Assessing Deployment Strategies for Ethanol and Flex Fuel Vehicles in the U.S. Light-Duty Vehicle Fleet

by

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B.S. Biomedical Engineering
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Submitted to the Engineering Systems Division
in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

Within the next 3-7 years the US light duty fleet and fuel supply will encounter what is commonly referred to as the "blend wall". This phenomenon describes the situation when more ethanol production has been mandated than can be blended legally in the existing gasoline fuel supply. While there are currently measures under review to extend fuel certification to from 10% to 15% ethanol blends, this will not be enough to reach the existing Renewable Fuel Standard targets that grow over the next decade to 36 billion gallons of biofuel.

This research focuses on a quantitative assessment of how to effectively use policies to match the deployment of ethanol with capable vehicles to use ethanol, and the infrastructure to the fuel. A model of the light duty vehicle fleet has been used find the number of vehicles required to meet ethanol fuel usage targets.

The key variables explored in this work are (i) the volumetric target for total biofuels (ii) the legal blend limit of ethanol in gasoline, (iii) fleet vehicle sales penetration and (iv) a metric for the relative utilization of ethanol and gasoline for flex fuel vehicles. Each of these factors can be varied independently to understand the existing relationship between each in the context of the US light-duty vehicle fleet.

Ultimately, coordinated polices focusing on each of these key factors can ease the transformation of the automotive fuel industry away from petroleum dominated supplies.

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1. Introduction & Problem Statement

The goal of this chapter is to outline some of the complexity involved in the challenge of deploying alternative liquid fuels. Ultimately there are many interwoven issues, but these challenges can be made tractable through special attention to the critical variables.

"...It's more like a rooster, chicken & egg problem" – Don Mackenzie

1.1. *Motivating Factors*

Searching for alternatives

Personal transportation in the United States is largely centered on the automobile. Cars and light trucks account for more than 70% of all energy used in highway and non-highway transportation energy. Approximately 240 million vehicles constitute the light-duty vehicle (LDV) fleet. Motor gasoline consumption is roughly 9 million barrels per day, which is 40% of the world supply. In 2007 the U.S. transportation petroleum use was 185% of U.S. production (Davis 2008). These statistics help to highlight the scale of consumption as well as the central reliance on petroleum resources.

The main drivers behind policies for alternative biofuels include energy supply security, support for domestic industries, reduction of oil imports and the potential for reduction in greenhouse gas emissions (Sims, et al. 2008). Additional support comes from recent conflicts with oil producing countries, as well as price fluctuations. All of these factors motivate the exploration of alternatives to petroleum.

Ethanol has emerged as a near term fuel which has achieved scale to greater than any other alternative fuels, including fossil based alternatives like liquefied petroleum gas (LPG) and compressed natural gas (CNG). Ethanol is by far the largest non-petroleum alternative fuel (Davis 2008). While the environmental credentials are still a topic of debate, the use of ethanol is effective at simply displacing petroleum. The costs of deploying ethanol however are not trivial. The strategy of using ethanol as a fuel should be seen in the context of the multidimensional motivations that support its development. Commonly biofuels are treated as simply a greenhouse gas reduction strategy in policy. However the reasons more commonly used to support biofuels have to do with the domestic economic development and energy security arguments.

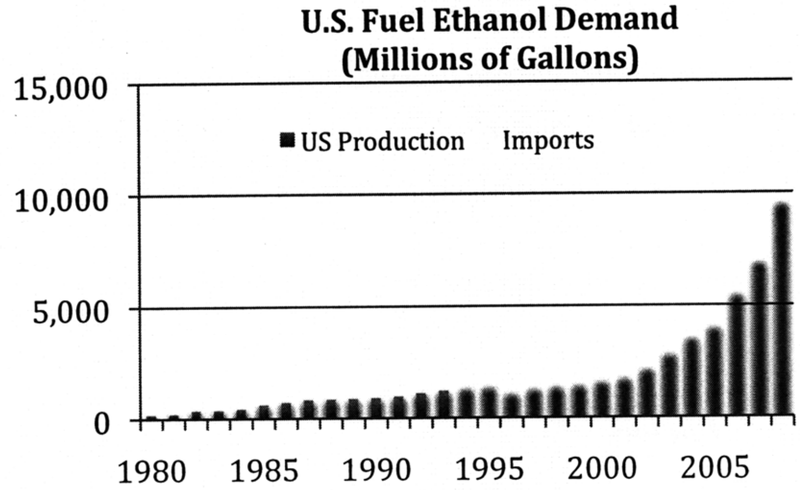

Figure 1: Historic Ethanol Production in the United States and imports (Renewable Fuels Association 2008)

Course Correction

Transforming the vehicle and fuel fleet in the US is not a trivial matter. In the process of doing so, refueling infrastructure, vehicles and other existing systems must be altered. Biofuels and in particular ethanol offer hope as the largest non-petroleum based alternative fuel in the automotive market (US DOE: Energy Efficiency and Renewable Energy 2009). This type of success cannot be ignored.

However, there is a range of problems that emerge from the introduction of a new fuel system. The goal of this work is not simply to list the challenges, but to systematically explore the linked aspects of vehicle and fuel deployment in order to guide technology and policy decisions over the next two decades.

The current biofuel mandates for the next decade include biofuel than can be used legally in gasoline blends if ethanol is used to meet the requirements. Section 211 of the Clean Air Act controls the addition of additives such as ethanol to limits that allow the blend to "substantially similar" pre-existing fuels. The interpretation of this statute has limited the legal blend of ethanol in gasoline to 10% by volume. Higher blends of ethanol, like E85, may only be sold to vehicles that have been certified by the manufacturer. However, there are not enough of these vehicles to use the high blends of ethanol that would be required to meet the original standards. Additionally, there are not enough stations to distribute the fuel even if there were enough vehicles. Lastly, even with stations to distribute ethanol, and vehicles to use high blends of ethanol, there is very little reason for drivers to use high blends of ethanol. Other biofuels are on the horizon, but none will scale in time to meet the current requirements. These combinations of factors leave US fuel policy in a position of pushing more fuels while phasing out incentives for the vehicles, which will use the fuel. The combination of these factors is increasing pressure to certify higher blends of ethanol with uncertain consequences.

This research will systematically and quantitatively address each of the factors that present major obstacles to implementation of biofuels policy. It is hypothesized that coordinated policies along each factor; biofuels targets, ethanol blend limits, vehicle deployment, refueling deployment and customer purchase incentives will enable an effective transformation of the liquid fuel system to diversify away from petroleum sources of energy. The overarching question, which forms the foundation of this work, is how can benefits of ethanol be derived while minimizing the risks.

1.2.*Scope*

In this work, the focus is on the deployment of alternative vehicles, and specifically with matching the deployment of vehicles, fuels and infrastructure. Previous, and ongoing work by many research groups and organizations focuses on the environmental impact biofuels (Edwards, et al. 2006).

The net impact of a particular fuel or vehicle technology must be assessed across a broad scope of its impact. A life cycle analysis (LCA) has been utilized in understanding how vehicle emissions and fuel consumption vary with the addition of new technology. This technique is particularly important with the use of biofuels for transportation. In an LCA for automotive applications the impact of the fuel is typically called a well-to-wheels analysis (WTW). This can be further broken down into well-to-tank (WTT) which covers all the inputs that are used to make the fuel available for use, and tank-to-wheels (TTW) which refers to all emissions and effects from the utilization of the fuel (Edwards, et al. 2006).

This report will focus more on the TTW aspects of the biofuel system. As stated, there are challenges and opportunities regarding the use of ethanol that are not environmental. In this work the focus the technical and logistical impacts of ethanol and deployment of ethanol capable vehicles.

As ethanol blend percentages increase there are specific fuel properties that present the opportunity for improvements in efficiency and performance for light duty vehicles.

Understanding these improvements is important for guiding long term policy by fuel makers and distributers, auto manufacturers and government agencies.

The model results within the context of this research should not be viewed as predictions. The examples are meant to be illustrative examples of how various technologies and policies can overlap. Scenarios have been chosen for ease of understanding and relative simplicity. The lessons elicited should help bring better understandings of the fleet-wide interactions between vehicles, refueling infrastructure deployment and consumer demand.

1.3. *Thesis Outline*

There is a set of fundamental questions that will be addressed in this report. Each of these questions stem from variables in the following equation:

Equation 1: $Total\_Biofuel(t) \sim \sum Blend_i\% * Fleet_i\% * Utilization_i\%$

- Total Biofuel: The amount of biofuel used in the light duty vehicle fleet in a given year is dependent upon the following a set of proportions, each with additional embedded factors. Biofuels are either ethanol or non-ethanol fully miscible alternatives.
- Blend Percentage: The component of fuel that contains blended ethanol. This factor is often represented as a volumetric percentage. E85 is used as the high blend of ethanol and E10 or potentially E15 may be used in the traditional gasoline supply.
- Fleet Percentage: There is a limited proportion of the fleet that is capable of operating on E85. While this value is calculated on a fleet basis, the fleet is an accumulation of new vehicle sales, which is the more common representation of market penetration.
- Utilization Percentage: For a given flex fuel vehicle, there is a choice of using E85 or regular gasoline. The utilization refers to how many vehicle miles are traveled using E85.

The following chapters will explore in depth the issues that relate to each of these factors and how they impact the deployment of ethanol and ethanol capable vehicles.

Chapter 2: Fleet Model Methodology

The core analysis tool in this work is a model of all the cars and light trucks in the US fleet. Vehicles are separated by fuel type and assumptions are included for technological development over time. Each of the following sections will specifically address an input area for parameters in the model.

Chapter 3: Total Biofuel (Policy & Availability)

The amount of biofuel used for blending is currently set as a matter of policy mandate. The Renewable Fuel Standard introduced in the 2007 Energy Independence and Security Act (EISA) will be the principal reference point for total biofuel targets in the US fleet context. However there are uncertainties regarding the amount and type of fuel that will be available. Therefore an assessment of the availability of feedstocks and maturity of fuel conversion technology will be included in the analysis for this chapter.

Chapter 4: Blend Level (Policy & Impacts)

Currently the legal limit for ethanol blends in gasoline is set at 10% by volume for conventional vehicles. This chapter will explore some of the considerations for increasing this limit to 15% by volume as well as address some of the basic fuel properties of ethanol that change as a function of blend percentage. For the purposes of this analysis there are effectively two types of fuel blends, those which can be used in the existing gasoline supply in any vehicle and a high blend of ethanol (E85) which can only be used in an FFV.

Chapter 5: Fleet (Deployment & Efficiency)

Chapter 5 lays out a set of FFV deployment scenarios, which can be used to better understand the requirements for meeting the total biofuels targets laid out in Chapter 3. Additionally, there are design options for increased performance and efficiency in these vehicles based on the fuel properties discussed in Chapter 4. The analysis in this chapter will therefore include a discussion of the amount and type of vehicles deployed and the effects within the fleet.

Chapter 6: Utilization (Availability & Attractiveness)

The utilization value represents the percentage of FFV miles traveled on E85. This value is used as the output of the fleet model for all of the previous chapters. In order to translate these results into actionable policies it is important to understand the factors that are embedded in the utilization term. Utilization values can be achieved through a combination of fuel availability and fuel attractiveness. Availability is achieved through the conversion of retail fuel stations, and attractiveness is a function of price and vehicle performance on a given fuel. Chapter 6 includes a discussion of reasonable estimates for these values in order to test the reasonability of the existing deployment scenarios.

Chapter 7: Findings and Recommendations

All of the previous chapters build up the support for selecting specific vehicle development scenarios while highlighting critical challenges and related issues. Ultimately this analysis can provide a set of recommendations for navigating the crucial tradeoffs that exist in the deployment of ethanol-fueled vehicles.

2. Fleet Model Methodology

This chapter provides an overview of the methods and assumptions used to assess changes in vehicles and fuels in the US light duty fleet.

Foundations of the Model

The analysis tool at the heart of this research is a fleet model, which has been developed and refined by several researchers in the MIT Sloan Automotive Laboratory. The fleet model has multiple sets of input variables, which can be adjusted to achieve different scenario results. Previously it has been used to illustrate strategies for meeting fuel economy or greenhouse gas targets (Cheah, et al. 2007). Detailed discussion of the model and relevant calibration can be found in "On the Road in 2035" (Bandivadekar, et al. 2008). While these variables are important for the behavior of the fleet dynamics, they are not the focus of this analysis. The existing fleet model was extended for the purposes of this analysis, to represent flex fuel vehicles as a vehicle class and to add E85 as an independent fuel.

The dynamics of fleet turnover are governed by a set of assumptions shown in Figure 2 and are used to formulate the baseline behavior of the fleet out to 2035. The average fleet fuel consumption improves over time based on a relative Emphasis on Reducing Fuel Consumption (ERFC). This concept has been described extensively by Bandivadekar et al. (2008). While the ERFC term includes strategies like weight reduction, there are additional light weighting strategies which can be pursued. Sales of cars and light trucks are treated separately and are assumed to retain fixed proportions.

REFERNCE CASE ASSUMPTION	CARS	LIGHT TRUCKS
New Vehicle Sales		
Sales Growth	0.8% per year	
Share of new sales that are light trucks	55%	
Scrappage Rate		
Median lifetime (years)	16.9	15.5
Vehicle Kilometers Traveled (VKT)		
Starting VKT for 2000 Model Year	27,000	27,770
Degradation rate	4%	5%
Annual Growth in individual vehicle travel	0.5% (2005 to 2020) 0.25% (2020 to 2030) 0.1% (2030 to 2035)	
On-Road Vehicle Fuel Consumption		
Adjustment Factor	22%	
Baseline Vehicle Mix (new vehicle sales in 2035)		
NA PFI	2%	2%
Turbo	50%	50%
Diesel	9%	9%
Hybrid	30%	30%
PHEV	9%	9%
Emphasis on Reducing fuel Consumption	65%	
Additional Vehicle weight reduction (0-35%)	17%	

Table 1: Fleet Model baseline assumptions

In order to make the output of the fleet model relevant for future policy makers it was assumed that CAFE regulations were met in 2020 with combined fuel economy of 35 mpg for combined cars and light trucks. The vehicle technology mix continues this trend to meet continuing stringency increases out to 2035. Each vehicle powertrain technology is assumed to have a level of potential for low fuel consumption shown in Table 2.

Propulsion System	Cars			Light Trucks		
	Fuel Consumption (l/100 km)	Relative to current Gasoline ICE	Relative to 2035 gasoline ICE	Fuel Consumption (l/100 km)	Relative to current Gasoline ICE	Relative to 2035 gasoline ICE
Current Gasoline	8.8	1	--	13.6	1	--
Current Diesel	7.4	0.84	--	10.1	0.74	--
Current Turbo gasoline	7.9	0.9	--	11.3	8.3	--
Current Hybrid	6.2	0.7	--	9.5	0.7	--
2035 Gasoline	5.5	0.63	1	8.6	0.63	1
2035 Diesel	4.7	0.53	0.85	6.8	0.5	0.79
2035 Turbo Gasoline	4.9	0.56	0.89	7.3	0.54	0.85
2035 Hybrid	3.1	0.35	0.56	4.8	0.35	0.56
2035 Plug-in Hybrid	1.5	0.18	0.28	2.4	0.18	0.28

Table 2: Assumptions for technology progress of alternative powertrains assuming Constant vehicle size and performance (Bandivadekar, et al. 2008).

The model takes inputs for the segmentation of new vehicle sales. Flex fuel vehicles are assumed to be an overlapping vehicle class. This means that all non-diesel powertrains are assumed equally likely to be FFVs. Diesel vehicles are considered with as a separate class of vehicles with separate fuel demand. FFVs retain the efficiency improvement each respective powertrain and may have increased fuel economy while operating on ethanol. This optimization assumption is set to zero in the reference case.

Ethanol is considered to be an "immiscible biofuel" in concentrations greater that 10% by volume (E10) unless otherwise stated. The criterion for miscibility is that special vehicle design is not required. Any biofuel that goes into the diesel supply would be considered to be a "miscible biofuel" and would help meet the biofuel target but would not require the deployment of an FFV. Diesel biofuels are assumed to be miscible in the diesel fuel supply without requiring vehicle modifications.

Ethanol & Vehicle Analysis

The guiding framework for the model is based on Equation 1 in which the required volume of ethanol used in the vehicle fleet is considered as an input variable to the model in the form of the Renewable Fuel Standard. If this volume is less than or equal to the EPA blend limit, then it is blended in the existing gasoline stock. However, when the mandated volume exceeds the legally allowable limit then the excess volume must be used in a higher blend of E85. The model includes an option to adjust the legal certification limit to E15 starting in 2012.

Additional inputs are used for the fleet sales percentage and the output of the model calculation is in utilization percentage as defined on the basis of miles traveled. This should not be confused with similar concepts such as percentage of total vehicle energy demand or percent of refueling events where E85 is used. Some of these subtleties will be discussed in Chapter 6.

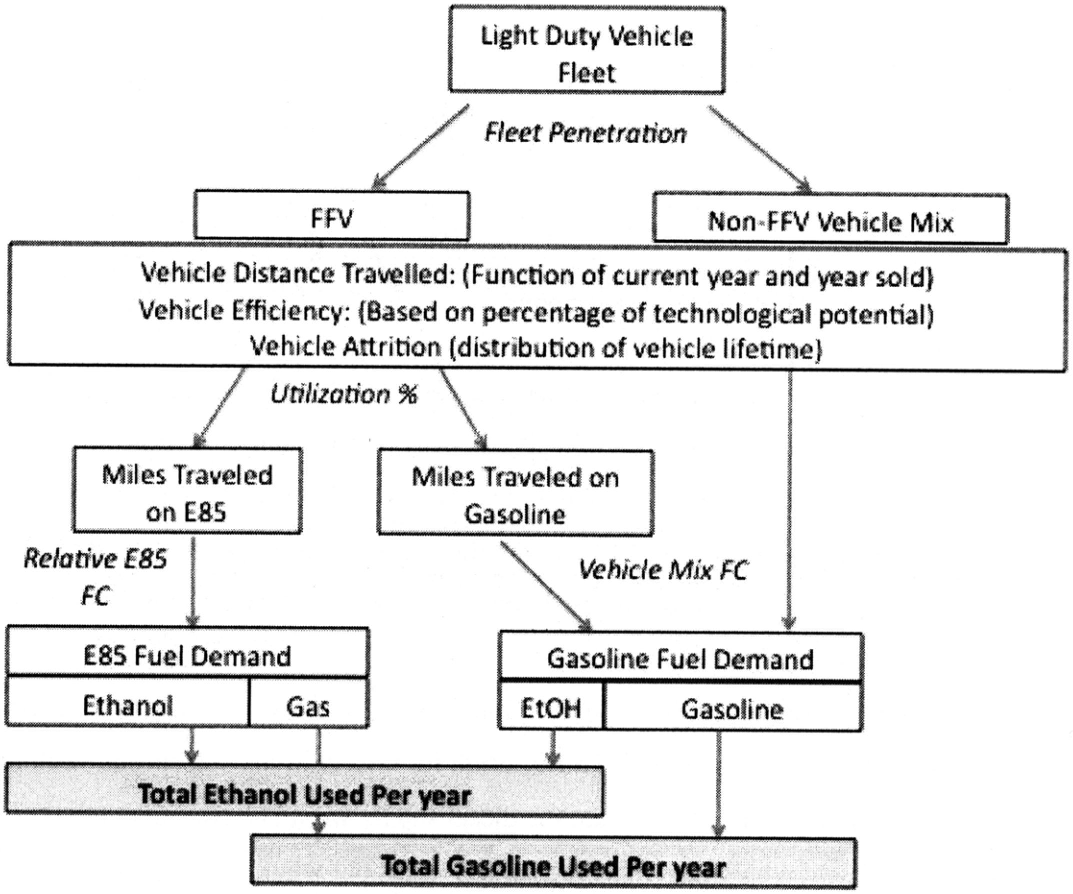

Figure 3: Updated fleet model structure for flex fuel vehicles (FFVs) showing the accounting approach for non-diesel vehicles. FC stands for Fuel Consumption, and EtOH is ethanol.

The breakdown of the model shown in Figure 3 is based on several key variables that determine the relative fleet composition and ultimate fuel use. These variables interact on the basis of the following general equation and internal fleet model mechanics:

Equation 1: $Total\_Biofuel(t) \sim \sum Blend_i\% * Fleet_i\% * Utilization_i\%$

- <u>Fleet Penetration:</u> Each scenario has a set percentage of new vehicle sales each year that are capable of running on E85. This segments the fleet into FFV and Non-FFV vehicles

- Utilization: A given flex fuel vehicle will only travel a certain proportion of miles using E85 as a fuel. This factor provides the breakdown between miles traveled on E85 and miles traveled on gasoline.
- Vehicle Mix Fuel Efficiency: The baseline vehicle sales mix is an aggregated composition of powertrain types. The combination of these and endogenous technological development in fuel economy leads to the fuel requirement for a given set of miles traveled.
- Relative E85 Efficiency: Flex fuel vehicles have the capability of having increased fuel economy relative to the same vehicle operating on gasoline. This term is also referred to as FFV "optimization" which can be in the form of performance or efficiency as discussed in Chapter 5.
- Blend Percentages: The fuel demand for blended gasoline and E85 each breaks down into a net demand for ethanol and gasoline. The blend proportions of ethanol in gasoline may change from 10% to 15% depending on the scenario.

The model uses iterative solving techniques to match utilization with a set of variables in each scenario. This utilization value is the minimum required to meet fuel mandates based on the existing vehicles, efficiency, biofuels target and other variables. The values of utilization used in the model for utilization are mostly meaningful within the range of 0-100%. Utilization greater than 100% would mean that the vehicle miles traveled (VMT) of FFVs would have to be greater than that of normal vehicles. This is not a meaningful result in the context of this study.

The model has the capability of solving for a solution to Equation 1 through two methods. In both cases the total fuel target and blend level are set.

1. National Deployment: Vehicle penetration scenarios are set, and the model *solves for the required utilization.*
2. Regional Deployment: The utilization rate is set to a high value and the model *solves for the required new vehicle sales data.*

The use of a high utilization rate simulates the localized deployment of dedicated ethanol vehicles. This type of calculation shows a baseline for the minimum number of sales required as discussed in Chapter 5.

Baseline Fleet Performance

The fleet model leads to important changes in the vehicle technology mix and fuel consumption over the next 20 years. An important constraint on the model is that it meets CAFE standards that have been set for 2020. Part of the baseline assumption is that these standards continue to increase in stringency out to 2035. While these assumptions have an effect on the biofuel deployment these variables are not the focus of this work. The sensitivity of fuel use to the assumptions in Table 2 are discussed at length in "On the Road in 2035" and other reports (Cheah, et al. 2007).

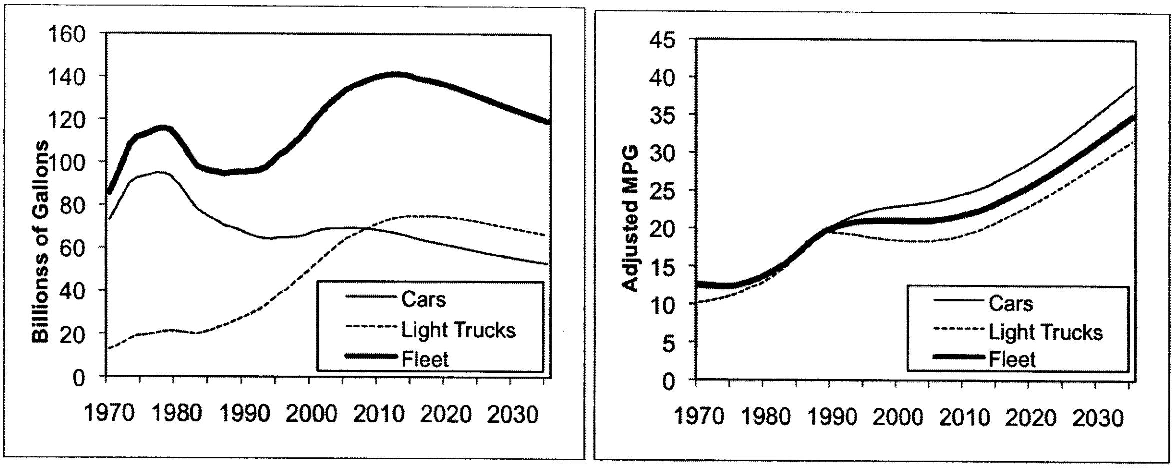

Figure 4: Baseline performance of the fleet model. Fleet fuel consumption is shown in billions of gallons broken out by cars and light trucks. Fleet average fuel consumption is shown in adjusted miles per gallon using a 22% adjustment factor from EPA fuel economy values.

It is critical to note that steadily increasing fuel economy is a part of the reference case in this model. Declining VKT growth and more efficient powertrains shown in Table 1 lead to a plateau and decline in total fuel used in the US LDV fleet. This means that fundamentally a constant volume fuel mandate will represent an increasing percentage of the total gasoline fuel supply. The following chapter will discuss potential scenarios for the available volume of biofuels.

3. Total Biofuel Targets: Policy & Production

This chapter will address two questions that are central to the fleet model scenarios:

1) *What scale may biofuel production standards reach in 2035?*
2) *What types of fuels are likely to be available to meet these standards?*

3.1. *Policy Context*

The current ethanol market operates with near complete reliance on multiple policy measures. Nearly every policy tool is applied in some way towards ethanol production including taxes, subsidies and tariffs. The Volumetric Ethanol Excise Tax Credit (VEETC) went into effect in 2005 and is commonly referred to as the blender tax credit. Every gallon of ethanol is given this credit whether it is blended into E10 to provide $0.051 or E85 for $0.43 per gallon. Imported ethanol is subject to a $0.54 per gallon tariff in order to offset the tax credit. Many states also waive their excise gasoline taxes on fuel that has ethanol blended, particularly at higher volume concentrations (American Coalition for Ethanol 2008).

More recently, support for biofuel production has come from the Energy Independence and Security Act of 2007 (EISA), which included a significant increase in the Renewable Fuel Standard (RFS). The RFS states the total volume of biofuel that must be blended in the liquid fuel supply in a given year. Current blend requirements are ramping up to 36 billion gallons of renewable fuel by 2022. This renewable fuel mandate replaced the previous version from EPACT 2005, which peaked at 7.5 billion gallons in 2012 (Cong. 2005).

