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Consumer Preferences for Hydrogen Vehicles: An Empirical Analysis Based on the Choice Experiment Method

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Abstract

This study, from a consumer perspective, employs a discrete choice experiment and utilizes data from 507 survey responses collected in five cities across China. Through a mixed logit model, the study analyzes consumer preferences and heterogeneity regarding different attributes of hydrogen vehicles (HVs) and estimates consumers' willingness to pay for these attributes, providing guidance for future HV promotion policies. The results reveal that: (1) Price factors significantly influence consumers' purchasing decisions, with consumers showing a negative preference for vehicle purchase prices and a significant positive preference for government subsidies. (2) Convenience is a critical factor, as consumers prefer vehicles with longer driving ranges and denser hydrogen refueling station networks. (3) Environmental benefits positively influence purchasing decisions, as environmental attributes have become a key consideration for consumers when choosing HVs. (4) Significant heterogeneity exists in consumer preferences based on socio-economic factors.The findings offer practical insights for future HV promotion policies. Policymakers should consider consumer heterogeneity, optimize purchase subsidy policies, and accelerate hydrogen refueling infrastructure development to improve convenience. Moreover, differentiated policy strategies should target consumers with varying income and education levels, thereby promoting HV adoption, enhancing market penetration, and achieving the dual goals of economic viability and environmental benefits.

Keywords

hydrogen vehicles, choice experiment, willingness to pay, mixed logit model

1. Introduction

The "dual carbon" goals of achieving carbon peaking and carbon neutrality pose significant challenges to China's transition toward a green and low-carbon economic structure. As one of the primary sources of energy consumption and greenhouse gas emissions, the transportation sector accounted for approximately 10.4% of China's total carbon emissions as of September 2021. Among these, road transportation contributed over 85% of the transportation sector's emissions, making it the dominant source of carbon emissions in the sector and a critical target for emission reduction efforts. Therefore, one of the essential measures to achieve the "dual carbon" goals is to promote the transition from traditional fuel vehicles to new energy vehicles (NEVs).

Currently, the Chinese government is strongly supporting the development of the electric vehicle industry. However, the role of electric vehicles in carbon reduction remains limited due to the heavy reliance on coal in China's electricity generation, which indirectly produces substantial carbon dioxide emissions (Li et al., 2017). Consequently, hydrogen energy vehicles have emerged as a promising alternative with greater potential for carbon emission reduction.

At present, the application of hydrogen energy in the transportation sector is primarily focused on "hard-to-abate" areas, such as heavy-duty trucks and shipping. Hydrogen fuel cells offer significant advantages, including high energy density, short refueling time, and superior low-temperature performance. These attributes allow hydrogen vehicles to effectively replace diesel and natural gas while overcoming the limitations of electric vehicles in terms of range and battery lifespan. In the future, hydrogen energy vehicles are expected to become a primary option for mass-market transportation in a low-carbon society. China's hydrogen energy industry already has a certain degree of industrialization, and the government has introduced policies such as the Energy Technology Revolution and Innovation Action Plan (2016-2030), which explicitly outlines the task of "hydrogen energy and fuel cell innovation." These policies provide robust support for the nationwide promotion of hydrogen energy and fuel cell technologies. According to statistics from the Ministry of Public Security, by the end of 2020, the number of NEVs in China reached 4.92 million, accounting for 1.75% of the total vehicle stock. Among these, hydrogen energy vehicles numbered only 7,352, representing merely 0.15%. This highlights the vast market potential for hydrogen energy vehicles.

However, the large-scale adoption of new products requires recognition and acceptance from the consumer market (He et al., 2016). Given that hydrogen energy vehicles are relatively unfamiliar to the general public at this stage, their promotion will require a gradual process. It is therefore necessary to investigate and quantify urban residents' preferences and willingness to pay (WTP) for hydrogen energy vehicles. Such insights can help governments better balance the social costs and economic benefits of promoting hydrogen energy vehicles and provide a scientific basis for formulating regional industrial support policies.

The choice experiment (CE) method, proposed based on Lancaster's consumer theory and random utility theory, is a commonly used approach for evaluating willingness to pay (WTP). It has been widely applied in fields such as agriculture, resources, and the environment to assess the value of ecosystems and provide targeted policy recommendations (Ma & Zhang, 2013; Gong et al., 2016; Yao et al., 2017). In recent years, the CE method has also been extensively applied in the transportation sector, though most research has focused on electric vehicles (EVs). Relevant studies have shown that high purchase costs, long charging times, and limited driving range are the primary factors deterring consumers from purchasing EVs (Li et al., 2017). Moreover, the economic foundation and policy support of local governments significantly influence the adoption of EVs (Li et al., 2017). At the same time, consumers' WTP for EVs varies depending on survey samples and research regions. Overall, the public is more willing to pay for increased driving range, shorter charging times, and a greater number of charging stations, while they are relatively less willing to pay for reductions in pollutant emissions (Hardman et al., 2016; Li et al., 2019). In addition, consumers' socio-economic characteristics and government policies also influence their decision-making behavior, though their overall impact is relatively small (Li et al., 2017).

