# THE FUTURE DEMAND
# FOR ALTERNATIVE FUEL PASSENGER VEHICLES:
# A PRELIMINARY LITERATURE REVIEW

**UC Davis – Caltrans Air Quality Project**
**http://aqp.engr.ucdavis.edu**

**Task Order No. 31**

**Interim Report**
**July 13, 2003**

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Caltrans request to study the impacts of alternative scenarios for zero/low emissions vehicle penetration, with special emphasis on modeling the impact of different scenarios on emissions inventories.

**TABLE OF CONTENTS**

## LIST OF TABLES

# 1. INTRODUCTION

The United States is heavily and increasingly dependent on foreign oil. The net importation of oil accounted for 21.5% (3.16 million barrels net importation per day) of the U.S. energy use in 1970, and steadily increased to 55.5% (10.90 million barrels net importation per day) in 2001. Among all sectors, transportation constituted more than two-thirds of energy consumption in the U.S. in 2001, of which petroleum accounted for an overwhelming proportion (96.9%) of energy demand (Davis and Diegel, 2002). The continued growth in the amount of imported oil required to meet our demand for petroleum products threatens national and economic security, and is not sustainable in the long term. Accordingly, the U.S. government has been adopting a wide range of policies to reduce energy consumption in the transportation sector since the energy crisis of 1973, such as reducing individuals' dependence on personal vehicles, and promoting higher average vehicle fuel economies. However, policies to change individuals' travel behavior have been of limited effectiveness because of the gap between policy assumptions and individuals' actual desires and constraints (Salomon and Mokhtarian, 1997), and overall fuel economy has been declining since 1988, due to the increasing share of light-duty trucks (including minivans and pickup trucks as well as sport utility vehicles (SUVs)) in the passenger vehicle fleet (EPA, 2001). On the other hand, substituting alternative fuels for petroleum products, encouraged by the Energy Policy ACT of 1992 (EPACT92), is promising to reduce the nation's dependence on imported oil and conserve limited, non-renewable resources for future generations.

Global warming is another major worldwide concern associated with petroleum consumption. The surface temperature of the earth has risen by 0.6 degrees Celsius since the late 19th century (IPCC, 2001). Carbon dioxide ($CO_2$), the main "greenhouse gas", greatly contributes to the climate change. The U.S. is the largest emitter of $CO_2$ in the world, accounting for about 23% of the world's $CO_2$ emissions (compared to 4.6% of its population (Census Bureau, 2002) but 32.5% of the global total gross domestic product (GDP) (World Bank, 2002)). In 2000, the transportation sector accounted for 33% of the U.S. total $CO_2$ emissions from fossil energy consumption (Davis and Diegel, 2002). Replacing gasoline-based vehicles with alternative fuel vehicles (AFVs) is expected to significantly reduce $CO_2$ emissions from the transportation sector. Further, AFVs offer tailpipe emission benefits, especially with respect to ozone-forming pollutants such as carbon monoxide (CO) and nitrogen oxides ($NO_x$). Compared to a reformulated gasoline vehicle, a compressed natural gas vehicle reduces approximately 80% of tailpipe emissions, and a liquefied petroleum gas vehicle eliminates about 60% (AFDC, 2002e).

Mainly motivated by these concerns regarding petroleum consumption, climate change, and mobile source emissions, AFVs have been appealing transportation technologies since at least 1990. The public and private sectors have invested billions of dollars into the development of AFVs. At this time, a few types of AFVs are on the road in the U.S., and some demonstration plans for AFVs are in process. These vehicles are potential substitutes for current gasoline vehicles, and may account for a considerable share of the automobile market in the future. Conversely, it is also possible that some types of AFVs will die out since they fail to meet the requirements of potential consumers and hence do not achieve sufficient market share to be viable. However, how AFVs behave in the market depends on a variety of endogenous and exogenous factors, such as their performance, their limitations, consumer preferences, the regulatory environment, the price and availability of gasoline, and so on. Therefore, it is difficult to forecast the market penetration of various AFVs. Yet, the forecasts of AFVs' markets are essential to evaluating their potential contributions to the reduction of energy consumption and emissions in the transportation sector.

The assumed effects of various AFV regulations on the demand for low emission light duty passenger vehicles are incorporated into EMFAC 2001, a powerful emission-modeling tool for quantification of pollutants from on-road sources (available at http://www.arb.ca.gov/ msei/on-road/downloads/docs/emfac2001_documentation.doc). As an example, EMFAC 2001 assumes that advanced technology-partial zero emission vehicles (AT-PZEVs) account for 0.9% of 2003 model year vehicles, and will increase to 12.9% in 2020. In model year 2003, the Honda Civic GX (CNG) and Hybrid (EA-electric assist system) are classified as AT-PZEVs (CARB, 2003a). Other AFVs have the potential to be AT-PZEVs. It is important that these assumed implementation schedules be accurate since they directly affect the outcomes of the emission model. Thus, building models that forecast the demand for AFVs can be useful in evaluating and/or updating these assumed implementation schedules.

The purpose of this research is to estimate the demand for AFVs under different scenarios based on current and assumed conditions for the factors listed above (and possibly estimate the reductions of emissions and imported energy based on different scenarios). In this study, we focus on forecasting the U.S. demand for alternative fuel passenger vehicles, including light-duty automobiles and light-duty trucks, with a timeframe from 2005 to 2025.

The current report is a preliminary literature review that will provide a foundation upon which to proceed. Further review of the literature will be ongoing throughout the project. The organization of this report is as follows. The next section will focus on the supply of alternative fuel passenger vehicles. We provide a brief overview of the current status (including limitations) of the main AFV technologies, and the future outlook. Sections 3 and 4 concentrate on the demand side. Section 3 summarizes disaggregate studies of conventional vehicle and AFV choices, while Section 4 reviews aggregate models of vehicle ownership forecasting. Section 5 describes a methodology for modeling the diffusion of new technologies, which may be applied to the case of AFVs. Section 6 presents a potential approach for our future work on this subject. Section 7 provides a summary of this preliminary report.

## 2. THE SUPPLY OF ALTERNATIVE FUEL PASSENGER VEHICLES AND THEIR LIMITATIONS

### 2.1 Supply of Alternative Fuel Passenger Vehicles

Under EPACT92, alternative fuels were defined as fuels which are not derived from petroleum, including the following: (1) methanol, ethanol, and other alcohols; (2) blends of 85% or more of alcohol with gasoline; (3) natural gas and liquid fuels domestically produced from natural gas; (4) liquefied petroleum gas (propane); (5) coal-derived liquid fuels; and (6) hydrogen and electricity.

The Energy Information Administration (EIA) in the Department of Energy (DOE) reported that eight types of fuel were used to power AFVs in the U.S. during the last decade: liquefied petroleum gas (LPG), compressed natural gas (CNG), liquefied natural gas (LNG), methanol

85% (M85), methanol neat (M100), ethanol 85% (E85), ethanol 95% (E95), and electricity, respectively.

