DEVELOPMENT AND USE OF CARCARBON

BASELINE SCENARIO FOR AN ALTERNATIVE VEHICLE & FUEL CHOICE MODEL WITH ENERGY & EMISSIONS ANALYSIS OUTPUTS

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1. Introduction

This report presents the results of the third year of study by a research team at the Center for Energy and Environmental Policy, University of Delaware, funded by a generous grant by the BP Foundation. The purpose of this study is to examine the climate change implications of the introduction of hydrogen fuel cell vehicles into the U.S. transportation sector. The previously developed first year report focused on how state policy interacts with the developing hydrogen economy. Our second year report created a modeling tool to quantitatively measure the carbon impacts of hydrogen fuel cell vehicles on U.S. fleets. (Waegel et al, 2006b; Waegel et al, 2005) This third year report presents a more complex and flexible model intended to handle a large range of vehicles, fuels and technologies and corresponding policy scenarios.

The model, dubbed *CarCarbon*, can be used as a projection tool to shed light on the future of vehicular transportation. Specifically, CarCarbon provides projections regarding types of vehicles people will be driving in future years and the effect these vehicles will have on carbon dioxide emissions and energy consumption. The model relies on a number of attributes, such as vehicle ownership growth, fuel economy trends, the price of fuels, and many others in order to create a projection of market demand for various vehicle technologies, such as gas-electric hybrids, gasoline internal combustion engines (ICEs), or hydrogen fuel cell vehicles. The market demand for the various technologies is combined with the expected growth rate of the vehicle ownership each year in order to create a 25-year annual "snapshot" representative of the on-road vehicle population. With this data, it is possible to predict the emissions of the vehicle population in each year and the amount of fuel being consumed.

Through this model we may determine the effects of policy on future emissions and energy consumption of the United States. The effects of a gasoline tax, incentives program for hybrid vehicles, or the rising costs of gasoline may be determined by including them in the model and comparing the projection to a baseline scenario based on a business as usual set of assumptions and predictions. Thus, not only does this model provide a picture of what will happen if no changes are made, it also shows how the future can be guided via progressive policy initiatives and which policy methods will have the greatest effect.

The remainder of this document describes CarCarbon in detail, including the mechanics and improvements over our previous model. Also described is the baseline scenario, which will form the basis for all future scenarios conducted with the model. The report section on the baseline scenario includes the inputs, assumptions, and inherent projections that were used to fortify the baseline as well as the resulting outputs. It shows a future with increasing fuel economies, greater use of alternative fuels, and, despite these factors, continued rises in carbon dioxide emissions and reliance on foreign energy sources.

1.1. CarCarbon

CarCarbon employs a complex structure of equations, inputs and algorithms in order to accurately model the adoption of new technologies into the U.S. vehicle fleet. Figure 1 identifies the structural flow of the new model. Consulting this diagram in conjunction with the following model description will assist in understanding the basic structure and development of CarCarbon.

CarCarbon has a number of very strong areas that can be necessary for the accurate prediction of technology adoption in the vehicular market. A first of these areas in CarCarbon is the ability to reflect the different factors affecting acquisition and retirement of new vehicles into the general pool of passenger cars, trucks and sport-utility vehicles (SUVs). A total of 15 vehicle technology types are incorporated into the model: conventional gasoline (CG); conventional diesel (CD); dedicated ethanol (EtOH); dedicated biodiesel (BD); hybrid gasoline electric (HEV); hybrid ethanol electric; hybrid biodiesel electric; flex ethanol; flex biodiesel; dedicated compressed natural gas (CNG); dedicated liquid natural gas (LNG); flex CNG; flex LNG; flex liquid petroleum gas (LPG); and hydrogen (H_2). It is the researchers' opinion that this vehicle technology list incorporates all possible types of fuels and motive technologies which may be developed in the passenger and commercial vehicle sectors within a reasonable timeframe.

A second major area in CarCarbon is the ability to incorporate fuel blending in fuel options. Even better, blends can remain constant or change over the course of the timeline of the model. As each of the technologies can handle different blends and different fuels, each is capable of being blended at different levels. This is particularly important for examining ethanol-gasoline blends, biodiesel-petrodiesel blends, and hydrogen from different sources. The H_2 option is especially important as it allows for variations to occur in how H_2 is being secured. The variation in the blends can measurably affect the emissions levels from the vehicle pool and the ability to vary blends in fuel also illuminates important differences in how vehicle technology and fuel choice synergistically affect the emissions profile of a vehicle pool.

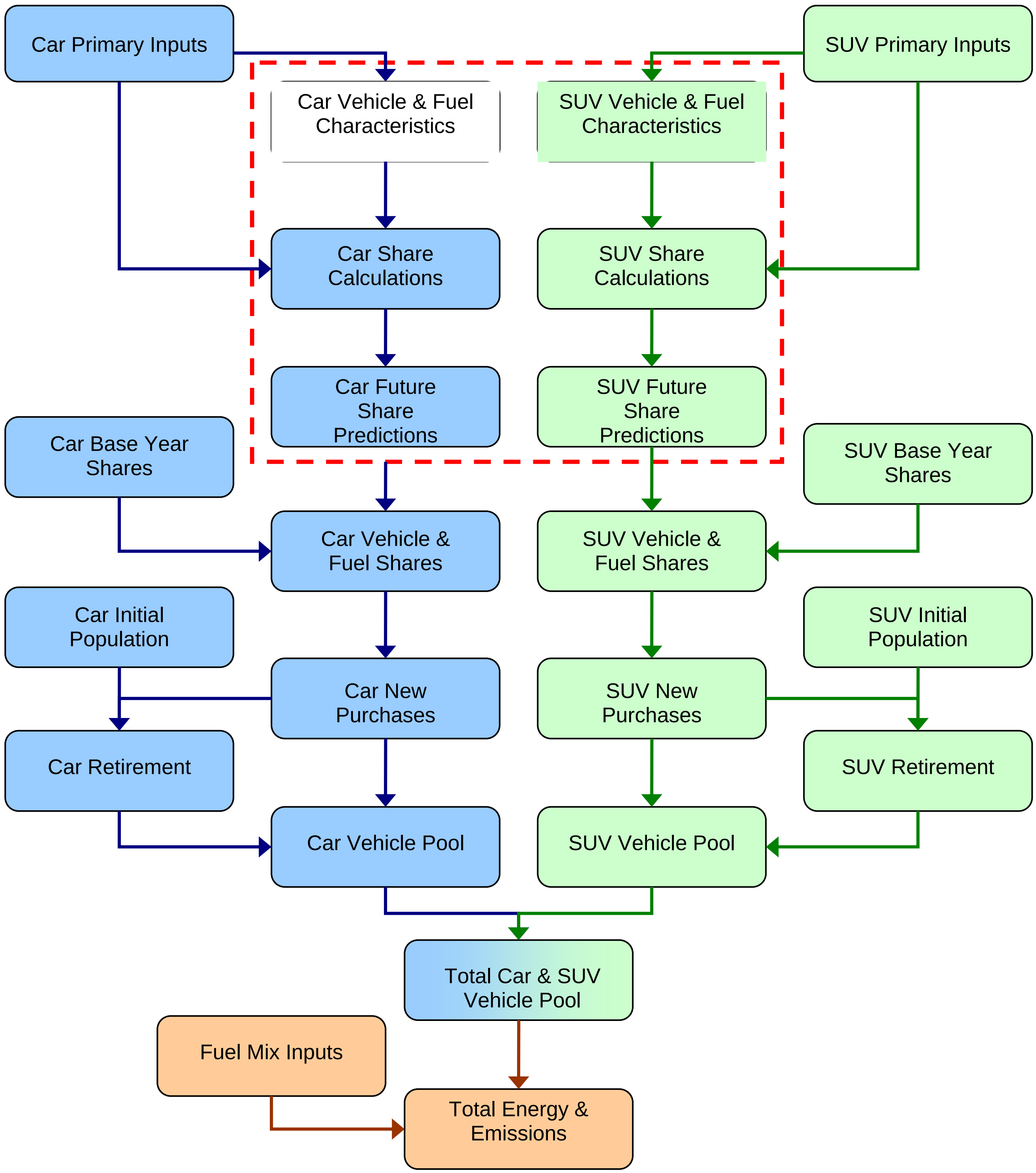
A third major area in CarCarbon is the ability to account for variability in inputs across the projection period. Inputs which can be varied over time include: vehicle prices; expected vehicle lifetimes; average miles driven annually per vehicle; fuel prices; vehicle type fuel economies; fuel blends; fueling availability; and make and model availability. This capability gives the model a great deal of flexibility and enables more realistic scenario designs.

A fourth major area in CarCarbon is the incorporation of vehicle aging and eventual retirement; namely, the method by which vehicles are removed from vehicle pools over time. Vehicle types can be tracked through their lifetime, from manufacture to scrapping. A "skewed" normal distribution is utilized to determine the rate of retirement. This reflects a low retirement rate in early years due to car accidents and unusual mechanical problems, a high retirement rate in the middle years, and a low retirement rate in later years on the assumption that the majority of vehicles do not last beyond an "average" expected lifetime. Under the model, most retirements occur within two years of the expected lifespan of the vehicle. This method of vehicle retirement presents a realistic portrait of vehicle pool trends for privately owned vehicles.

The final and most significant area is the utilization of algorithms and formulas originally developed in the TAFV Alternative Fuels and Vehicles Choice Model (Greene, 2001). Greene's model was first developed in the early 1990s to calculate the change in market share amongst competing technologies. The change in market share is calculated through a dynamic process influenced by numerous factors including: vehicle cost; fuel cost; fueling availability; luggage space; fuel economy; make and model availability; maintenance cost; multi fuel capability; home refueling capability; range; top speed; and acceleration. These factors are all monetized (evaluated on how a change in the factor would relate to a change in willingness to pay) by multiplying them by a coefficient that is determined by examining market trends for those factors that cannot be directly monetized and by examining the price elasticity of vehicle demand based on initial cost. In this way, all factors are represented in a utility function which is employed to predict market shares. The utilities of the factors are combined in the model to give each vehicle-fuel combination an aggregate utility.

The market shares cannot be determined by direct comparison of the individual utilities, however. Instead market shares are determined in a decision tree, with each fork in the tree splitting the market share between two branches. For example, luggage space may be an important factor in the decision between an SUV and a sedan, but it will not influence the decision to utilize ethanol or gasoline, which is instead decided by fuel price. Thus the decision tree is divided into tiers, with each tier covering a basic set of choices. In Greene's model, the top tier is small sedans, large sedans, small light trucks, and large light trucks. This was never built into his actual model, however, and the tree simply begins with the assumption that sedans are being chosen. In the future it is theoretically possibly to expand his model to cover

Figure 1: CarCarbon Structural Flow Chart



this first tier but, for now, an alternative has been enacted to cover the broader categories of sedans and SUVs.

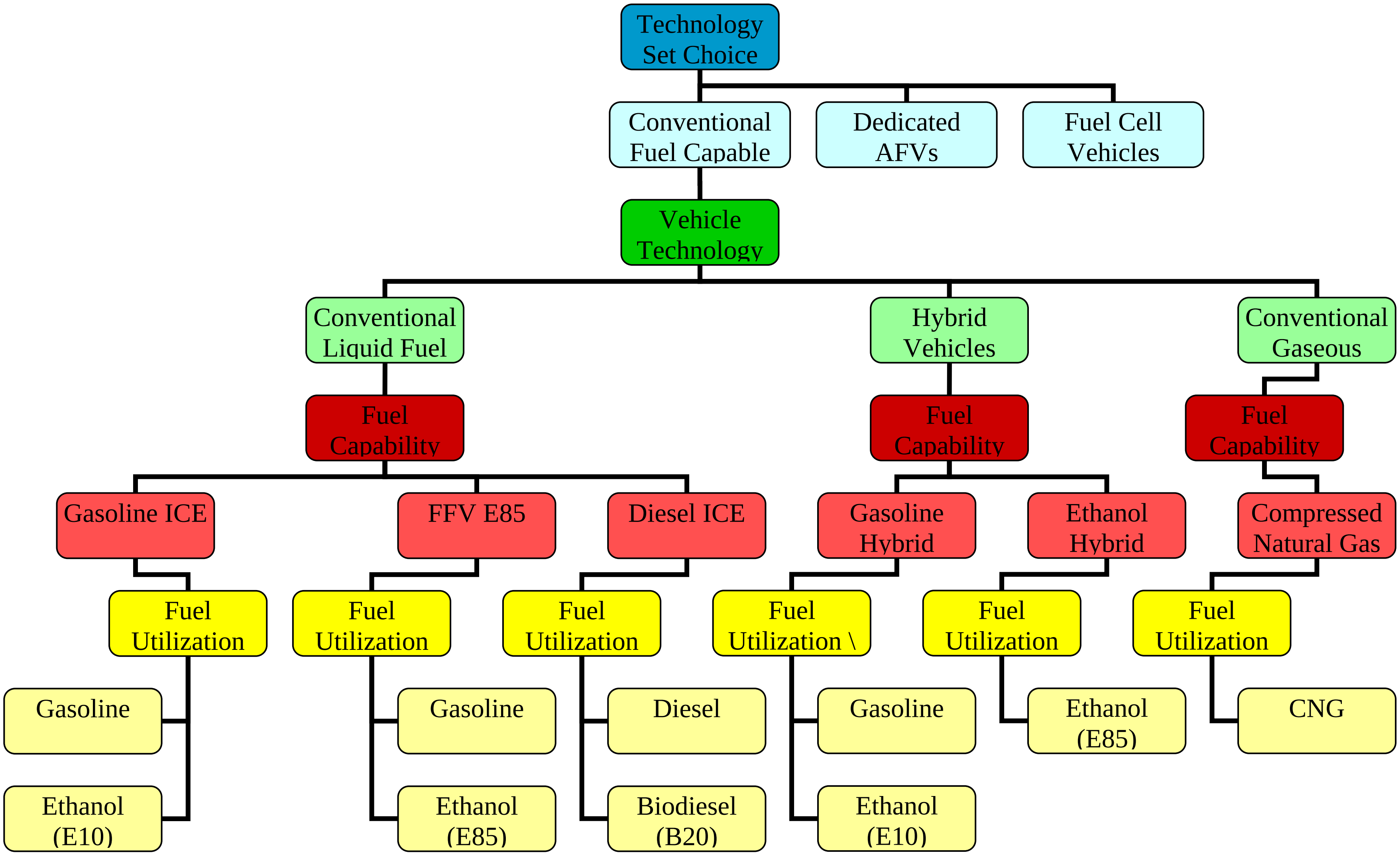
As seen in Figure 2 the initial decision for modeling purposes is amongst basic technology-fuel sets. In Greene's model this decision covers four basic technology sets: electric vehicles (which we have removed); hydrogen fuel cell vehicles; dedicated alternative fuel vehicles; and conventional fuel capable vehicles (some of which may be flex fuel vehicles). Once the choice has been made among the technology-fuel sets, the second choice refines the on-board technology. For example, assuming that conventional fuel capable vehicles are chosen in the initial step; the next step is to determine whether or not the vehicle will operate on a conventional liquid fueled engine, a hybrid engine, or a gaseous engine. The third choice is to determine the specific fuel capability of the vehicle. Assuming that a conventional liquid fuel engine is chosen (for example), the model considers whether the vehicle will have a standard gasoline engine, a flex fuel E85 capable engine, or a diesel engine. The final step choice is to determine the fuel mix being used in the engine, if necessary.

The market shares are determined from the bottom of the tree moving upward. At the base level – fuel choice – each fuel has a utility determined by summing the relative factors multiplied by their coefficients. Market share within the fuel choice step is determined by the relative utility of each choice compared to others within that decision node. Once the market shares for that node have been determined, the next node up is addressed. Each choice within this node has a utility, but it is determined not only by the factors relevant to that choice but also by the mean utility of the pending choices further up the tree. Thus the choice between a conventional gasoline engine and a conventional diesel engine is not only determined by comparing the traits of those technologies but also by comparing the mean utility of fuel choices. This continues all of the way up the tree until each decision node has its market shares predicted. The overall market share of each technology may be determined by multiplying the market shares for each decision node lead.

One point of interest that helps to reassure the validity of this method is to examine price elasticity at each level of the tree. At the higher level of the tree, price elasticity is relatively low, while at lower levels of the tree price elasticity is relatively high. This concept holds true in real-world applications; if a vehicle-purchaser is deciding between an SUV and a sedan, then price difference between the two options would need to be relatively large to encourage a switch from one to the other as they are two very different technology types in terms of performance. But when deciding fuel choice, say between conventional diesel and BD20, it would only take a small price difference to encourage a large level of switching between the two. Thus, as decisions are made on lower levels of the tree and the differences between the vehicles narrow, it takes an ever greater difference in utility between options to affect market shares.

Figure 2 more closely examines the decision making process performed in Greene's model. Its placement within the overall model may be seen as those areas encompasses by the dashed red line in Figure 1.

Figure 2: Greene's Decision Tree



Source: Greene, 2001 (N.B. This figure only displays a single branch of the three Technology Set Choices)

1.2. Vehicle Pool and Emissions

In order to project beyond a single year's change in market shares, our model takes the formulas and algorithms adopted from Greene's model and conducts 25 calculations - once for each year of the 25-year simularion. Each run of Greene's model refers to the time variable inputs discussed above and to the market shares of the previous year. These market shares are then utilized to determine what percentage of each of the 15 examined vehicle types will make up the number of new vehicles purchased that year. The number of new vehicles purchased that year is equal to the total number of vehicles retired that year from all technology types [replacement] added to the number of vehicles that would need to be purchased to make the fleet grow at a certain rate for that year [growth]. The growth rate of the vehicle pool is determined by the user as a percentage for each year and can be positive or negative. The vehicle pool for each technology is tracked separately with the number of vehicles of that technology type in any given year equal to the number of vehicles from the previous year minus the number of vehicles being retired that year plus the number of new vehicles of that type being purchased that year.

