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Market competition and social welfare analysis for E10 and E85 with a game theory model

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Market competition and social welfare analysis for E10 and E85 with a game theory model

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ABSTRACT

With the increasing concern about the petroleum reserve, fossil fuel prices, and the global warming, people have been looking for renewable and environmental friendly energy sources to replace the use of fossil fuels. Ethanol is produced from agricultural feedstock and has proved to be an appropriate substitute to fossil fuels. Fuel blenders blend ethanol into gasoline in different ratios. Currently E10 and E85 are two of the main transportation fuels with ethanol and they are competing in the market. This study investigates the competition between E10 and E85 with an oligopoly Cournot model and derives several market indices from the equilibrium to measure the performance of the market: E85's market share, E85 price premium which indicate the consumers' additional willingness to pay, and the social welfare which indicates the societal wellbeing from the products. The author addressed several questions on how the government policies impact the market equilibrium, how the industry size affects the market performance of E85, and whether E85 has a bright prospect with the increase of FFVs number. The results from the numerical examples show that the current blending mandate is not binding and the elimination of the tax credit will lead E85 to a more unfavorable situation. The decreasing of the number of firms in the industry, if possible in the future, would give E85 more market share. The increasing of E85's market share is very limited through the increasing of the proportion of FFVs.

The results have some important implications for policy makers. A theoretical feedback is given to the policy makers about the current situation of the ethanol blending mandates and the effect of the eliminating the tax credits. The results also pointed out the fact for policy makers that it is not so useful to increase the number of FFVs in order to promote the consumption of E85 unless it can make the proportion of FFVs go higher than 90%.

Key words: Ethanol, E10, E85, Flexible-fuel Vehicles, Cournot game theory model, Market share, Social welfare, Tax credits, Mandates

CHAPTER 1. INTRODUCTION

1.1 MOTIVATION

With the rising gasoline price and the increasing concerns on the global warming, there is an urgent need for a cleaner and renewable transportation fuel to supplement and replace the fossil fuel. Ethanol is a renewable fuel produced from agricultural feedstock and it can reduce the greenhouse gas emission level, so it proved to be a good substitute to conventional fossil fuels. Government has introduced several policies to support the production and consumption of ethanol, such as the tax credits (expired at the end of 2011) and the mandates from the Renewable Fuel Standard. Ethanol is mainly used as a gasoline additive and currently most of the ethanol is blended to be E10 and some stations also sell E85 with special pumps. We propose to divide the consumers into two groups: regular vehicles group and flexible fuel vehicles group. The flexible fuel vehicles can run on blended gasoline with up to 85% of ethanol while the regular vehicles group can only run on gasoline blended with up to 10% of ethanol (some newer ones can use up to 15%). E10 and E85 are two competing products on the transportation fuel markets.

The literature on comparing E10 and E85 from the economic or market side is very scarce. The motivation of this study is to fill this blank and initiate more future research on this topic. There are three major objectives of this study: First, to build a model to investigate the competition between E10 and E85; Second, to analyze how the government policies and subsidies affect the market performance of the two products; Third, to find out whether E85 is a promising transportation fuel in the long run.

1.2 Structure of work

In chapter two, I will give a detailed introduction to the background of the ethanol industry and some historical market data about E10 and E85. Then I will briefly talk about the energy contents of different fuels which will be used in the model analysis. I will also discuss the advantages of ethanol over gasoline and talk about public debates about whether ethanol really reduces greenhouse gas emission. Then I will introduce the related government policies including the tax credits, the Renewable Fuel Standard, the blending mandates and corresponding RINs market.

