Modeling the acceptance of taxi owners and drivers to operate premium electric taxis: Policy insights into improving taxi service quality and reducing air pollution

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Abstract

Taxis are the main contributor to the emissions of roadside pollutants and greenhouse gases. Many studies have shown that electrifying the taxi fleet is effective in reducing roadside pollution and carbon footprint. However, high ownership cost of electric taxis, limited driving range, and availability of chargers are constraining their deployment. Government subsidy has been sought for in many applications, yet the required amount can be enormous and remains infeasible in many jurisdictions. To address these issues, electric taxis are proposed to provide premium services and let all stakeholders share the financial input. That is, a higher fare will be charged to the taxi customers for a higher service quality. The taxi drivers with higher incomes will be able to pay more to rent the electric taxis. With an increase of rental income to the taxi owners, fewer financial incentives from the government will be required. This study aims to uncover the factors underpinning how taxi owners and drivers choose between conventional taxis and the proposed premium electric taxis. Stated-preference surveys were conducted in Hong Kong, and two separate binary logistic regression models were calibrated accordingly. It was found that the (subsidized) vehicle purchase price, rental income, and battery lifespan were influential to the owners, while fare income, the rental cost, the access time to chargers, and the range per charge significantly affected taxi drivers' decisions. An equilibrium model with an iterative solution procedure is proposed to illustrate the interactions between the stakeholders and predict the changes in percentage-of-switch under different policy settings. Policy implications to improve taxi service and reduce roadside emissions and pollution are hence discussed.

Keywords: Roadside emission reduction, Electric vehicles, Premium taxi service, Stated-preference survey, Sustainable transportation

1. INTRODUCTION

Conventional vehicles with internal combustion engines are the main contributor to roadside pollution globally. They are also one of the main users of energy resources producing a significant amount of Carbon Dioxide (CO_2) emissions (Yang et al., 2017a). In Hong Kong, the transport sector is the largest petroleum product user and the second largest producer of CO_2 emissions (Electrical and Mechanical Service Department, 2016). Hong Kong faces significant challenges from high roadside pollution levels and carbon footprint generated by the transport sector, which is the largest contributor to Carbon Monoxide (CO), and one of the main contributors to Volatile Organic Compound (VOC) and Nitrogen Oxides (NO_x) (Environmental Protection Department, 2017; Clean Air Network, 2017). Roadside emission levels of these pollutants are on average two to four times higher than the city's average (Hedley Environmental Index, 2017). Most notably, the concentration level of NO_x has never met the World Health Organization (WHO) standard in the past 20 years (Clean Air Network, 2017).

The high concentration levels of roadside pollutants are mainly caused by private cars, buses, goods vehicles, and taxis movements on the roads. Due to their operational nature, both buses and taxis have exceptionally long daily driving mileage even their fleet sizes are small (Transport Advisory Committee, 2014). As longer daily driving mileages imply higher energy consumption and emissions, improving the environmental-friendliness of buses and taxis can be an effective way of reducing the overall roadside pollution and carbon footprint of the transport sector. In the past decade, the annual driving mileage and annual energy consumption of taxis grew by 39.6% and 30.3% respectively while the fleet size remained the same. Meanwhile, buses' collective energy consumption dropped by 12.5%

with almost the same driving mileage (Electrical & Mechanical Services Department, 2016). These figures show that while buses are becoming more and more energy efficient, the taxi fleet is generating more emissions.

Financial support has facilitated the improvement of buses' environmental performance. The government has been subsidizing the bus operators to replace pre-Euro V buses with cleaner Euro V and hybrid ones, while electric buses are being tested. However, as a major road user, the conventional taxis are not receiving any support in reducing their emission levels of harmful pollutants or CO_2. Hong Kong aims to reduce its overall carbon footprint by 70% of the 2005 level by the end of 2030 (Environment Bureau, 2017). It is also the government's goal to ensure the concentration levels of all major pollutants meeting the WHO standards. Taxis have been overlooked in the government's transportation and environmental policy framework and should be included in the effort of reducing the environmental impacts of the transport industry.

Many studies have suggested that the use of Battery Electric Vehicles (BEVs) remains a viable option to reduce roadside pollution, energy consumption, and the resultant CO_2 emissions (Steinhilber et al., 2013; Buekers et al., 2014; and Bonges III and Lusk, 2016). Cities across the globe are actively promoting the use of BEVs in public transport and taxi operations, most of these efforts are backed by strong financial support from the government. Studies on BEVs and electric taxis (eTaxis) have gained high popularity in recent years. The rationale, impacts, and implications have been reviewed extensively (Hao et al., 2014). On a city scale, Shenzhen operates one of the world's largest eTaxi fleets with considerable subsidies from the government and support from BEV manufacturers (Li et al., 2016). Beijing is deploying a large-scale eTaxi fleet that is also supported by the government subsidy and investment in infrastructure (Zou et al., 2016). New York City has launched plans to replace one-third of the current taxi fleet with eTaxis by offering direct driver subsidies (NYC Taxi & Limousine Commission, 2013). Researchers have further expanded the idea to a fully automated fleet of eTaxis in Manhattan and estimated that the greenhouse gas emissions and energy consumption could be reduced by 73% and 58%, respectively if all taxis in Manhattan were upgraded (Bauer et al., 2018). In Stockholm, Hagman and Langbroek (2018) conducted a thorough investigation of the cost and revenue implications of introducing eTaxis. Their study acknowledged the adverse effect of the time spent on charging. However, the time spent can be compensated by the more favorable policy towards green vehicles in Sweden. Increasing the percentage of BEVs in the existing taxi fleet is a possible way for Hong Kong to meet its emission targets. However, the high ownership cost of BEVs is a significant factor constraining their deployment for the taxi operators that are split to taxi owners and drivers in many cities.

Regarding taxi owners, Gao and Kitirattragarn (2008) conducted a study to reveal New York taxi owners' preference on hybrid vehicles, and the reduction in emissions these new vehicles can bring. The study found that stronger government incentives were needed to achieve a higher share of hybrid vehicles and greater emission reduction. Yang et al. (2014) provided a novel approach to investigating the profit maximization of eTaxi operations when electricity prices were uncertain. Wang et al. (2015) presented a cost-benefit analysis encompassing factors beyond electricity price, including battery price and life-cycle, as well as predicting the change in service price. Carpenter et al. (2014) studied the case of San Francisco using a time-series analysis to compute the return on investment when taxi companies switched to a BEV operation. They found that such a transition could still be profitable even though San Francisco had the highest electricity price among major US cities. Regarding taxi drivers, studies on "range anxiety" has been the primary focus. Range anxiety – the fear of battery power depletion in the middle of the journey (Neubauer and Wood, 2014) – has a high impact on taxi drivers as they also fear that insufficient range may affect their income. Lu et al. (2012) proposed a new dispatching method considering the different needs of operating an eTaxi fleet, which has taken into account the charging time, distance to the nearest station, and the remaining range per charge. Gacias and Meunier (2015) have looked into the operational design to prevent possible power failures. The strategic placement and distribution of charging stations are crucial to reducing range anxiety. Many algorithms have been proposed to solve the problems of where and how to place charging stations across a network. Yang et al. (2017b) provided an integer linear program optimization approach using regression with real taxi GPS data and logarithmic transformation to determine the size and locations of eTaxi charging stations. Wu and Sioshansi (2017) developed a stochastic flow-capturing location optimization model for the positioning of fast-charge stations, especially under uncertain traffic flow conditions.