**Table 1. Estimated Number of AFVs in Use in the U.S., by Fuel, 1993-2002**

| ***Fuel Type*** | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|---|---|
| ***LPG*** | 269,000 | 264,000 | 259,000 | 263,000 | 263,000 | 266,000 | 267,833 | 272,193 | 276,597 | 281,286 |
| ***CNG*** | 32,714 | 41,227 | 50,218 | 60,144 | 68,571 | 78,782 | 91,267 | 100,738 | 113,835 | 126,341 |
| ***LNG*** | 299 | 484 | 603 | 663 | 813 | 1,172 | 1,681 | 2,090 | 2,576 | 3,187 |
| ***M85***[a] | 10,263 | 15,484 | 18,319 | 20,265 | 21,040 | 19,648 | 18,964 | 10,426 | 7,827 | 5,873 |
| ***M100***[a] | 414 | 415 | 386 | 172 | 172 | 200 | 198 | 0 | 0 | 0 |
| ***E85***[a b] | 441 | 605 | 1,527 | 4,536 | 9,130 | 12,788 | 24,604 | 58,621 | 71,336 | 82,477 |
| ***E95***[a] | 27 | 33 | 136 | 361 | 347 | 14 | 14 | 4 | 0 | 0 |
| ***Electricity*** | 1,690 | 2,224 | 2,860 | 3,280 | 4,453 | 5,243 | 6,964 | 11,834 | 17,848 | 19,755 |
| ***Total*** | 314,848 | 324,472 | 333,049 | 352,421 | 367,526 | 383,847 | 411,525 | 455,906 | 490,019 | 518,919 |

[a] The remaining portion of 85-percent methanol and both ethanol fuels is gasoline.
[b] In 1997, some vehicle manufacturers began including E85-fueling capability in certain model lines of vehicles. For 2000, the EIA estimated that the number of E85 vehicles that are capable of operating on E85, gasoline, or both, is 2,652,592. Many of these AFVs are sold and used as traditional gasoline-powered vehicles. In this table, AFVs in use include only those E85 vehicles believed to be intended for use as AFVs. These are primarily fleet-operated vehicles.
**Notes**: •Estimates for 2000 are revised. Estimates for 2001 are preliminary and estimates for 2002, in italics, are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available. •Beginning in 1999, LPG estimates are no longer rounded to the nearest thousand. Previously, the estimates were rounded in order to reflect the greatest uncertainty. •Vehicle counts reported by the Federal Agencies for years 2000, 2001, and 2002, may include vehicles ordered but not delivered. The greatest discrepancy between reported and actual in use vehicles occurs for the U.S. Postal Service.
**Sources:** 1993-1995: Science Applications International Corporation, "Alternative Transportation Fuels and Vehicles Data Development," unpublished final report prepared for the Energy Information Administration (McLean, VA, July 1996) and U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy1996-2002: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels.

Adapted from the EIA, DOE (http://www.eia.doe.gov/cneaf/alternate/page/datatables/atf1-13_00.html, accessed on November 25, 2002)

Table 1 presents the EIA-estimated number of AFVs in use in the U.S., by fuel, 1993-2002. The EIA estimated that the number of vehicles (including both light-duty and heavy-duty vehicles) fueled by CNG, E85, and LPG is about 490,000 in 2002, which accounts for approximately 0.2 percent of the total registered vehicles in the U.S. As shown in Table 1, although LPG vehicles experienced a nearly flat growth during the past ten years, and consequently lost some of their market share, they still constitute the largest population among all AFV types. The number of CNG vehicles is steadily increasing in the U.S. It is estimated that CNG vehicles experienced an average annual growth rate of 17.4 percent from 1993 to 2000. For E85, the most common vehicles are flex-fueled ones, which can be fueled either by gasoline or by ethanol or by any blend of both fuels. For 2000, the EIA estimated that there were more than 2.6 million on-road vehicles that can be fueled by E85, but that the overwhelming proportion of these vehicles were operating on gasoline. However, these vehicles have the potential to switch to E85 when competitive conditions are met. Under this assumption, E85 vehicles would have the largest population, rather than LPG vehicles.

Generally, E85 and M85 work best in light-duty vehicles, while E95 and M100 have been used for heavy-duty vehicles (Joyce, 2001; AFDC, 2002a). As illustrated in Table 1, vehicles fueled by E95 and M100 were phased out by 2001, and the number of M85 vehicles has been declining since 1998. Further, automobile manufacturers have not provided new M85 vehicles for several successive model years (AFDC, 2000a; AFDC, 2001; AFDC, 2002b). Consequently, the number of M85 vehicles in use will continue to decline as older vehicles are retired. These indicators suggest that M85, M100, and E95 vehicles have lost or are losing their market shares.

In 2000, LNG light-duty vehicles accounted for a little more than 10% of total LNG vehicles (as shown in Table 2). That is, LNG is overwhelmingly used in heavy-duty vehicles. Similar to M85 vehicles, no new LNG light-duty vehicles have been made in recent years (AFDC, 2000a; AFDC, 2001; AFDC, 2002b). This suggests that LNG light-duty vehicles have failed to attract considerable private and commercial demand.

Although the number of battery electric vehicles (BEVs) has increased since 1993, their production has been mainly motivated by ZEV regulations, not by the market. Currently, the technology does not meet most consumers' requirements due to its inherent limitations including long recharging time, poor performance, and, especially, limited range (typically, 50-130 miles). Even multi-vehicle households are reluctant to purchase BEVs (Andan and Faivre D'Arcier, 1997). Due to limited demand, the production of BEVs has been declining in recent years: General Motors suspended its production of BEVs in 1999; Honda abandoned its BEV project in 1999; and Toyota discontinued its production of the RAV4, the last BEV model for the retail market, in 2003. At present, almost all on-road BEVs in the U.S. were made years ago and are out of production. Further, amendments to the ZEV mandate approved by the California Air

Resources Board (CARB) on April 24, 2003 offer another option to automakers – they can produce fuel cell vehicles instead of BEVs to meet their ZEV requirements. The amendments are likely to contribute to the continued stagnation or further decline of the market penetration of BEVs. On the other hand, it was believed that BEVs have potential niche markets for community or neighborhood transportation uses, in places with cheap electricity and better accessibility, and in regions with zero-emission mandates (Chan, 2002). Daimler Chrysler was advertising its GEM neighborhood vehicle on television in California as late as fall 2002 or winter 2003. However, Ford announced that its production of Th!nk City (a neighborhood electric vehicle) in the U.S. will be halted by 2003 because of lackluster demand.

**Table 2. Estimated Number of AFVs in Use in the U.S., by Fuel and Weight Category, 1998, 2000, and 2002**

| | 1998 | | | 2000 | | | 2002 | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Fuel*** | Light Duty | Heavy Duty | Total | Light Duty | Heavy Duty | Total | Light Duty | Heavy Duty | Total |
| ***LPG*** | 212,000 | 54,000 | 266,000 | 215,992 | 56,201 | 272,193 | 222,674 | 58,612 | 281,286 |
| ***CNG*** | 63,739 | 15,043 | 78,782 | 79,459 | 21,279 | 100,738 | 99,568 | 26,773 | 126,341 |
| ***LNG*** | 118 | 1,054 | 1,172 | 291 | 1,799 | 2,090 | 452 | 2,735 | 3,187 |
| ***E85*** [a] | 12,778 | 10 | 12,788 | 58,602 | 19 | 58,621 | 82,452 | 25 | 82,477 |
| ***Electricity*** | 4,996 | 247 | 5,243 | 11,198 | 636 | 11,834 | 18,564 | 1,191 | 19,755 |
| ***Total*** | 313,258 | 70,589 | 383,847 | 375,954 | 79,952 | 455,906 | 429,577 | 89,342 | 518,919 |

[a.] The remaining portion of 85-percent ethanol fuel is gasoline.
**Note**: Weight classes are based on Environmental Protection Agency definitions: light duty is less than or equal to 8,500 pounds gross vehicle weight; heavy duty is greater than 8,500 pounds gross vehicle weight. Estimates for 2002 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available. •Beginning in 1999, LPG estimates are no longer rounded to the nearest thousand. Previously, the estimates were rounded in order to reflect the greatest uncertainty. •Vehicle counts reported by the Federal Agencies for years 2000, 2001, and 2002, may include vehicles ordered but not delivered. The greatest discrepancy between reported and actual in use vehicles occurs for the U.S. Postal Service.
**Source**: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels.