As hydrogen vehicles (HVs) are still in the early stages of development, existing research primarily focuses on technical issues such as hydrogen production, storage, and safety (Shao & Yi, 2019; Yin, 2021; Ma, 2017), as well as industrial development (Liu, 2013; et al., 2004). Some studies have proposed measures to effectively promote the large-scale application of hydrogen energy, including the implementation of green hydrogen production demonstration projects and learning from the hydrogen energy development models of other developed countries. These measures aim to enhance public recognition and acceptance of hydrogen energy and further promote the development of the hydrogen energy industry in China (Yi et al., 2018; Sun, 2020; Fu & Xiong, 2020). However, research on public attitudes toward hydrogen energy vehicles remains limited. Existing studies show that the public generally holds a positive attitude toward HVs as an alternative to traditional fuel vehicles (Kovač et al., 2021) . Moreover, key attributes such as fuel efficiency, driving range, emission reduction capability, and refueling time significantly influence consumers' willingness to pay (WTP) (Kim et al., 2019; Li et al., 2020). Nevertheless, the application of the choice experiment (CE) method in the field of HVs remains scarce, and research on consumers' preferences for HEV attributes and their WTP is still lacking.

Based on this, this study conducted field surveys in five different cities in China, collecting 507 valid samples. By employing a choice experiment model and utilizing a mixed logit model, we explore consumer preferences for hydrogen vehicle attributes and the sources of preference heterogeneity. Furthermore, we estimate consumers' willingness to pay for various attributes of hydrogen vehicles, providing a scientific basis to support the development of hydrogen vehicles.

2. Method

2.1 Design of Choice Experiment

This study considers five important attributes that affect consumers' purchase of a hydrogen vehicle, including purchase price, government subsidies, driving range, hydrogenation refueling station density, and CO_2 emission reduction. Among them, the purchase price is based on the current price of the main hydrogen energy automobile manufacturers, and four levels of 300,000, 500,000, 700,000, and 900,000

Yuan per vehicle are set. Government subsidies are based on the current national and local governments' subsidy policies for hydrogen energy vehicles. There are five levels: 50,000 yuan/vehicle, 100,000 yuan/vehicle, 150,000 yuan/vehicle, 200,000 yuan/vehicle, and 250,000 yuan/vehicle. The driving range is based on the current hydrogen vehicle brand cruising range parameter, and the setting is 300, 600, 900, and 1,200 kilometers. Based on the current plan of hydrogen energy industry in China, the density of hydrogenation refueling stations is set at three levels: one hydrogen refueling station per 8 kilometers, one hydrogen refueling station per 12 kilometers, and one hydrogen refueling station per 16 kilometers. Compared to traditional fuel vehicles, carbon dioxide emissions are based on the existing literature to set four levels of reduction: 30%, 50%, 70%, and 90%. The specific option of the five attribute variables are shown in Table 1.

Table 1. Choice Experiment Attributes and Status Levels

Attributes	Description	Attribute level
Purchase Price	The amount that residents need to pay for a hydrogen energy vehicle	300,000 yuan; 500,000 yuan; 700,000 yuan; 900,000 yuan
Government Subsidies	Amount of government subsidy a consumer receives for each hydrogen vehicle purchased	50,000 yuan/vehicle; 100,000 yuan/vehicle; 150,000 yuan/vehicle; 200,000 yuan/vehicle; 250,000 yuan/vehicle
Driving Range	How many kilometers per hydrogenation	300 km; 600 km; 900 km; 1,200 km
Hydrogenation Refueling Station Density	Average number of kilometers driven to the nearest hydrogen station	One hydrogen station per 8 km; per 12 km; per 16 km
CO_2 Emissions Reduction	How much carbon dioxide emissions can be reduced by driving the same kilometers of hydrogen energy vehicles	Emission reduction 30 %, 50 %, 70 %, 90 %.