Many of the above taxi owner studies have only looked at their willingness-to-buy in relation to government subsidies, but have not discussed the relation with taxi drivers, who in many markets are different from taxi owners with intrinsically different considerations. Meanwhile, the taxi driver studies have mainly focused on how to alleviate their range anxiety after the deployment of eTaxis, but very few have looked at their preferences and choices before such deployment. As far as the authors know, there has been a lack of comprehensive study to uncover the connections between taxi owners, taxi drivers, and the government. In fact, taxi owners, taxi drivers, and the government are all key stakeholders in the market that interact with each other, which should be discussed jointly.

In this study, we propose a new operational design of switching a portion of the existing conventional taxis to eTaxis by providing premium services in the dispatching mode. We aim to reveal the taxi owners' and drivers' preferences between conventional taxis and the proposed premium eTaxis and determine the factors that influence their decisions. We also attempt to establish an equilibrium model to depict the interactions between taxi owners, taxi drivers, and the government. Stated-preference surveys were conducted to capture how various operational characteristics of eTaxis may affect taxi owners' and drivers' selections. Two binary logistic regression models were calibrated to analyze their behaviors separately. An iterative solution procedure was developed to determine the tripartite equilibria in different combinations of cost, income, and subsidy levels. A sensitivity analysis was also performed to establish how different levels of charging infrastructure provisions affect the percentage-of-switch from conventional taxis to the premium eTaxis. Policy implications are suggested based on the model results and the sensitivity analysis.

The main contributions of this paper are as follows.
1) It proposes a new taxi operational design that has the potential of improving the service quality and environmental friendliness of the taxi industry;
2) It introduces two separate binary logistic regression models to depict how taxi owners and drivers choose between conventional taxis and the proposed premium eTaxis;
3) It offers an equilibrium model and an iterative solution procedure to determine the achievable percentage in an existing taxi fleet that can be switched to the premium eTaxis under various combinations of subsidy offered by the government, the purchase price borne by the taxi owners, and the income expected to be received by the drivers; and
4) It provides policy insights into how the different levels of charging infrastructure provision affect the willingness of both the taxi owners and drivers switching to the premium eTaxis.

The remainder of this paper proceeds as follows. Section 2 explains the proposed premium eTaxi operation; Section 3 describes the data collection process, the operating characteristics, the key aspects in association with the premium eTaxis, and the design of the stated-preference surveys. Section 4 explains the methodology. Section 5 discusses the results with policy implications, and Section 6 concludes the paper with future research directions.

2. NEW OPERATIONAL DESIGN: PREMIUM ETAXIS IN THE DISPATCHING MODE

Promoting eTaxis can be challenging. First, their high ownership cost prevents the operators from self-initiating a switch, and this is where the government subsidy plays a pivotal role. The comparatively more successful implementation of eTaxi schemes are primarily seen in China where the position of the government is decidedly strong and enormous funding can be provided (Yang et al., 2018), yet the required financial input can be large, which remains infeasible in many jurisdictions. To reduce the government's financial burden, charging a higher fare to the customers is a possible solution. However, there has been a lack of justification for a fare increase for environment protection, because the customers will not accept price discrimination for using a greener vehicle type where the service level is the same. Hence, offering a differentiated service becomes the ground of the fare increases. The customers are requested to pay together with other stakeholders for the transition to eTaxis. In return, they are receiving a higher quality service of premium eTaxis. The higher fare incentivizes the taxi drivers to switch to eTaxis and enables them to afford the higher rental fee imposed by the taxi owners. Consequently, the total government subsidy required can be reduced. The Tesla-operated airport taxi service in Amsterdam is an example of this approach where a higher fare is charged for a differentiated service segment in which a €10,000 subsidy is provided only to the purchase of each vehicle (Netherland Enterprise Agency, 2015).

It is not uncommon for taxi operators to provide differentiated services. For instance, premium taxi services can be found in Tokyo, Sydney, Melbourne, and Singapore. Olason (2001) shared the case study of Raleigh (State Capital of North Carolina in the US) where two different levels of subsidized taxi services were provided to eligible persons. Wong et al. (2008) incorporated the concept of premium taxis in a multi-class, multi-mode study to model market equilibrium, based on the assumption that lower-income individuals would choose the normal taxis, and higher-income individuals would choose the luxury taxis. There is a finer market niche within the taxi clientele that demands a higher service quality and is willing to pay a premium for the quality. In recent years, conventional taxi operators are facing competition with ridesourcing operators, such as Lyft and Uber, which provide taxi-like point-to-point transportation services with a higher service quality. Several studies regarding this have discussed taxi operations with different service standards (e.g., Nie, 2017; Rayle et al., 2016), which confirmed the existence of demand for better service taxis and found differences in user and trip characteristics.

To operate premium taxi services with eTaxis, the dispatching mode similar to Lyft and Uber is considered the most appropriate. The customer places an order before travel, the order is assigned to the nearest driver, and the customer is picked up by the driver directly. The driver then returns to a docking location (with charging facility provisions) after completing the previous assignment. This mode reduces the cruising distance for customer-search and creates charging opportunities between each order assignment. BEV battery charging technology has been improved a lot in the past few years. Benefited by high capacity lithium-ion batteries, BEVs can cruise up to 480 km on one full charge. The latest fast-charge technology can provide sufficient power for driving up to 100 km in 10 minutes (Tesla Inc., 2017), which allows drivers to charge their vehicles multiple times a day without shortening the operational hours. The dispatching mode suits the fast-charge mechanism and mitigates taxi drivers' concerns of charging time and driving range.

One of the key criteria making this operational design successful is to provide a higher service quality to the customers. We envision that the service quality can be uplifted by both vehicles and drivers. For the vehicles, newer, more spacious, and quieter BEVs are readily available in the market, such as Tesla Model S, BMW i3, Nissan Leaf, and BYD e6, which can provide improved traveling experiences to the customers and improve their level of satisfaction. Regarding service attitudes and driving behaviors of drivers, the drivers are required to provide courteous services, assist customers in boarding and alighting, and help with loading luggage. A permit system can be introduced together with more stringent quality assurance throughout the operation using, for example, customer feedback and rating mechanism, or a point-based evaluation system. Permits may be revoked if the service standards are constantly sub-optimal. In addition, the top areas of complaints on taxi are usually refusal of hire, fare overcharging, intentional detours, service attitude, and driving behavior (Transport Advisory Committee, 2017; Wong and Szeto, 2018). The dispatching mode of the new operational design means that all taxi drivers are assigned to taxi orders, drivers will no longer be able to refuse a customer on the streets. As the dispatching operation is based on GPS devices, fare overcharging and intentional detours will also be eliminated.

To sum up, we consider the proposal of introducing premium eTaxis in the dispatching mode a viable option due to the following reasons: (1) eTaxis consume less energy and generate less greenhouse gas emissions and air pollutants; (2) a premium service caters for a market niche with a higher fare, a higher fare can reduce the subsidy level while increasing incomes for both the taxi owners and drivers; (3) the premium service requires a smaller initial fleet size, which implies fewer start-up inputs and can also serve as a trial and demonstration scheme in a city; and (4) the dispatching mode allows eTaxis to be fast-charged multiple times a day, provides more direct services than other operating modes, and further reduces environmental impacts.