In chapter 3, some related literature is presented. Quite a few articles discussed on the policies for ethanol industry and had a common idea that the ethanol industry does not need both of the mandates and tax credits. Tax credits are subsidizing the consumption of gasoline fuels instead of the ethanol industry if it exists along with the mandates. Some articles talked about the constraints for the developing of E85 and concluded that the limited availability of E85 fueling stations and the small number of FFVs on roads are among the main constraints. Some articles studies on the gasoline price elasticity for different time periods and this helped the parameter estimation in the demand function of the model in this study. Several other articles analyzed the economic sustainability of E85 and concluded that the possibility of E85 to be price competitive with E10 is low.

In chapter 4, an oligopoly Cournot model is formulated to investigate the competition between E10 and E85. Three market indices are derived from the equilibrium including the market share of E85, the green price premium over regular product price, and the total social welfare. The first two indices are good indicator to the market performance of E85: a higher market share and a lower price premium indicate a greater consumer acceptance. The third index is a measure of the entire society's well-being got from the producing and consuming of the fuels. The social welfare analysis will provide insights for relevant decision makers, such as the government, and regulatory agencies.

In chapter 5, numerical examples for different scenarios are presented to answer four questions on how the change of policies and market conditions affect the competition between E10 and E85. The result shows that currently the blending mandate is not binding. The elimination of tax credit will lead to an even lower market share of E85 and make it more difficult to survive given the current market. The result also tells that if in the future, the transportation fuel industry will size down facing the challenge from new energy sources, E85 market share will increase and this also increase the total social welfare. The final implication from the examples is that the prospect for E85 to be market competitive by increasing the number of FFVs is dim.

Chapter 6 will conclude this study and point out some future research directions.

CHAPTER 2. BACKGROUND

2.1 ETHANOL FEEDSTOCK

Ethanol is currently the primary biofuel mainly as an additive to gasoline. Ethanol is a renewable energy carrier and it can be produced from a variety of agricultural feedstocks such as sugar cane, sugar beet, sorghum, corn stover, switchgrass, miscanthus, etc. In other words, almost all plant-based materials that contain sugar or starch can be used as ethanol feedstock. Currently, the majority of ethanol is produced from starch- and sugar-based feedstocks. Among these feedstocks, corn plays the most important role in the U.S. and it is the feedstock for more than 90% of current U.S. ethanol production [1]. Another feedstock for ethanol is the cellulosic biomass including agricultural residue, forestry residue, woody biomass, municipal wastes, etc. Cellulosic feedstocks have some advantages over the starch- and sugar-based feedstocks. First, they are much more abundant than the starch- and sugar-based feedstocks. Secondly, using cellulosic feedstock is not competing with the feedstock which can also be used for human or animal feed. Corn ethanol production significantly increases the market need for corn grain and this leads to the price increase of corn and other food products as well. The U.S. policy has reflected the concerns, for example, the corn ethanol blenders' credits have expired at the end of 2011. However, limitations also have been placed on cellulosic biomass. The government limits the amount of crop residues removed from the land, in order to avoid erosion and to keep the sustainability of the land. However, currently the cellulosic feedstock is still very abundant. The third advantage of cellulosic feedstock is that they are more environmental friendly than corn based biofuels. The carbon intensity of cellulosic ethanol is only 28 gCO_2e/MJ, compared to gasoline's 96 gCO_2e/MJ and corn ethanol's 69 gCO_2e/MJ [2], which leads to a 70% reduction in greenhouse gas emission. Despite of the advantages, currently the main feedstock for ethanol production in U.S. is still corn, because corn is easier and less expensive to process. It costs about

$2.2 per gallon to produce cellulosic ethanol, estimated by the Department of Energy, which is twice as much as processing ethanol from corn [3].

2.2 E10 AND E85 ON FUEL MARKET

The large scale production of ethanol fuel in U.S. can date back to 1980s. Since then, the production quantities have grown rapidly from 175 million gallons in 1980 to 13,230 million gallons in 2010, which made U.S. the world's top ethanol fuel producer. Brazil is another major producer of ethanol and its 2010 production quantity is 6,921million gallons. Ethanol production in U.S. and Brazil accounts for 88% of the world production [4]. Other countries that have ethanol industries include European Union, China, Canada, and Australia.