With the total number of vehicle technology types known for each year, it is then possible to determine the emissions of each technology type and the entire pool. The basic algorithm is:

$$CO_2 = [\# \text{ of Vehicles}] * ([\text{Annual Miles}] / [\text{Miles / Gal}]) * [CO_2 / \text{Gal}]$$

Results may be obtained relatively easily from the model. The number of vehicles of each technology type is known from the calculations of the model. The annual miles driven and the fuel economy (MPG) are two of the inputs to the Greene model. And the emissions factor (CO_2 / Gal) can be determined by the fuel blend being used on average for each technology type. The amount of carbon dioxide per unit of fuel was gathered primarily from two sources. The values for hydrogen from different sources originate from the 2004 National Academies Report on the Hydrogen Economy and the remainder of the values were pulled out of the GREET model (Argonne National Laboratory, 2007). This calculation can then yield CO_2 emissions for each technology type for 25 years. The placement of this equation within the overall model may be seen in Figure 1 as the block entitled 'Total Energy and Emissions' as the end of the flow chart.

2. The U.S. Baseline Scenario

The baseline scenario for the United States presents a projection representative of what may come to be if no major policy, social, or technological changes are made in the next 25 years. The data in the scenario is best divided into inputs and outputs. In the baseline scenario the major inputs are the cost of the fuels, the fuel economy (or efficiency) of the different vehicle types, the prices of the vehicles themselves, the availability of the fuel, and the number of makes and models there are of each technology type. It was assumed that the number of miles driven annually by each vehicle would remain constant. Given that this is supposed to represent a baseline scenario with little to no change to the current trends, this scenario's inputs tend to be relatively static, with only minor changes, reflecting historical trends occur. As a result, the outputs of the scenario are also relatively static showing slow and steady changes.

The outputs of the scenario are the market share and absolute number operating of the different vehicle types, the amount of energy being consumed by each vehicle type, and the amount of carbon dioxide being released by each vehicle type. Additionally, since no major technological or social changes are assumed to occur, all technology types that are not currently being used at some reasonable level or expected to be used at a significant level in the near future were excluded. Thus the technologies considered were: (1) conventional gasoline ICE; (2) conventional diesel ICE; (3) flex fuel gasoline-ethanol ICE; (4) flex fuel diesel-biodiesel ICE; (5) hybrid gasoline-electric; and (6) hydrogen fuel cell.[1] The following pages are a description and explanation of the inputs used and the resulting outputs.

2.1. Model Inputs

2.1.1. Fuel Cost

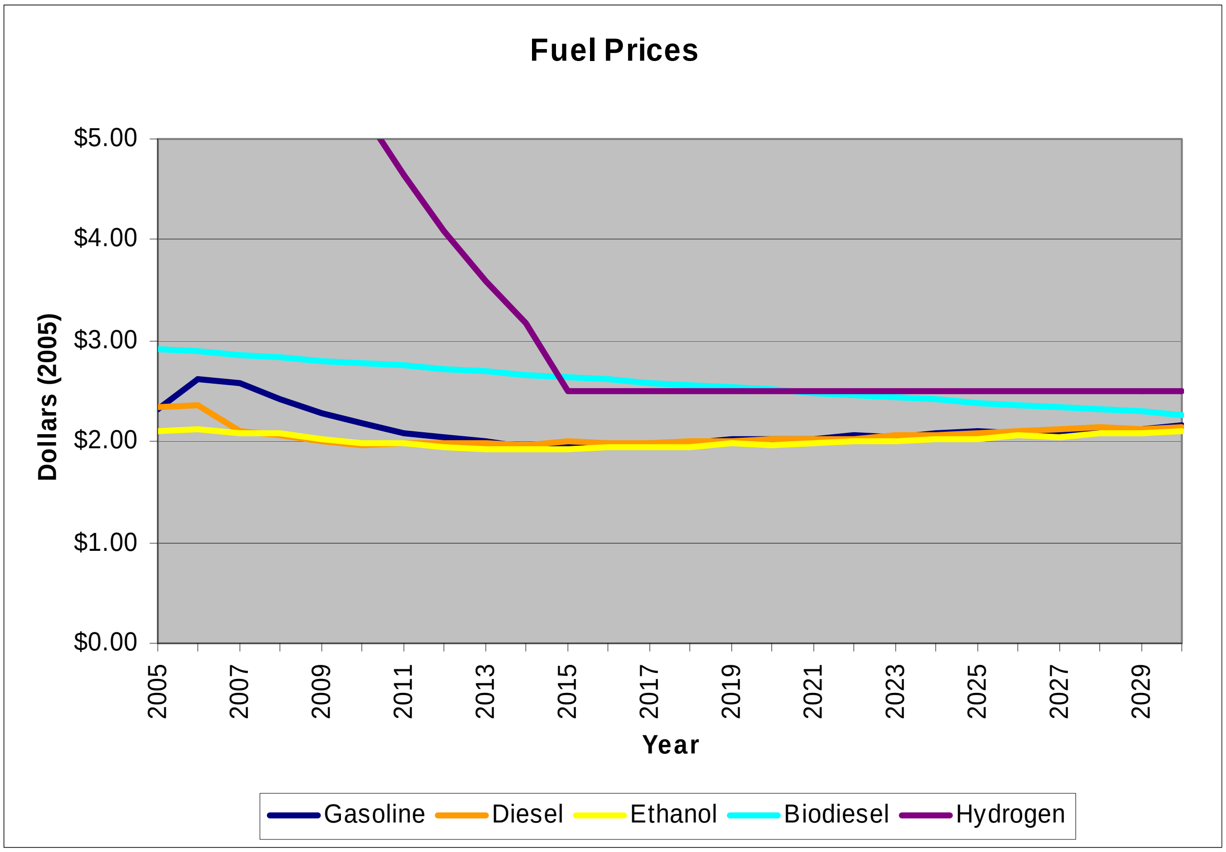
Since numerous projections of fuel costs already exist, it was decided to rely on an previously published projection rather than attempting to create a new fuel cost projection. The projections made in the Annual Energy Outlook published by the Department of Energy's Energy Information Administration, was deemed to be the most reliable source. The 2007 edition of the Annual Energy Outlook included fuel price projections for all but one of the pertinent fuels to be utilized in the scenario: gasoline, diesel, ethanol, and biodiesel. (EIA, 2007) The only fuel price that was not present was a projection of the cost of hydrogen. Given the relatively early stages of development for this technology, no reliable, peer reviewed or widely accepted price projection has been made. Instead, to determine the values to use in the model, the price goals defined by the DOE's Hydrogen program were utilized. (EERE, Hydrogen, Fuel Cells, Infrastructure and Technologies Program). The prices are illustrated below in Figure 3. They are shown in a more relative sense in dollars per BTU in Figure 4.

One concern of ours regarding the DOE's projection is the trend in diesel and gasoline prices. Their projection shows the current annual average of these prices accurately, but their projection shows a future decrease in price, which is expected to remain at that lower level. While this projection for oil prices seems to contradict our basic expectations of future oil prices, what is more disturbing has been the trend in oil projections made in the Annual Energy Outlook

[1] All other technologies were removed from the model by setting their vehicle prices at $1,000,000 and as a result they accounted for a constant zero percent of the market share.

over the past several years. This data can be seen below in Figure 5. What is disturbing about this data is that it shows that the DOE consistently predicts that the current gasoline prices are the peak of a small bump and that beginning in the next year the prices will begin to decline and level off at some lower price. This graph shows, however, that they have been consistently incorrect in this projection and that the peaks they are describing each year are instead, just points on an upward slope that does not seem to have any predictable end.

Figure 3: Fuel prices in 2005 dollars per gallon



(Source: EIA, 2007; EERE, Hydrogen, Fuel Cells, Infrastructure and Technologies Program)
(Note: dollars per kg for hydrogen)

While this fuel price projection does raise some concerns, it is still the most reliable source of future fuel price information that we were able to find. Because of this, the reference case outlined in the 2007 *Annual Energy Outlook* is the one that will be used in the baseline scenario for the United States. Another scenario showing the rising gas prices illustrated by the 'high price' projection in the Annual Energy Outlook will be created to show the effects of a steadily increasing price for crude oil and petroleum products.

Figure 4: Projected price of the fuels expressed in 2005 dollars per BTU

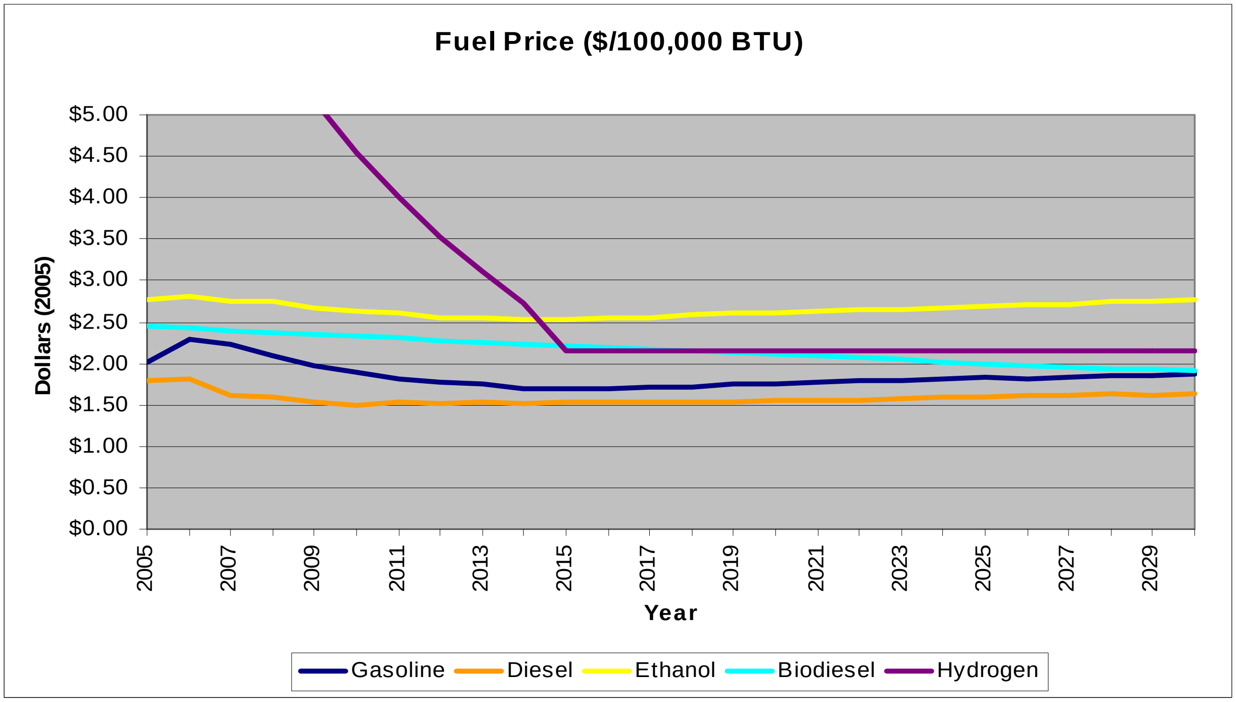
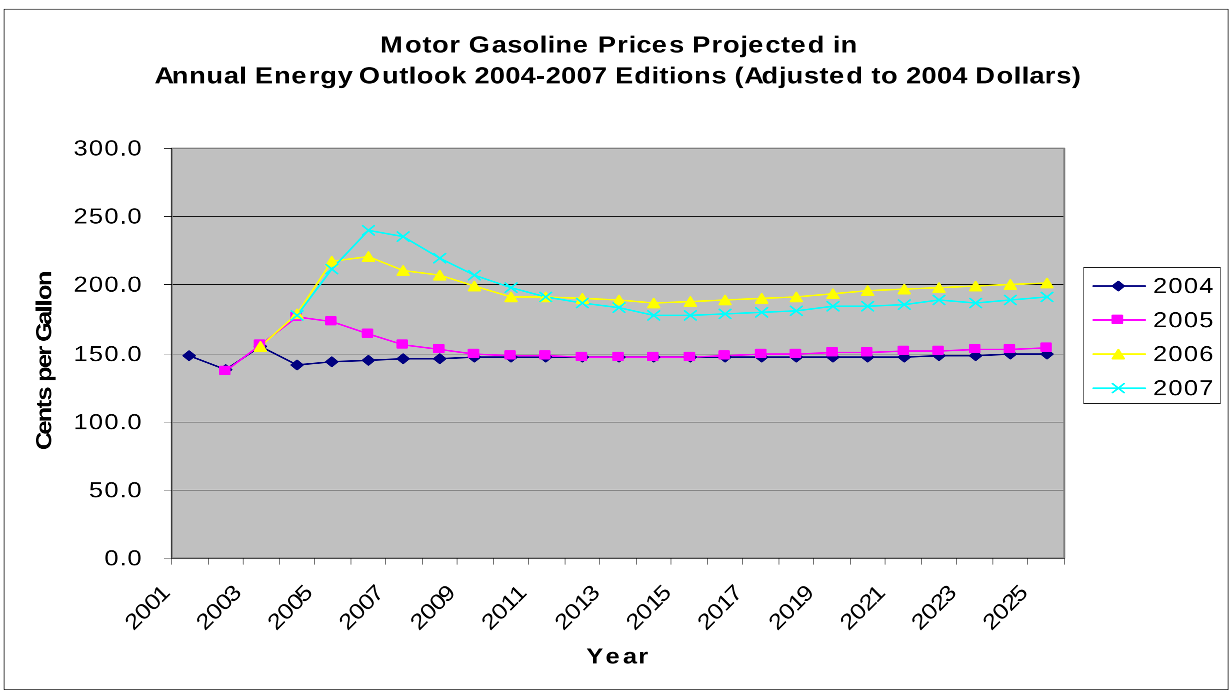


Figure 5: Projections of gasoline prices made in the Annual Energy Outlook in the 2004-2007 editions



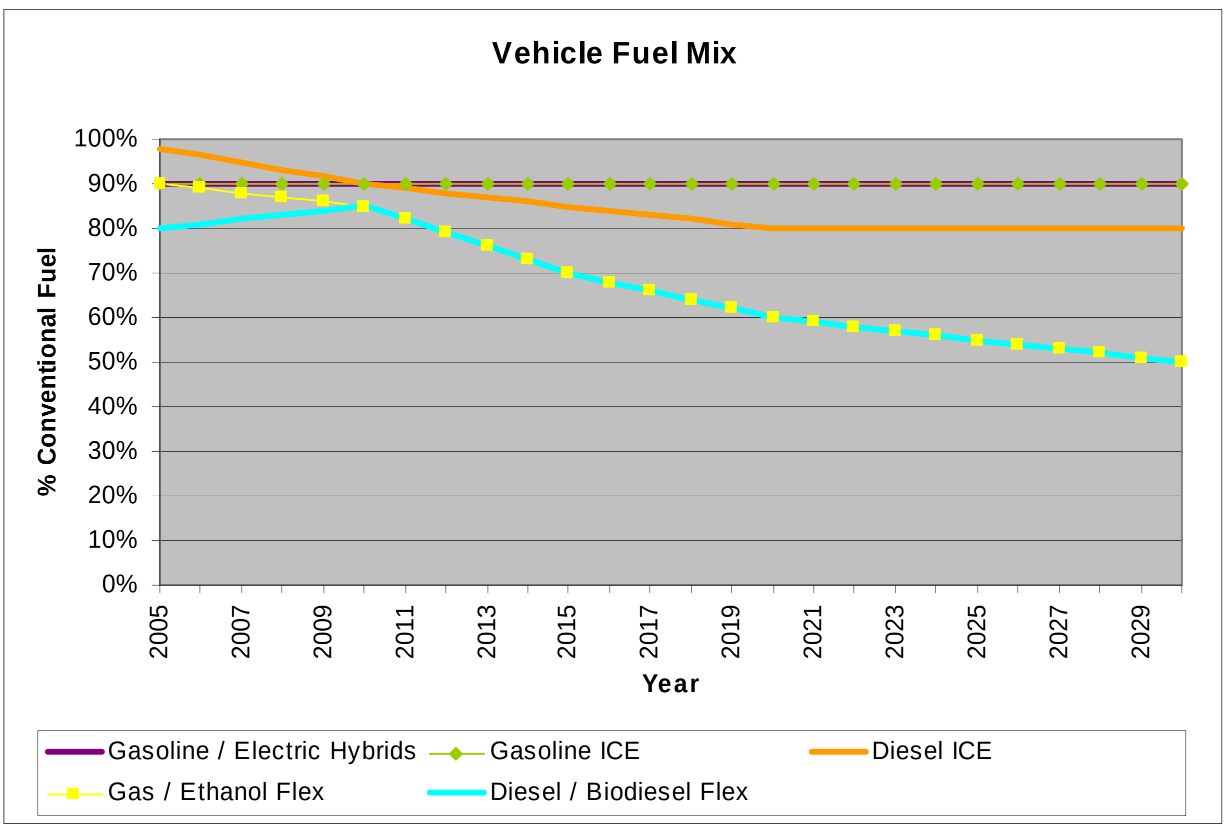
Source: EIA, 2007; EIA, 2006; EIA, 2005; EIA, 2004

2.1.2. Fuel Mixing

One of the options that was not included in the model created for the 2005-06 report was the ability to show the effects of blending fuels for use in the same type of vehicle. History and studies have shown that many vehicle technologies can accept a range of different fuel blends and these blends will all have varying environmental effects. Such fuel mixing is currently being utilized in the U.S. through the low level blending of ethanol with gasoline and the low level blending of biodiesel in diesel. Technologically, according to engine manufacturers, both conventional diesel and conventional gasoline ICE's are capable of accepting up to 20% and 10% of the biofuels respectively. With some small technological modifications these numbers could rise.