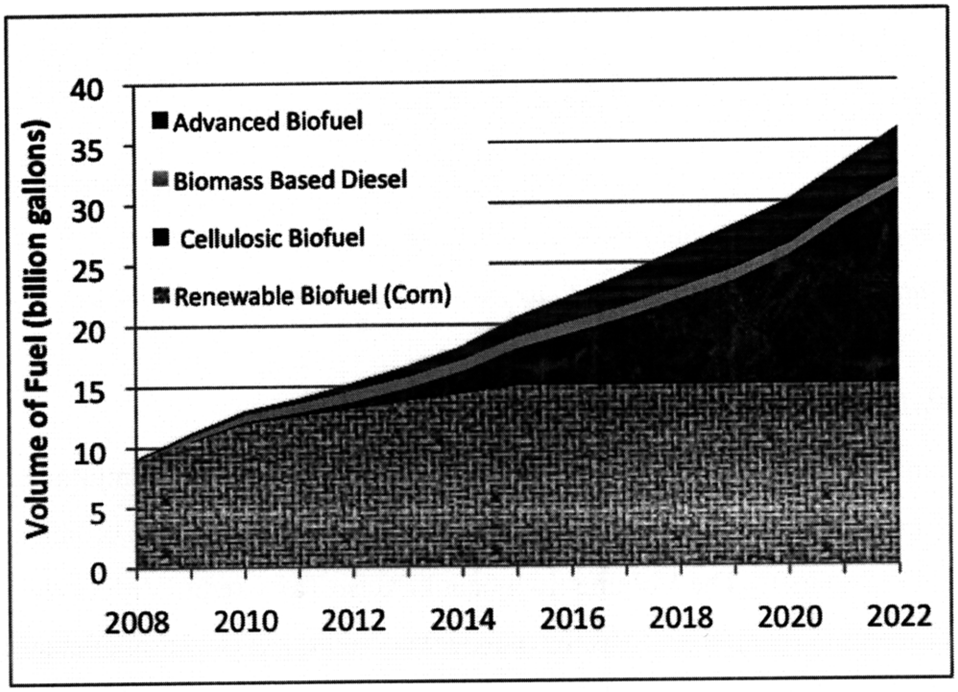

Figure 5: Renewable Fuel Standard contained within the 2007 Energy Bill (EISA). Total biofuels reach 36 billion gallons per year in 2022 with corn ethanol limited at 15 billion gallons and 22 billion gallons of biofuel achieving at least a 50% Life cycle benefit against a 2005 petroleum baseline. No less than 1 billion gallons of this may be biomass-based diesel after 2012. 16 billion gallons out of the 22 are cellulosic biofuels must achieve 60% life cycle GHG benefits.(C. United States 2007).

The RFS mandates shown in Figure 5 are made on a volumetric basis and segmented on a life cycle greenhouse gas (GHG) reduction against a gasoline baseline. Official life cycle assessment (LCA) techniques have not been set at this time been set, but the EISA explicitly states that land use change must be considered. This is a highly contentious issue, which has the power to drastically affect the way that fuels will be viewed for this policy. The amount of corn based renewable fuel is limited to 15 billion gallons. Some amount of biofuel must come from feedstocks defined as cellulosic, while the remaining volume may be non-specific biofuel as long as it meets the LCA requirements of 50% benefit against baseline. There is no explicit mention of the type of fuel that must be produced except the provisions for biomass-based diesel, which grow to a minimum of 1 billion gallons. The bill stipulates that while economic hardship can lead to the reduction of the mandate if the fuel is not available, that the proportions of cellulosic to corn ethanol must remain the same.

The scale and timing of the RFS mandates create a situation where it is unlikely to be successful in the exiting policy framework. The current legal limit for blending remains at 10% by volume. However, in the next few years it is virtually certain that the current Renewable Fuel Standard will exceed this legal blend limit. The term "blend wall" has been used to describe the situation when more fuel is mandated than can be blended in gasoline. The EPA has announced for 2009 that the blending requirements are 10.21% (US EPA 2008). The standard applies to the continental US with opt-in available for Alaska and Hawaii, which Hawaii has chosen to do. Small refiners are exempt from the requirements until 2011, which account for 13.5% of total fuel production. Once the total amount of fuel covered by the RFS increases in 2011 the volumetric requirements will result in a smaller blend percentage. It is clear, however , that the blend wall is a near term problem and is likely to impact fuel distribution within the next 3-7 years. In order for the entire RFS volume in 2022, estimates show that ethanol blends greater that 20% would need to be used in all gasoline. Figure 6 below shows an illustration of the required blend level that would be required in order to extend the blend wall.

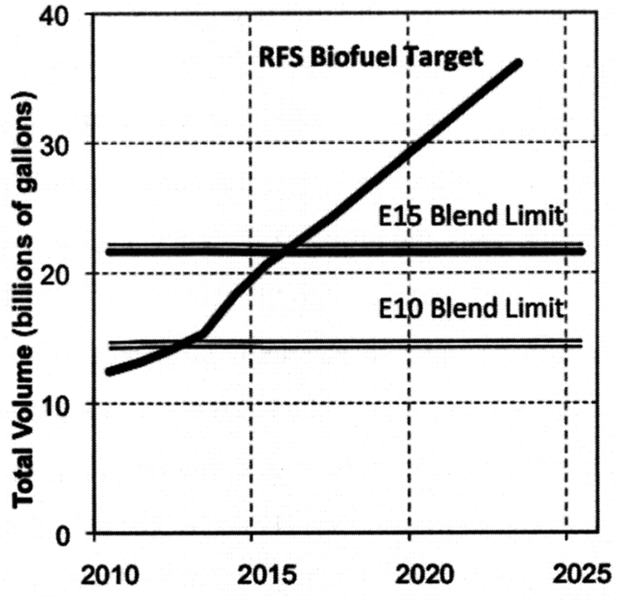

Figure 6: Illustration of the blend wall issue assuming no E85 use. The E10 blend limit is the amount of ethanol that could be used to meet the RFS requirements if all gasoline included 10% ethanol. The E15 blend limit occurs when all states blend 15% ethanol in all gasoline. The blend limit lines are shown for the highest possible value assuming no decrease in total fuel use.

Thus far, the EPA has denied waiver requests to reduce the RFS (US EPA 2008). There is some question as to whether or not the RFS will be attainable in 2022. Current policy continues to drive towards increasing volumes of ethanol production. However, the implementation of these policies may be tempered by the availability of fuel. The next section will explore the production of biofuels. At the end of this chapter both the policy and technology aspects of biofuel targets will be combined to generate scenarios for use in the fleet model simulation.

3.2. *Production of Biofuels*

It is still uncertain which types of feedstocks and fuels are most likely to meet the RFS requirements in the US. There are three major factors that can be used to reach a better understanding of total availability of biofuels. These are:

- Conversion Technology: The technology that is used will determine what types of fuels can be made. However conversion will rely on specific types of feedstocks. Capital intensity and technological complexity will also determine scalability.
- Biomass Resources: The feedstocks will determine geographic distribution, carbon intensity with a strong feedback into the scalability.
- Scalability: The combination of the first two factors with a consideration for cost competitiveness will constrain the proliferation of biofuel production.

There is a strong interplay between each these factors. Biomass resources can be considered as long as there is viable conversion technology to convert the feedstock into fuel. The combination of feedstock costs and process efficiency leads to a general cost competitiveness, which may then feedback into the selection of feedstocks and fuels. It is valuable to address each of these topics to ascertain reasonable estimates of how much of which type of biofuel will be available and when. The US biofuels market is dominated by ethanol, and domestic ethanol is made almost exclusively from corn (Wright, et al. 2006). The more important question for meeting future RFS targets is how the cellulosic fuels will be made. For advanced biofuels there are three basic categories of biomass conversion (Sandia National Labs, GM R&D Center 2008).

1. **Biochemical:** These processes are catalyst by microorganisms, which carry out fermentation reactions. Cellulosic materials can be broken down by specific enzymes or by redesigned bacteria.
2. **Thermo-chemical:** Inorganic catalysts are used along with high pressures and temperatures to break down cellulosic material. Then catalytic synthesis is used to create different types of fuels.
3. **Biochemical/Thermo-chemical:** There are options to combine these two processes by first gasifying cellulosic feedstocks and then using the gas as a feedstock for biological fermentation

The cellulosic ethanol plants that are being planned and developed today are the best resource for understanding the type of fuel processes which will be first to scale up. The data for understanding the biomass resources and conversion technology maturity comes from an accumulation of press releases from companies, and also from the US Department of Energy (DOE), which has provided loan guarantees to some of the biofuel producers. Figure 7 below shows a map of the locations for proposed cellulosic ethanol projects in 2008 numbered from 1-24 corresponding to values in the Appendix. Some projects have been cancelled, and others have been added from the time of this assessment.

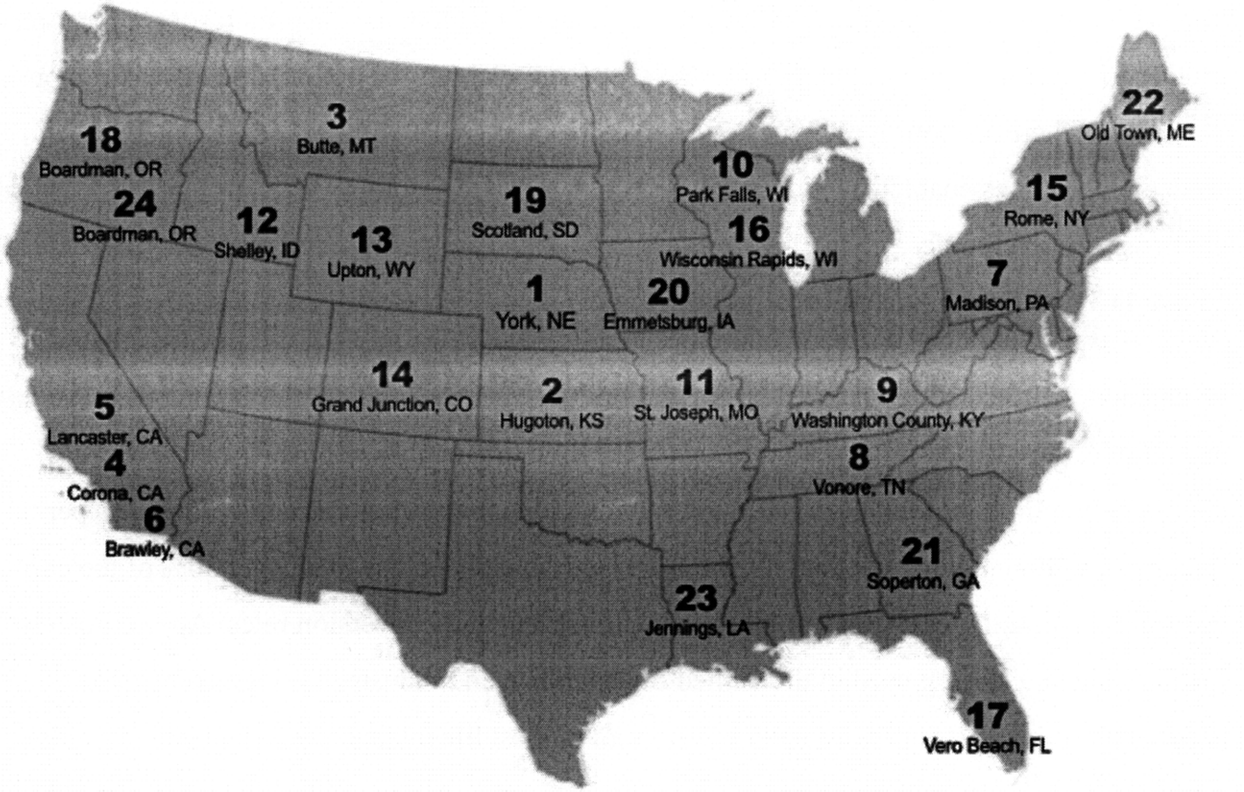

Figure 7: Geographic representation of cellulosic pilot plants in planning or construction phases. (Renewable Fuels Association 2008)

All of the proposed pilot facilities share the goal of scaling up production to meet the RFS mandate for cellulosic biofuel. However, the pilot scale is usually on the order of 25,000 gallons per year while commercial scale for corn ethanol production facilities is around 100 million gallons per year. Ultimately the RFS target is 16 billion gallons in 2022, which means that plant scaling must happen relatively quickly (C. United States 2007). The currently planned cellulosic facilities will need to scale to 100 million gallon annual capacity by 2015 in order to meet the RFS requirements The RFS continues to grow after 2017 at the same rate. The development of cellulosic plants will also depend on the biomass feedstocks, which will be used in the fuel conversion. Based on the current rate of progress for cellulosic plants it can be reasonably expected that some of the RFS target volumes for cellulosic biofuels will not be met. Additionally, this shows that the current technology, though somewhat varied is almost exclusively for the production of ethanol. The lack of near term evidence of scalability for other fuels is an indication that commercial production will continue to lag that of ethanol.

Feedstock Resources

The deployment cellulosic ethanol fuel relies on biomass feedstocks for conversion. The type of feedstock will play a role in the total amount of fuel that can be produced, the location of production, and the type of fuel. For these reasons, an overview of potential feedstock options is warranted. There are four basic types of biomass resources that will be discussed here. Each feedstock becomes enabled as processing and conversion technology develops, and has particular challenges to overcome.

Phase 1) Traditional Agricultural Products

Corn ethanol has been and continues to dominate US biofuels. Current corn ethanol production is projected to reach 10 billion gallons per year by 2010. Corn Planting Acreage has stayed relatively steady around 80 million acres while the number of bushels per acre has continued to climb steadily past 150. With continuing conversation rates of 2.7 bushels per gallon, 15 billion gallons of ethanol from corn is reasonably achievable using 30% of the corn crop and continuing technological improvement in yield and conversion rates. Approximately 90 Million tons of corn are used in the United States today, and industry average conversion is around 200 L per metric ton. Ethanol can present modest life cycle benefits in GHGs but also interferes with existing agricultural activities and can stress water and fertilizer use. (Groode 2008)

Phase 2) Agricultural & Industrial Residues

The production of corn and other traditional crops generates additional biomass that is not used. The increase in corn planting acres comes with a corresponding increase in the availability of corn stover. This is a cellulosic feedstock that requires special treatments, but allows for the co-location of new cellulosic ethanol plants next to existing plants without major changes in supply chain. Roughly half of the dry tonnage per acre for corn results in unused residue. Estimates from 2001 put total crop residues at nearly 500 million dry tons per year out of which 225 million are from corn. It is important to note that crop residues are often used to displace fertilizer requirements by returning nutrients to the soil. USDA Estimates of the actual availability of corn stover specifically are closer to 100 million dry tones (US Department of Agriculture 2007).

The next largest available source of crop residues would be from soybeans, which provides more than 100 million dry tons per year with 50% removal. Total assessments of the resources from sustainable harvest are as high at 368 million dry tons per year from the combination of various agricultural residues. Many of these residues are already used for existing energy resources such as co-firing (Wright, et al. 2006).

The second type of cellulosic residues come from the forestry and paper industries. There are abundant woody biomass references from urban sources such as construction and demolition. Collection and processing mechanisms have not yet been well established for many of these residues. The heterogeneity of some feedstocks also presents a challenge for processing biofuels.

Phase 3) Dedicated biomass feedstocks

Several different types of energy crops have been proposed, ranging from fast growing strains of prairie grasses, to woody feedstocks such as poplar or miscanthus. In many cases the growth of energy crops is proposed on Conservation Reserve Program (CRP land). There will be some price at which farmers might switch corn-planting acres to grow switchgrass. Analysis by Groode (2008) also includes a measure of the capacity of CRP land. The management of these lands will play a role in how much dedicated feedstocks may be deployed for biofuel production.

Phase 4) Potential new types of farming resources

After agricultural products, residues, and dedicated fuel crops there are other non-traditional feedstocks that have been proposed. Algae biofuels are the primary example in this category. Algae as a feedstock is still in the early phases of exploration but presents some promise for use as a source of bio-oil for biodiesel. Algae represent an opportunity for decreased land use, but still have significant water and capital requirements to create a viable production system (Sims, et al. 2008).

Total Available Biomass

There have been several studies over the past two decades looking at he availability of biomass, and there are general assumptions that must be made at each point. Many of the studies suggest that hundreds of millions of tons of biomass are obtainable in a sustainable manner (U.S. DOE, USDA 2005). For example BP has estimated that biofuel could account for 10-30% of the global transportation fuel market by 2030 (Ellerbusch 2008). Similarly, Sandia National Labs in partnership with GM suggest that the volumes of 60 billion gallons of ethanol could be produced by 2030 (Sandia National Labs, GM R&D Center 2008). Others, however, warn of major environmental damage that can result from expanded biofuel production (Melillo, et al. 2009).

Based on current trends it is likely that agricultural crops will continue to play a large role, but feedstocks will begin to expand into waste steams and move towards dedicated energy crops as the value increases. The general assessment is that there is enough biomass to support continued growth of biofuel development. However, growth of this industry will be constrained by logistics in managing the biofuel supply chain as well as competition between biofuels as well as against traditional fuels.

There are increasingly studies that delve into the issues of supply chain logistics and sourcing biomass to conversion facilities (University of California, Davis 2008). However, there is evidence to suggest that the total availability of biomass is not the limiting factor for existing biomass targets. The constraints will be on what can be economically recovered and converted.

Fuel Types, Maturity & Market development

While there are many types of biofuel under development, there are few that have been able to reach large scale and widespread deployment. Table 3 below shows a broad assessment of the various types of biofuels that are currently being produced and the level of production maturity that has been achieved. There are essentially three phases that emerge: the large-scale commercial developments, pilot plant stage developments, and lab scale technology development. There is still significant stratification within each class shown by the changing orders of magnitude of production. This is not an exhaustive list, but provides some assessment of the range of options that are currently under investigation. Additionally, new projects are emerging to advance the development of each fuel.

Fuel	Benefits	US Scale of Production order of magnitude (Gallons/yr.)	Maturity	Key Companies
Grain Ethanol	High-Octane, available feedstocks	${}_{10}10$	Commercially Proven	POET, ADM
Biodiesel	Miscible fuel, increased lubricity	${}_{10}8$	Commercially Available	Imperium Renewables
Cellulosic Ethanol	Ethanol Production, diverse waste feedstocks	${}_{10}5$	Pilot Development	Verenium, Coskata
Renewable Diesel	Better feedstocks than biodiesel	${}_{10}4$	Commercial Production	UOP, Connoco
Syngas Liquids	Integrate biomass and fossil sources, high quality fuels	${}_{10}3$	Pilot Development	Range, Coskata
Butanol	Low volatility, high energy density, water tolerant	${}_{10}2$	High level research	BP, DuPont, Gevo
Pyrolysis Liquids	Refinery feedstocks	${}_{10}2$	Commercial production of chemicals	Uniol AS, Choren
Algae Diesel	High yield per acre, Use direct CO_2 streams	${}_{10}2$	Demonstration Phase	Solazyme, PetroSun
BioCrude	Integration with existing fuels	${}_{10}2$	Lab Scale Investigation	LS9, Amyris

Table 3: Production of various biofuels divided up in to commercial, pilot and R&D stages (adapted and augmented from (National Renewable Energy Laboroatory 2006))

While ethanol and specifically that which has been produced from corn has attained early market leadership, there is a range of other fuels, which are prepared to compete with corn ethanol. The landscape of biomass feedstocks and conversion technology is dynamic and intricate even only addressing the basic factors above. Fundamentally there is a sequence of developments for each technology to reach scale, which are not trivial. Corn ethanol technology has existed for decades but is still not cost competitive with recent gasoline prices without heavy subsidization.

The assessment in this chapter thus far has provided an overview of the existing biofuels policy as well as emerging options for future fuel feedstocks and formulations. These variables can now be assembled into representative scenarios in the final section of this chapter.

3.3. *Scenario Analysis: How Much of What, and When?*

The biofuel policies in the US are currently based on the Renewable Fuel Standard as described in the beginning of this chapter. However there are two key areas of uncertainty in the application of this mandate through 2022 and out to 2035.

1) Total amount of biofuels mandated by year.
2) Type of fuels that will be used to meet this standard

A complex landscape of fuels, feedstocks and technologies is emerging, and it is not clear how the competition between biofuels will play out through 2035. There is also some doubt regarding the specific policies that will support biofuel production. In order to deal with these uncertainties in the context of the fleet model, a range of possible future scenarios must be explored. While the RFS, as written, can be taken as a baseline through 2022 there are reasonable doubts that these targets will be met, especially given the current state of development for cellulosic pilot plants. Additional support for seeing the RFS targets delayed comes from the EIA Annual Energy Outlook.

The EIA reference case, projects a slight delay with RFS goals met in 2027 instead of 2022. In the long term scenario for 2030 biofuel production continues to increase. The EIA scenarios are not meant to serve as forecasts, but can be useful as baseline scenarios for comparison. (EIA 2009)

In the case of rapid technological development and high gasoline prices, it may be possible for biofuel mandates to continue growing. Based on the range of assessments a set of possible future biofuel targets were assembled. These include the following cases:

- <u>Reference Case</u>: The current RFS, with increasing cellulosic targets to reach a total biofuels targets of 60 billion gallons in 2035.
- <u>Delayed RFS</u>: A three-year delay in cellulosic targets with an eventual achievement of the original RFS targets in of 36 billion gallons 2035. Any additional growth in cellulosic fuels is used to displace corn ethanol.

Both cases can be represented with the development of non-ethanol biofuels that would be legally miscible in the gasoline supply. This would include products like butanol or a biosynthetic gasoline fuel. In this case the assumed penetration is that 50% of the cellulosic fuels component becomes the miscible alternative. The mix of cellulosic and corn ethanol does not effect the deployment of FFVs, but will change the net GHG intensity of the fuel mix, and may allow for the use of unconventional oil resources. The two major fuel scenarios are shown in Figure 8. Each scenario includes a second option for the inclusion of non-ethanol miscible biofuels. This type of fuel is assumed to contribute to meeting the fuel requirements without requiring any vehicle modifications or blend limits.

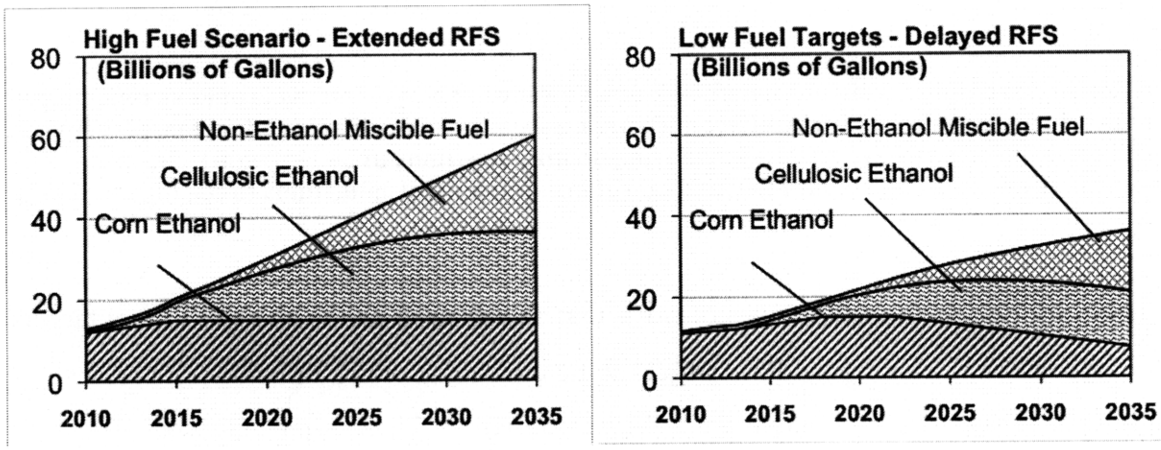

Figure 8: (left) The high target fuel scenario reaches the existing RFS targets of 36 billion gallons of biofuel 2023. This trajectory continues to reach 60 billion gallons total in 2035. Here the scenario is shown with 50% penetration of non-ethanol miscible fuels. The scenario is also run with a minimum of 1 billion gallons of miscible biofuels. (right) The low fuel target scenario is shown with existing RFS targets reached in 2035. Additional growth in cellulosic ethanol is used to displace corn ethanol. This graph is also shown with the option addtion of miscible fuels. The baseline case includes only 1 billion gallons of miscible biofuels.

These two cases represent an aggressive and conservative estimate respectively of the potential biofuel development. In all further discussion these two scenarios will be referenced as the high fuel case and the delayed RFS case for biofuel targets. They effects of changing between the high and low fuel targets on utilization is shown in Figure 9. The baseline FFV deployment scenario is used which includes a linear market penetration leading to 50% of new vehicle sales in 2035.

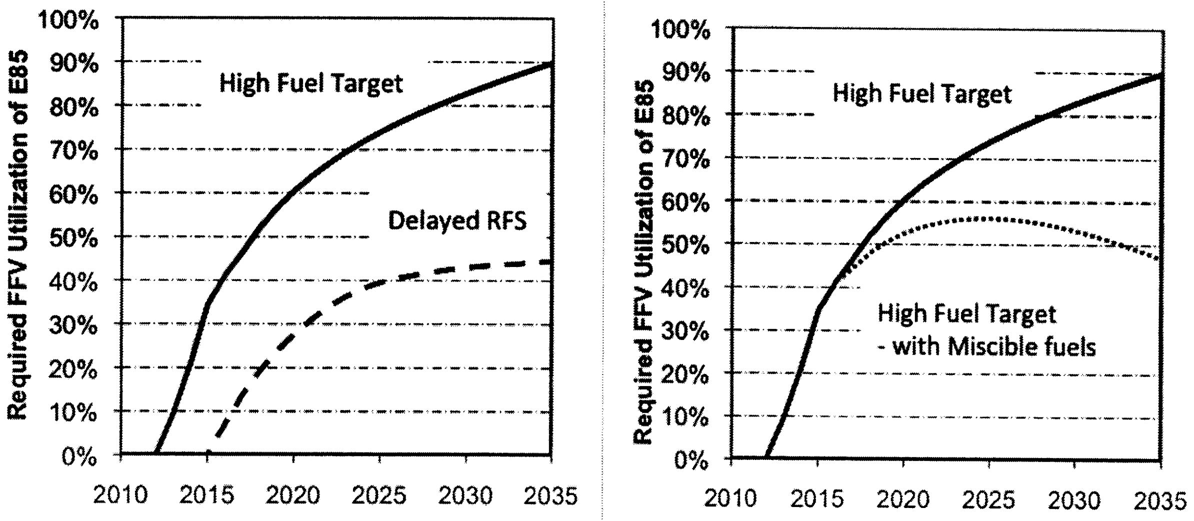

Figure 9: (left) The required utilization is shown for reference deployment levels of FFVs reaching 50% of new vehicle sales in 2035. The effect of changing scenarios from the high fuel target of 60 billion gallons in 2035 to the delayed RFS achieving 36 billion gallons in 2035. (right) The same scenario assumptions are shown with the addition of non-ethanol miscible fuels to the high fuel target scenario.