According to the number of attributes and state levels designed in this study, theoretically, two sets of choice experiments can be combined into different options of 960 groups (4 × 4 × 3 × 5 × 4). To facilitate the selection of respondents on the basis of obtaining as much effective information as possible, 100 options were screened by partial factorial design method, and then these options were combined and paired according to the efficiency principle. The incentive compatibility principle was satisfied during the selection process. At the same time, in order to avoid mandatory selection, an exit option (maintaining the status quo) was added to each selection set and used as a benchmark item. In the end, each interviewee would randomly select five groups of selected sets from the above pairing combinations, and then they need to select one of the most preferred solutions in each selection set. Table 2 shows an example of choice set.

Table 2. An Example of Choice Set

	Plan A	Plan B	Plan C
Purchase Price	700,000 yuan	900,000 yuan	
Government Subsidies	One-time subsidy of 200,000 yuan per vehicle	One-time subsidy of 100,000 yuan per vehicle	
Driving Range	Hydrogenation has a driving range of 600 km at a time	Hydrogenation has a driving range of 900 km at a time	□ Status quo (not purchase)
Hydrogenation Refueling Station Density	One hydrogen station per 16 km	One hydrogen station per 8 km	
CO_2 Emissions Reduction	70% less than fuel vehicles	70% less than fuel vehicles	
Selection	□ Plan A	□ Pan B	□ Pan C

2.2 Data Collection

This study employed a random sampling method to conduct field surveys in the central urban areas of Beijing, Baoding, Anqing, Xinzhou, and Neijiang. Beijing is the capital of China, Baoding is located in the eastern region, Anqing and Xinzhou are situated in the central region, and Neijiang is in the western region. The survey covers regions with different levels of economic development across eastern, central, and western China, while also taking into account the diversity between large cities and small to medium-sized cities. This approach helps to comprehensively capture consumer preferences for hydrogen vehicles and the sources of preference heterogeneity, thereby enhancing the generalizability and scientific validity of the research findings.

During the survey, interviewers conducted one-on-one interviews with respondents from household units through door-to-door visits. Before respondents completed the questionnaire, the interviewers provided a detailed explanation of the specific meanings of each attribute and its corresponding levels in the questionnaire. Respondents were also explicitly informed that all choices were based on hypothetical future policy scenarios for the development of hydrogen energy vehicles. Subsequently, during the survey process, interviewers further clarified the meanings of each set of policy attribute combinations and guided respondents to make their selections based on personal preferences.

After excluding questionnaires with incomplete or unreasonable responses, 507 valid questionnaires were retained. Since each respondent participated in five choice experiments, with each experiment containing three choice sets, a total of 7,065 observations were obtained in this study.

2.3 Variable Setting

The dependent variable in this study is whether a specific combination scheme is selected. If a respondent chooses the scheme, it is assigned a value of 1; if not, it is assigned a value of 0. The explanatory variables used to analyze consumer preferences for hydrogen energy vehicles are the attribute levels of the combination schemes. Additionally, explanatory variables describing respondent characteristics are included to analyze the sources of heterogeneity in consumer preferences.

Given that the Mixed Logit regression model belongs to the generalized linear model family and has limited expressive capacity, continuous variables such as respondents' age, education level, and annual household income were discretized. This approach simplifies the model, facilitates faster model iteration, and reduces the risk of overfitting, thereby enhancing the model's explanatory power. Detailed explanations and descriptive statistics of the variables are provided in Table 4.

Table 4. Sample Descriptive Statistics (N=7605)

Variable	Description	Definition	Mean	Std. dev.
Selection	Whether to purchase under this plan	1=purchase; 0=not purchase	0.33	0.47
Price	Purchase price	30; 50; 70; 90 (ten thousand Yuan)	47.66	26.19
Subsidies	Government subsidies	5; 10; 15; 20; 25 (ten thousand Yuan)	10.70	9.46
Range	Driving range	3; 6; 9; 12 (hundred km)	7.56	2.58
Density	Hydrogen refueling station density	8; 12; 16 (km per station)	8.85	5.53
Reduction	CO_2 emissions reduction	3; 5; 7; 9 (tenths)	3.99	3.34
Gender	Gender of the respondent	0=male; 1=female	0.50	0.50
Age	Age group of the respondent	1=25 years or below; 2=26-35 years; 3=36-45 years; 4=45 years or above	2.28	1.12
Education	Respondent's years of education	1=0-6 years; 2=7-12 years; 3=12-16years; 4=16 years or above	2.76	0.66
Income	Household's annual income	1=Below 100 thousand;2=100-200 thousand; 3=200-500 thousand;4=500-1,000 thousand; 5= Above 1 million	1.93	0.95
Experience	Years of driving experience	1=0 year; 2=1-2 years; 3=3-5 years; 4=6-10 years; 5=11-20 years; 6=more than 20 years	2.57	1.54