Additionally, with the utilization of flex fuel vehicles, or vehicles that can run on either fuel, the potential for fuel mixing rises dramatically so that ICE's can run on either entirely petrofuels, entirely biofuels, or a blend. By introducing fuel mixing to the model we can now more accurately gauge the economic and environmental effects of this growing trend. The projections for fuel mixing in the different technologies are displayed below in Figure 6.

Figure 6: Blend of bio vs. petro fuels being utilized in ICE's



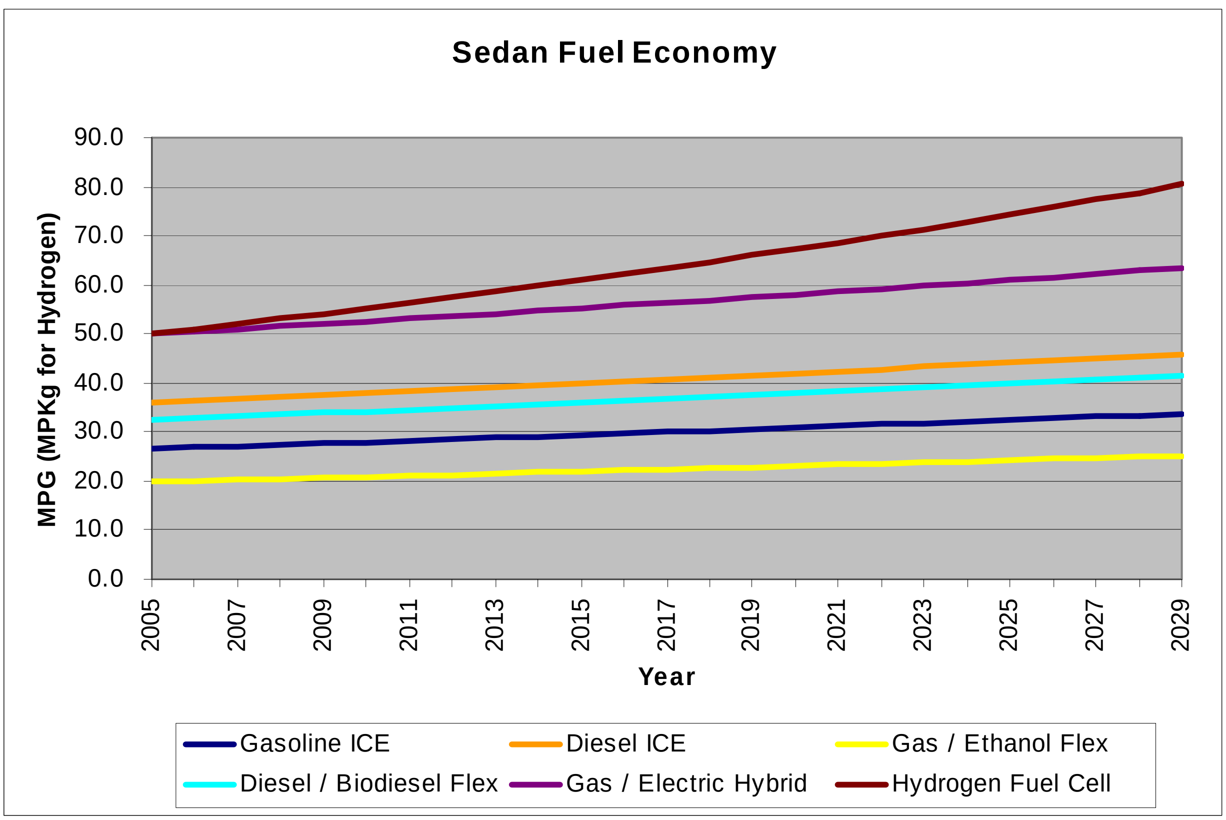
Source: Alternative Fuels Data Center, 2006

As can be seen, the level of fuel blending remains heavily weighted towards petro fuels, especially in the non-flex fuel capable vehicles. These conventional vehicles are assumed to remain at the current levels of technology and without small but significant technological alterations using higher blends of biofuels will either damage the vehicle or, at the very least, void manufacturers warranties. The use of biofuels in flex fuel vehicles begins at levels similar to those of conventional vehicles, as has been shown in studies of flex fuel fleets and individual vehicles. The level of fuel blending in the flex fuel vehicles is assumed to increase to 50% for both ethanol-gasoline and biodiesel-diesel flex fuel vehicles by 2030 as the technology becomes more prevalent and the current political support for biofuels continues. Gasoline-electric hybrids are assumed to use the same fuel mixture as conventional gasoline ICE's.

2.1.3. Vehicle Efficiencies

The fuel economies of the various technologies play an obviously important role in any model studying vehicle populations and carbon dioxide emissions. The fuel economy not only controls the amount of carbon dioxide emissions per mile of travel, but it also is the second largest source of cost after the initial vehicle price. In a time when fuel prices are both volatile and, on average, rising, fuel economy of vehicle technologies is playing an ever increasing role in the public's vehicle selection. This can be demonstrated by the unexpected and sudden success of hybrid vehicles and the new emphasis on fuel economy in car commercials. The fuel economies used in the U.S. baseline scenario can be seen below in Figures 7 and 8, showing sedan fuel economies and SUV economies respectively.

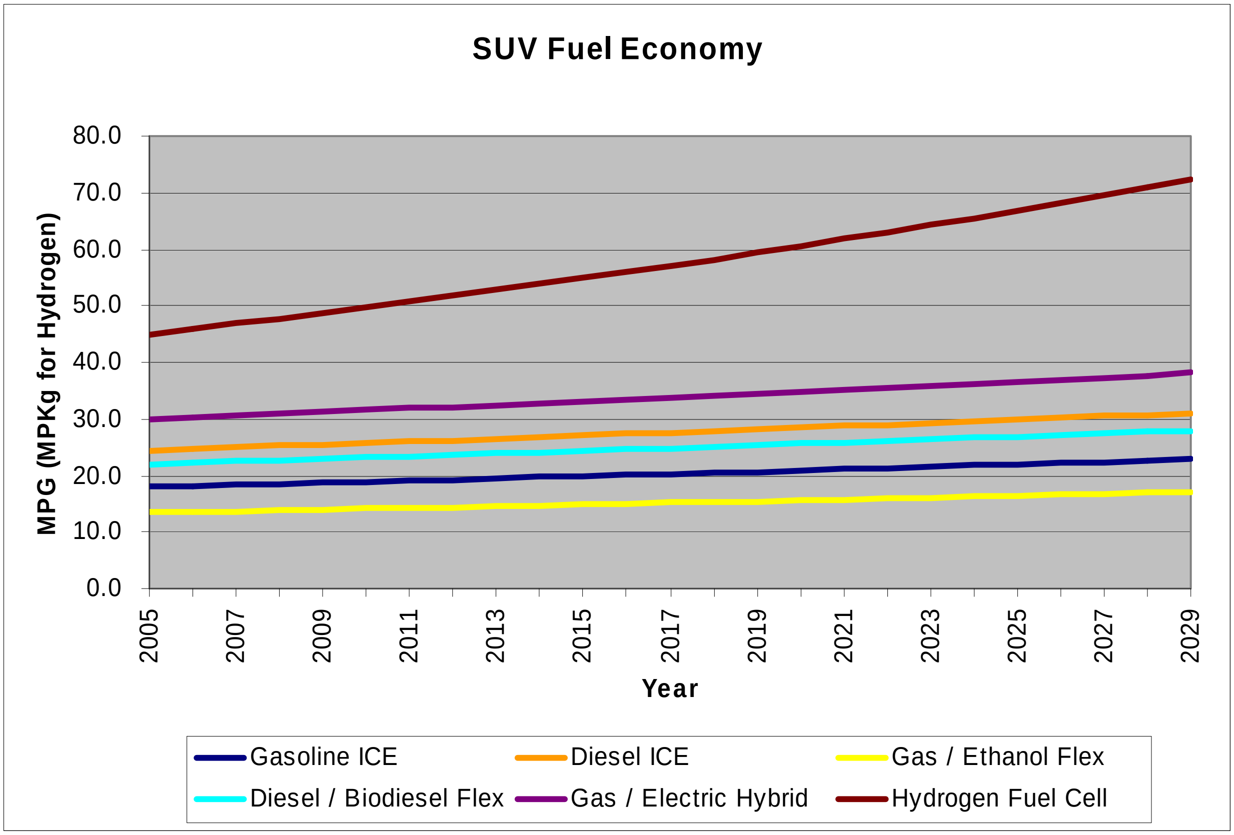
Figure 7: Sedan Fuel Economy



Source: EERE, 2007; Davis and Diegel, 2007

The initial fuel economies for Year 1 were determined through data obtained from the 2007 Fuel Economy Guide. This gave the fuel economies for all the vehicles currently being marketed. From this data a weighted average based on the numbers of each make and model on the road was constructed, creating the initial values for the model. Hydrogen vehicles are currently all prototypes still, the initial value of 50mpkg was compiled from an average of those prototypes. From the base year, all of the fuel economies were assumed to increase at a rate of 1% a year, except for hydrogen which is assumed to increase at 2% a year due to its higher theoretical efficiency; 1% was chosen due to historical trends and technological feasibility.

Figure 8: SUV Fuel Economy

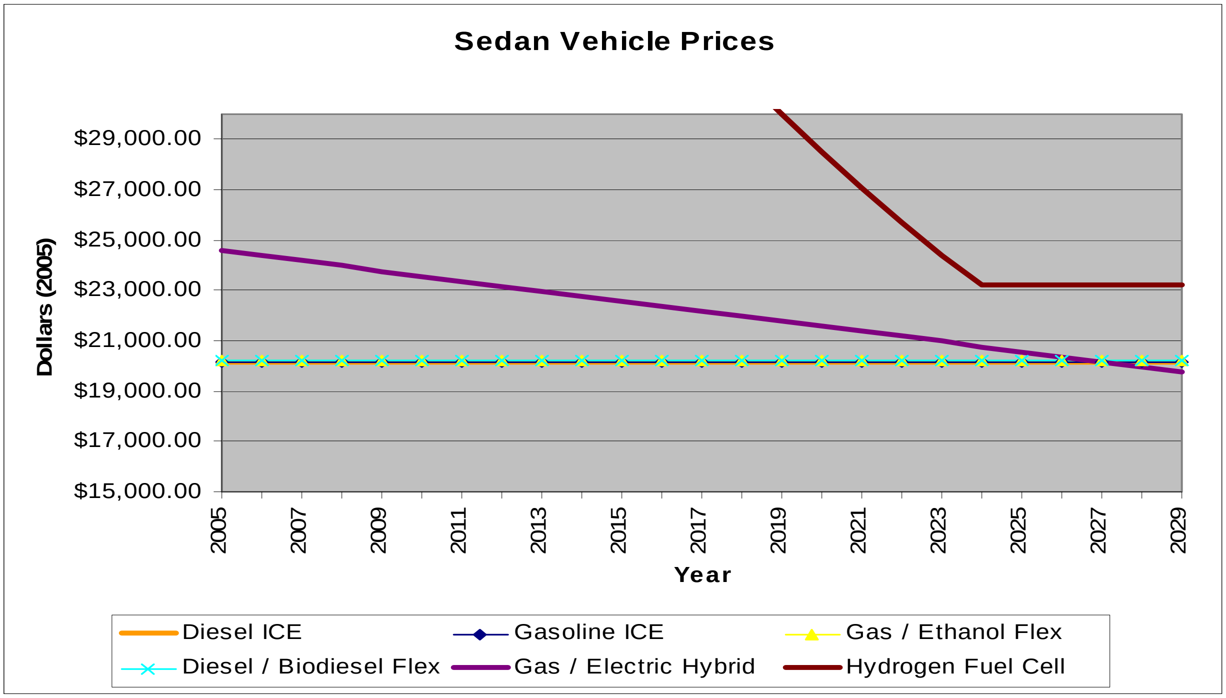


Source: EERE, 2007; Davis and Diegel, 2007

2.1.4. Vehicle Prices

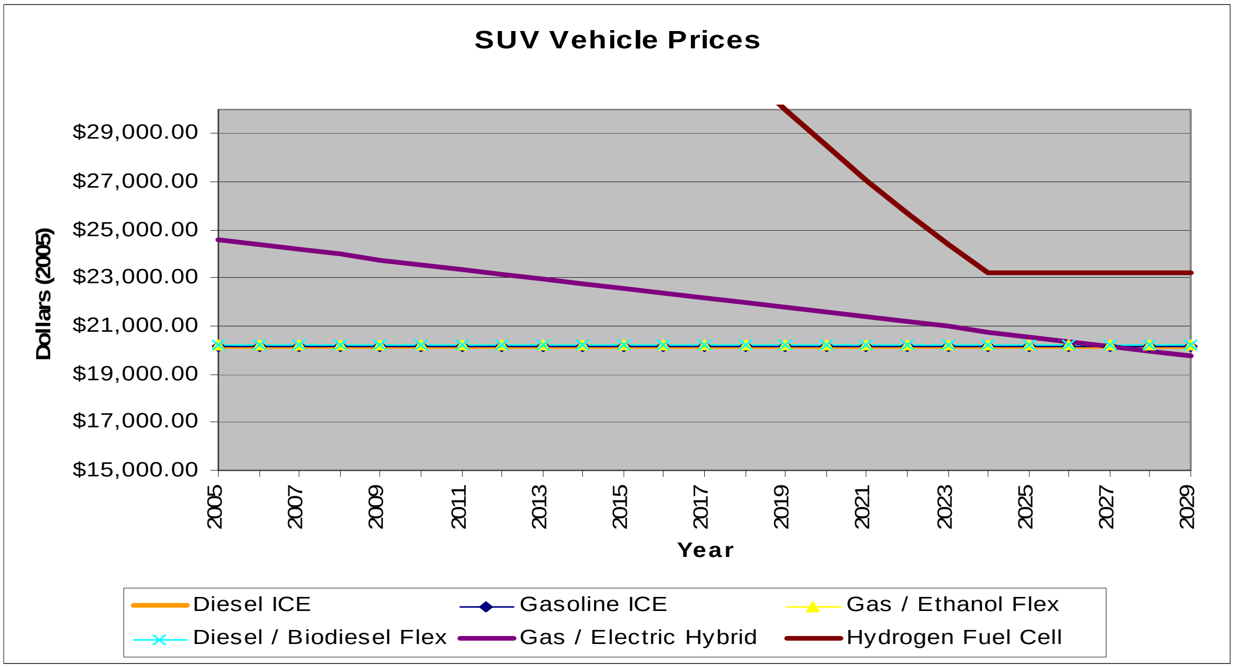
Vehicle prices have proven to be the most sensitive factor in our model. Since all other factors are converted into an eventual monetary value in order to determine overall utility, the price elasticity observed in the vehicle market is utilized to determine the elasticity of all factors. All initial prices, except for hydrogen vehicles, are calculated by averaging the MSRP for all non-luxury midsize sedans and SUVs. In our baseline scenario, all of the technologies are assumed to have a constant and equal value throughout the model. The two exceptions to this are gasoline-electric hybrid and hydrogen vehicles.

Figure 9: Sedan Vehicle Prices (2005 Dollars)



Source: Davis and Diegel, 2007; EERE, Hydrogen, Fuel Cells, Infrastructure and Technologies Program

Figure 10: SUV Vehicle Prices (2005 Dollars)



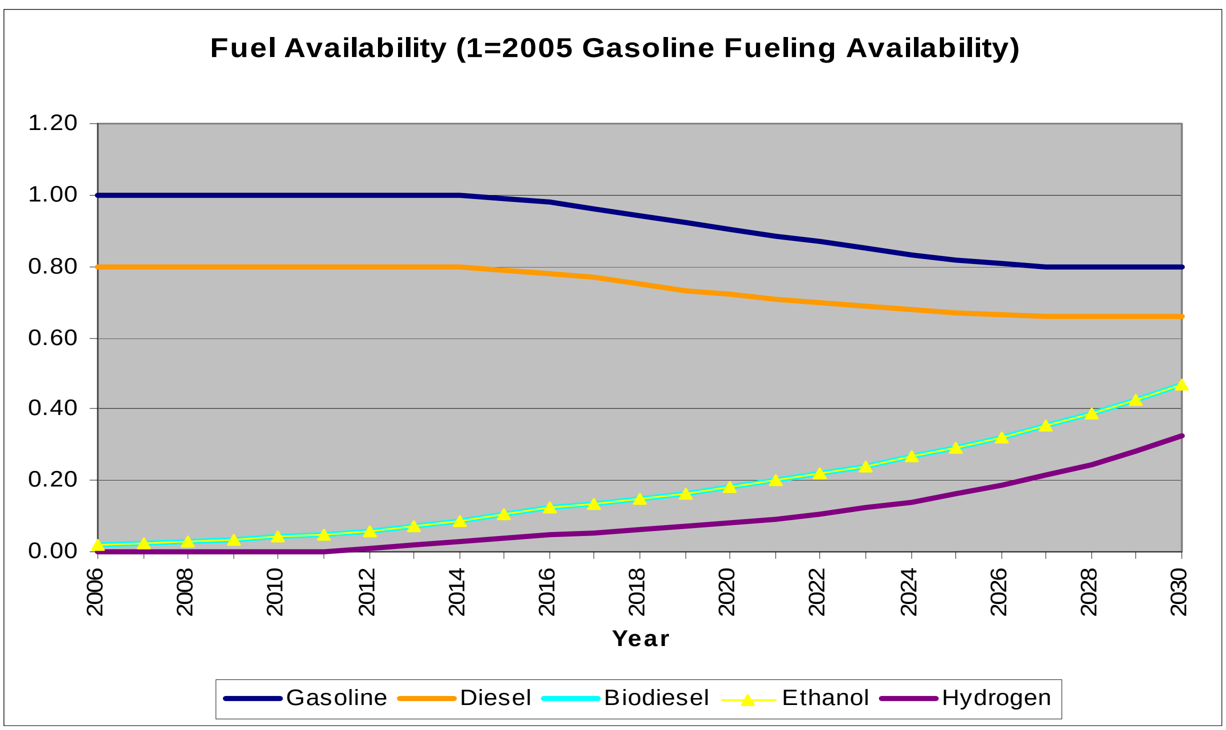
Source: Davis and Diegel, 2007; EERE, Hydrogen, Fuel Cells, Infrastructure and Technologies Program

Currently a premium of, on average, $4,500 is paid for a hybrid vehicle as compared to a conventional counterpart and hydrogen vehicles, being at the prototype stage, cost upward of a million dollars. The premium for gasoline-electric hybrid vehicles is assumed to steadily erode away until finally completely disappearing in the 23rd year of the projection, 2028. Hydrogen vehicles go through several stages of price drops, eventually reaching $23,000 by the end of the study. It is primarily for this reason that they play an essentially non-existent role in our baseline scenario. All other vehicle prices are assumed to be constant due to a lack of major technological or policy shifts. These prices do not include any incentives or subsidies in the baseline scenario.

