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Ownership and Usage Analysis of Alternative Fuel Vehicles in the United States with the 2017 National Household Travel Survey Data

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Abstract: By using the 2017 National Household Travel Survey (NHTS) data, this study explores the status quo of ownership and usage of conventional vehicles (CVs) and alternative fuel vehicles (AFVs), i.e., Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs), in the United States. The young ages of HEVs (6.0 years), PHEVs (3.2 years) and BEVs (3.1 years) demonstrate the significance of the 2017 NHTS data. The results show that after two decades of development, AFVs only occupy about 5% of annual vehicle sales, and their share does not show big increases in recent years. Meanwhile, although HEVs still dominate the AFV market, the share of PHEVs & BEVs has risen to nearly 50% in 2017. In terms of ownership, income still seems to be a major factor influencing AFV adoption, with the median annual household incomes of CVs, HEVs, PHEVs and BEVs being $75,000, $100,000, $150,000 and $200,000, respectively. Besides, AFV households are more likely to live in urban areas, especially large metropolitan areas. Additionally, for AFVs, the proportions of old drivers are much smaller than CVs, indicating this age group might still have concerns regarding adopting AFVs. In terms of travel patterns, the mean and 85th percentile daily trip distances of PHEVs and HEVs are significantly larger than CVs, followed by BEVs. BEVs might still be able to replace CVs for meeting most travel demands after a single charge, considering most observed daily trip distances are fewer than 93.5 km for CVs. However, the observed max daily trip distances of AFVs are still much smaller than CVs, implying increasing the endurance to meet extremely long-distance travel demands is pivotal for encouraging consumers to adopt AFVs instead of CVs in the future.

Keywords: alternative fuel vehicle; hybrid electric vehicle; plug-in hybrid electric vehicle; battery electric vehicle; 2017 National Household Travel Survey; ownership; travel patterns

1. Introduction

Transportation is one of the major energy consumers and emission sources. In the United States (U.S.), transportation consumed 29% of energy in 2017 [1] and emitted 28% of greenhouse gas (GHG) in 2016 [2]. Due to concerns involving fuel price rises, pollution and global warming, regulations on fuel economy and emissions of vehicles have been increasingly stringent in the past few decades, which has been prompting automakers to develop more energy-efficient and emission-reducing vehicles. One important solution is to develop hybrid electric vehicles (HEVs). Compared to conventional vehicles (CVs) with internal combustion engine (ICE), a hybrid electric vehicle (HEV) combines an ICE system with one or more electric motors that use energy stored in batteries, thus achieving a better fuel economy and low emissions [3]. The batteries are usually charged by regenerative braking and ICEs. Although the concept of HEVs was proposed as early as 1901 [4], they were not commercially available in large scale until the release of the Toyota Prius in Japan in 1997, followed by the Honda Insight in 1999 [5]. In 2002, Lave and MacLean compared the second generation of Toyota Prius to the conventional ICE—Toyota Corolla, where Prius was proved to have lower pollutant and carbon dioxide emissions and a better fuel economy than the Corolla [6].

With technological advances, plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) have also been developed and made widely available in the auto market in the past decade. PHEVs also combine the battery-electric vehicle technology with an ICE system, but they generally have larger battery packs than HEVs, and thus can travel for some distance just using electricity [7]. Meanwhile, their batteries can also be charged from external chargers in addition to using energy from regenerative braking and the ICEs. PHEVs could significantly improve fuel economy over standard HEVs [8]. BEVs only use battery packs to store the electricity to power them. Their batteries are usually charged by plugging vehicles into external electric power sources [9], thus fast charging may apply. BEVs generally have shorter ranges than CVs, but their major advantage is zero emissions at the point of use [9]. In the past two decades, HEVs, PHEVs and BEVs have become non-ignorable players in the auto market. In the U.S., the total sales of HEVs, PHEVs and BEVs reached up to 565,930 units in 2017 [10,11], occupying about a 3.28% market share [12]. Compared with CVs, HEVs, PHEVs and BEVs belong to the category of alternative fuel vehicles (AFVs), which also includes hydrogen fuel cell vehicles (HFCVs), compressed natural gas (CNG) vehicles, solar vehicles, biodiesel vehicles, and so on. However, currently, their market shares are still very small compared with HEVs, PHEVs and BEVs in the U.S.

Accompanying the arrival of AFVs, numerous studies have been conducted to explore their characteristics from the perspectives of vehicle technology [13], environmental protection [14], charging infrastructure [15,16], market penetration rate [17], consumer acceptance [18–21], and so on. However, due to the short history of AFVs, especially for PHEVs and BEVs, in the auto market, there is still a lack of knowledge on the characteristics of ownership and usage of AFVs in practice. These features can be represented by three questions: What AFVs are used now? Who owns them? How are they used? This knowledge is critical for all stakeholders in the realm of AFVs. They can help automakers to determine AFV design and sales, policymakers to formulate AFV purchase incentives & perks, transportation agencies to construct AFV-compatible infrastructure and consumers to determine whether to adopt AFVs or not. For example, knowing about the demographic and socio-economic features of AFV owners is greatly helpful for automakers in setting prices and promotion strategies, while identifying daily travel distances of BEVs is critical for public utilities agencies to determine the layout of charging stations.

