Sustainable Transport through Provision of Electric Vehicle Taxis: A Case Study in Seoul

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Abstract: *As a prelude to scaled-up deployment of electric vehicles, this paper examines the economic feasibility of replacing the current fleet of fossil fuel taxis in Seoul with electric vehicle (EV) taxis by phasing the former out based on their opertional lifetime. In the cost-benefit analysis for such a transition, costs of purchasing vehicles and constructing and maintaining charging infrastructure are estimated based on the market prices and characteristics of taxi transport in Seoul. On the benefit side, the avoided environmental costs due to reduced air pollutants and greenhouse gas emissions are calculated. The transport planning model, especially traffic assignment, is incorporated in the calculation process for a better estimation of the avoided costs through more accurate link flows and speeds on the road network. Savings from the fuel switich to electricity from liquefied petroleum gas for taxis are also estimated. The resultant benefit-cost ratio signifies economic viability of the deployment of EV taxis. The results of the study are encouraging and could be a good piece of rationale to push forward with electric vehicles. That will be even more so if decreasing battery costs and shortening charging time come into play.*

Keywords: *Sustainable Transport, Electric Vehicle Taxi, Air Pollutant, Greenhouse Gas, Economic Feasibility*

1. Introduction

Transport is one of the main sources of greenhouse gas (GHG) emissions and ambient air pollution in urban areas. According to the Intergovernmental Panel on Climate Change (IPCC), globally 14% of GHG emissions in 2010 were released from the transport sector. Transport is responsible for around half of energy-related nitrogen oxide (NO_x) emissions and is an important source of primary particulate matter, $PM_{2.5}$ which affects human health more than any other pollutant. Given the global trend of rapid urbanization with increasing demand for mobility particularly in developing countries, such environmental and health externalities from the transport sector will continue to be exacerbated under the business-as-usual scenario.

Electric vehicles have long been hailed as a means for mitigating environmental problems in transport. They normally do not produce any tailpipe GHG or air pollutants emissions. If well-to-wheel energy used in electric vehicles is produced through renewable sources, benefits of running fleets of electric vehicles are even greater. Despite the intrinsic benefits of electric vehicles, mass diffusion of electric vehicles has proven to be difficult so far. More expensive prices of electric vehicles relative to their fossil fuel counterparts have been a major barrier to their scaled-up deployment. However, the cost of batteries, which makes up between one-third and half of the vehicle cost now, is coming down rapidly and it is projected that the cost of lithium-ion batteries would reach USD 100/kWh by 2023, at which point an entry-level equivalent of a Tesla Model S, for instance, can be purchased for USD 15,000 (Seba, 2014). Inadequate charging stations and long charging time are other impediments to rapid adoption of electric vehicles. As technology advances, driving ranges of electric vehicles will become longer with less charging time[1], which will relieve the pressure to build many charging stations.

Even as electric vehicles become more competitive, the public may not opt for these new options quickly except some early adopters partly due to the inertia of using the vehicles familiar to them. This is potentially where the government can intervene and take the initiative to make the transition to electric vehicles for its mobility needs by, for example, replacing its official-purpose vehicles with electric ones. Another fleet of vehicles that might be electrified with relative ease through appropriate policy mandates or incentives from the government is taxis or rental cars.

Taxis in urban areas have the characteristic that their daily travel distances are much longer than those of private cars which usually sit in parking spaces most of the day. This mean that the impact of a fossil fuel taxi on the environment would be disproportionately higher compared to a comparable private vehicle. As such, replacing conventional taxis with electric ones would greatly reduce per vehicle GHG and air pollutants emissions. It will also help raise awareness of electric vehicles as taxis tend to be easily noticed on the streets. Countries like the U.S., Germany, and the Netherlands are actively running electric vehicle (EV) taxies, while London, UK plans to issue new taxi licenses only for electric vehicles from 2018. Under the Seoul Transport Vision 2030, the city government of Seoul, Republic of Korea has made 11 "promises" to provide the citizens with mobility services that are human-oriented, shared, and environmentally friendly. Although not explicitly considered in the vision document, EV taxis can be an option to implement one of the promises, "introduction of environmentally friendly transportation modes." Currently a total of 60 EV taxis are in operation in Seoul as a pilot project since 2015.

