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# A hybrid electric vehicle market penetration model to identify the best policy mix: A consumer ownership cycle approach ☆

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## HIGHLIGHTS

- Our model captures circular causal dynamics among consumer purchase, use and retirement.
- We suggest a new HEV market penetration model of identifying the better combination of policies.
- Combination of purchase tax credit and retirement subsidy is effective more than any single policy.
- Smaller one among policy incentives become a bottleneck for market penetration.
- 50% tax credit and $1300 retirement subsidy can achieve Korean objective of 800,000 HEVs by 2020.

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## ABSTRACT

HEV market penetration exists in a circular loop of purchase, use, retirement, and repurchase, i.e., the consumer ownership cycle. Existing HEV market penetration models focus on a single linear process, such as purchasing, without considering other processes. Market penetration policies based on such models can facilitate a single process, but they cannot boost market penetration as planned. Combining system dynamics with consumer choice models, we propose a new HEV market penetration model to describe the dynamic circular market penetration process as well as its interaction with macroeconomic conditions and government policies. In this way, our model finds bottlenecks, estimates the future effects of different policies to solve bottlenecks, and identifies more effective combinations of policies to boost HEV market penetration. Our empirical analysis of Korean HEV market penetration reveals that combining a tax incentive and retirement subsidy will be more effective than offering either of those alone. Also, HEV market penetration becomes slower when the tax incentive is smaller than the retirement subsidy (or vice versa) because consumers escape the market penetration loop.

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## 1. Introduction

Electric vehicles (EVs) are one way to reduce emissions in the transport sector, but they face several market barriers to their widespread use: the price of electricity, availability of a charging infrastructure, and consumer acceptance [1]. As a bridge to EVs, hybrid electric vehicles (HEVs) have been introduced, but these have also suffered from slow market penetration. The HEV market share in 2014 was just 1.0% in the EU and 3.0% in the US, both of which were far below the policy objective of 10% by 2012 [2,3]. Similarly, the Korean government has promoted HEV market penetration; unfortunately, the HEV market share in Korea was 0.006% of all passenger cars in 2012 [4].

Market forecasting models serve the needs of policymakers in setting achievable policy objectives and designing policies. However, as the HEV market becomes more and more complicated, the gap between the predicted and actual HEV market penetration has widened, necessitating more advanced models. In the HEV/EV market modeling literature, the primary methods can be categorized as agent-based models, market penetration rate/time series models, and consumer choice models [5]. Agent-based models have the advantages of considering multiple agents and describing complex interactions, but they are limited by their complexity, sensitivity, and limited data availability. Market penetration/times

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series models, which use time-series data, are easy-to-implement and intuitive; however, they are too simple to consider the various actors, factors, and interactions in HEV market penetration. Consumer choice models are relatively free from those problems and have made advances in considering various technological, economic, demographic, and organizational factors, including the infrastructure [6,7,8], advancement of technology [7,9], and geo-demographic characteristics [10].

However, all three models have some common drawbacks. They ignore post-purchase consumer behavior, and they use vehicle sales indicators. Market penetration depends not only on buying decisions but also on post-purchase behavior, which is composed of vehicle use, retirement, and repurchase. Purchase and post-purchase behavior interact with and continuously influence one another [11]. Also, vehicle sales indicators often overestimate future market penetration because they cannot consider how many fewer vehicles will be in use because of consumer switching and vehicle retirement. Existing models overlook those details, which explains why they tend to over- or underestimate market penetration figures. Despite the importance of purchase and post-purchase behavior over the whole consumer ownership cycle, researchers have made few efforts to operationalize those concepts. Several previous studies simply assumed that retirement and replacement behaviors were constant [8,12,13]). An ownership indicator has been used only rarely and was not then coupled with the consumer ownership cycle [14].

To address these issues, we here suggest a new ownership-based HEV market penetration model that considers the whole cycle of consumer behavior; this model also forecasts future HEV market penetration according to different policy choices. By combining a consumer choice model with system dynamics (SD), our model not only captures the circular causal relationships among HEV choice, use, and retirement, but also better describes the manner in which each consumer behavior interacts dynamically and mutually with external technological, economic, and policy factors. Put differently, our model improves the explanatory power of the HEV market penetration process and better estimates the future effects of different policies on HEV market penetration.