The National Household Travel Survey (NHTS) is a periodic national survey conducted in the U.S. to assist transportation planners and policy makers who need comprehensive data on travel and transportation patterns of the U.S. [22]. Data is collected on the trips of households and individuals for the surveyed households over a 24-h period. The questionnaire includes purpose of the trip, means of transportation, travel time of trip, and time of day/day of week. This data is collected for all trips, modes, purposes, trip lengths and all areas of the country, urban and rural. The NHTS was conducted in 1969, 1977, 1983, 1990, 1995, 2001, 2009, and 2017, respectively. In the 2009 NHTS, AFV information was first collected, where each vehicle in the household with a model year of 2002 or newer was asked whether it was a hybrid or alternate fuel use vehicle [23]. In the 2017 NHTS [24], respondents were required to further indicate AFV types, including biodiesel, PHEV, BEV, HEV and other fuels. Therefore, the 2017 NHTS data is the 1st NHTS data, which might be used in analyzing the ownership and usage characteristics of AFVs in detail. Numerous studies have demonstrated the value of the NHTS data in exploring a variety of transportation research topics, such as ride-hailing [25], walking and cycling [26], travel patterns of older people [27,28], immigrants [29] and students [30], and so on. There are also some exploratory studies involved in speculating and forecasting usage features of AFVs with NHTS data, mainly using the 2009 NHTS data [31–37] and the 2001 NHTS data [38–41]. However, none of them were able to identify the actual ownership and usage features of HEVs, PHEVs and BEVs due to unavailability of AFV information in former NHTSs. In addition, some studies have tried to analyze travel patterns of AFVs with the data of the California Household Travel Survey (CHTS) conducted by the California Department of Transportation during January 2012 through January 2013 [42–44]. However, considering the fast development of AFVs, the CHTS data might not be able to reflect the current status quo of AFVs. For example, the Model S sedan from Tesla is now one of the most popular BEVs [10], but it was not released until 22 June 2012 [45]. Thus, the CHTS data were not expected to include many Model S vehicles. In addition, the CHTS data were only collected in California. Considering the huge differences of economy, weather, terrain, oil price and charging infrastructure across states in the U.S., the findings from the CHTS might not be generalized to other states or the national level. Additionally, some studies tried to use the naturalistic driving data to analyze travel patterns of drivers [46–48], but most of them did not specifically focus on AFVs in vehicle selection.

Therefore, this study focuses on using the 2017 NHTS data to obtain basic ideas of actual ownership and usage characteristics of AFVs in the U.S. The paper is organized as follows. Section 2 introduces the 2017 NHTS data. Section 3.1 presents vehicle features of AFVs. Section 3.2 explores the ownership features of AFVs in terms of main drivers and households. Section 3.3 analyzes travel patterns of AFVs. Section 4 gives conclusions and areas for discussion.

2. Materials

The 2017 NHTS was conducted by the Federal Highway Administration, U.S. Department of Transportation from April 2016 through to April 2017. The 2017 NHTS collected vehicles from all 50 states and the District of Columbia of the U.S. It includes the core national samples plus samples from 13 state and local planning agencies from around the country [24]. Researchers collected data from roughly 130,000 households and 275,000 persons in the U.S., sampled based on postal address lists. Each participating household reported all travels by household members on a randomly assigned 24-h single "travel day". They were assigned travel days for all 7 days of the week, including all holidays.

The 2017 NHTS data consists of four datasets: household, person, trip, and vehicle [24]. Hybrid vehicle information can be retrieved from two fields of the vehicle dataset: fuel type and hybridization of the vehicle. For fuel type, subjects were asked to report the type of fuel used by each household vehicle with choices being "I don't know", "I prefer not to answer", "gas", "diesel", "hybrid, electric or alternative fuel", and "some other fuel". They were also asked type of hybrid vehicle for vehicles that were reported to use "hybrid, electronic or alternative fuel" with choices being "not ascertained", "I don't know", "appropriate skip", "biodiesel", "plug-in hybrid", "electric", "not plug-in hybrid", and "some other fuel". Based on specific keywords, household, person and trip information linked to vehicles can be retrieved.

By vehicle type, vehicles are reclassified into car, van, sport utility vehicle (SUV), pickup truck, and others; by fuel type, they are divided into CV, HEV, PHEV, BEV, and others. The composition of vehicles by vehicle type and fuel type can be seen in Table 1.

Table 1. Composition of vehicles by vehicle type and fuel type.

Vehicle Type	CV	AFV				Total
		HEV	PHEV	BEV	Others	
Automobile/Car/Station Wagon	116,937	4,438	440	459	117	122,391
Van	13,141	14	3	1	25	13,184
SUV	59,709	523	22	13	86	60,353
Pickup Truck	46,159	10	0	0	63	46,232
Others	13,753	11	17	134	40	13,955
Total	249,699	4,996	482	607	331	256,115

Note: for vehicle type, others include unknown vehicles, vehicles not answered, other trucks, recreational vehicles (RVs), motorcycles, and something else; for hybrid vehicles, others include biodiesel and some other fuel vehicles.

It can be found that:

- AFVs only occupy 2.5% of total surveyed vehicles, which implies that there is still a long way to go for AFVs after nearly twenty years of development.
- Most AFVs belong to HEVs, PHEVs and BEVs. HEVs has the largest share (77.9%), whereas PHEVs and BEVs only have very small shares (7.5% and 9.5%). That is, HEVs still currently dominate the AFV market as a whole.
- AFVs vary a lot by vehicle type. Most AFVs are cars, whereas very few of them are SUVs, vans and pickup trucks, which however occupy nearly half of total surveyed vehicles. Thus, it implies that development of alternative fuel SUVs, vans and pickup trucks should be taken into account for automakers in their future plan, especially plug-in hybrid electric and battery electric SUVs, vans and pickup trucks.

Considering automobiles/cars/station wagons (named as "cars"), vans, SUVs and pickup trucks are typical household vehicle types for daily travel in the U.S., the following analysis will focus on analyzing cars, vans, SUVs and pickup trucks of CV, HEV, PHEV and BEV. These vehicles occupy 94.4% of total surveyed vehicles, and 92.3% of total surveyed AFVs. Thus, the data are thought to be big enough to represent the whole sample.

3. Results

3.1. What AFVs are Running in the U.S.?

3.1.1. Vehicle Model Analysis

The composition of vehicles by vehicle model and fuel type can be seen in Table 2, where only the top 6 models by count are shown. Compared with CVs, the AFV market shows very obvious concentrations. The top 6 CV models only occupy 17.4% of total CVs, whereas the proportions are 76.4%, 88.0% and 78.6% for HEVs, PHEVs and BEVs, respectively. Therefore, the AFV market is currently dominated by few auto models in the U.S. The data does not indicate whether and how this concentration influences the AFV development, but it implies that there might be still ample space for new competitors to join if the AFV market is expected to be as mature as the CV market.

