sustainability

Review

A Feasibility Test on Adopting Electric Vehicles to Serve as Taxis in Daejeon Metropolitan City of South Korea

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Abstract: For realizing sustainable development, EV (Electric Vehicle) is currently considered as one of the most promising alternative due to its cleanness and inexhaustibility. However, the development and dissemination of EV has stagnated because it faces major constraints such as battery performance and an excessively long charging time. Thus, this study examined the feasibility of using EVs as taxis by analyzing real data from a pilot project in Daejeon, a metropolitan city in South Korea for proposing the effective way to adopt EV. To reflect reality and improve accuracy, we adopted scenarios and assumptions based on in-depth interviews with groups of experts. The resulting initial benefit-to-cost (B/C) ratio for EV taxis is approximately 0.4, which is quite low compared to 0.7 for traditional taxis. However, after incorporating some further assumptions into the calculation, the B/C ratio shifts to approximately 0.7, which is more appropriate for EV adoption. For this improvement to be achieved, the dissemination of a charging infrastructure, improvement of the business model and policy support is strongly needed. Limitations to this work and potential areas for future study are also fully discussed.

Keywords: electric vehicle; EV taxi; B/C analysis; feasibility test; sustainability

1. Introduction

Given environmental pollution, carbon dioxide emissions, and the energy crisis, a worldwide effort is being made to shift toward sustainable growth [1,2]. Given the currently extensive production and operation of automobiles and the correspondingly heavy consumption of fossil fuel and emissions of pollutants, concern has arisen regarding the need for a clean and sustainable fuel supply. In particular, there are many issues related to the limited fossil-based fuel supply [3] and its negative impact on the environment through the heavy emission of greenhouse gases, especially CO_2 [4,5]. To alleviate the chronic problems created by automobiles, governments have set rules to reduce greenhouse gas emissions, and automobile manufacturers have developed many alternatives to the internal-combustion engine [6] for automobiles including various hybrid and electric motors [7]. Although the internal-combustion engine automobile is still dominant, the number of hybrid and electric vehicles is growing, with more developed countries such as the US, Japan, China and Europe taking the lead in this growth [8–10].

Since the first EV (Electric Vehicle) sale of a Nissan Leaf in December 2010, the sales and interest in EVs has steadily increased. Currently, approximately 15 million barrels of oil are combusted in the US every day, and two thirds of them represent automobile fuel [11], which explains why the US and other countries are trying to manufacture effective EVs. EVs are well known for being eco-friendly [12,13] and economic, but they have several disadvantages such as requiring charging stations, long charging times, small vehicle size and anxiety about their range [3,14,15].

Disadvantages such as long charging times and range anxiety could be crucial hindrances to commercializing EVs [16]: EVs require almost an hour to charge completely and can run for only 100~150 km when fully charged. These disadvantages are technical matters and are expected to improve in the future. Meanwhile, for EVs to become commercialized, users need to become more familiar with them, as many people consider EVs to be less efficient and less convenient despite their prominent advantages [17]. Therefore, it could be advisable to supply EVs as public vehicles such as taxis in addition to private usage. In particular, taxi service can potentially maximize the efficiency of the EV while managing its vulnerable points. For example, despite long hours of operation, taxis inevitably experience periods where the vehicle is empty and regular stoppages for the driver's meals, and the operational distance for each passenger tends to be short.

The purpose of this study is to evaluate whether it is economically feasible for taxis to be substituted by EVs by applying economic analysis to data obtained from an actual test. This test put three EV taxis into operation for five months (October to February) to capture and verify conditions such as seasonal variations that might drive differences in feasibility. A feasibility test is applied to determine whether this system (switching taxis to EVs) is economically or practically feasible [18], and thus this study aims to determine whether EV taxis could be feasible in the very near future.

The concept of the EV emerged nearly a half century ago, but commercialization took place only a half-decade ago. Consequently, many previous studies address the technical aspects of EVs, but far fewer cover the commercialization or feasibility of EVs. This study on the feasibility of using EVs as taxis is essentially a pioneering piece of work.

2. Literature Review

2.1. Electric Vehicles

A vehicle's influence on the environment depends on its source of energy [19]. Land vehicles heavily depend on oil, potentially driving a shortage of crude oil in the foreseeable future [20–23]. The energy uses for transport have expanded, leading to problems in energy security and environmental sustainability [24]. As a result, people are looking for solutions for several different problems and consider the EV to be one of the most optimized alternatives [25]. Though EVs still face technological and economic barriers [26–30], they can reduce dependency on fossil fuel and create opportunities to decrease greenhouse gas emissions from the transportation sector [31,32]. Furthermore, the running cost for EVs is projected to drop by approximately 75% by 2030 [33]. Other significant strengths of EVs compared with internal combustion engine vehicles have also been studied by researchers [6,34].

EVs have been introduced into the public market and are expected to contribute to the mitigation of traditional fuel consumption [24] with the help of a variety of political supports [35–37]. Because the introduction of EV taxis is a mainstream political strategy for mitigating environmental impacts, almost all automakers are interested in EVs and in developing vehicles using new technologies [38,39]. An effective and practical public transportation system is highly necessary for economic and environmental growth [22,40]. In addition, EVs, including EV taxis, can be an economically feasible option for mitigating carbon emissions if their batteries are charged with electricity generated through low carbon systems, such as renewable energy [24].

2.2. Electric Vehicle Taxis

To fulfill public needs, various countries have adopted EVs as taxis in local provinces [41]. Compared to the US and the EU, East Asian countries have more actively introduced and expanded the use of EVs due to sustainability issues such as the Fukushima accident, environmental pollution and over dependency on fossil fuel. The Chinese government is executing one of the most active and aggressive action plans, with major subsidies and regulations to adopt EV taxis and expand their use. In particular, the Chinese government is strongly encouraging local governments to buy local brand

EVs [42], which are mostly produced by BYD [43]. In the case of Shenzhen, the local government is already operating hundreds of BYD's EV taxis in the city [44]. Since 2010, 800 EV taxis have been adopted among the city's 12,000 taxis. The Chinese government's energy policy does not levy fuel surcharges on EV taxis; thus, EV taxis in Shenzhen have the highest earning rate among all EV taxis worldwide. Hong Kong, Beijing and Shanghai have also adopted and expanded the use of EV taxis since 2012, and many local governments of mid-sized cities also plan to introduce EV taxis [45].