Above all, our model can help policymakers set achievable policy objectives and design a more effective combination of policies to facilitate HEV market penetration. To promote HEV market penetration, many countries already provide policy incentives, including subsidies and tax incentives; however, they tend to cut back on them in response to slow economic growth. Therefore, under budget constraints, policymakers must find ways to meet policy targets while also minimizing incentives. Our model can provide policymakers with a solution to this problem.

## 2. Market forecasting models for HEVs

Focusing on consumer choice, early studies used the multinomial logit model [15], nested logit model [16], and joint mixed logit model [17] to predict future consumer decisions based on HEV purchasing. Given the small amount of data available on vehicle sales and consumer demographics, some researchers also used surveys to obtain complementary consumer data, or they estimated the sensitivity of purchasing decisions using key factors such as vehicle attributes and consumer profiles [17].

As more types of data have become available, subsequent models have incorporated more and more factors that influence consumer decisions. These new factors include government incentives [18], traffic policies [19], and technological progress [12]. Advanced technologies, including optimal energy management [20,21], weight [22], batteries [23], and charging, have driven changes in government regulations, consumer behavior, and HEV competitiveness, and the reverse has also been true [3,24,25]. Infrastructure management techniques have also improved, including charging demand [26], deployment of charging stations [27], and the use of renewable energy [28]. Such interactions have increased the complexity of HEV market penetration processes. Taking another step, some researchers have combined multi-criteria analysis with consumer choice models to further investigate the influence of various factors on consumer choices [29,30].

The accumulation of time series data has allowed researchers to use market penetration models including logistic, Gompertz, and Bass models. In response to the complicated HEV market penetration landscape, other researchers have adopted advanced market penetration models to include emerging factors while relaxing strong assumptions. This approach has the advantage of better representing reality. For instance, early models assumed market potential to be a constant, but it is regarded as a time-varying variable in the extended Bass model [31] and the time-varying logistic and Gompertz model [32]. However, those models are not useful when only small amounts of data are available. Instead, some researchers have improved basic market penetration models to consider consumer motivation [33], consumer HEV awareness [31], network externality [34], and other factors.

It is natural that there is feedback and interaction among the factors in HEV market penetration. Consumer choice models, as well as market penetration models, have difficulty in considering such dynamic mechanisms. SD is appropriate for representing the feedback and interactions in a systematic way, which makes it useful for analyzing circular causalities. Using SD, several studies have integrated consumer choice models with market penetration models to describe dynamic interactions, including circular causalities among consumer preferences and complementary resources [35], network effects between the refueling infrastructure and vehicle adoption [8], and feedback effects between the market share and technological performance [7]. Other researchers have developed agent-based models to consider sensitivities and nonlinear interactions among consumer attributes, vehicle attributes, policies, spatial factors, social factors, and media influence [9,36,37]. SD is used to improve consumer choice and market penetration models, integrate more than two models, and develop agent-based models.

However, previous models neglected the important dynamic interactions between consumer purchases and post-purchase behavior. Several studies have suggested that purchase behavior affects post-purchase behavior and considered variables such as vehicle retirement and repurchase [7,35,36]. Also, a few studies have analyzed vehicle retirement behavior and the effect of retirement incentives in the US [38], UK [39], and elsewhere. However, post-purchase behavior has rarely been considered in previous models; if it was included, it was assumed to be a constant without any dynamic interaction. In reality, consumer purchase and post-purchase behavior have interactions with and are continuously influenced by a variety of factors. This warrants the use of a new model to represent these complex dynamic interactions over the whole consumer ownership cycle.

## 3. HEV market penetration model

### 3.1. Overall structure

Our model has three requirements: (1) a description of consumer behavior in terms of vehicle purchase, use, retirement, and repurchase; (2) the structurization of dynamic interactions and causalities between consumer behavior and influencing variables; and (3) the development of a tool that can be used to estimate policy effects.

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