Distance	Average distance per trip	1=Not driving；2=0-3 km; 3=3-6 km; 4=6-10 km; 5=10-20 km; 6=20-30 km;7=30-50 km; 8= More than 50 km	2.71	1.97
Knowledge	Knowledge about HVs	1=Yes; 0= No	0.31	0.46

2.4 Specification of the Model

The choice experiment method is based on Lancaster's consumer theory (Lancaster, 1966) and random utility theory. According to Lancaster's consumer theory, any product or item can be described by a set of characteristics with varying levels, and consumers derive utility from these characteristics. Random utility theory suggests that utility represents the benefits a choice provides to the decision-maker and the satisfaction an individual perceives from alternative options (Luce, 2012). Regardless of which option the decision-maker chooses, the individual gains some level of utility. Moreover, based on the principle of utility maximization, decision-makers always choose the option that offers the highest total utility, which is the sum of defined (deterministic) utility and random utility (Wang et al., 2019).

The random utility U that the decision-maker derives from choice alternative is given by the following equation:

$$U_{nj} = V_{nj} + \varepsilon_{nj} = \alpha x_j + \beta z_j + \varepsilon_{nj} \quad (1)$$

The random utility consists of a deterministic utility and a random error term ε. The deterministic utility is determined by the attribute levels of the combination scheme and the socioeconomic characteristics of the decision-maker z_j, where and are vectors representing the random components. The error term accounts for the unobservable part of the utility. The probability of choosing each alternative can be expressed as a function of its deterministic utility: $P = F(V)$, with the specific form of the function depending on the distribution of the random error term.

The probability that decision-maker selects a specific policy combination scheme can be expressed as:

$$\begin{aligned} P_{ni} &= Prob\left(U_{ni} > U_{nj}, \forall j \neq i\right) \\ &= Prob\left(v_{ni} + \varepsilon_{ni} > v_{nj} + \varepsilon_{nj}, \forall j \neq i\right) \\ &= Prob\left(\varepsilon_{nj} - \varepsilon_{ni} < v_{ni} - v_{nj}, \forall j \neq i\right) \end{aligned} \quad (2)$$

The probability follows a cumulative distribution function:

$$P_{ni} = \int I\left(\varepsilon_{nj} - \varepsilon_{ni} < v_{ni} - v_{nj}, \forall j \neq i\right) f(\varepsilon_n) d\epsilon_n \quad (3)$$

Here, is an indicator function. When the condition inside the parentheses is true, $I = 1$; otherwise, $I = 0$. Equation (3) represents the multidimensional integral of the joint density function of the unobservable part of utility. The resulting discrete choice model depends on the assumptions made about the distribution of the random terms. When estimating the parameters of the choice experiment model, it is typically assumed that the random terms are independent and follow a Gumbel distribution. Under this assumption, the probability of a decision-maker choosing a particular alternative is given by:

$$P_{ni} = \frac{exp(V_{ni})}{\sum_{j=1}^{J} exp(V_{ni})} \tag{4}$$

The utility derived from the choice can be expressed in a linear form as:

$$V_{ni} = \beta x'_{ni} + \gamma z'_{n} \tag{5}$$

In the utility function, represents explanatory variables that vary with both individual and alternative ,z'_{n} represents explanatory variables that vary only with individual, is the coefficient vector for the explanatory variables.

During parameter estimation, respondents are typically heterogeneous, and their preferences for hydrogen vehicle attributes may also vary. When heterogeneity exists, imposing assumptions of homogeneous preferences and responses can lead to biased parameter and probability estimates (Otieno et al., 2011). To account for this, this study employs the Mixed Logit model for parameter estimation. The Mixed Logit model, also known as the Random Parameters Logit (RPL) model, is a commonly used method to evaluate preference heterogeneity. It is robust in exploring decision-making behavior in the presence of heterogeneous preferences within the sample. The Mixed Logit model is highly flexible, capable of approximating any random utility model, and relaxes the restrictive assumptions of the traditional Conditional Logit model by allowing preference parameters to vary within the sample according to specified distributions (McFadden & Train, 2000). Additionally, it is particularly effective in handling cases where a respondent makes multiple choices (Brownstone & Train, 1998).The choice probability of a respondent using the Mixed Logit model can be expressed as:

$$P_{ni} = \int \frac{exp(\beta x'_{ni})}{\sum_{j=1}^{J} exp(\beta x'_{nj})} f(\beta \setminus \theta) d\beta \tag{6}$$

In the equation, β is the vector of parameters specific to respondent n, $f(\beta \setminus \theta)$ is the probability density function of β, which describes the distribution of the random parameters across the population.

