

1 **Market Penetration Model for Autonomous Vehicles Based on Previous Technology**  
2 **Adoption Experiences**

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**1 ABSTRACT**

2 This paper presents the effort in developing a market penetration model for autonomous vehicle  
3 technology adoption, based on similar technologies and previous trends in the United States.  
4 Generalized Bass diffusion models are developed, based on data from previous technologies,  
5 including sales and price data on conventional automobiles and hybrid electric vehicles, and the  
6 usage of internet and cellphones. Based on the adoption patterns of previous technologies, two  
7 values representing the innovation factor (risk taking capacity) and the imitation factor (culture  
8 and lifestyle preferences) are selected for AV market penetration. In addition, external variables  
9 such as the price of the AVs relative to conventional vehicles, and economic wealth are  
10 incorporated into the model. The market size for AV adoption is determined based on the usage of  
11 internet, and household is considered as the unit. Given the uncertainties in market size and price  
12 of AVs, sensitivity analysis are also conducted to understand the possible impacts of these factors  
13 on user adoption. In general larger market size leads to higher adoption rate, while the initial cost  
14 of AVs relative to conventional vehicles does not seem to influence the diffusion process much.  
15 This paper contributes to the literature by adding a quantitative analysis of AV market penetration  
16 based on past technology adoption experiences. The study results provide valuable insights in  
17 terms of the possible market diffusion patterns and the impacts of different factors on user  
18 adoption.

## 1 INTRODUCTION

2 Autonomous vehicle (AV) development is a considerable accomplishment of the 21<sup>st</sup> century.  
3 AVs, also known as self-driving vehicles, robotic cars, or driverless cars, are defined as computer  
4 equipped vehicles which can be driven and operated without human driver's active control (1, 2).  
5 AVs are capable of fulfilling the main transportation capabilities using information provided by  
6 their sensors about the surrounding environment, and do not need connection with infrastructures  
7 and other vehicles (3). Automated vehicles may be autonomous (with only vehicle sensors) or may  
8 be connected (cars and roadside infrastructure communicate wirelessly). The National Highway  
9 Traffic Safety Administration (NHTSA) defined five levels of automation, starting from level 0  
10 which is the basic traditional vehicles with no automation up to level four with full self-driving  
11 automation (4). This study considers Level four AVs, when vehicles can perform all driving  
12 functions and monitor roadway conditions for an entire trip, and so may operate with occupants  
13 who cannot drive and without human occupants (4).

14 Self-driving vehicles may have seemed to be a distant dream several years ago, but manufactures'  
15 prototypes including Google self-driving cars, Mercedes-Benz S 500 Intelligent Drive and Audi  
16 A7 Piloted Driving showed that AVs are becoming real now. Google self-driving vehicles have  
17 traveled more than 1 million miles from 2009 to May 2015 without human intervention (5) and  
18 several other companies plan to release the AVs in the next decade (6-9). On the other hand,  
19 legislators are considering bills regarding AV tests and utilizations. Until July 2015, five states of  
20 California, Florida, Michigan, Nevada, Tennessee and also District of Columbia have passed laws  
21 on testing autonomous vehicles and sixteen other states are considering bills related to autonomous  
22 driving in 2015 (10).

23 In light of the fast developing technologies, several studies have been conducted to predict AV  
24 adoption rate. Litman (2014) predicted the implementation of AVs based on previous vehicle  
25 related technologies (automatic transmission, air bags, hybrid vehicles, subscription vehicle  
26 services and vehicle navigation systems) and also fleet turnover rates (11). The study predicted  
27 that AVs would be on streets with high cost in 2020s, and it would take up to 2050s to reach 80-  
28 100% market share. Fagnant and Kockelman (2015) predicted a sooner mass-market presentation  
29 start for autonomous vehicles, considering that Nissan and Volvo announced their commercially  
30 viable autonomous vehicles in 2020 and five years for price drop down (2). Wallace and Silberg  
31 (2012) proposed three possible adoption scenarios, including aggressive adoption, base case  
32 adoption and conservative adoption. The adoption scenarios were composed of various elements  
33 including cost, technology, and consumer acceptance, etc. (12).

34 Although the above studies all provide valuable perspectives in estimating AV adoption rate, most  
35 of them are based on qualitative estimates or focused on the technology aspects only. This paper  
36 intends to use a mathematical modeling approach that considers the market size, user adoption  
37 behavior, and historical data on the penetration patterns of previous technologies. In this regard,  
38 market diffusion models have been proven a powerful tool in predicting the market for new  
39 products. Diffusion models can estimate how the new product will penetrate the market and also  
40 estimate the market potential for that product. It provides important information for manufacturers