3. DATA

3.1 Hong Kong as a case study

Taxis form an important part of Hong Kong's transportation system. Currently, there are 18,163 licensed taxis and about 40,000 active taxi drivers providing personalized services to nearly a million customers daily (Transport Department, 2017). The 18,163 taxis are owned by over 9,000 license holders, 60% of them are owned by individuals, and the rest are owned by taxi associations. The majority of the individual owners are drivers themselves who also rent their vehicles to other drivers (Legislative Council, 2015, 2016, 2017). Hong Kong taxi market is highly concentrated at the cruising mode, which taxis circulate on the streets in search of customers, resulting in the long driving mileage and high energy consumption (Wong et al., 2014). Almost all taxis in Hong Kong are powered by Liquefied Petroleum Gas (LPG). The poor maintenance of the catalytic converters has made the LPG taxis one of the major sources of NO_x pollution (Lau et al., 2012). In an attempt to promote greener transport, the government introduced 48 eTaxis in 2012 by offering taxi owners a one-off HK$300,000 subsidy from the Pilot Green Transport Fund. However, due to their insufficient driving range, long charging time, and the shortage of charging facilities, taxi drivers claimed that their incomes were heavily impaired. As a result, all 48 eTaxis is no longer operational (Environmental Protection Department, 2015).

In addition to the environmental deficiencies, local taxis also suffer from a severely poor service reputation. The annual number of complaints about taxi service quality grew from 7,253 in 2006 to 10,547 in 2016 (Transport Advisory Committee, 2017). The government, the taxi industry, and the media all acknowledged that the taxis were in need of service improvements (Transport Advisory Committee, 2008). Nonetheless, due to lack of competition and effective means of control, many attempts made by the local taxi associations to improve service quality had no real impact. The consistently low service standard not only affects customer experiences but also encourages taxi customers to make more use of private cars or even to purchase new ones, which may further worsen pollution and energy consumption issues.

Given Hong Kong's situation, this newly proposed operational design can be considered, in particular, by switching only a portion of the conventional LPG taxis to premium eTaxis may not significantly affect taxi medallion prices and not add more vehicles to the streets. The past efforts had tried to address the environmental and service issues individually without success. New possibilities have risen that enable the industry to consider improving the service quality and environmental friendliness of taxis at the same time. The study findings can help improve the taxi market in Hong Kong and provide some policy insights to other cities with a similar taxi service provision.

3.2 Data collection

Questionnaire surveys were conducted from November 2016 to January 2017 targeting the taxi owners and drivers. Face-to-face interviews were conducted at seven LPG filling stations and popular shift-changing locations. Moreover, thousands of questionnaires with prepaid envelopes were distributed to the taxi drivers at selected taxi stands across Hong Kong and to the taxi associations. 854 completed questionnaires were obtained in total, including 12 responses from the taxi associations, 687 responses from the taxi drivers, and the remaining 155 from those who both owned and drove their taxis. The samples of the taxi associations represent 21% of the 56 taxi associations that own 7,300 taxis in Hong Kong (Transport Department, 2017). The response rates were 41% in face-to-face interviews, and 7% in mail-back surveys.

The questionnaire comprised three parts: (1) to collect the operating characteristics of taxi owners and drivers; (2) to identify important factors of buying and renting a premium eTaxi; and (3) to obtain the purchasing and renting decisions of taxi owners and drivers, respectively, in hypothetical scenarios.

3.3 The operating characteristics of interviewed taxi owners and drivers

Figure 1 summarizes the operating characteristics of the respondents collected from the first section of the questionnaire. For the taxi owners, it is observed that the majority of them owned only one vehicle. Respondents who owned more than three taxis were scarce. This distribution agrees with the recent taxi license ownership statistics published by the Legislative Council (2017). More than half of the interviewed owners reported that their vehicles were aged over eight years, and almost 30% were 12 years or above. Regarding owners' monthly rental income, over 50% of the respondents had an average income between HK$20,001 and 25,000 (which was equivalent to a per-shift rent level of HK$360 to 460 given a 28-day, 2-shift-per-day operation per month).

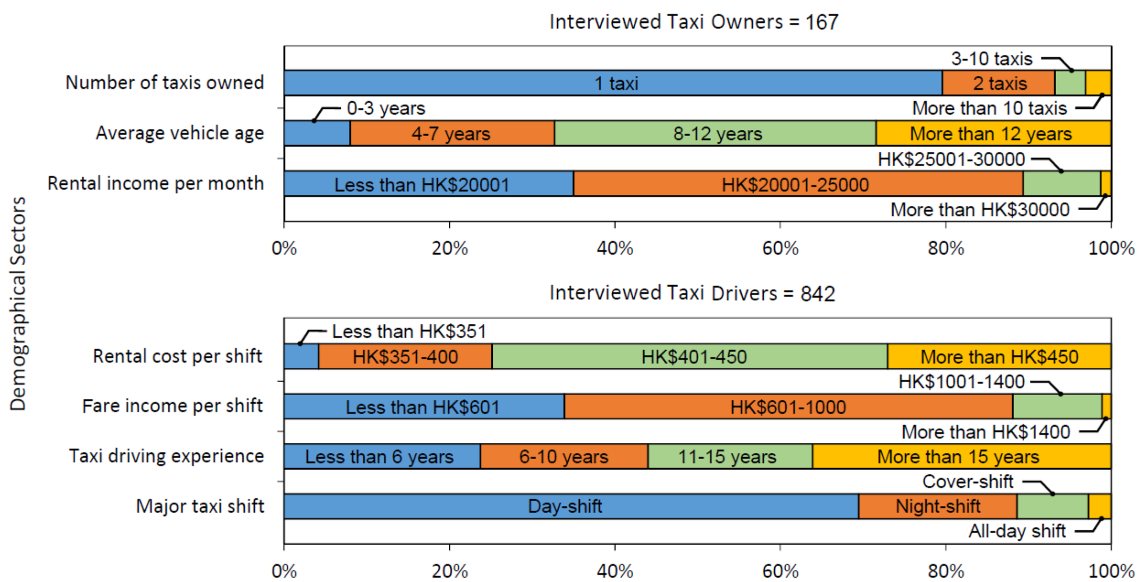


Figure 1. The operating characteristics of the interviewed taxi owners and taxi drivers

Among the taxi drivers, slightly less than 50% of them paid a rent of between HK$400 and 450. Very few enjoyed a rent of lower than HK$350, while nearly 30% were at the higher rent level of HK$450. Regarding drivers' income per shift, the majority of the interviewees had an income of between HK$601 to 1,000. Because of the low passenger demand after midnight, some taxis were not operated during night time. The majority of respondents were day-shift drivers, which is considered reasonable to reflect the actual situation.

3.4 The important aspects in the considerations of purchasing and renting eTaxis

In the second section of the questionnaire, the respondents were given eight operational aspects of eTaxis that may influence their willingness-to-switch. They were asked to give a score from 1 to 5 representing the level of importance of each aspect, where 1 meant highly unimportant, 3 meant neutral, and 5 meant highly important. Figure 2 illustrates the relative importance of each operational aspect.

It can be seen that charging time, the driving range per charge, and the location of chargers were the highest rated factors among all groups of respondents. The results justify the need for fast-charging facilities as well as increasing the number of charging locations. There are currently 1,600 public chargers in Hong Kong, of which only 24 of them are standard semi-fast-chargers. The provision of chargers is inadequate to support a reasonable fleet of eTaxis. In comparison, the income after switching was slightly less important. It may suggest that the respondents had higher confidence in the income from premium eTaxis than range-related aspects. All the cost aspects were of great importance to respondents who owned vehicles but were not drivers themselves. To this group of respondents, taxis were an investment. It explains the high importance of battery lifespan, which represents the length of return-on-investment. The group of respondents who drove their own taxis situates in between pure owners and pure drivers.