Finally, to analyze the marginal value of different hydrogen vehicle attributes, the point estimate of the value for a unit change in non-price attributes can be calculated using Equation (7). WTP represents the marginal rate of substitution between the price attribute and other attributes (Morrison et al., 2002). Specifically, WTP can be expressed as the ratio of the estimated coefficient of the non-price attribute to the estimated coefficient of the price attribute:

$$WTP = -\frac{\beta_{other\ attributes}}{\beta_{price}} \tag{7}$$

3. Result

3.1 Analysis of Consumers' Preferences for HVs

This study employs Stata 17.0 software to conduct regression analysis using the Mixed Logit model. In Model 1, Purchase Price is specified as a fixed parameter, while other attribute variables are treated as random parameters. To evaluate the impact of consumers' actual purchase price on purchase intentions, the variable actual price is generated as the difference between purchase price and government subsidies, and it is specified as a fixed parameter in Model 2. The estimation results are presented in Table 5.

The results indicate that, in Model 1, the coefficients of purchase price and hydrogenation refueling station density are significantly negative, while the coefficients of government subsidies, driving range, and CO_2 emissions reduction are significantly positive. In Model 2, the coefficient of actual purchase price is significantly negative, and the directions of other attributes remain consistent with those in Model 1. These findings suggest that consumers are more inclined to choose options with lower purchase price and actual purchase price, higher government subsidies, longer driving range, more densely distributed hydrogenation stations, and more significant CO_2 emissions reduction. The detailed analysis is as follows:

(1) Price factors significantly influence consumers' purchase decisions. Consumers exhibit a significantly negative preference for purchase price and a significantly positive preference for government subsidies, consistent with general trends in the new energy vehicle market. During the early stages of promoting hydrogen vehicles, price subsidy policies remain critical. By directly reducing purchase costs, subsidies effectively alleviate consumers' concerns about high upfront investments, lower the barriers to technology adoption, and foster market growth. This suggests that, at the current stage of development, government subsidies remain an essential policy tool for stimulating the market.

Table 5. Mixed Logit Estimation of Consumers' Preferences for HVs

Variable	Model 1		Model 2	
	Mean	SD	Mean	SD
Price	-0.0198***			
	(0.0018)			
Subsidies	0.0240***	0.0690***		
	(0.0068)	(0.0088)		
Actual Price			-0.0187***	
			(0.0017)	
Range	0.0476***	-0.0689**	0.0499***	-0.0622*
	(0.0137)	(0.0304)	(0.0133)	(0.0366)
Density	-0.0386***	0.1481***	-0.0343**	0.1553***
	(0.0139)	(0.0159)	(0.0137)	(0.0161)
Reduction	0.0788***	0.2392***	0.0756***	0.2556***
	(0.0218)	(0.0287)	(0.0207)	(0.0265)
Log likelihood	-2288.7529		-2310.7231	
LR chi2	738.49***		694.59***	
Observation sample	7605			

Note. ***、**、* represent significance at 1%, 5%, 10%, standard errors in parentheses.

(2) Convenience of use is a key factor influencing consumer choices. The significantly positive coefficient of driving range indicates that consumers prefer models with greater range, reflecting their desire to ensure that daily usage needs are met. Meanwhile, the negative coefficient of hydrogenation refueling station density suggests that consumers favor a denser hydrogen refueling infrastructure. This highlights the importance of convenience in the user experience of HVs. Strong endurance capabilities and a well-connected refueling network can significantly boost consumer confidence in using new technologies and reduce their concerns about practical usability.

(3) Environmental benefits positively drive purchase decisions.The significantly positive coefficient of CO_2 emissions reduction demonstrates that consumers recognize the environmental value of hydrogen vehicles. This finding underscores the importance of environmental awareness in purchase decisions, reflecting the growing emphasis consumers place on the environmental benefits of products as society transitions toward carbon neutrality. Environmental attributes have evolved from an additional value to a core factor influencing vehicle purchase decisions.

(4) Consumer preferences exhibit significant heterogeneity.The significant standard deviation coefficients for variables such as government subsidies, driving range, hydrogenation refueling station density, and CO_2 emissions reduction indicate notable differences in how individual consumers prioritize these attributes. This heterogeneity likely stems from variations in consumers' income levels, travel needs, and environmental awareness, among other individual characteristics. This finding not only confirms the necessity of employing the Mixed Logit model but also provides a basis for developing differentiated market strategies.