There are two fundamental types of shifts that occur based on the changes in fuel targets and fuel composition. Delaying the RFS targets shifts the date at which utilization increases begin, and also reduces the total maximum utilization required. There is an additional effect whereby the same volume of ethanol requires a lower utilization rate. 36 Billion gallons of fuel requires a utilization of nearly 70% in 2023, however in 2035 it is only 45%. This decrease is due to the continual build-up of FFVS in the fleet, which spreads the utilization requirement over a greater number of vehicles.

The gradual introduction of non-ethanol miscible fuels decreases the utilization requirement for FFVS over time by reducing the amount of ethanol that must be used. In each case there may be an additional effect from the introduction of non-ethanol biofuels. These may be diesel, or a synthetic gasoline. The same effect can be achieved by reducing the biofuel targets if ethanol is the only biofuel available.

For a given vehicle deployment scenario all fuel scenario options can be plotted on the same graph. There are two total fuel targets, and each target includes the option for a separate fuel mix. The combined results for baseline FFV deployment are shown in Figure 10 These four cases can be plotted together to better understand the relative impacts of each. This graph shown in Figure 11 will be revisited in successive chapters to show how additional policies effect utilization.

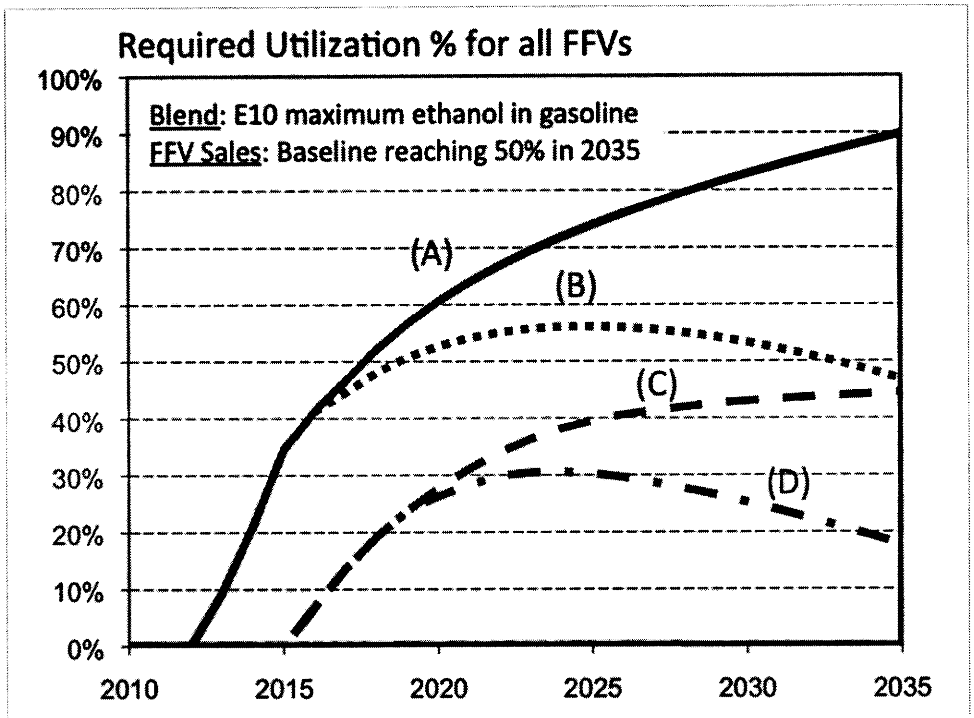

Figure 11: Combined results for utilization requirement of FFVS to meet all four fuel scenario targets (A) High fuel target - 60 Billion gallons of ethanol required in 2035 (B) High fuel target with the introduction of miscible biofuel (C). Low fuel target reaching 36 billion gallons in 2035 (D) Low fuel target with the introduction of miscible biofuel.

The relative effect of adding miscible biofuels has significant impact in both cases. It is notable that in the delayed RFS case the required utilization actually falls in the later years. This is due to the combined effects of delayed targets, decreased ethanol fuel and accumulation of capable vehicles in the fleet. The effects of reducing utilization requirements are counter-balanced by an overall decrease in total fleet fuel consumption.

The standards for biofuel production are based on a set volume amount, but the blend limits are on a percentage of fuel used. This means that the decreasing total fuel consumption, shown in Chapter 2 for the baseline case, makes biofuel targets more difficult to meet in terms of utilization. The baseline fleet scenario represents a more challenging case for later years because of continual improvements in fuel economy.

The dominant alternative fuels for transportation in the United States will likely continue to be ethanol over the next 15 years. There is potential for ethanol to reach steadily increasing volumes out to 2020. Ethanol dominance in biofuels will likely be challenged by the emergence of other advanced biofuels that may prove easier to blend with conventional fuels. The percentage blend percentage of ethanol in gasoline and E85 will therefore depend on the type of biofuels available and the total fleet fuel use of the US LDV fleet at that time. The following chapter will address many of the issues that emerge from varying blends of ethanol in gasoline.

4. Blend Levels: Fuel Properties & Policies

This chapter will address the types of ethanol blends, which are likely to be available, and the fuel property concerns that exist with these blends. Understanding the positives and negatives of ethanol as a blend component is critical to evaluating the future utility and desirability of ethanol. This chapter forms the foundation of chapter 5 by identifying aspects of ethanol which effect vehicle performance, as well as setting up the scenario assumptions for legal blend limits.

Fuel policy regarding ethanol can be a very contentious issue because the impacts cut across several different areas of concern for multiple stakeholders. It is valuable to begin with these concerns because the addition of ethanol will provide some combination of opportunity and risk to each stakeholder. The net balance of benefits against costs will factor into the amount of resistance to ethanol policies.

There are major industries involved in each step of the value chain that relates to ethanol introduction. Feedstock producers, ethanol producers, refineries, distribution systems, retail fuel stations, automakers, drivers, and the government all have reason for concern regarding how ethanol is introduced as a transportation fuel. Due to the interconnected nature of the entire fuel value chain each group must also be concerned with the concerns of the end user of the fuel. The degree of concern also varies, but the main point is that there are a range of fuel properties that change significantly with the addition of ethanol and that this impact can be felt in different ways by all stakeholders in the fuel system.

The reason for concern varies by stakeholder group, but for most it is the result of the interaction with some existing fuel policy or a matter of performance. The following sections will discuss some of the tradeoffs that exist in blending ethanol into gasoline.

4.1. *Fuel Policy Overview*

Mid Level Blend Certification

The blend wall limit, discussed in Chapter 3, exists at the current maximum of 10% ethanol. Attempts to increase the amount of ethanol fuel sold can be achieved by increasing the blend level in the fuel supply. Blends can increase in an incremental fashion by increasing the E10 blend limit to E15 and E20, or by increasing the sales of high blends like E85. However, as recently as 2005, E85 only accounted for 1.2% of ethanol sales in the US (Davis 2008).

The core questions with respect to blending is whether or not mid level blends of ethanol such as E15 or E20 should be certified by the EPA as a replacement fuel. Recently, the state of Minnesota has sought a waiver for E20 blends and more recently a coalition of ethanol producers has requested a waiver for E15 (Growth Energy on Behald of 52 US Ethanol Manufacturers 2009).

A new fuel blend will lead to risk for existing vehicles that may see impacts in emissions, drivability and warranty concerns. The certification of E15 creates an issue where government agencies are put in the position of deciding whether or not a vehicle can operate outside of its originally intended fuel use. Even if E15 is certified as a fuel drivers may not choose to use the fuel if the manufacturer does not recommend using E15.

Another key gating items for the certification of E15 is challenge of adaptability in the current infrastructure. Recently Underwriters Laboratories (UL) has agreed to use the UL 87 certification towards fuels containing ethanol blends up to 15% (Underwriters Laboratories 2009). There are no clear answers yet although; extensive work is underway by the DOE to examine whether or not E15 can be used as a direct fuel replacement.

Regional Policies for Vapor Pressure

The blend level of ethanol affects many other fuel properties, which are currently regulated. One particular example is the vapor pressure of gasoline fuel. There are standards drawn for the US based on spatial and temporal dimensions. Northern states may have higher vapor pressure because of the tendency towards lower temperatures. Similarly, there are seasonal blends along two seasons, which have lower vapor pressure in the summer and higher in the winter. During the period of June through September 15 the maximum RVP is 7.8 psi in southern states. In the rest of the country the maximum is 9.0 psi. There are additional, state-specific low vapor pressure programs. These regional policies may require 7.8 or lower RVP (Marathon Oil Corporation 2008).

The adjustment in fuel volatility also aids cold start operation. If fuels are not volatile enough it can lead to increased hydrocarbon emissions during startup if the fuel is not fully vaporized. Certain urban areas have been designated ozone nonattainment zones by the EPA, where there are specific requirements for reformulated gasoline to have a VOC reduction of 20-25%. This may also be coupled with a vapor pressure or ethanol requirement. One of the most contentious policy issues has been the issuance of a 1psi waiver ethanol blends between 9-10%. Initially the EPA denied this waiver, but strong pressure from the ethanol industry reversed this decision. Some environmental groups teamed up with the oil industry in opposing the waiver (Segal 1993).

Variability in Blends

Common terminology is used to represent ethanol blends such as E10 for 10% ethanol and E85 for 85% ethanol. However there is inherent variability in these blends due to seasonal variations and blending techniques. When ethanol is first distilled and filtered to become 100 % ethanol is must be denatured to avoid taxation as liquor(Alcohol and Tobaco Tax and Trade Bureau 2008). Typically pure ethanol is blended with 2-5% gasoline as a denaturant. This means that the ethanol used for blending begins as E95 and therefore E85 typically contains 80% ethanol. However this can be much lower in the winter due to changing vapor pressure requirements. The Coordinating Research Council (CRC) conducted a survey of commercially available E85 in the winter to test the actual concentration of ethanol. The results are shown in Figure 12 which indicates that actual blends may be as low as 60 or 70% for part of the year despite being labeled as E85 (Coordinating Research Council 2007).

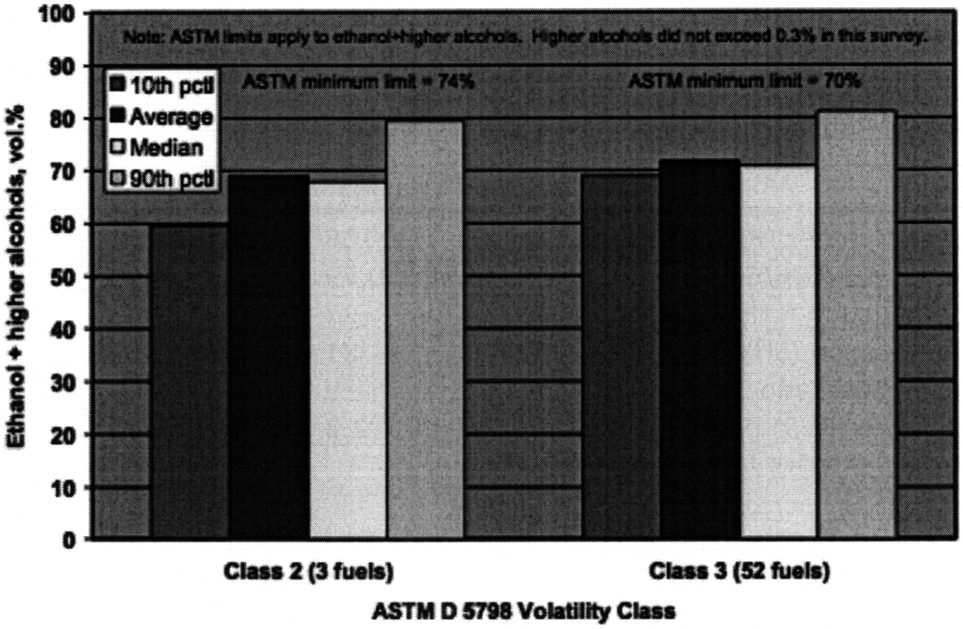

Figure 12: Results from a CRC study of 15 states for winter blends of E85 (Coordinating Research Council 2007).

The method of blending also can have an impact of the fuel properties of the mixture. Splash blends use existing gasoline feedstocks. While specialty blends of ethanol can utilize lighter fractions of gasoline to balance out the vapor pressure of ethanol. The location of blending will also determine other fuel properties. For example if 87 octane is blended with ethanol the then consumers buying E10 regular will actually get higher octane fuels. Currently the energy content of fuel is not labeled.

4.2. *Fuel Property Overview*

Gasoline as a fuel consists of many different compounds, the proportions of which are finely tuned in the refining process to achieve fuels that perform well, within existing cost constraints. Ethanol is a single molecule and therefore has constant properties, but does exhibit some nonlinear trends as it is blended with gasoline. The effect of ethanol blending on gasoline fuel properties will determine which blends are most suitable for use and will guide the design of refineries, distribution networks and vehicles.

Fundamental properties of ethanol and gasoline can be compared in Table 4, and will be used for reference in the rest of this work. It is important to note that there is variability especially in the values for gasoline since there are many types, grades and composition factors. While the values for ethanol are more consistent the blends of ethanol and gasoline can exhibit very different qualities. The volumetric energy density is perhaps the most important value since it will be used in later calculations. For the purposes of this work ethanol is considered to have 66% the energy in gasoline on a volumetric basis.

Fuel Property	Ethanol (E100)	Gasoline
Research Octane Number (RON)	108	90-100
Specific Gravity (kg/l) 60F/60F	0.79	0.75
Net Heat of Combustion (LHV) MJ/kg	27	43
Net heat of Combustion (LHV) MJ/l	21	32
Stoichiometric air/fuel ratio	9	14.6
Reid Vapor Pressure (RVP) psi.	2.3	8-15

Table 4: Fuel Property overview for ethanol and gasoline.

Molecular Composition

Ethanol is different from conventional hydrocarbons in several ways. One of the key differences is the oxygen content. Ethanol is also partially oxidized relative unlike other hydrocarbons, which results in lower energy content. The partial oxidation however also means that less oxygen is required in combustion which leads to a lower gravimetric air to fuel ratio. However, due to the change in energy density, the air required at a given engine load is roughly the same for E85 (Wittek, Tiemann and Pichinger 2009).

The molecular composition of the fuel is measured by the percentage composition of hydrogen, carbon and oxygen. While oxygen relates to the amount of air needed, the H:C ratio is a way of determining emissions in the fuel. Shorter chain saturated hydrocarbons have a higher H:C ratio than longer chain hydrocarbons. This means that in complete combustion fewer carbon products are formed from the fuel. Ethanol produces a slightly lower amount of CO_2/MJ of fuel burned than gasoline just based on its molecular composition. Further improvements are possible based on efficiency differences between the utilization of the fuels, which will be discussed in Chapter 5.

Energy Content

Ethanol by itself contains approximately 2/3 the energy content of gasoline on a volumetric basis. The total energy content scales linearly with the volumetric percentage of ethanol as shown in Figure 13. Blends of E85 typically contain 70-80% of the energy per unit volume when compared to regular gasoline.

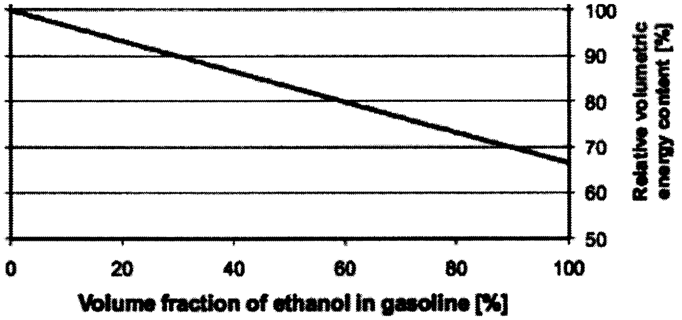

Figure 13: Relative energy as a function of ethanol blends in gasoline (Wallner and Miers 2008).

The practical effect of having less energy per volume means that fuel injectors must deliver a greater amount of fuel at a given engine load. The effects the size and calibration of the injectors over the range of operation and is a contributing factor in the needed specialization of flexible fuel vehicles.

For constant energy efficiency and volume of fuel tank, a lower energy density means more frequent refueling. Increased fuel purchase means more expense unless the cost is equivalent per unit energy. Ethanol blends typically sell for less per gallon than gasoline, but are not even on a pure energy basis. On a gasoline equivalent energy basis, ethanol has been more expensive however by roughly 30% (US DOE Office of Energy Efficiency and Renewable Energy 2007). Labeling at the pump can often obscure this relationship because fuel is sold per unit of volume.

Octane

Knock is a type of abnormal combustion that occurs in the cylinder, which causes a loud pinging noise, which is typically deemed unacceptable for driving quality. Sustained knock over long periods of time could lead to severe engine damage to cylinder heads and piston rings. Knock occurs when the fuel air mixture in the cylinder spontaneously ignites in advance of the normal flame front (Heywood 1988). Knock is a key, limiting factor in engine design, though there are many strategies to manage its occurrence.

The anti-knock qualities of a fuel are tested in two types of octane test to provide two different anti-knock index values. The Research Octane Number (RON) and Motor Octane Number (MON) are measured through slightly different conditions, but provide relative values for the resistance to knock.

Engine Parameters	**Parameter Variation**	**Octane Requirement variation (RON or MON)**
Compression Ratio	+1	+4 to +7
Spark Advance (CA)	+1	+0.5 to +1
Intake Air Temperature (°C)	+25	+1 to +4
Intake Air Pressure (mbar)	-10	-0.5 to -1
Equivalance Ratio	+0.2	-4
Hygrometry (g water/kg dry air)	+4	-1
Altitude (m)	+300	-1 to -1.5

Table 5: Factors affecting anti-knock performance Guibet and Faure-Birchem 1999)

Energy is required to refine gasoline and produce higher octane products. However the higher octane values of fuel enable increase performance and efficiency in vehicles that use the fuel. The supply side and demand side energy consumption can be balanced based on the cost and energy requirements of the refinery and the vehicle.

During the phase out of lead as an anti-knock additive, a landmark study by CONCAWE was performed to explore the optimum octane level for fuel. This study is part of what led Europe to settle on the 95 RON standard for gasoline (Kahsnitz, et al. 1983).

The key point is that there is some measurable benefit to refiners if they can avoid energy and product expenditures to increase the octane of fuel products. Lead was an additive that was used to avoid more costly expenditures, but has been phased out for a variety of reasons. Now, with the increased availability of ethanol there is an opportunity again for refiners to save on costs of increasing fuel octane.

Vapor Pressure

The vapor pressure is another key fuel property. While it is not as immediate a concern to consumers the way octane is, vapor pressure is still carefully controlled as mentioned in the policy section of this chapter.

The vapor pressure deals with the equilibrium between the vapor and liquid phases of the fuel. This is an important metric in relation to startup of the vehicle and evaporative emissions. Higher vapor pressures means that the fuel will evaporate more readily, while low vapor pressures means that it will tend to remain more in the liquid phase. The ASTM certified method for measuring vapor pressure of fuels is called Reid Vapor Pressure (RVP). In cold weather a low vapor pressure can make it difficult for the engine to start due to the lack of vaporization of the fuel. However, in warm weather a high vapor pressure can also inhibit startup due to an issue known as vapor lock where the fuel vaporizes in the fuel lines and prevents fuel injection (Chevron 2004).

Ethanol has a non-linear relationship with vapor pressure as the blend increase as shown in **Figure 14**. Low-level blends increase the vapor pressure despite the fact that ethanol alone has a lower vapor pressure. The reason for limiting maximum concentration of ethanol to 85% or E85 is due to the vapor pressure. Even E85 however can have lower blends of ethanol in the winter to meet RVP requirements as shown in previous sections.

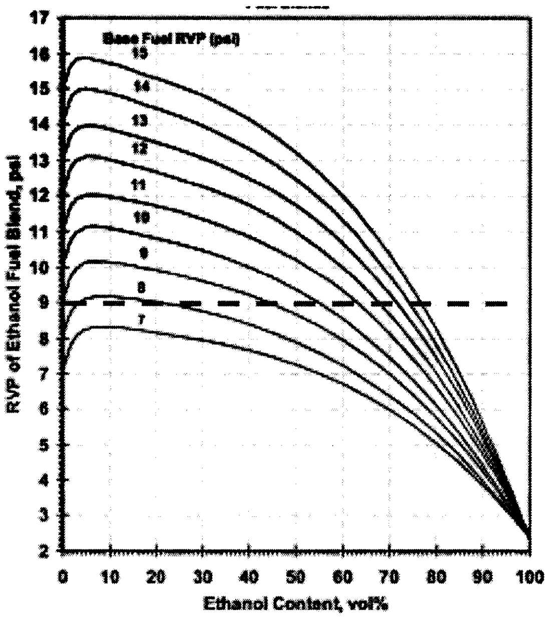

Figure 14 - Effects of ethanol on fuel vapor pressure as a function of volumetric blend. Reid Vapor Pressure (RVP) must be below 9psi unless a specific waiver is granted (Reddy 2007).

Heat of Vaporization.

The enthalpy, or heat, or vaporization refers to the amount of energy required to vaporize liquid fuel. This energy can come from a variety of sources, depending on the design of the engine in which the fuel is used. Thermal energy can be transferred from the intake air, valves, or the piston head or cylinder walls in the case of direct injection.

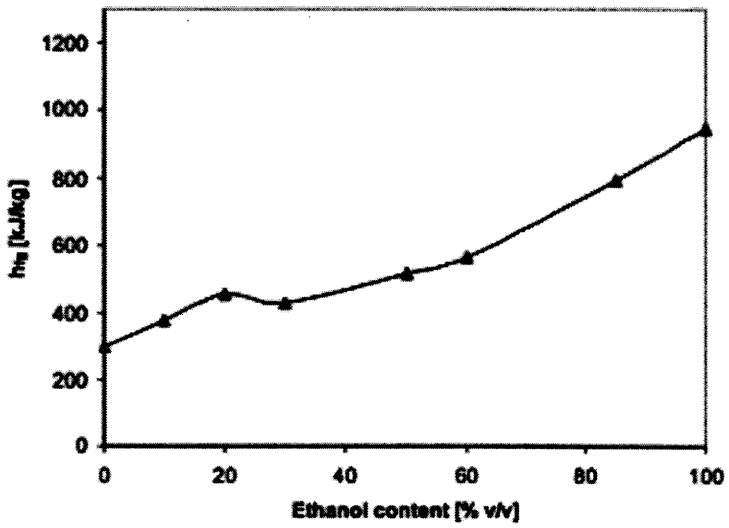

Figure 15: Effect of Ethanol of heat of vaporization (Kar, et al. 2008).

A higher heat of vaporization can help cool some engine components, reduce flame temperature, increase thermal efficiency, and reduce NOX emissions. However, during early operation when the engine is still warming up some of the fuel may not be fully vaporized leading to higher hydrocarbon emissions. These impacts will be discussed further in Chapter 5.

Driveability Performance

The addition of ethanol to fuel creates changes to many properties that have been reference points in the fuel industry for years. A more obscure fuel rating is known as driveability, which encompasses a number of performance factors of a fuel in the vehicle. This includes engine problems such as stalling, stumble, hesitation and surge. Fuel properties mentioned above such as Air to fuel ratio, volatility and other engine parameters can determine this metric which is a unitless index calculated from the distillation curve of the fuel. However, ethanol and oxygenated gasoline do not show the same driveability performance based on this equation. While some concerns persist, driveability has primarily been a metric of importance for carbureted engines. With modern port fuel of MPI injection systems the effects the driveability index are decreased (McArragher, et al. 1999).

The range of gasoline compounds in fuel exists for a set of reasons. The replacement of gasoline with ethanol can reduce some of these functions. **Figure 16** below shows some of the regions in which the evaporation curve for gasoline relates to important functions of the fuel. Some of these functions relate to problems that are outdated due to the replacement of carbureted systems with port fuel injection. Issues like cold start however still persist, which is part of the reason that traditional FFVs are limited to E85 rather than 100% ethanol.

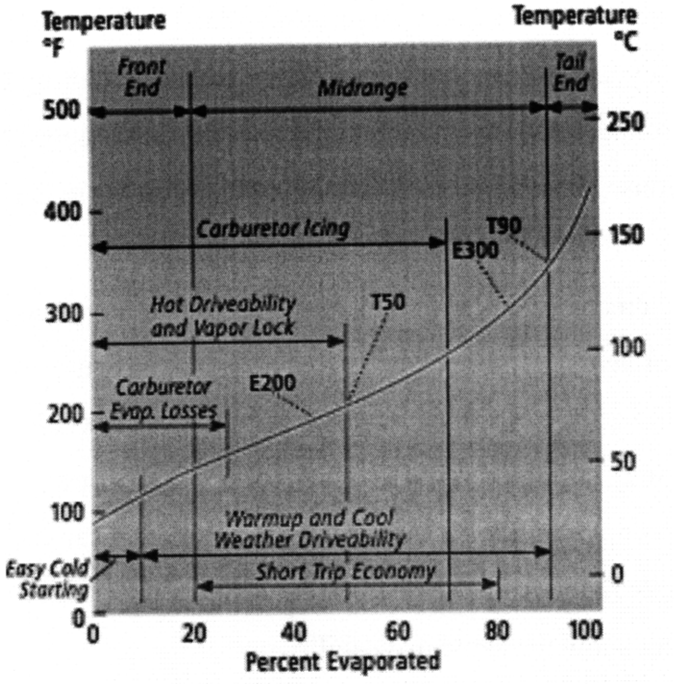

Figure 16: Correlation of Distillation profile ranges with gasoline performance In this case the notation "E100" does not refer to a blend of 100% ethanol but the percentage of fuel that is evaporated at 200 degrees Fahrenheit (Chevron 2004).

Blending ethanol in fuel has some real impacts on the operations of different engines due to the changing evaporation curve of gasoline. These effects often are cause for changing vehicle design and can generate resistance from automakers and refiners who may have to alter existing operating procedures to accommodate to new fuel composition.