With a view to full deployment of EV taxis in Seoul, this paper examines the economic feasibility of replacing the current fleet of taxis with EV taxis by phasing the former out based on their operational lifetime. To this end, a cost-benefit analysis is conducted where the transport planning model is incorporated to estimate vehicle speeds on the roads more accurately. This is a novel feature that distinguishes this paper from other similar work where the city-wise average vehicle speed is often used, bearing the risk of calculating emission factors inaccurately. The paper is organized as follows. In Section 2, characteristics of taxi transport in Seoul are described. Costs and benefits of the introduction of EV taxis are calculated in Section 3. How the transport planning model is used within the cost-benefit analysis is explained in the section. In Section 4, findings and conclusions are provided.

2. Taxi Transport in Seoul

There are 72,007 taxis in Seoul as of 2016, 49,269 of which are owned by individuals and the remainder by companies. Although the fleet of taxis constitutes only 2.34% of the total registered vehicles in Seoul, their modal share is 6.8%, transporting over 2 million trips per day in 2014. The average daily distance driven by a taxi is above 200 km, while that of a private vehicle is only 35 km.

[1] As a promising sign of technological advance, researchers at Purdue University have recently unveiled an "instantly rechargeable" method that is said to reach full power in the same amount of time it takes to refill a gas tank. More on http://www.dailymail.co.uk/sciencetech/article-4567718/The-instantly-rechargeable-battery-electric-cars.html.

The operational lifetime of individually owned taxis is 7-9 years depending on the engine displacement. On the other hand, company taxis can be operated for 4-6 years.

Table 1. Registered vehicles in Seoul (unit: vehicle, %)

Year	Registered Vehicles	Taxi			
		Private	Company	Total	%
2012	2,969,184	49,424	22,801	72,225	2.43
2013	2,973,877	49,398	22,787	72,185	2.43
2014	3,013,541	49,373	22,787	72,160	2.39
2015	3,056,588	49,336	22,760	72,096	2.36
2016	3,083,007	49,269	22,738	72,007	2.34

Source: Seoul Statistics (http://stat.seoul.go.kr)

Table 2. Mode share (unit: 1,000 trips/day, %)

Year	Total Trips	Bus	Taxi	Subway /Train	Passenger Car	Others
2011	31,885	23.5	7.0	28.0	37.1	4.4
2012	32,150	23.1	6.9	27.4	38.2	4.4
2013	32,516	22.9	6.8	27.1	38.8	4.4
2014	32,690	22.8	6.8	27.0	39.0	4.4
2015	32,410	23.0	6.8	26.5	39.3	4.4

Source: 56th Seoul Statistics Yearbook (2016)

Taxis in Seoul run on liquefied petroleum gas (LPG). According to the National Air Pollutants Emission Service, 13.6% of CO, 8.8% of NO_x, and 9.9% of SO_2 in road transport were emitted by taxis in Seoul in 2013. The statistics from the National GHG Emission Total Information System show that 5.6% of CO_2 were attributable to taxis. These are substantial proportions considering the less than 3% of vehicle share of taxis. This backs up our assertion that the impact of a fossil fuel taxi on the environment would be disproportionately higher compared to a comparable private vehicle.