The Japanese government has also executed various EV taxi projects in different cities. Unlike the Chinese government, Japan's local governments have mostly focused on underprivileged residents such as senior citizens, rural citizens, and disabled citizens and have offered substantial subsidies along with strict regulations. Moreover, to successfully adopt EV taxis and expand their use, the Japanese government has also focused on developing its business model. In Nagasaki and Kanagawa, the local government is adopting EV taxis in rental car and car sharing businesses. At the same time, they also provide special parking places and subsidies for EVs. Furthermore, local governments have launched tourist-oriented EV taxi services in some sightseeing areas. Most Japanese EV taxis are Nissan's Leaf [46].

In South Korea, Daejeon, Jeju Province and Seoul have prepared for the commercialization of EV taxi services. A pilot test of EV taxis in Daejeon City was launched on 6 September 2013, and three EVs made by Renault-Samsung Motors, all SM3 ZEs, were adopted. This is the first empirical study on electric taxis in South Korea that analyzes their economic feasibility prior to an actual introduction. Based on the results of this research on economic and technological feasibility, Daejeon City planned to replace approximately 500 internal combustion engine taxis with EV taxis in 2014 [47]. Jeju Province is also pushing forward an EV taxi project. The provincial office and Jeju Electric Automobile Services, who offer charging infrastructure, also plan to conduct an economic feasibility study based on three to ten SM3 ZEs. Given the transportation circumstances of Jeju, the provincial office is also planning to build charging stations in some major locations such as Jeju City and Seoguipo City [48]. EV taxis were first seen in Seoul two years ago, when the city government started a trial run involving 10 electric taxis. In addition, starting in 2013, buyers of EVs have received subsidies of as much as 50 percent of the price difference from an internal combustion engine vehicle [37]. Beyond China, Japan and Korea, New York City, United States; Barcelona, Spain; London, UK; and Montreal, Canada have tried to adopt EV taxis starting with pilot projects. However, these attempted expansions have not been very successful. Details are shown in Table 1.

Table 1. Worldwide Electric Vehicle Taxi cases.

Country	**City**	**Details**
United States	New York	4 Nissan Leaf EV taxis operated during April 2013–March 2014 NYC government planned to replace 1/3 of yellow cab with EV
China	Shenzhen	Local government has adopted 800 BYD e6 as EV taxis since 2010 216 charging stations have been established (1 for 4 taxis) 2–3 charges were needed per day
	Hong Kong	45 BYD e6 were adopted as EV taxis Pilot project period: May 2013–November 2013 9 charging stations and 47 charging machines have been installed
Japan	Kanagawa	35 Nissan Leaf were adopted as EV since December 2011 22 taxi companies operated the pilot project
	Osaka	50 Nissan Leaf were adopted as EV taxi since 2011
South Korea	Jeju	SM3 ze was adopted during March 2013–March 2014 Local government has placed the highest subsidy to EV taxis
	Soeul	40 SM3 ze were adopted as EV taxis Project period: May 2015–September 2015
	Daejeon	3 SM3 ze were adopted as EV taxis during September 2013–May 2014

3. Data Collection and Methodology

In our research, we ran 3 fully electric powered vehicles as taxis from September 2013 to March 2014 to collect benefit and cost data. Each taxi corporation recommended and selected 2 skilled drivers for each EV, thus, 6 drivers were hired to drive three EVs. During this period, the data were directly collected from cars, charging stations, and taxi operators via wireless network devices and regular meetings. To check the operation status of EV Taxi, we equipped CAN network device for real-time monitoring of EV's operation status to make sure that EV taxi is constantly moving around city without any malfunction. For collecting data from charging machine properly, each taxi corporation checked the charging machine every day for proper operation. In addition, we visited three charging machines to collect the data biweekly. The charging machine manufacturers regularly visited the charging machine for inspection. No charging machine broke down during the whole project period. Lastly, to gather the operation profit data and meaningful qualitative data from taxi operators, we have visited every taxi corporation biweekly. Each meeting lasted for 2–3 h, during our visits, we have discussed about the business profit pattern and characteristics with taxi operators. Furthermore, we interviewed with taxi drivers and asked them about the problems of driving/operating, when and how they go back for charging, feedback from customers and all of the suggestions and meaningful facts.

After collecting all of relative data, we performed feasibility tests (benefit-to-cost analysis) and a comparison analysis against an LPG (Liquefied Petroleum Gas) taxi (one to one analysis) that was being used in Daejeon Metropolitan City as a public taxi. Some scenario analyses and assumptions are included in the feasibility test. For conducting the reality-reflecting B/C analysis, we adopted the variables and scenarios after getting confirmation by different groups of experts, and only took factors that actually planned to be improved or introduced in the future pilot project.

3.1. Profile of Electric Vehicles and Charging Machines

A total of 3 fully electric powered vehicles, SM3 ZEs from Renault Samsung Motors, and 3 high-speed charging machines from Joong Ang Control, JC 6331s, were used to conduct the entire experiment during our research. The fully-charged mileage of SM3 Ze is 123 km and the charging time of JC 6331s is 40 min. A detailed functional diagram of the car, the charging machine and the car components are shown in Figure 1.

(**a**) (**b**)

Figure 1. Functional diagram of Electric Vehicle and charging machine: (**a**) 1. Electric Vehicle: SM3 ZE, 2. Standard Charging Cable, 3. Charging Machine: JC 6331; and (**b**) 1. Electric Motor, 2. 12 V supplementary Battery, 3. Charging Inlet, 4. High Voltage Cable, 5. 400 V Traction Battery [47].

3.2. Vehicle Data

To monitor the EV status, we installed a wireless data collecting device on the EV taxis. As the taxis moved around the city, the device automatically sent all performance and operational data for the vehicle to a hard drive on the web. Processing the raw data from the web hard drive gave us reliable data that we could use for the feasibility test. The CAN network was sending the information about the on/off status of engine, air conditioner/heater, whether passenger was seated or not. The collected data and the process are shown in Figure 2.