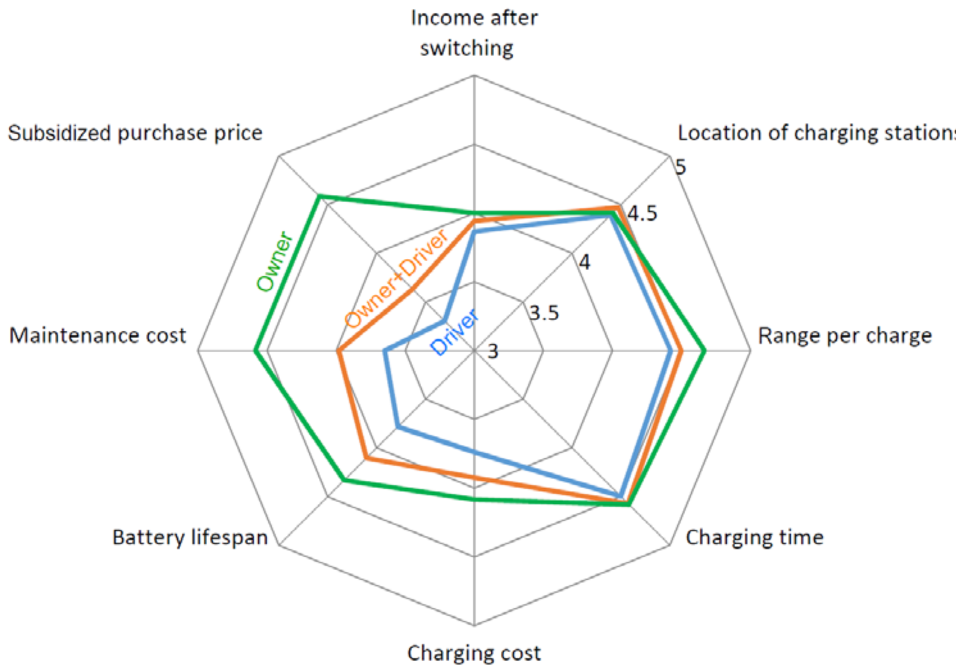


Figure 2. The importance levels of various operational aspects

3.5 Taxi owners' and drivers' preferences between premium eTaxis and LPG taxis

The third section of the questionnaire aims to capture the decision-making processes of whether to switch to the premium eTaxis. This section targets the taxi owners and drivers separately. The taxi owners were asked whether to purchase a premium eTaxi while the taxi drivers were asked whether to rent a premium eTaxi from taxi owners.

Previous literature has repeatedly found that car buyers appear to fixate on the purchase price of BEVs (e.g., Deloitte, 2011; Larson et al., 2014). As seen in Figure 2, the taxi owners considered the cost of owning a premium eTaxi highly important. Additionally, other economic aspects including the income associated with owning an eTaxi, the cost of maintaining the fleet, and the lifespan that determines the period of return were also deemed important. Therefore, in modeling the decision-making process of taxi owners, we defined the purchase price (less any government subsidy), rental income per month, operational cost per month, and battery lifespan as the four attributes in the taxi owners' choices.

For the taxi drivers, in addition to the same consideration factors of cost and income, factors that may adversely affect their revenue-making were also highly important, namely the range per charge and accessibility to a charging station. Therefore, we defined the income per shift, the rental cost per shift, access time (including queue time) to a charging station, and the range per 10-minute fast-charge as the four attributes in taxi drivers' choices.

Table 1 tabulates the attributes and their levels for both the taxi owners' and drivers' decisions. Three levels were designed for each attribute to capture the non-linear effects. A fractional factorial design was adopted to generate 28 hypothetical scenarios, and they were randomly divided into seven sets. Each respondent was asked to make four independent decisions in four hypothetical conditions. In total, 668 observations from the owners and 3,368 observations from the drivers were obtained.

Table 1. Attributes and levels used in the stated preference survey

	Attributes	Levels
Owner decisions	Subsidized purchase price ('000 HK$)	200, 250, 300
	Rental income per month ('000 HK$)	22, 27, 32
	Operational cost per month ('000 HK$)	2.5, 3, 3.5
	Battery lifespan (year)	7, 10, 13
Driver decisions	Income per shift (HK$)	1200, 1500, 1800
	Rental cost per shift (HK$)	420, 470, 520
	Access time to a charging station (min)	10, 14, 18
	Range per 10-minute fast-charge (km)	50, 70, 100

4. METHOD

4.1 Binary logistic regression models for taxi owners and taxi drivers

The respondents were asked to make binary choices between the two alternatives of conventional LPG taxis and premium eTaxis. The theoretical basis of random utility as postulated in Domencich and McFadden (1975) is applied to formulate the probability of their individual choices. To predict whether conventional LPG taxis or premium eTaxis will be chosen, the values of the utilities of one alternative is contrasted with those of the other and transformed into a probability value (Ortúzar and Willumsen, 1994). Based on the assumption that each taxi owner or taxi driver chooses between a conventional LPG taxi and a premium eTaxi by maximizing his/her overall utility, a binary logistic modeling approach is used to describe their choice behaviors. This modeling form has been commonly adopted in a lot of transportation research on various aspects (e.g., Jai et al., 2018; Wong et al., 2018; Zhao et al., 2018). Two independent binary logistic regression models for taxi owners and drivers were calibrated based on the data collected in the stated-preference questionnaire surveys. The model for taxi owners takes the following form:

$$P_i = \frac{1}{1 + \exp\left[-(\alpha_{\mathrm{U}} U + \alpha_{\mathrm{I}} I + \alpha_{\mathrm{E}} E + \alpha_{\mathrm{B}} B + W)\right]}, \tag{1}$$

where P_i is the probability that a taxi owner *i* chooses owing a premium eTaxi. U, I, E, and B denote the subsidized purchase price of a new premium eTaxi, the rental income per month, the operational cost per month, and battery lifespan, respectively. α_{U}, α_{I}, α_{E}, and α_{B} are the respective coefficients. W is the constant term for taxi owners.

Similar to Equation (1), the model for taxi drivers takes the following form.

$$Q_j = \frac{1}{1 + \exp\left[-(\beta_{\mathrm{N}} N + \beta_{\mathrm{R}} R + \beta_{\mathrm{A}} A + \beta_{\mathrm{M}} M + D)\right]}, \tag{2}$$

where Q_j is the probability that a taxi driver *j* chooses renting a premium eTaxi. N, R, A, and M represent the income per shift, the rental cost per shift, access time (including queue time) to a charging station, and the range per 10-minute fast-charge, respectively. β_{N}, β_{R}, β_{A}, and β_{M} are the respective coefficients. D is the constant term for taxi drivers.

It is important to clarify that the attributes in Equations (1) and (2) are the perceived values to a taxi owner or a taxi driver, respectively, of the associated decision. It is assumed that every taxi owner or driver has the same perception of attributes in this study. Therefore, the subscripts *i* and *j* are omitted on the right-hand side of Equations (1) and (2) for the sake of simplicity.