Table 2. Composition of vehicles by vehicle model and fuel type.

CV		HEV		PHEV		BEV	
Model	**Units**	**Model**	**Units**	**Model**	**Units**	**Model**	**Units**
F-Series Pickup	11,020	Prius	2653	Volt	187	Leaf	182
C, K, R, V-Series pickup/Silverado	7525	Camry	425	Prius	93	Tesla	121
Camry	6636	Civic/CRX, del Sol	227	Fusion	60	500/500c	27
Accord	6381	Fusion	205	C-Max	53	Spark	17
Civic/CRX, del Sol	4834	Highlander	163	A3	11	Golf/Cabriolet/Cabrio/GTI/GLI	14
Ram Pickup	4776	RX330/350/400h/450h	137	Leaf	5	Fortwo	11
Top 6 sum	41,172		3810		409		372
Top 6 proportion	17.4%		76.4%		88.0%		78.6%

3.1.2. Vehicle Age Analysis

The histograms of vehicle model years by fuel type are shown in Figure 1. Most surveyed CVs showed significant appearances since 2000, whereas HEVs and PHEVs & BEVs did not significantly appear until 2005 and 2010, respectively. Vehicle age, which is defined as the difference of 2017 and model year [49], is also calculated. On average, CVs, HEVs, PHEVs and BEVs are 10.4 years, 6.0 years, 3.2 years and 3.1 years old, respectively. The small vehicle ages of AFVs confirm the significance of the 2017 NHTS data in exploring the features of AFVs. Even for CVs, the average age of 10.4 years implies that the 2017 NHTS data could reflect the status quo of CVs more precisely than former NHTSs, since the nearest NHTS, i.e., the 2009 NHTS, was also conducted nearly 10 years ago.

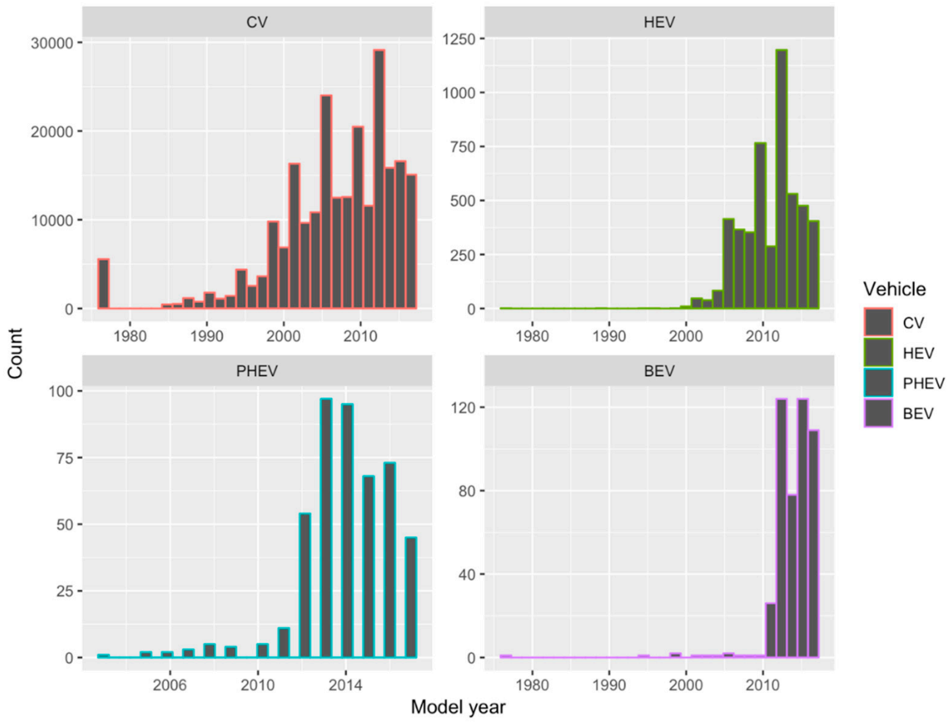

Figure 1. Histograms of vehicle model years by fuel type.

The proportion of AFVs out of total vehicles by model year is shown in Figure 2. Currently, the annual AFV proportion is around 5% in the U.S. Although it has generally shown an increasing trend since 2000, it has only experienced very small increases but also big fluctuations since 2010. There seems to be a bottleneck in the AFV development now, which needs further investigation. The proportion of HEVs, PHEVs, and BEVs out of AFVs by model year is shown in Figure 3. The proportions of PHEVs and BEVs have been very close and also increasing very rapidly since 2010. Although HEVs still dominate the AFV market, the market share of PHEVs and BEVs has risen to nearly 50% in 2017. It seems that 2017 is a watershed for the AFV market, which has begun to be dominated by PHEVs and BEVs. Future studies may include the data for 2018 to determine whether this is a temporary trend or not.