2.1.5. Fueling Availability

In Greene's initial study it was concluded that fueling availability played a significant factor in the lack of adoption of new technologies if the fueling availability was 10-20% or lower compared to the current availability of gasoline. After this level has been reached, however, any further increases play a much less significant role in assisting or hindering the purchase of a technology. For the initial values, gasoline was set at 100%, diesel at 50%, ethanol and biodiesel at 2%, and hydrogen at 0%. Over time the availability of gasoline is assumed to drop to 62% and diesel is kept at one half of gasoline's availability. Biodiesel and ethanol rise at a rate of 20% for the first 10 years and then 10% for the remaining 15 years, eventually reaching 47% availability. Hydrogen reaches 4% availability after 10 years and then rises by 15% a year, eventually reaching 33% availability in 2030.

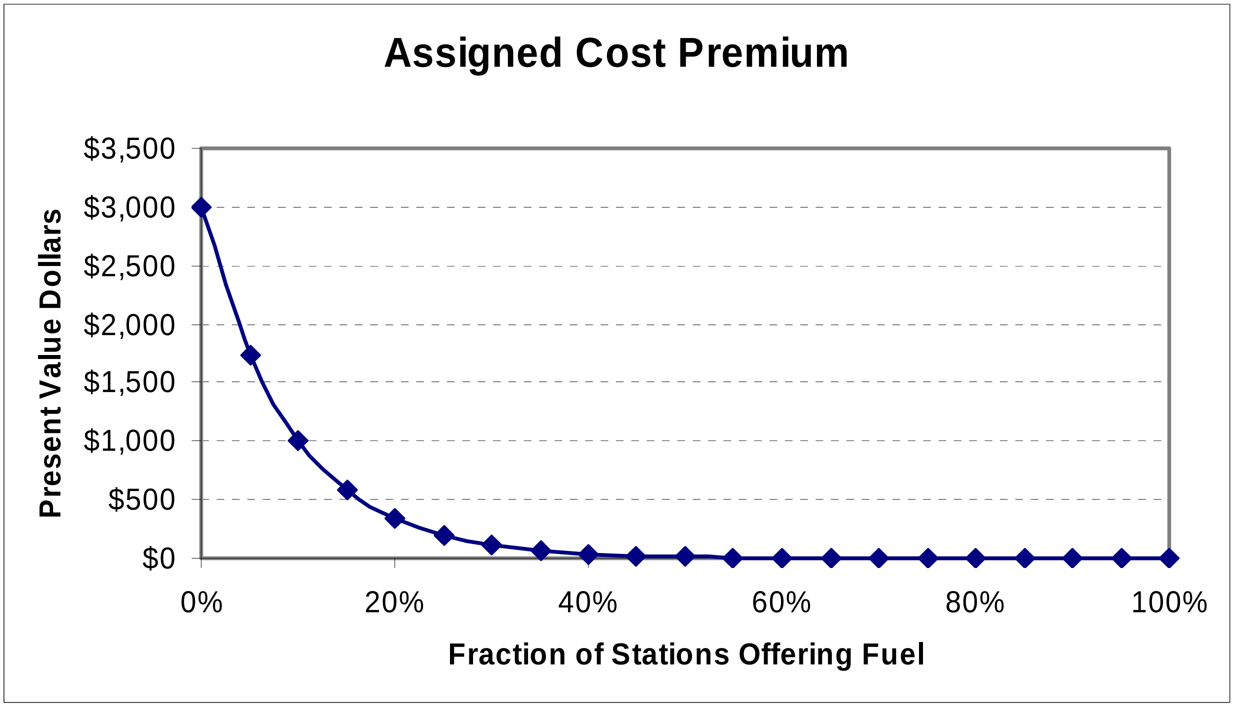
Figure 11: Fueling Availability as Compared to 2005 Gasoline Fueling Availability



Source: Alternative Fuels Data Center, 2007

Fueling availability is one of the more difficult variables to project given that its values are not independent of the outputs of the model. The fueling availability will not only help to determine the number of vehicles of each technology type on the road but will also, in turn, be determined by the makeup of the vehicle pool. In this there is a chicken vs. egg conundrum and as such only a conservative projection may be made for this input. It is thus fortunate that the results of the model are not sensitive to this input except in those cases where it is below 20%. This is due to the nature of the model. Since all inputs are given a certain cost in order to weight them, a cost curve was implemented in Green's model in order to give varying costs to different levels of fueling availability. This is shown below in Figure 12.

Figure 12: Fueling Availability Cost Curve



Source: Greene, 2001

2.1.6. Make/Model Availability

Make and model availability is similar in respect to fueling availability. It is far more sensitive at low levels and it also suffers from a chicken vs. egg situation, making it difficult to project. For the initial levels, an actual count of the different makes and models offered of each vehicle type was made using the 2007 Fuel Economy Guide issued by the Department of Energy. The vast majority of the alternative vehicle technologies (including diesel) started below 10 makes and models available. Gasoline-electric hybrids were available in 7 makes and models for sedans and 8 makes and models for SUVs. Ethanol-gasoline flex fuel vehicles were available in low numbers in sedans, but had 20 makes and models available as SUVs. Hydrogen fuel cell vehicles were initially unavailable as both sedans and SUVs, and only a few biodiesel flex fuel vehicles were available as sedans or SUV's.

Figure 13: Sedan Make/Model Availability

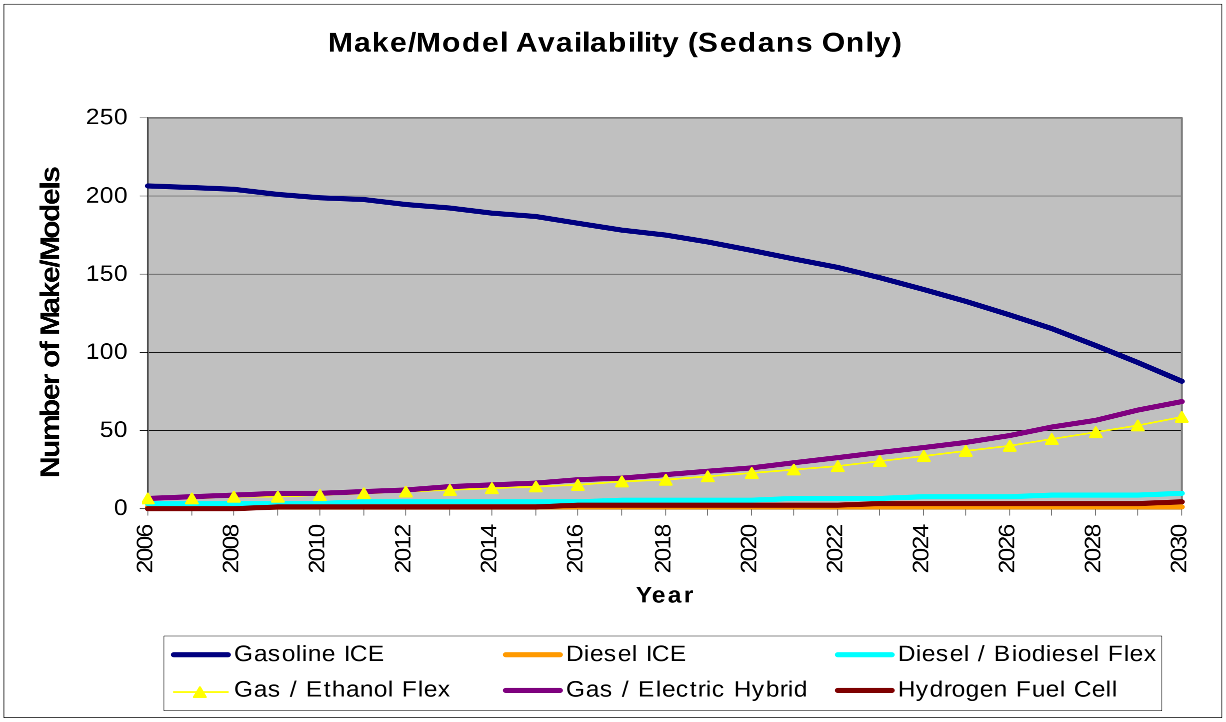
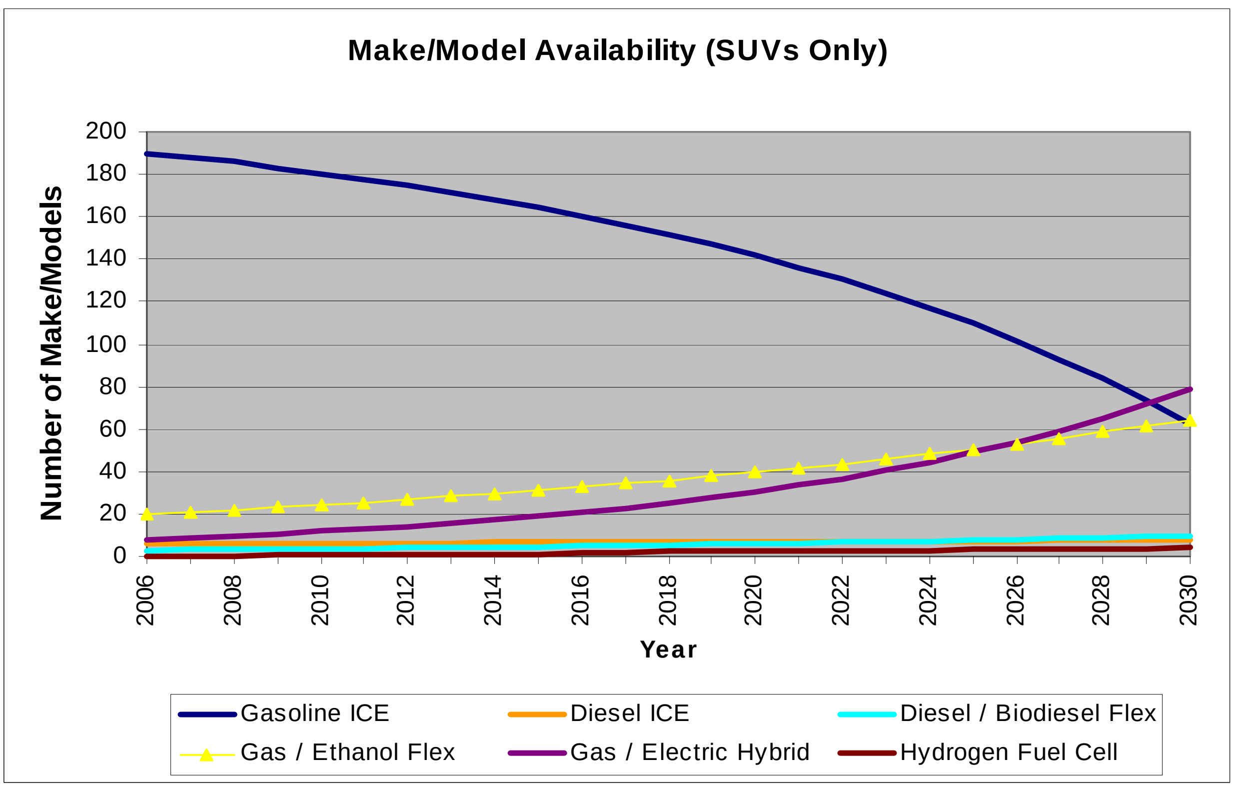
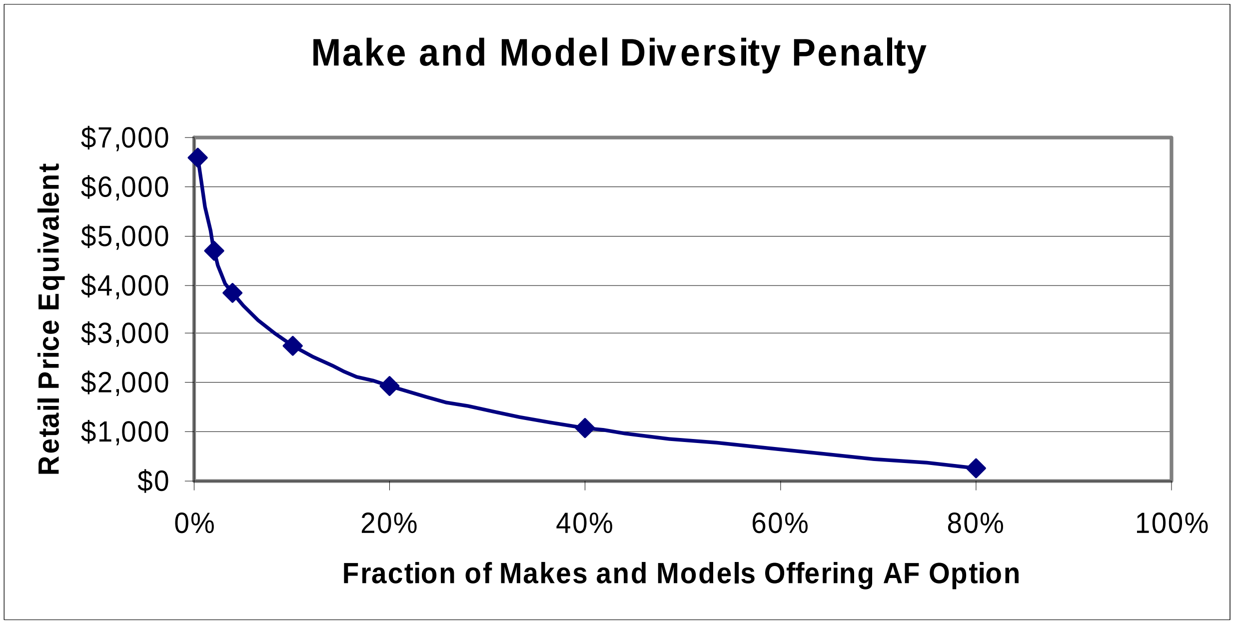


Figure 14: SUV Make/Model Availability



In the baseline scenario the number of flex fuel makes and models was expected to increase at 5% a year while the number of gasoline-electric hybrid vehicles was expected to increase at 10% a year. Conventional diesels remain constant through the study. Hydrogen vehicles are introduced as only 1 model in year 10 and this grows to 4 models by 2030 at the end of the projection. The number of gasoline makes and models decreases as the alternative increase so that the overall number of makes and models remains relatively constant.

Figure 15: Make/Model Availability Premium



Source: Greene, 2001

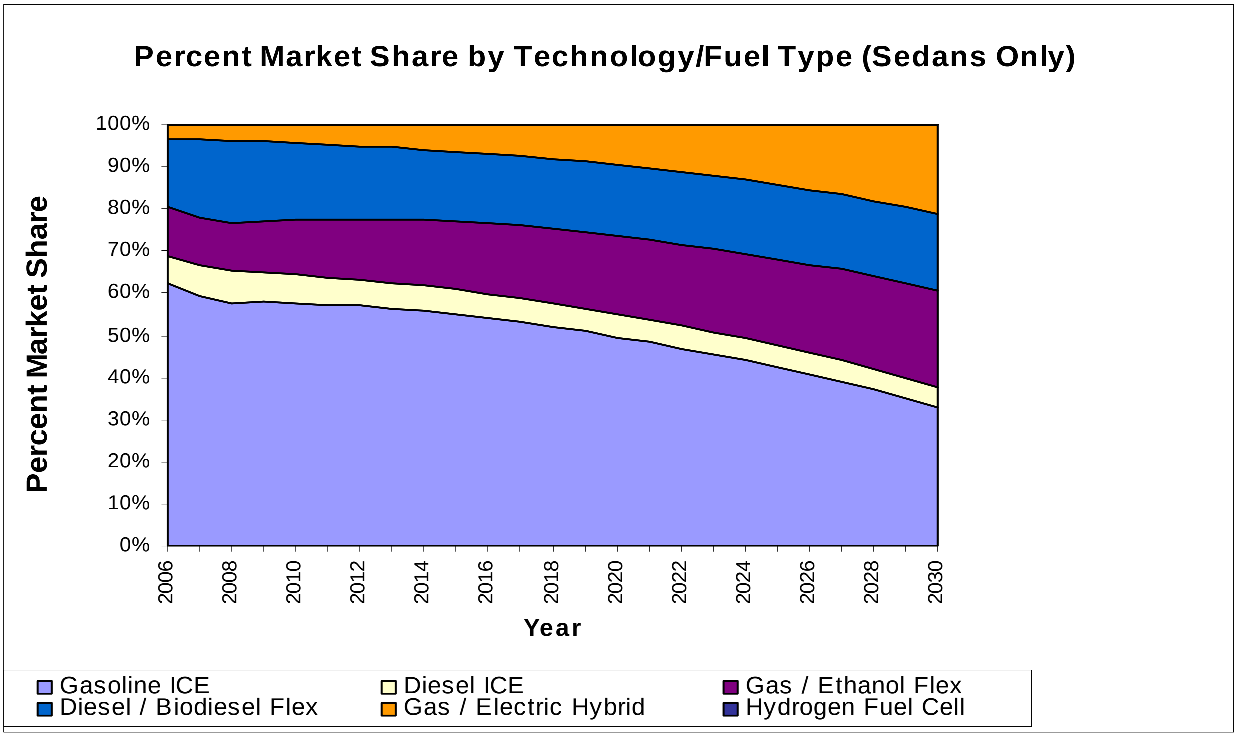
2.2. Scenario Results

The following subsections within Section 2 describe the resultant outputs from the CarCarbon model based on the inputs that have been described above. They represent the predictions of the model and the energy, emissions, and vehicle populations that accompany those predictions. Combined, they form the predicted results of continuing along a Business As Usual pathway in terms of our transportation and energy policies.