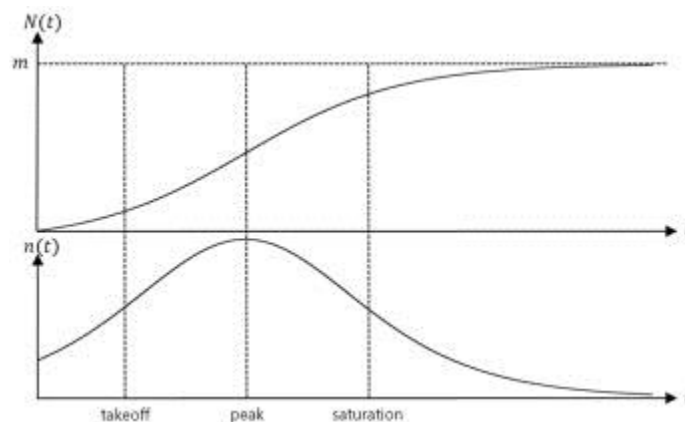
1 to control their products based on the market behavior, also it is very critical for policy makers to  
 2 prepare all the required infrastructures to manage the adoption process. The results of this study  
 3 can contribute to the literature by providing a mathematical approach to market penetration  
 4 prediction of AVs, for which the assumptions and inputs of the model can be easily modified and  
 5 updated based on the latest knowledge of the market and technology progress.

6 The next section summarizes the literature review on the use of diffusion models to predict market  
 7 penetration for new automobile related technologies, followed by the methodology section that  
 8 introduces the modeling framework. Model results and sensitivity analysis are presented next, and  
 9 the last section concludes this study.

## 10 LITERATURE REVIEW

### 11 Bass Diffusion Models

12 Generally, diffusion models assume the cumulative sales of a new product over time will be an S-  
 13 shaped curve (Figure 1, up). The curve slope at each time point represents the adoption rate.  
 14 Adoption rate starts low at the beginning periods of product launch, which reflects consumers'  
 15 conservativeness regarding the new product especially if they are not familiar with the product.  
 16 Gradually, the rate may increase (if the product is successful), as personal recommendations, social  
 17 and media commercials may persuade followers to use the product. Depending on the product,  
 18 market saturation will occur in a few months or years when the adoption rate starts to decrease to  
 19 almost zero. The most popular first-purchase diffusion models in marketing are Bass, Fourt and  
 20 Woodlock, and Mansfield (13). Among these, the Bass model have been used widely in market  
 21 penetration forecasting of new products.



22

23 **FIGURE 1 Bass model cumulative and non-cumulative adopters curve (14)**

24 Bass diffusion models assume adopters of a new innovation are influenced either by mass media,  
 25 or by word of mouth (13). In other words these two means of communication are the two most  
 26 important factors on consumers' acceptance (i.e. purchase the new product or subscribe to the new  
 27 system). The people who are influenced by mass media are called innovators and the second group  
 28 are known as imitators in market diffusion model literature. Based on Bass assumption, innovators

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1 exist in the whole diffusion process while imitators join the market after several sale periods.  
 2 Figure 1 shows the trend of a nominal product sale during sale periods. Non-cumulative adopters  
 3 will reach to a maximum point which corresponds to inflection point of cumulative S-shaped  
 4 curve.

5 The basic Bass model equation, which is derived from a hazard function (the probability that an  
 6 adoption will occur at time  $t$ , given it has not yet occurred), is shown in Eq. 1 (13):

$$7 \quad n(t) = \frac{dN(t)}{d(t)} = p[m - N(t)] + \frac{q}{m}N(t)[m - N(t)] \quad (1)$$

8 where  $N(t)$  is the cumulative number of adopters at time  $t$ ,  $m$  is the potential market size,  $p$  and  $q$   
 9 are coefficients of innovation and imitation, respectively. Eq. 1 is a first-order differential equation,  
 10 which can be solve to Eq. 2 using an integration:

$$11 \quad N(t) = m \left( \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}} \right) \quad (2)$$

12 However as mentioned before, the Bass diffusion model is not able to consider external influencer  
 13 variables, such as cost reduction effects. For this reason a generalized Bass diffusion model is  
 14 developed to overcome basic model limitations. Generalized Bass model includes a mapping  
 15 function of  $x(t)$ :

$$16 \quad n(t) = \frac{dN(t)}{d(t)} \cdot x(t) \quad (3)$$

17 Which  $x(t) = x(t; \theta)$ ,  $\theta \in R^k$  is assumed to be nonnegative and integrate-able (15):

$$18 \quad N(t) = m \left( \frac{1 - e^{-(p+q) \int_0^t x(\tau) d\tau}}{1 + \frac{q}{p} e^{-(p+q) \int_0^t x(\tau) d\tau}} \right), t, p, q > 0 \quad (4)$$

19 When there is not any external variables,  $x(t) = 1$  and generalized model will shrink to the base  
 20 model. To estimate a generalized Bass model, basic Bass model coefficients ( $p$ ,  $q$  and  $m$ ) should  
 21 be estimated with external variables coefficients. The mapping function is normally shown as Eq.  
 22 5:

$$23 \quad x(T) = 1 + \beta_1 X_1 + \beta_2 X_2 \quad (5)$$

24 In which  $X_i$  represent the external variables, i.e. price and advertisement rate and  $\beta_i$  are the  
 25 corresponding coefficients.

## 26 Applications of Diffusion Model in Automobile Technologies

27 Diffusion models have been used in several automobile related technology studies, which  
 28 generally can be categorized into two groups based on the modeling framework; a group which

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1 used conventional diffusion models (i.e. Bass) (16-18), and other group which have used Stated  
2 Preference (SP) surveys and developed discrete choice models (19-21).