Adapted from the EIA, DOE (http://www.eia.doe.gov/cneaf/alternate/page/datatables/atf1-13_00.html, accessed on November 25, 2002)

Although the introduction of BEVs in the U.S. has not been satisfactory, hybrid electric vehicles are advancing rapidly at the forefront of transportation technology. Different from BEVs, the batteries of hybrid electric vehicles (HEVs) do not need an external source since they are recharged during operation. Further, hybrid power systems address many underperformance issues of electric power systems, especially the limited range (actually, HEVs even double the range of conventional vehicles). Compared to conventional vehicles, HEVs greatly increase fuel economy, and produce low levels of greenhouse gas ($CO_2$) and tailpipe emissions. However, under EPACT92, HEVs are not considered to be alternative fuel vehicles since they still rely on gasoline. On the other hand, according to California's Zero Emission Vehicle mandate, HEVs are classified as AT-PZEVs, and could earn 0.2 PZEV credit. But until recently, current HEVs on the retail market (the Toyota Prius, Honda Insight and Civic Hybrid (integrated motor assist system)) could not earn ZEV credits since they did not meet all requirements of AT-PZEVs, which were (1) to meet the standards of Super Ultra Low Emission Vehicle (SULEV) tailpipe emissions, (2) zero evaporative emissions, and (3) a 150,000-mile warranty on emission control equipment (CARB, 2001). However, the April 24 amendments to the CARB ZEV mandate acknowledged the increasing market popularity of HEVs and explicitly called for production targets. Specifically, it called for 420,000 HEVs to be manufactured by 2011 (Rogers, 2003).

**Table 3. Sales of Hybrid Electric Vehicles in the U.S.**

| *Year* | Honda Insight | Toyota Prius | Honda Civic Hybrid |
|---|---|---|---|
| ***1999*** | 17 | 0 | 0 |
| ***2000*** | 3,788 | 5,562 | 0 |
| ***2001*** | 4,853 | 13,568 | 0 |
| ***2002 (January-June)*** | 1,297 | 10,049 | Not available |
| ***Total (as of June 30, 2002)*** | 9,955 | 29,179 | Not available |

Source: Office of Transportation Technologies, DOE (http://www.ott.doe.gov/facts/archives/fotw230.shtml, accessed on November 25, 2002)

The HEVs available for sale are roughly cost- and performance-competitive to conventional vehicles, and demand for them is proliferating. In December 1997, Toyota introduced its Prius, the first commercial HEV, in Japan, and about 37,000 Toyota Prius vehicles were sold worldwide in 2001. As shown in Table 3, about 40,000 HEVs are on the road in the U.S. since the Honda Insight and Toyota Prius were introduced in 1999 and 2000, respectively. Since the production of HEVs is motivated by the market, not by mandates, HEVs have the capability of continued growth in the automobile market. Current HEVs are dependent on petroleum products;

however, a large population of HEVs on the road could significantly reduce gasoline consumption in the transportation sector, and hence reduce the importation of oil. Also, they are beneficial to clean air. Therefore, the HEV is considered a viable alternative in this study.

Another potential AFV is the fuel cell vehicle (FCV). Depending on their configurations, FCVs could operate on a variety of fuels such as hydrogen, methanol, natural gas and so on. Like a BEV, an FCV is powered by an electric motor. However, different from a BEV, it has the same driving range and convenience as a conventional vehicle (CARB, 2002). It produces zero or near-zero tailpipe emissions, depending on the fuel used in the fuel cell; an FCV with hydrogen fuel would be credited as a pure ZEV. The fuel cell is accepted worldwide as a very promising technology for use in vehicles. However, FCV technology is currently in the development stage. Many automobile manufacturers have invested billions of dollars into FCV development. In October 2002, the first hydrogen station in the San Francisco Bay Area opened to fill up 16 fuel-cell prototypes being tested by the California Fuel Cell Partnership (CaFCP). The 2003 Honda FCX, fueled by hydrogen, is the first FCV to be certified by the Environmental Protection Agency (EPA) and California Air Resources Board (CARB), and Honda plans to lease 30 FCVs in California and Tokyo during the next two or three years. Other automakers – Ford, Daimler Chrysler, Nissan, and Toyota – have announced plans to sell a limited number of FCVs in the U.S. by 2002-2004. However, none of them have publicized plans for the mass production of FCVs (DOE, 2002a).

In view of the discussion above, we select LPG vehicles, CNG vehicles, E85 vehicles, HEVs, and FCVs as the alternatives for further research. FCV technology is the least mature technology among these. The April 24, 2003 amendments to the California Zero Emission Vehicle mandate require the large automakers to produce approximately 250 FCVs by 2008, 2,500 by 2011, and 25,000 by 2014 as an option to meet their ZEV requirements (CARB, 2003b; Rogers, 2003)[1]. Conventional wisdom holds that the mass sale of FCVs will not be possible until 2010 (Sperling, 2002). Therefore, the FCV is treated as a medium-to-long term alternative. On the other hand,

[1] The amendments also require the production of 3.4 million partially zero emission vehicles (PZEVS) by 2010. These are gasoline vehicles with especially low emissions (5% of the usual amount), including current models such as the Toyota Camry, BMW 325, and Nissan Sentra.

the other four technologies are currently commercially available, and are considered to be near-term alternatives.

## 2.2 Limitations of Alternative Fuel Passenger Vehicles

Table 4 presents a comparison of AFVs to conventional vehicles on key dimensions. Currently, the major barrier for widespread use of CNG, E85, and LPG vehicles is the availability of refueling stations. Among these, LPG vehicles have the largest number of refueling stations, as shown in Table 4. However, the number of available LPG stations represents less than 2% of the number devoted to gasoline and diesel services. Also, only 2.2% of vehicles that are capable of being fueled by E85 are operating on E85 in 2000, mainly due to deficient fuel infrastructures (most E85 stations are located in the Midwest). Further, these three AFVs require special training on vehicle operation and maintenance, inconvenient for consumers.

**Table 4. Comparison of AFVs to Conventional Vehicles on Key Dimensions**

| ***Fuel Type*** | Gasoline | CNG | E85 | LPG |
|---|---|---|---|---|
| ***Number of Stations*** | >200,000 [1,a] | 1,229 [b] | 151 [b] | 3,339 [b] |
| ***Relative Range*** [2] | 1 | 0.5[c] | > 0.7[d] | Somewhat < 1[e] |
| ***Additional Initial Cost*** | - | Automaker's price premium: $1,500-$6,000<br>Conversion: $2,000-$3,000 [f] | Same as gasoline vehicle [g] | Conversion: $2,500[e] |
| **Fuel Price** [h] | $1.52 per gallon | $0.89 per GGE | $1.80 per GGE | $1.62 per GGE |
| ***Maintenance and Reliability*** | - | Gas tanks require periodic inspection and certification. [f] | Require special lubricants and E85 replacement parts. [g] | - |
| ***Safety*** | - | Require special training to operate and maintain vehicles. Training and certification technicians are required.[f] | Require special training to operate and maintain vehicles. [g] | Require special training to operate and maintain vehicles. [e] |
| ***Domestic Content of Fuel*** | 45% [i] | 90% [f] | 100% [g] | 95%-98% [e] |

1. Including diesel stations.
2. Relative range = (range of the vehicle) / (range of a comparable gasoline vehicle)

Sources:

a. (EIA, 1999); d. (NEVC, 2001); g. (AFDC, 2002a);
b. (AFDC, 2002f); e. (AFDC, 2002d); h. (AFDC, 2000b);
c. (CEC, 1999); f. (AFDC, 2002c); i. (Davis and Diegel, 2002).