2.2.1. Number of Vehicles

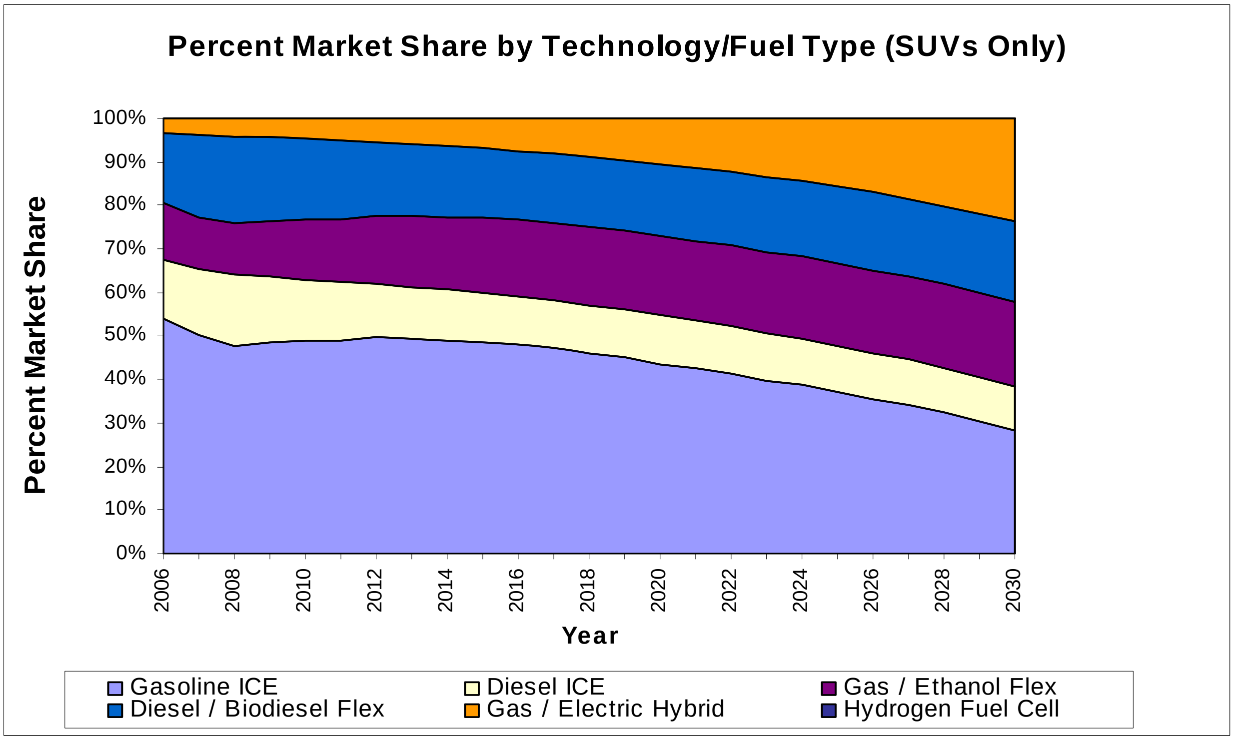
The results of the model for the number of vehicles may be displayed in two ways. The first is as the percentage market share for each year. This is the breakdown in percentages of the vehicles purchased according to technology type. This is shown in Figures 15 and 16. The second way of displaying the data is to show the total number of vehicles on the road of each technology type. So not only does this show the vehicles that were purchased in that year but also all the vehicles that were purchased in all previous years that have yet to be retired, broken down by technology type. This data is shown in Figures 17, 18, and 19.

Figure 16: Sedan Market Share



(N.B. Model Predicted No HFCV Penetration)

Figure 17: SUV Market Share



(N.B. Model Predicted No HFCV Penetration)

The market shares by technology shows a steady annual decrease in the market share of conventional gasoline ICE's. The remainder of the market share is made up by a smaller yet persistent level of diesel vehicles, equal and relatively constant levels of flex-fuel vehicles, and a steadily increasing percent market share of hybrid vehicles. The primary promoter of change in this scenario is the decreasing level of premiums for gasoline-hybrid electric vehicles. This leads to gasoline-electric hybrids accounting for a growing portion of the overall market share.

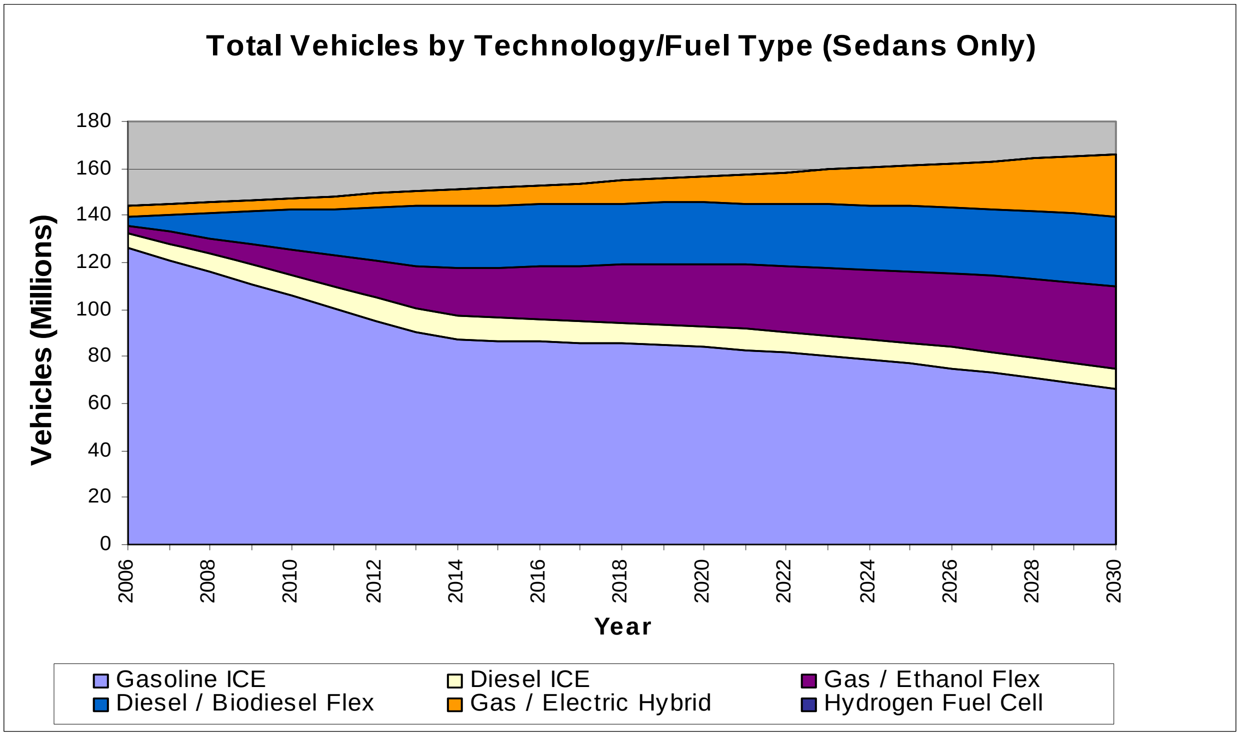
The other noticeable impact occurs in year 4 when the rate of decrease in market share for conventional gasoline ICE's slows in sedans and actually partially reverses in SUV's before continuing to decrease. This occurs due to the EIA 2007 Annual Energy Outlook projection of gas prices. During this period the EIA projects that gas prices will drop from their current peak and then level out. This slows the growth of all other alternatives.

Examining the graphs showing the total number of vehicles on the road rather than market shares (Figures 17, 18, and 19), it is obvious how there is a significant delay before market shifts translate into real change. While the absolute number of gasoline ICE's does decrease starting in year 1, the vehicle population does not begin to really resemble the projected market shares until year 10 (2015) by which time the majority of the vehicles from the initial vehicle pool will have been retired.

Also of interest is the difference between the absolute number of conventional gasoline ICE's in the sedan pool as compared to the SUV pool. While the sedan gasoline ICE's steadily decrease in the absolute number on the road, the SUV pool conventional gasoline ICE vehicles decrease for the first ten years before continuing to rise. This is due to the tremendous rate of growth which SUV's have historically been experiencing over the last two decades, even in the era of rising gas prices. This shows that not only must the types of vehicles being sold change, but so must also the rate of growth our vehicle pools are experiencing. Alternative fuel vehicles cannot create a change in our effects on the environment for as long as they merely account for a portion or even all of our vehicle growth, they must also supplant some of the absolute number of vehicles currently on the road.

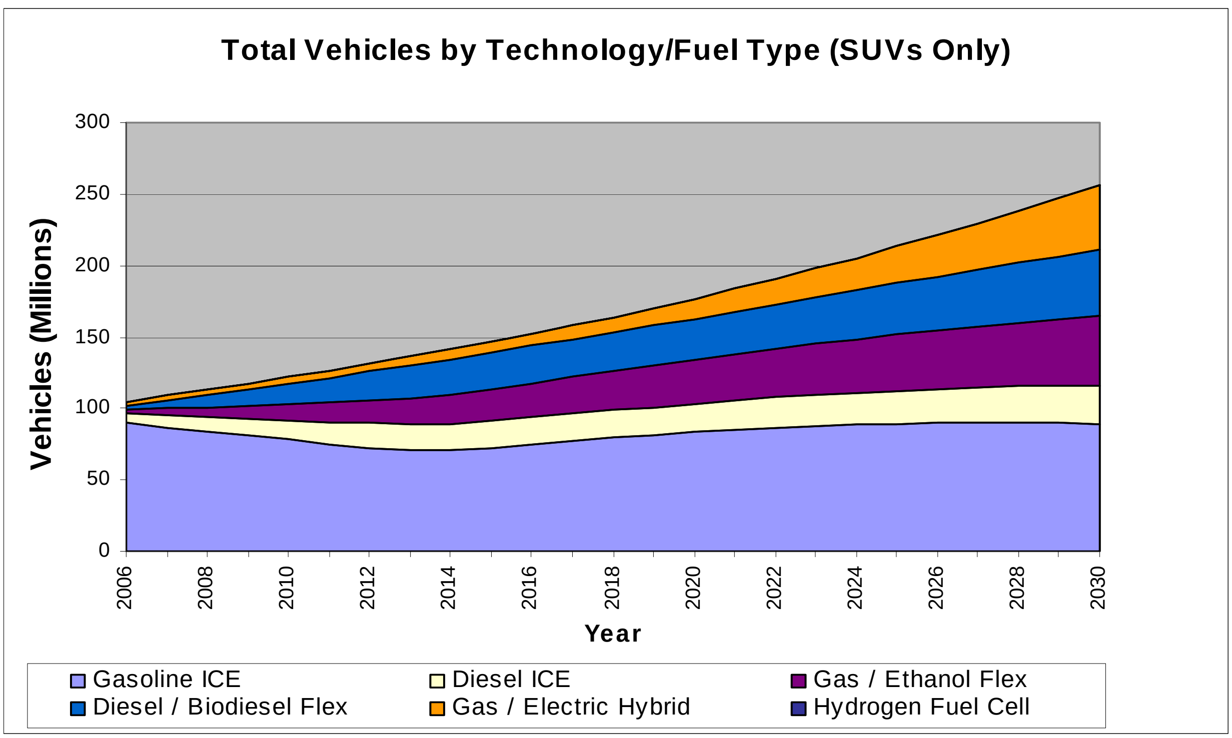
Hydrogen fails to enter into this scenario completely. This is due to several different factors, all of which combine to prevent their entry into the market. This primarily include: vehicle cost, fuel availability, and make and model availability. Costs are assumed to stay relatively high compared to the other technology types, despite lowering in their absolute price dramatically. Because of this, fuel availability and make and model availability are assumed to remain low. This indicates that it is only through an intense policy program and political intervention will hydrogen be able to enter into the market in any significant manner by 2030.

Figure 18: Sedans by Technology Type



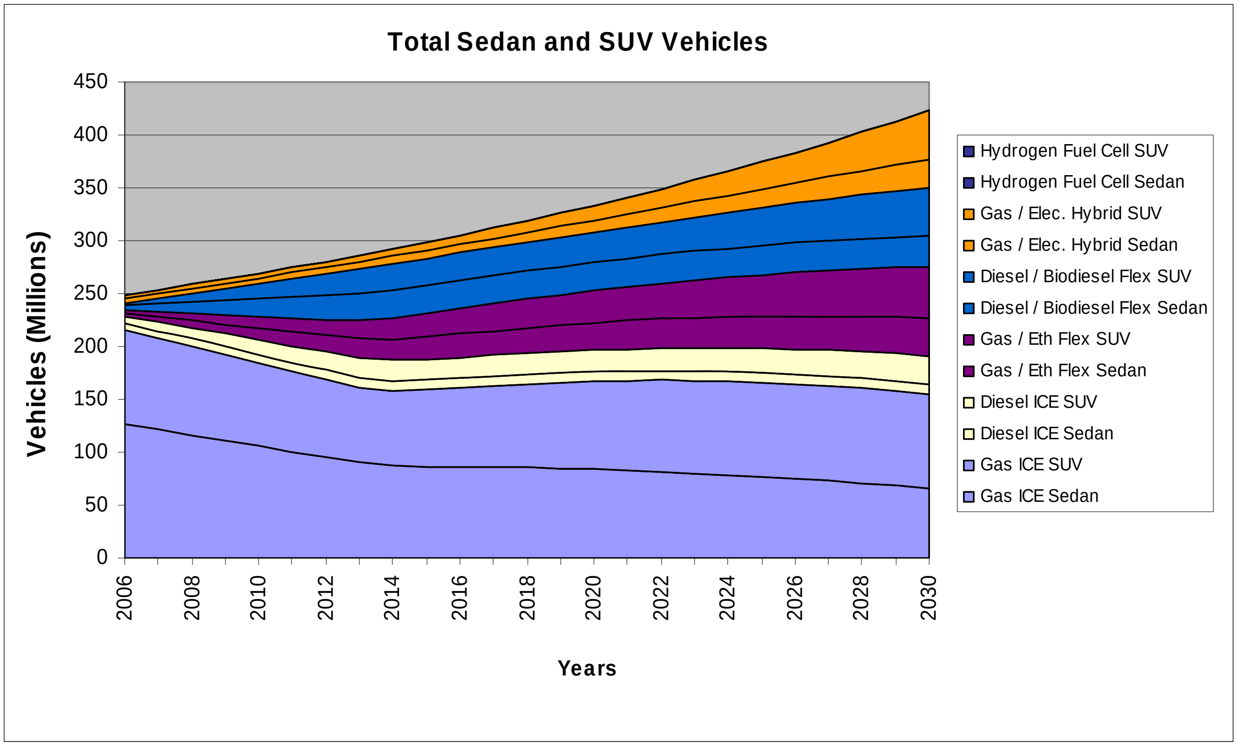
(N.B. Model Predicted No HFCV Penetration)

Figure 19: SUVs by Technology Type



(N.B. Model Predicted No HFCV Penetration)

Figure 20: All Vehicles by Technology Type



(N.B. Model Predicted No HFCV Penetration)

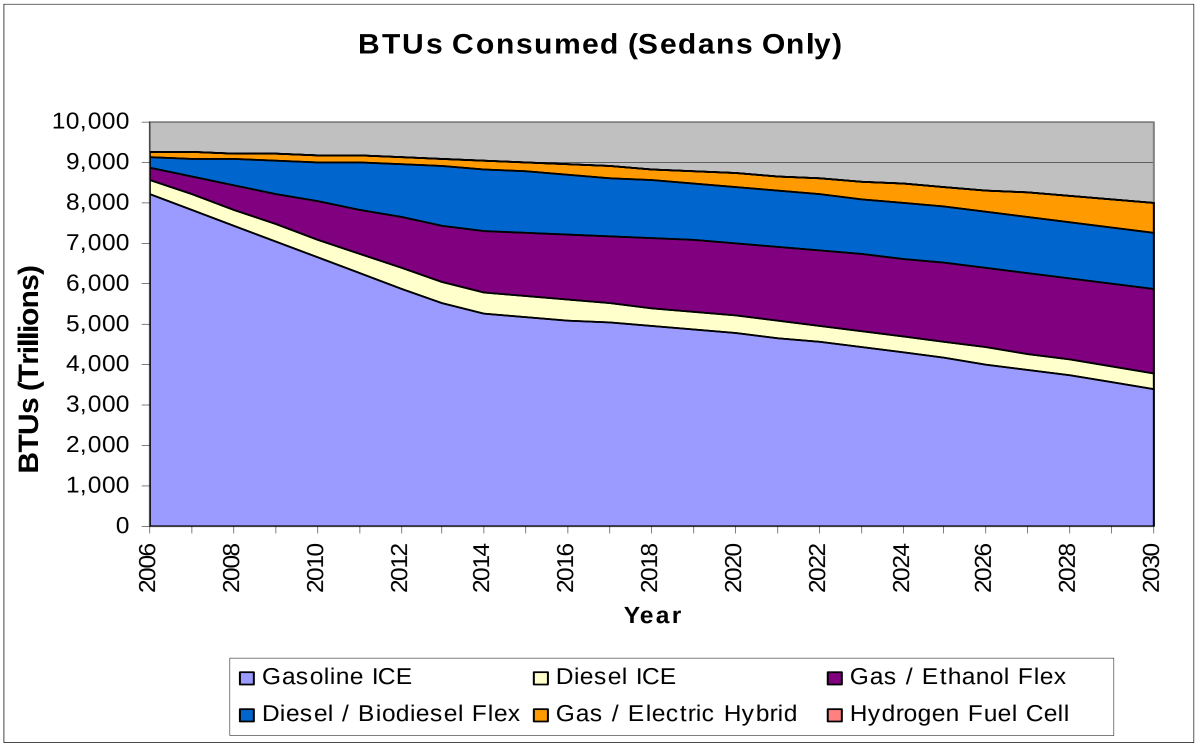
2.2.2. Energy Consumed by Vehicle Type

A second factor to consider is the total amounts of energy being consumed by the different technology types. All of the fuels consumed were converted into BTUs so that they could be equally compared. This shows some interesting facts. First is that the number of BTUs being consumed by the sedan pool actually decreases (Figure 20), despite the fact that the absolute number of sedans on the road increases. This is due entirely to the fact that the number of conventional gasoline sedans is decreasing and being replaced by alternatives and that any growth in this pool is made up entirely of alternatives which are more efficient.