3 Massiani and Gohs (2015) developed a Bass model based on Germany data for new automotive  
4 technologies (16). New registrations for Liquefied Petroleum Gas (LPG), Compressed Natural Gas  
5 (CNG) vehicles, Elective Vehicles (EV) and Hybrid Electric Vehicles (HEV) were used in this  
6 study as sales data for new automotive technologies. The study estimated the parameters with  
7 varying levels of market size, and found that the innovation coefficient (p) was highly affected by  
8 changes in market size while the imitation coefficient (q) was not influenced by market size. The  
9 authors found an inverse relationship between assumed market size (M) and innovation coefficient  
10 in this study. This will make it very difficult to draw conclusions for the value of (p) when M is  
11 fixed, but not precise. This study also provided a fair guidance on using endogenous or exogenous  
12 market potential value when applying a Bass model in automotive industry.

13 Cordill (2012) proposed a diffusion model to study the future of HEV market (17). Innovation (p)  
14 and imitation coefficient (q) were estimated for three EV technologies of Prius, Hybrid Civic and  
15 Ford Escape using 2000-2010 sales data, followed by a survey to develop a model defining  
16 important factors affecting consumer's preference. Respondents who liked to purchase an EV in  
17 the near future were classified as innovation group and other participants were classified as  
18 imitation group. It was concluded that selected vehicle price, gas saving and price of gas are the  
19 three most important factors for both groups, while emission and operation reliability were two  
20 other factors affecting the innovators preference and the availability of future tax benefits and  
21 vehicle crash report were found to affect the imitators choice.

22 Park et al. (2011) developed a market penetration forecasting model for Hydrogen Fuel Cell  
23 Vehicles (HFCV) considering infrastructure and cost reduction effects for Korea (18). Based on  
24 their results, HFCV market would be saturated in 2038 in Korea and in 2050 in the US. The  
25 parameters of generalized Bass model was estimated based on the historical sales of Prius HEV  
26 and its prices in comparison with Toyota Corolla as the representation of conventional vehicles.

27 Another group of market penetration studies used SP surveys and choice modeling approach to  
28 estimate diffusion models for new automobile related technologies. Jensen et al. (2014) proposed  
29 a forecasting method for EV demand in Denmark using regression method and also diffusion  
30 model parameters. The study indicated that alternative specific constant (ASC) of logit models can  
31 overshadow the market penetration, hence the authors used adjusted model with diffusion  
32 parameters (19). McCoy and Lyons (2014) conducted an agent-based model to simulate market  
33 diffusion of EVs in Ireland (20). Analysis of four neighborhoods with different socioeconomic and  
34 demographic properties was conducted, and as expected it was found that the wealthier  
35 neighborhoods with more homeowners would have much higher adoption level than less wealthy  
36 neighborhoods. Brown (2013) simulated the EV diffusion model in Boston using a discrete choice  
37 model (21). Results showed that EVs would share 1-22% of the entire vehicle market of Boston in  
38 2030. Regarding factors affecting market share, financial incentive availability showed positive  
39 effects.

1 The geographical transferability of estimated data was also important for market analysis. Jensen  
2 et al. (2014) used Norwegian new car registration data from 2003 to 2013 to estimate the EV  
3 demand model in Denmark market (19), and used the results directly since lifestyle and economic  
4 conditions of the two countries were generally very similar. However Park et al. (2011) which  
5 used Japanese sale volume of HEVs to estimate a diffusion model for HFCV in Korea adjusted the  
6 imitation parameter based on other previously estimated models in the two countries (18).

7 The Bass model has been widely employed in studies related to new technologies, including those  
8 in the automobile industry, yet this approach has not been applied to understand the market  
9 adoption of AVs. Considering the advantages of this approach – it uses mathematical models and  
10 considers the influence of market size, user behavior and historical data from other products, and  
11 the assumptions and inputs can be easily modified and updated to better reflect the latest  
12 knowledge of the market and the technology – this study employs this model to study the market  
13 penetration pattern of AVs. The details of the methodology and assumptions are described in the  
14 following section.

## 15 **METHODOLOGY**

16 In this study, a Generalized Bass diffusion modeling approach is used to estimate the market  
17 penetration for AVs in the US, since the basic Bass model cannot consider influences of any  
18 external variables, i.e. effect of product price during time (18).

19 Historical sales information is required to estimate the generalized Bass model. Since no sales data  
20 would be available for brand new products, a similar technology/product would be selected and it  
21 is assumed that the new product will resemble the existing product in terms of user adoption  
22 pattern. For instance Park et al. (2011) estimated the market diffusion model of HFCVs for Korea,  
23 based on the data obtained for HFCVs in Japan with some adjustment to the local market (18).

24 For this study, our estimation is based on the historical sales data for HEV in the US. The  
25 assumption is that the market penetration pattern of the AVs would be similar as for the HEVs in  
26 the US market. The HEV technology is preferred over other automotive features such as automatic  
27 transmission or rear camera, because the latter features only changed a portion of the driving task  
28 to a limited degree, and there were not as much resistance when they were first introduced. On the  
29 other hand, the first years of HEV deployment have seen conservative and skeptical user adoption,  
30 as would be expected for AV adoptions. However, it should also be noted that HEVs would not be  
31 as revolutionize as AVs in changing the way people travel. To overcome this limitation, our study  
32 also used data from internet and cellphone adoption to adjust the diffusion model, which is  
33 discussed in more detail later in this section.