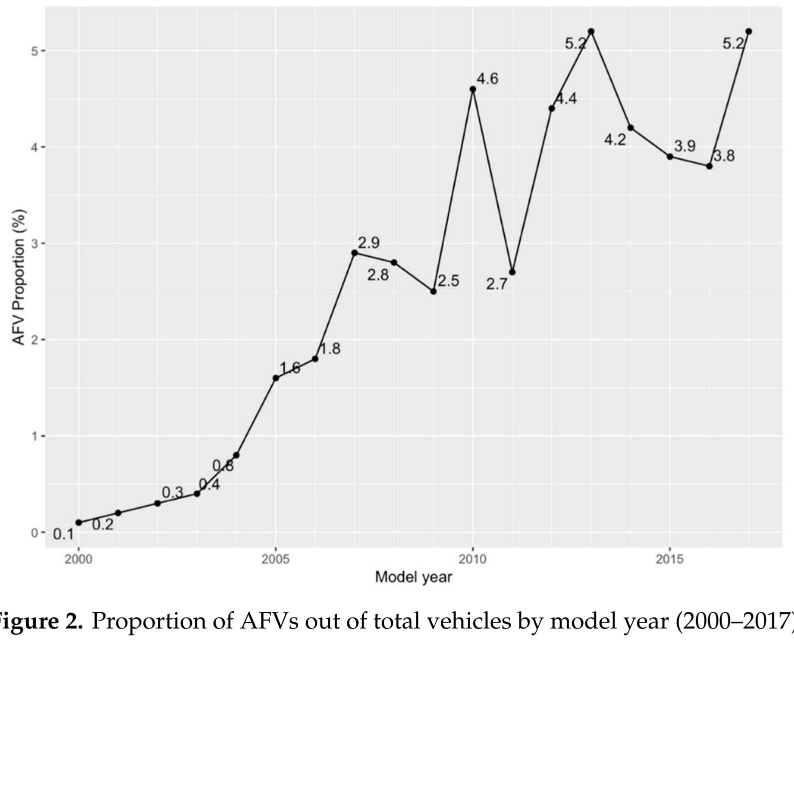

Figure 2. Proportion of AFVs out of total vehicles by model year (2000–2017).

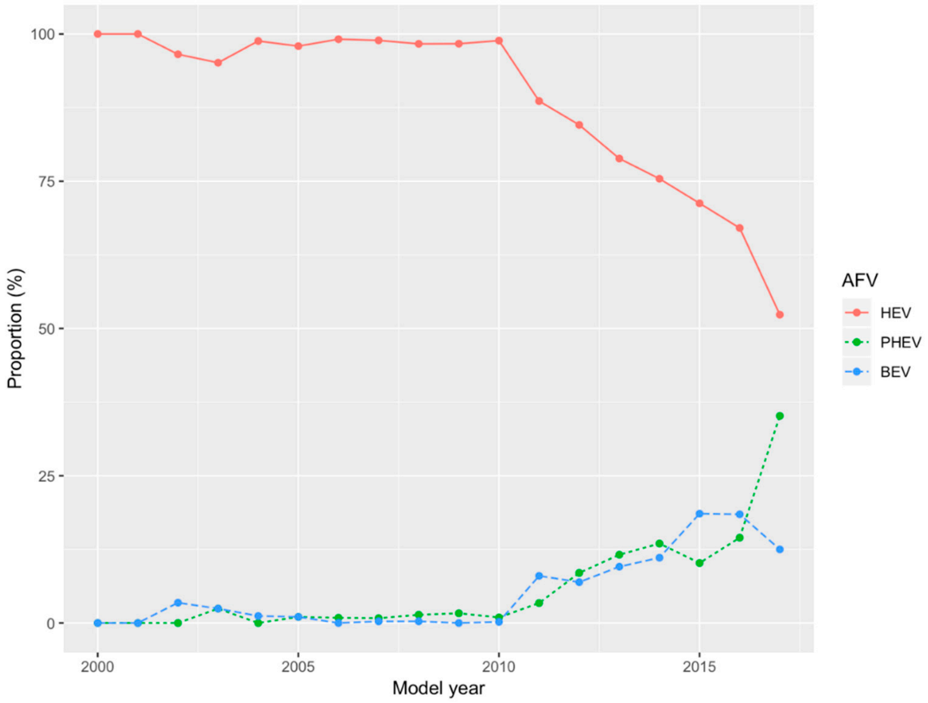

Figure 3. Proportions of HEVs, PHEVs and BEVs out of AFVs by model year (2000–2017).

3.2. Who Owns AFVs in the U.S.?

3.2.1. Vehicle Main Driver Analysis

Vehicle main drivers determine the travel patterns of vehicles. A summary of demographic features of vehicle main drivers by fuel type is given in Table 3.

Table 3. Demographic features of vehicle main drivers by fuel type.

Variable	Definition	CV	HEV	PHEV	BEV
Average age	Years	54.4	54.8	53.2	52.0
Young driver proportion	<25, %	5.1%	3.2%	1.5%	0.9%
Old driver proportion	≥65, %	31.4%	30.7%	26.3%	19.3%
Gender	Male, %	52.8%	43.0%	59.4%	58.0%
Race	Asian, %	3.7%	7.5%	7.9%	14.1%
	African American, %	6.2%	2.6%	2.2%	1.5%
	White, %	84.5%	85.5%	84.2%	79.5%
	Other, %	5.2%.	4.9%	5.7%	4.9%
Education	Bachelor's degree or higher, %	46.6%	74.8%	82.6%	80.0%

It can be found that:

- On average, main drivers of CVs, HEVs, PHEVs and BEVs are 54.4, 54.8, 53.2 and 52.0 years old, respectively. Table 4 shows the results of two-sample *t*-test to vehicle main driver ages. Main drivers of CVs and HEVs do not show significant age differences, and main drivers of PHEVs and HEVs do not show significance age differences either. However, main drivers of CVs and HEVs are 1.8 years older than those of PHEVs and BEVs on average, which might be mainly attributed to the small proportions of old drivers for PHEVs and BEVs. A possible explanation is that most old drivers might be still unfamiliar with PHEVs and BEVs due to their short history, and they might have concerns and a lack of knowledge and confidence to adopt them. However, old people actually are found to be eager to adopt new technology [50], which might be also kind of proved by the close age distributions of main driver of CVs and HEVs. Old people are thought to be much more familiar with HEVs than PHEVs and BEVs because of their longer presence in the auto market. Therefore, it is reasonable to infer that it is possible for old drivers to adopt more PHEVs and BEVs in the future if they are given appropriate instructions and guidance.