4.2 The equilibrium modeling concept

Figure 3 illustrates the relationships and interactions between taxi owners, drivers, and the external factors with are mostly controlled by the government and the customers. The purchase price a taxi owner has to pay is influenced by vehicle market value, registration tax, as well as the amount of the government subsidy. As taxi drivers usually rent their vehicles from taxi owners, the purchase price also determines the rent level that is imposed on these drivers. In return, this cost level is translated to the income level of the owners. A large government subsidy given to the taxi owners can reduce the level of rent charged to the taxi drivers while maintaining a reasonable level of income for the taxi owners. These three variables are inter-related and inter-dependent across two modeling levels of the taxi owners and drivers. Meanwhile, the income of the taxi drivers is dependent on the passenger demand and the fare structure of the premium service. A previous government study revealed that 40% of the customers would use both the ordinary and the premium services, 9% of the customers indicated that they would "definitely use the premium service" if the fare were 30% to 50% higher (Legislative Council, 2016). However, the passenger demand is not within the scope of this study and is suggested to be addressed in a future study. Operational costs consisting of maintenance, annual license, and insurance costs are also borne by the owners. For the drivers, the time taken to a charging station is affected by the density and location of charging stations, as well as the fleet size of premium eTaxis. Lastly, battery lifespan (a factor that influences taxi owners' decision) and the driving range per 10-minute fast-charge (a factor that influences drivers' decision) are both limited by the development of batteries and charging technologies.

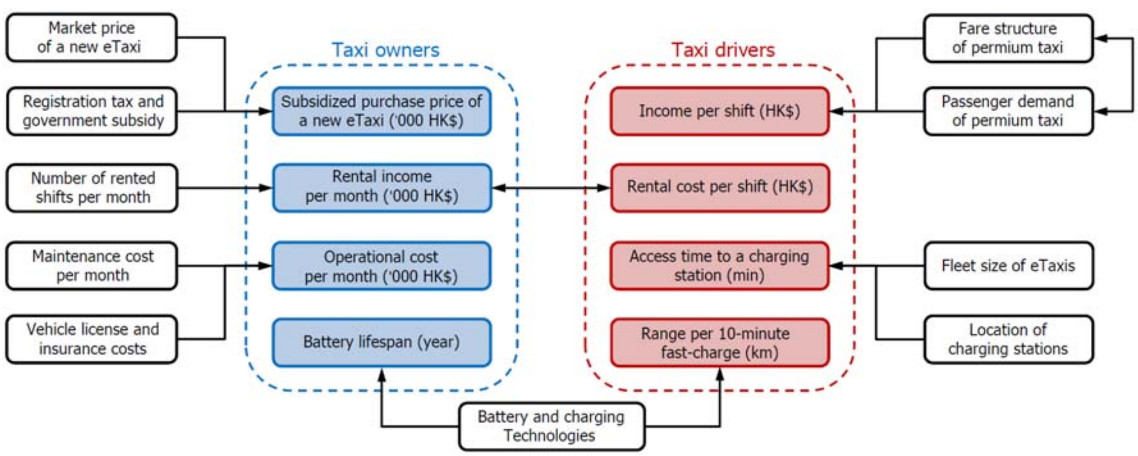


Figure 3. Interactions between taxi owners, taxi drivers, and other external factors

The owners' monthly rental income interacts with the drivers' rental cost per shift as well as the number of rented shifts per month (n), that is

$$I = nR\,. \tag{3}$$

The access time (including queue time) is a perceived value in relation to how easily accessible the charging facilities are. In reality, this time consists of a density part and a quantity part, where the former depicts the distribution of charging locations in a city and the latter reflects the number of chargers provided at each location. However, the exact value requires a separate simulation study considering the trip routes, taxi movements, the geographical layout, queueing behaviors, and the dispatching method. It is suggested to be determined in a future study. As the access time is directly related to the overall charging infrastructure provision, we use this variable to illustrate how different provision level may affect taxi drivers' willingness-to-switch in the sensitivity analyses.

In addition to the taxi owners and drivers, the government plays an important role in determining the percentage-of-switch from conventional LPG taxis to premium eTaxis. For the incentives to the taxi owners, the government may consider (1) providing direct subsidies to the purchase of new premium eTaxis. For the incentives to the taxi drivers, the government may consider (2) adjusting the fare structure for premium services to maximize drivers' income level and (3) providing more charging stations for reducing the access time. Sensitivity analyses are performed to determine the effects of these three approaches on the percentage-of-switch.

4.3 The iterative solution procedure

It is reasonable to assume that the owners of conventional taxis become more interested in switching to eTaxis when there are plenty of demands from taxi drivers. The owners can then ask for a higher rental cost from the taxi drivers. Similarly, the taxi owners become hesitant in switching where there is a lack of taxi drivers, which implies that the owners may have to reduce the rental cost to attract the taxi drivers to the market. More taxi drivers enter the market when the rental cost of eTaxis is low and leave the market when they cannot afford the high rental cost. As a result, we believe that the taxi market is self-adjusted by varying the monthly rental cost to achieve an equilibrium that the probability of the taxi owners P_i^{O} who are willing to switch to own premium eTaxis is the same as that of the taxi drivers P_j^{D} who are willing to rent and operate premium eTaxis. Therefore, an iterative solution procedure is proposed for the equilibrium model to obtain a convergent solution. An adjustment factor to the monthly rental income is used in this procedure and expressed as follows:

$$\omega^{(k)} = \begin{cases} (1-\delta), & \text{if } P_i^{(k)} - Q_j^{(k)} > \varepsilon; \\ (1+\delta), & \text{if } Q_j^{(k)} - P_i^{(k)} > \varepsilon, \end{cases} \tag{4}$$

$$I^{(k)} = \omega^{(k)} I^{(k-1)}, \tag{5}$$

where $0 < \delta < 1$, $\varepsilon > 0$. $\omega^{(k)}$ is the adjustment factor in iteration *k*. $P_i^{(k)}$ and $Q_j^{(k)}$ are the probabilities of the taxi owners and drivers buying and renting a premium eTaxi, respectively. If the difference between these two probabilities is within the acceptable tolerance ε, no adjustment is made to the monthly rental income; otherwise, the reduction factor $(1-\delta)$ or the expansion factor $(1+\delta)$ is applied. Equations (4) and (5) are used to update the monthly rental income in Equation (3) during the solution procedure until a convergent solution is obtained. The solution procedure can be summarized as follows:

Step 1 – Initialization and parameter setting

Initialize U, $I^{(0)}$, E, B, N, A, M, and n. Set δ and ε. Set the iteration number $k = 1$.

Step 2 – Compute the probability of the taxi owners buying a premium eTaxi

Apply the taxi owner model in Equation (1) based on the monthly rental income $I^{(k\text{-}1)}$ in iteration $k-1$ to obtain $P_i^{(k)}$.

Step 3 – Compute the probability of the taxi drivers renting a premium eTaxi

Apply the taxi driver model in Equations (2) and (3) to obtain $Q_j^{(k)}$.

Step 4 – Convergence test

If $\left|P_i^{(k)} - Q_j^{(k)}\right| \le \varepsilon$, then stop; otherwise, go to Step 5.

Step 5 – Adjust the rental income per month for the taxi owners

Adjust the rental income per month $I^{(k)}$ according to Equations (4) and (5). Then, set $k = k+1$ and go to Step 2.

The above solution procedure is repeated for different combinations of the subsidized purchase price of a new eTaxi, driver's income per shift, and the charging facility provision factor to evaluate how the policy measures can influence the percentage-of-switch from conventional LPG taxis to premium eTaxis.