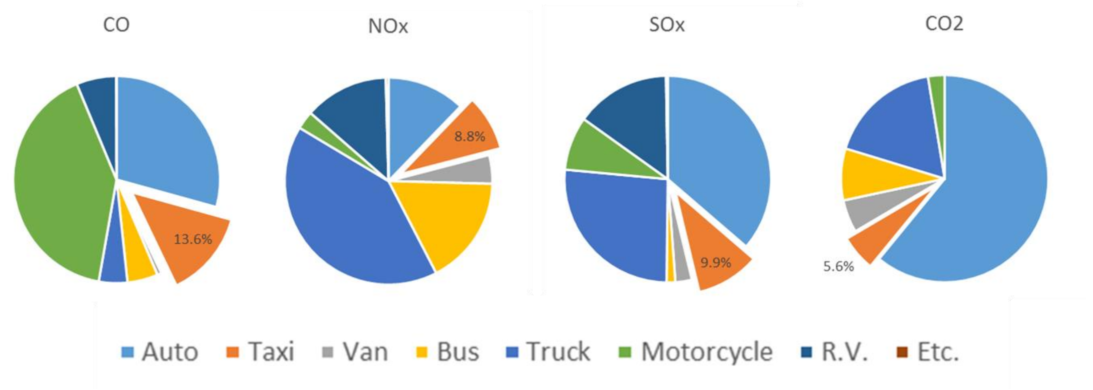

Figure 1. Air pollutants & GHG emitted in road transport

Source: National Air Pollutants Emission Service (http://airemiss.nier.go.kr), National Greenhouse Gases (GHG) Emission Total Information System (http://netis.kemco.or.kr)

Through well-to-wheel analysis, the European Emissions Test Program study shows that the emission from LPG is clearly lower than petrol and diesel on NO_x, essentially equivalent to petrol and well below diesel on particulate matter, and just below petrol yet above diesel on hydrocarbons (Atlantic Consulting, 2009). For carbon monoxide, LPG comes out higher than petrol and both are significantly higher than diesel. These emission characteristics of LPG are overall in line with the measured statistics in Seoul shown in Figure 1.

3. Costs and Benefits of EV Taxis

The elements of cost and benefit taken into consideration in economic feasibility analysis for transport projects vary across countries, although core elements are largely similar. Table 3 is a summary of those elements that are considered in selected countries.

Table 3. Elements of cost and benefit

Elements			Korea	UK	Japan	Germany
Cost	Construction		○	○	○	○
	Purchasing Vehicles		○			
	Operation and Maintenance		○	○	○	○
Benefit	Operating Costs Reduction		○	○	○	○
	Travel Time Reduction		○	○	○	○
	Traffic Accidents Reduction		○	○	○	○
	Environmental Improvements	Air Pollution	○	○	○	○
		GHG	○	○	○	○
		Noise	○	○	○	○
	Parking Availability		○			
	Transport Provider Profitability			○	○	
	Amenities Enhancement				○	
	Physical Activity Promotion			○		
	Improved Reliability			○		
	Option Values			○		
	Regional Development			○	○	○

Source: Korean Development Institute; Department for Transport of United Kingdom; Ministry of Land, Infrastructure, Transportation and Tourism of Japan; and German Federal Ministry of Transport

For the cost-benefit analysis at hand, we consider the elements of cost and benefits shown in Table 4. It is assumed that taxis are decommissioned and replaced by new ones after 7 years in use. Taking into account this operational lifetime of taxis, the appraisal period is chosen to be 7 years. The discount rate is set to 5.5% that is typically used in economic feasibility studies for transport projects in Korea (Korean Development Institute, 2008).

Table 4. Cost and benefit elements and parameters considered

Category	**Elements**	
Cost	Purchasing Vehicles	
	Charging Infrastructure Construction	
Benefit	Operating Costs Reduction	
	Environmental Improvements	Air Pollution
		GHG
Appraisal Period	7 years	
Discount Rate	5.5%	

3.1. Cost Analysis

Purchasing Vehicles

The costs for purchasing vehicles, used in this analysis, are USD 17,201 for a LPG taxi and USD 37,776 for an EV taxi, respectively. These are the current market prices of the typical LPG taxi (Hyundai Sonata model) and the Renault Samsung SM3 EV taxi. It is assumed that LPG taxis are replaced by EV taxis when their operational lifetime comes to an end. This would face least resistance from the taxi owners. Based on the taxi vehicle age information from the national vehicle registration data and the operational lifetime of 7 years, yearly demands of taxi replacement are calculated as in Table 5. From these demand numbers, the additional cost incurred due to the transition to EV taxis is estimated for each year.