- The proportion of male main drivers of PHEVs and BEVs are obviously higher than that of CVs, which means PHEVs and BEVs might be more attractive to males rather than females. However, more than half of main drivers of HEVs are females, which is contrary to other vehicle types. Further investigations are suggested to define the reason.
- Compared with CVs, AFV main drivers have much larger proportions of Asians but much smaller proportions of African Americans. One possible explanation to this finding might be related to incomes of these groups: the proportions of people in poverty for Asians and African Americans are 10.0% and 21.2% in 2017, respectively [51]. As is shown later, income plays a critical role in AFV adoption.
- Finally, the proportions of main drivers with the bachelor's degree or higher are much larger for AFVs than that of CVs. Higher-educated people are generally expected to have higher incomes and be more welcome to the concept of sustainable transportation. Thus, they are more likely to adopt AFVs.

Table 4. The two-sample *t*-test results of vehicles main driver age.

Test	Sample 1: Mean Main Driver Age (Years)	Sample 2: Mean Main Driver Age (Years)	*t*-Statistic	*p*-Value
1	CV: 54.4	HEV: 54.8	−1.679	0.093
2	CV & HEV: 54.4	PHEV & BEV: 52.6	3.966	<0.001 *
3	PHEV: 53.2	BEV: 52.0	1.313	0.190

Note: *, significant at 0.05.

3.2.2. Vehicle Household Analysis

A summary of the socio-economic features of vehicle households by fuel type is given in Table 5.

Table 5. Socio-economic features of vehicle households by fuel type.

Variable	Definition	CV	HEV	PHEV	BEV
Median annual household income	$1000	75	125	150	200
Average number of workers in household	Persons	1.0	1.2	1.4	1.5
Household in urban area	%	76.6%	82.9%	88.1%	88.8%
Household in urban area with 1 million or more population	%	31.8%	41.8%	52.6%	61.6%
Life cycle composition	Adults with no children, %	38.4%	38.1%	38.9%	37.4%
	Adults with children, %	22.6%	25.6%	32.2%	38.7%
	Retired adults with no children, %	39.0%	36.2%	28.9%	24.0%
Household vehicle size (Only CVs, HEVs, PHEVs and BEVs)	One vehicle, %	34.6%	21.3%	16.6%	7.3%
	More than 1 vehicle, %	65.4%	78.7%	83.4%	92.7%

It can be found that:

- The median annual household incomes of CVs, HEVs, PHEVs and BEVs are $75K, $125K, $150K, and $200K, respectively, indicating big income differences. The cumulative density function (CDF) plots of annual household income of vehicles by fuel type are shown in Figure 4, which further confirms the solid positive relationship between vehicle type and income. Due to the high purchase costs of AFVs, it is not a surprise that income is an important factor influencing their adoption. The finding may also explain why the average numbers of workers in households increase in sequence from CVs, HEVs, PHEVs to BEVs. For example, the average number of workers of BEV households is nearly 1.5 times that of CV households.

- In terms of living areas, compared with CVs, households of AFVs are more likely to live in urban areas, especially urban areas with a population of 1 million or greater. As a comparison, 61.3% of BEV households live in urban areas with a population of 1 million or greater, whereas the proportion is only 30.1% for CV households. That may be because households are more likely to have higher incomes and access to the well-developed charging infrastructure in big metropolitan areas.
- In terms of life cycle composition, CV and HEV households are very close. The proportions of households with adults and children for PHEVs & BEVs are obviously larger than those for CVs and HEVs, whereas the proportions of households with retired adults without children for PHEVs & BEVs are obviously smaller than those for CVs & HEVs. The finding is consistent with the average ages of main drivers shown in Section 3.2.1. One possible explanation is that compared to CVs and HEVs, the retired adults might be more unfamiliar with PHEVs and BEVs due to their short history in the auto market, which might produce concerns and prevent their adoption of PHEVs and BEVs. However, considering the similar life cycle compositions of CVs and HEVs, it is thought to be very possible for retired adults to accept PHEVs and BEVs if automakers could make more efforts on developing customized vehicle designs and promotions aiming at old people.
- In terms of household vehicle size, the proportions of AFV households with more than one vehicle are much larger than CV households. In particular, 92.7% of BEV households own more than one vehicle, whereas this proportion is only 65.5% for CV households. This leads to one question: are AFVs thought to be as reliable as CVs for households? In other words, could AFVs meet daily travel demands of the same people as CVs? The following section would answer this question by travel pattern analysis.