34 Amongst several factors which may affect the adoption behavior, AV technology price, US market  
35 technology acceptance rate and economic wealth are considered in this study. To estimate the  
36 generalized Bass model, historical price ratio of a representative HEV to a representative  
37 conventional vehicle is analyzed. For the technology acceptance taste of US consumers, the  
38 diffusion model used information based on internet subscription and cellphone consumption in the

1 US market. The reason of studying the internet and cellphone usage, is that these two advanced  
 2 technologies can be seen as two revolutionary forces in the history of communications, such role  
 3 we believe AVs will play in the automobile industry. So it is anticipated that the penetration  
 4 patterns of internet and cellphone usage can reveal some insights to analyze US costumers'  
 5 behavior when facing new revolutionary technologies. As for the economic wealth, the US Gross  
 6 Domestic Product (GDP) per capita (current US\$) is used in this study. Several specifications of  
 7 the models are estimated and compared based on model performances. Then sensitivity analysis is  
 8 conducted on two important factors which may affect the adoption projection: market size and AV  
 9 price ratio to conventional vehicle price.

10 To establish the basics for model estimation, it is assumed that the AV market diffusion are similar  
 11 to the pattern for HEVs. The historical sales data of a representative HEV vehicle is collected and  
 12 listed in Table 1. Toyota Prius has been selected as the HEV technology representative vehicle,  
 13 because it is the best-selling HEV not only in the US, but in the whole world. Prius was launched  
 14 in 1997 in Japan and three years later in the US. Shortly after, HEV Prius became the best-selling  
 15 HEV for many years. Prius's price has not changed for the first three years of sale in the US with  
 16 a slight drop in the fourth year. Later the price raised in line with general inflation. Toyota Corolla  
 17 was selected as the representative conventional vehicle, to consider the price ratio factor effect in  
 18 the generalized Bass model. Corolla was selected because it has the same size and is manufactured  
 19 by the same company as Prius, but also because of its high sales statistics. The sales and price data  
 20 for Prius and Toyota Corolla were obtained from an online source (22).

21 To consider external effects and estimate  $\beta$  in Eq. 5, price ratio and new technology acceptance  
 22 rate variables are incorporated into the function as below:

$$23 \quad x(T) = 1 + \beta_1 \frac{P(t)-P(t-1)}{P(t-1)} + \beta_2 \frac{T(t)-T(t-1)}{T(t-1)} \quad (6)$$

24 In which,  $P(t)$  is Prius to Toyota Corolla price ratio during a sales period,  $t$ .

$$25 \quad P(t) = \frac{\text{Price of Prius}}{\text{Price of Conventional Vehicle (corolla)}} \quad (7)$$

26 As can be derived from Table 1, the price ratio is about 1.56 in 2001 and dropped to 1.34 in 2014,  
 27 indicating that Prius was priced about 56% higher than a conventional vehicle when it was first  
 28 introduced to the market, and then after 14 annual periods it decreased to about 34%. This trend is  
 29 known as technology price dropdown.

30  $T(t)$  is the technology acceptance taste variable. For this study, it is estimated based on the data for  
 31 internet subscribers and cellphone subscribers in the US market. It is reasonable to assume that the  
 32 sales trend of AVs may not completely obey the HEV sales data, since AV technologies also  
 33 involve considerable progress in the field of information technology. To account for consumer's  
 34 behavioral attitudes toward technology acceptance into the diffusion model, it is assumed that the  
 35 AV market penetration should have some similarities with the historical trend of cellphone or  
 36 internet users' in the US.



1 In addition, the economic wealth of the population may also have influence on the user adoption  
 2 of new technologies, therefore also incorporated into the diffusion model. Other data in Table 1  
 3 except vehicles information are collected from World Bank online source (23).

4 **TABLE 1 Data for Generalized Bass Model Estimation**

Year	Prius Price (US\$)	Toyota Corolla Price (US\$)	Prius Annual Sales (1000)	Internet Subscribers (per 100 US people)	Cellphone Subscribers (per 100 US people)	Economic Wealth (GDP per capita-current US\$)
2001	18,793	12,042	15.6	43.1	38.0	37,273.60
2002	18,793	12,042	20.1	49.1	45.0	38,166.00
2003	18,793	13,283	24.6	58.8	49.0	39,677.20
2004	18,687	13,374	54.0	61.7	55.0	41,921.80
2005	19,590	13,563	107.9	64.8	63.0	44,307.90
2006	20,006	13,859	107.0	68.0	68.0	46,437.10
2007	20,419	14,040	181.2	68.9	76.0	48,061.50
2008	21,064	14,131	158.6	75.0	82.0	48,401.40
2009	21,758	15,326	139.7	74.0	85.0	47,001.60
2010	20,330	15,417	140.9	71.0	89.0	48,374.10
2011	22,108	16,284	128.1	71.7	91.0	49,781.40
2012	22,560	16,570	147.5	69.7	94.0	51,456.70
2013	22,748	16,821	145.2	79.3	96.0	52,980.00
2014	22,748	16,944	98.6	84.2	96.0	54,629.50

5 Given all the information shown in Table 1, the generalized diffusion model for AV is estimated,  
 6 without restricting the market size. Then sensitivity analysis are conducted to examine: how will  
 7 the market size affect AV technology market penetration, and also how will price affect the market  
 8 size and the diffusion process.