Water Tolerance

Ethanol is originally produced at low concentrations from fermentation processes and must undergo distillation processes to remove water and become more concentrated. The inherent limit for distillation of ethanol in water occurs at 92.5% ethanol, which is known as the azeotrope. This mixture of ethanol with water is considered hydrous ethanol. An additional filtration process must be administered to produce pure ethanol (McAloon, et al. 2000). The dehydration of ethanol can have impacts on the vapor pressure of blends (Tanaka, et al. 2007) as well as the tendency to pick up water in pipelines (Hammel-Smith, et al. 2002). Using hydrous ethanol can save some processing energy but leads to a slightly lower energy content of the fuel, and increases the heat of vaporization. Engines must be specifically designed to accommodate pure hydrous ethanol (IEA 2004).

Unlike gasoline, blends of anhydrous ethanol have the tendency to absorb moisture as shown in Figure 17. Upon picking up enough water the ethanol can then fall out of solution with gasoline. This is known as phase separation and is one of the main reasons why ethanol cannot be transported in conventional pipelines, which contain residual water.

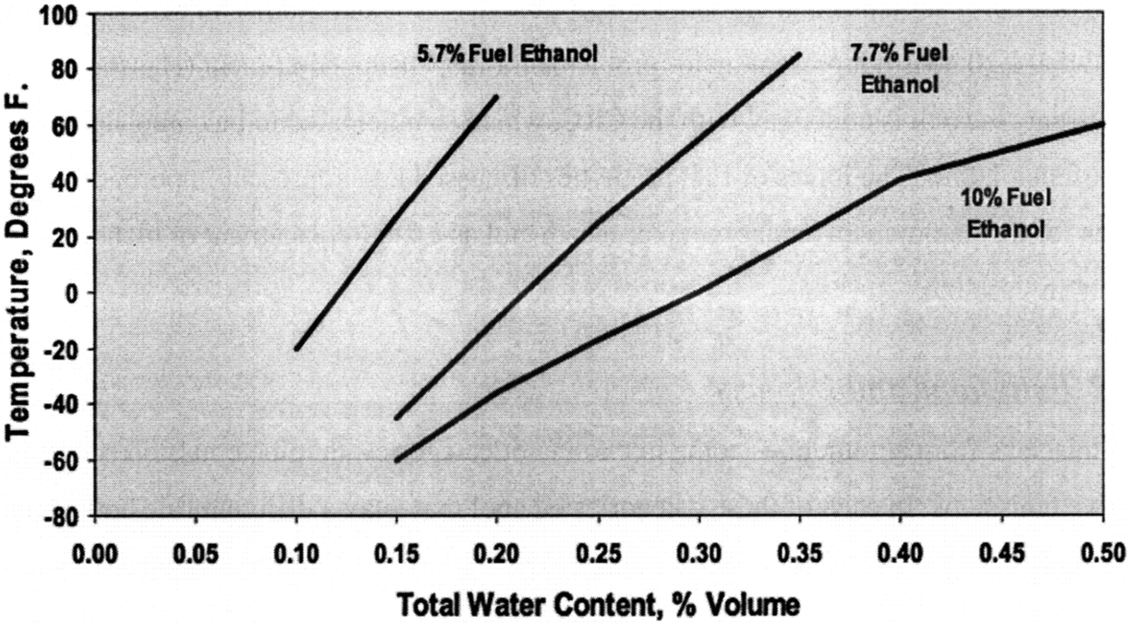

Figure 17: Water tolerance of gasoline/ethanol blends depends on the blend percentage, volumetric water content and temperature. Phase separation occurs at the lines shown where ethanol begins to separate from the fuel mixture(Bauman 2007).

This effect can also be detrimental if it occurs in the fuel tank of a vehicle. Extra precautions must be taken with ethanol to seal the fuel tank to prevent moisture from condensing and separating from the fuel. The water tolerance of ethanol is worse at lower blends as shown in Figure 17.

Materials Compatibility

Ethanol does exhibit interactions with different classes of materials such as metals, plastics, and rubbers. Greater electrical conductivity of ethanol can lead to galvanic corrosion in vulnerable metals. Ethanol blends can increase elastomeric swelling, particularly in Viton A rubber commonly used in gasket seals. Simultaneously the hardness and tensile strength may decrease and lead to cracking. Phase separation from water can make all of these effects more intense. All of these effects however depend greatly on the type of elastomer used. Teflon for example is more stable, but more expensive as well (Hodam 2008).

Additional concerns exist for permeability of certain compounds, which can result in higher permeability issues leading to evaporative emissions. These factors can be mitigated with additional material strategies such as adding nylon coatings (Hammel-Smith, et al. 2002).

Many material concerns exist for non-road applications such as boats, which may have aluminum or fiber glass tanks that are more susceptible to corrosion. Studies in Minnesota have concluded that E20 does not present major problems for dispensing equipment (Hanson, et al. 2008). Current research is underway with the CRC, which is anticipated to be complete in fall 2009 (Groschen 2009). The issues of fuel properties discussed here represent important challenges for the deployment and acceptance as ethanol as a fuel replacement or blend component in gasoline.

4.3. *Emissions and Impacts*

Emissions from automobiles come in two major categories, tailpipe emission and evaporative emissions. In each of these categories ethanol may play a different role both across ethanol blend amounts, and across species of emissions within each category. Ethanol has been promoted in the past as a way of alleviating various types of emissions, but these benefits depend on the blend level and may no exist at all. In the decision to pursue blend of ethanol it is critical to maintain a conscientious understanding of multiple issues. Commonly the debate over alternative fuels is dominated by CO_2 discussions to the potential detriment of local air quality concerns.

Global Emissions

In tailpipe emissions the dominant species is CO_2 and is currently the least regulated. While CO_2 does not have any local harmful effects it is the primary greenhouse gas in the atmosphere contributing to global warming. Emissions of CO_2 can be used as a proxy for vehicle efficiency, and life cycle studies can include production of the fuel in the net CO_2 per mile.

The EPA is charged with developing the life cycle methods for assessing biofuels compliance with the EISA RFS. This remains a highly contentious issue, which has not been resolved completely. Draft assessments of lifecycle GHG intensity are shown in Table 6 below. The clear case is that corn ethanol currently provides little or negative benefit in terms of GHGs with respect to conventional gasoline. However there are other ethanol production technologies and feedstocks, which can afford drastic reduction in life cycle GHG emissions.

Draft Lifecycle GHG Emission Reduction Results For Different Time Horizon and Discount Rates		
Fuel Pathway	**100 Year 2% Discount Rate**	**30 Year 0% Discount Rate**
Corn Ethanol (Natural Gas Dry Mill)	-16%	+5%
Corn Ethanol (Best Case Natural Gas Dry Mill)	-39%	-18%
Corn Ethanol (Coal Dry Mill)	+13%	+34%
Corn Ethanol (Biomass Dry Mill)	-39%	-18%
Corn Ethanol (Biomass Dry Mill with CHP)	-47%	-26%
Soy-Based Biodiesel	-22%	+4%
Waste Great Biodiesel	-80%	-80%
Sugarcane Ethanol	-44%	-26%
Switchgrass Ethanol	-128%	-124%
Corn Stover Ethanol	-115%	-116%

Table 6: EPA values from notice of proposed rulemaking on the net lifecycle greenhouse gas emissions by component with a 30 year time horizon and 0% discount rate. These values are part of preliminary estimates, which have not been made law at the time of writing (US EPA 2009).

Criteria Emissions

In perfect stoichiometric combustion between fuel and oxygen the only products are carbon dioxide and water. However, engines are far from perfect stoichiometric operation and fuels contain many different types of impurities so there is a range of intermediate combustion products. The National Air Quality Standards (NAAQS) include regulation for six pollutants which are considered criteria pollutants. These include nitrogen oxides (NO, and NO2) referred to as NOx, Carbon Monoxide (CO) Ozone (O3) as well as Sulfur Dioxide (SO2), Lead and Particulate Matter (PM). In gasoline spark ignition vehicles the primary emphasis is placed on CO, NOx and other ozone precursors.

Weighting Factors for Hazardous Air Pollutants and Ozone

Ethanol can provide some mixed results in exhaust emissions. Given complex interactions in the fuel and the emissions themselves it is often hard to determine whether the effects of ethanol are net positive of benefit. Some of the emissions produced are not yet specifically regulated, but are linked to harmful effects in humans. Specifically with hazardous air pollutants standards have been developed to weight tradeoffs between different types of pollutants. Similar reactivity values are used to estimate the formation of Ozone from Volatile Organic Compounds (VOCs).

The EPA potency factors are derived from a series of different animal studies. The risk potency is also a function of the ambient concentration. Table 7 is meant to represent the relative values of risk associated with a change in fuel for a single flex fuel vehicle. In this case the generalized indication is that switching to operation on E85 from gasoline for one vehicle example vehicle represents a decrease in health risks from the associated emissions.

	FTP g/mi.		EPA Potency	Relative Potency	
	E85	Gasoline	1/(ug/m3)	E85	Gasoline
Acetaldehyde	6	3	2.20E-06	1.32E-05	6.60E-06
1,3 Butadiene	3	3.8	3.00E-05	9.00E-05	1.14E-04
Formaldehyde	1	0.01	5.50E-09	5.50E-09	5.50E-11
Benzene	0.2	3.8	7.80E-06	1.56E-06	2.96E-05
Total	10.2	10.61		1.05E-04	1.50E-04

Table 7: Summary of Saab Biopower toxic emissions with EPA potency factors (West, Lopez, et al. 2007).

An expanded list of VOCs can be weighted for their reactivity, or tendency to produce Ozone. Maximum Index of Reactivity (MIR) values have been developed through detailed analysis of chemical mechanisms by the California Air Resources Board. In this case the reactivity factors show that simple mass based relationships do not necessarily hold the same proportions.

An additional study of ethanol in lower blends has shown a variety of effects on emissions which are not uniform across different non-FFVs(West, Knoll, et al. 2008). Some HC and CO can be reduced with some blends of ethanol, while some VOCs, particularly Formaldehyde, may be increased (Hochhauser 2008), Based on the complex interaction between these various forms of pollution it is unclear what the net ozone effect might be without very detailed study. It is important to realize that single species emissions quotes do not capture the full story and even net emissions of total hydrocarbons can very in actual impact depending on the composition of the exhaust. Ethanol does not provide universal emissions benefits, or even consistent benefits by species or by blend level.

Heat Soak, Refueling and other Emissions Losses

The emissions of VOCs are not only generated from combustion products in the exhaust. Some VOCs are generated through diurnal heat soak losses (HSL) in the range of 250 mg/day of testing. California requires that heat soak losses be analyzed using real-time emissions measurements in a specialized containment shed. The temperature of the fuel tank is then heated from 60-80 degrees F. The Califonia LEV II requirements have phased in through 2006 but continue in stringency don to 36 mg/test for PZEV certification. A report by the CRC[1] analyzed HSL from a set of separate simulated vehicle test rigs including regular and flex fuel vehicle designs. Results showed that fuel plays a role in permeation losses, but that losses had more to do with the types of materials used. Additionally, while the mass based emissions increased with increasing ethanol fuel, the net ozone formation was the same when the MIR values for ozone formation potential were used (Haskew, Liberty and McClement 2006).

More evaporative emissions occur from leak paths of fuel vapors during the refueling process or through the engine air canister. Figure 18 shows two ways in which vapors can escape directly from the vehicle. The most intuitive path is out through the fuel inlet. Test results show that this factor is dependent of vapor pressure, and a 1psi increase in RVP from blending ethanol does result in a slight increase in refueling losses of approximately 10%. However, using specialized vapor capture nozzles can reduce these effects.

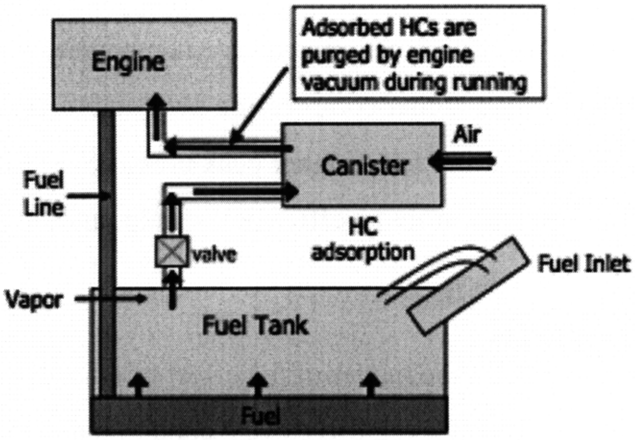

Figure 18: Schematic of fuel vapor leak pathways (Tanaka, et al. 2007)

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[1] The coordinating research council is a non-profit gorup consisiting of the American Petroleum Institute (API) and a large group of automobile manufacturers.

The second vapor pathway occurs while the vehicle is sitting in place. Fuel vapor is released through the canister as shown in Figure 18. The type of engine and canister sizing can have a significant affect on the variability of emissions between vehicles. However, there is a clear impact from a 1psi increase in vapor pressure. It should be noted that the HSL component of emissions are a relatively small component of emissions. The diurnal bleeding losses (DBL) through the canister are more significant (Tanaka, et al. 2007).

One of the major effects of ethanol is increased vapor pressure at lower blends. Vapor pressure is a highly regulated fuel property, which varies seasonally and geographically to help reduce ozone in urban areas. Despite these concerns, many of the mechanisms for evaporative emissions are solvable with materials or slight changes in fuel system design. In general, low blends of ethanol will increase vapor pressure but will displace more of the evaporative emissions with less reactive ethanol.

Emissions Tradeoffs

Several basic fuel properties of ethanol lead to inherent differences in emissions. As an oxygenate ethanol has been shown to lead to reduced CO and hydrocarbon emissions in low blends (Hochhauser 2008). The lower flame temperature of ethanol can also leads to lower NOX formation, which is highly temperature dependent. However these effects are not uniform across all operating conditions blends of ethanol or different types of vehicles.

While the traditional improvements cited with ethanol are CO, HC and NOX, this is not always the case and emissions results are very much based on operating parameters. For example, operating an engine with a higher compression ratio and/or advanced spark timing can lead to higher NOX formation resulting from higher peak pressures and temperatures. Both spark timing and compression are desirable from an efficiency standpoint, but do propose a minor tradeoff (Heywood 1988).

Summary of Emissions Effects

There are no clear answers in the matter of the effect of ethanol on emissions. The results vary from vehicle to vehicle, by blend level, drive cycle condition and local weather. Additionally the effect of each type of emission is different and may be counterbalanced by other operating effects.

Neither E10 nor E85 are likely to be the "best blends" from the perspective of many different fuel properties. Thus far they have been pursued as method of using large quantities of ethanol rather than using ethanol in the most efficient or emissions reducing manner.

Carbon Dioxide (CO2): Corn ethanol can offer a slight benefit in lifecycle ghgs with the use of low carbon co-firing energy.

Carbon Monoxide (CO): Reductions of approximately 10% are possible with low blends of ethanol but it appears that this effect stagnates at 10% ethanol by volume and does not increase over further increasing blends.

Nitrogen Oxides (NOx): Slight reductions are possible at low and high blends, but it appears that this trend can reverse in mid level blends of ethanol.

Hazardous Air Pollutants (HAPs): There are mixed results here with a decrease in gasoline aromatics and an increase in Aldehydes. The risk factors of each appear to tip this balance in the favor of ethanol, even at high blends. However, it is unclear how future benzene reduction in fuel will affect this balance. Catalyst improvements may also minimize the effect of Aldehydes.

Volatile Organic Compounds (VOCs): Again results are mixed because each compound emitted has a different index of reactivity. Ethanol blends tend to produce more emissions on a mass basis but the lower reactivity of ethanol balances this effect to some extent.

In the context of ethanol policy the focus on deployment should not necessarily preclude a discussion of effective deployment of the fuel for local environmental or health concerns. Often the focus of biofuels policy is on greenhouse gasses. Ethanol and early oxygenates were supported to reduce CO and ozone formation. The net effect from ethanol in exhaust appears to be neutral on ozone formation potential however. Ethanol may lead to higher formations of formaldehyde, but this effect is balanced to some degree by the displacements of other toxic emissions. Ultimately ethanol may represent some tradeoff between local air pollution and global air pollution. However, specific design of vehicle and refueling systems can shift the balance to have less effect on local emissions.

4.4. *Scenario Analysis: Effects of Mid-Level Blends*

The major policy questions for mid level blend are focused on what

1. What percentage of ethanol volumetric blend is certified as a legal fuel?
2. When does this standard come into effect?
3. For which vehicles does this standard apply?

Based on the results from recent tests it seems feasible that the EPA may certify E15. Studies conducted by the CRC and West et al. (2009) indicate some negative impacts on emissions and driveability that do not appear to be significant enough to deny extension of the blend limit. Since UL has agreed to certify dispensing apparatus to this amount there is lower risk for retail station owners. The time frame for this certification may reasonably be in the range of 2012 to 2015, providing time for current studies on material effects to be completed and the EPA to issue a ruling.

The remaining question then, is how many vehicles will be operated on E15. This is perhaps the most difficult question because it involves a decision by automakers to extend warranties of existing vehicles on E15. For the EPA to certify a higher blend than was anticipated by automakers there may need to be some sort of government warrantee risk sharing program.

In this case however the fleet model can be used as an assessment of the largest improvement possible with certification of blends. To this end, E15 is assumed to be widely available and used in all vehicles starting in 2012. The impact of this policy is shown in Figure 19 in relationship to the model results with only E10 Certified. The output of the model is again in utilization percentage, which is the metric for how much each FFV must use E85.

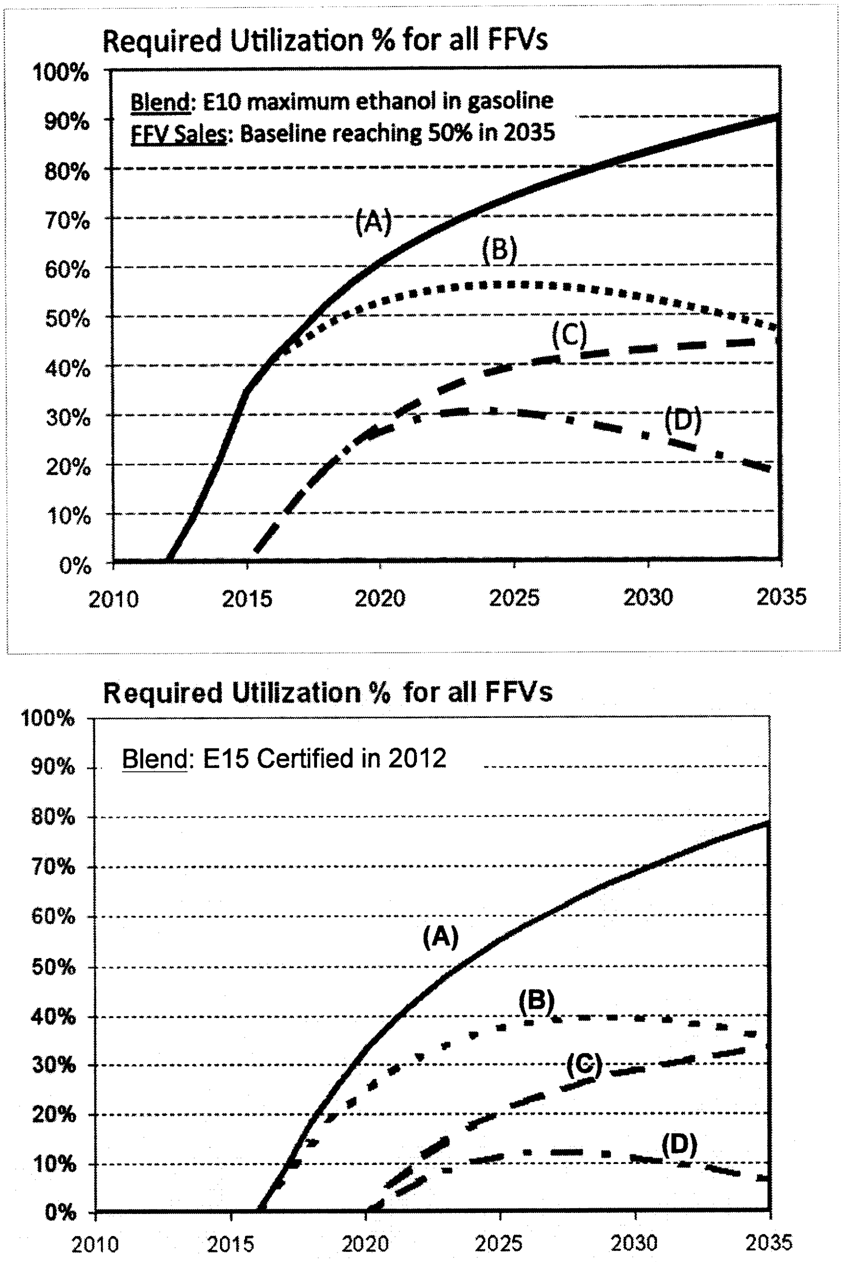


Figure 19: The top figure shows the reference case described in Chapter 3 for reference. The bottom figure shows the same results with the addition of E15 certification in 2012. The sequence of assumptions is the same for both graphs with regard to biofuels targets and miscible biofuels. (A) 60 billion gallons in 2035 (B&C) reach 36 billion in 2035 (D) Entry of miscible biofuels decreases total ethanol targets further as shown in Chapter 3.

There are two key differences in required FFV utilization % that result from the certification of E15. One is the notable time shift in the observation of the blend wall. Instead of the 2013-2015 time frame the increase in utilization does not occur until 2015 or even 2020 in the delayed RFS case. Second, the peaks value for utilization in each scenario is decreased with the certification of E15. Case "B" with aggressive targets only requires the utilization levels of

Case “C” when it is combined with the E15 certification policy. These results represent a maximum impact under the assumption that all vehicles use E15 in the entire gasoline supply. The reduction in utilization is partly due to the greater ethanol blended in gasoline, the second effect is that additional time elapses before the blend wall which allows for more FFVs to enter the fleet.

The additional option of certifying E20 may emerge, but that scenario is not graphed in this example. Additional overlaying strategies may be pursued through eh deployment of advanced vehicles which will be explored in the following chapter.

The modeling techniques used in this report do not include the capability to do emissions modeling at the vehicle level, or predict warranty concerns from the use of E15 in legacy vehicles. These concerns are valuable in order to form the context of the assumptions being made. Less likelihood is place on the emergence of an E20 blend unless vehicle modifications are made. However in the future, E85 may also decrease in popularity in favor of mid level blends due to concerns over emissions.

There is not a framework in place to certify vehicles for emissions based on a range of fuel blends. If flex fuel vehicles begin operating on E0, E10, E15, and E85 and perhaps even intermediate blends then there may be different effects to which the emissions after-treatment system must adapt.

5. Fleet Vehicles: Efficiency & Deployment

This chapter will discuss existing flex fuel vehicles and options for the design of future powertrains to take advantage of ethanol fuel properties. This discussion will be used to form the inputs for the number of FFVs sold each year and their relative fuel consumption vs. gasoline.

5.1. *Policy Context*

The American Motor Fuels Act (AMFA) of 1988 provided the first incentives for flex fuel vehicles and worked within provisions of CAFE. Flex fuel vehicles were sold previously because of these CAFE credits that were calculated using the following equation (Title 49. USC Section 329).

Equation 2:

$$FE = \left[\frac{0.5}{FE_{gas}} + \frac{0.5}{FE_{alt}/0.15}\right]^{-1}$$

It was assumed in the calculation of fuel economy that FFVs would run on renewable fuel half the time. While running on a fuel alternative the fuel economy (FE_{alt}) was given more than 6.5 times its fuel economy on gas (FE_{gas}) original value due to a presumed gasoline equivalency (Collantes 2008). This credit system was originally set to expire in 2010, but was extended to phase out through 2019. This incentive was widely recognized as a misrepresentation of the true fuel economy for FFVs, but it was the only incentive for FFV production. While AMFA was successful in getting more flex fuel vehicles on the road there was a disconnect with the amount of fuel used, deployment of infrastructure to provide the fuel, and incentives for drivers to use gasoline alternatives (U.S. Department of Transportation, U.S. Department of Energy, U.S. Environmentla Protection Agency 2002).

American auto manufactures have stated intent to increase FFV production with the potential of producing half of their model lineup with flex fuel capability in 2012 (Associated Press 2007). However, this intent is only on the part of the domestic automakers GM, Ford and Chrystler. Given the current financial situation of the domestic auto industry it is not clear whether or not these commitments will still be held, and if they are how many vehicles will actually be produced as FFVs.

More recently there has been legislation introduced to attempt accelerated deployment of FFVs. The Open Fuel Standard Act was introduced in July 2008 by Senators Brownback Salazar, Collins Lieberman and Thune. The stated plan was to require half of all new vehicles sold to be flex fuel capable starting in 2012. In 2015, 80 percent of new vehicles would be required to be flex fuel. The fuel specifications included ethanol and methanol at volumetric blends up to 85% (Brownback 2009).

Flex Fuel Fleet

In the United States there are an estimated 7 million flex fuel vehicles on the road today. FFVs are almost exclusively produced by American auto manufacturers as shown in the figure below. While there were approximately 1 million FFVs sold in 2007, more than half of the units sold were trucks. This is presumably due the general sales composition for American auto companies, the greater need for CAFE credit in light truck fleets and the nature of the US market in regions where ethanol is more available (Wingfield 2008).

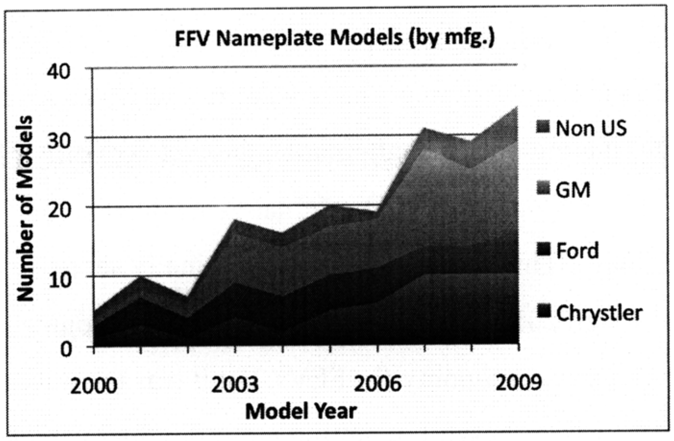


Figure 20: Break Down of FFV models offered by Manufacturer (US DOE: EERE 2008)

The cost of producing a flex fuel vehicle is estimated to be $100 or less to the auto manufacturer. Basic changes to the vehicle include the injector orifice sizing to accommodate higher fuel flow at peak loads and gasket material that is more tolerant to ethanol. Currently flex fuel capability sells as a zero cost option where it is available (Union of Concerned Scientists 2006).