Table 5. Purchasing vehicles (unit: vehicles, million dollars)

Year	Taxi Replacement Demand	Vehicle Purchasing Cost		(B) – (A)
		LPG (A)	EV (B)	
2018	12,351	212.4	466.6	254.1
2019	10,418	179.2	393.6	214.4
2020	10,934	188.1	413.0	225.0
2021	11,406	196.2	430.9	234.7
2022	7,028	120.9	265.5	144.6
2023	8,180	140.7	309.0	168.3
2024	11,690	201.1	441.6	240.5
Total	72,007			

Charging Infrastructure Construction

Under the current battery capacity and driving range of an EV taxi, Ko et al. (2017) estimated that it needs to be recharged 2.96 times per day to cover the same daily driving distance of an LPG taxi in Seoul. Thus, the total daily charging demand is calculated as the number of EV taxis in operation multiplied by 2.96. The moments for EV taxis to be recharged will not be uniformly distributed across the day as customer demand for taxis fluctuates over time. By analyzing the digital tachograph data of LPG taxis, Ko et al. (2017) found that a late hour of Friday is the busiest time for taxis and projected that 11.04% of the daily charging demand will occur in that period of hour. Using this statistic, the maximum hourly charging demand is calculated as the total daily charging demand multiplied by 11.04%.

It takes 30 minutes to fast charge an EV taxi. One of the required specifications of fast charging stations in Korea is that it should be able to charge three vehicles at the same time (with three charging cables). Taking these into account, the number of charging stations to cover the maximum hourly charging demand is obtained by dividing the latter by 6. The current market price of constructing such a fast charging station is USD 39,904 with annual maintenance costs of USD 1,596 (Lee and Kim, 2016). Table 6 summarizes the above caculations along with costs of providing charging stations. The fact that exisiting charging stations continue to serve some portion of the maximum hourly charging demand in the future, incurring only maintenance costs, is reflected in the calculations.

Table 6. Charging infrastructure construction (unit: vehicles, number of times, million dollars)

Year	EV Taxis in Operation	Total Daily Charging Demand	Maximum Hourly Charging Demand	Additional Charging Stations Needed	Cost
2018	12,351	36,559	4,036	673	27.9
2019	22,769	67,396	7,441	567	24.6
2020	33,703	99,761	11,014	596	26.7
2021	45,109	133,523	14,741	621	28.7
2022	52,137	154,326	17,038	383	19.8
2023	60,317	178,538	19,711	446	23.0
2024	72,007	213,141	23,531	637	31.7

3.2. Benefit analysis

Environmental Improvements

The estimation of the benefits from reduced air pollutants and GHG emissions is carried out by the process depicted in Figure 2. The backbone of the process is the traffic assignment step of the four-stage transport planning model (Ortuzar and Willumsen, 2011), where traffic flows of origin-destination pairs are assigned to the road network according to Wardrop's first principle, also known as user equilibrium, "The journey times on all the routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused route" (Wardrop, 1952). This equilibrium is mathematically equivalent to the Nash equilibrium.

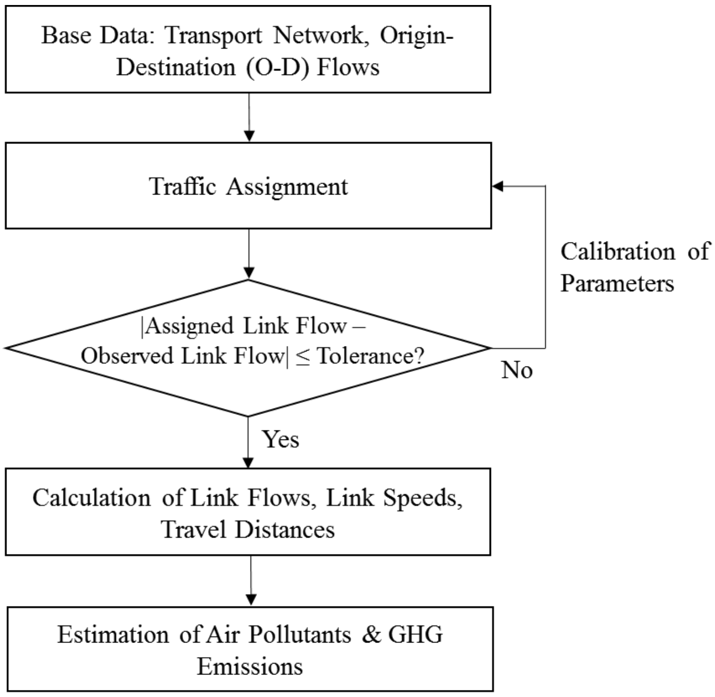

Figure 2. Process of estimating environmental benefits based on transport planning model