5. RESULTS AND DISCUSSION

5.1 The results of the two sub-models

The widely used modeling software SPSS was used to calibrate the sub-models in this study. The coefficient of each variable in the choice models of taxi owners and drivers are tabulated in Table 2. Three out of four variables in the owner model have their parameters that are significant at the 1% level, whereas all parameters in the driver model are significant at the 1% level. Therefore, we conclude that the subsidized purchase price, the monthly rental income, and battery lifespan are the significant factors that affect the choices of taxi owners; the income per shift, the rental cost per shift, the access time to a charging station, and the range per 10-minute fast-charge are the significant factors that affect the choices of taxi drivers. The McFadden's pseudo R^2 of the owner and the driver models are 0.21 and 0.13, respectively. According to McFadden (1974), a pseudo R^2 value between 0.2 and 0.4 represents "excellent fit"; the values imply that the owner model provides a rather good fit whereas the driver model is slightly less so.

In the owner model, the purchase price is highly influential – note that the coefficient reflects the change in willingness-to-buy per HK$1,000. The negative coefficient (-0.016) implies that a higher subsidy level leads to higher taxi owners' willingness-to-buy. As explained in the earlier sections, a premium service with higher fare increases the income of drivers and justifies the owners to charge a higher rent from the drivers. The coefficient of rental income is positive (0.239), which suggests that the expected increase in rental income encourages the owners to buy. The battery lifespan also has a positive coefficient (0.273). A longer battery lifespan certainly makes owning eTaxis more attractive – each additional year of lifespan equates to a considerable increase in their willingness-to-buy. The magnitude of the coefficient of battery lifespan is stronger than that of rental income as a longer battery lifespan results in a longer profit-making period. Operational cost, on the other hand, does not return a statistically significant result. However, this variable still shows a trend that a high operational cost can potentially deter the owners from buying electric vehicles. The negative constant implies an inherently resisting attitude of the owners. Switching to a new vehicle type poses more business risks to the taxi owners than non-switching and requires the adaptation of the taxi owners to a new operation mode.

Table 2. The results of the binary logistic regression models

Models	Attributes	Coefficients [*t*-statistics][a]
Owner decisions	Subsidized purchase price ('000 HK$)	-0.016[b] [-6.5]
	Rental income per month ('000 HK$)	0.239[b] [8.6]
	Operational cost per month ('000 HK$)	-0.493 [-1.7]
	Battery lifespan (year)	0.273[b] [6.8]
	Constant for taxi owners	-4.187[b] [-4.9]
Driver decisions	Income per shift (HK$)	0.002[b] [11.2]
	Rental cost per shift (HK$)	-0.003[b] [-3.1]
	Access time to a charging station (min)	-0.075[b] [-4.9]
	Range per 10-minute fast-charge (km)	0.034[b] [17.5]
	Constant for taxi drivers	-4.244[b] [-7.4]

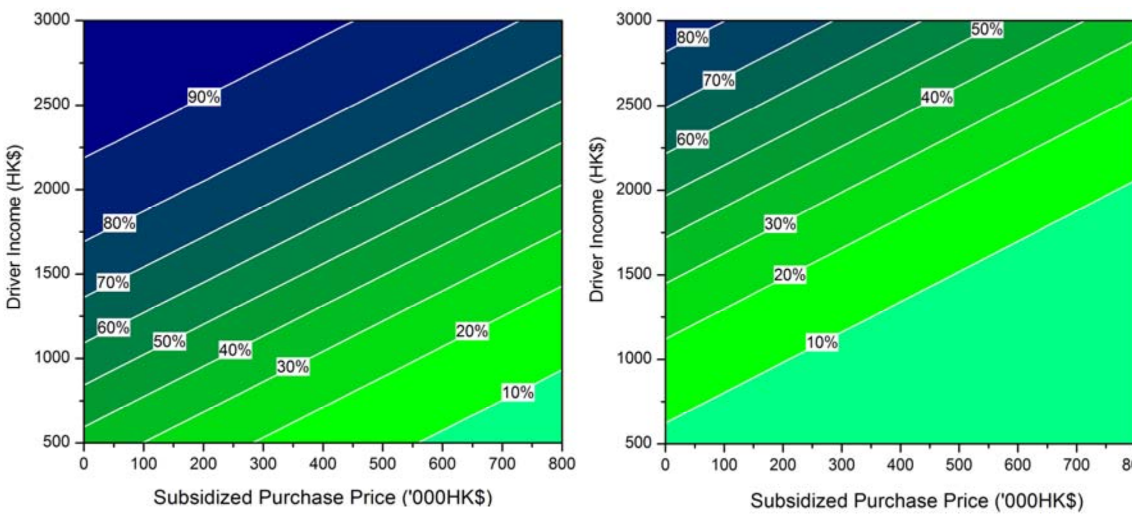
Notes: [a] The values in brackets represent the t-statistics of the explanatory variables.
[b] The parameters are significant at the 1% level.

The taxi drivers perceive the switch somewhat similarly to the taxi owners. The income and rental cost per shift are highly influential in taxi drivers' decisions of whether to switch to premium eTaxis. The coefficient of the rental cost per shift is negative (-0.003). It indicates that the possible increase in the rental cost adversely reduces the drivers' willingness-to-switch. As the coefficient of the income per shift is 0.002, the magnitude of the positive impact associated with an increase in income is smaller than the negative impact associated with an increase in cost. Therefore, the potential increase in income must outweigh the increase in rent to ensure a positive effect in the drivers' willingness-to-switch. As illustrated in Section 3, the rental cost per shift will, in return, affect taxi owners' incomes. Therefore, the financial incentive to the taxi owners will have an indirect but definitive effect on the drivers' willingness-to-switch. The coefficients of the access time and the driving range are -0.075 and 0.034, respectively. They represent that the taxi drivers were less influenced by the driving range than by distance to the nearest charging station. The longer it takes to reach a charger, the less time a driver has on revenue-making. Likewise, the longer the driving range per charge sustains, the longer a driver can spend on serving customers. Notably, the negative constant also captures the drivers' inherent unwillingness to change, which is understandable as the switch from driving conventional LPG taxis to premium eTaxis imposes a potentially drastic change to their accustomed work style and implies additional risks to profit making. The negativity also captures the group of drivers who do not wish to meet the higher requirements associated with premium services.

5.2 The results of the sensitivity analyses

Assume the (initial) monthly rental income of owners is HK$27,000, the monthly operational cost is HK$3,000, the battery lifespan is 7 years, the (average) travel time to the nearest charging station is 10 minutes, the range per 10-minute fast-charge is 100km, and the number of rented shifts per month is 56 (2 shifts per day and 28 days per month). Given that $\delta = 0.01$ and $\varepsilon = 0.0001$, a set of sensitivity analyses has been performed to evaluate the effectiveness of different settings of policy measures.

Two values of access time have been taken to compare the different results of different charging facility provision levels. Access time = 0 minute indicates a perfect situation when the access time to any charger can be neglected by the drivers, representing an extremely optimal situation where the density and quantity of charging facilities match the demand perfectly. Access time = 30 minutes indicates the current situation when a driver needs 30 minutes to reach an available charger. According to the Environmental Protection Department (2018), at present, there is only one common type fast-charger every 10 km in Hong Kong. Noted that the average driving speed is only 22.7 km/h in the urban area (Transport Advisory Committee, 2014), the access time to a fast-charger in today's situation is at best 30 minutes. This value exemplifies an extremely suboptimal situation where the charging facilities are scarcely distributed and the number of chargers at each location is insufficient. We believe that the actual percentage-of-switch will be controlled with these upper and lower bounds under different charging facility provision levels.