The future progression of FFV sales is unclear due to the current phase out of CAFE support. FFV sales may also decline because the dominant manufacturers of FFVs are showing declining sales. However, Toyota has begun introduction of FFV models, and ethanol capability is a relatively cheap modification which uses existing technology there is some potential for much faster deployment than other alternative powertrains such as hybrids.

Challenges still exist for producing FFVs that were mentioned in Chapter 4. Ethanol has an effect of increasing aldehyde emissions, which makes it more difficult for E85 vehicles to meet emissions requirements. While most FFVs are certified Tier II bin 5 there are a few that are listed as Tier II bin 4 (Davis 2008). Lower formaldehyde emissions are possible with specific catalyst changes, but this presents a challenge for FFV production in the context of tightening emissions regulations.

FFV Sales Scenarios

There a wide range of possibilities for future sales deployment of Flex fuel vehicles. Without a clear policy incentive for ethanol capable vehicles the percent of new vehicles sales may stagnate or even decline. In the presence of aggressive policy mandates, half of new vehicle sales might be ethanol capable in just a few years. However, given that the automakers that are currently producing FFVs are seeing declining sales, the reference sales scenario grows slowly, but eventually reaches 50% in 2035 as shown in Figure 21. This case is used as a baseline and leads allows for achieving the aggressive target biofuels scenario without exceeding 100% utilization.

The Open Fuel Standard policy is used as a model for the aggressive deployment scenario. However it may be too aggressive or the US fleet considering that it would rely on the fast deployment of FFVs by foreign manufactures, However a Delayed version of this policy is used as the agressive FFV deployment scenario under strong guiding policy.

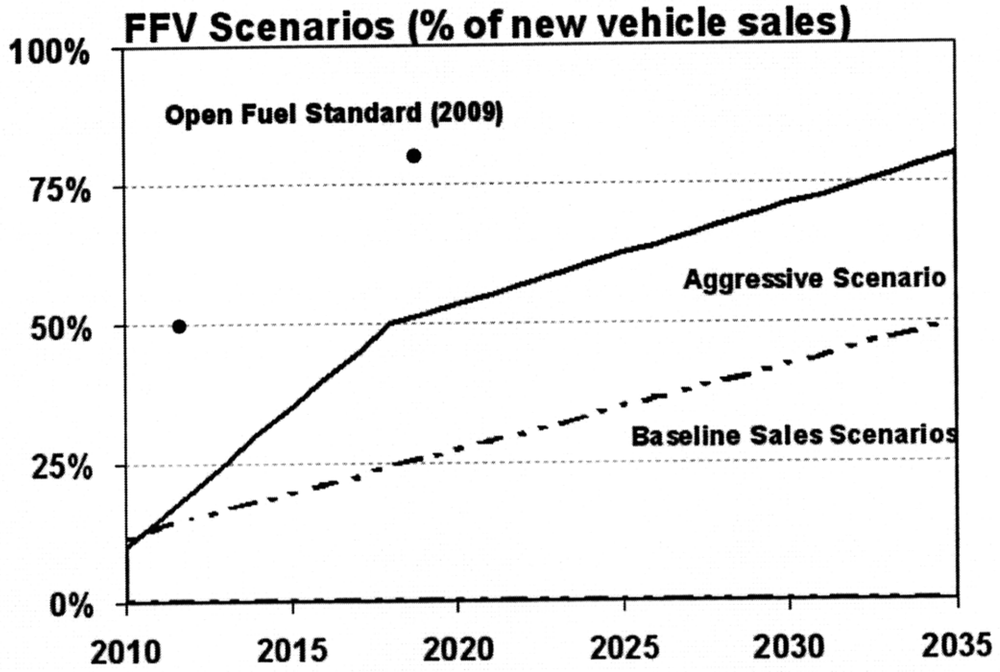


Figure 21: Scenarios for Flex fuel vehicle deployment. The baseline scenario is a steady extrapolation of existing growth. The Advanced scenario is based on the Open Fuel Standard proposal, delayed by a few years to be slightly less aggressive.

The relative benefit of advanced vehicle deployment cases varies depending on the total amount of fuel required. It should also be noted the Open Fuel Standard currently provides recognition to diesel vehicles which are not treated separately from flex fuel vehicles.

There is a geographic distribution component to deployment, which will be discussed in Chapter 6. This addresses the issue of how the need for ethanol vehicles is affected by a regional deployment strategy versus a national deployment strategy. The sales volumes required may be lower in a regional strategy if the utilization rate is higher. This difference will also have an impact on the potential for optimization with is the topic for the following section.

The deployment of new vehicles must take into account technological development. The fleet model structure, discussed in Chapter 2, provides for technological evolution of the fleet as the mix of vehicle technology changes. Assumptions must also be made about the technological development of FFV technology to discern the relative fuel consumption of these vehicles on E85 and gasoline.

5.2. *Engine Opportunity*

Thus far, several different options have been discussed for using ethanol more effectively. As an alternative fuel, ethanol can be used to displace gasoline, which can be a direct goal independent of others. Ethanol can provide net GHG benefit depending on how the fuel is made and the boundaries of the LCA calculations. Ethanol also offers some additional octane value, which can be used to decrease the requirements on refineries to produce high octane fuels. This can result in cost savings and marginal reduction in energy consumption at the refinery depending on the type of operations (Kahsnitz, et al. 1983). If ethanol is used to increase the octane of fuel then performance and fuel economy improvements may be possible in FFVs. Ethanol can offer additional advantages for engines in the form of knock resistance and cooling power. The anti-knock properties along with others covered in Chapter 4 have impacts on different areas of operation in current and future engine designs.

Current Flex Fuel Vehicles

The design of flex fuel vehicles has not changed to exploit any advantage of ethanol fuel properties (Ward's Automotive Group 2008). The dominant effect of ethanol is on the volumetric measure of fuel economy in miles per gallon. The focus of this section will be on the energetic measure of fuel efficiency, which can be represented in gasoline equivalency mpg of in fuel consumption (L/100km).

Studies vary on the effect of operating current flex fuel vehicles on ethanol. The listed EPA numbers from fueleconomy.gov suggest that there is no statistically significant change in fuel economy of FFVs when operating on either fuel (Roberts 2007). A separate study suggests that in fact there are some differences in city and highway fuel economy for FFVs when operating on ethanol relative to gasoline. Figure 22 shows results from this analysis which suggest that FFVs roughly achieve <5% fuel economy benefit in drive cycle benchmarking.

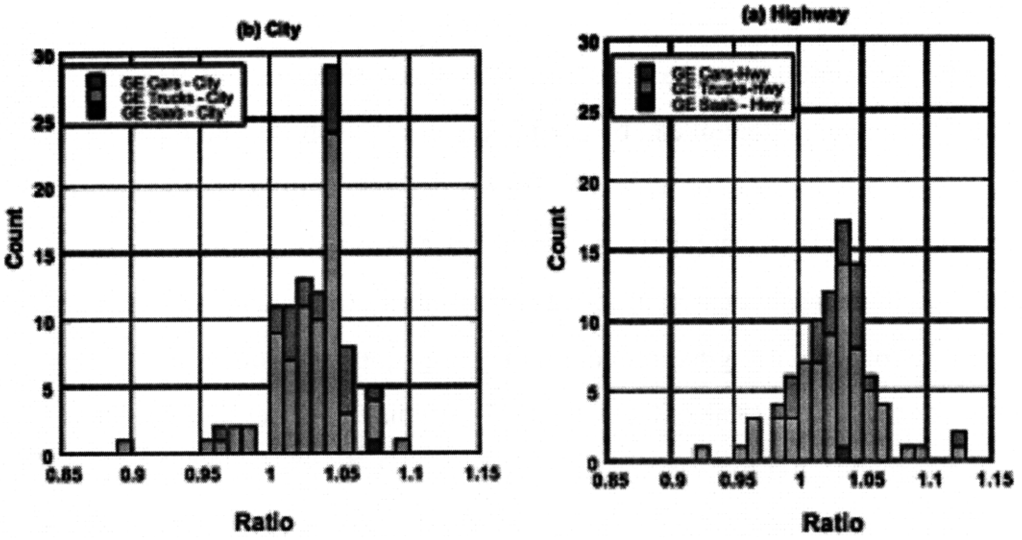


Figure 22: Analysis from (West, Lopez, et al. 2007) showing relative fuel economy in flex fuel vehicles operating on E85 vs. gasoline.

The report by (West, Lopez, et al. 2007) was focused on the benchmarking of the Saab BioPower, which an emerging class of vehicles that are "optimized" to take advantage of ethanol fuel properties. For general purposes the use of the term optimization will refer to the differential in vehicle performance for a vehicle running on ethanol compared to the same vehicle running on regular gasoline. The benefits can be in the form of fuel economy or other performance metrics like acceleration or peak torque. These benefits are the result of changing fuel properties of ethanol and specific interactions with different regions of engine operation.

Octane Rating

The principal advantage of ethanol has to do with normal knock control due to a higher octane rating. Regions of the engine map where knock typically occurs are at lower RPM and wide-open throttle (WOT). Aggressive acceleration such, hill climbs, or towing are operating cases that will tend towards higher loads at low RPM. There are a number of operating strategies that can be used to combat knock in these cases. For a given octane fuel, knock can be avoided by reducing the compression ratio or delaying the spark timing. In either of these strategies there are sacrifices in thermal efficiency as shown in Figure 23. Knock sensors can detect the onset of knock and then retard spark timing accordingly, virtually eliminating driver experience of the knock phenomenon. Newer cars can advance spark timing in addition to retarding, which means that they can take advantage of higher octane fuels in previously knock limited regions.

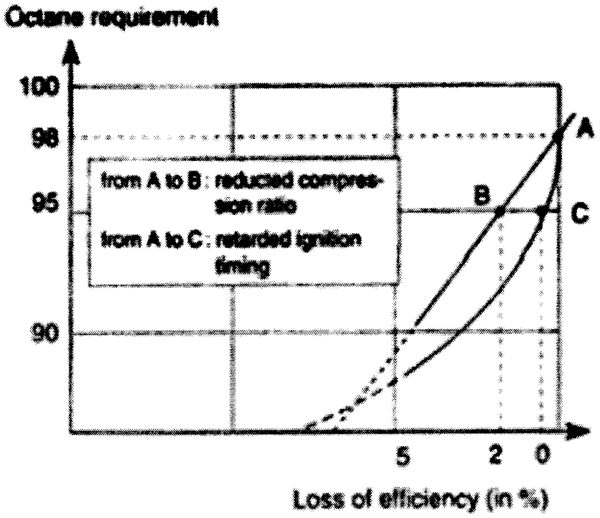


Figure 23:Tradeoff between compression ratio and spark timing in efficiency terms (Guibet and Faure-Birchem 1999)

Some luxury and performance vehicles recommend higher-octane fuels to take advantage of higher compression ratios or boost pressures and the octane enables performance at high loads for peak performance. Increasing compression ratio and/or turbo-charging will advance the onset of knock. This has been an empirically studied phenomenon with greater emerging theoretical understanding (Gerty and Heywood 2006).

Cooling Power

There are additional anti-knock properties of ethanol not captured entirely by the octane number. During engine operation heat from parts of the engine is used to vaporize fuel before combustion. Increasing the energy required to vaporize fuel, confers a "cooling power" to the fuel. An increase of the heat of vaporization by less than 8 kJ/kg has the same impact as increasing the RON value of the fuel by one point during operation in a DI engine. An E10 blend can typically provide this level of cooling power increase against regular gasoline (Milpied, et al. 2008).

One of the major impacts on volumetric efficiency can be achieved through the charge cooling effect. Colder air is denser and therefore more can occupy the same cylinder volume. Direct injection contributes to charge cooling by evaporating the fuel inside the cylinder. Higher heat of vaporization of fuel can also increase the charge cooling effect as long as there is effective heat transfer from the air to the fuel. Volumetric efficiency is decreased however through the displacement of air by fuel vapor. Larger volumes of ethanol are required at a given power due to it's lower energy density. This results in slightly lower volumetric efficiency on high ethanol blends. These effects may vary depending on the blend of ethanol as shown in (Nakata, et al. 2006) and (Taniguchi, Yoshida and Tsukasaki 2007).

Molecular Effects

When compared to gasoline, ethanol has a much simpler molecular structure, and is one compound instead of many. As ethanol is partially oxidized this contributes to a lower air to fuel ratio. At a given load this effect is largely balanced by the decreasing energy density of ethanol which means that for a given amount of energy the air required is roughly the same (Hammel-Smith, et al. 2002).

The higher number of ethanol molecules required due to a lower energy density can actually contribute marginally to a reduction mechanical losses due to pumping work. For a given amount of air post throttle the are more ethanol molecules being injected into the cylinder which raises the intake pressure relative to gasoline and can decrease the mechanical losses of the intake processes (Heywood 1988).

There is some evidence to suggest that ethanol can tolerate leaner operation due to a slightly improved flame speed. This will allow higher rates of exhaust gas recirculation to achieve other benefits as well (Marriott, Wiles and Gwidt 2008).

Compression ratio and Turbocharging

The effects of ethanol on volumetric efficiency, thermal efficiency and spark timing can deliver the observed effects of increased FFV energy efficiency when operating on E85. The next logical progression is to explore the potential for increased efficiency if an engine is designed to take advantage of these properties. For roughly ever 4 or 5 increase in RON the compression ratio can be increased by one. This imparts both a gain in efficiency and an increase in peak load. (Guibet and Faure-Birchem 1999)

The major gains in thermal efficiency are mostly realized at wide-open throttle (WOT). Also, there are diminishing returns to increasing compression ratio, and at some point the engine walls must be strengthened to accommodate the higher pressure, which adds to cost and weight. Some of the increase in torque can be used to downsize the engine to maintain constant torque, but decreasing cylinder bore sizes reduces the thermal efficiency of the engine (Heywood 1988).

Several companies including MCE-5, Honda, FEV, Renault and others are in the process of developing Variable Compression Ratio (VCR) engines, which are able to adjust engine compression depending on the speed load, and type of fuel. This type of technology would deliver a baseline efficiency improvement in gasoline engines but would also provide additional marginal gains for blends of ethanol fuel (Wittek, Tiemann and Pichinger 2009). Higher performance and efficiency are possible based on higher compression ratios on E85 as shown in Figure 24.

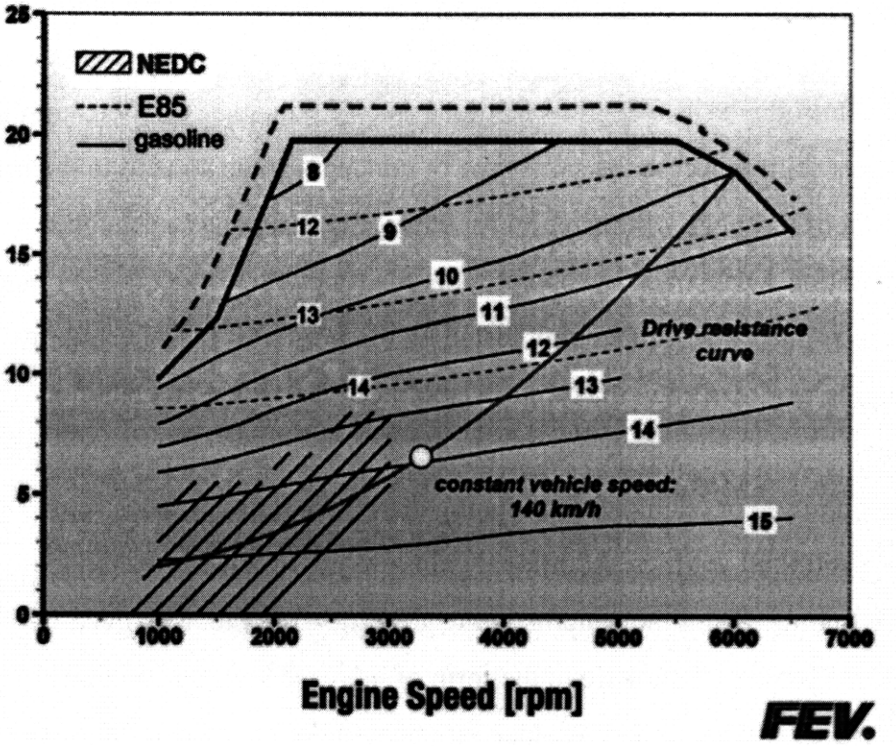


Figure 24: FEV engine map for a variable compression ratio engine operating on gasoline or E85. Higher compression ratios and maximum BMEP (shown on the vertical axis) are possible when operating on E85 (FEV 2008).

Similar to increased compression ratio, turbocharging can increase performance and efficiency in an engine. There is, however a tradeoff between increasing compression and increasing boost pressure for a given octane fuel. In either case, the increase in peak torque can be used to increase performance or used to increase efficiency by keeping performance constant and downsizing the engine (Gerty and Heywood 2006). In the case of ethanol companies like Saab are already producing the first turbocharged ethanol optimized vehicles that advertize significant performance gains while operating on E85 (West, Lopez, et al. 2007).

A number of other companies are pursuing flexible boosting, or flexible injection strategies to transform the possible improvements with ethanol into efficiency gains as well. Ricardo (Christie, Fortino and Yilmaz 2009) and Ethanol Boosting Systems (EBS) suggest that significant efficiency improvements are possible by using ethanol to allow for more aggressive boosted downsized engines. Some strategies include variable boost, variable compression or variable ethanol injection in the EBS concept to allow for flexible optimization while operating on ethanol (Blumberg, et al. 2009).

Ethanol Optimization

Ethanol fuel provides a resource, which can be developed to reduce fuel consumption or to improve performance. Performance can be understood as faster acceleration or increased vehicle size. This concept is introduced as a degree of Emphasis on Reducing Fuel Consumption (ERFC) mentioned in Chapter 2. In this case the same type of concept can be applied to the use of the technological potential of biofuels. Optimization for ethanol is defined as a change in performance of fuel consumption when a vehicle operates on one fuel with respect to the other.

With FFVs the terms of the tradeoff are complicated by the presence of fuel economy values for each fuel. Changing engine design may improve both of these values together or improve fuel economy on ethanol without improving fuel economy on gasoline, or even at the expense of gasoline fuel economy. For example, introducing direct injection provides some efficiency advantages for gasoline SI engines. Additional gains are possible when running ethanol in DI, which do not subtract from the benefits in the gasoline example. However, in many cases the benefits from running ethanol are in the form of increased torque and power.

In order to convert these benefits in performance into benefits in fuel consumption the engine must be downsized. Figure 25 shows the effects of compression ratio and turbo charging on brake thermal efficiency, as well as additional gains that can be achieved through downsizing. Ethanol enables increases in compression ratio and boosting. In a dedicated ethanol engine downsizing would allow for additional gains. However, when the downsized engine runs on gasoline the performance is diminished which means that the gains of operating on ethanol have come at the expense of operating performance on gasoline. This illustrates a tradeoff between performance and efficiency that relies on the availability of ethanol fuel.

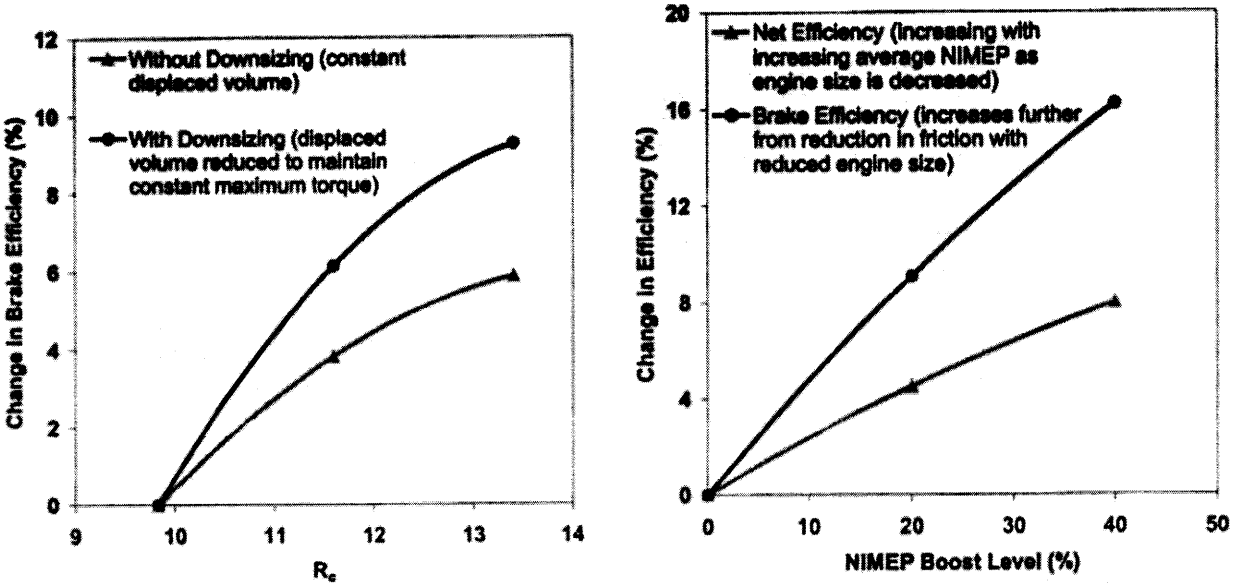


Figure 25: In the case of compression ratio (R_C) and boosting of Net Indicated Mean Effective Pressure (NIMEP) there are initial gains in brake thermal efficiency. If performance is maintained constant and the engine is downsized there are additional gains possible (Gerty and Heywood 2006).

Vehicles can use variable adjustments like VCR systems, preserve gasoline performance and only provide benefits while operating on ethanol fuel. Experimental systems like VCR engines would allow for the compression ratio gains in efficiency and performance to be achieved when ethanol is used. However the downsizing gains would not be realized. Other concepts like EBS offer some possibility that downsizing optimization may be achieved even when ethanol is not widely available. The EBS concept allows for minimal use of E85, which allows much longer range between E85 refueling which still achieving the optimization benefits. However the dual fueling has often been cited as a social acceptance hurdle and there are technical challenges relating to injector cooling that must still be addressed (Blumberg, et al. 2009).

5.3. *Flex Fuel Design Space*

There are several fundamental strategies to reducing petroleum consumption and greenhouse gasses from automotive transportation. Reductions must be made one of the following areas: Total vehicles, miles travelled per vehicle, fuel consumption per vehicle, or the carbon intensity of the energy used. In the context of this research, vehicles sales and vehicle miles traveled (VMT) are considered to be set. This leaves two fundamental paths for reducing petroleum consumption and greenhouse gas emissions from transportation vehicles.

1) Displacing petroleum fuel with an alternative fuel.
2) Increasing efficiency of automotive powertrains

It is critical to note in this case that these strategies are not mutually exclusive, and in fact can be synergistic. Biofuels can enable additional improvements in fuel economy or performance with existing technology. When gasoline consumption is normalized at 1, relative improvements in fuel economy, or blending fuel alternatives like ethanol, can reduce the relative gasoline requirements as shown in Figure 26.

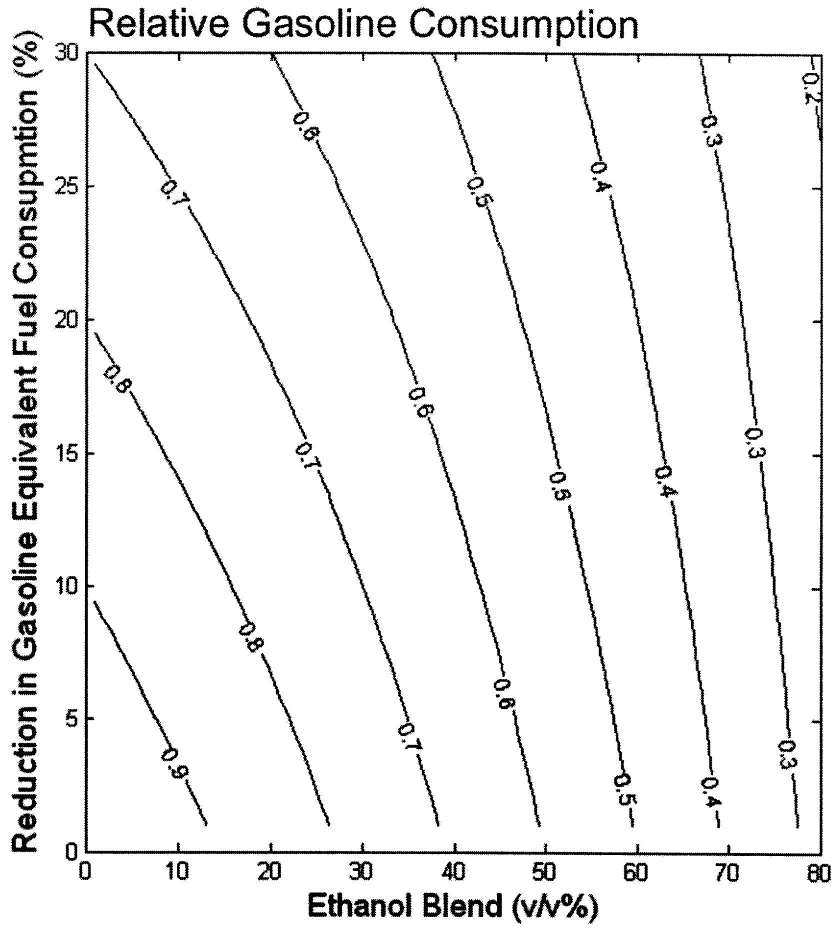


Figure 26: Reduction in gasoline used per unit mile as a function of ethanol blends. This assumes that every unit of ethanol displaces an energy equivalent volume of gasoline, and that no gasoline is used to produce ethanol.

Relative gasoline consumption as shown in Figure 26 does not account for the emissions associated with production of ethanol. While the displacement of gasoline usage can be an end in itself, more attention has been placed on the effect of reducing life cycle emissions. The relative improvements in GHG intensity for each mile traveled will depend on the efficiency of the vehicle and the GHG intensity of the fuel used.