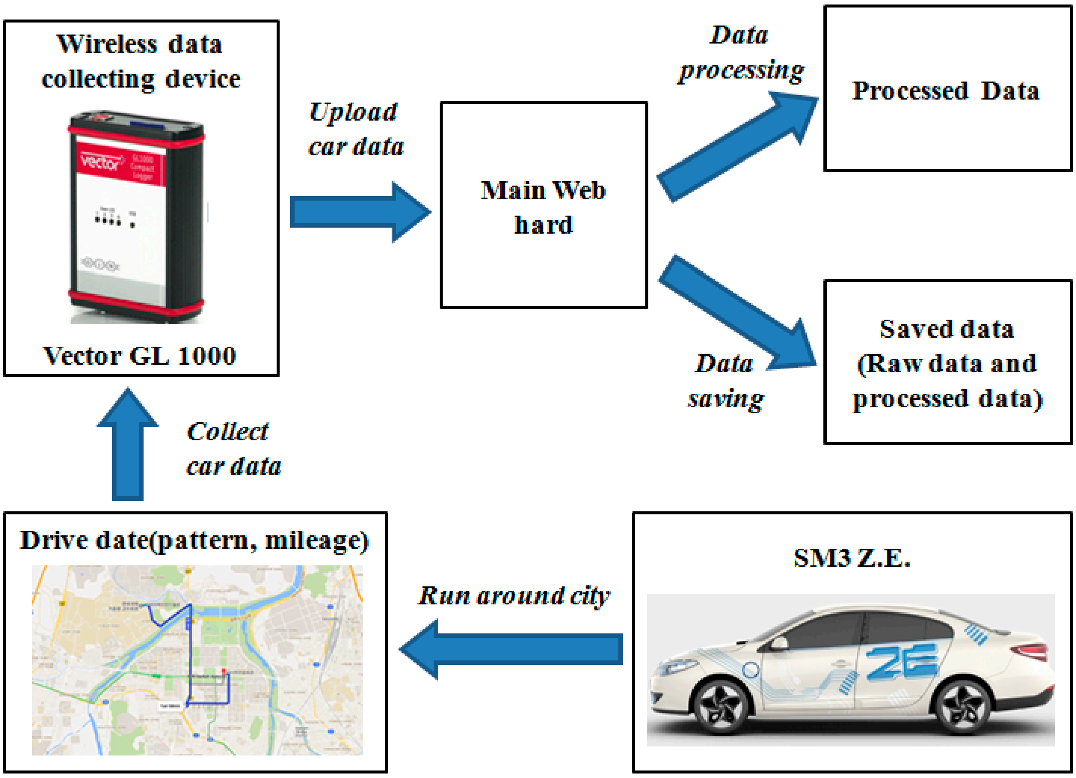

Figure 2. Process of vehicle data collection.

3.3. Charging Infrastructure Data

One of the most significant cost variables is fuel. Compared to LPG taxis, electricity is the only fuel for an EV taxi, which is why EV has the most competitive promise: low fuel cost and high environmental performance. As shown in Figure 2, we visited every charging station, logged in with a password, and extracted and saved the data biweekly. Data include charging time, charging period, and charging fee about each taxi. We have double checked if there were some errors in charging or price information. The errors were rarely discovered because the charging machine is EV exclusive and managed by taxi corporations every day.

3.4. Business Profit

For the benefits, the most important and significant variable is business profit. To collect an accurate and reliable business profit, we received a daily revenue report for each taxi by e-mail and contrast the report to original one by visiting the taxi operators regularly. The information included in business report were overall cruising distance, cruising distance with passenger and without passenger, total fuel usage, maximum speed, time of passenger get in and get out, operating distance, revenue and so on. Moreover, while collecting empirical data, we also collected qualitative data such as any driving inconveniences and customer comments by interviewing the taxi drivers biweekly. Some unexpected scenarios such as "receiving tips" and "run offs" without paying were not included in the B/C analysis because they never happened during the whole pilot period.

3.5. Benefit-to-Cost Analysis of EV

To examine EV taxis' economic feasibility, we adopted a B/C ratio analysis because it is the most reliable method for analyzing the feasibility of new products and technologies. We primarily used the NPV (net present value) to calculate the benefit and cost data for the vehicles and infrastructure and to conduct the feasibility test. The benefit data consist of business profit, government EV purchase subsidy, and sensitivity factors (business model, policy support, operational patterns). The cost data consist of production costs including personnel, fuel cost, O&M (operations and maintenance) costs, depreciation, maintenance fees, and general costs including insurance and taxes.

A benefit-to-cost analysis examines the ratio of the total discounted benefits and costs and provides a comparison between the two. The calculated value is usually referred to prior to an investment decision.

$$\frac{B}{C} = \frac{\sum_{t=0}^{n} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}} \tag{1}$$

where B_t is the benefit in year t, C_t is the cost in year t, r is the discount ratio, and n is the project duration. The benefit-to-cost analysis was conducted by summing the costs and benefits of EV taxis and current LPG taxis over an operating lifespan of 6 years. We set t at 6 years after in-depth meetings with groups of experts, who determined that 6 years is the appropriate parameter to determine the feasibility of introducing EV taxis. Using a discount rate of 5%, the NPV of the sums was calculated. The NPV for current LPG taxis was subtracted from the NPV of EV taxis to show the final result of the benefit-to-cost analysis. The formulation is shown below:

$$\text{NPV} = \sum \frac{B_{er} + B_{ee} - \left(C_{ept} + C_{epb} + C_{eb} + C_{eo} + C_{ee}\right)}{(1+r)^n} - \sum \frac{B_{lr} - \left(C_{lp} + C_{lf}\right)}{(1+r)^n}, \tag{2}$$

where B_{er} is the fare revenue per EV taxi, B_{ee} is the environmental benefit of an EV taxi, C_{ept} is the purchasing cost of an EV taxi, C_{epb} is the purchasing cost of a batteries during the 6 years of operation per EV taxi, C_{eb} is the charging station construction cost per EV taxi, C_{eo} is the charging station operation cost per EV taxi, C_{ee} is the electricity cost per EV taxi, B_{lr} is the fare revenue per LPG taxi, C_{lp} is the purchasing cost of an LPG taxi, and C_{lf} is the fuel cost per LPG taxi.

By reference to "Final Report: Taxi fares standard shipping cost calculation and verification (2012)", the cost structure and criteria of LPG taxis were calculated. The shipping cost is calculated as costs, general and administrative expenses and other expenses are shown in the Table 2.

