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When to switch to a hybrid electric vehicle: A replacement optimisation decision

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ABSTRACT

This research proposes a replacement purchase decision model in which trade-in and subsidy are provided for vehicle owners to replace their old conventional fuel-powered vehicles with hybrid electric vehicles (HEVs). The uncertainty in fuel prices has distinguished this model for its ability to illustrate a time-dependent cost trade-off between HEV-induced economic benefit and replacement cost. A cost-effective replacement time (CERT) is quantitatively determined using a dynamic programming approach. Afterwards, the theoretical model is illustrated with an empirical example, of which the result shows that the adoption of BYD Qin HEV in China is not optimal at current fuel price without subsidies. Moreover, sensitive analyses are presented, revealing significant effects of subsidy level, fuel price, and personal travel mileage on the cost-effective replacement time. Results suggest that the effect of subsidy is attenuated by an increase in fuel price, whereas CERT is shortened by a decrease in fuel price volatility. The implications and recommendations for policymakers are also provided.

1. Introduction

Private vehicle ownership has experienced a tremendous growth in China in recent years. In particular, the number of private vehicles increased from 0.8 million in 1990 to 124.3 million in 2015 (MPS, 2015). However, over 6 per cent of the total emissions in China have come from the carbon emissions of these private vehicles (NBSC, 2013). Moreover, these vehicles result in various problems, such as noise and air pollution (Santos et al., 2010). To reduce the greenhouse gas and particulate matter generated by road transportation, hybrid electric vehicles (HEVs) with increased fuel economy and low CO_2 emission in their entire life cycles (including the production, operation and disposal phases; Nakano et al., 2008) have been developed. However, the China Association of Automobile Manufacturers (CAAM, 2015) explains that only 17 per cent of the HEV purchases in 2013 were made by individual consumers. Although the Chinese government has implemented a series of relevant policies to commercialise HEVs and set a target of achieving five million fuel-efficient vehicle sales until 2020 (SCC, 2012), the market share of HEVs remains low. The total sale of HEV in 2015 is less than 0.3 million (CAD, 2016), which lags behind its planned level. Previous studies have explored many theoretical and empirical aspects of the market penetration of HEVs (Won et al., 2009). Various parameters, such as energy price, policy combinations, and operating and maintenance costs are found to be of great significance in the HEV purchase optimisation (Lee et al., 2016). For example, Hsu et al. (2013) argued that the growth of HEV sale is insignificant without the advantage of increased energy prices.

Most HEV market penetration models focus on single purchasing process, without considering replacement purchase. Few articles proffered at least an optimal replacement time. However, HEVs are significantly more acceptable to one- or multi-car households in China than those without private vehicles (Potoglou and Kanaroglou, 2007). Zhang et al. (2013) proposed that Chinese consumers tend to purchase a conventional fuel-powered vehicle (CFPV) as their first vehicle and merely consider HEV as a second vehicle. Many HEV buyers in China are replacement buyers who are willing to upgrade their old conventional vehicles to fuel-efficient vehicles (Wang et al., 2016). It is more important to analyse replacement purchases of HEVs. This paper attempts to determine a cost-effective replacement time (CERT) for HEV buyers, which minimises their total costs of personal transport.

Unlike in new purchases, the issue of retiring old conventional vehicles significantly affects the replacement time decision and the influence of existing government policies (Benzion et al., 2008). As

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a mature vehicle market, the US has witnessed over 95 per cent ratio of replacement purchases (Singh et al., 2004). Extensive effort has been exerted and numerous policy measures have been initiated to encourage consumers to replace their vehicles, which will increase the market demand and sales of automobiles (Davis and Kahn, 2010). The vehicle purchases in the Chinese automobile market may be dominated by replacement purchases in the near future because of the maturity of this market (Huo and Wang, 2012). However, the second-hand car market in China remains a niche market that is neither mature nor pervasive (CIRN, 2014). The idled car after purchasing a new one is often regarded as waste, thereby attenuating the consumers' replacement purchase intention (Bolton and Alba, 2012). This phenomenon may be one of the major reason of HEV's low market share in China.

China has recently exerted effort to facilitate vehicle replacements. Many subsidy policies on HEVs have been implemented rapidly in many cities, such as Shenzhen, Shanghai, Taiyuan, and Hefei (Yiche, 2014). For example, the 'Ten Cities, Thousand Vehicles' program, which was initiated in 2009 and later extended to more cities and vehicle numbers, emphasized that HEV buyers would receive a subsidy of up to 50,000 CNY from the central government and an additional subsidy from the local government. A series of trade-in strategies has also been launched to assist HEV buyers solve their old vehicle retiring problems by surrendering their old vehicles for a trade-in credit that will enable them to purchase an HEV. Many Chinese households will be able to afford environmental vehicles when they are given subsidies for trading in their old vehicles. However, is switching to a fuel-efficient vehicle considered optimal? In particular, as the sales of fuel-efficient vehicles increase along with fuel prices (Klier and Linn, 2008), what is the CERT when the fluctuations in fuel price are considered? How must the government respond to the new challenges when such fluctuations become considerably frequent?