As mentioned, the main use of ethanol in transportation fuels is as an additive to gasoline. The blend ratio of gasoline and ethanol can range from E10 to E100. The "E" numbers for ethanol fuel describe the percentage of ethanol in the mixture by volume. For instance, E10 is a mixture of 10% of ethanol and 90% of gasoline in volume, and E85 is a mixture of 85% of ethanol and 15% of gasoline. Currently, the two major ethanol fuel products are E10 and E85. Figure 1 shows the distribution system of ethanol going into transportation fuels.

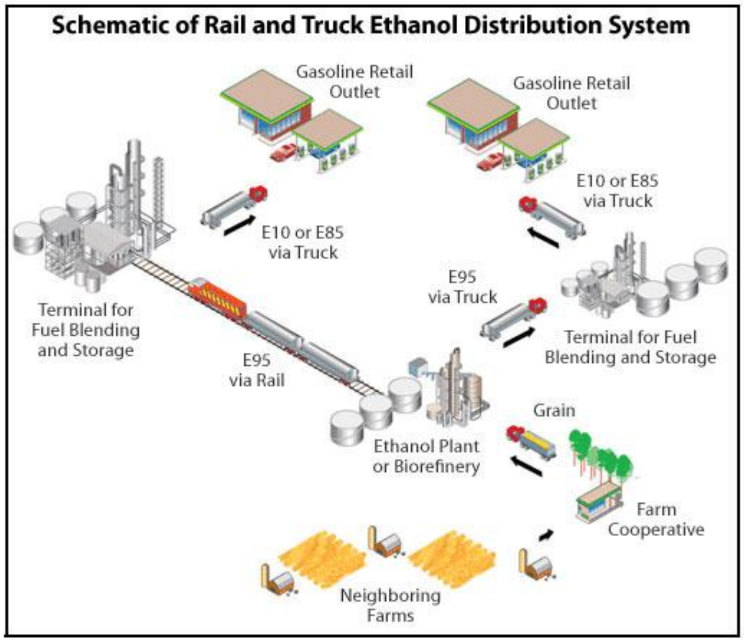

Figure 1. Ethanol Distribution System [5]

Ten states in U.S. including Minnesota, Missouri, Montana, Oregon, Washington, Florida, Hawaii, Iowa, Kansas and Louisiana mandate the use of E10 in all standard transportation fuel and in 2010, two thirds of the nation's gas supply is E10 [6]. Most of the U.S. cars are able to run on blends up to 10% ethanol. There is another kind of vehicles called flexible-fuel vehicles (FFV). Though technology exists to allow ethanol FFVs to run on any mixture of gasoline and ethanol, from pure gasoline to pure ethanol, North American FFVs are optimized to run on a maximum blend of 85% ethanol with 15% gasoline. E85 is produced for this type of vehicle. Though FFVs are still a minority on U.S. road, its number is increasing rapidly in the past years. Till January 2011, the total FFVs produced/sold in U.S. market reaches 10 million [7]. FFV is an important requirement for using E85 and another requirement is the availability of the E85 fuel. As of Jan 2011, there are only 2524 stations carrying E85 [8] around the U.S. Figure 2 is an E85 fueling stations map showing stations densities by states. To promote the consumption of E85 to a higher level, more and more E85 fuel and retail stations are in demand.