Another common shortcoming of these AFVs is that their ranges are less than those of conventional vehicles. Among these, CNG vehicles have the shortest ranges, 150 – 250 miles, which are about half of conventional vehicle ranges (CEC, 1999). Similar to CNG, the low energy density of E85 leads to shorter ranges of E85 vehicles. Therefore, CNG and E85 vehicles may require more frequent refueling. A larger fuel tank may help compensate for the loss of vehicle range, but at the expense of occupying more of the limited vehicle space. The reduced range makes these AFVs uncompetitive with conventional vehicles, at least for long-distance commuters.

As for fuel prices, E85 and LPG have higher prices per gasoline-gallon-equivalent (GGE) than gasoline. The higher fuel prices will inhibit private consumers' voluntary use of E85 and LPG. Although ethanol used as a transportation fuel is subsidized by the Federal excise and energy tax, the price of E85 per GGE still ranks highest. The incentive will shrink from 54 cents per gallon in 2001 to 51 cents per gallon by 2005, and is scheduled to remain in effect through 2007 (Joyce, 2001). After 2007, ethanol prices are expected to be higher. Most ethanol in the U.S. is made in the Midwest from excess corn crops in that area, and thus their feedstock directly affects ethanol prices. For example, the severe flooding of the Mississippi River in 1993 led to a temporary increase in regional ethanol prices (CEC, 1999).

The propane industry has been criticized by some for not promoting the fuel's use as an alternative transportation fuel (Joyce, 2001), particularly compared to the natural gas industry, which aggressively advertises its fuel for vehicular use. Propane industry officials have stated that the industry lacks the internal cohesion necessary to promote the use of propane as a transportation fuel. Officials have also noted that, traditionally, the propane industry has been made up of small-scale suppliers who primarily serve residential customers. Some of these suppliers fear that growth in the use of propane as a transportation fuel would cause the deterioration of the suppliers' smaller businesses. And some propane consumers have expressed concern that increasing demand for propane as a vehicle fuel would increase prices. However, the General Accounting Office concluded that there will only be a small increase in propane's use as an alternative transportation fuel over the next 10 years and that propane consumption by non-transportation sectors will not be affected by this increased demand. In particular, it projected that the overall price of LPG will increase only 3.28 cents per gallon by 2010, and thus have little impact on the propane industry (GAO, 1998).

As shown in Table 4, the initial costs of CNG vehicles and LPG vehicles will limit their demand. For CNG vehicles, whether directly manufactured or converted, their initial costs are higher than those of their counterparts. The incremental costs of a Ford Crown Victoria CNG vehicle were $3,802 in model year 2002 (GSA, 2002). Although the price of CNG itself is much lower than that of gasoline, the additional costs of CNG vehicles cannot be compensated for by the low fuel price (CEC, 1999). With respect to LPG vehicles, most vehicles are conversions, with the conversion costing about 10 percent of the conventional vehicle base price (AFDC, 2002d). LPG vehicles made by manufacturers are more expensive than equivalent conventional vehicles. In 2002, a bi-fuel Ford F-150 cost about $3,500 more than a gasoline Ford F-150 (GSA, 2002). Tax incentives provided by federal, state, and local governments may offset some of these price premiums. Through the year 2004, a clean fuel passenger vehicle is eligible for a federal tax deduction, but the deduction amount declines $500 each year, from $2,000 in 2001 to $500 in 2004. California incentives go up to $3,000 for dedicated natural gas vehicles through March 1, 2004 (DOE, 2003). However, these incentives are not enough to compensate the incremental costs. Further, it is uncertain whether the tax deductions will continue after 2004. Therefore, the higher initial costs of CNG and LPG vehicles continue to be an obstacle for their market penetrations.

Specifically for CNG vehicles, natural gas needs to be compressed to about 3000 psi for vehicle use, thus pressurized tanks require periodic inspection and certification. Although the tanks have been designed to be as safe as gasoline tanks, safety may still be a concern for consumers. Except for their range, the operational performances of CNG vehicles are competitive to those of comparable conventional vehicles, but cylinder location and number may reduce their payload capacity (AFDC, 2002c). The demand for CNG vehicles in the future light-duty vehicle market will depend on the public acceptance of shorter range, technology advances, reduced costs because of mass production, and future policies (CEC, 1999).

Except for their range, the operational performances of E85 vehicles are also competitive to those of comparable conventional vehicles (AFDC, 2002a). The emissions of E85 vehicles are equivalent to those of conventional vehicles; the life-cycle emission reduction in greenhouse gases for ethanol is superior to most fuels. However, the higher volatility of E85 will result in higher evaporative emissions at fuel stations (CEC, 1999). The future demand for E85 vehicles is mainly dependent on fuel price and the availability of refueling infrastructures.

Generally, the operational performances of LPG vehicles are equivalent to those of comparable conventional vehicles (AFDC, 2002d). Their widespread use has the potential to reduce tailpipe emissions and our dependence on foreign oil. However, continued growth in the demand for LPG vehicles relies on the commercialization of conversion equipment, a "chicken-and-egg" dilemma. Without a steady and growing demand, the production of conversion equipment cannot form a viable market, and hence the variety and availability of LPG vehicles will be constrained to those provided by the auto manufacturers (CEC, 1999). Conversely, if the LPG vehicle selection is limited, the demand will be constrained.

**Table 5. Cost Difference for Honda Insight (Hybrid) and Honda Civic Hatchback (Gasoline)**

| | |
|---|---|
| ***Insight purchase price (MSRP)*** [a] | $18,800 |
| ***Fuel cost savings*** [b] | $2,500 |
| ***Insight net cost*** | $16,380 |
| ***Civic purchase price (MSRP)*** | $12,100 |
| ***Net cost difference*** | $4,280 |

a. This price has been subsidized by the manufacturer to motivate sales.
b. Fuel cost savings are over ten-year ownership (15,000 miles per year), at a gasoline price of $1.20 per gallon.

Source: (Yacobucci, 2000)

Although HEVs are less expensive than BEVs, their initial prices are higher than conventional vehicles. As shown in Table 5, a comparison between the Honda Insight and Civic suggests that the Honda Insight is still relatively expensive even when fuel savings are considered in the long term (Yacobucci, 2000). The cost difference is expected to decrease with the mass production of HEVs. On the other hand, current HEVs are two-seater vehicles (Honda Insight) or compacts (Toyota Prius and Honda Civic Hybrid), which limits their market shares. However, the vehicle type selection will not be a major problem in the development of an HEV market, since according to automakers, more choices including SUVs, pickups and so on will be available in the next several model years (DOE, 2002c). Another limitation of HEVs is that their electronic components may require maintenance from certified dealers (Yacobucci, 2000).

Among the four currently-available technologies being considered here, for several of them, a number of important factors have considerable uncertainty as far as prospective consumers are concerned: cost, maintenance, refueling, and so on. Compared to the others, HEVs may look especially attractive with respect to refueling and range, suggesting that the HEV could be a useful bridge or interim technology.

The development of FCVs is facing many challenges. First, compared to an internal combustion engine (ICE), the cost of a comparable fuel cell stack is extraordinarily expensive, more than ten times as much as that of an ICE. Therefore, significant efforts will be involved to reduce the stack cost. Up till now, it is still uncertain which fuel (hydrogen, methanol, ethanol, or natural gas) will end up being chosen as the primary fuel for FCVs although hydrogen is currently the most promising one. Further, the growth of the refueling infrastructure will take significant money and time. Since there are almost no hydrogen stations and few methanol, ethanol and natural gas stations in the U.S., the refueling infrastructure is a major barrier to the widespread adoption of FCVs, and consumers may be required to pay a premium to support its growth (Yacobucci, 2000). Currently, the range of the Honda FCX is 170 miles, significantly less than that of a conventional vehicle, due to limited storage capacity (DOE, 2002a). Therefore, additional effort will be involved to develop the pressurized tanks or hybrid systems that are required in order to store hydrogen more effectively and safely. Cold-weather operation is another major problem for the development of FCVs since water, a byproduct of the fuel cell, can freeze at low temperatures (DOE, 2002b). Other limitations of FCVs are their weight and specialized maintenance requirements (Yacobucci, 2000).