Efficiencies also improve in the SUV pool, but due to the much higher rate of growth as compared to the Sedan pool it can be seen that the number of BTUs consumed increases along with the number of SUV's on the road. (Figure 21) While it can be inferred that the number of BTUs consumed by the SUV pool decreases compared to a scenario in which no alternatives are introduced, the level of BTUs consumed still increases compared to the initial value, although there is a slight decrease in BTUs of gasoline being consumed.

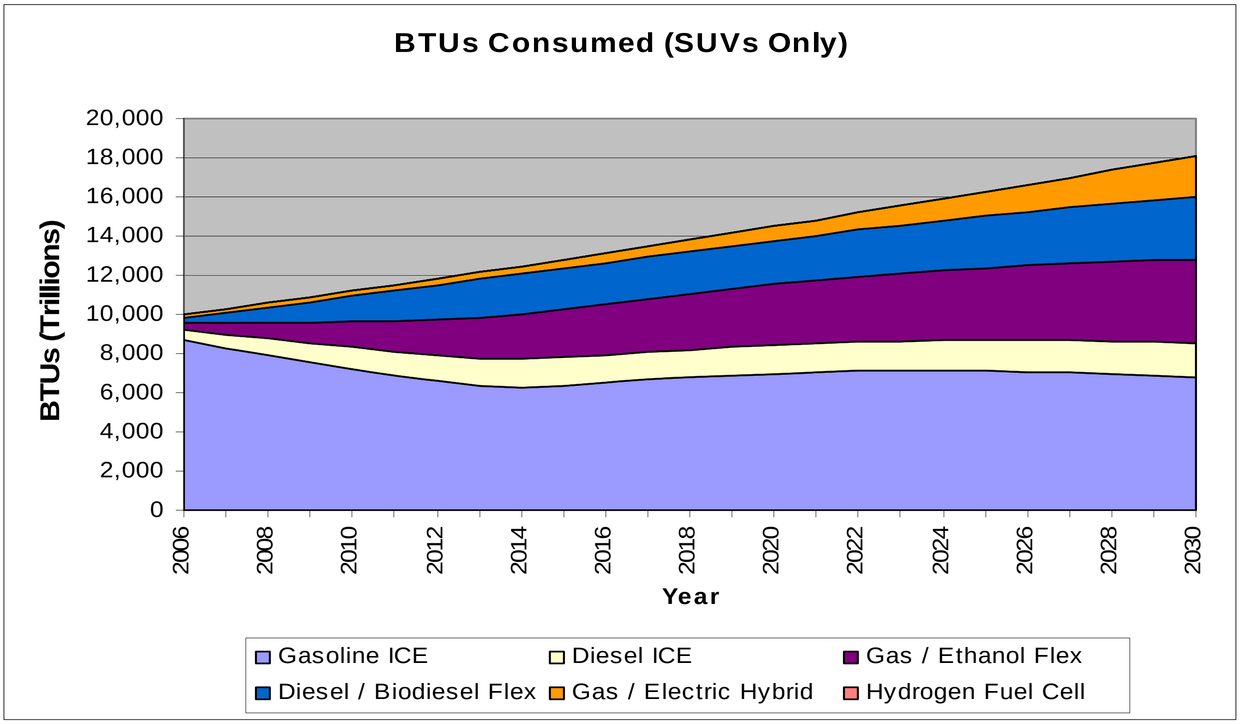
The combined graphs (Figure 22) show a steadily increasing level of BTUs consumption, although there is a significant overall decrease in the level of BTUs of gasoline consumed. This represents a significant improvement over the U.S.A.'s current situation in terms of energy imports and energy security. It shows a scenario in which fossil fuel imports are decreasing as domestic sources of energy increase.

Figure 21: Sedan Energy Consumption



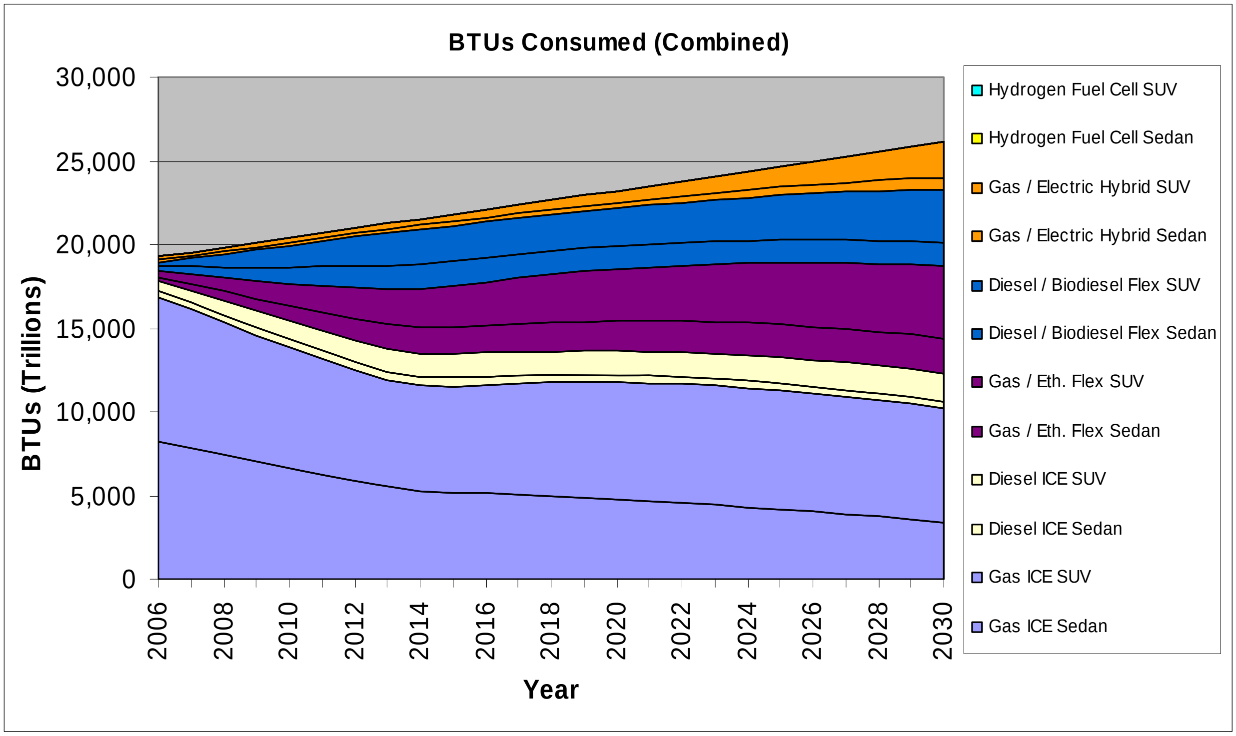
(N.B. Model Predicted No HFCV Penetration)

Figure 22: SUV Energy Consumption



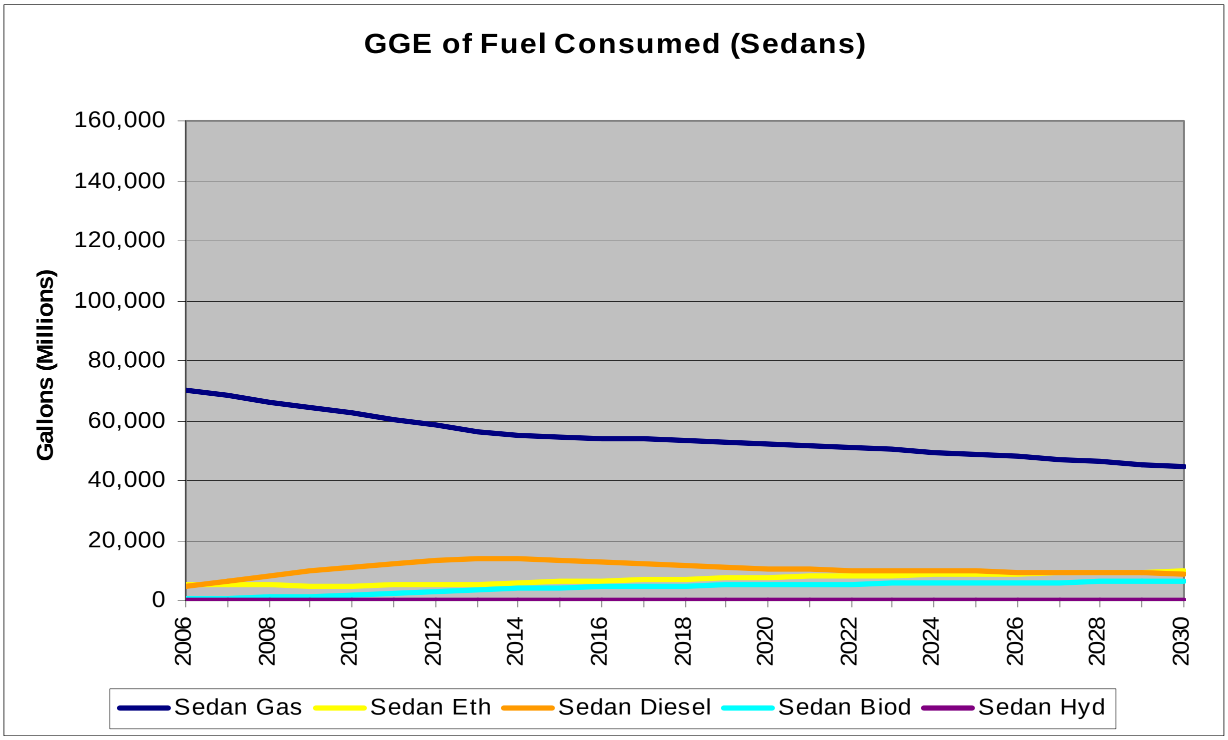
(N.B. Model Predicted No HFCV Penetration)

Figure 23: All Vehicle Energy Consumption



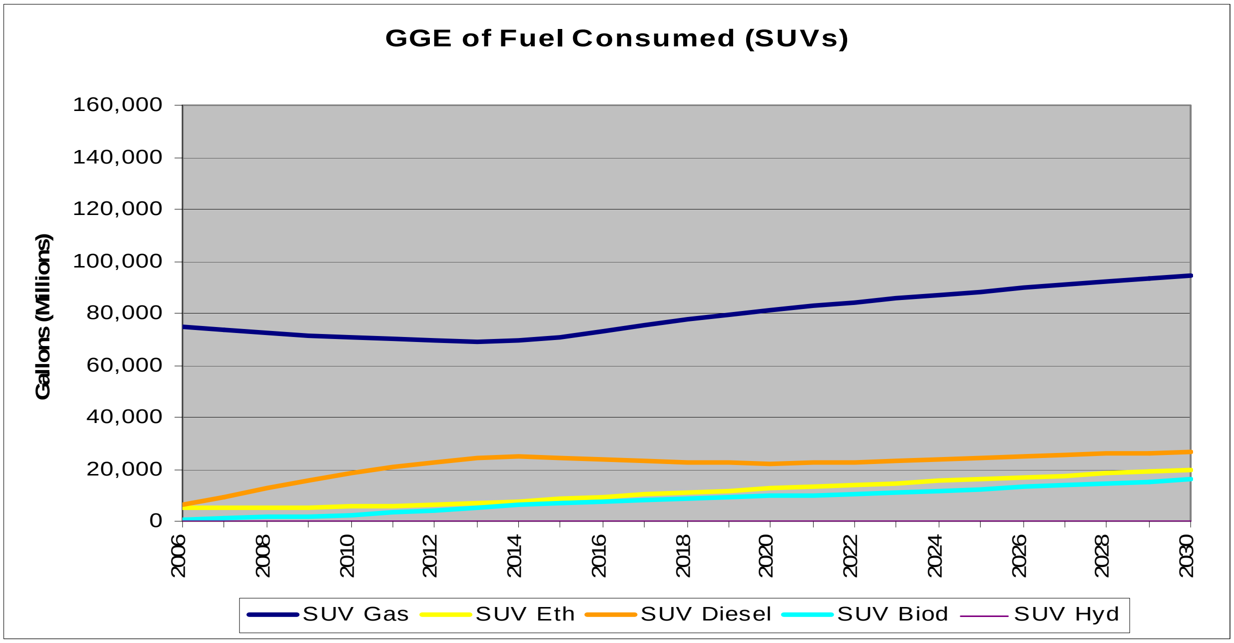
(N.B. Model Predicted No HFCV Penetration)

Figure 24: Gallons of Gasoline Equivalent Consumed by Vehicle Technology Per Sedan



(N.B. Model Predicted No HFCV Penetration)

Figure 25: Gallons of Gasoline Equivalent Consumed by Vehicle Technology Per SUV



(N.B. Model Predicted No HFCV Penetration)

2.2.3. Energy Consumed by Fuel Type

The energy consumption of the baseline scenario may be viewed in an additional manner by examining the raw amounts of fuel being consumed in each year of the scenario. This is of particular interest when considering energy security and sustainability. This data can vary significantly compared to the BTU's consumed by the different technology types due to fuel mixing. So while the previous section displayed energy consumption in terms of the vehicles running, this section displays the total amounts of each type of fuel being consumed across all technology types, thus summing the gasoline consumed in Gasoline ICEs, Gas / Electric Hybrids, and Gas / Ethanol Flex vehicles, and so on for all the different fuels.

As can be seen in Figure 24, there is a dramatic decline in the gasoline consumed by sedans, almost 40%. At the same time the utilization of other alternatives remains relatively low, but it is through their combined substitution and through fuel economy improvements that the usage of gasoline is able to be so reduced. Figure 25 shows that, even with greater levels of usage of alternative fuels, gasoline consumption rises at an alarming rate, primarily due to the high growth rate of the SUV population. These values combine in Figure 26, which shows the total consumption of all fuels. As can be see, while the consumption of gasoline in the final year of the projection is lower than that of the first year, it is on the rise and is on track to continue rising beyond current levels. The combined fuel consumption is largely dominated by the SUV fuel consumption, especially in later years of the scenario.