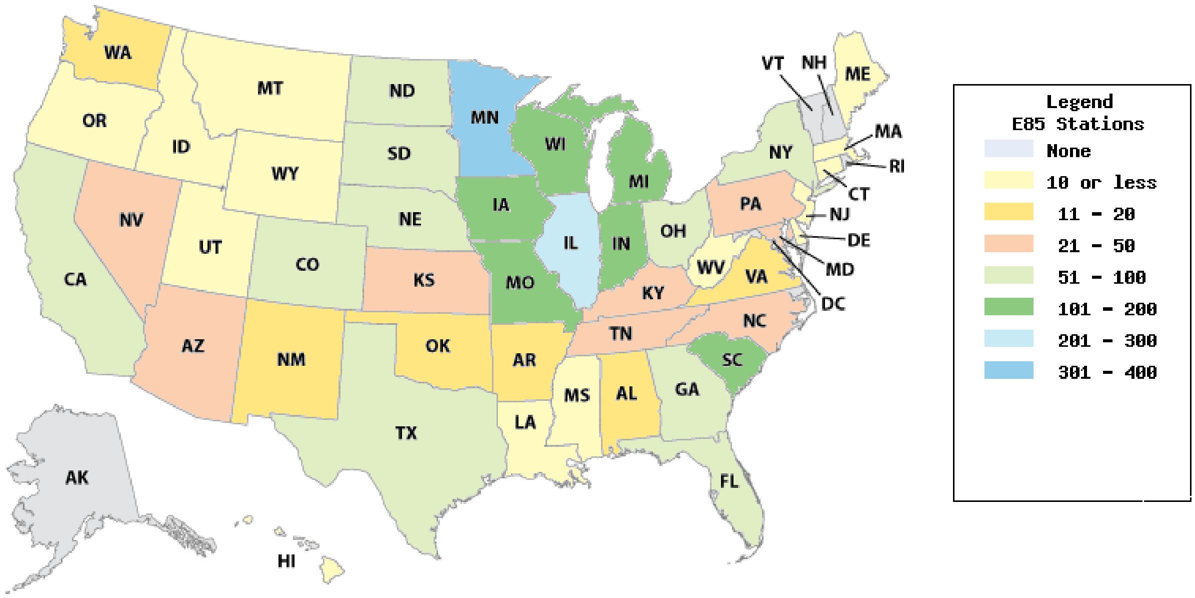

Figure 2. E85 Fueling Stations Map [9]

Since most of the ethanol in U.S. is produced from corn, the majority of the ethanol plants are built in Midwest where corn supply is abundant. These states include Missouri, Wisconsin, Illinois, Nebraska, Minnesota, North Dakota, Iowa, South Dakota, Kansas, and Michigan. As of March 2012, there are 218 ethanol producers around the country and among them, 120 plants are located in the states listed above [10]. The total capacity of these producers adds up to 14,745million gallons per year and among the states producing ethanol, Iowa is on the top of the list with 3,579million gallons capacity per year [11].

The price of E85 is highly related and influenced by the price of gasoline. There are two reasons for this. First, the production process of ethanol uses gasoline as a fuel so the gasoline price is regarded as a production cost of ethanol. Second, E85 is a substitute to gasoline in the transportation fuel market, so it’s competing with other transportation fuels in the market. In 2011, the average gasoline price fluctuates frequently and the range is fairly large. It went as high as $3.95/gallon in May and fell back to $3.2/gallon in December. The fluctuation of E85 price is very similar to that of gasoline. In

May, it went up to $3.3/gallon and in December, it fell down to $2.98/gallon. The price gap between gasoline and ethanol always remain in the range of $0.25/gallon to $0.75/gallon [12].

Although the retail price of E85 is much lower than that of gasoline, it is not as significant as it appears, because the energy content of E85 is much less than that of E10. Energy content (or energy density) is a term used to describe the amount of energy stored in a given fuel per unit volume. The energy content of E10 is 33.18 MJ/L and for E85, it's 25.65 MJ/L [13]. That is to say, the energy content of E85 is only about 77% of that of E10, which means, if your car can run 100 miles on 5 gallons of E10, it can only run 77 miles using the same volume of E85. Therefore, the consumers may prefer E10 to E85 if they take the energy densities into consideration. That's why there is competition between E10 and E85: E85 has advantage over E10 on the retail price but it has lower energy content. In reality, there are other factors which may influence consumer choices at the gas stations. Some consumers are willing to pay a price premium for E85, because they value the fuel's environmental and social benefits. Some consumers want to stick with E10 just because of the hesitance to change.