## 3. THE DEMAND FOR CONVENTIONAL AND ALTERNATIVE FUEL PASSENGER VEHICLES: DISAGGREGATE STUDIES

A lot of studies focusing on automobile demand or ownership have been conducted since 1940. The models used in these studies can be classified into two categories: disaggregate and aggregate. Generally, disaggregate models consider the household as the analysis unit and utilize random utility theory to predict household vehicle choice, while aggregate models are used to forecast a regional or national automobile demand or ownership rate. In this section, we review some disaggregate studies of conventional vehicle choice and AFV choice; aggregate studies are reviewed in Section 4. Most published disaggregate studies of conventional vehicle choice concentrate on vehicle attributes, household and primary driver characteristics, and brand loyalty. On the other hand, most studies of AFV choice not only focus on vehicle attributes and household characteristics, but also include some variables that are not applicable for conventional vehicles but which greatly affect AFV choice, such as availability of fuel stations, refueling time, maintenance cost, and so on. Further, most AFV choice models are based on stated preference surveys since some AFVs analyzed in these models were not available on the retail market, at least at the time that the surveys were conducted. The review of the disaggregate demand for conventional vehicles and AFVs provides insight into the relationship between household vehicle choice and various explanatory variables.

### 3.1 Conventional Vehicle Choice

We reviewed nine studies, spanning two decades, involving conventional vehicle choice models. All these papers (Lave and Train, 1979; Manski and Sherman, 1980; Hocherman, et al., 1983; Berkovec and Rust, 1985; Berkovec, 1985; Mannering and Winston, 1985; Kitamura, et al., 2000; Brownstone, et al., 2000; Mannering, et al., 2002) utilized discrete choice models such as multinomial logit and nested logit to analyze conventional vehicle choice. Table 6 summarizes the significant results of these models (refer to Choo and Mokhtarian, 2002 for detailed descriptions of each study). As indicated in Table 6, conventional vehicle choice models can be further classified into two groups: vehicle-purchasing models (four of the nine studies reviewed) or vehicle-holding models, depending on whether the model relates only to recently-purchased or to any owned vehicles, respectively. Leased vehicles are sometimes included in both models. Unlike vehicle-purchasing models, vehicle-holding models often contain additional variables relating to used vehicles such as vehicle age, scrappage rate and transaction cost (Choo and Mokhtarian, 2002). Both the results of vehicle-purchasing models and those of vehicle-holding models can increase our insight into vehicle choice.

## Table 6: Significant Results of Conventional Vehicle Choice Models

| ***Reference*** | Lave and Train (1979) | Manski and Sherman (1980) | Hocherman, et al. (1983) |
|---|---|---|---|
| ***Model Type*** | Multinomial logit model of vehicle type purchased | Multinomial logit model of vehicle holdings | Two-stage nested logit model of vehicle type purchased, conditional on a purchase being made |
| ***Dependent Variables*** | - subsubcompact<br>- sports<br>- subcompact-A<br>- subcompact-B<br>- compact-A<br>- compact-B<br>- intermediate<br>- standard-A<br>- standard-B<br>- luxury | Chosen alternative plus 25 alternative makes/models/ vintage (randomly selected from 600 vehicle types) | Upper level:<br>Buying a first car or replacing an existing car<br><br>Lower level:<br>Chosen alternative plus 19 alternative makes/models/ vintages (randomly selected from 950 vehicle types |
| ***Significant Explanatory Variables*** | - purchase price /income (–)<br>- auto weight*age of respondent (+)<br>- no. of household members (+, for subsubcompact and subcompact A)<br>- when no. of household vehicles >2 (+, for smaller cars) | - purchase price (–)<br>- higher operating cost and low income HH (–)<br>- no. of seats (+)<br>- vehicle weight and HH age (+)<br>- acceleration time (+)<br>- luggage space (+)<br>- scrappage rate (–)<br>- transaction-search cost (–) | - purchase price (–)<br>- operating cost (–)<br>- engine size (+)<br>- vehicle age (–)<br>- income (+)<br>- brand loyalty (+)<br>- no. of same make cars (+)<br>- horsepower/weight (+)<br>- older or high-income (+, expensive cars) |
| ***Reference*** | Berkovec and Rust (1985) | Berkovec (1985) | Mannering and Winston (1985) |
| ***Model Type*** | Nested logit model of vehicle holdings | Nested logit model of vehicle holdings | Multinomial logit model of vehicle holdings |
| ***Dependent Variables*** | Upper level:<br>vehicle age groups<br>- new (1977-78)<br>- mid (1973-76)<br>- old (1967-72)<br><br>Lower level:<br>5 vehicle classes<br>- subcompact<br>- compact<br>- intermediate<br>- standard<br>- luxury/sports | Upper level:<br>No. of vehicles (0, 1, 2, and 3)<br><br>Lower level:<br>131 vehicle classes and vintages<br>- 10 years (1969-1978)<br>- 13 vehicle classes each year: (domestic) subcompact, compact, sporty, intermediate, standard, luxury, pickup truck, van, and utility vehicle; (foreign) subcompact, larger, sports, and luxury<br>- all models before 1969 | Chosen alternative plus 9 alternative makes/models/ vintages (randomly selected from 2,000 vehicle types) |
| ***Significant Explanatory Variables*** | - purchase price (–)<br>- operating cost (–)<br>- no. of seats (+)<br>- vehicle age (–)<br>- turning radius in urban (–)<br>- horsepower/weight (+)<br>- transaction (+) | - purchase price (–)<br>- no. of seats (+)<br>- proportion of makes/models in class to total make/models (+) | - purchase price/income (–)<br>- operating cost/income (–)<br>- lagged utilization of same vehicle or same make (+) |

Note: Sign in parentheses means positive or negative effect on the choice of the associated vehicle

**(Table 6. Continued)**

| ***Reference*** | Kitamura, et al. (2000) | Brownstone, et al. (2000) | Mannering, et al. (2002) |
|---|---|---|---|
| ***Model Type*** | Multinomial logit model of vehicle holdings | Multinomial logit model of vehicle purchased | Nested logit model of vehicle purchased |
| ***Dependent Variables*** | - 4-door sedan<br>- 2-door coupe<br>- van/wagon<br>- sports car<br>- sports utility<br>- pickup truck | A 689-level classification according to vintage, body type, import/domestic, and price level. | Upper level:<br>Vehicle acquisition type<br>- cash, non-cash (lease, finance)<br><br>Lower level:<br>Chosen alternative plus 9 alternative makes and models (randomly selected from 175 vehicle types) |
| ***Significant Explanatory Variables*** | - age of respondent (+, for 4-door, 2-door, and van/wagon)<br>- male (– , for all but pickup)<br>- college degree (+, for 4-door)<br>- no. of household members (+, for van/wagon)<br>- high income (+, for SUV)<br>- low income (+, for Pickup and 2-door couple)<br>- transit accessibility (+, for 4-door) | -price/ln(income) (-)<br>-operating cost (-)<br>-import (-)<br>-no. of vehicles in class (+)<br>-new (+)<br>-pollution (+) (problematic)<br>-small car (-)<br>-sports car (-)<br>-sports car with HH size >=3 (+)<br>-minivan with HH size >=3 (+) | - purchase price/income (–)<br>- passenger side airbag (+)<br>- horsepower (+)<br>- vehicle residual value (+)<br>- consecutive purchases (+) |

Note: Sign in parentheses means positive or negative effect on the choice of the associated vehicle
Source: Choo and Mokhtarian (2002)

The overview of these models suggests several common effects on vehicle choice. First, a higher purchase price decreases the probability of choosing a vehicle in eight of the nine models studied. Second, operating cost is significantly negative in five models (Kitamura, et al. (2002) did not include this variable). Third, brand-loyalty-related variables are significant in all five models (Hocherman, et al., 1983; Berkovec, 1985; Mannering and Winston, 1985; Brownstone, et al., 2000; Mannering, et al., 2002) that included them as explanatory variables. Finally, number of seats, luggage space, engine size and horsepower frequently appear in these models, meaning that people prefer capacious and powerful vehicles. However, it is difficult to make general conclusions on vehicle type choice from these models because different vehicle type categories were used in each model.