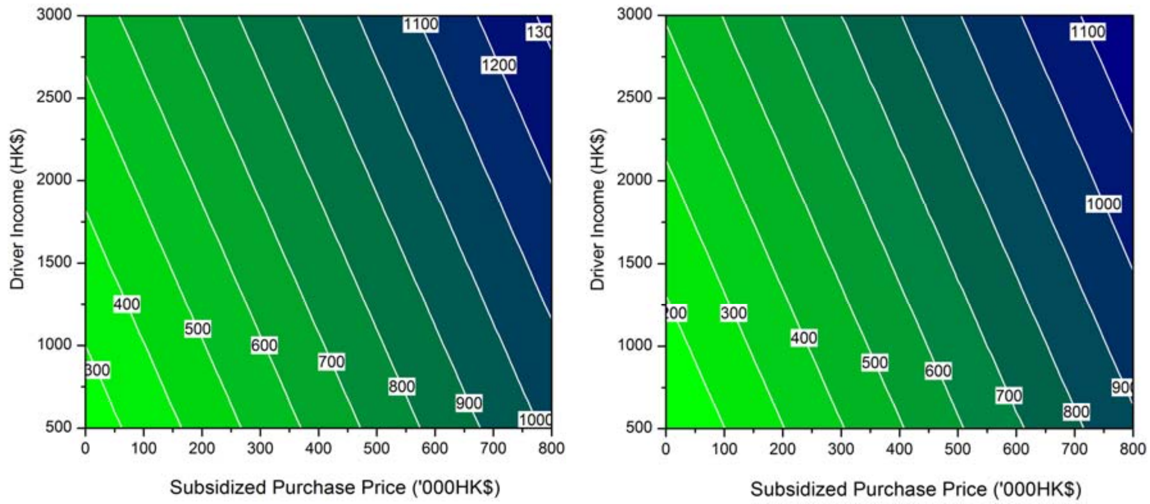


(a) Access time = 0 min

(b) Access time = 30 min

Figure 4. The percentage-of-switch to premium eTaxis in relation to the subsidized purchase price and the driver income

Figure 4 shows the different patterns of the percentage-of-switch in relation to the subsidized purchase price and the (anticipated) driver income per shift. Figures 4a and 4b demonstrate the vast differences of the percentage-of-switch at a perfect scenario and a "do-nothing" scenario regarding charging facility provision levels. In general, the percentage-of-switch increases as the purchase price decreases (i.e., the subsidy level increases) and driver income grows. In 2012's attempt, the government provided an HK$300,000 through the Pilot Green Transport Fund to the owners who switched to eTaxis. The subsidized purchase price of an eTaxi was about HK$300,000. Taking this as the benchmark, when the access time is at the perfect 0-minute level, a nearly 40% of switching can be expected when the driver income is maintained at around HK$1,100, which is comparable to the current driver income. If no subsidy is provided and the full market price of a typical eTaxi is HK$800,000, 15% of switching can still be achieved. Conversely, when the access time is at the low end of 30-minutes, switching to eTaxis became increasingly difficult. With the same combination of the HK$300,000 subsidy and the driver income of HK$1,100, the percentage-of-switch is only 9%. For no subsidy is provided and the owners must bear the full price, the attainable switching is as low as 2%. Altogether, the graphical results in Figure 4 show that a higher subsidy level leads to a higher the percentage-of-switch and a higher driver income makes the effect stronger. Meanwhile, when the infrastructure input is sufficient, a low or even no subsidy can still yield in a reasonable initial fleet size to gain market penetration.



(a) Access time = 0 min (b) Access time = 30 min

Figure 5. Rental cost per shift (HK$) of premium eTaxis in relation to the subsidized purchase price and the driver income

The rent level per shift determines the cost of the drivers and the income of the owners. Figure 5 presents the changing rent levels that are acceptable to both the owners and drivers at the same combinations of the subsidized purchase price and the (anticipated) driver income. Similarly, two figures are shown for the two extreme access time values. From the different directions of the contour lines in Figures 4 and 5, it is discernible that while the percentage-of-switch is sensitive to both the purchase price and the driver income, the rental cost is mostly sensitive to the owners' cost. This pattern suggests that the taxi owners are likely to increase the rent level significantly if fewer subsidies are offered. Looking at the variations in the two extreme values of access time, with the same combination of HK$300,000 purchase price and HK$1,100 driver income, the resultant rent levels are around HK$600 and HK$450, respectively when access time is perfect and sub-optimal. For a much lower willingness-to-switch among the drivers, the owners have to charge a lower rent. It consequently drives down the willingness-to-buy of the owners. However, the range of rent levels is not heavily impacted by the different charging infrastructure provision level as the percentage-of-switch. The rents are an economic decision of the owners rather than an operational constraint of the drivers.

5.3 Environmental benefits

Currently, over half of the taxis in Hong Kong are aged ten years or older and are nearing the time to be replaced with new vehicles. The proposed premium eTaxis is a feasible option to reduce the environmental impacts of the taxi industry. In Hong Kong, the average per-vehicle NO_x emission intensity is 0.07 g/km (Ning and Chan, 2007), and the CO_2-equivalent emissions per passenger-kilometer of LPG taxis and eTaxis are 121 g and 107 g respectively (Leung et al., 2010; CLP, 2018). Given that the annual driving mileage of all taxis is about 2,399 million km (Transport Advisory Committee, 2014), for every 10% of LPG taxis switched to eTaxis, 18 tons of NO_x can be taken off the streets while 3,359 tons of CO_2-equivalent emissions can be reduced. The government is working with the power generation companies to reduce the share of coal to 25% by 2020 (Environment Bureau, 2017). We can expect that the CO_2-equivalent emission of eTaxis will continue to decrease and their impact on reducing greenhouse gas emissions will expand. Furthermore, the unit fuel consumption of the LPG taxis is 0.111 L/km. For every 10% of switching to eTaxis, 26.6 million liters of LPG can be saved. A reduction of CO_2 emissions can also produce significant social cost savings. Literature suggests that the unit social cost of CO_2 emissions is up to HK$1,711/ton (Moore and Diaz, 2015), a social cost saving of HK$6 million for every 10% of switching. The reduction of other air pollutants and energy consumption will also bring considerable savings on external cost for the society as a whole.

5.4 Policy implications

The government's environmental targets determine the required eTaxi fleet size. Whether the target fleet size is achievable is highly dependent on the level of subsidies, as well as the income levels expected by both the drivers and the owners. Providing incentives to the industry in support of the transition to greener vehicles has been in practice in Hong Kong. In as early as 2000, the government offered financial aid to the taxi owners to upgrade the highly polluting diesel vehicles to LPG vehicles. In 2012, the government offered up to HK$300,000 to taxi owners through the Pilot Green Transport Fund to support their switch to eTaxis; an ongoing incentive scheme supporting the commercial vehicles (including buses) to upgrade polluting vehicles to meet Euro IV standards is also in place. Moreover, the government is also supporting the bus industry in testing the feasibility of electric buses. The government can place itself in a more pivotal position to promote wider use of eTaxis through direct subsidies. For instance, if the 2012 Pilot Green Transport Fund value of HK$300,000 can be offered again, the subsidized purchase price of a common model of BEVs, Tesla Model S, will cost HK$260,000, which is as low as that of an LPG taxi. Currently, a typical Toyota Crown LPG taxi operating in Hong Kong costs about HK$250,000 (Toyota Hong Kong, 2017), and a typical Tesla Model S costs HK$560,000 (Tesla Inc., 2017). It can secure a minimum percentage-of-switch between around 10% and 45%, depending on whether the government takes an aggressive or a "do-nothing" approach on the provision of chargers.