## 9 MODEL RESULTS

10 To estimate the generalized Bass diffusion models in this study, non-linear least square estimation  
 11 method was used with SPSS software (24). The estimated coefficients of the models, including the  
 12 basic model and the generalized model are summarized in Table 2. As a reference, the Bass model  
 13 for conventional vehicles (auto) is also estimated based on data for the period of 1920-2014. The  
 14 coefficients are shown in the first row. The second the third rows show the coefficients for the  
 15 Bass and the generalized Bass model for HEVs. As explained, to bring US consumer's technology  
 16 acceptance taste into account, Bass model formulation is also applied on historical subscription  
 17 data of internet and cellphone in the US, and the results are shown in the last two rows in Table 2.

1 Price ratio and economic wealth are incorporated as external variables for the HEV generalized  
 2 Bass model. For comparison purposes, the diffusion coefficients obtained from previous studies  
 3 on the adoption of new automobile technologies are also summarized and presented in Table 3.

4 **TABLE 2 Estimation Result for Bass Diffusion Models**

Parameter	m	p	q	Price ratio	Economic Wealth	R <sup>2</sup>
Bass (auto)	504,136,121	0.000242	0.091202			0.997
Bass (HEV)	1,650,320	0.010402	0.389704			0.997
G-Bass (HEV)	1,750,697	0.015459	0.341865	-1.314	8.913	0.999
Bass (Internet)	76%	0.006673	0.390604			0.992
Bass (Cellphone)	329,582,323	0.001725	0.264384			0.999

5 **TABLE 3 Bass Model Parameters from Selected Studies**

Authors	Model	Vehicle technology	p	q
Massiani and Gohs (2015)	Bass model	EV	0.0019	1.2513
Massiani and Gohs (2015)	Bass model	LPG	0.0779	0.3718
Massiani and Gohs (2015)	Bass model	CNG	0.1187	0.0349
Jensen et al. (2014)	Bass model	EV	0.002	0.23
Cordill (2012)	Regression model	EV Prius	0.0016	1.4451
Cordill (2012)	Regression model	EV Hybrid Civic	0.0034	0.0631
Cordill (2012)	Regression model	EV Ford Escape	0.0367	0.4322
Park et al. (2011)	Generalized Bass Model	HCFV	0.0037	0.3454

6 Comparing the estimated innovation factors p across the models, it shows that the estimated value  
 7 for HEV (0.010, and 0.015) in the US market is very high. The intuitive meaning of p factor  
 8 represents how quickly the new technology is being adopted by the users. Looking at Tables 2 and  
 9 3, the largest values of p factor are for CNG and HEVs. Simply, it can be seen that these  
 10 technologies were not that revolutionary. When HEVs were introduced in the US market around  
 11 year 2000, the consumers were relatively familiar with the product. On the contrary, the p factor  
 12 for conventional automobile adoption is about 0.0002, which indicates that the market was more  
 13 conservative when automobiles were first introduced around 1920. The adoptions of cellphone and  
 14 internet reveal a similar case (with p value around 0.00067 and 0.0017, respectively). Considering  
 15 that AV technology is also a revolution in the automobile industry which needs several years to be  
 16 accepted by innovators, and taking into account the diffusion patterns of other technologies, a  
 17 value of 0.001 for the p-factor for AV technology was chosen for this study. The assumption is  
 18 that AV adoption would be more optimistic than the conventional automobile adoption but more  
 19 conservative than EVs, internet and cellphone adoptions. However it should be noted that this  
 20 assumption can be updated when more knowledge is available about user acceptance.

21 The imitation factor q estimates of both base Bass and generalized models for HEV are very close  
 22 to the average imitation factor values of previous studies. Unlike the innovation factor which  
 23 mostly deals with consumer's risk taking capacity, imitation factor represents consumer's cultural