### 3.2 Alternative Fuel Vehicle Choice

We conducted a literature review on some disaggregate studies of AFV choice done during the past ten years. Similar to conventional vehicle choice, most studies (Brownstone et al., 2000; Ewing and Sarigöllü, 1998; Golob et al., 1997; Bunch et al., 1993) introduced multinomial, conditional, or nested logit models for AFV choice. AFVs incorporated in these models include electric vehicles, LPG vehicles, hybrid electric vehicles, CNG vehicles, methanol vehicles and unspecified alternative fuel vehicles. Table 7 summarizes some significant results of those studies reviewed. Similar to conventional vehicle choice, purchase price and/or operating cost are significant in most AFV choice models. Specific to AFVs, vehicle performance variables often appear in these models; especially, the driving range of AFVs is a major concern for AFV choice. Compared to conventional vehicles, a lower emission rate increases an individual's probability of choosing AFVs, suggesting that the innovative attribute of AFVs is well accepted by at least a niche market, environmentalists. Fuel availability and fuel flexibility both positively affect AFV choice.

**Table 7. Significant Results of Alternative Fuel Vehicle Choice Models**

| *Reference* | *Description* | *Significant Results* |
|---|---|---|
| Dagsvik, et al. (2002) | Luce model based on stated preference survey.<br><br>Alternatives:<br>Gasoline vehicle (GV)<br>LPG vehicle (LPG)<br>Electric vehicle (EV)<br>Hybrid Vehicle (HEV) | Given that all attributes are equal, and refueling and maintenance infrastructure are well equipped:<br>-AFVs are competitive<br>-Purchase price (-)<br>-Driving range (+)<br>-Top speed (+, only for 18-29 year old males)<br>-Fuel consumption (-)<br>-EV, women (+)<br>-HEV, all age groups and gender groups (+)<br>-LPG, almost all (except 18-29 year old males) (+) |
| Brownstone, et al. (2000) | Multinomial logit model based on stated preference survey<br><br>Base: midsize/large gasoline vehicle<br>Alternatives:<br>EV<br>CNG vehicle (CNG)<br>Methanol vehicle | -Price/ln(income) (-)<br>-Operating cost (-)<br>-Range (+)<br>-Acceleration (-)<br>-Top speed (+)<br>-Pollution (-)<br>-Station availability (+)<br>-SUV, sports car (+)<br>-Sports car with HH size >=3 (-)<br>-Station Wagon, truck and van (-)<br>-Minivan with HH size >=3 (+)<br>-College * EV (+)<br>-Electric truck, electric sports car (-)<br>-CNG and Methanol constant (+)<br>-EV constant (-, insignificant) |
| Ewing and Sarigöllü (1998) | Multinomial logit model based on stated preference survey<br><br>Base: GV<br>Alternatives:<br>EV<br>More fuel-efficient gasoline and alternative-fuel vehicle (FEV) | -Price (-), maintenance cost (-), refueling time (-)<br>-Emission rate (-)<br>-Acceleration (+), range (+)<br>-Commuting cost (-), commuting time (-)<br>-Older people (-)<br>-FEV*Renter (dummy) (-)<br>-FEV*owning more than 1-vehicle (dummy) (-)<br>-EV*Amount extra willing to pay for a ZEV, if given access to express lane (+)<br>-Female and older are less sensitive to acceleration and range<br>-Acceleration (+, for share-ride commuting (dummy), and for next car would be a sports car (dummy))<br>-Commuting cost (-, for female, and for next car would be a van (dummy); + for the older)<br>-FEV constant and EV constant (+) |
| Golob, et al. (1997) | Conditional logit model based on stated preference survey<br><br>Base: GV<br>Alternative:<br>EV<br>CNG vehicle (CNG)<br>Methanol vehicle | -Emission (-, for government and school)<br>-Capital cost (-)<br>-Operating cost (-)<br>-Range (+)<br>-Station density (+)<br>-CNG duel fuel (+)<br>-Gasoline on-site refueling available (+)<br>-CNG station time (-)<br>-EV, CNG, and Methanol constant (-) |

Note: Sign in parentheses means positive or negative effect on the choice of the associated vehicle

**(Table 7. Continued)**

| *Reference* | *Description* | *Significant Results* |
|---|---|---|
| Golob, et al. (1997) | Conditional logit model based on stated preference survey<br><br>Base: GV<br>Alternative:<br>EV<br>CNG vehicle (CNG)<br>Methanol vehicle | -Emission (-, for government and school)<br>-Capital cost (-)<br>-Operating cost (-)<br>-Range (+)<br>-Station density (+)<br>-CNG duel fuel (+)<br>-Gasoline on-site refueling available (+)<br>-CNG station time (-)<br>-EV, CNG, and Methanol constant (-) |
| Kurani, et al. (1996) | - | Purchases of battery-EV by multi-vehicle HHs would account for 7-18% of annual LDV sales in CA |
| Bunch, et al. (1993) | Nested multinomial logit model based on stated preference survey<br><br>Base: GV<br>Alternative:<br>EV<br>HEV<br>Unspecified (Methanol, ethanol, CNG or propane) liquid and gaseous fuel vehicle (AFV) | -Purchase price (-)<br>-Fuel cost (-)<br>-Range (100 mi) (+), Rang^2 (-) (maximum 300 miles)<br>-Emission level (-), emission level ^2 (+) (minimum 1.5 times as many as current)<br>-Fuel availability (+), fuel availability ^2 (-) (maximum 90% of stations)<br>-Multiple fuel (+)<br>-EV low performance (-)<br>-EV low performance with hybrid (fuel flexibility) (+)<br>-Range*female dummy (-) → less sensitive to range<br>-Range *HH workers per vehicle (+)<br>-GV constant *income (+)<br>-EV constant*college dummy (+)<br>-EV constant*age 55+ dummy (-)<br>-EV constant*1-veh HH dummy (-)<br>Next purchase<br>-Range* Full size Pickup or Van dummy (+)→ more sensitive to range<br>-Range * Compact Pickup dummy (-) → less sensitive to range<br>-Range* Sports car dummy (-) →less sensitive to range<br>-EV constant * SUV dummy (-) →Lower preference |

Note: Sign in parentheses means positive or negative effect on the choice of the associated vehicle

## 4. THE DEMAND FOR PASSENGER VEHICLES: AGGREGATE VEHICLE OWNERSHIP FORECASTING MODELS

In this section, ten studies focusing on aggregate automobile demand or ownership are reviewed. Table 8 summarizes this previous research on aggregate automobile demand models. Among these models, regression analysis was commonly used to estimate automobile demand (Dyckman, 1965; Tanner, 1979; Khan and Willumsen, 1986; Madre, 1990; Button et al., 1993; Dargay and Gately, 1999). Time series and/or cross-sectional data were employed to conduct the analyses in these models. Specifically, a linear or sigmoid curve was assumed to illustrate the relationships between aggregate automobile demand or ownership and various explanatory variables, and the ordinary least squares method was extensively applied to estimate the demand equations. Besides regression analysis, aggregating automobile demand or ownership using disaggregate discrete choice models was utilized by Manski (1980) and Train (1986). However, one common problem of most regression models and aggregate discrete choice models is that they usually develop one equation to estimate automobile demand or ownership, ignoring the interaction and simultaneity of some endogenous variables, such as the relationship between automobile demand and the driving population (Abu-Eisheh, 2001). To capture these effects, simultaneous equation models were recently used to estimate aggregate automobile demand or ownership (Abu-Eisheh, 2001; Chung and Lee, 2002).