2.3 Advantages ethanol over gasoline

Now we have a brief introduction of ethanol and its fuel products, but why do we use ethanol as a transportation fuel to compete with gasoline in the market? Why does the government implement a lot of policies and mandates to promote the production and consumption of ethanol products? We all know that gasoline is a product of crude oil, a kind of fossil fuel that is a non-renewable resource. The crude oil resource will be exhausted by 2060 if at current speed. People have been looking for new energy sources to replace it and ethanol is among the list of effective replacement to fossil fuel.

In addition, ethanol also has some advantages over gasoline. **The first benefit** is potentially reduced pollution emission especially carbon dioxide in earth's atmosphere. Carbon dioxide is one of the several greenhouse gases emitted by human activities. Renewable energy sources will have a lower emission level than fossil fuels. Previous studies showed that the direct greenhouse gas emission of ethanol is estimated to be reduced by 25% compared to gasoline [2]. However, this is still under debating. There are studies showing that there is a considerable amount of emission from the land use change or indirect effects in the ethanol production process. From Table1 we can see the land use or other indirect effects of using ethanol was estimated to be equivalent to 30 gCO_2e/MJ. When added with the direct emissions, the total emissions from consuming ethanol could be higher than that of using gasoline. Recently, a new study has partly cleared away this concern. A study coming out of University of Nebraska—Lincoln says that we have underestimated the potential of corn ethanol to reduce the GHG emission before. This research shows that on average, the direct emission from ethanol is 51% lower than gasoline [14]. In this case, even if we include the indirect emission, ethanol is still more environmental friendly compared to gasoline. **Another advantage** of ethanol over gasoline is that it provides the possibility of localized production of fuel in agricultural areas. For example, If Iowa can produce as much corn ethanol to meet the local fuel demands at a low cost and the vehicles are flexible-fuel vehicles, then we don’t need to transport fuels from other states.

Table 1. Carbon Intensity Lookup Table for Gasoline and Ethanol [2]

Fuel	Pathway Description	Carbon Intensity Values (gCO_2e/MJ)		
		Direct Emissions	Land use or Other Indirect Effect	Total
Gasoline	CARBOB- based on the average crude oil delivered to California refineries and average California refinery efficiencies	95.86	0	95.86
Ethanol from Corn	Midwest average; 80% Dry Mill; 20% Wet Mill; Dry DGS; NG	69.40	30	99.40

The reduction of greenhouse gas emission has some economic benefit if we know the concept of emission cost. Carbon dioxide is the primary cause of climate change, especially global warming, so it has some bad effects to the social benefits. To measure this effect, we use the term social cost of carbon (SCC). SCC is the marginal cost of emitting one ton of carbon dioxide to the atmosphere. The measurement of this cost is partially based on the cost to offset the negative consequences of the pollution. Estimates of the SCC are subjective and uncertain due to the underlying uncertainty in the science of climate change. Usually, the effect of CO_2 is measured by the weight of the pollution. Sometimes, it is directly measured by the weight of CO_2, abbreviated as "tCO_2", and sometimes it is measured only by the weight of C, excluding the weight of the oxygen atoms, abbreviated as "tC". Peer-reviewed estimates of the SCC for 2005 had an average value of $43/tC with a standard deviation of $83/tC [15], or after transformation, average $12/$tCO_2$ with a standard deviation of $23/$tCO_2$.