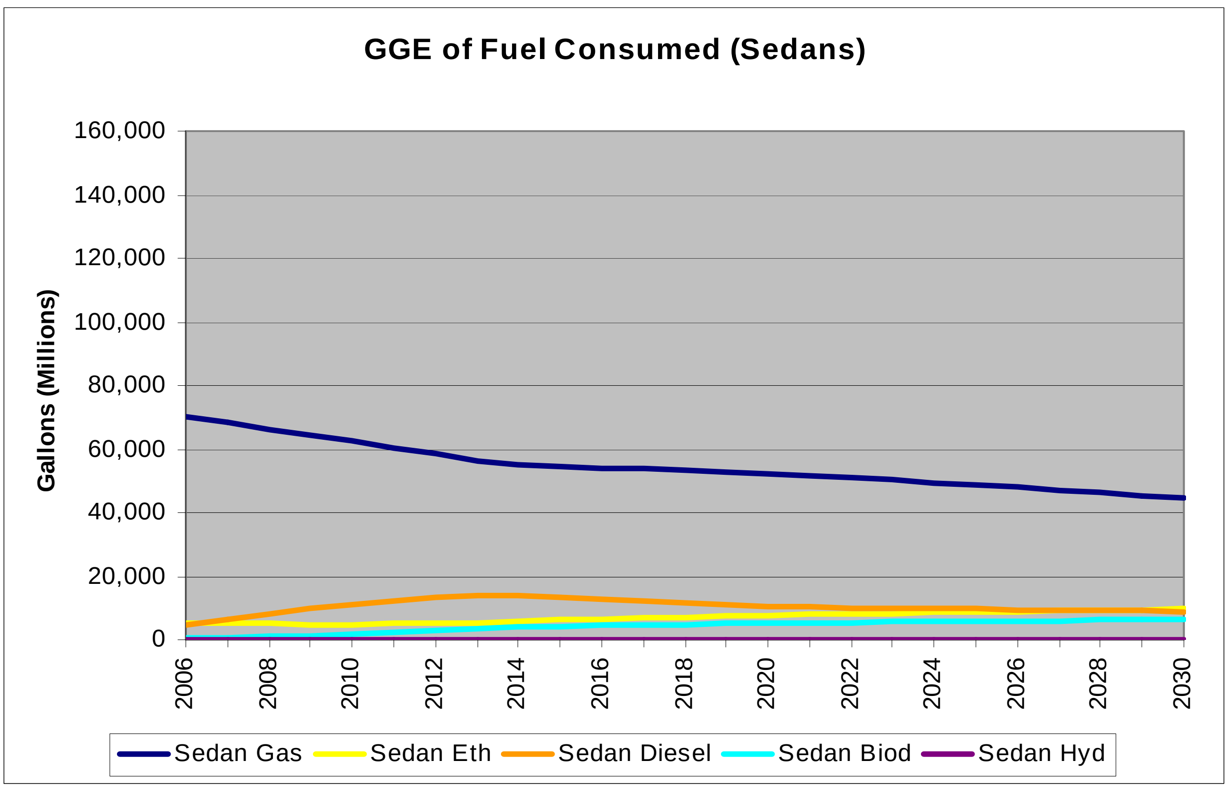
Below, Figure 23 shows the conversion factors for all relevant fuels into Gallons of Gasoline Equivalent (GGE). This figure shows how many gallons of gasoline are equivalent to a single gallon of another fuel. Numbers that are greater than 1 show that the other fuel has a greater energy content per gallon than does gasoline, while numbers that are lower than 1 show that the fuel has a lower energy per gallon than gasoline does. The units of fuel are converted into GGE in order to display the energy values on an equal ground in terms of total energy consumed.

Figure 26: GGE Conversion Table

Fuel (1 Gallon)	Gallons of Gasoline Equivalent (GGE)
Gasoline	1.000
Diesel	1.135
Ethanol	0.658
Biodiesel	1.037
Hydrogen	1.008

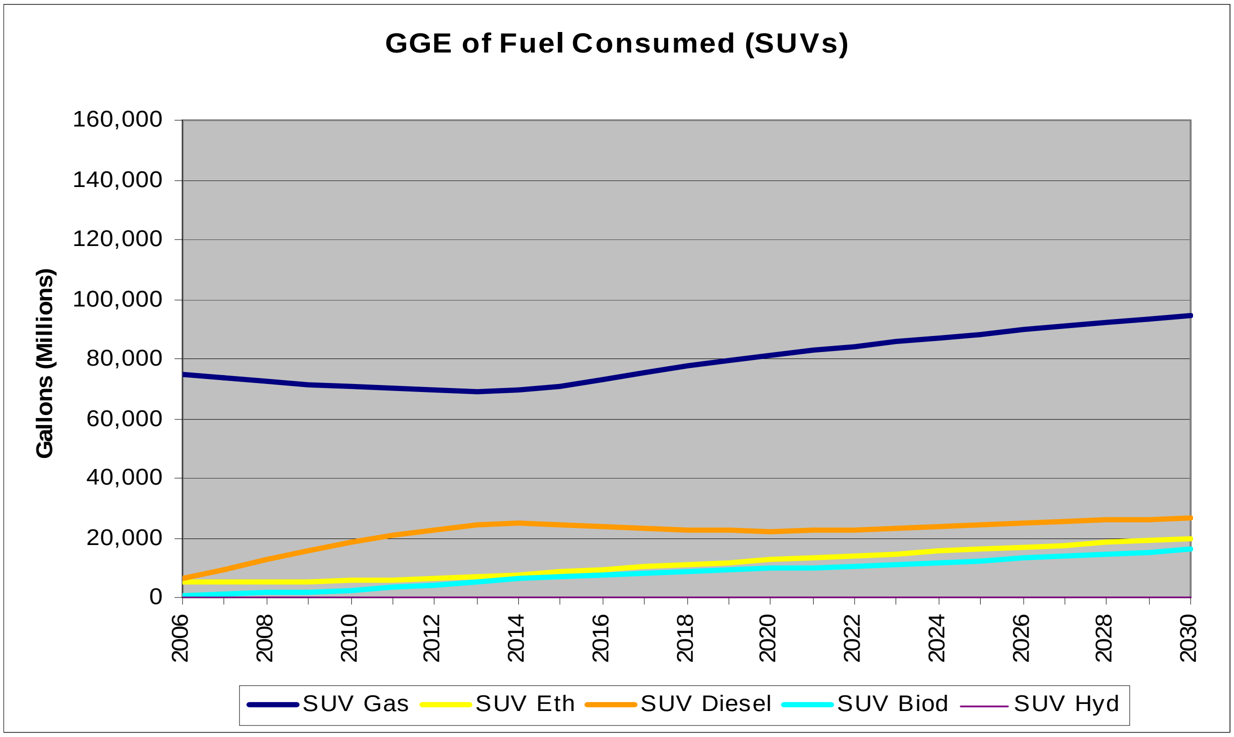
Figure 27 and Figure 28 show the same data as Figure 24 and 25 only they are normalized so that they show the per vehicle values for GGE consumed and the data is also divided by the technology type rather than the fuel type. Thus this data shows the average energy being consumed on an annual basis by a Gasoline ICE, Diesel ICE, Ethanol Flex Fuel, Biodiesel Flex Fuel and Hybrid Gasoline-Electric vehicles. This data is interesting because it shows the decreasing per vehicle fuel consumption while the aggregated data shows overall increases in fuel consumed. This indicates that rising emissions are due, not by changing technology, but rather by the overall increase in Total Vehicle Miles Traveled due to rising vehicle populations.

Figure 27: Sedan Fuel Consumption



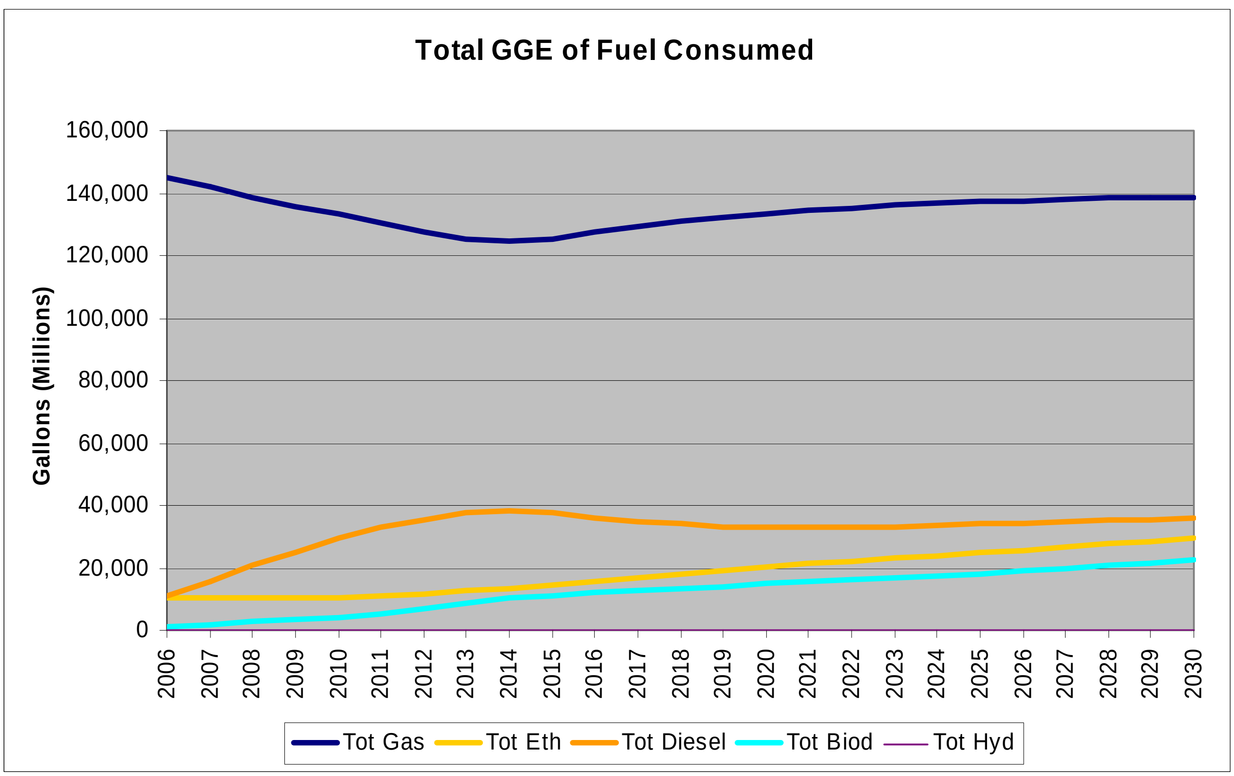
(N.B. Model Predicted No HFCV Penetration)

Figure 28: SUVs Fuel Consumption



(N.B. Model Predicted No HFCV Penetration)

Figure 29: All Vehicle Fuel Consumption



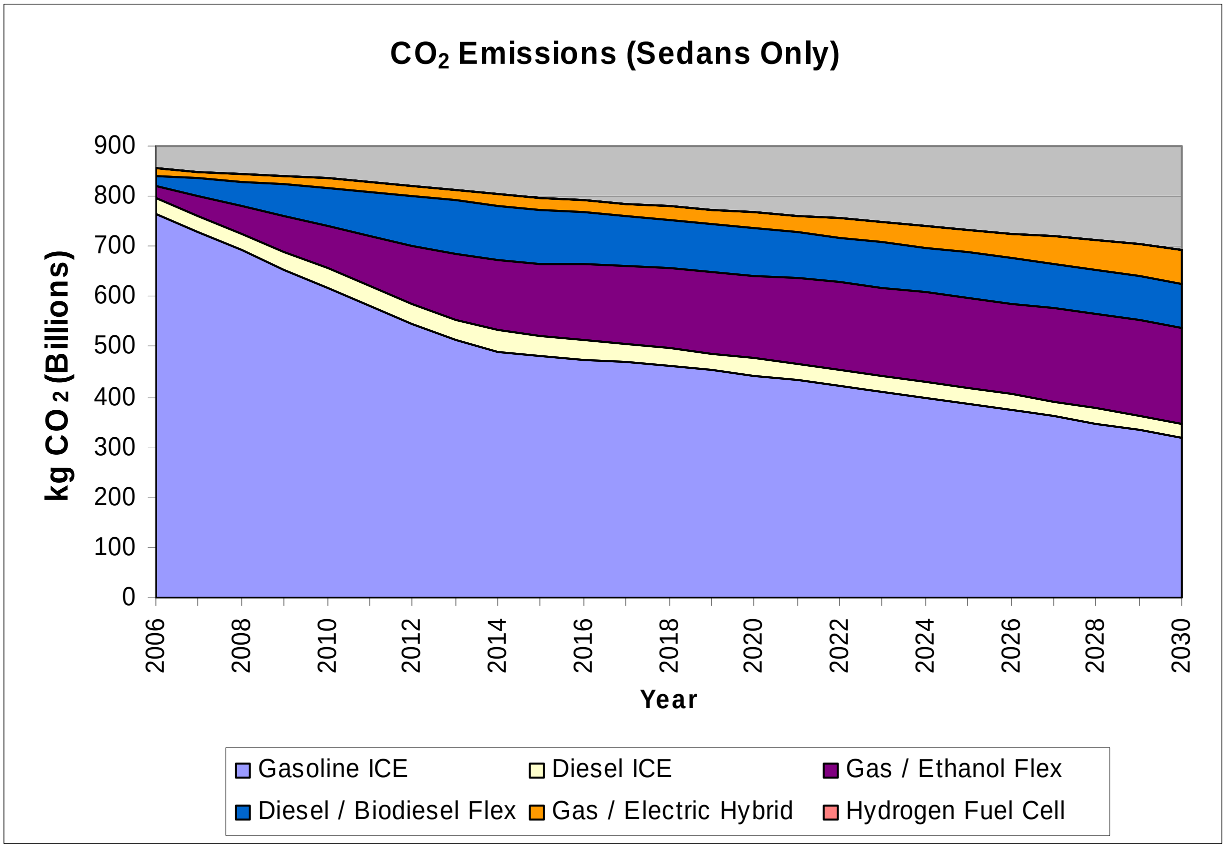
(N.B. Model Predicted No HFCV Penetration)

2.2.4. CO_2 Emissions

Despite significant introductions of gasoline-electric hybrid, biodiesel-diesel flex, and ethanol-gasoline flex vehicles, the baseline scenario shows continued increases in carbon dioxide emissions. The pattern followed is very similar to the one seen in the consumption of BTU's, which is not surprising. The carbon dioxide emissions from sedans show a slow and steady decrease while the carbon dioxide emissions from the SUVs show significant increase. These combine to show moderate increases in carbon dioxide from the overall pool of vehicles and continued unsustainability and danger from climate change.

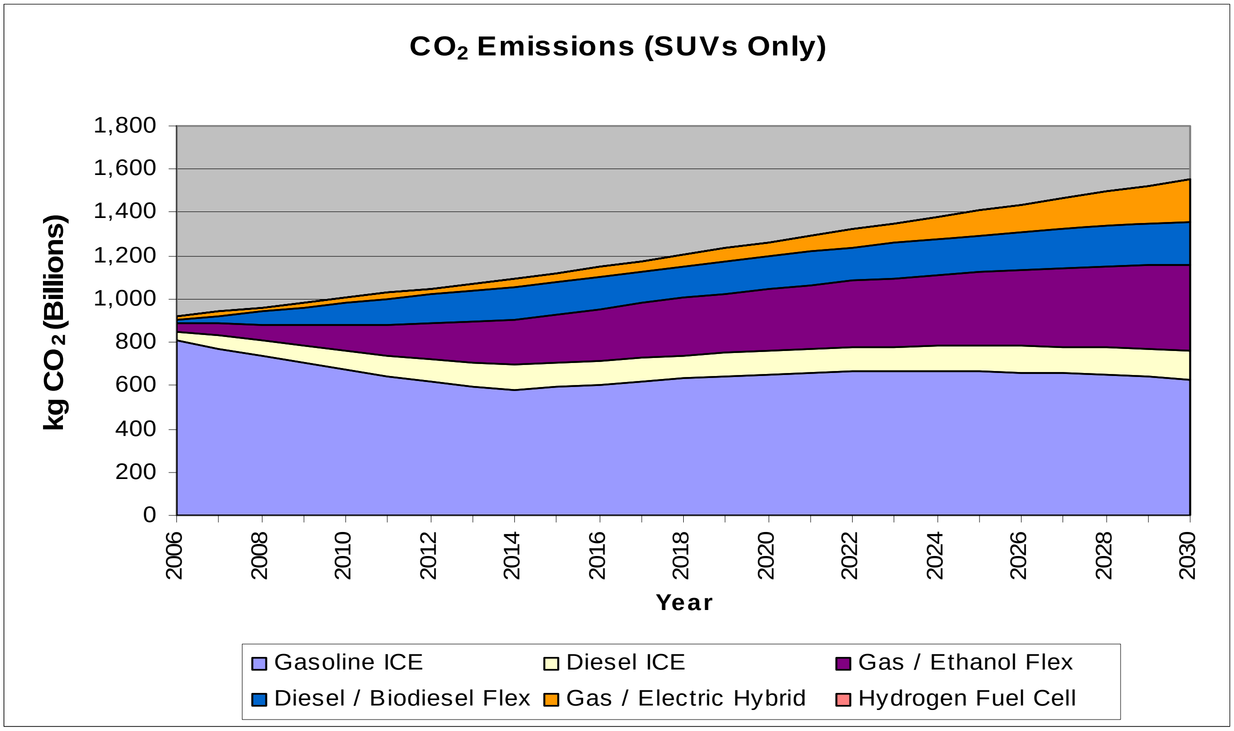
The majority of the emissions throughout the scenario come from the use of petroleum, either through the used of diesel fuel or gasoline. All five of the technologies that make up the vast majority of the overall emissions use either gasoline or diesel. Even those technologies that could use entirely biofuels (flex ethanol and flex biodiesel) are using at least 50% petrofuel at the end of the study. Despite a drop in emissions from sedans, the overall growth rate of the SUV pool overcomes any technological benefits that are gained in the mild transition to alternative technologies. Most of these benefits are realized in the first ten years of the projection as the vehicle population transitions over to match the vehicle market shares predicted. After this occurs then the growth rate of the vehicle pool overcomes the modest efficiency and fuel choice improvements that occur, resulting in continued growth of emissions.