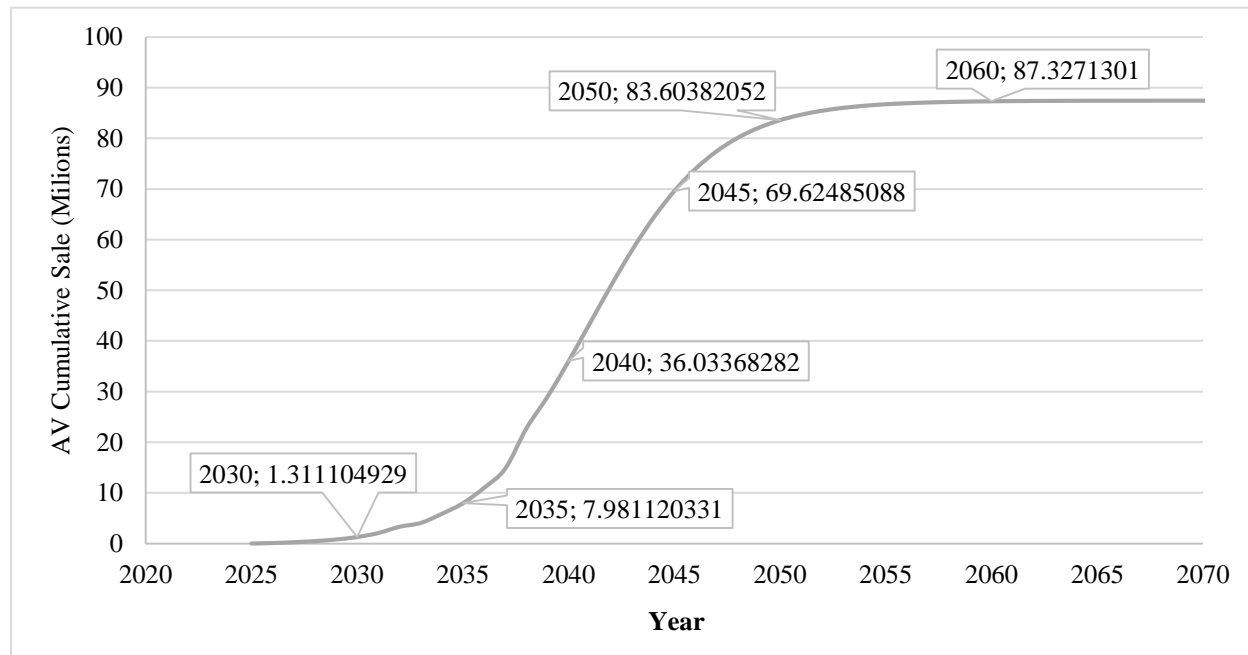
1 and lifestyle preferences. The intuitive meaning of q factor represents how quickly the technology  
 2 may be adopted by the imitators (followers after the innovators). It can be seen that the innovation  
 3 factors vary largely for different technologies while the imitation factors are relatively close as  
 4 shown in Table 2. This factor is estimated to be 0.0912 for conventional automobiles in the US,  
 5 which indicates that society lifestyle and welfare can affect the imitation factor considerably. In  
 6 this study, the estimated value of 0.341865 is kept for the AV diffusion model.

7 The estimated market size for HEV does not seem reasonable for AV (the m parameter), compared  
 8 to the entire vehicle market in the US. Up to 2012, a total of 254 million vehicles have been  
 9 registered in the US. The diffusion model for automobiles recommends a saturation market size of  
 10 approximately 500 million vehicles (cumulative from 1920). AV technology will bring  
 11 considerable changes in people's life, i.e. increases social welfare, and enhances safety.  
 12 Accordingly, the market size for AV would be considerably large. Considering the usage of  
 13 internet and the market size for cellphones, it shows the potential and capacity of US consumers  
 14 in adopting new technologies, especially when they are affordable for them. Although AV  
 15 technology may not be as affordable at the first periods of sales, it can dictate itself into people's  
 16 life when price dropdown occurs. Based on the usage of internet, this study assumes a market size  
 17 of 75% of households for AVs. Considering that one of the most promising features of AVs is the  
 18 potential to facilitate carpool/shared use and more efficient use of the vehicles, the market size is  
 19 considered as household based instead of individual based. Although the U.S. households  
 20 commonly enjoy multiple vehicles today, AV technology is likely to reduce vehicle ownership  
 21 significantly. Given that there are 115,610,216 households in the US based on census data (25),  
 22 the market size for AV is estimated to be close to 87 million vehicles. Again, this assumption  
 23 should be updated when more information is available regarding vehicle ownership. The  
 24 sensitivity analysis presented later also shows the impacts of market size on market penetration of  
 25 AVs.

26 The estimated price ratio coefficient is negative which is reasonable and means a decrease in price  
 27 ratio will lead to increase in the cumulative sale. The price ratio decreased from 1.56 to 1.34 for  
 28 HEV relative to conventional vehicles during a 15-year period. It is anticipated that initially AVs  
 29 would have a considerably higher price than conventional vehicles, however this price ratio will  
 30 decrease after some years and the innovation will become affordable for medium income level  
 31 households. Economic wealth showed significant effect on HEV sales. Therefore this variable is  
 32 also incorporated into the model for AV adoption assuming that economic wealth has similar  
 33 impacts on AV adoption as on HEV. The final adopted parameters for AV market diffusion is  
 34 presented in Table 4. The corresponding diffusing curve is illustrated in Figure 2.