3.2 Analysis of the Sources of Heterogeneity in Consumer Preferences for HVs

The estimation results of the baseline model (Model 1), which only includes attribute variables of HVs, have confirmed the existence of heterogeneity in consumer preferences for HVs. To further analyze the sources of this heterogeneity, this section incorporates interaction terms between consumers' characteristic variables and the random parameters into the model. A total of eight Mixed Logit models were constructed for this analysis.

Models 3 to 6 introduce interaction terms between four socioeconomic variables and the random parameters. These socioeconomic characteristics include gender, age, education, and annual household income. The estimation results are detailed in Table 6.

The results of Model 3 indicate that the interaction terms between gender and the random parameters are not statistically significant, suggesting that gender is not a primary source of heterogeneity in consumer preferences. This implies that both male and female consumers focus primarily on the economic efficiency and practical performance of hydrogen vehicles, with gender differences having a minimal impact on their preference structures.

The analysis of Model 4 reveals that the interaction terms between age and driving range as well as age and emission reduction are significantly negative at the 10% and 5% significance levels, with coefficients of -0.0191 and -0.0435, respectively. These findings indicate that older consumers have a lower utility evaluation for driving range and place less emphasis on emission reduction benefits. This may be because older consumers tend to prioritize vehicle reliability and economic practicality over environmental or technological attributes. Furthermore, older consumers may have less trust in hydrogen technology, leading to weakened preferences for driving range and environmental benefits. Additionally, they are more likely to engage in short-distance driving, reducing the importance of extended driving range, and they may have less concern about environmental issues compared to younger consumers.

Model 5 shows that the interaction terms between education level and driving range as well as education level and emission reduction are significantly positive at the 10% and 5% levels, with coefficients of 0.0360 and 0.0725, respectively. This indicates that highly educated consumers have a stronger positive evaluation of driving range and place greater importance on emission reduction benefits. This phenomenon can be explained by the fact that consumers with higher education levels tend to have stronger environmental awareness and are more willing to contribute to environmental protection. Moreover, their greater familiarity with hydrogen technology enhances their confidence in technological advancements that improve driving range, which increases their acceptance of hydrogen vehicles.

The results of Model 6 indicate that the interaction terms between income level and subsidies, driving range, and hydrogen station density are all significant. The interaction term for subsidies has a negative coefficient (-0.0112), while the interaction terms for driving range (0.0284) and hydrogen station density (0.0337) have positive coefficients. These results suggest that high-income consumers are less dependent on government subsidies and place greater importance on the vehicle's driving range while being less sensitive to the distance between hydrogen refueling stations. This can be attributed to the fact that high-income consumers typically have more flexible budgets, meaning they prioritize vehicle performance over financial incentives. Additionally, high-income consumers may own multiple vehicles, and hydrogen vehicles may serve as a secondary option, reducing their reliance on refueling infrastructure. At the same time, they have a stronger demand for extended driving range due to their likely preference for high-performance vehicles.

Models 7 to 9 expand the analysis by introducing interaction terms for driving-related factors, including driving experience, average trip distance, and knowledge about hydrogen vehicles (HVs). The estimation results are presented in Table 7.

Model 7 shows that driving experience is significantly and negatively associated with the interaction term for subsidies at the 10% significance level (-0.0075). This indicates that consumers with more driving experience are less reliant on government subsidies. A possible explanation is that experienced drivers have a more comprehensive understanding of vehicle ownership costs and are less dependent on upfront purchase subsidies, focusing instead on the total cost of ownership.

Table 6. Heterogeneity Analysis: Socioeconomic Characteristics

Variable		Model 3	Model 4	Model 5	Model 6
Price	Mean	-0.0198***	-0.0198***	-0.0200***	-0.0199***
Subsidies	Mean	0.0241***	0.0332**	0.0144	0.0467***
	SD	0.0690***	0.0682***	0.0698***	0.0685***
Range	Mean	0.0367*	0.0901***	-0.0508	-0.0071
	SD	-0.0693**	-0.0655**	-0.0664**	-0.0748**
Density	Mean	-0.0436**	-0.0216	-0.0555	-0.1084***
	SD	0.1479***	0.1475***	0.1492***	0.1518***
Reduction	Mean	0.0952***	0.1766***	-0.1188	0.0194
	SD	0.2382***	0.2363***	0.2362***	0.2341***