Figure 30: Sedan CO2 Emissions



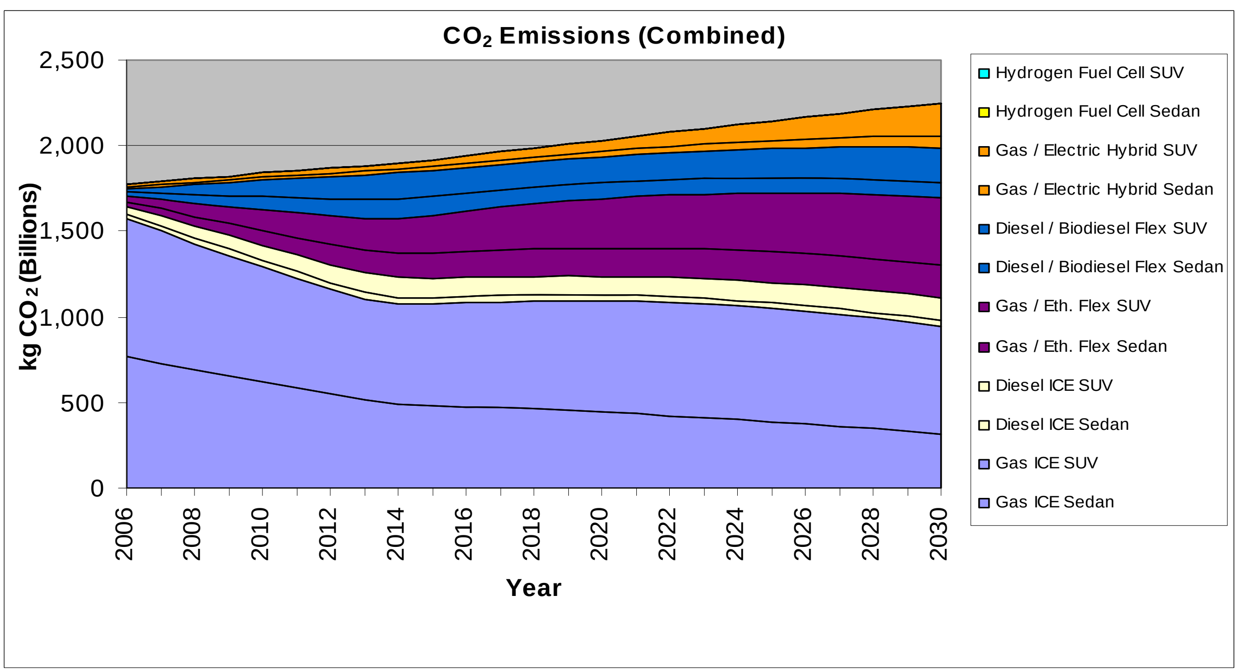
(N.B. Model Predicted No HFCV Penetration)

Figure 31: SUV CO2 Emissions



(N.B. Model Predicted No HFCV Penetration)

Figure 32: All Vehicle CO2 Emissions (N.B. Model Predicted No HFCV Penetration)



(N.B. Model Predicted No HFCV Penetration)

2.2.5. Normalized Emissions

While the preceding graphs show the dilemma of growing carbon emissions in the baseline scenario, it is important to illustrate that the growth in emissions is primarily due to the fact that the number of vehicles on the road is increasing, according to historical trends, and that on a per vehicle basis, emissions are actually decreasing annually. The following graphs (Figures 32 and 33) show carbon dioxide emissions on a per vehicle basis. They also include an "Average" line, which shows the average level of emissions being emitted amongst the technologies. This decrease is due to two factors which have already been discussed, greater fuel mixing with lower carbon fuels and the gradual increase in efficiency experienced by all technologies.

These two figures illustrate the fact that technology improvements are occurring, and that because of them any single car on the road in the future will have decreased emissions compared to its counterpart that is on the road today. Despite this and despite the fact that the baseline scenario shows a trend of switching to the lower emission technology types, the aggregate level of carbon dioxide emissions continues to grow. This clearly shows that real changes in the U.S. emissions future cannot occur through the intervention of technology alone.

Figure 33: CO_2 emissions per year per sedan

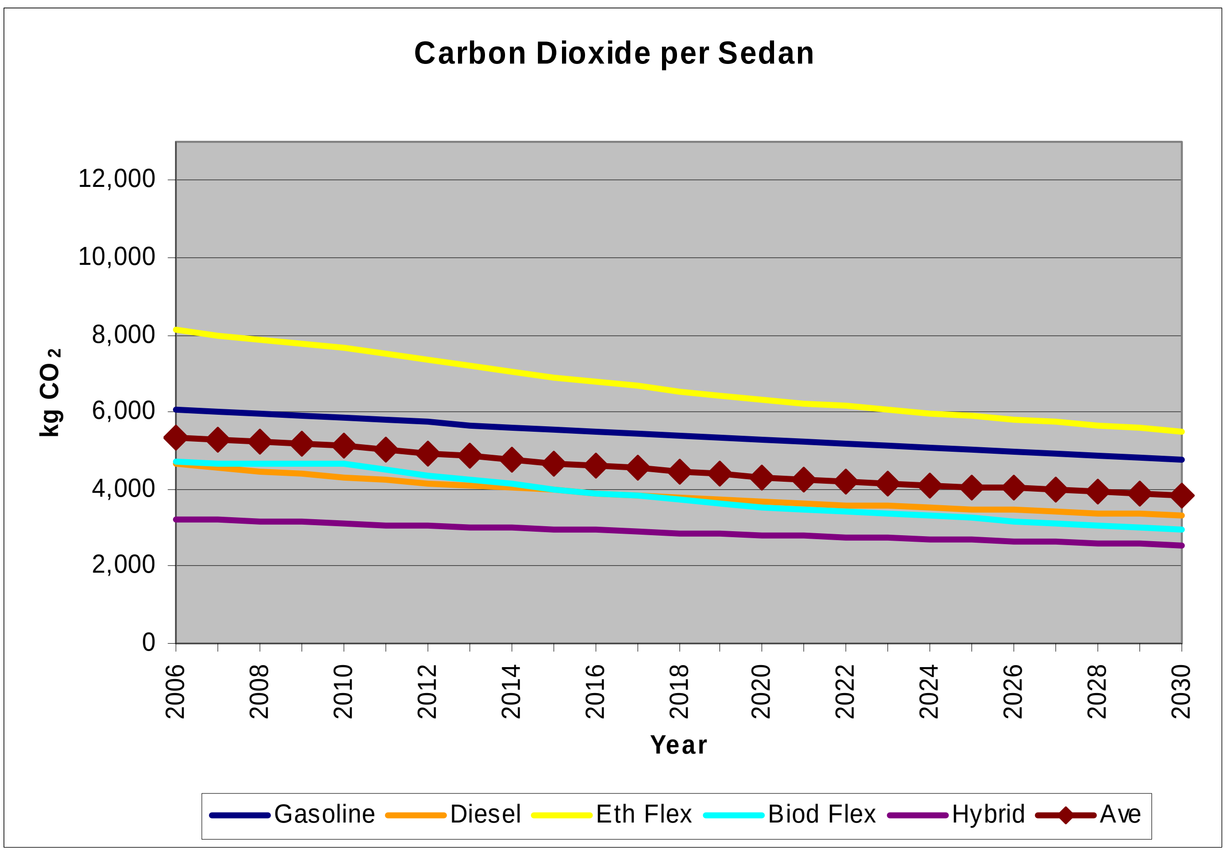
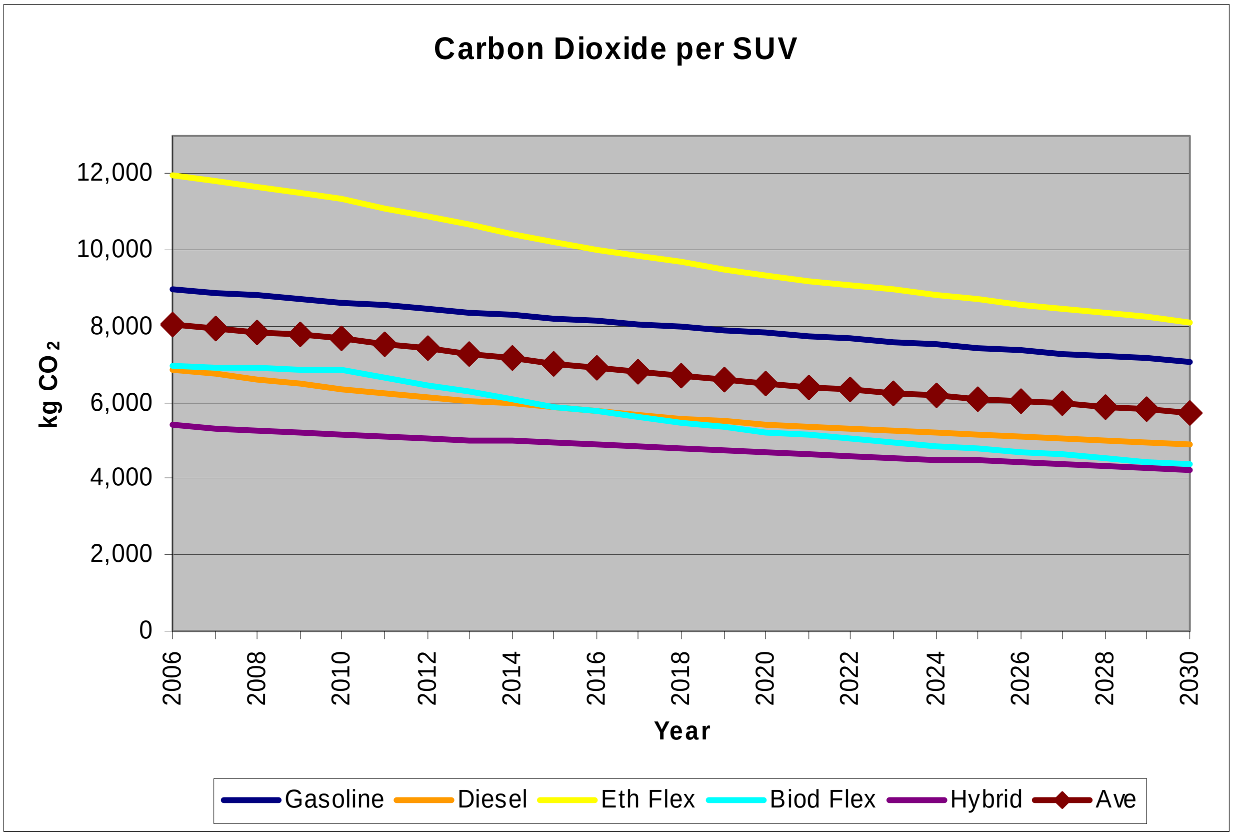


Figure 34: CO_2 emissions per year per SUV



Despite increases in nearly every factor that would lead to decreased overall emissions levels, the growth rate over the SUV vehicle pool easily overwhelms these combined improvements leading to a state of rising annual emissions. This shows that technological improvements alone, as they are proceeding currently, cannot lead to a future of decreasing carbon emissions. In order to obtain that outcome their must be even greater technological innovation, policy intervention, or a drastic change in societal consumptive patterns.

3. Alternative Scenarios

As the baseline scenario is only a benchmark, additional scenarios will be created that will gauge the effects of policies, social trends, and technology improvements as compared to the baseline. Due to the complexity of the model there are a large number of potential alternative scenarios that could be enacted. However, there are several that seem important to explore that the model is particularly suited to develop. These scenarios will allow the policy maker to gauge the environmental and economic impact of policies and will be useful in helping to focus the efforts and energies towards those polices that are the most effective.

3.1. Taxes

Taxation is an important policy tool that allows the politician to enter the economic sphere. In the field of transportation there are several ways in which taxes may be applied in order to shape the future. Taxes may be generally applied to two areas: 1) the vehicles and 2) the fuels. Thus two alternative scenarios would be one in which a tax is applied to conventional fossil fuel burning vehicles (Gasoline ICE and Diesel CE) and a second in which a tax is applied to the petroleum fuels, gasoline and diesel. The model is well suited to both of these options, particularly taxing the vehicles. Added to this section would be a scenario highlighting the concerns illustrated in section 2.a.i. regarding the relatively stable projection of U.S. gasoline prices in the future. A scenario could be conducted showing the effects of other gasoline price projections including the AER high gasoline projection as well as those from other sources.

The one concern comes with a scenario taxing fuels. While the model would accurately gauge the effect that the higher fuel price would have on the purchase of vehicles that rely on that fuel, it would not be able to determine the effect that the higher gasoline price would have on miles driven per year, thus overall carbon dioxide emissions. While the model could not determine this automatically, historical trends could be examined in order to manual change the miles driven per year to vary with the fuel price, thus giving an accurate carbon dioxide emissions level for all years.

3.2. Incentives and Subsidies

This category can be seen as the opposite of the previous section. Whereas the taxes would raise the cost of those technological options that would be undesirable, this section would explore the option of artificially decreasing the cost of those options that are viewed as beneficial. Incentives could be applied to any combination of vehicles by artificially lowering their purchase price by a set amount as compared to the baseline while subsidies could be applied to fuels by lowering their costs by a set amount or simply fixing them at a set amount. These policies could be applied across the entire projection or could be applied and phased out in any desired set of years.

3.3. Social Changes

This category is less concrete and more goal-oriented than the others and would not be aimed at judging the effects of any single policy, but would rather set out to determine the environmental and climate change effects of broad social movements. Such scenarios could include reducing the growth rate of new vehicle purchases or decreasing annual miles driven. These scenarios could mimic social changes such as increased reliance on public transportation, changes in population distributions, or slowed population growth.

3.4. Fuel Mixing

This category of scenarios would explore the role of fuel mixing in the emissions future of the U.S. Currently there is a certain level of mandated fuel mixing with ethanol and gasoline in the U.S. and this is a policy that could be expanded or added to in the future. This change could come through mandate or through economic forces, but it could have a dramatic impact on the energy and emissions profile of the U.S. as well as highlight important concerns over increased reliance on biofuels, such as the food vs. fuel debate.

3.5. Technological Advance

A final set of scenarios that could be examined would look at those technological improvements that could be made to the transportation technology available. This would primarily focus on the role of fuel economy in determining emissions and would examine fuel economy increase mandates such as is being considered by the U.S. legislature at this time. Currently fuel economy mandates have not changed in decades and there is significant room for technological innovation and improvement in conventional gasoline ICEs.

3.6. Sensitivity Analysis

In addition to the variety of scenarios that could be run, it would also be advantageous to conduct a sensitivity analysis of the model. The purpose behind this would be two-fold. Firstly, it will allow us to focus study on those areas of the model that are shown to be extremely sensitive and to consider policies that would affect those areas. Secondly, it would demonstrate what areas of the model are unlikely to cause any significant change in the projected emissions profile. Through a sensitivity analysis, we will be able to effectively determine which inputs will be able to achieve the desired results with the minimum amount of change and effort versus those inputs that have relatively little impact on emissions futures. It is our intention to proceed with this step next in order to better inform any further scenarios we develop. We will conduct this analysis by making proportional changes to each input and gauging the overall effect. Any future scenarios will focus on those inputs with the greatest impact.

4. References

Alternative Fuels Data Center Website. US Department of Energy: Energy and Efficiency and Renewable Energy. Available online at: http://www.eere.energy.gov/afdc/altfuel/biodiesel.html. Last accessed: September 22, 2006.

Argonne National Laboratory. 2007. *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model*. Available online at: http://www.transportation.anl.gov/ software/GREET/. Last accessed: August 22, 2007.

Davis, S.C. and S.W. Diegel May 2007. *Transportation Energy Data Book: Edition 26*, ORNL-6978. Available online at: http://cta.ornl.gov/data/Index.shtml. Last accessed: August 22, 2007.

EERE (U.S. DOE: Energy, Efficiency, and Renewable Energy). Hydrogen, Fuel Cells, Infrastructure and Technologies Program Website. Available online at: http://www.eere.energy.gov/hydrogenandfuelcells/education/. Last accessed: August 11, 2005.

EERE (U.S. DOE: Energy, Efficiency, and Renewable Energy). 2007. The 2007 Fuel Economy Guide. Available online at: http://www.fueleconomy.gov. Last accessed: August 22, 2007.

Energy Information Administration. 2007. Annual Energy Outlook 2007. Available Online at: http://www.eia.doe.gov/oiaf/aeo/index.html. Last Accessed: August 22, 2007.

Energy Information Administration. 2006. Annual Energy Outlook 2006. Available online at: http://tonto.eia.doe.gov/bookshelf/SearchResults.asp?title=Annual+Energy+Review. Last accessed: August 22, 2007.

Energy Information Administration. 2005. Annual Energy Outlook 2005. Available online at: http://tonto.eia.doe.gov/bookshelf/SearchResults.asp?title=Annual+Energy+Review. Last accessed: August 22, 2007.

Energy Information Administration. 2004. Annual Energy Outlook 2004. Available online at: http://tonto.eia.doe.gov/bookshelf/SearchResults.asp?title=Annual+Energy+Review. Last accessed: August 22, 2007.

Greene, D.L. 2001. *TAFV Alternative Fuels and Vehicles Choice Model Documentation*. ORNL/TM-2001/134, Oak Ridge National Laboratory, Oak Ridge, Tennessee, July. Available online at: http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2001_134.pdf. Last accessed: August 21, 2007.

The National Academies (NAS). 2004. National Research Council and National Academy of Engineering. “The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.” Washington, D.C.: National Academies Press.

Waegel, Alex; Byrne, John; Tobin, Dan; and Haney, Bryan. 2006a."Hydrogen Highways: Lessons on the Energy Technology-Policy Interface." *Bulletin of Science, Technology and Society*, Vol. 26, No. 4. Pp. 288-298.

Waegel, Alex; Byrne, John; Alleng, Gerard; Tobin, Dan; Haney, Bryan; Karki, Jyoti; and Suarez, Jorge 2006b. *Pathways to a U.S. Hydrogen Economy: Competitors and Diffusion Scenarios*. A Report to the BP Foundation

Waegel, Alex; Byrne, John; Glover, Leigh; Hughes, Kristen; Tobin, Dan; Jefferis, Brian; Shishido, Karen; Wang, Huei; and O'Grady, Vincent. 2005. *Pathways to a U.S. Hydrogen Economy: Technical and Policy Challenges*. A Report to the BP Foundation.