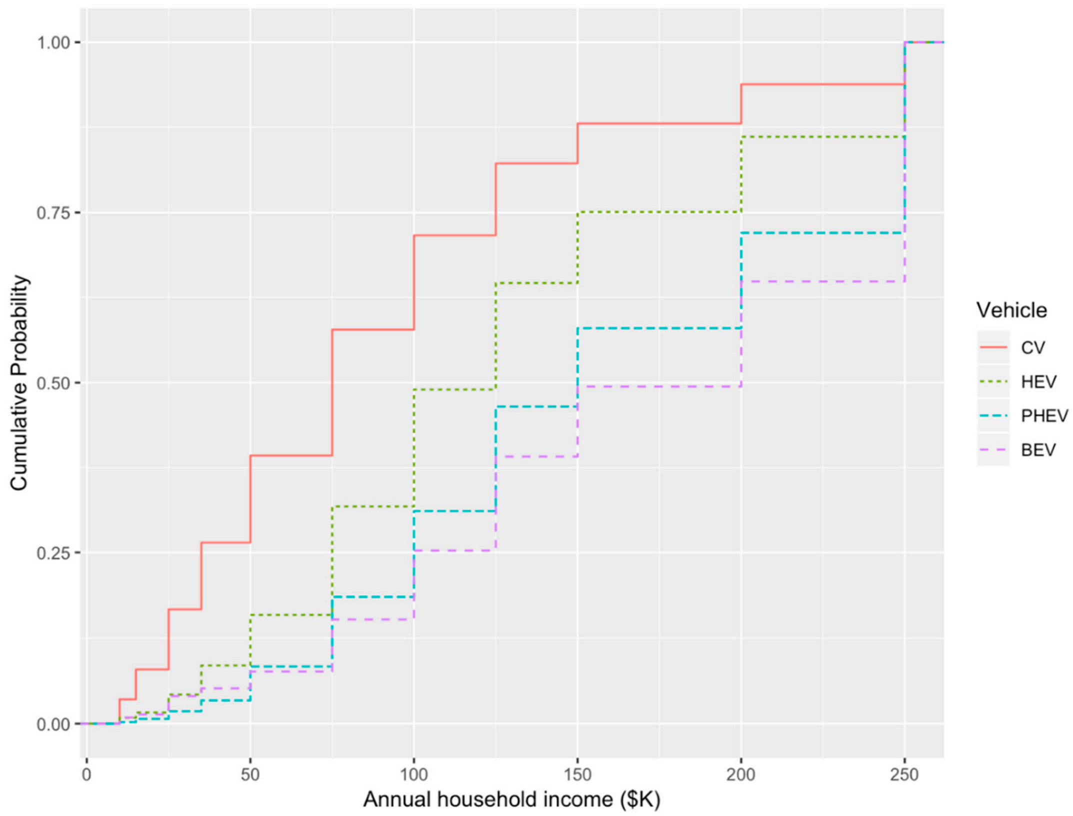

Figure 4. The CDF plots of annual household income of vehicles by fuel type.

3.3. How Are AFVs Used in the U.S.?

Travel patterns are critical to figure out whether vehicles can meet travel demands of users. Here, travel patterns would be analyzed at trip level and daily level separately to get a full understanding of AFV usage characteristics.

3.3.1. Trip Level Analysis

Trip distance and trip duration are used as trip-level indicators. For each indicator, the mean value, the 85th percentile value and the maximum value are used to represent the mean, general and extreme travel demands, respectively (Table 6). It should be noted that only trips with explicit trip distances and trip durations are taken into account in the analysis. It can be found that:

- In terms of the mean trip distance and the mean trip duration, HEVs & PHEVs do not show statistically significant differences ($t = -1.484$, p-value = 0.138), but they have significantly larger values than CVs ($t = -4.697$, p-value < 0.001) and BEVs ($t = -5.153$, p-value < 0.001). This means that HEVs & PHEVs have similar travel patterns, probably because of their similarities in power sources. In terms of BEVs, this result is consistent with a former study, where the average trip lengths of PHEVs were also found to be longer than BEVs [52]. However, it is surprising to find that HEVs & PHEVs are used more than CVs in practice.
- Although the mean trip distance and the mean trip duration of BEVs are smaller than those of CVs, the 85th percentile trip distances and the 85th percentile trip durations of CVs and BEVs are very close. For CVs, more than 85% of trips last no more than 23.7 km in distance and 30 min in duration. At this range, BEVs could replace CVs in meeting most practical trip demands.
- The max trip distances and max trip durations of CVs, HEVs, PHEVs and BEVs greatly decline in order. For BEVs, the max trip distance and the max trip duration are only 242.5 km and 180 min, respectively, which are only 12.8% and 15.0% of those of CVs. Even for HEVs, the max trip distance and the max trip duration are still only 50.2% and 58.2% of those of CVs. It is thought that AFVs may still have some difficulties in meeting extreme travel demands, which might be mainly attributed to their limitation in endurance.
- It is surprising that the max trip distances and the max trip durations of HEVs and PHEVs are also much smaller than CVs. Different from BEVs, HEVs and PHEVs could also run with gasolines, thus theoretically they could run as far as CVs. Further investigation is needed to find out why this discrepancy exists.
- Besides, based on the mean trip distance and the mean trip duration, the mean trip speeds of CVs, HEVs, PHEVs and BEVs are calculated to be 43.9 km/h, 44.9 km/h, 46.7 km/h and 40.2 km/h, respectively. It seems that BEVs generally run slower than CVs, HEVs and PHEVs.

Table 6. Trip-level travel exposures of vehicles by fuel type.

Vehicle	Mean		85th Percentile		Maximum	
	Distance (km)	Duration (min)	Distance (km)	Duration (min)	Distance (km)	Duration (min)
CV	14.5	19.8	23.7	30	1888.5	1200
HEV	15.5	20.7	25.8	31	948.9	698
PHEV	16.8	21.6	28.7	35	385.1	275
BEV	12.8	19.1	23.8	30	242.5	180

The proportion distribution of trips by trip start hour and fuel type is shown in Figure 5. HEVs and PHEVs do not show big differences from CVs in terms of trip start hour, but BEVs obviously had more trips at 7 am and 8 am than HEVs, PHEVs and CVs. That is, there are more trips for BEV drivers in morning peak hours, which needs further investigation.