In conducting traffic assignment, it is of paramount importance to calibrate parameters of link performance functions so that the flows assigned on links of the road network are sufficiently close to the observed ones on those links. Once the calibration process is done, data of interest such as link flows, link speeds, and travel distances can be obtained from the results of traffic assignment. With the road network of Seoul and the associated origin-destination traffic flow data provided the Korea Transport Database, traffic assignment was carried out via the transport planning software Emme 3. Figure 3 is the road network of Seoul and the results of traffic assignment are graphically shown in Figure 4 (the thicker the link, the higher the traffic volume on it).

Figure 3. Road network of Seoul

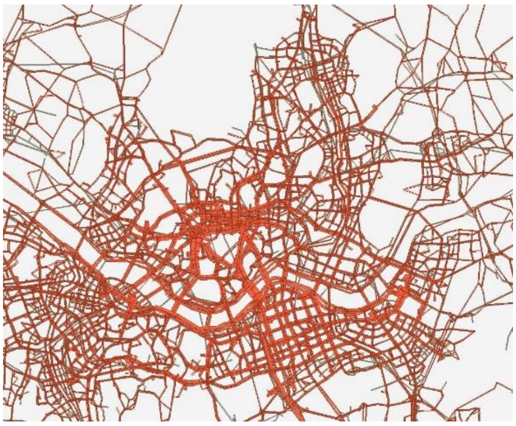

Figure 4. Results of traffic assignment

For a certain air pollutant or GHG, the amount of emission by vehicles on the road network is calculated on the basis of the corresponding emission factor. The emission factor is a function of vehicle speed and has different forms depending on vehicle and fuel type. Table 7 shows the emission factors for CO, NO_x, and CO_2 for LPG taxis used in this study, where *Y* is the emission amount (g/km) and *v* is the speed of vehicle (km/h).

Table 7. Emission factors

	Year of Vehicle Manufacture	Formula
CO	Prior to 1999	$Y = 350.12 \times v^{-1.2852}$
	2000–2002	$Y = 53.445 \times v^{-0.8327}$
	2003–2005	$Y = 13.380 \times v^{-0.5948}$
	After 2006	$Y = 46.661 \times v^{-0.9760}$
NO_x	Prior to 1999	$Y = 3.9363 \times v^{-0.5648}$
	2000–2002	$Y = 4.8692 \times v^{-0.7475}$
	2003–2005	$Y = 2.2994 \times v^{-0.6773}$
	After 2006	$Y = 3.1607 \times v^{-0.5998}$
CO_2	All	If $v < 65.4$ km/h, $Y = 1521.36 \times v^{-0.6128}$ If $v \geq 65.4$ km/h, $Y = 0.0264v^2 - 4.1928v + 279.93$

Source: National Institute of Environmental Research (2013), Ministry of Land, Infrastructure and Transport (2014)

By combining the results of traffic assignment, i.e., link flows, link speeds, and travel distances with the emission factors, it is estimated that the current fleet of LPG taxis emits 16,449 tonnes of CO, 3,046 tonnes of NOx, and 1,387,295 tonnes of CO2 per year. In other words, each LPG taxi adds 228 kg of CO, 42 kg of NO_x, and 19,266 kg of CO_2 to the air each year. If LPG taxis are replaced with EV taxis, these air pollutants and GHG emissions are avoided. To monetize the avoided emissions, we need the "social costs" of air pollutants and GHG. The guidelines of Korea Development Institute (2008) are to use USD 8.81, 10.60, and 0.05 as the social costs of a kilogram of CO, NO_x, and CO_2, respectively. Putting these all together, Table 8 shows the avoided emission costs as the LPG taxis are gradually replaced by EV taxis.