Another econometric approach to model aggregate automobile demand is the stock adjustment concept proposed by Nerlove (1957). This approach was initially used to model the demand for divisible, homogeneous, and perishable goods. The concept assumes that the desired aggregate automobile stocks in a specific year are a function of prices, incomes, and other variables. The model includes a scrappage equation expressing actual used vehicle stocks as a function of actual new and used vehicle stocks in the previous year, and an equation indicating new vehicle purchases (Manski, 1980). However, both the theory and the practice of this approach were questioned by Manski (1980). First, the distinct automobile market makes it implausible to use this concept to estimate automobile demand for a variety of reasons. Second, the model assumes that new and used vehicle prices are predetermined; however, used vehicle prices cannot be predetermined due to the competitive market. Finally, differentiating automobiles by specifying only a small group of automobile classes cannot meet the homogeneity requirements of the stock adjustment concept; but if automobiles are divided into a large number of classes, we lose the simplicity, a major advantage of the stock adjustment concept (Manski, 1980). Presumably for these reasons, this approach is seldom undertaken today.

## Table 8. Summary of Previous Aggregate Automobile Demand Models

| | | |
|---|---|---|
| ***Reference*** | Dyckman (1965) | Tanner (1979) |
| ***Scope*** | The United States | Great Britain |
| ***Data Period*** | 1929-1962 time series | 1953-1974 time series |
| ***Model*** | Log-linear regression | Semi-logarithmic regression |
| ***Dependent Variable*** | -Demand for new cars per capita | -Cars per person |
| ***Explanatory Variables ("0": tested but not significant)*** | -New-car sales (0)<br>-Income or discretionary income (+)<br>-Prices (-)<br>-Automobile stocks (-)<br>-Credit (+)<br>-Liquid assets (0) | -Income index (+)<br>-Cost index of motoring (-) |
| ***Reference*** | Khan and Willumsen (1986) | Button et al. (1993) |
| ***Scope*** | Developing countries | Low income countries |
| ***Data Period*** | 1970-1975 cross-section | 1968-1987 cross-section time series |
| ***Model*** | Log-linear regression | Log-linear and quasi-logistic |
| ***Dependent Variable*** | -Cars per thousand population | -Aggregate ratio of total registered vehicles to population |
| ***Explanatory Variables ("0": tested but not significant)*** | -Gross national product per head (+)<br>-Purchase and registration tax per vehicle (0)<br>-Ownership tax per vehicle (0)<br>-Import duty per vehicle (0)<br>-Population density (0) | -Time trend (+)<br>-Gross national product (+)<br>-Country specific dummy (+ or -) |
| ***Reference*** | Dargay and Gately (1999) | Madre (1990) |
| ***Scope*** | OECD countries as well as China, India, and Pakistan | France |
| ***Data Period*** | 1960-1992 cross-section time series | 1972-1987 time series |
| ***Model*** | Gompertz | Cramer (probit) |
| ***Dependent Variable*** | -Vehicle ownership ratio | -Household vehicle ownership |
| ***Explanatory Variables*** | - Per-capita income (+) | -Real income (+)<br>-Time (+) |
| ***Reference*** | Manski (1980) | Train (1986) |
| ***Scope*** | N/A | The United States |
| ***Data Period*** | N/A | 1978 National Transportation Survey |
| ***Model*** | Aggregate discrete choice | Multinomial logit |
| ***Dependent Variables*** | -Used car price<br>-Annual used car scrappage<br>-Aggregate auto demand<br>-Annual new car purchases | -Vehicle quantity |
| ***Explanatory Variables ("0": tested but not significant)*** | -New car price<br>-Used car scrap value<br>-The "quality" of new and used cars.<br>-Population size<br>-Aggregate auto ownership at beginning of year<br>-Average abnormal maintenance costs<br>-Consumer's rate of time discount | -Household income (+)<br>-Number of workers (+)<br>-Number of members (0)<br>-Annual transit trips per capita in area (-)<br>-Average utility in class/vintage choice (+) |

*Note: Sign in parentheses means positive or negative effect on the dependent variable(s).*

**(Table 8. Continued)**

| *Reference* | Abu-Eisheh (2001) | Chung and Lee (2002) |
|---|---|---|
| *Scope* | Palestinian Territories | South Korea |
| *Data Period* | 1971-1998 time series | 1970-1998 time series |
| *Model* | Simultaneous equations | Simultaneous equations |
| *Dependent Variables* | -Total number of automobiles<br>-Number of drivers per household | -Number of automobile<br>-Driving population<br>-Road length |
| *Explanatory Variables[1] ("0": tested but not significant)* | -Total number of automobiles<br>-Number of drivers per household<br>-Gross domestic product<br>-Transportation consumer price index<br>-Average number of persons per household<br>-Palestinian National Authority indicator<br>-Percentage of population living in urban areas<br>-Percentage of population with age 15-64 | -Number of automobile<br>-Driving population<br>-Road length<br>-Household size<br>-Economically active population<br>-Personal transportation expenditure<br>-Urbanized area<br>-Population density in urbanized area<br>-Gross national income (0) |

1. All variables except gross national income in these two studies are significant in one or more equations.

Through these studies, a variety of variables were found to significantly affect aggregate automobile demand or ownership, in expected ways. These variables include income-related ones (income or discretionary income, income index, gross national product, per-capita income, and household income), cost-related ones (price, cost index of motoring, transportation consumer price index, and personal transportation expenditure), land use-related ones (urbanized area and population density or percentage of population in urbanized area), demographic characteristics (number of workers, household size, percentage of population within specific age, and economically active population) and other variables (automobile stocks, annual transit trips per capita in the area, and so on).

## 5. DIFFUSION OF ALTERNATIVE FUEL PASSENGER VEHICLES

Compared to conventional vehicles, AFVs can be considered new transportation technologies. Therefore, we can apply technological substitution theory to explore the future AFV market. Generally, the adoption frequency of a new technology over time follows a normal distribution. Based on the normal, bell-shaped curve, the adopters in the market are classified into five categories: innovators (2.5% of the total adopters at saturation), early adopters (13.5%), early majority (34%), late majority (34%), and laggards (16%) (Rogers, 1983). The cumulative adoption of a new technology follows a sigmoid curve, with adoption growing slowly in its initial year, growing steeply as it reaches its half-way point, and growing flatly as it is close to its saturation level (maximum penetration). However, the specific shape of the curve is dependent on the rate of substitution, saturation level and adoption delay, and can be described by the following generalized model (Sharif and Kabir, 1976), among others:

$$\ln\left(\frac{f(t)}{F - f(t)}\right) = c_1 + c_2 t - \sigma \frac{F}{F - f(t)},$$

where

$t$ is the time, where in the initial year $t$ = 0;

$f(t)$ is the proportion of adopters up to year $t$;

$F$ is the saturation level of substitution;

$c_1$ is an integration constant;

$c_2$ is the imitation coefficient indicating the rate of adoption; and

$\sigma$ is the delay coefficient, ranging from 0 to 1.