We used the same expense category as used for LPG taxis to analyze the cost structure of EV taxis. We analyzed the transportation cost data based on the "2011 Financial Statements", and the following parameters were applied to the real costs. The cost increase of four main insurances is also reflected. In addition, we also analyzed operation record based on "Taco running papers", which are written by taxi companies. The main items included mileage, sales distance, operating frequency, operating hours, total driving hours, and transportation receipts. Since transportation costs can be different depending on the purpose of the report and characteristics of taxi companies, we followed a custom in both LPG and EV taxi payment.

If there was no significant difference between an item for LPG taxis shown in Table 3 and the same item for EV taxis shown in Table 4, we used the identical cost. Additionally, the inflation rate was assumed at 3.2% in this study.

Table 2. Standard for Cost and Benefit of LPG (Liquefied Petroleum Gas) Taxi.

Main	Division	Sub	Method to Calculate
1. Personnel Expenses	Direct	Driver Maintenance	Average of drivers belonging to 22 taxi companies.
	Indirect	Administrative	
2. Welfare Expenses	Direct Legal/Other Welfare Indirect Legal/Other Welfare		Legal Welfare: Premium rate of 4 main insurances Other Welfare: Actual amount of money in financial statements
3. Fuel Expenses	LPG Expenses Other Oil Expenses		Based on applied amount of subsidized fuel by 22 taxi companies
4. Tire Expenses	New Tire		Actual amount of money in financial statements
5. Maintenance	Parts and Outsourcing Repair Cost		Actual amount of money in financial statements
6. Vehicle Insurance	Liability Insurance		Actual amount of money in financial statements
7. Depreciation	Vehicle Depreciation		Vehicle pricing and fixed installment method for taxis of 22 companies
8. Accident Compensation	Accident Compensation		Actual amount of money in financial statements
9. Other Expenses	Other Expenses		Actual amount of money in financial statements
10. Reasonable Profit	Based on rule of law article 8, calculated it as 10% of value added. Arithmetic expression: [Direct Cost + General Management Expenses − External Value Creation] × 10%		

Table 3. Cost of LPG taxi.

Year	Transportation Cost							General Management Expenses					Total
	Fuel Expenses	Personnel	Welfare	Vehicle	Depreciation Cost	Vehicle	Accident	Personnel	Welfare	Taxes	Other	Reasonable	
2014	14,294	37,658	2681	1720	2833	3944	113	3639	500	871	2143	6042	76,438
2015	14,751	38,863	2767	1776	2833	4070	117	3755	517	899	2212	6226	78,786
2016	15,223	40,106	2856	1832	2833	4201	121	3876	533	927	2282	6415	81,205
2017	15,710	41,390	2947	1891	2833	4335	125	4000	550	957	2355	6610	83,703
2018	16,213	42,714	3041	1952	2834	4474	129	4128	568	988	2431	6812	86,284
2019	16,732	44,081	3139	2014	2834	4617	133	4260	586	1019	2509	7020	88,944
Total	92,923	244,812	17,431	11,185	17,000	25,641	738	23,658	3254	5661	13,932	39,125	495,360

Table 4. Cost of EV taxi.

Cost Type		EV Taxi Cost Standard
Transportation Cost	Fuel Expenses	Average of real collected data from September 2013 to February 2014
	Personnel Expenses	Equal to criteria of LPG taxi
	Welfare Expenses	Equal to criteria of LPG taxi
	Maintenance	113% of cost of LPG taxi ※ Given the price gap between EV and LPG taxis
	Depreciation Cost	1 Cycle Cost based on Price of EV (Renault SM3 ZE)
	Vehicle Insurance	113% of cost of LPG taxi
	Accident Compensation	113% of cost of LPG taxi
General Management Expenses	Personnel Expenses	Equal to criteria of LPG taxi
	Welfare Expenses	Equal to criteria of LPG taxi
	Taxes and Public Utilities Charge Expenses	Equal to criteria of LPG taxi
	Battery Expenses	Given the price of EV (Renault SM3 ZE) 2013
	Other Expenses	Equal to criteria of LPG taxi
	Reasonable Profit	Equal to criteria of LPG taxi
Investment Cost	Charger Installation	Given the price of EV Charger made by JOAS

As shown in Table 5, an EV taxi's operating income is an average daily income of $97.2 multiplied by 304 business days. Taxi fares reflected a rate increase of 17.86 percent after 2017.

Table 5. Income Structure of EV.

Year	Operating Income	Non-Operating Income					Total
		Acquisition Tax	Public Bond	Subsidy (Ministry of Environment)	Subsidy (Local Government)	Subtotal	
2014	29,554	755	340	15,000	5000	21,095	50,649
2015	29,554	-	-	-	-	-	29,554
2016	29,554	-	-	-	-	-	29,554
2017	34,832	-	-	-	-	-	34,832
2018	34,832	-	-	-	-	-	34,832
2019	34,832	-	-	-	-	-	34,832
Total	193,158	755	340	15,000	5000	21,095	214,252

3.6. Scenario analysis of EV

Because this pilot project has many inescapable limitations, we have conducted a few different scenarios to better capture reality. We analyzed three different scenarios: the best, most likely and worst scenarios. For accuracy, we conducted in-depth interviews with groups of EV experts, charging machine experts, taxi corporation experts, transportation policy experts, and business model experts. During the interviews, we asked the different expert groups which factors would improve and how much performance would improve if EV taxis entered the diffusion stage of technological development. According to the results of these in-depth interviews, we were able to calculate a mean value for the possible percentage change in each factor.

4. Results

We used the benefit-to-cost analysis for the economic feasibility analysis. Given the many potential variables for environmental changes, we established a scenario and analyzed the economic feasibility case by case. We used pricing scenarios for the cost parameters, including changes in fuel cost, price and performance changes for EVs and batteries, etc. In addition, we used several possible policies and tax benefits, such as subsidies for vehicles and chargers, as variables on the benefit side. The details for the options are shown in Table 6.