Table 8. Avoided environmental cost (unit: vehicles, million dollars)

Year	EV Taxis in Operation	Avoided Cost			
		CO	NO_x	CO_2	Total
2018	12,351	24.9	5.5	11.3	41.7
2019	22,769	45.8	10.2	20.8	76.8
2020	33,703	67.8	15.1	30.8	113.7
2021	45,109	90.8	20.2	41.2	152.2
2022	52,137	104.9	23.4	47.6	176.0
2023	60,317	121.4	27.0	55.1	203.6
2024	72,007	144.9	32.3	65.8	243.0

Operating Costs Reduction

Table 9 shows the prevailing data on fuel efficiency and fuel price for LPG and EV taxis collected from vehicle manufacturers' websites, Korea National Oil Corporation, and Korean Electric Power Corporation. While the per unit fuel efficiency of EV taxis is 61% of that of LPG taxis, the per unit price of electricity is 20% of that LPG. Hence, savings from fuel change are expected.

Table 9. Fuel efficiency and fuel price

	Fuel Efficiency	Fuel Price
LPG Taxi	7.9 km/liter	USD 0.75/liter
EV Taxi	4.8 km/kWh	USD 0.15/kWh

Based on these data and the average driving distance of a taxi per year, the savings from the fuel switch to electricity from LPG are estimated as in Table 10.

Table 10. Savings from fuel change (unit: vehicles, million dollars)

Year	EV Taxis in Operation	Fuel cost		(A) – (B)
		LPG (A)	EV (B)	
2018	12,351	96.7	31.8	64.9
2019	22,769	178.3	58.7	119.6
2020	33,703	263.9	86.9	177.1
2021	45,109	353.3	116.3	237.0
2022	52,137	408.3	134.4	273.9
2023	60,317	472.4	155.5	316.9
2024	72,007	563.9	185.6	378.3

EV taxis would also be much cheaper to maintain than LPG taxis. Although data is limted, it is said that an electric vehicle would require 90% less money on repairs during the lifetime of the vehicle compared to a gasoline or diesel vehicle (Seba, 2014). This benefit is not quantified here due to data limitations.

3.3. Economic Feasibility

From the cost and benefit calculations above, it can be seen in Table 11 that the gradual deployment of EV taxis in Seoul proves to be economically feasible, yielding the benefit-cost ratio greater than 1.0. In fact, the ratio would be even higher if rapidly declining battery costs (so as EV taxi prices) and maintenance cost savings had been considered in the analysis.

Table 11. Economic feasibility (unit: million dollars)

Year	Yearly Value		Net Present Value	
	Cost	Benefit	Cost	Benefit
2018	282.0	106.6	282.0	106.6
2019	239.0	196.5	226.5	186.2
2020	251.7	290.8	226.1	261.3
2021	263.4	389.2	224.3	331.5
2022	164.4	449.9	132.7	363.1
2023	191.3	520.4	146.4	398.2
2024	272.2	621.3	197.4	450.6
Total			1,435.5	2,097.5
B/C	1.46			

4. Conclusions

To keep pace with the Paris Climate Agreement and the UN Sustainable Development Goals, it becomes more important than ever to transform transport systems into greener and more sustainable ones. There is no silver bullet to achieve this objective at once and it will require a multitude of endeavors with long-term commitments. As a small part of such efforts, this study investigated the economic feasibility of replacing the current fleet of LPG taxis in Seoul with EV taxis by phasing the former out based on their lifetime, in recognition of intrinsic advantages of electric vehicles over fossil fuel vehicles and rapid advances in technology.

In the cost-benefit analysis for such a transition to EV taxis, costs of purchasing vehicles and constructing and maintaining charging infrastructure were estimated based on the market prices and characteristics of taxi transport in Seoul. On the benefit side, the avoided environmental costs due to reduced air pollutants and GHG emissions were calculated. The transport planning model, especially traffic assignment, was incorporated in the calculation process for a better estimation of the avoided costs through more accurate link flows and speeds on the road network. Savings from the fuel switch to electricity from LPG for taxis were also estimated. The resultant benefit-cost ratio was 1.46, signifying economic viability of the deployment of EV taxis.

There could be some aspects that hinder the adoption of electric vehicles but are not easily quantifiable, such as inconvenience due to more frequent visits to charging stations and longer charging time compared to fossil fuel vehicles. Nevertheless, the results of this study are encouraging and could be a good piece of rationale to push forward with electric vehicles. That will be even more so if decreasing battery costs and shortening charging time come into play.

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