On the other hand, higher driver and owner incomes through the higher fare charged by providing a premium service will further increase the percentage-of-switch at the same subsidy level, or decrease the subsidy required at the same percentage-of-switch. When sufficient charging infrastructure is provided and driver income increases from the current HK$1,100 to 1,300, the required subsidy can be reduced to only HK$100,000 for a 30% switch. Therefore, the fare structure of the premium service should be established strategically to ensure sufficient passenger demand and maximize driver income.

Indeed, the provision of charging facilities is highly influential to the percentage-of-switch. A clear contrast can be seen when the access times to the nearest charger are at 0 minute and 30 minutes. In the extreme case of owners having to pay an HK$800,000 purchase price, we can still achieve a percentage-of-switch as high as 25% when driver income increases to HK$1,500 while highly accessible chargers are distributed throughout the city. With or without subsidy, the provision of charging facilities is instrumental in meeting a reasonable eTaxi fleet size.

Other than the significant attributes discussed above, more streamlined administration and policy frameworks are also desirable. Regarding the administration framework, a centralized dispatching platform should be established to manage the demand and supply of the premium eTaxi service. As shown in the model results, both the access time to a charging station and the range per 10-minute charge are influential to the taxi drivers' decisions. Therefore, such platform should have the ability to dispatch a premium eTaxi to the nearest customer who made a request and to assign a premium eTaxi to the nearest charging station when necessary to (1) minimize range loss due to excessive driving between assignments and between charges and (2) minimize access time to the charging stations for the taxi drivers. The model results also reveal that both the taxi owners and the taxi drivers wish to reduce their respective costs. In addition to providing subsidies, the policy framework should also aim to reduce other ancillary cost items such as licensing and insurance fees. Moreover, although the variable of operational cost did not show a statistically significant result in the model, the policy setting should not neglect the potentially positive impact of a good provision of maintenance services. The government may consider facilitating maintenance agreements between premium eTaxi operators and BEV manufacturers to ease maintenance and overhaul processes for the taxi owners and drivers. Last but not least, battery performance such as charging time, the range per charge, and lifespan are of great concern to potential premium eTaxi buyers and renters. The premium eTaxis proposed in this study requires a battery to be fast-charged frequently throughout a day's operation, and therefore, batteries may face a higher risk of early deterioration. An industry or government-led battery replacement scheme can be helpful to extend the revenue-making time of the premium eTaxi fleet, hence increasing the overall willingness-to-switch and willingness-to-buy of the taxi owners and drivers, respectively.

Regarding service improvement, as discussed in Section 2, better riding comfort can be provided by the electric vehicles, and the dispatching operation with onboard GPS device can eliminate refusal of hire, fare overcharging, and intentional detours. However, other essential elements of a premium service such as driver's professionalism, courteousness, and the driver's compliance to service standards are the non-quantifiable elements that also form an integral part of a premium service. We suggest the policymakers to carefully define the service requirements and implementation plans before launching any premium services. For instance, a dedicated permit is suggested before operating a premium eTaxi, and this permit is attainable through additional tests and appraisals. To ensure a consistently high-quality service of the premium eTaxis, the conventional taxi industry could consider establishing a customer-feedback based assessment system that can monitor drivers' professionalism while addressing customers' complaints and concerns more efficiently. We believe that there are quality taxi drivers among Hong Kong's existing taxi driver population who are willing and capable of providing high-level services to their customers. The premium eTaxi proposal provides such an opportunity for them and rewards them with a better working environment and a higher income.

We have applied the proposed premium eTaxi design under the operating environment of Hong Kong. With empirical data, we are able to establish equilibrium matrices of taxi owners, drivers, and the government in terms of cost, income, subsidy level, and infrastructure provision. Based on the insights revealed in the Hong Kong example, we believe that the proposed design and the equilibrium model can be applied to the taxi operations in other metropolitan areas. Regarding operational design, deploying eTaxi as a premium service can reduce the environmental impact of the taxis while improving their service standards. Meanwhile, the higher fare charged by the premium service also reduces the direct monetary subsidy that is usually imperative to the successful deployment of electric vehicles. Regarding the choice of taxi owners and drivers, the importance of revenue making duration both in terms of how many years a battery can last for the owners and how frequent a battery needs to be charged for the drivers are also meaningful to other cities. This equilibrium structure provides a framework for the cities where taxi drivers rent their vehicles from medallion and license owners or taxi companies. Such renter-owner relationship can be found in many cities such as New York, Boston, Vancouver, Stockholm, London, and Shanghai (Schaller 2007; Hagman and Langbroek, 2018; Li et al., 2016). The proposed equilibrium model could be useful for the policymakers in these markets to determine their degrees of involvement in relation to their respective environmental, social, and economic targets as part of the consideration of eTaxi deployment.

6. CONCLUSION

The taxi industry is witnessing rapid changes worldwide. As a public service, its environmental performance and service quality are both under scrutiny. The popularization of BEVs sheds new light on reducing taxis' environmental impact. However, the higher ownership cost of BEVs hampers the wider use of this mode. Having recognized the existing challenges of the taxi industry and the need for higher taxi service quality, this paper proposed to operate eTaxis as a premium service to cater for a market niche, to incentivize the participation of the industry by the possibility of charging higher fares, to reduce government's monetary input, and to improve the environmental-friendliness of the taxi industry.

Hong Kong's aging and polluting LPG taxi fleet is contributing to high roadside pollution and CO_2 emissions. It also has a poor service reputation. The government's failed attempt at introducing BEVs into the taxi fleet showed a number of critical shortcomings and the taxi industry objected to the proposal of adding new taxis to the premium market. This study takes Hong Kong as a case study and conducted stated-preference surveys of the taxi owners and drivers to identify the factors that may influence their willingness-to-switch and willingness-to-buy to the proposed premium eTaxis, respectively. Two binary logistic regression models have been calibrated. The results showed that the owners and drivers were highly sensitive to the financial aspects, i.e., the income and cost of operating the premium eTaxis. The operational aspects, including the range per charge, the access time to a charging station, and battery lifespan have also shown strong influential impacts. Based on the calibrated results, an equilibrium model with a solution procedure is developed to examine how the change of cost and income of operating premium eTaxis would affect the percentage-of-switch in relation to the different levels of government input. Government input can be reflected in the forms of a direct subsidy and input into charging facilities. The importance of the financial aspects of the models suggests a direct government subsidy would lead to a higher percentage-of-switch. The sensitivity analyses with different charging facility provision levels revealed that the more accessible the chargers are, the less the subsidy is needed for the same percentage-of-switch. When operating a premium eTaxi becomes highly convenient and the charging process does not affect the revenue-making hours of the drivers, the deployment of eTaxis can be left entirely to the market with a low or even no subsidy.

The technology of electric vehicles is advancing and the acceptance of the public is growing. The new operational design and models proposed in this study offer a new consideration to the deployment of a greener taxi vehicle with the potentials to reduce greenhouse gas emissions, roadside air pollutants, and energy consumption and to improve the quality of the taxi services. A number of areas need to be further explored in future studies: (1) a simulation study should be developed to determine the access time to chargers more accurately. The results will provide more tangible policy recommendations to the government in terms of the locations, capacity, and density of chargers to be placed; and (2) a stated-preference survey to interview taxi customers should be conducted to understand their preference between the conventional LPG taxis and the premium eTaxis. The results will help model the passenger demands for both markets and provide suggestions to the government regarding the fare structure of the premium service.

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