The operating revenue of the EV taxis was calculated by multiplying the number of annual working days (304 days) and $97.2 daily average revenue over the time period of the demonstration. The annual operating revenue is $29,549. Given the cycle of the taxi fare changes, the values reflect a 17.86% fare hike after 2017. We try to reflect non-operating income in accordance with acquisitions and bonds, ministry subsidies for vehicle purchase, and Daejeon subsidies for vehicle purchase; central government policies were analyzed according to the selected scenario. At first, we tried to analyze 24 scenarios using four categories (2 × 2 × 3 × 2). However, in accordance with expert group interview, we picked out only the plausible cases. Assuming that the current policy is continued, we considered B06 to be the most likely among the 12 cases that were plausible. On the cost side, based on the options by scenario given in Table 6, we established 24 different cost cases for analysis considering the number of chargers per car, battery replacement during operations and price changes for different elements. Overall, 12 × 24 = 288 cases were analyzed in the research. The calculated benefits and costs are shown in Tables 7 and 8, respectively.

The analysis of the B/C ratio on a case-by-case basis for EV taxis as shown in Table 9 provides an average of 0.42, which is much lower than the LPG taxis' average of 0.72. This value is calculated by applying the average of the daily income and collected fuel expenses. Therefore, this result could differ slightly depending on the driving distance and a seasonal mileage gap. Indeed, among the 21 weeks of the research period, a period of rapidly increasing energy consumption when air temperature was below 12 °C accounts for approximately 70% of the total period. Therefore, the actual fuel expenses could be expected to decrease.

Because the B/C ratio analysis was based on the only dataset collected, the actual result is considered to be more conservative than the actual costs and benefits when the dissemination of EV taxis is completed. As many engineers, manufacturers, policy makers, and taxi drivers implied that there were so many inevitable constraints during the pilot operating and some factors will be improved very soon in the next pilot operating. Thus, we conducted numerous in-depth interviews and surveys with a group of experts consisting of EV manufacturers, battery engineers, charger engineers, representatives from a taxi driver association, and the transportation division of the Daejeon Metropolitan City government for reflecting the reality. We designed several steps for eliciting the expert knowledge efficiently. Firstly, we conducted open structured pilot survey before the real survey to determine the accurate components to improve the experiment. In our pilot session, we asked expert groups which parts and how much of an EV's benefit/cost ratio will increase or decrease if they are operating in real conditions, and the respondents were allowed to answer without any scale. As a result, none of them suggested more than 50% of improvement, and no one suggested the cost of EV will increase in the future stage which means the bottom limit is bigger than zero. In line with this result, we were able to set the range from 0% to 50%, respectively. Secondly, we adopted the Likert scale to make the options into 0%, 10%, 20%, 30%, 40% and 50% for simplicity and clarity. Lastly, after our second survey with expert group has completed, we conducted the interviews with the experts for reviewing and checking the final result thoroughly. We held two symposiums and three briefing sessions to complete the surveys and in-depth interviews with expert groups, and spend more than 60 h on in-depth interviews with expert groups totally. The details of expert groups are listed in Table 10.

Table 6. Option by scenario (unit: dollar).

Cases	Charger		Battery Replacement		Vehicle Price		Fuel Expenses
	EV Distribution	Installation Subsidy	Replacement Cycle	Price Change	Governmental Subsidy	Local Subsidy	
Best	8550 (4 EVs)	6550 ($8000) 8550 (current standard)	13,800 (once)	-	26,500 ($15,000)	21,500 ($5000)	7729 (10% reduction)
Most-likely	34,200 (1 EV)	26,200 ($8000) 34,200 (current standard)	27,600 (twice)	9660 (30% ↓) 12,700 (10% ↓) 13,800 (current standard)	31,500 ($10,000)	26,500 ($5000)	8588 (current standard)
Worst	-	- - -	41,400 (three times)	22,360 (30% ↓) 25,400 (10% ↓) 27,600 (current standard)	41,500 (no subsidy)	41,500 (no subsidy)	9447 (10% increase)

Table 7. Calculated Benefit of EV taxi (unit: dollar).

Case	Operating Income	Non-Operating Income					Total
		Acquisition Tax	Public Bond	Subsidy (Ministry of Environment)	Subsidy (Local Government)	Subtotal	
B01	193,158	755	340	15,000	-	16,095	209,253
B02	193,158	755	340	-	-	1095	194,253
B03	193,158	-	-	15,000	-	15,000	208,158
B04	193,158	755	340	10,000	-	11,095	204,253
B05	193,158	-	-	10,000	-	10,000	203,158
B06	193,158	755	340	15,000	5000	21,095	214,253
B07	193,158	-	-	15,000	5000	20,000	213,158
B08	193,158	755	340	10,000	5000	16,095	209,253
B09	193,158	755	340	-	5000	6095	199,253
B10	193,158	-	-	10,000	5000	15,000	208,158
B11	193,158	-	-	-	5000	5000	198,158
B12	193,158	-	-	-	-	-	193,158

Table 8. Calculated Cost of EV taxi (unit: dollar).

Case	Condition			Total Cost	Compare to LPG Taxi
LPG	Total Cost of LPG taxi (1 cycle)			495,360	
C01	One Charger per 1 EV taxi	Battery Replacement: Once	General	489,859	−5402
C02			Twice Electric Charge	498,543	3183
C03			90% Battery Price	488,748	−6612
C04			Charger Subsidy	481,958	−13,402
C05		Battery Replacement: Twice	General	505,138	9778
C06			Twice Electric Charge	513,723	18,363
C07			90% Battery Price	502,719	7359
C08			Charger Subsidy	497,138	1778
C09		Battery Replacement: Three times	General	520,318	24,958
C10			Twice Electric Charge	528,904	33,544
C11			90% Battery Price	517,899	22,539
C12			Charger Subsidy	512,319	16,959
C13	One Charger per 4 EV taxis	Battery Replacement: Once	General	464,308	−31,052
C14			Twice Electric Charge	472,893	−22,467
C15			90% Battery Price	463,098	−32,262
C16			Charger Subsidy	462,308	−33,052
C17		Battery Replacement: Twice	General	479,488	−15,872
C18			Twice Electric Charge	488,073	−7287
C19			90% Battery Price	477,069	−18,291
C20			Charger Subsidy	277,488	−17,872
C21		Battery Replacement: Three times	General	494,668	−692
C22			Twice Electric Charge	503,254	7894
C23			90% Battery Price	492,249	−3111
C24			Charger Subsidy	492,669	−2691

Table 9. Calculated B/C Ratio of EV taxi (unit: dollar).