The GHG intensity for each vehicle mile can be normalized to a reference value for an vehicle operating on traditional gasoline. From this initial emissions value of 1, every % reduction in fuel consumption results in a corresponding decrease in associated emissions. For example if the fuel consumption per mile were cut in half each mile would result in 0.5 GHG intensity per mile with respect to the original normalize performance.

The GHG intensity of the fuel depends on the mix of biofuels in the gasoline supply and the relative carbon intensity of the biofuels. The relative GHG of an aggregate volume of a biofuel blend will result from the production weighted average of lifecycle GHG intensity and the blend percentage. To illustrate this calculation the RFS target production for 2022 can be used. The current classification of fuels segments classes of fuels by 20%, 60%, and 50% reductions which means. Each fuel therefore has 80%, 40% or 50% the GHG intensity per unit energy with respect to the original fuel baseline. These classifications can be adjusted within the statute by 10%. The resulting weighted average GHG intensity is shown in the top part of Table 8. These values correspond to what would be achieved in 2022 if the RFS volumetric standards are met. However the actual carbon intensity may exist at a range of other values.

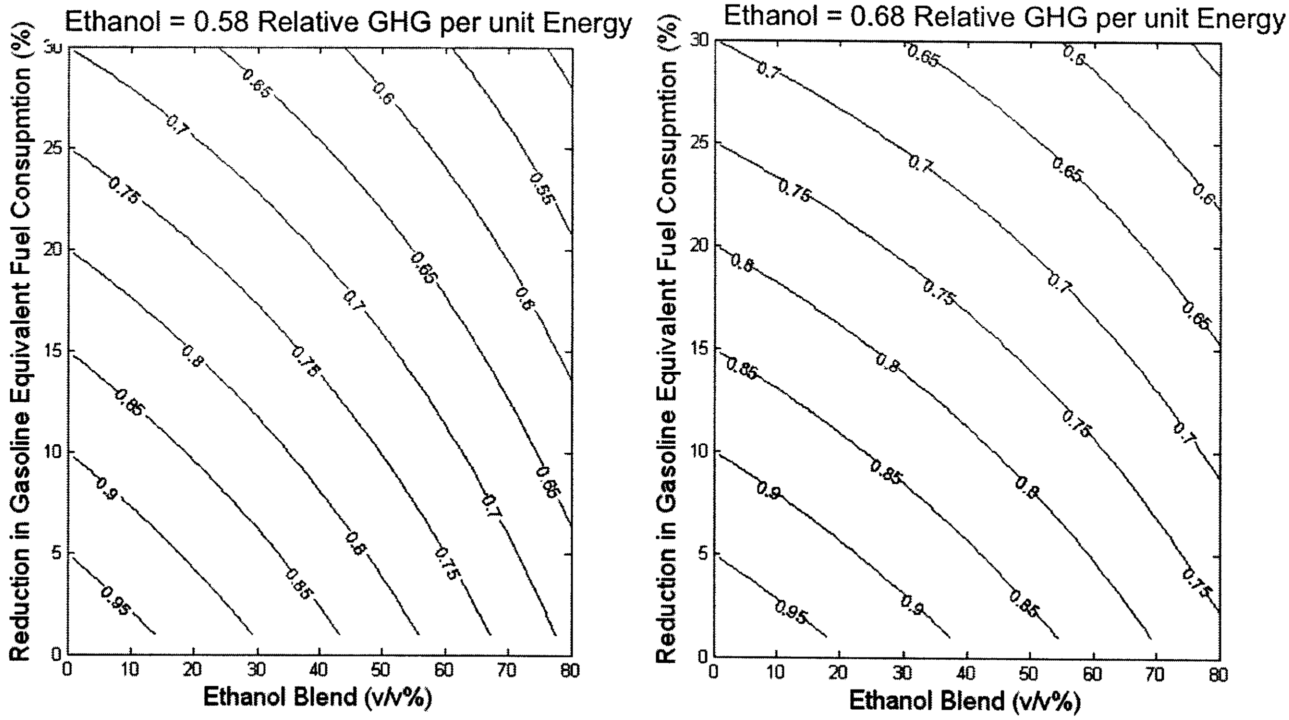
Reference LCA GHG intensity of biofuel against a Petroleum Baseline (Energy Basis)

RFS Classification	Current RFS Statute Targets	Potential Adjusted Reduction Levels
Corn Ethanol	80%	90%
Cellulosic Biofuels	40%	50%
Other Advanced	50%	60%
Weighted Average	**58%**	**68%**
Ethanol Blend (v/v%)	Relative Carbon intensity per mile	
10%	0.97	0.98
20%	0.94	0.95
30%	0.91	0.93
40%	0.87	0.90
50%	0.83	0.87
60%	0.79	0.84
70%	0.74	0.81
80%	0.69	0.77
100%	0.58	0.68

Table 8: Relative carbon intensity per mile driven is shown as a function of volumetric ethanol blend. Varying assumptions for relative life cycle GHG impact are shown based on categories from the current RFS.

The methods for calculating life cycle GHGs are highly contentious and are in the process of being resolved. This debate continues and will not be uniform across all types of ethanol production. In this case the values from the 2007 RFS are used as a benchmark to show the potential effect of carbon reductions. Today the weighted average of ethanol may be closer to 80% or higher depending on the methods used for life cycle assessment.

The two strategies of vehicle efficiency and biofuel blending can be represented on the same graph to show the combined effect on relative carbon equivalent GHG intensity for a mile driven. Figure 27 shows graphs corresponding to two the values for weighted carbon intensity of ethanol based on the assumptions shown in Table 8. Each line on the graph shows a contour representing equal normalized carbon intensity per mile.

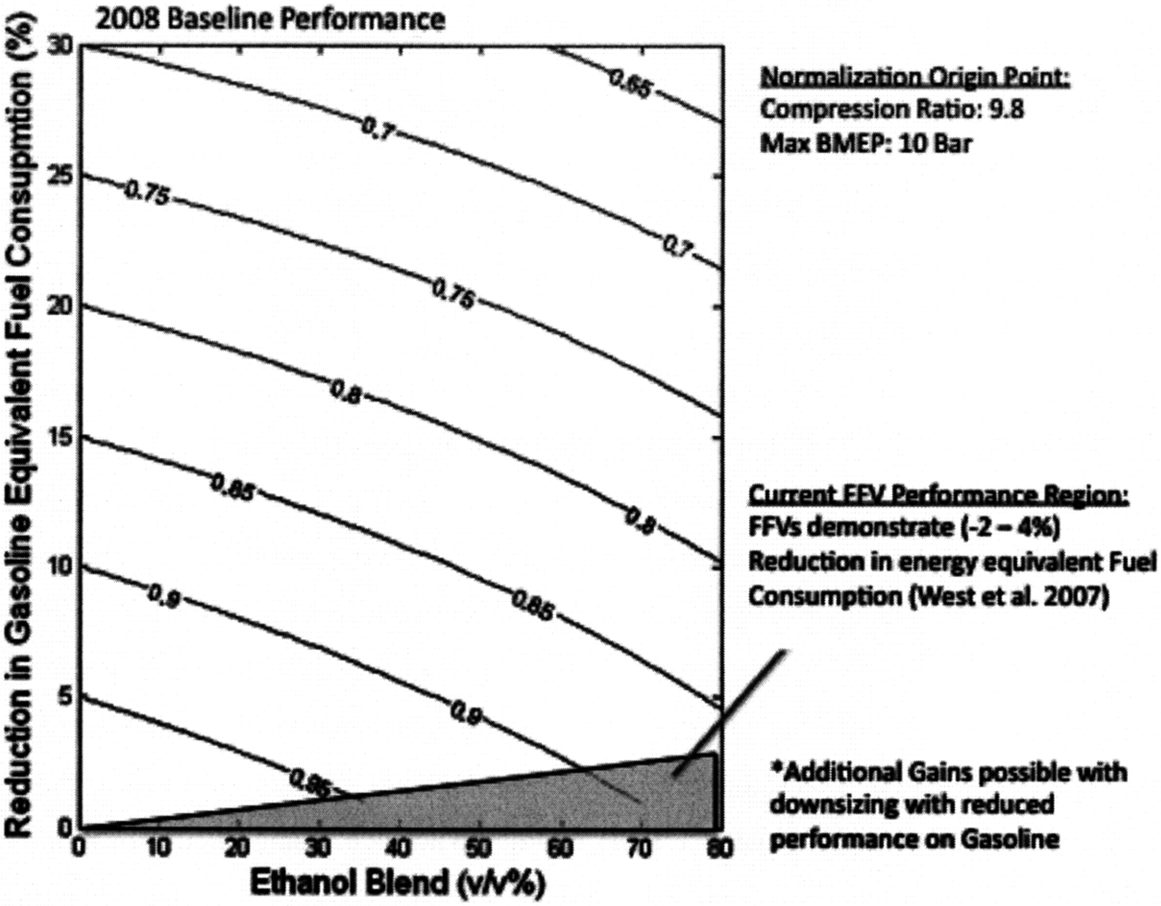

Ethanol = 0.58 Relative GHG per unit Energy

Ethanol = 0.68 Relative GHG per unit Energy

Figure 27: Relative carbon equivalent per vehicle mile traveled from a reference normalized to 1 at the origin. Improvements in vehicle fuel consumption on the vertical axis translate directly into reductions in equivalent carbon per mile. The blending of ethanol results in reductions in carbon intensity according to the assumptions for the carbon intensity of the fuel. Two different assumptions are shown (left) 58% carbon intensity with respect to baseline fuel (right) 68% carbon intensity with respect to baseline fuel.

The graphs in Figure 27 represent approximations of what ethanol might offer for carbon reduction in 2022 and beyond. The picture today looks somewhat different. Some estimates suggest that ethanol may even represent increased carbon intensity with respect to gasoline as shown in Table 6. In this case the contour lines would slope upward with increasing ethanol content. Estimates for the benefit of ethanol today can vary so for the 2008 reference a value of 85% GHG intensity was used for ethanol in Figure 28.

The FFVs that are currently offered provide some increase in fuel economy when operating on ethanol without any additional engine design modification. The range of values is shown in Figure 22 with a median value of 3-4%. The low energy density dominates the fuel economy values when examined on a volumetric basis so the energy equivalent improvements are not generally noticeable to the driver. The design window in Figure 28 is shown on the basis of energy equivalency. In order for the volumetric miles per gallon to be equal a vehicle would have to achieve 30% better fuel consumption while operating on E85.



Normalization Origin Point:
Compression Ratio: 9.8
Max BMEP: 10 Bar

Current FFV Performance Region:
FFVs demonstrate (~2 – 4%)
Reduction in energy equivalent Fuel
Consumption (West et al. 2007)

*Additional Gains possible with
downsizing with reduced
performance on Gasoline

Figure 28: FFV design space representing 2008 baseline data. The bottom region shows the current efficiency range of FFVs. Ethanol is assumed to have 85% carbon intensity with respect to baseline gasoline for the contour lines.

The design window in Figure 28 includes several features and assumptions which are important to note. The data for constructing this range are based on operating points on E85. The area in the interim are assumed to represent vehicle operation on mixtures of E85 and normal gasoline which result in intermediate ethanol blends. The efficiency improvements from ethanol can also accompanied by torque and power increases due to anti-knock behavior at peak loads. Any performance improvements are not captured in Figure 28. Additional gains may be possible if performance improvements are used to downsize the engine. However, downsizing can have an adverse effect on the performance of the FFV while operating on gasoline.

The combination of ethanol blends and vehicle efficiency provides a framework for the discussion of future vehicle design options. For simplicity the normalized vehicle at the origin is assumed to be a naturally aspirated (NA) port fuel injection (PFI) gasoline vehicle operating on gasoline. Normazilzed performance is based on a compression ratio (CR) or 9.8 and a maximum Break Mean Effective Pressure (BMEP) of 10 bar. Relative improcements in fuel consumption are possible through powertrain modifications while holding performance constant. Relative fuel consumption values for each powertrain are provided in Chapter 2 in Table 2. In this case attention is focused on the turbo gasoline powertrain which can currently provide a 10%-14% reduction in fuel consumption with max BMEP increased to 15 bar (Gerty and Heywood 2006). The relative powertrain efficiency improvement remains in around 10% whether the baseline gasoline vehicle is a 2005 NA PFI or the same basic technology in 2035.

The baseline efficiency of turbo-charged gasoline engines can be increased with the introduction of ethanol due to resistance to knock. Increasing boost pressure and compression ratio together with engine downsizing allow for significant improvements in fuel consumption. Projections from Blumberg (2009) suggest that max BMEP values of 22 bar may be possible with a compression ratio of 14 in a DI ethanol engine. Experimental projections in the same range are shown by Wittek (2009) for the EBS system. Maximum pressure tolerance of the engine would need to be in the range of 150 bar in order to achieve. Using calculations for potential efficiency improvements from Gerty and Heywood (2006) potential reduction in fuel economy for a dedicated E85 GTDI FFV might achieve 20-25%. Figure 29 shows the region of fuel consumption improvements that may be possible against the normalized fuel consumption of a vehicle NA PFI vehicle ($R_C = 9.8$, Max BEMP = 10).

In order to reach the upper range of efficiency it is assumed that a vehicle operating on E85 can reach maximum BMEP fo 20-30 bar with a compression ratio (R_C)of 13.5. These assumptions will necessarily include structural modifications to the engine, including extra cost and weight. Due to the complexity of these projections it is not possible to achieve a precise value. The degree of downsizing will also be subject to many constraints. The greatest efficiency gains will therefore come from in engines that start from a larger displaced volume.

The design window that is used in Figure 29 represents the region in which separate vehicles might be designed. The light bands are used to suggest that each vehicle may have a range of operating fuel consumption for a particular range of ethanol blend. The range displayed represents maximum values that require engine downsizing. This means that any vehicle designed for one blend range of ethanol would suffer decreased performance when operating on a lower blend of ethanol. Dotted lines are used to indicate that a single vehicle would not be capable of achieving the maximum efficiency ranges for all blends.

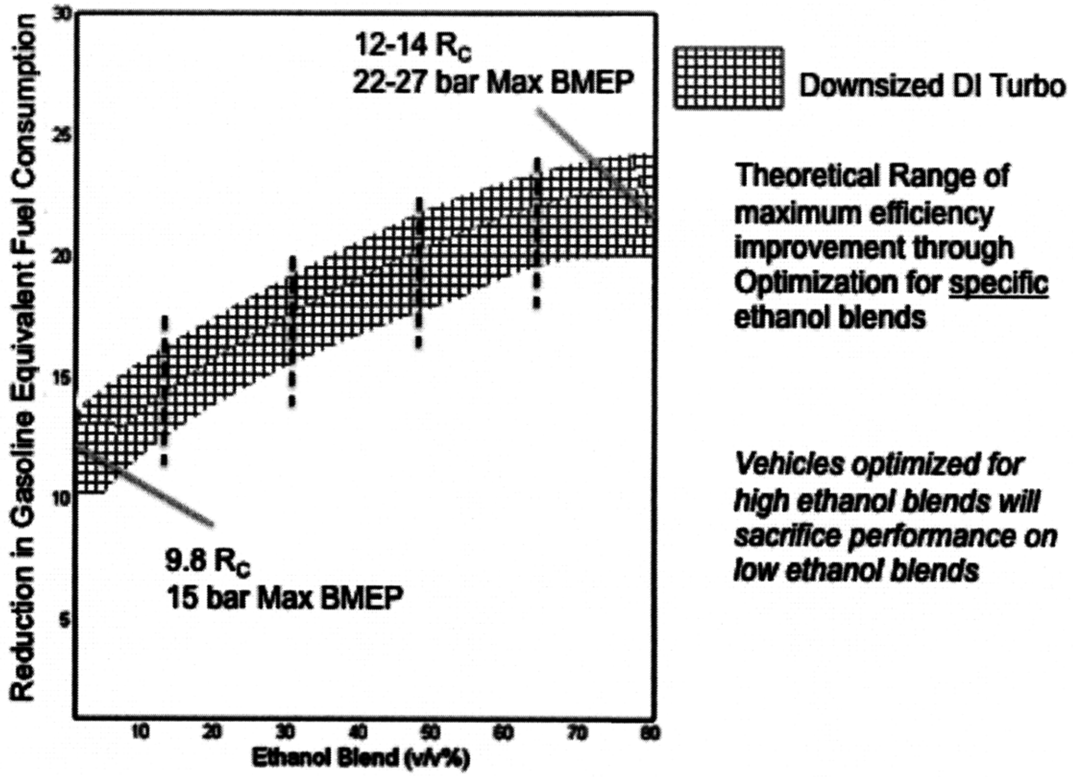


Figure 29: Estimated maximum efficiency potential for Gasoline Turbo Direct Injection (GTDI) vehicles as a function of dedicated ethanol blend level for constant performance operation.

There are two additional concept engine systems that offer different types of improvements on the basic turbocharged platform. The Ethanol Boosting System (EBS) as well as Variable Compression Ratio (VCR) systems discussed earlier. Results by Stein (2009) suggest that the compression ratio can be increased from 9.8 to 12.1 in an 18 bar max BMEP engine using only 1-16% effective ethanol blends. If this engine is downsized to maintain performance that leads to an additional efficiency gain shown in Figure 30. If the max BMEP can be extended to 27 bar as projected this would enable additional efficiency improvements up to 25% using extrapolated projections from Gerty and Heywood (2006). Preliminary testing does not indicate what effective percentage blend would be required to achieve the highest efficiencies. Drive cycle variation has a direct effect on how much ethanol is used leading to areas of uncertainty shown in Figure 30.

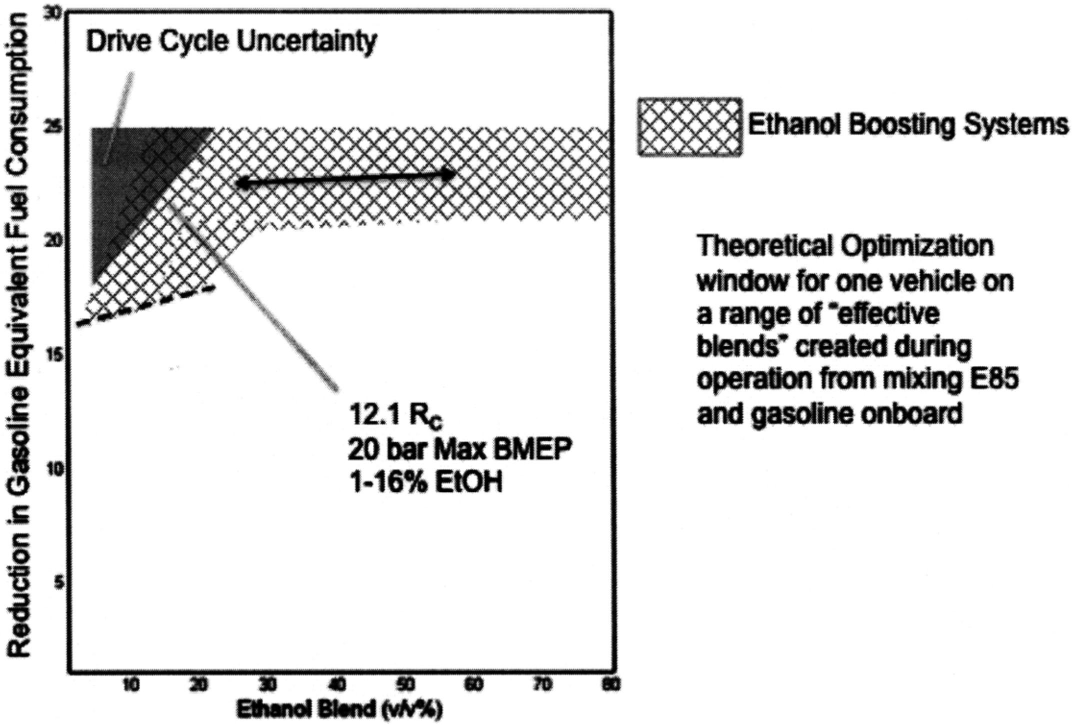


Figure 30: Ethanol boosting systems potential design and operation window. Grey area indicates uncertainty due to the effects of changing drive cycle behavior. For maximum efficiency the maximum BMEP would need to be 22-27 bar. Reference performance point is based on (Stein, House and Leone 2009) with downsizing.

In this design window for EBS a single vehicle would be capable of higher efficiencies with a lower range of effective ethanol blend. This potential is shown with the double arrow indicating flexibility in blends. The dotted line in Figure 30 shows a division between a non-downsized engine that would achieve higher performance.

The variable compression ratio engine can offer performance and efficiency benefits while operating on ethanol. The potential efficiency gains are shown in Figure 31 based on estimates by Wittek, Tiemann and Pichinger 2009. VCR systems may be downsized after additional boosting if ethanol operation will be dominant. In the undownsized case addition of ethanol will extent the max BMEP range and increase assis high load efficiency. The effective compression ratio refers to the compression ratio at part load which dictates fuel economy for most drive cycles. Ethanol does not change the compression ratio in this reagion so the contributions of ethanol will be more towards performance.

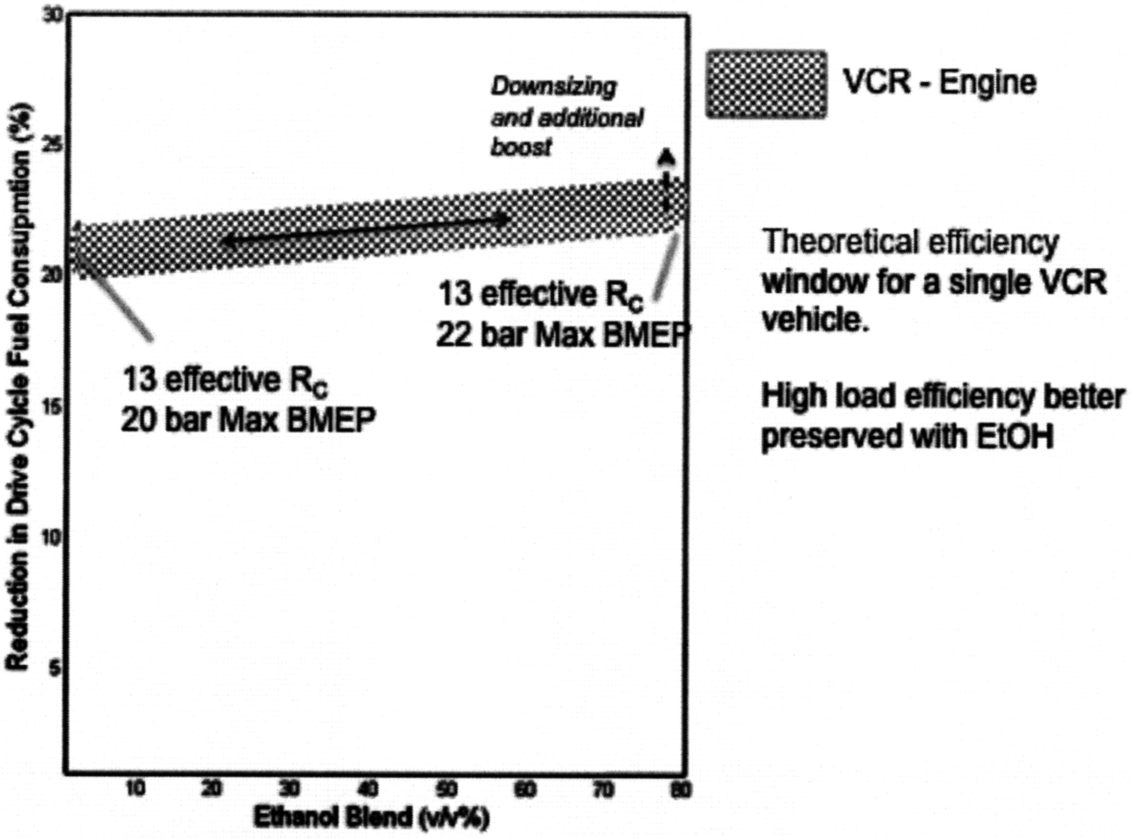


Figure 31: Estimated fuel consumption benefits possible with the use of a concept variable compression ratio engine.

The effectiveness of each set of vehicle design options can be judged by overlaying the previous graphs for either relative gasoline use or relative carbon emissions, depending on the goal and the values for GHG displacement. There is a direct effect, however, which can be measured which is the specific displacement ratio of gasoline per unit ethanol used. This method, described by Stein, House and Leone (2009) can be used to understand potential cost balancing between gasoline and ethanol. For example, in a vehicle with no efficiency benefit from ethanol, one gallon of ethanol displaces roughly 0.7 gallons gasoline. Howeve, if ethanol use confers increased efficinecy such that one unit of ethanol displaces one unit of gasoline then that would justify cost equivalency on a volumetric basis. Similarly, if using 1 gallon of ethanol could displace 2 gallons of gasoline then it would be worth twice as much. The potential leveraging effect of ethanol is displayed in Figure 32. The reduction in equivalent fuel consumption must be due to the introduction of ethanol so the values for the leveraging effect are undefined for unblended fuels.