35 **TABLE 4 AV Market Diffusion Model Coefficients**

Parameter	M	p	q	Price	Economic Wealth
Bass (AV)	86,707,662	0.001	0.341865	-1.314	8.913



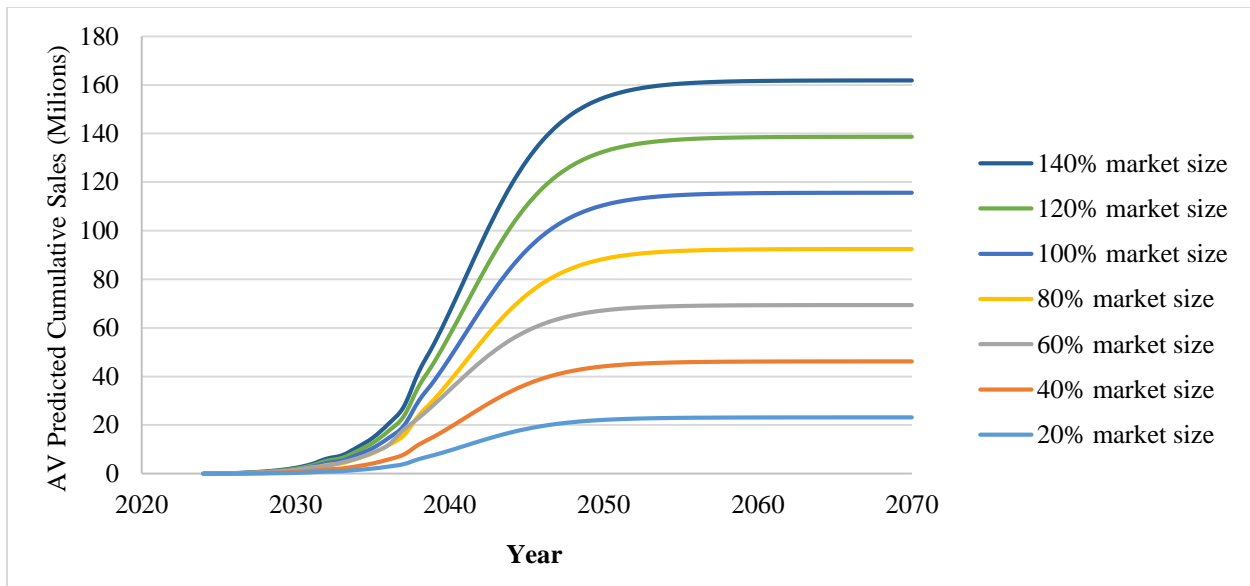
3 **FIGURE 2 Forecasted AV market penetration curve.**

4 Figure 2 shows the market penetration prediction based on the assumptions indicated above, and  
 5 considering less than 100,000 sold vehicles per year as market saturation point. Assume that AV  
 6 sales start at year 2025, the projection shows 1.3 million vehicles be sold in five years, and the  
 7 usage may increase to 36 million in another ten years. The curve shows that the market will be  
 8 saturated in 2059 when approximately 87 million AVs would have been sold. This projection  
 9 seems to be in accordance with Litman's study (2014), which predicted that in 2050s, 80-100% of  
 10 sold cars would be AVs (11).

## 11 SENSITIVITY ANALYSIS

12 Sensitivity analysis is a useful tool in identifying model uncertainties. The assumption is to keep  
 13 all other variables constant, and see how model results change based on the value changes in one  
 14 factor of interest. In this study, the market size and price ratio values may change considerably. To  
 15 see how these factors may change the adoption pattern of AVs, sensitivity analysis is conducted  
 16 for both market size and price ratio variables.

17 In terms of market size, the values are changed between 20-140% of US households. Market  
 18 penetration curves estimated based on different market sizes are illustrated in Figure 3. The figure  
 19 shows much higher adoption rates when market size is larger, indicated by the deeper slopes. While  
 20 the saturation point does not differ much across the market size levels, with the soonest  
 21 occurring around 2055 with 20% market size (about 23 million vehicles) and the latest around  
 22 2060 with 140% market size (about 162 million vehicles).



1

2

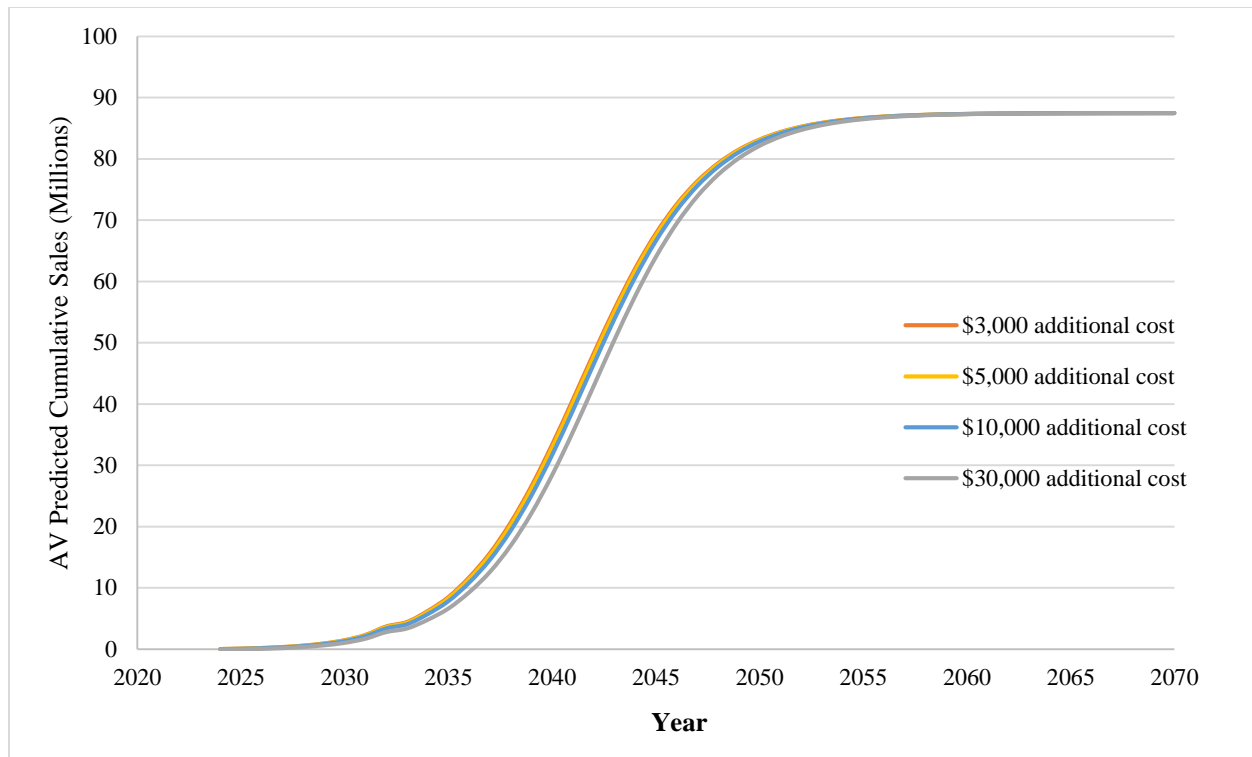
**FIGURE 3 Sensitivity analysis results on market size.**