Case	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12	Average
C01	0.43	0.40	0.42	0.42	0.41	0.44	0.44	0.43	0.41	0.42	0.40	0.39	0.42
C02	0.42	0.39	0.42	0.41	0.41	0.43	0.43	0.42	0.40	0.42	0.40	0.39	0.41
C03	0.43	0.40	0.43	0.42	0.42	0.44	0.44	0.43	0.41	0.43	0.41	0.40	0.42
C04	0.43	0.40	0.43	0.42	0.42	0.44	0.44	0.43	0.41	0.43	0.41	0.40	0.42
C05	0.41	0.38	0.41	0.40	0.40	0.42	0.42	0.41	0.39	0.41	0.39	0.38	0.40
C06	0.41	0.38	0.41	0.40	0.40	0.42	0.41	0.41	0.39	0.41	0.39	0.38	0.40
C07	0.42	0.39	0.41	0.41	0.40	0.43	0.42	0.42	0.40	0.41	0.39	0.38	0.41
C08	0.42	0.39	0.42	0.41	0.41	0.43	0.43	0.42	0.40	0.42	0.40	0.39	0.41
C09	0.40	0.37	0.40	0.39	0.39	0.41	0.41	0.40	0.38	0.40	0.38	0.37	0.39
C10	0.40	0.37	0.39	0.39	0.38	0.41	0.40	0.40	0.38	0.39	0.37	0.37	0.39
C11	0.40	0.38	0.40	0.39	0.39	0.41	0.41	0.40	0.38	0.40	0.38	0.37	0.39
C12	0.41	0.38	0.41	0.40	0.40	0.42	0.42	0.41	0.39	0.41	0.39	0.38	0.40
C13	0.45	0.42	0.45	0.44	0.44	0.46	0.46	0.45	0.43	0.45	0.43	0.42	0.44
C14	0.44	0.41	0.44	0.43	0.43	0.45	0.45	0.44	0.42	0.44	0.42	0.41	0.43
C15	0.45	0.42	0.45	0.44	0.44	0.46	0.46	0.45	0.43	0.45	0.43	0.42	0.44
C16	0.45	0.42	0.45	0.44	0.44	0.46	0.46	0.45	0.43	0.45	0.43	0.42	0.44
C17	0.44	0.41	0.43	0.43	0.42	0.45	0.44	0.44	0.42	0.43	0.41	0.40	0.43
C18	0.43	0.40	0.43	0.42	0.42	0.44	0.44	0.43	0.41	0.43	0.41	0.40	0.42
C19	0.44	0.41	0.44	0.43	0.43	0.45	0.45	0.44	0.42	0.44	0.42	0.40	0.43
C20	0.44	0.41	0.44	0.43	0.43	0.45	0.45	0.44	0.42	0.44	0.42	0.40	0.43
C21	0.42	0.39	0.42	0.41	0.41	0.43	0.43	0.42	0.40	0.42	0.40	0.39	0.41
C22	0.42	0.39	0.41	0.41	0.40	0.43	0.42	0.42	0.40	0.41	0.39	0.38	0.41
C23	0.43	0.39	0.42	0.41	0.41	0.44	0.43	0.43	0.40	0.42	0.40	0.39	0.42
C24	0.42	0.39	0.42	0.41	0.41	0.43	0.43	0.42	0.40	0.42	0.40	0.39	0.42
Avg	0.43	0.39	0.42	0.42	0.41	0.44	0.43	0.43	0.40	0.42	0.40	0.39	0.42

Table 10. Details of expert groups.

	Name	Institution	Position
1	Song Eung Seok	Renault Samsung Motors, EV Program	Program Director
2	Lee Sang Tae	Renault Samsung Motors, EV Program	Department Head
3	Yoo Dong Hun	Renault Samsung Motors, EV Operation	Department Head
4	Lee Jong Guk	Renault Samsung Motors, EV Operation	Department Head
5	Yoon Ye Won	Renault Samsung Motors, Quality Control	Senior Researcher
6	Gang Chang Yeb	Renault Samsung Motors, EV Marketing	Senior Researcher
7	Jeong Tae Young	Jong Ang Control/Headquarter	Part Director
8	Kim Sung Tae	Daejeon Taxi Association	Chairman
9	Jang munsuk	Dong San Wun Soo Taxi Corporation	Director
10	Lee Chul Min	Dong San Wun Soo Taxi Corporation	Department Head
11	Heo Yeong Soo	Yoo Jin Taxi Corporation	Director
12	Jeon Young Kil	Yoo Jin Taxi Corporation	Department Head
13	Han Sang Hun	Bo Sung Taxi Corporation	Director
14	Jo Hyun Min	Bo Sung Taxi Corporation	Department Head
15	Yoo Se Jong	Daejeon Metropolitan City Government	Department Head
16	Min Dong Hee	Daejeon Metropolitan City Government	Senior Officer
17	Kim Dae Joon	Daejeon Metropolitan City Government	Senior Officer
18	Kim Jeong Hong	Daejeon Metropolitan City Government	Senior Officer
19	Song Chi Young	Daejeon Metropolitan City Government	Senior Officer
20	Yoo Hea Geum	Daejeon Metropolitan City Government	Senior Researcher
21	Han Dae Hee	Daejeon Metropolitan City Government	Senior Researcher
22	Keum Dong Suk	KAIST, Green Transportation	Professor
23	Ye Hwa Soo	KAIST, Green Transportation	Professor
24	Paulo Filho	KAIST, Green Transportation	Senior Researcher
25	Kang Min Gook	KAIST, Green Transportation	Senior Researcher
26	Oh Sae Chul	Korea Environment Corporation	Department Head
27	Jeong Won Sun	Korea Automotive Technology Institute	Department Head
28	Park Kyung Lin	Jeju National University	Professor
29	Park Kuang Chil	Ministry of Environment	Senior Officer
30	Shim Ji Young	Ministry of Land and Transportation	Senior Officer
31	Lim Kuen Hee	Korea Electro technology Institute	Department Head
32	Hwang In Seong	Korea Electronics Technology Institute	Researcher
33	Hwang Sang Kyu	The Korea Transport Institute	Department Head
34	Kim Kyu Ok	The Korea Transport Institute	Senior Researcher
35	Choi Jea Hyuk	Hyundai Mobis	Senior Researcher
36	Choi Ho Jeong	Hyundai Motor	Senior Researcher
37	Kim Yoon Suk	Hyundai Motor	Senior Researcher
38	Son Byung Joon	LG Electronics	Senior Researcher
39	Lim Yoo Shin	Samsung Electronics	Senior Researcher
40	Kim Kyung Bae	Transportation Newspaper	Editor
41	Kim Dong Suk	Electronic Newspaper	Editor
42	Kim Young Hwan	Science and Technology Policy Institute	Senior Researcher
43	Kuak Ki HO	Bukyung National University	Professor
44	Kwon Sang jib	Dongguk University	Professor
45	Kim Sung Bem	Kumoh National Institute of Technology	Professor

Consequently, as shown in Table 11, 45 experts pointed out the two most important factors (charging machine sharing/dissemination and operating income improvement), which possibly change in operating income side, two most important factors on non-operating income side (tax exemption and subsidy) and two possible changes in cost side (economics of scale and technology development).