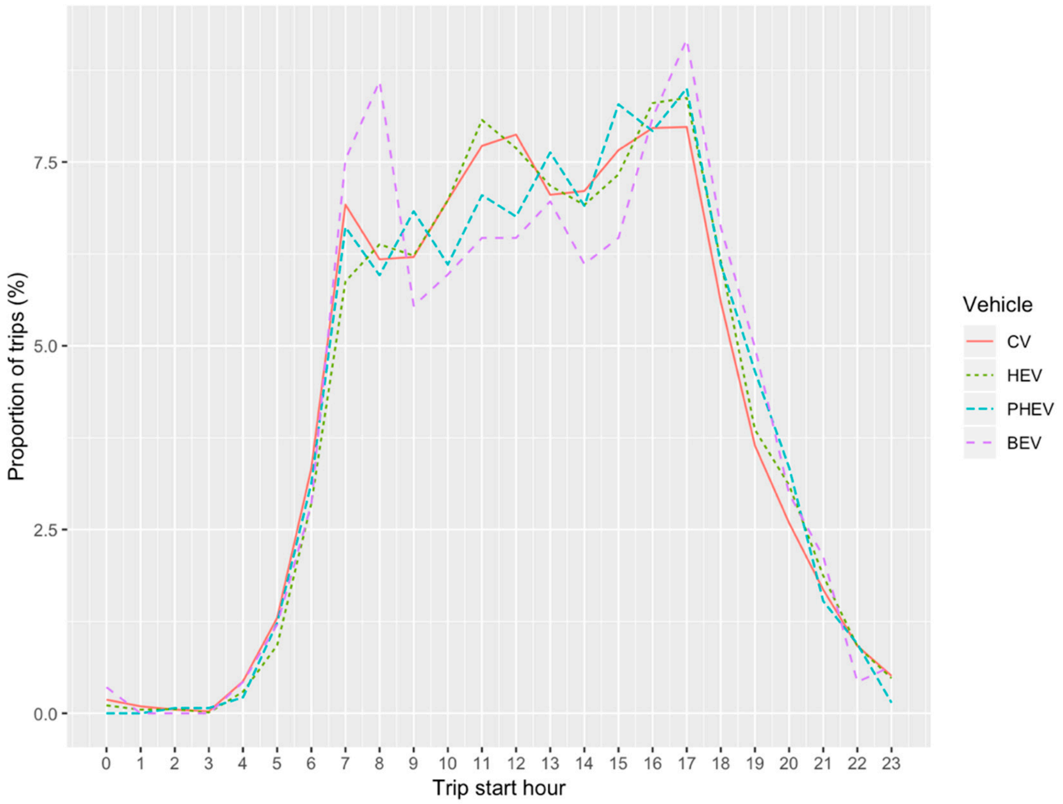

Figure 5. The proportion of trips by trip start hour and fuel type.

3.3.2. Daily Level Analysis

Daily level performance measures, such as daily trip distance [53–59] and daily trip duration [58], have been widely used to identify travel patterns of vehicles. They are especially important for studying travel patterns of PHEVs and BEVs, considering many of them are primarily charged at night at home. In this section, in addition to daily trip distance and daily trip duration, daily trip frequency, i.e., the number of trips occurring per day, is also calculated as an indicator. For each indicator, the mean value, the 85th percentile value and the maximum value are calculated to represent the mean, general and extreme daily travel demands, respectively (Table 7).

Table 7. Daily-level travel exposures of vehicles by fuel type.

Vehicle	Mean			85th Percentile			Maximum		
	Distance (km)	Duration (min)	Frequency	Distance (km)	Duration (min)	Frequency	Distance (km)	Duration (min)	Frequency
CV	56.9	77.7	3.9	93.5	125	6	1888.5	1217	32
HEV	64.8	86.3	4.2	109.9	140	6	1208.1	815	39
PHEV	66.4	85.5	4.0	114.9	140	6	670.2	390	11
BEV	51.3	76.9	4.0	81.4	125	6	402.0	400	15

It can be found that:

- For all vehicle types, the mean daily trip frequencies are around 4.0 and the 85th percentile daily trip frequencies are 6. Neither of them shows big differences. The finding is thought to be reasonable as the basic daily travel demands, including working, shopping and schooling, are supposed to be consistent for most individuals/households.
- In terms of the mean and 85th percentile values of daily trip distance and daily trip duration, HEVs & PHEVs are very close, obviously larger than CVs and BEVs, whereas BEVs have the

smallest indicator values. That is, HEVs and PHEVs are used much more than CVs and BEVs, where BEVs are used least in practice.

- It should be noted that the mean and 85th percentile daily trip durations of BEVs are very close to those of CVs. The differences of their mean and 85th percentile daily trip distance are only 5.6 km and 12.1 km, respectively. Besides, for CVs, more than 85% of trips last no more than 93.5 km in distance and 125 min in duration. Considering the normal ranges of most BEVs are over 160 km with a single charge [60] and assuming that BEVs are primarily charged at home at night, BEVs might still be able to replace CVs for meeting most daily travel needs.
- The max values of daily performance measures of CVs are still much larger than those of AFVs, in addition to the max daily trip frequency of HEVs. The max daily trip distance and the max daily trip duration of HEVs are 64.0% and 67.0% of those of CVs, whereas the max daily trip distance and the max daily trip duration of BEVs are only 21.3% and 32.9% of those of CVs. The finding confirms that compared with CVs, the capacity of meeting extremely long-distance and high-frequency travel demands might be one of major limitations for AFVs, especially for BEVs.

4. Conclusions and Discussions

In the past two decades, AFVs, mainly consisting of HEVs, PHEVs and BEVs have received much attention and made much progress in commercialization under the context of reducing fossil fuel consumption and emission in transportation. Compared to CVs driven only by ICEs, these AFVs are equipped with either extra rechargeable battery packs besides ICEs or pure rechargeable battery packs. Due to the generally high purchase costs, many policies of purchase incentives and perks have been formulated to promote AFV sales. However, after nearly two decades of development for HEVs and one decade for PHEVs and BEVs, there is still a lack of understanding of the actual ownership and usage characteristics of AFVs at the national level of the U.S. In particular, considering the impending expiration of electric vehicle tax credits for some models in 2018 [61], it is time to review the state of the art of AFV usages in the U.S. Based on the latest 2017 NHTS data of the U.S., this paper focuses on answering three basis questions involving in ownership and usage of AFVs: What AFVs are running in the U.S.? Who owns them? How are they used? The significance of the 2017 NHTS is that it is the first NHTS to collect specific information of HEVs, PHEVs and BEVs. Besides, both the wide data collection range covering all 50 states and the Districted of Columbia of the U.S., and the small average ages of HEVs (6.0 years), PHEVs (3.2 years) and BEVs (3.1 years) suggest that the 2017 NHTS data might be one of the best available datasets to give answers to these questions. The findings from this study are thought to be updated, credible and reliable.