3 Regarding price ratio between AVs and conventional vehicles, according to a study by Information  
 4 Handling Services (his) Automotive, the AV technology will add \$7,000 to \$10,000 to a  
 5 conventional vehicles price in 2025 (26). For this study, the generalized Bass model is only able  
 6 to consider the effect of the initial price ratio when the new product is first introduced. Although  
 7 the prices for both AVs and conventional vehicles may drop, and the difference between their  
 8 prices may drop eventually, the sensitivity analysis only reflects the effects on the initial price  
 9 ratio.

10 Four different values were chosen to represent the initial additional cost for AVs, \$3,000, \$5,000,  
 11 \$10,000, and \$30,000 for sensitivity analysis. The additional cost of \$30,000 is not very likely to  
 12 happen in reality, but was chosen to test how the model reacts to this extreme value. The diffusion  
 13 curves are presented in Figure 4.

14 As shown in Figure 4, the penetration curves are very close, except that the diffusion curve is  
 15 shifted to one year later when additional cost changes from \$10,000 to \$30,000. This could indicate  
 16 that the external variables have less effect in comparison with the three major variables (market  
 17 size, the innovation factor, and the imitation factor) in the Bass model. This is a limitation of the  
 18 Bass model, which is not able to consider external variables' effect on market diffusion very well  
 19 as in accordance with Bass (27). Indeed this is a limitation of this study. There are several factors  
 20 affecting AV market penetration, i.e. legal frameworks, personal preferences, technology, and  
 21 price, etc. Future studies will be pursued to improve the modeling approach to incorporate external  
 22 factors.

23



**FIGURE 4 Sensitivity analysis results on additional cost of AVs.**

### CONCLUSIONS

A market diffusion model is estimated in this study to examine the penetration pattern of AVs. Understanding the market penetration pattern is critical to policy makers and planners to manage and facilitate the adoption of new technologies. Since AVs have not been introduced to the market, this paper used data from previous technologies. Particularly, sales and price data on conventional automobiles and HEVs, and the usage of internet and cellphones in the US are collected and used for model estimation.

Based on the adoption patterns of previous technologies, two values representing the innovation factor (risk taking capacity) and the imitation factor (culture and lifestyle preferences) are selected for AV market penetration. In addition, external variables such as the price of the AVs relative to conventional vehicles, and economic wealth are incorporated into the model. The market size for AV adoption is determined considering household as the unit. The model results and the produced penetration curve reveal interesting results. Assuming AVs become available in 2025, the market may reach about 8 million in ten years, and saturation may occur in 35 years assuming a 75% market size.

Given the uncertainties in market size and price of AVs, sensitivity analysis are also conducted to understand the possible impacts of these factors on user adoption. In general larger market size leads to higher adoption rate, while the initial cost of AVs relative to conventional vehicles does not seem to influence the diffusion process much.

1 This paper contributes to the literature by providing a quantitative modeling approach to AV  
 2 market penetration estimation based on past technology adoption experiences. The study results  
 3 provide valuable insights in terms of the possible market diffusion patterns and the impacts of  
 4 different factors on user adoption. The analysis provided in this paper can benefit from further  
 5 research in refining and updating the assumptions applied, such as regarding the market size,  
 6 vehicle ownership and technology acceptance tastes, etc. Future studies using SP surveys could be  
 7 a good approach to advancing the understanding in market penetration for AVs in terms of public  
 8 acceptance and user preferences focusing on detailed market segments. One major limitation of  
 9 this study is that the Bass model does not considers external variables very well. Future  
 10 improvements on the modeling approach will be further pursued.

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