Table 11. Calculated Percentage of Possible Increase/Decrease of Benefit and Cost.

Type of Income		Possible Changes	Calculated Percentage by Survey		
			Option	Number	Average
Benefit Side	Operating income	Operating income increase by sharing the charging machine and infrastructure dissemination	0% 10% 20% 30% 40% 50%	0 1 9 24 8 3	30.89%
		Operating income increase by business model improvement	0% 10% 20% 30% 40% 50%	2 17 21 4 1 0	16.67%
	Non-operating income	Non-operating income increase by decrease of acquisition tax and increase of public bond	0% 10% 20% 30% 40% 50%	8 28 7 2 0 0	10.67%
		Non-operating income increase by increase of subsidy	0% 10% 20% 30% 40% 50%	5 13 15 7 3 2	19.11%
Cost Side		Total cost decrease by economics of scale (mass production, dissemination) and technology innovation (battery and vehicle performance improvement)	0% 10% 20% 30% 40% 50%	1 28 14 2 0 0	13.78%

By including this calculated percentage in the previous analysis, the new B/C ratio is shown in Table 12. As shown in Table 12, the average value of the new B/C ratio is 0.7, which indicates that EV taxis would be quite reasonable to adopt compared to the LPG ratio of 0.72. Interestingly, the highest value calculated is 0.78, which is higher than the ratio of conventional taxis. This result means that EV taxis have the potential to be a feasible alternative for taxi operations if some related conditions are improved.

We reflected and analyzed each additional benefit in terms of the city, citizens, and taxi operators. In order to reflect their benefits, we adopt "Double Bounded Dichotomous Choice Question (DBDC question)", which is the best way to organize similar scenarios with the common market trading. This method has been adopted in valuation of public goods. In addition, this method was recommended in the report that was published by National Oceanic and Atmospheric Administration (NOAA) in 1993 [49,50].

During the pilot operating of three EVs, we were able to find much meaningful evidence other than empirical data. Firstly, because the EV has weakness in its charging infrastructure and mileage, every taxi driver tends to drive more conservatively than a normal taxi drive. Among the six drivers, none of them drove past using more than 80% of EV's full battery, which means going for recharge when they have 20% battery remaining. Consequently, the operating hours of EV become relatively shorter than LPG taxis. Moreover, from the daily report of business provided by Taxi Corporation, we found that majority of the passengers used EV taxi service for short distances less than 10 km. Secondly, the customers are satisfied with the performance of the EVs. Especially, they are very satisfied with the EV's quietness and also have positive attitude on EV's less pollution. The taxi drivers were also very satisfied with its greater acceleration capacity and less vibration impact.

Table 12. Renewed B/C ratio.

	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12	Average
C01	0.72	0.68	0.72	0.71	0.70	0.73	0.73	0.72	0.69	0.72	0.69	0.67	0.71
C02	0.71	0.67	0.70	0.69	0.69	0.72	0.72	0.71	0.68	0.70	0.68	0.66	0.69
C03	0.72	0.68	0.72	0.71	0.70	0.74	0.73	0.72	0.69	0.72	0.69	0.68	0.71
C04	0.73	0.69	0.73	0.72	0.71	0.75	0.74	0.73	0.70	0.73	0.70	0.69	0.72
C05	0.70	0.66	0.70	0.68	0.68	0.71	0.71	0.70	0.67	0.70	0.67	0.65	0.69
C06	0.69	0.65	0.68	0.67	0.67	0.70	0.70	0.69	0.66	0.68	0.66	0.64	0.67
C07	0.70	0.66	0.70	0.69	0.69	0.72	0.71	0.70	0.67	0.70	0.67	0.66	0.69
C08	0.71	0.67	0.71	0.70	0.69	0.72	0.72	0.71	0.68	0.71	0.68	0.66	0.70
C09	0.68	0.64	0.68	0.66	0.66	0.69	0.69	0.68	0.65	0.68	0.65	0.64	0.67
C10	0.67	0.63	0.66	0.65	0.65	0.68	0.68	0.67	0.64	0.66	0.64	0.63	0.65
C11	0.68	0.64	0.68	0.67	0.66	0.69	0.69	0.68	0.65	0.68	0.65	0.64	0.67
C12	0.69	0.65	0.69	0.67	0.67	0.70	0.70	0.69	0.66	0.69	0.66	0.65	0.68
C13	0.76	0.72	0.76	0.74	0.74	0.77	0.77	0.76	0.73	0.76	0.73	0.71	0.75
C14	0.75	0.70	0.74	0.73	0.73	0.76	0.76	0.75	0.72	0.74	0.71	0.70	0.73
C15	0.76	0.72	0.76	0.75	0.74	0.78	0.77	0.76	0.73	0.76	0.73	0.71	0.75
C16	0.76	0.72	0.76	0.75	0.74	0.78	0.77	0.76	0.73	0.76	0.73	0.72	0.75
C17	0.74	0.69	0.73	0.72	0.72	0.75	0.75	0.74	0.71	0.73	0.70	0.69	0.72
C18	0.72	0.68	0.72	0.71	0.71	0.74	0.73	0.72	0.69	0.72	0.69	0.68	0.71
C19	0.74	0.70	0.74	0.72	0.72	0.75	0.75	0.74	0.71	0.74	0.71	0.69	0.73
C20	0.74	0.70	0.74	0.72	0.72	0.75	0.75	0.74	0.71	0.74	0.71	0.69	0.73
C21	0.71	0.67	0.71	0.70	0.70	0.73	0.72	0.71	0.69	0.71	0.68	0.67	0.70
C22	0.70	0.66	0.70	0.69	0.68	0.71	0.71	0.70	0.67	0.70	0.67	0.66	0.69
C23	0.72	0.67	0.71	0.70	0.70	0.73	0.73	0.72	0.69	0.71	0.69	0.67	0.70
C24	0.72	0.67	0.71	0.70	0.70	0.73	0.73	0.72	0.69	0.71	0.69	0.67	0.70
Avg	0.72	0.67	0.71	0.70	0.70	0.73	0.73	0.72	0.69	0.71	0.69	0.67	0.70

