infrastructure construction plans were proposed according to the public-sector electric vehicle operating environment.

The economic efficiency of each route for 20 years was analyzed, considering both single and composite routes. For the single routes, the economic efficiency increased in the order of plug-in, battery-swapping, and wireless vehicles according to the operating environment of the route. The battery-swapping vehicles provided higher economic efficiencies than the plug-in vehicles for routes with higher operating ratios. Meanwhile, for the composite routes, the initial infrastructure construction costs could be reduced according to the operating ratio of each route by installing battery-swapping facilities at the intersections of multiple routes. Accordingly, the battery-swapping vehicles yielded the highest economic efficiencies for the composite routes. Therefore, the appropriate charging type differed even for the same electric bus operating environment depending on characteristics such as the charging time, operating distance, and initial infrastructure investment cost.

In the future, additional analysis of charging infrastructure construction plans according to the operating environments of public-sector electric vehicles as well as analysis of the influences of the power system and stabilization strategy are expected to contribute to the stable operation and popularization of electric vehicles.

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