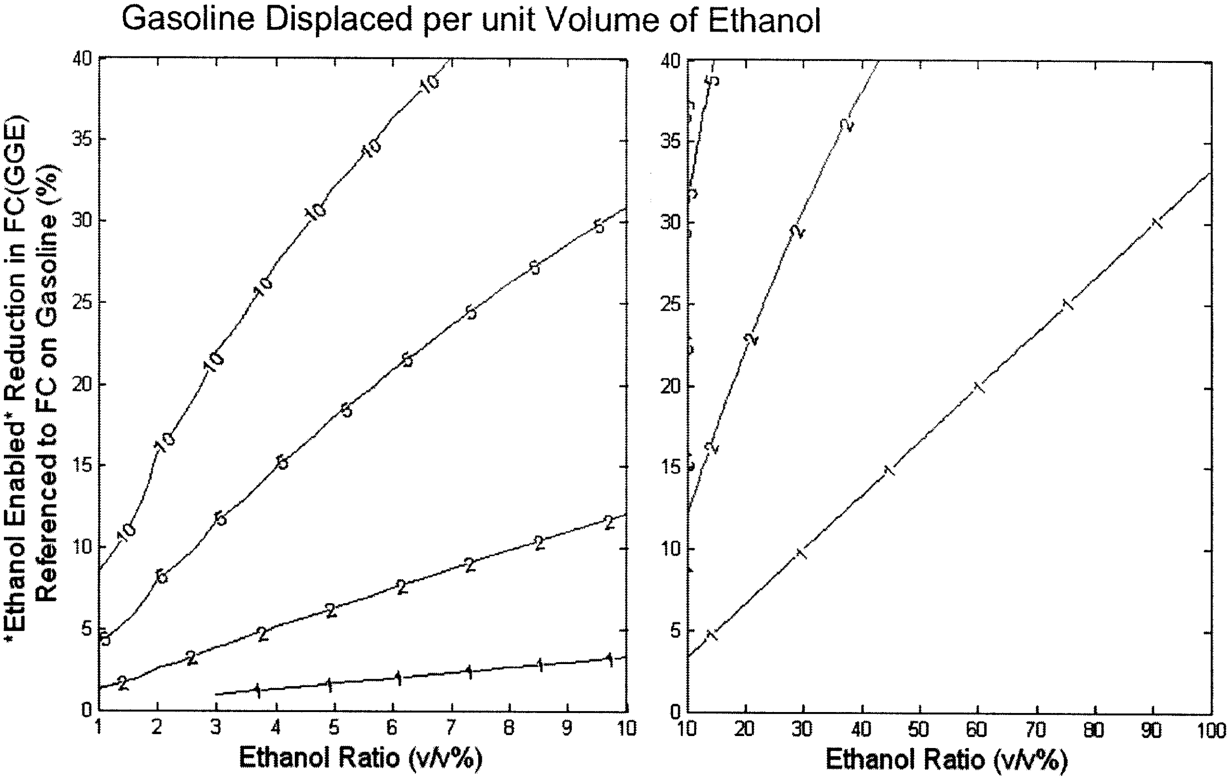


Figure 32: The leverating effect is graphed as the gasoline displaced per unit ethanol given a certain level of relative fuel consumption. This leveraging effect may be very high for ethanol blends less than 10% (left). Blends between 10-100% (right) would yield lower leveraging values for the same fuel consumption reductions. Fuel Consumption (FC) is used on a gallon of gasoline equivalency (GGE) basis.

In Figure 32, the normalization point at the axis must be shifted to be the original vehicle while operating on gasoline. The efficiency gains must be relative to a system with no ethanol rather than an already improved gasoline engine for these values to be meaningful. The greatest gains are possible along the fuel consumption axis. This suggests that if greater gains in efficiency can be achieved by using less ethanol then the leveraging effect is greatest. This would mean that ethanol could sell competitively at equal price per volume with gasoline. The price of ethanol and availability may even be a factor for the control strategy of an EBS engine as suggested (Stein, House and Leone 2009)

The range of values shown by the design window indicates that ethanol need not be used exclusively to increase efficiency, but can improve performance as well. There are costs associated with each point on this plot and the benefits can accrue to the driver, in the form of fuel savings, performance or to the environment in the form of decreased carbon intensity. The development of vehicles in this design space will determine the relative efficiency of FFVs and can have an impact on the total biofuel used by each vehicle.

5.4.*Scenario Analysis: Effects of FFV Sales*

The principal scenario results based on the information in this Chapter have to do with the number of vehicle sales in a given year. New FFV sales will determine how much fuel must be used per vehicle in a given year to meet total biofuel requirements in that year. Figure 43 shows the change in utilization requirement that results from changing FFV sales scenarios from the baseline reaching 50% market penetration in 2035, to the aggressive deployment that reaches 50% in 2018 and 80% in 2035. The fuel scenarios described in Chapter 3 remain the same for both graphs. The high fuel targets are denoted by (A) with the addition of non-ethanol fuels in (B). The Low fuel target reaching 36 billion gallons in 2035 is shown in (C) with the addition of non-ethanol fuels in (D).

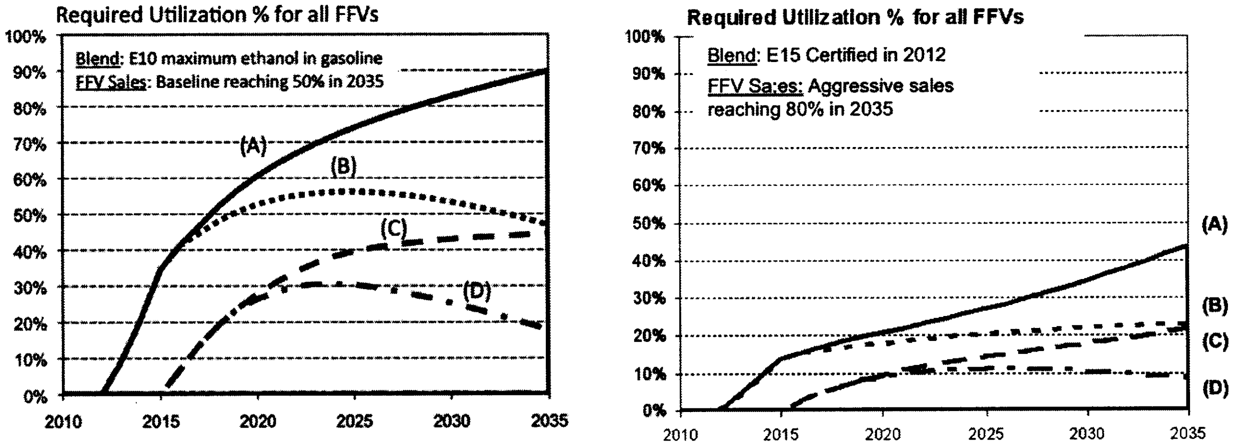


Figure 33: Comparison of the effects of FFV deployment rates on required E85 utilization rates under different total biofuel target scenarios.

There are two key differences in the vehicle deployment scenarios that have an impact on the results. The simple metric of new vehicle market share achieved in 2035 is an early indicator. The magnitude of 50% versus 80% plays a significant role in decreasing the required utilization pervehicle. The other differentiating feature between vehicle deployment scenarios is the shape of the penetration curve. In the delayed OFS scenario there is a steep initial increase to 50% market share in 2018 followed by a slower progression to 80% market share in 2035. Early market penetration helps to build of fleet stock which contributes to later biofuel use.

There are any number of intermediate sales scenarios which could be used to model these results. However the important message is that early high deployment of FFVs has a strong effect on reducing utilization requirements for the following decades. If miscible biofuels are introduced at scale then the utilization requirements may stay almost flat at 20% as shown in Figure 33.

The second half of this chapter deals with the type of FFV powertrains that might be developed to take advantage of ethanol fuel properties. If ethanol fuel properties are used to improve fuel economy on ethanol then this would result in less ethanol used per mile. However, decreasing the use of ethanol per mile will increase the number of miles traveled on ethanol required to meet a given volume requirement. In order to test this effect FFVs were modeled with a relative fuel consumption benefit when operating on E85. As this value changed from 0% to 15% the required utilization increased as shown in Figure 44. While the possible optimization ranges are theoretically much higher some of these efficiency increase may be used for performance increases rather than for efficiency. The optimization factor can be used to represent an aggregate across the fleet. The effect of optimization has very little effect on utilization when compared to other policies like changing fuel targets or sales.

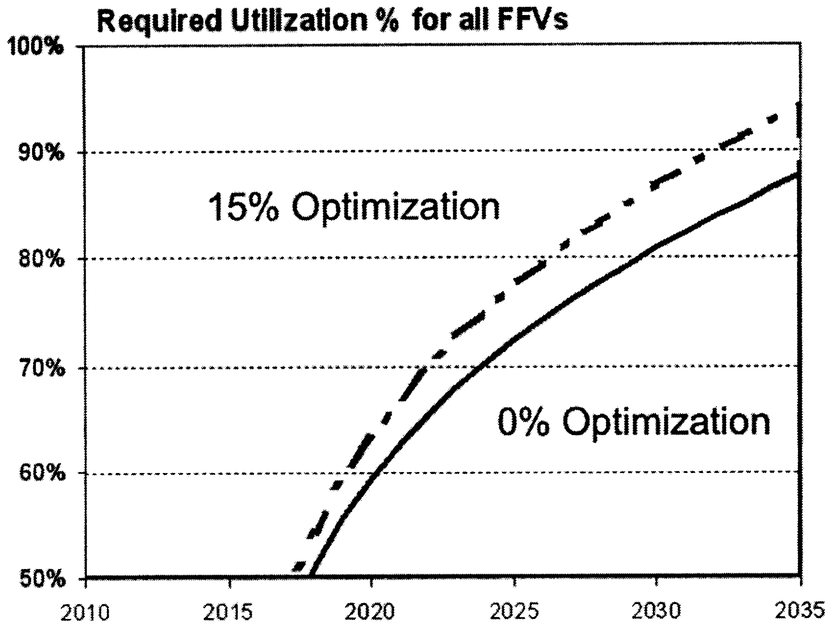


Figure 34: Model results for the effect of optimization on required utilization of E85 by FFVs in the reference scenario set. Optimization values are represented as the relative decrease in fuel consumption of a flex fuel vehicle while operating on E85. As optimization for fuel economy increases so does the required utilization as each mile driven requires less ethanol fuel. The high fuel target and reference sales rates are used for this illustration.

Summary

There are a wide range of engine efficiency improvements that are possible at present for improving engine efficiency and performance. The addition of ethanol blends has the capacity to increase the impact of some vehicle design strategies. In this way ethanol can provide more efficiency increases with conventional technology at very low costs. At the same time, ethanol capability does not displace any other powertrain option such as hybridization. Current flex fuel vehicles are not utilizing these advantages to a large degree, except in a handful of cases. Ethanol optimization offers one of the lowest vehicle cost options.

The improvement of FFV efficiency or performance when operating on E85 does not significantly detract from the goal of using more biofuels and can offer good reason for drivers to choose this alternative fuel. In fact improved FFV performance on ethanol may assist vehicle sales. In vehicle deployment, early and significant penetration of FFVs can greatly reduce the utilization stress for the decades that follow as long as FFVs follow the same utilization patterns in a given year. The delayed deployment of FFVs creates higher demands on the infrastructure availability and attractiveness of the fuel, which will be discussed, in the next Chapter.

6. Utilization: Availability & Attractiveness

Early in Chapter 2 the basic definition of utilization was developed as the percentage of miles traveled by FFVs that are fueled by E85. This value must begin to rise when target biofuel usage exceeds what can be blended legally or logistically in the traditional gasoline supply. In order to translate the results from the previous sections into actionable recommendations it is critical to understand what is required to achieve these utilization values. Two major perspectives can be used for this question.

1) Availability: What type of retail station deployment is necessary to provide drivers of a given region with access to E85?
2) Attractiveness: Once drivers of FFVs gain access to E85 what reasons exist for the purchase of this fuel?

There is some minimum percentage of equally distributed fueling stations necessary in a given area so that the driver can encounters an alternative fuel station when they wish to refuel. There is a second component is attractiveness which guides the drivers decision to choose the E85 over regular gasoline. For example, if a driver encounters the alternative fuel 100% of refueling visits, but E85 is equally as attractive as gasoline (a 50% attractiveness rating), then the net utilization will only be 50%. Through the same assumption, if the fuel is 100% available, but the fuel is not attractive, or 0% then the utilization will be 0%. This highlights the need to multiple strategies in the deployment of fuels to not only make it available, but also make it attractive when drivers have a choice of fuels.

The availability of fuel and its corresponding utilization has important feedbacks into the fleet section because it constrains the degree of optimization that is likely in new vehicles. Simply, the higher the utilization rate for a given vehicle the more apt the consumer will be to select a vehicle, which is optimized for a given fuel.

The scenario results from the end of Chapter 5 suggests how a set of policies might be used to control the requirements for utilization percentage to reasonable values. This Chapter will explore what these reasonable limits might be.

6.1.*Retail Availability of Ethanol*

The challenge of distributing alternative fuel is often described as a "chicken and egg" dilemma. Retail fueling stations are not likely to offer E85 until there is a substantial customer base of FFVs and people are unlikely to buy FFVs until there is widely available E85. This has been the prevailing logic of alternative fuels, but in this example that are some important additional challenges as well as areas of opportunity to break this standoff.

The simplest way of measuring availability is as a simple percentage of existing fueling stations that offer E85. The national total number of stations has been declining but is currently around 160,000. The number of E85 pumps is on the rise, but remains below 2,000(EPA 2009). This means that the national average availability is only a little over 1%. The distribution by individual state varies drastically. This average value matches fairly well with the observed utilization value based on FFV vehicles and total E85 sales (Davis 2008).

State	% Stations Offering E85	Population	Population Rank
Minnesota	9.9%	5,197,621	21
South Dakota	7.5%	804,194	46
Indiana	7.1%	6,345,289	16
Iowa	4.0%	2,988,046	30
Illinois	3.7%	12,852,548	5
North Dakota	3.3%	639,715	48
Colorado	3.2%	4,861,515	20
Nebraska	3.1%	1,774,571	38
Wisconsin	2.9%	5,601,640	20
Dist. of Col.	2.5%	588,292	51

Table 9: Breakdown of states by highest percentage of retail gasoline stations offering. Many of the states with the highest retail penetration of E85 also have relatively low populations.

Population density is a factor that should be understood in qualifying the metric of station percentage. Table 9 shows that there while there are some states that are leading in the penetration of alternative fuel stations that these are not the states with the highest population. An additional concern is within each state is the geographic distribution of stations. Research by (Struben and Sterman 2007) has shown that rural fuel availability as well as urban plays a large role in adoption of alternative fuel vehicles. FFVs may be alleviated from this constraint because they can operate on either fuel.

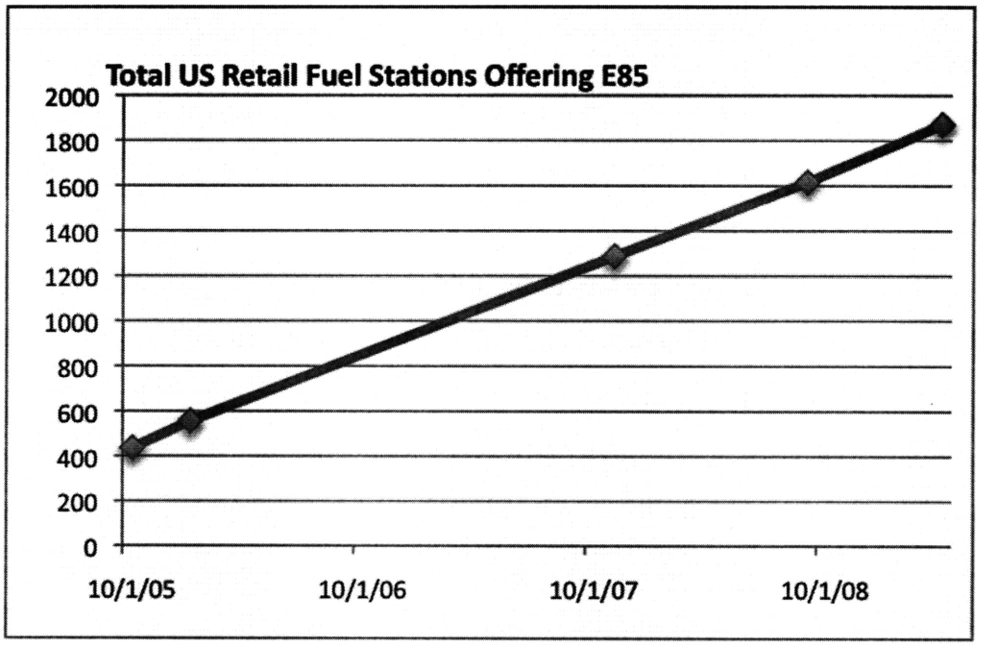


Figure 35: Since 2005 there has been a steady increase in the number of retail fuel outlets offering E85. (US DOE: Energy Efficiency and Renewable Energy 2009)

The current national trend for retail gasoline station conversion to offer E85 is proceeding at a rate of approximately 400-500 stations per year in aggregate. If this trend continues and the total number of gasoline stations levels at 160,000 then in 2020 the current 1% will reach 5% of total stations. Many of the previous scenario results showed required utilization values in the 20%-80% range for this same time period.

It is worth reiterating that the percent of stations does not directly mean utilization percentages of the same level are possible, or even expected. For example, diesel fuel is sold as a functioning alternative with only 40-50% of retail stations offering the fuel(Argyropolos, Naughton and Hernandez 2005). This aggregate value can serve as a benchmark for E85, which is not constrained by the same fuel exclusivity as diesel. Using this framework, retail availability of E85 would only have to reach 50% in order to achieve maximum utilization.

Previous studies have used survey data to estimate the availability of fuel needed to reach a utilization level based on different price data. Results of are shown in Figure 36 that suggest 50%-60% fuel availability is required to reach the peak utilization for a given price. This value for purchase decision does not directly translate to the miles traveled percentage that is used for utilization in the context of this study as long as there is a difference in energy density. Relative rice, in this case, is used as the metric for attractiveness (Greene 1997).

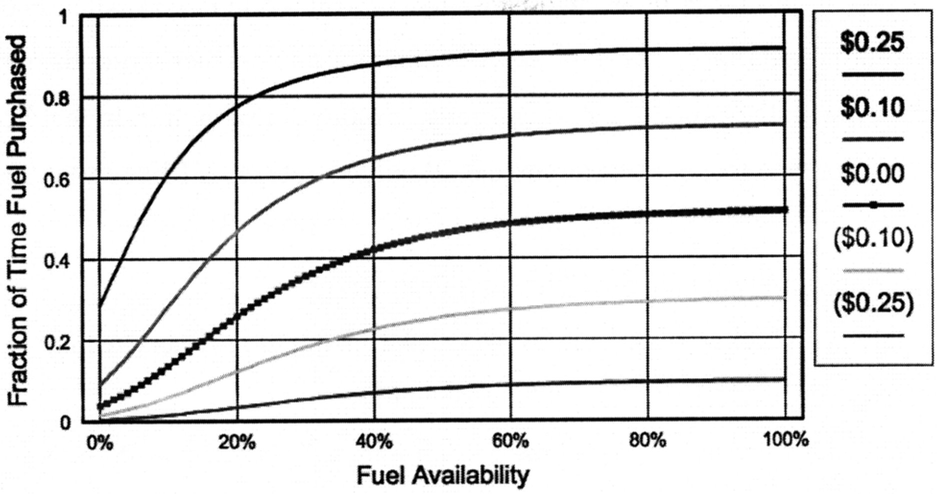


Figure 36: Results from a study by Greene (1997) showing the effect of Fuel availability measured as percent of retail stations offering alternative fuels at a given price disparity (higher prices are shown in parentheses and lead to lower fractional purchase decisions). Price is used in this case as a proxy for attractiveness of the fuel to determine a similar metric to utilization percentage on the vertical axis.

The most recent energy legislation in the Energy Independence and Security Act of 2007 provides incentives for the conversion of gasoline stations to be E85 capable. In order to recoup even a reduced cost, each station must do a certain volume of business with a given profit margin to achieve return on this investment. This encourages the development of E85 stations in high throughput urban areas and discourages a new E85 station from operating close to an existing station (Johnson and Melendez 2007).

Not all E85 station conversions are alike however. In Minnesota particularly there are flexible blending pumps that facilitate the distribution of a wide range of E85 blends beyond just E85. These blender pumps add cost, but can allow drivers to choose intermediate blends depending on the relative cost of gasoline and ethanol. In the event the E15 is certified as a fuel there is potential for stations to offer this blend on site rather than purchasing E15 blended from the fuel terminal (Hammel-Smith, et al. 2002).

The function of ethanol blender pumps is similar to that of conventional midgrade blending. In this case the station has a dedicated ethanol tank that then can be mixed with the standard 87 octane fuel which is normally E10 to provide a range of blends sometimes including 20,30, 40, and 50 percent ethanol. FFVs are the only vehicles legally permitted to use any blend higher than E10.

The reason for the wider proliferation of blender pumps in Minnesota in particular, is the anticipation of possible future regulations. The capital investment for a retail fuel station is significant and is undertaken with the expectation of a decade or more of usable life. In the face of policy uncertainty it makes sense for retailers to pursue a flexible strategy. If Minnesota then receives a waiver for intermediate ethanol blends, then the market for E20 will expand.

There are several areas of opportunity for flexible blending in the future:

- Drivers may use E15 with higher octane rather than an E15 from the refinery, which would likely be adjusted to meet minimum 87 octane values.
- Retailers are ready for E15 certification and the potential for E20, as well as if certain vehicles are warranted to work on other mid-level blends
- In the long term they may be an opportunity to have specifically adjusted vapor pressure values at the pump based on a specific blend of biofuel components.

There are also several key challenges facing flexible blending:

- Additional costs of installation.
- The retailer assumers greater liability in distribution of illegal fuel blends
- Fuel quality becomes more difficult to regulate when there are more locations for blending.

The way that ethanol is sold at the retail level has impacts throughout the value chain. In particular the way ethanol blended on at the pump to make E15 provides higher octane fuel to the driver. This may also impact premium fuel sales that achieve higher profit margins. The availability of higher octane fuels at the pump can also impact the design of vehicles as discussed in Chapter 5. The way that ethanol is made available at the pump then influences the "Attractiveness" of the fuel.

6.2. *Factors contributing to Fuel Attractiveness*

Fuel choice factors are even more difficult to describe analytically than station availability. The definition for attractiveness of fuel is defined as the likelihood of purchase against other alternatives. In demand modeling this probability is described by the relative utility of each fuel in the following multinomial logit model formulation (Small and Verhoef 2007).

Equation 3: $$P(i \mid C_n) = \frac{e^{\mu V_{in}}}{\sum_{j \in C_n} e^{\mu V_{jn}}}$$

Where C_n is the choice set of fuels and μ is a scale parameter (normally assumed to be 1). This equation describes the intuitive relationship that if two options are provide equally utility then the probability of selecting one will be 50%. The utility function V is described by the following equation, which weighs different attributes of a particular fuel with k fuel properties each denoted as X with affinity parameters β. In this random utility model formulation there is an error term ε which is used to represent distribution effects in the population as well as influence factors not included in the standard fuel properties.

Equation 4: $$V_{in} = \sum_k \beta_{Xk} X_{ik} + \varepsilon_{ik}$$

The range of fuel parameters that can include the following.

- Perceived price of fuel
- Additive package of detergents
- Octane as measured by (R+M)/2 Method
- Expected anti-knock qualities such as cooling power which may depend on the vehicle design
- Expected emissions performance
- Perceived environmental friendliness of the fuel
- Perceived geographic origin of the fuel

The affinity values for each of these fuel attributes will vary by person, by geography and depend on the type of vehicle and the purpose of the vehicle trip. Previously work by Greene (1997) uses price as the dominant factor in fuel choice decisions. For this reason all other factors can be understood in units of dollars or "willingness to pay" rather than in utility.

While price dominates fuel choice there has been demonstrate WTP for other properties as well. The most obvious example of WTP is with premium fuel. A subset of drivers has consistently demonstrated that premium fuel is worth more. The first assumption is that this decision is based on actual attributes of the product such as octane or additives. However, it is important to concede that some fraction of premium fuel purchasing is due to misconceptions on the part of the customer. In fact there have been studies in the past to suggest that premium fuel purchase is greater than what it might be if customers had better information (Setiawan and Sperling 1993).

Ethanol presents additional dimensions that may be of value to consumers. The case for consumers being mistaken remains as a possibility particularly because the energy content for E85 and regular gasoline is different. However, the national average price for E85 consistently follows gasoline with around 30% higher than the price on an energy basis. While E85 sales are not a large portion of as sales, this suggests that there is a segment of flex fuel vehicle drivers who are willing to pay more for ethanol for a certain set of attributes of that fuel.

The different attributes of ethanol are that it may have lower greenhouse gas intensity, a higher octane, and is almost exclusively produced domestically. Some combination of these factors contributes to a willingness to pay in excess of traditional gasoline among flex fuel vehicle drivers. In current fuel markets however these attributes are not well understood and are not yet labeled for the consumer so there is a higher likelihood that these attributes are assumed by consumers, based on insufficient information.

There are several factors in fuel station selection, which are not included in the fuel choice itself. Anecdotal evidence suggests that the convenience factor of the location, peripheral services like a car wash or even the price of milk in the attached convenience store can play a role as well.

Despite the multitude of factors leading to fuel decisions, there are other relative factors relating to the vehicle itself. As mentioned before, an optimized vehicle is more likely to lead the driver to use E85 and the availability of E85 reinforces the decision to buy an optimized vehicle. Additional constraints enter into vehicle selection such as maintenance and resale value(Kayser 2000).

6.3.*Scenario Analysis: Deployment strategies*

National Station Deployment

The current rate of station deployment, if it continues, will provide a certain degree of fuel availability. With an assumed attractiveness of 50% suggesting that E85 and gasoline provide equal utility to FFV drivers it is possible to represent this as a baseline utilization percentage that is possible. The current rate of station deployment will reach 8% of total stations in 2035. If 40% station penetration were assumed necessary for complete utilization then the maximum utilization possible would be 20% assuming 100% attractiveness. With a 50% attractiveness for E85 the maximum utilization value falls to 10% utilization in 2035. This utilization baseline can even be lower if ethanol cannot achieve equal utility with gasoline.

In some of the scenarios is should be noted that some of the utilization requirements drop over time after reaching a peak. This is a critical change that can represent risk or opportunity for fuel retailers, auto, makers and fuel providers. The decreasing requirement for utilization means that the combination of stations and attractiveness are decreased, or that sales may level off. If more fuel cannot be produced to maintain levels of utilization it is likely that the price will rise to decrease attractiveness. This means that utilization per vehicle will fall, but the same amount of fuel will be distributed at a higher price. This can lean to higher profit margin as long as the costs of producing the fuel are not also rising.

Regional Vehicle Deployment

The deployment of E85 dispensing at stations across the entire country may be very challenging. However, concentrating the deployment of stations in a set geographic area can provide high availability in that area. This type of regional deployment strategy would mean that deployment efforts are focused in a region like the Midwest where fuel availability is already greater. If FFV sales are concentrated in regions with high availability then it ease the requirements for total vehicle sales. Otherwise there is a chance that FFVs are deployed in areas without stations.

A regional deployment strategy was simulated in the model by setting utilization at a constant 90%. The model was then used to solve for the required FFV market share in a given year to reach each respective biofuels target. Results are shown in Figure 37 for all target fuel scenarios.