Subsidies×Gender	-0.0004			
Range×Gender	0.0223			
Density×Gender	0.0103			
Reduction×Gender	-0.0334			
Subsidies×Age		-0.0040		
Range×Age		-0.0191*		
Density×Age		-0.0074		
Reduction×Age		-0.0435**		
Subsidies×Education			0.0034	
Range×Education			0.0360*	
Density×Education			0.0057	
Reduction×Education			0.0725**	
Subsidies×Income				-0.0112*
Range×Income				0.0284**
Density×Income				0.0337***
Reduction×Income				0.0325
Log likelihood	-2288.0209	-2279.617	-2282.0781	-2279.9445
LR chi2	735.07***	714.75***	738.63***	740.97***

Table 7. Heterogeneity Analysis: Driving Characteristics

Variable		Model 7	Model 8	Model 9
Price	Mean	-0.0198***	-0.0198***	-0.0199***
Subsidies	Mean	0.0433***	0.0354***	0.0206**
	SD	0.0688***	0.0692***	0.0716***
Range	Mean	0.0503*	0.0479**	0.0385**
	SD	-0.0689**	-0.0694**	-0.0671**
Density	Mean	-0.0543**	-0.0564***	-0.0553***
	SD	0.1479***	0.1477***	0.1434***
Reduction	Mean	0.0782**	0.0852**	0.0789***
	SD	0.2406***	0.2404***	0.2357***

Subsidies×Experience	-0.0075*		
Range×Experience	-0.0012		
Density×Experience	0.0060		
Reduction×Experience	-0.0001		
Subsidies×Distance		-0.0042	
Range×Distance		-0.0001	
Density×Distance		0.0066	
Reduction×Distance		-0.0024	
Subsidies×Knowledge			0.0094
Range×Knowledge			0.0270
Density×Knowledge			0.0551**
Reduction×Knowledge			0.0091
Log likelihood	-2286.8713	-2287.5861	-2283.6398
LR chi2	737.41***	739.15***	725.09***

Model 7 shows that driving experience is significantly and negatively associated with the interaction term for subsidies at the 10% significance level (-0.0075). This indicates that consumers with more driving experience are less reliant on government subsidies. A possible explanation is that experienced drivers have a more comprehensive understanding of vehicle ownership costs and are less dependent on upfront purchase subsidies, focusing instead on the total cost of ownership.

The results of Model 8 indicate that the interaction terms between average trip distance and all random parameters are not significant. This suggests that average trip distance has a limited influence on consumer preferences for the key attributes. It reflects that the target consumers for hydrogen vehicles do not exhibit substantial preference differences based on their travel distance. One possible explanation is that the relatively long driving range of hydrogen vehicles is sufficient to meet the daily needs of consumers with varying trip distances, thereby reducing the impact of average trip distance on their purchasing preferences.

Model 9 reveals that the interaction term between hydrogen vehicle knowledge and hydrogen station density is significantly positive at the 5% significance level (0.0551). This implies that consumers with greater knowledge of hydrogen vehicles exhibit a higher tolerance for lower hydrogen station density. This finding reflects a deeper understanding of hydrogen vehicle technology among informed consumers, such as the relatively long driving range of hydrogen vehicles, which can partially offset the inconvenience caused by a sparse refueling infrastructure. Moreover, consumers with higher levels of knowledge may also have greater confidence in the gradual improvement of hydrogen infrastructure and technological advancements, leading to a higher acceptance of the current state of hydrogen station density.

3.3 Analysis of Consumers' WTP for Different Attributes of HVs

Consumers exhibit significant differences in their preferences for various attributes of hydrogen vehicles. In the design process of hydrogen vehicles, trade-offs and compromises often need to be made between different attributes. Therefore, understanding consumers' preference intensity for each attribute is of great importance. Based on Equation (7) and the estimated coefficients of different hydrogen vehicle attributes in Model 2, the willingness to pay for each attribute was calculated to reflect the strength of consumer preferences. The calculation results are presented in Table 8.

The WTP for driving range is 26,700 yuan, indicating that consumers are willing to pay a premium of 26,700 yuan for every 100-kilometer increase in range. This value highlights the significant influence of driving range on consumer purchasing decisions. A sufficient driving range can effectively alleviate range anxiety, improving the user experience. Additionally, a longer driving range reduces the need for frequent refueling, which is particularly valuable given the current underdeveloped hydrogen refueling network.

The WTP for hydrogen refueling station density is 18,300 yuan, meaning consumers are willing to pay 18,300 yuan for every 1-kilometer reduction in the distance between hydrogen refueling stations. This result underscores the critical role of infrastructure convenience in consumer decision-making. The relatively high willingness to pay suggests two key points: first, consumers place great importance on the convenience of hydrogen refueling, likely due to the insufficient coverage of the current refueling network; second, optimizing the layout of hydrogen refueling stations may serve as a crucial lever for promoting the development of the hydrogen vehicle market.