The third term on the right hand side of the equation above can be used to capture the effects of exogenous factors that tend to delay the diffusion of the technology. When $\sigma$=0, that is, we ignore all the effects of such exogenous factors, the generalized model is reduced to the most optimistic Blackman model (Blackman, 1972); when $\sigma$ = 1, it becomes the most pessimistic Floyd model (Floyd, 1968). When we choose different values from 0 to 1 for $\sigma$, we can obtain a set of smooth sigmoid curves falling between the optimistic curve and the pessimistic curve, indicating the effects of different rates of delay.

For a fixed $\sigma$, two coefficients, $c_1$ and $c_2$, can be estimated, given the adoption levels in two different years and an assumed saturation level. Similarly, given the adoption level in one year, we can predict the market penetration of a new technology by assuming the rate of adoption ($c_2$) and the saturation level. The rate of adoption is mainly explained by five attributes of a new technology: relative advantage (the extent to which the new technology is perceived to be better than the one it substitutes), compatibility (the extent to which a new technology is perceived to be consistent with the experiences and requirements of potential adopters), complexity (the extent to which a new technology is perceived to be difficult to use), trialability (the extent to which a new technology can be experimented with on a limited basis) and observability (the extent to which the utility of a new technology is visible to the public). Relative advantage, compatibility, trialability, and observability of a new technology are found to be positively related to its rate of adoption, while complexity is negatively associated with its rate of adoption (Rogers, 1983).

## 6. POTENTIAL APPROACH FOR FUTURE WORK

As indicated in the Introduction, the purpose of this study is to estimate the future demand for AFVs. A number of different approaches to this purpose are possible, but all of them share the need to specify some key boundaries: time frame, geographical scope, and technologies considered. The **vehicle/technologies to be considered** have already been proposed in Section 2, for reasons given there: LPG vehicles, CNG vehicles, E85 vehicles, HEVs, and FCVs (the first four believed to be the most viable currently commercially-available alternatives, and the fifth constituting the currently most-promising medium-to-longer-term alternative). With respect to the **time frame**, we propose to model out to the year 2025, with particular attention to the intermediate years of 2005 and 2010. These are milestone years for specific conformity requirements.

With respect to the **geographical scope** of the project, the two main choices are statewide or nationwide. The arguments for keeping the project at the state level are that: (1) The funding agency, Caltrans, is particularly interested in the fuel consumption and air quality implications of the adoption of AFVs in California; and (2) Regulatory and market factors in California, while by no means deterministically predictable over the time span of the study, are at least more well-defined and homogeneous than in the nation as a whole. Taking a state-level perspective could reduce those sources of uncertainty in the model. On the other hand, the arguments for taking a nationwide perspective are that: (1) More detailed data on current AFV adoption are available at the nationwide level than at the statewide level; and (2) Although the vehicle market in

California is large and its regulatory environment is proactive and leading-edge, future adoption in California will not take place in a vacuum; rather, the availability and prices of AFVs will very much depend on adoption nationwide. For these reasons, we propose to keep the analysis at the nationwide level.

With respect to modeling methodologies, so far we have identified two major studies that have developed forecasts of the adoption of AFVs. The "Program for Improved Vehicle Demand Forecasting Models" (www.its.uci.edu/its/research/fuel.html, accessed October 29, 2002) was funded by Southern California Edison and the California Energy Commission. Directed by faculty and researchers at UC Irvine (Golob, Brownstone, Bradley, Torous), UC Davis (Bunch, Kitamura), and San Diego State University (Kazimi), this project incorporated the results of disaggregate models of vehicle type preference, developed from stated preference panel surveys, into a year-by-year microsimulation model that generated synthetic households and their vehicle choices, and aggregated the results. Development of the "Transitional Alternative Fuel Vehicles" (TAFV) Model (pzl1.ed.ornl.gov/altfuels.htm, accessed November 5, 2002) was directed by Leiby of Oak Ridge National Lab and Rubin of the University of Maine. It is a dynamic macro-scale model that forecasts new vehicle sales and the on-road vehicle stock in various vehicle and fuel type classes, year-by-year for 1996-2010.

Both of these models resulted from large-scale, multi-year efforts that are well beyond the scope of the current project. Within the constraints of this study, we propose to develop a simpler, "quick-and-dirty" model. Specifically, we propose to follow the relatively simple but powerful diffusion of innovations model presented in Section 5, with one potential enhancement. Applications of this model have often taken $c_2$ (the adoption rate), $F$ (the saturation level), and $\sigma$ (the delay coefficient) to be constants. It stands to reason, however, that those indicators are not constant at all. We suggest trying to "parameterize" $c_2$, $F$, and $\sigma$, making them time-dependent functions of a small number of other explanatory variables. For example, the saturation level F that is reasonable to assume could in fact change over time with, e.g., the availability of more refueling stations.

We would develop separate models for each of the four currently-available technologies, with different weights (and potentially, different variables altogether) allowed for the explanatory variables parameterizing the quantities of interest. We could only permit a small number of explanatory variables to enter the model, since there are very few years of observational data available: 10 for LPG, CNG and E85, and only four for HEVs. It will probably not be possible to find time-varying data on all the inputs of interest, so for some explanatory variables we may generate judgemental values. We will build the model in a user-friendly Excel-based framework, with graphical plots of output measures, and allow most of the inputs to be set by the user (with defaults provided). Thus, the model can and should be recalibrated frequently (at least annually) as better data become available. The methodological approach of this model will be at least as important a contribution as the numerical results themselves, which in view of the numerous uncertainties surrounding AFVs at this time, can only be considered tentative. This would be a potentially novel application of a diffusion of innovations model with time-varying parameters, and setting out the methodology for doing this will provide a framework that should be relatively easy and useful to build upon. The use of judgementally-generated input values is likely to be an enduring feature of the methodology, consistent with the limited state of knowledge and few observational cases inherent to all new technology adoption scenarios (for example, there are no years of observation on the adoption of FCVs). Future applications could consider using Delphi or other expert judgement techniques to estimate some of the key inputs.

## 7. SUMMARY

AFVs have experienced creative development and dramatic growth in the U.S. during the past decade. However, currently, all AFVs combined only account for about 0.2% of total registered vehicles in the U.S. Therefore, a great deal of concerted effort is required to facilitate the development and continued growth of AFVs. The widespread use of AFVs has the potential to improve air quality, reduce greenhouse gas effects, and mitigate our dependence on imported oil. To evaluate the effects of AFVs on energy consumption and emissions in the transportation sector, it is essential to predict the future market for AFVs. This research is focused on the forecast of the future demand for light-duty AFVs under different scenarios, with a timeframe from 2005 to 2025.

Through the analysis of the current status of AFVs, CNG vehicles, E85 vehicles, LPG vehicles, and HEVs are considered to be near-term alternatives, and FCVs are considered to be the medium- and long-term alternative. The limitations of the various kinds of AFVs are also reviewed, which will serve as the basis for different assumptions in further research. This review suggests that HEVs could be a useful interim technology.

With respect to modeling the demand for AFVs, we first reviewed disaggregate studies of conventional vehicle and AFV choices. This review provides insight into the relationship between household vehicle choice and various explanatory variables. The review of aggregate automobile demand models provides a "big picture" look at expected trends, utilizing a variety of methodologies and explanatory variables. Since AFVs can be considered new transportation technologies, technological substitution theory may be a useful tool for forecasting the future demand for AFVs. We propose to use an enhanced version of the classical diffusion-of-innovations model as our approach to developing such a forecast tool.

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