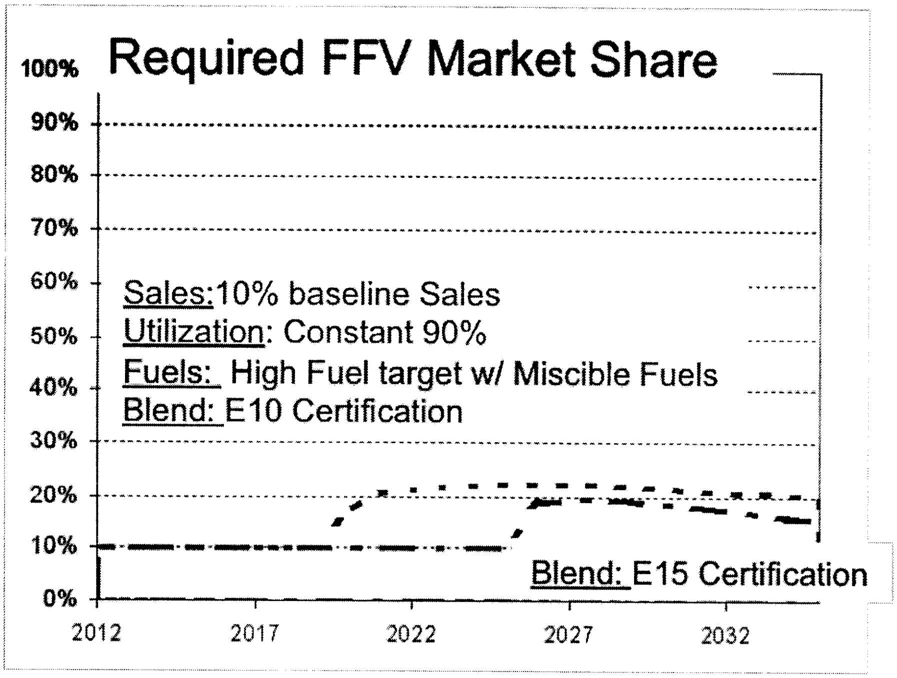


Figure 37: Utilization values are set at 90% to simulate dedicated ethanol vehicle sales in a given region. Results are shown in the percentage of new vehicles sold that must be flex fuel capable in order to meet biofuel targets. Here combinations of policies are shown, with the potential additional effect of E15 certification.

The results suggest that while regional sales can be a powerful strategy for the deployment of optimized vehicles, the region of vehicle sales must include roughly 20% FFV market share, depending on the biofuel target. These requirements can be brought down by selling vehicles into the fleet earlier. The principal difference is that these vehicles must have utilization rates of 90%. It will be difficult to obtain high utiliztion with these vehicles unless the price of E85 drops drastically with respect to gasoline or other factors increase the attractiveness of E85.

Regional deployment with high utilization provides an opportunity for greater optimization. From an auto-make perspective this means that there may be more sales of optimized FFVs, where in a national deployment strategy there are likely to be higher sales of less optimized vehicles due to lower availability levels.

National fuel policy may be used to set biofuels targets in this case, but state level policies would be require to push through regional deployment strategies. A collection of midwest states might pursue such a strategy by providing extra incentives for station deployment of vehicle sales.

Station Development requirements

Utilization requirements are useful as a comparative value between scenarios. In order to understand the feasibility of obtaining each utilization value it is important to investigate the requirements are included in utilization. Thus far, utilization has been the output value from the fleet model because of the complexity of interactions between availability and attractiveness. Attractiveness depends on a number of fuel factors, but especially on the price differential between E85 and gasoline. The availability of stations has to do with percentage of total, but also on the spatial distribution and the travel or refueling habits of local drivers. Simplifying assumptions must be made to obtain a reasonable range of values for required station conversions. These include an even distribution of outlets offering E85, and an unlimited capacity for each station, as well as negligible effects of queuing at each station. Under these assumptions a relative requirement for stations can be observed in Figure 38.

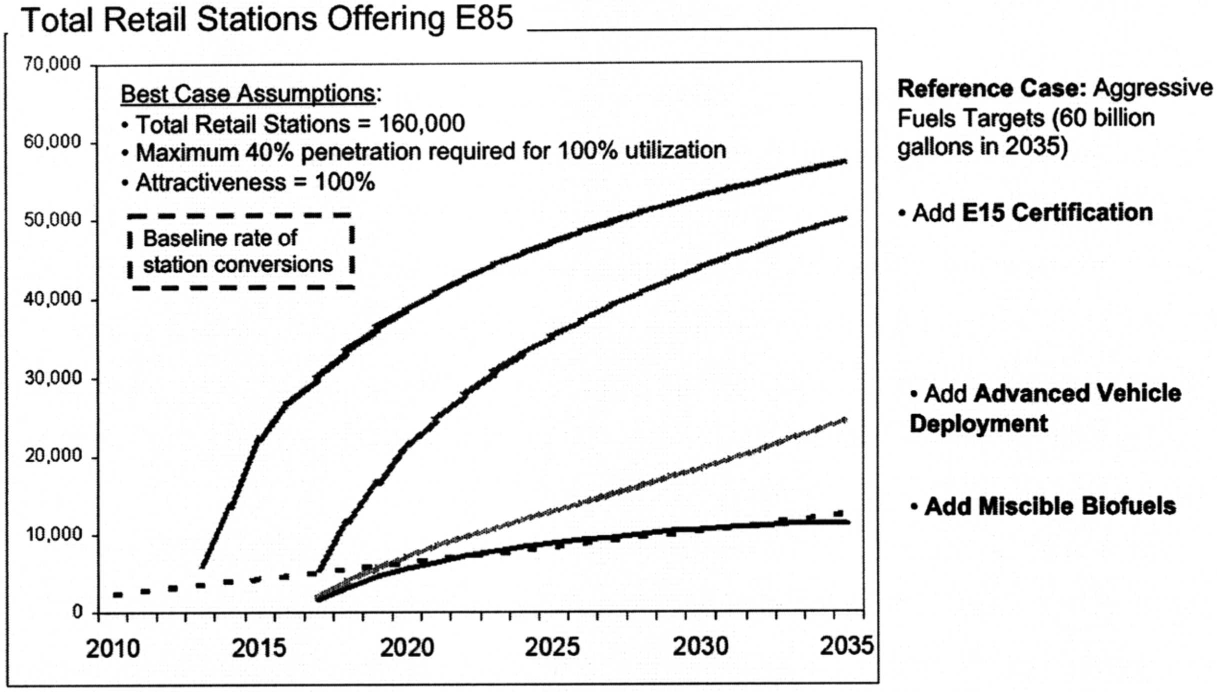


Figure 38: Utilization requirements from modeling results can be roughly translated into a requirement for total retail stations offering E85. The current rate of station deployment is extrapolated and shown with the dotted line. A combination of technology and policies may allow this rate of current station deployment to accommodate the utilization requirement if E85 is 100% with respect to gasoline.

A combination of policies are required to bring utilization requirements down to a range where current retail E85 conversion rates are successful at meeting the biofuel targets. Even under these results the attractiveness is assumed to be 100%. Many of the other assumptions including distribution and capacity of each station will mean that there will need to be many more retail conversions than are shown here. While 10,000 stations may be the absolute minimum needed in this example, if E85 is equally attractive to gasoline there would need to be double that amount. If stations are not also evenly distributed then the required number of conversions may be higher still.

Once the utilization value is translated into an actual station count it is clear that the current rate of conversions will not be successful in meeting even reduced ethanol deployment goals. The rate of station conversions to offer E85 may need to be twice the historic trend starting in 2012 to enable future ethanol deployment.

Summary

Deployment strategies for ethanol can be approached from several different perspectives. A national deployment strategy might focus on incentives for FFV sales. This type of vehicle-leading strategy would then create market incentive for retailers to make higher blends of fuel available to consumers. Eventually as availability of E85 increased, optimized, or even dedicated E85 vehicles might enter the market. A regional deployment strategy might focus more on deploying station infrastructure in an attempt to increase availability, then push for optimized ethanol vehicles to achieve high utilization rates. Ultimately some balance between these two strategies may prove effective in reaching desired biofuel targets.

The total targets for biofuels themselves should be considered in the context of what is required to meet them. The current pace of FFV deployment and station conversations to offer E85 suggest that even delayed goals for the RFS would not be achievable. Some measures will need to be taken in order to reconcile this gap. Much stronger policies are need to reinforce vehicle sales and fuel availability, or the fuel targets must be reduced to a more achievable range.

Ultimately, regardless of the methods of achieving fuel availability and sales of ethanol capable vehicles the decision to buy higher blends of ethanol will rest with the consumer. If there is no additional utility provided to the driver then E85 will simply not be sold. FFV optimization is a critical component of the motivation for FFV owners to buy ethanol. Ethanol can be used as a premium fuel to provide additional value to consumers. However when prices change flexible blending stations can allow retailers to adapt to changing consumer behavior.

Flexibility will be a valuable technological feature for both retailers and drivers. During deployment stages when there are fewer FFVs on the road retailers can provide ethanol in low or high blends depending on existing policy. Drivers with flexible optimization engines like VCR or variable boost may benefit from the use of ethanol when the encounter it, but not sacrifice performance on gasoline. Flexible injection systems like EBS allow for maximum improvements in efficiency while offering greatly improved distance between E85 refueling visits, which is critical in times of low station availability.

Finally, customers will benefit to greater access to information. Information on the energy content or price per energy of fuels will help drivers avoid paying more. Additionally, information about environmental impacts or production origin may increase the willingness to pay for biofuels. Consumer value and WTP for this type of information is not currently known, and may be prohibitively expensive to provide. However, when the types of fuel and blend levels are changing and proliferating greater access to information will help the alternative fuel market function more efficiently.

7. Findings and Recommendations

7.1. *Scenario Summary*

The objective of this report was to gain insight into the challenges of deploying ethanol and flex fuel vehicles in the US light duty vehicle fleet over the next three decades. The fleet model methodology used here has allowed for a systematic analysis of the major variables, which will determine the success of alternative fuel deployment. The most critical decision points in fuel systems policy are the total biofuel target, the legal blends of ethanol in gasoline, deployment strategies for vehicles and the ultimately the possibility and motivation of the driving public to purchase fuel alternatives. Each one of these key variables has been addressed from a systems level, which still giving attention to the intricacies of each area of challenge.

Thus far, various scenario approaches to the deployment of vehicles and fuels have been explored. In Chapter 3 the total biofuel targets were discussed to provide and aggressive and conservative option for the total and type of biofuels that may be used. Chapter 4 addressed the possibilities for certifying E15 along with E85. In Chapter 5, possible vehicle deployment options were laid out. In this final Chapter the effects of blend level and vehicle deployment can be seen together with changing biofuels targets. The 2x2 table in Figure 39 illustrates how graphs will be organized in order to summarize results from a coordinated set of policies.

Vehicle Deployment Options → **Ethanol Blend Options** ↓	Baseline FFV Deployment	Accelerated FFV Deployment
E10 in all gasoline and E85 available		
E15 in all gasoline and E85 available		

Figure 39: Chart of coordinated biofuel and vehicle deployment scenarios. Each graph quadrant will contain a graph which shows fuel scenario results for the reference case with the RFS extrapolated through 2035 or delayed to meet original targets in 2035. Both fuel targets are considered with the addition of miscible biofuels. These four fuel cases are subjected to two blend strategies (E10 and E15) separately. The matrix shows the additional affect of deployment rate for FFVSs

The combination of scenarios can be seen together by using a matrix arrangement shown in Figure 40. For each of the four main variables there are two modes, which are tested yielding a set of 16 model results.

- FFV Deployment: Reference Case (50% of new sales in 2035), Advanced (80% of new sales in 2035)
- Blend Requirement: Reference Case (E10), Advanced (E15 available in 2012)
- Biofuel Targets: Reference Case (existing RFS ramp extended to 2035), Delayed (existing RFS achieved in 2035)
- Type of Fuel: Reference (only ethanol), Advanced (50% of cellulosic biofuel as non-ethanol by 2035)

There are two key dimensions of the results, which are the date at which utilization requirements begin to rise, and the rate of rise thereafter. These points can be considered as the shifting blend wall. In the baseline examples the blend wall is reached in 2013 followed by a steep increase in required utilization. Through a combination of vehicle deployment acceleration, E15 certification, and fuel mix changes, utilization requirements can be limited to 20%. With delayed biofuel targets the blend wall can be moved back to 2020.

Once the blend wall is reached the requirements for E85 utilization for FFVs ramp at different rates. In advanced deployment examples the ramp is lower because the fleet has had more time to accumulate ethanol capable vehicles, so that the fuel use can be more evenly distributed.

The consideration of these combined polices should inform the decision to place policy emphasis on total biofuels targets, miscible biofuels, blend limits, vehicle deployment, infrastructure, fuel purchase incentives or vehicle design research. At the conclusion of this analysis there are some key findings, which can serve as a guide towards navigating the complex landscape of vehicles and fuels.

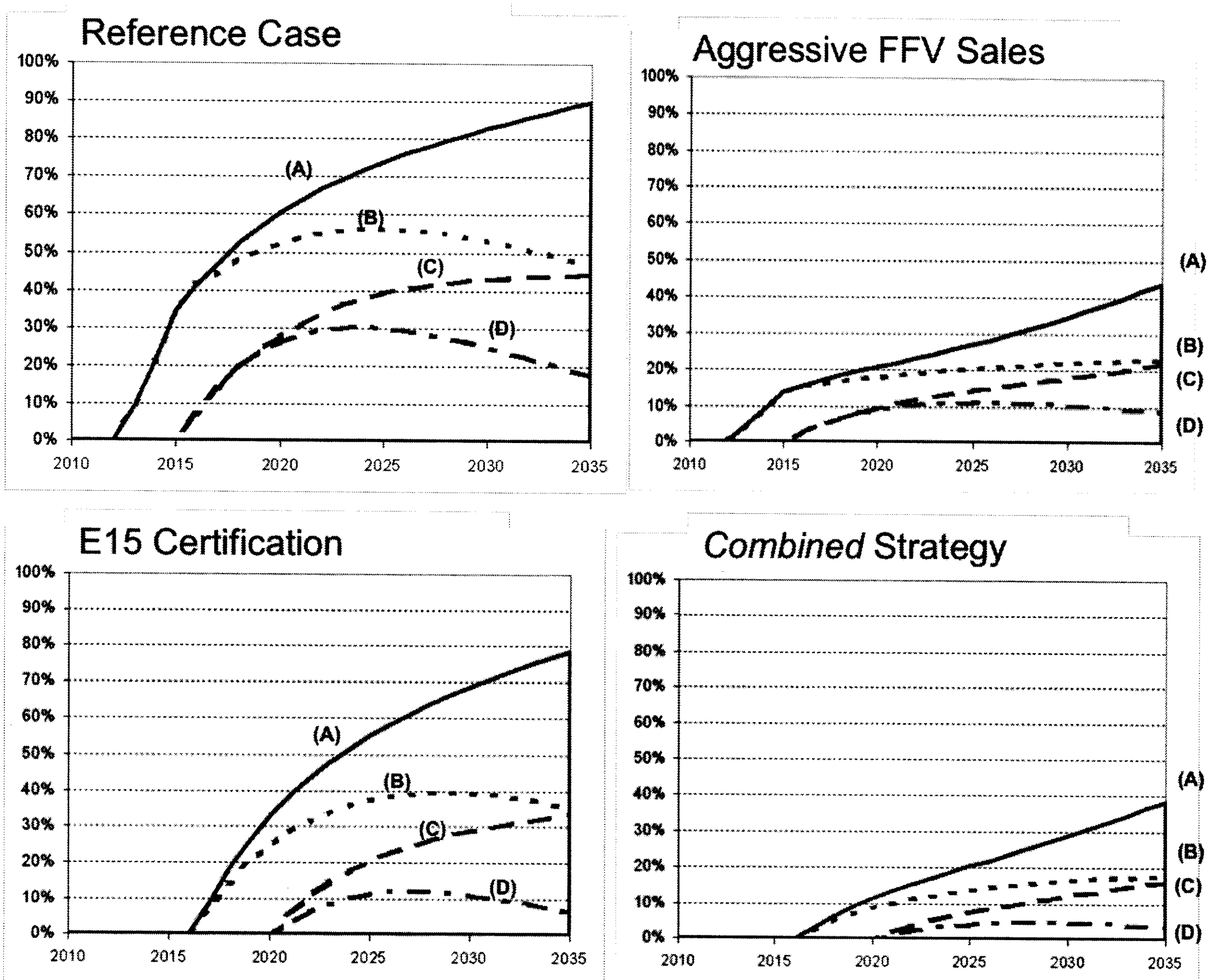


Figure 40: Scenario matrix of utilization requirements for FFVs to meet varying biofuel targets. Each plot shows four fuel scenarios. Listed in order of decreasing utilization requirement they are {(A) Baseline RFS with extended targets to 2035, (B)Baseline RFS with 50% miscible biofuels in 2035, (C)Delayed RFS reaching original targets in 2035, and (D) the Delayed RFS with 50% miscible biofuels}

7.2. *Summary of Findings*

This work covers a wide range of research from existing literature and also provides some new insights into the quantitative obstacles for vehicle and fuel deployment. This combined analysis and modeling of major factors yields a range of key research findings:

- Biofuels and ethanol in particular show promise as a domestically produced option to displace 10-20% of petroleum use in the next two decades represent a real near term scalable option for displacing petroleum. It is clear that existing methods and feedstocks for producing biofuels are not reaching environmental goals for GHG reductions. However there is significant potential for further reductions of GHGs and environmental impact from ethanol production.

- Ethanol is likely to be the dominant biofuel and only major alternative to petroleum for at least the next 10 years based on the current progress of technological development.
- The amount of ethanol available is quickly approaching the limits of what can be blended in gasoline at 10% by volume. Any additional ethanol volume that cannot be blended in the gasoline supply will need to be used as E85. Under the current standards the blend wall will likely be reached in the next 3-5 years. E15 certification represents a near term option for delaying the "blend wall" slightly but only by 1-3 years. This policy also involves some risks to automakers in particular.
- Ethanol use along with increased vehicle efficiency represent parallel paths towards the decarbonization of transportation. Ethanol capability is not exclusive to any other powertrain efficiency improvement. Adding flex fuel capability is one of the cheapest vehicle modifications that can be pursued, and is highly synergistic with direct injection turbocharged engines for improving vehicle efficiency and/or vehicle performance.
- The current rates of FFV deployment and retail offerings of E85 will not be sufficient to met the current RFS standards. Some form of advanced FFV deployment policy is needed to support the proposed fuel mandates if they are to succeed. Currently retail outlets offering E85 are ~1% of total gasoline outlets.
- In the event that ethanol is available and distributed through extensive infrastructure to capable vehicles in the form of E85, there must still be a reason for drivers to buy the fuel. FFV drivers have a choice in fuel and will choose the option that matches utility and price. Some form of price incentive may be necessary in order to sell E85 once it is available, or vehicles must be designed so that drivers derive greater value from using E85.
- Greater information is required in the fuel market so that drivers can make informed decisions about which fuels to buy, and potentially increase willingness to pay for alternative fuels.

Technical Ethanol Strategies

The presence of ethanol represents three opportunities for reduction in energy use and petroleum consumption. These strategies may be pursued independently or in combination depending on how ethanol is produced and distributed.

1. Straight fuel replacement: Ethanol can be used to displace petroleum. It has value as an alternative domestic fuel independent of any other factors.
2. Octane Increase: An increase in octane in the fuel supply can allow for improved vehicle performance and fuel economy. Alternatively the energy used in refining can be reduced while maintaining the same octane levels.
3. Environmental Strategy. Can provide reductions in the GHG intensity of transportation fuels depending on the feedstocks and conversion processes. There are some opportunities for local air quality improvements depending on the blend level of ethanol.

Ethanol can reasonably be pursued only as a straight fuel replacement even though most of the policy around it is in terms of environmental strategy. The both the air quality and global warming effects of ethanol can be dealt with through improving the technology for production and use in engines.

A key decision will exist for how the octane of ethanol is used. This will relate to whether or not ethanol is blended at the retail station or at the refinery. This decision has implications for who derives benefit from the octane and whether it accrues to refiners or the driving public.

Technical Ethanol Risks

The introduction of large amounts of ethanol into the gasoline supply also creates a number of key risks to stakeholders in the fuel system.

1. High Costs: Ethanol costs are significant for tax expenditures and still result in higher costs for consumers. Significant investment in infrastructure and vehicles will need to be undertaken to successfully deploy ethanol fuels at the current targeted levels.
2. Transient fuel: It is possible that ethanol will be obsolete as a fuel in 10 or more years and that later generations of biofuels will allow for equal scale of production without the same level of investments in vehicle capability of infrastructure modification.
3. Capital Risk: Ethanol can have detrimental effects on pipeline components, storage containers, valves, seals and gaskets over a long period of time. The initial testing for low blends of E15 may not be long enough to show damage that can occur 10 or 15 years in the future. Vehicle warranties may result in higher payouts by automakers and lower consumer satisfaction or re-sale value.

7.3. *Concluding Recommendations*

Coordinated Policy:

The Renewable Fuel Standard laid out an aggressive path for the development of biofuels through 2022. In the same piece of legislation the supports for flex fuel vehicles were set to expire phase out by 2019. Some incentives were given for station deployment, but these three aspects should be viewed as interlocking rather than disjointed.

The results of this analysis show that policies of accelerated flex fuel vehicle deployment and relaxed biofuel policy are quite successful in producing a manageable utilization requirement. However, steps must be taken to insure the attractiveness of any fuel alternative because availability of fuel and capability of vehicles is necessary, but not sufficient.

One major caveat is that some new problems are likely to emerge in the resolution of existing problems. The RFS may be tempered through the certification of E15, however this creates risk for automakers and drivers with vehicles already on the road. Incremental certification of E20 may be a logical next step, but automakers should be given advanced warning.

The deployment of biofuels was set with the RFS then other polices such as a vapor pressure waiver, and now perhaps E15 certification, follow. Biofuels targets need not be a policy that is set with all other policies then bending to accommodate it. Careful thought should be given with regard to what blend of ethanol might be most advantageous along multiple dimensions, and then structure policy to support that level of deployment.

Value of appropriate timing:

With a given trajectory of flex fuel vehicle deployment, delaying the RFS can decrease the utilization requirement for FFVs. This effect is due to the time frame for fleet turnover and the rate of accumulation of vehicles. Early deployment of vehicles will facilitate greater biofuels deployment in the future, but still provides drivers with a choice to use conventional fuels.

There can never be certainty regarding which fuels will be available in the future. However, based on the current rate of technological progress in biofuels there is reason for optimism that biofuels in 10-20 years will be closer in nature to current gasoline. Depending on the rate of and scale of this development there is a chance that the ethanol may be a passing fuel format which emerges at great scale and then disappears over two decades time. The investments in fuel infrastructure may warrant a longer view in structuring fuel policy.

Value of Flexibility in the Face of Uncertainty

The term flexibility is used in a variety of ways, but represents an important concept for several aspect of vehicle and fuel deployment. Flexible fuel vehicles allow drivers to have choice of fuels in a market otherwise dominated by petroleum. This capability allows the consumer to value other like environmental impact or point of origin, that may be increasingly important to consumers.

Ethanol capability is a first step, and additional value can be attained through appropriate use of any blend of ethanol, and even adjusting performance accordingly. Fuel formats are changing and regional fuels may emerge as technology and access to feedstocks vary. Flexible powertrains may be able to optimize performance to a high degree with low amounts of ethanol, with the additional capacity to displace more petroleum when ethanol is more available.

Flexibility in fuel dispensing allows for retailers to adapt to future changes in regulations or consumer preferences. Depending on the cost differential, E85 may be a less attractive fuel. However, at mild blend levels it may offer a low cost alternative blend to premium fuel.

Closing Thoughts

Ethanol may not be the best fuel, or even a dominant fuel in the future, but it could be. Adding ethanol capability to vehicles in the near term will allow the potential for future successful deployment of ethanol. Even in the event that ethanol production is constrained or there are other biofuel alternatives, small amounts of ethanol can afford increases in efficiency of modern engines.

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Appendix: Cellulosic Pilot Plant Survey

Number	Company	State	Location	Technology	Production Capacity (Million Gallons per Year)	Feedstocks
1	Abengoa	Nebraska	York	Biochemical	11	Agricultural Residue
2	Abengoa	Kansas	Hugoton	Biochemical	11.6	Agricultural Residue
3	AE Biofuels	Montana	Butte	Biochemical	<1	Agricultural Residue
4	Bluefire	California	Corona	Biochemical	18	MSW
5	Bluefire	California	Lancaster	Biochemical	3.1	MSW
6	California Ethanol + Power, LLC	California	Brawley	Biochemical	55	Agricultural Residue
7	Coskata	Pensylvania	Madison	Biochemical	<1	Agricultural Residue
8	DuPont Danisco	Tennessee	Vonroe	Biochemical	<1	Agricultural Residue
9	Ecofin, LLC	Kentucky	Washington County	Biochemical	1.3	Agricultural Residue
10	Flambeau River Biofuels	Wisconsin	Park Falls	Thermochemical	6	Woody Biomass
11	ICM, inc	Missouri	St. Joseph	Biochemical/ Thermochemical	1.5	Agricultural Residue
12	Iogen Corp.	Idaho	Shelley	Biochemical	18	Agricultural Residue
13	KL Process	Wyoming	Upton	Thermochemical	1.5	Woody Biomass
14	Lignol Innovations	Colorado	Grand Junction	Biochemical	2.5	Woody Biomass

15	Mascoma	New York	Rome	Biochemical	5	Agricultural Residue
16	New Page Corp	Wisconsin	Wisconsin Rapids	Thermochemical	5.5	Woody Biomass
17	New Plant Energy	Floriday	Vero Beach	Biochemical/ Thermochemical	8	MSW
18	Pacific Ethanol	Oregon	Boardman	Biochemical	2.7	Agricultural Residue
19	POET	South Dakota	Scotland	Biochemical	<1	Agricultural Residue
20	POET	Iowa	Emmetsburg	Biochemical	31	Agricultural Residue
21	Range Fuels	Georgia	Soperton	Thermochemical	20	Agricultural Residue
22	RSE Pulp & Chemical	Maine	Old Towne	Biochemical	2.2	Woody Biomass
23	Verenium	Louisiana	Jennings	Biochemical	1.4	Agricultural Residue
24	ZeaChem	Oregon	Boardman	Biochemical/ Thermochemical	1.5	Woody Biomass

Adapted from (Renewable Fuels Association 2008)