The WTP for CO_2 emissions reduction is 40,400 yuan, indicating that consumers are willing to pay 40,400 yuan for every 10% increase in carbon reduction. This demonstrates several important insights: first, environmental benefits have become a key dimension in consumers' evaluations of hydrogen vehicles, reflecting a growing public consciousness of environmental issues; second, the high willingness to pay provides a market basis for the environmental premium of hydrogen vehicles; and third, emphasizing environmental attributes in marketing strategies could yield positive results.

Table 8. Consumers' WTP for Different Attributes of HVs

Attributes	Coefficient	WTP
Actual Price	-0.0187	
Range	0.0499	2.67
Density	-0.0343	1.83
Reduction	0.0756	4.04

4. Discussion

To accurately evaluate consumers' preferences and willingness to pay for different attributes of hydrogen vehicles, this study, based on the assumption of consumer heterogeneity, combines literature review and the current market context to design an attribute combination for HVs and conducts a discrete choice experiment. Using the mixed logit model, the study measures consumer preferences for various HV attributes, providing references for the formulation and implementation of future HV promotion policies. The main findings of the study are as follows:

(1) Price factors significantly affect consumers' purchasing decisions: Consumers show a negative preference for purchase prices but a significant positive preference for government subsidies, indicating that subsidy policies remain an essential tool for promoting the HFCV market at the current stage.

(2) Convenience of use is a crucial factor influencing consumer choices: The positive coefficient for driving range suggests that consumers prefer models with longer ranges, while the negative coefficient for hydrogen refueling station density reflects a preference for a denser network of refueling stations, highlighting the critical role of convenience in enhancing user experience and purchase intention.

(3) Environmental benefits positively influence consumer purchasing decisions: The high marginal willingness to pay for carbon emission reduction demonstrates that environmental attributes have become a significant consideration for consumers when choosing HVs.

(4) Consumers exhibit significant heterogeneity in their preferences for HV attributes: Consumers with different income levels, education levels, and travel habits place varying degrees of importance on price, driving range, refueling station density, and environmental benefits. Specifically, high-income consumers are less sensitive to purchase prices and place greater emphasis on driving range and convenience, whereas low- and middle-income consumers are more price-sensitive and more reliant on government subsidies. Consumers with higher education levels prioritize environmental benefits more significantly, while those with lower education levels focus more on price and practicality. Regarding travel habits, consumers with longer average travel distances show a stronger preference for driving range but are relatively less dependent on the density of refueling stations.

The findings of this study provide the following insights for the formulation of future HV promotion policies:

(1) At the current stage, efforts should focus on optimizing subsidy policies to reduce purchase costs, particularly by providing more targeted economic incentives for low- and middle-income consumers to promote market adoption.

(2) Companies should enhance research and development on driving range performance, while governments should collaborate with relevant stakeholders to accelerate the development of a hydrogen refueling station network, thereby improving user convenience and lowering the barriers to technology adoption.

(3) Policymakers should fully consider the importance consumers place on environmental benefits and highlight the environmental advantages of HVs in promotional campaigns to attract environmentally

conscious consumers.

(4) Marketing and promotion strategies should be more differentiated to address the heterogeneity in consumer preferences. Combining consumers' socioeconomic characteristics, targeted marketing and policy combinations can be developed to maximize market coverage and drive the comprehensive growth of the HV market.

For example, for low- and middle-income groups, who are more sensitive to purchase prices, high-value, cost-effective, and economically priced HVs should be prioritized, supplemented by higher purchase subsidies or preferential loan policies to lower the financial barrier to entry. For high-income groups, premium models can be promoted with additional after-sales services (e.g., free hydrogen refueling, exclusive maintenance services) to attract their interest. For consumers with higher education levels, whose environmental awareness is stronger, marketing should emphasize the environmental benefits and social responsibility of HVs, using data-driven analysis and real-world examples to enhance their recognition of product value. Conversely, for consumers with lower education levels, information should be conveyed in a more straightforward and intuitive manner (e.g., through short videos or offline experience events), with an emphasis on the cost-effectiveness of the vehicles.

In conclusion, the promotion of HVs should remain consumer demand-oriented, fully accounting for consumer preferences and heterogeneity, and balancing economic, convenience, and environmental benefits to achieve the dual goals of market adoption and sustainable development.

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