This paper develops a mathematical model of HEV replacement purchase to explore the aforementioned questions. Two new factors, namely, trade-in strategy and fuel cost fluctuation, are incorporated into the promotional policy. By considering vehicle price, fuel price, fuel efficiency, subsidy and trade-ins, the current study investigates a realistic replacement purchase decision in the Chinese automobile market. The effects of subsidy, fuel price and travel mileage on CERT are also discussed to generate meaningful implications for policymakers, managers and citizens. The rest of paper is organised as follows. Section 2 reviews the literature on equipment replacement problems and trade-in strategies. Using this review, Section 3 proposes a replacement optimisation model. Accordingly, this model is used as Section 4 utilises the dynamic programming (DP) approach to determine the expression of the critical replacement purchase threshold (CRPT). Section 5 presents a numerical example to illustrate the model and conducts a series of sensitive analyses. Section 6 concludes this research and provides the implications and directions for further research.

2. Literature review

Previous studies have addressed the problem of equipment replacement optimisation. These studies often analyse a certain operating cost level of keeping the old equipment, which is equivalent to the long-term cost of replacing the old equipment with a new one. By applying the equipment examples to trucks (Ahmed, 1973), ships (Evans, 1989) and bus engines (Lammert, 2008), these studies reveal that operating and maintenance costs, as well as fuel efficiency, have significant effects on replacement age. Furthermore, Boudart and Figliozzi (2012) analysed the key technological and economic parameters involved in the decisions of minimising total fleet costs; they determined that changing fuel prices, improving fuel economy and deteriorating buses significantly affected the replacement time. Feng and Figliozzi (2014) performed a sensitivity analysis and suggested that government subsidies had the most significant effect on the optimal replacement age of a bus fleet. Silva (2013) compared the emissions and energy benefits of introducing new energy vehicles with that of shifting public transportation models in China. Specifically, he suggested that a 50 per cent market share of conventional vehicles replacement in 2050 would decrease CO_2 emissions by 70 per cent and NO_x + particulate matter by 23 per cent. However, few studies have investigated a replacement threshold of HEV or proffered an optimal replacement age.

Instead of considering the replacement purchase, most articles on HEV focused on the buying process. They compared HEVs with CFPVs or predicted the adoption or market share of HEVs. These articles identified economic benefit as a core element in the decisions of vehicle buyers. For example, Lave and MacLean (2002) performed an environmental–economic evaluation of Toyota Prius HEV and Corolla and suggested that the former required three times considerable gasoline price to become cost-competitive for US consumers. Lane and Potter (2007) proposed high purchase cost as a major barrier to HEV acceptance, whereas Heffner et al. (2007) indicated that numerous consumers would consider fuel price when estimating the benefits of adopting HEVs. Both of these studies are in agreement with Santini and Vyas (2005). Romm (2006) proposed that compared with traditional vehicles, the development of HEVs would be delayed by the high running costs and increasing performance concerns. Other costs associated with traveling by HEVs may also affect the acceptance of these vehicles. However, fuel price fluctuation is indirectly addressed in the aforementioned studies. Yamashita et al. (2013) developed a vehicle demand model that incorporated the effects of gasoline price fluctuation to estimate the market penetration of HEVs and determine an optimal policy decision. Their model demonstrated a significant difference in the HEV market growth in cases where fuel price uncertainty is considered and ignored. As a consequence, the uncertainty of gasoline price could be of great significance in the replacement purchase decision.

Replacement time also significantly varies under a trade-in strategy. Okada (2001) proposed that provided trade-ins for the idled vehicle would only exacerbate the retiring problem, thereby increasing the vehicle replacement intention of consumers. Lenski et al. (2010) argued that if the 'cash for clunkers' program was not introduced, the scrapping of old vehicles would be delayed by an additional 2.52 years because their owners had yet to receive the value of their money. Miravete and Moral (2009) proposed that trade-in strategies, such as the 'car allowance rebate system', significantly induced the adoption of hybrid engines. A properly designed trade-in strategy can even shift the preferences of consumers towards considerably fuel-efficient vehicles. Lorentziadis and Vournas (2011) analysed the subsidy programs for the acquisition of a fuel-efficient vehicle in a trade-in strategy and determined an appropriate subsidy level that could achieve a replacement target within a certain period. These findings indicate that similar strategies are being introduced in many countries to promote the replacement of old CFPVs with HEVs, thereby forming a brand-new decision problem on vehicle replacement age.

Considering fuel price uncertainty and trade-in strategy, this study observes the 'economic life' of the old CFPVs in China or the period between when these vehicles are purchased and when they must be replaced. This paper analyses the cost trade-off between the fuel efficiency of HEVs and the replacement cost. Unlike in previous studies, the trade-in credit provided for the old vehicle