5. Conclusions

This study investigates the feasibility of adopting EVs as taxis using real data obtained from pilot operations of an EV taxi project in Daejeon Metropolitan City. To obtain accurate and reliable data, we interviewed policy makers and reflected their opinions and on-going plans of the Daejeon Metropolitan City government at every stage of this research, including in the research design, data collection, B/C analysis, and, in particular, the scenarios and assumptions. According to the B/C ratio analysis, which only used data from the pilot operations, the average B/C ratio was 0.42 and had a range of 0.37~0.46, which is quite low for adoption compared to a 0.75 ratio for LPG taxis. However, because this pilot project had some inevitable constraints such as a limited number of charging machines and lack of experience in driving EVs, we adopted some assumptions drawn from interviews with a group of relevant experts. The assumptions are on both the benefit side and the cost side. On the benefit side, we tried to calculate how much the adoption and dissemination of EV taxis would increase operating and non-operating profit by conducting the expert survey and in-depth interviews. On the cost side, we also tried to calculate the potential decrease in the costs of EVs after EV taxis enter the dissemination stage through the expert survey and in-depth interviews. When including these assumptions in the analysis, the average B/C ratio for EV taxis rose to 0.7 in a range of 0.65–0.77, which makes the introduction of EV taxis as public transportation quite feasible.

Nevertheless, for this improvement, much effort will be needed from different groups. Throughout the entire set of in-depth interviews with the different expert groups after the pilot test, the most important areas in need of improvement prior to adopting EV taxis is the charging machines, the business model, policy support and related services. For infrastructure, the most important area is quantity and geographical position. In this pilot project, the greatest constraint was the charging machines. The charging machines were located in the company parking lots rather than in appropriate areas such as in the middle of the city or at a taxi stand. Furthermore, the taxi companies did not share charging machines, so each EV taxi had to return to its own company for charging instead of visiting the nearest charging machine.

There are also many implications and suggestions for the business model. First, given the long charging period, a battery change platform and a charger at the drivers' cafeteria were suggested. Installing a battery changing machine or a charging machine at the drivers' cafeteria could minimize the inconvenience of charging time. Additionally, integrating EV taxis with fixed section operation service for downtown/suburban districts could be considered to be the optimal option for EV taxi service. By establishing a fixed section operation service using EV taxis, the transportation efficiency and convenience of residents from suburban districts will increase without the need to worry about EV taxis' battery problems because this service would have a fixed and predictable distance. Last, mobile ESS service is needed to improve both operational efficiency and the safety of EV taxis. According to the drivers, they were not able to drive after they had exhausted 90% of their battery because there is no mobile charging machine if the EV taxi stops in the middle of the city. Thus, by adopting a mobile ESS charging service, both operating efficiency and safety will improve.

Finally, a more active and extensive government policy is needed for EV taxis. In China, more people intend to use EV taxis because they are cheaper due to a special payment structure. The payment structure for taxis in China is the sum of two parts: the actual fee for using the taxi and an "environmental improvement fee", which only charged for fossil fuel vehicles. The government of South Korea should introduce a similar payment structure to encourage EV taxis. In fact, the Korean transportation payment system also has a special structure called "free transit", which allows users to transit from buses to subways at no charge. To adopt and encourage EV taxis, the application of this free transit system to taxis is strongly needed. For example, the free transit pilot project of limousine bus and taxi in 2010 provided 2 USD (2000 KRW) discount when you transit from bus to taxi. Additionally, some direct encouragement such as establishing a green zone or green mileage is also needed to activate EV taxis in the city.

6. Discussion

Despite an actual pilot test and scenario and assumption analysis through in-depth interviews with a survey, this study has several limitations. First, the research results of the current study may be difficult to generalize because this study was conducted in a specific area, Daejeon Metropolitan City in South Korea, and the results from other areas could differ. Though an empirical test is very important prior to introducing new products or systems, this test included only three taxis, of the same model automobile, which three companies operated and managed. In addition, we also conducted the actual driving test from September to February. The research results for both spring and summer are calculated based on the results in this study and other previous studies.

Second, the real mileage may be higher than our calculations in this study. The three taxi companies operated their own EV taxi and did not share the charging infrastructure. If they had access to more charging infrastructure downtown or if they shared the three chargers, then the economically feasibility of EV taxis would be higher. Finally, the taxi drivers were extremely concerned about low batteries, because a dead EV will not move, so they returned to the charger earlier than needed.

Third, incomplete technology, such as the battery and the charging infrastructure, could distort the research results. When we performed the practical test in Daejeon Metropolitan City, one of the EV chargers stopped working for a long period. During this time, an EV taxi driver should borrow other chargers when they are not in use. We expect that if the technology were more saturated, we would obtain higher fuel efficiency from EV taxis.

Given the above limitations, future studies should have more EV taxi samples and one year of data from the EV taxis. We plan to collect all data from more EV taxis for at least one year, and then we will conduct analyses that will include more accurate fuel efficiency data. In addition, as infrastructure is built, we will be able to update the results, which will reflect the current technology development phase. Thus, in future study, more up-to-date and accurate mileage is expected, which will resolve the above limitations and provide implications to policy makers.

Author Contributions: Seoin Baek completed the first draft; Heetae Kim analyzed the data and wrote specific parts and revised the paper; and Hyun Joon Chang reviewed and revised the final version of paper.

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Abbreviations

The following abbreviations are used in this manuscript:

EV	Electric Vehicle
B/C	Benefit-to-Cost
O&M	Operations and Maintenance
NPV	Net Present Value
LPG	Liquefied Petroleum Gas
AVG (in Table)	Average

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