It is found that although the AFV adoption has been increasing, AFVs still only occupy a small share (less than the 5%) of the annual auto market in the U.S, and they show very slow recent increases. For the AFV market, the share of PHEVs & BEVs has risen to nearly 50% in 2017 from nearly zero in 2010, indicating a major growth prospective. In terms of vehicle types, nearly 90% of surveyed AFVs are cars. However, considering the major presences of vans, SUVs and pickup trucks in the auto market of the U.S., automakers may focus more on developing alternative fuel vans, SUVs and pickup trucks in the future. Besides, the AFV market is also dominated by few vehicle brands. In terms of vehicle ownership, the median annual household incomes of CVs, HEVs, PHEVs and BEVs are $75,000, $100,000, $150,000 and $200,000, respectively, which corroborates that income is one of major factors influencing adopting AFVs. Besides, AFV households are more likely to live in urban areas, especially large metropolitan areas, where charging stations are expected to be well-developed. These findings confirm that continuously lowering ownership costs and building more charging infrastructure are critical for further promoting AFV development. Meanwhile, in regards to vehicle main drivers, the proportions of old people (≥65) driving PHEVs and BEVs are only 26.3% and 19.3%, respectively, much lower than that of CVs. In terms of travel patterns, PHEVs and HEVs have very close mean and the 85th percentile daily trip distances and daily trip durations, which are significantly larger than those of CVs and BEVs, whereas BEVs have the smallest indicator values. Since more than 85% of daily travels last less than 93.5 km in distance and 125 min in duration for CVs, BEVs might still be capable of replacing CVs for meeting most travel demands. However, for extremely long-distance travel demands, AFVs are used far less than CVs, indicating there may be still an underlying concern to the endurance of AFVs for customers. Therefore, the development of battery technology to increase the endurance is critical for encouraging more people to adopt AFVs to replace CVs completely in the future.

4.1. Implications for AFV Stakeholders

The findings from this paper can help a number of stakeholders to fully identify the issues of the current AFV market from the perspectives of vehicle, people and usage, and provide many instructive insights to the future AFV development. Firstly, the paper indicates that the developments of AFVs seem to encounter a bottleneck in the U.S., as their market share does not have obvious increases since 2010, although people are expected to have more knowledge of AFVs over time. However, considering the increasing shares of PHEVs and BEVs in this time period, this means that the future AFV development may greatly depend on PHEVs and BEVs rather than HEVs in the U.S. Automakers and policymakers may adjust their development strategies based on this trend. Furthermore, they may also want to figure out the most attractive features of PHEVs and BEVs to consumers: high performance, technological innovation, environment protection [62], or low running costs? Thus, they can formulate customized sales and financial incentive policies.

A second implication is that it gives the household income indicators of owning AFVs in the U.S. Although income has been well-known as a major factor influencing the AFV adoption and many studies obtained some data on this area through questionnaires conducted on small scales, there is a lack of such information at the national level for the U.S. The income information related to AFVs presented in this study may help automakers to more accurately search for potential AFV customers with lower costs and formulate targeted sales policies. It may also instruct policymakers to design more effective financial incentive policies, as the current incentive policy is found to be misplaced for many BEV customers and the income cap or vehicle price eligibility gap-based incentives might be more appropriate [62]. This information is also a good reference for customers to determine whether it is a good time for them to adopt AFVs.

Finally, the travel pattern indicator values presented in this paper, especially the 85th percentile daily trip distance and the 85th percentile daily trip duration, may help automakers to determine the capacity of AFV batteries. Batteries with high capacity are usually costly. It is thought that appropriate batteries should be capable to meet most travel demands with the least costs. Additionally, while aiming for taxi/ride-sharing vehicles which have special requirements on battery capacity, the maximum indicator values might be consulted to design AFVs for taxi/ride-sharing purposes. This information might also be used by public utility agencies to determine the number, location, layout and size of charging stations.

4.2. Future Studies

This study concentrates on making a macroscopic analysis on the status quo of AFVs used in practice in the U.S., whereas future studies might be conducted in many aspects to get more details. Firstly, policy is proved to have great effects on the AFV adoption in numerous studies. In the U.S., although there are uniform federal policies, the state-level AFV purchase incentives vary a lot amongst states. Future researchers may want to explore how these policies influence the adoption of AFVs. Secondly, fuel price is another factor which might influence AFV adoption. In the past decade, fuel prices had very major fluctuations due to many events, such as the 2008 economic recession. Researchers may want to identify the influence of fuel price on the AFV adoption, which would be helpful in figuring out the long-term AFV adoption trend under the context of oil production. Thirdly, with the increase of AFVs, AFV crashes have also increased. However, different from CVs, it is found that AFV-related crashes provide many new challenges from collision types to salvation methods due to the presence of batteries. It is time to know about the features of AFV crashes, whether and how AFVs would affect traffic safety as a whole. Fourthly, a huge part of AFVs are adopted in public transportation and government agencies. These vehicles are expected to be very different from private vehicles in many aspects, such as vehicle design, battery capacity, incentives, travel pattern, and so on. Future studies may combine these vehicles and private vehicles to get a full understanding on how AFVs is reshaping the transportation mode of this country. Fifthly, the lifespan of a hybrid vehicle battery is usually 5 to 10 years [63]. As is shown in the paper, PHEVs and BEVs had significant appearances since 2010 in the U.S., which means these vehicles may start to have batteries replaced on a large scale in practice. Considering the high battery replacement costs and battery recycling challenges, it is time to explore whether and how the practical battery replacement experiences influence customers' attitudes to adopt PHEVs and BEVs. Finally, HFCVs have gained much attention recently [64,65]. HFCVs are famous for having zero emissions at point of use, fast refueling and a high driving range [66]. Although their current market share is insignificant (as of February, 2019, only 6558 HFCVs were sold in the U.S. [67]) due to high purchase prices, high fuel cost and limited refueling infrastructure [68–70], HFCVs are thought to be economically competitive with technological advancements and more hydrogen refueling stations being built in the future [71]. Their market share is expected to increase to 21% in North America by 2040 [72]. Unfortunately, the information of HFCVs was not explicitly collected in the 2017 NHTS. Thus, HFCVs are not taken into account in this study. However, considering the enormous potential of HFCVs, it is also important to identify ownership and usage features of HFCVs. Future studies might consider combine the NHTS data with other specific HFCV survey data to make such analysis. It should be noted that currently, 40 out of total 45 hydrogen fueling stations in the U.S. are located in California [73]. Thus, only the NHTS data of California might be used in these analyses.

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