It is fair that the parties who emit the greenhouse gases take responsibility to offset the negative consequences. However, implementation is not easy both politically and practically. Currently, there are no federal carbon taxes in either Canada or United States, though some Canadian provinces and U.S. states have implemented the carbon taxes at regional levels. Colorado passed the carbon tax proposal in 2006 to impose additional tax on electricity consumption from conventional sources and subsidies for electricity from renewable energy. Currently the tax is set at $0.0049/kWh for residential use and $0.0009/kWh for commercial, and $0.0003 for industrial use [16]. In California, the bay Area Air Quality Management District passed a carbon tax on business of $0.044 per ton of CO_2 in May 2008 [17]. In recent years, there is a widespread opposition to such emission policies like carbon tax and cap-and-trade which pose extra burdens on the industry.

2.4 RFS, Mandate and RINs

The rising demand for oil would accentuate the vulnerability of the fuel supply and result in price shock. Besides, the rising amount of GHG emissions from transportation fuels, if unchecked, may lead to severe climate change and negative impacts to the environment. Renewable fuels represent a key route to bring alternatives to gasoline and alleviate these problems fundamentally. To reduce the dependence on fossil fuels and to address climate change concerns, U.S. government has been implementing a series of policies to support the production and consumption of renewable fuels. In 2005, United States Environmental Protection Agency (EPA) created the Energy Policy Act (EPAct). Under this act, the Renewable Fuel Standard (RFS) program was created in collaboration with refiners, renewable fuel producers and many other stakeholders. This RFS established the first renewable fuel volume mandate in the United States, which requires 7.5 billion gallons of renewable fuels to be blended in to gasoline by the year of 2012. In 2007, under the Energy Independence and Security Act (EISA), the RFS program was expanded in several ways and released a new program called RFS2. The expansions in RFS2 include increasing the volume of renewable fuel required to be blended into transportation fuel from 9 billion gallons in 2008 to 36 billion gallons by 2022 [18]. Specific mandates were created for various types of biofuels, such as advanced biofuels, cellulosic biofuels, and biomass-based diesel. Figure 3 shows RFS requirements through 2022 by feedstock types.

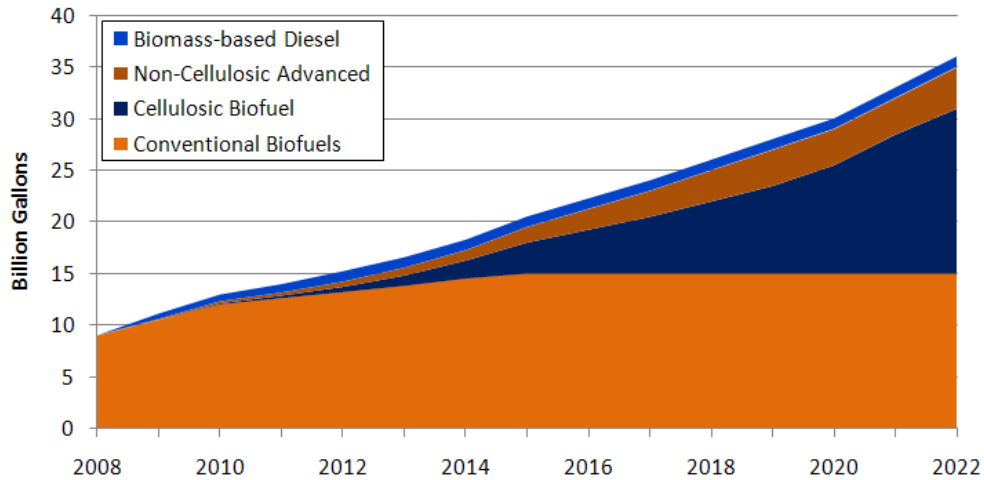

Figure 3. Renewable Fuel Standard requirements through 2022 [19]

Estimating the total amount of fuel to be consumed in the USA and the planed volume of renewable fuel required to be blended into fossil fuels for a certain year, EPA divides the mandate among the obligated parties, including fossil fuel producers and importers. For example, EISA set a total mandate of 13.95 billion gallons of total renewable fuel to be blended in gasoline in 2011, and EPA calculated the final percentage standard for renewable fuel at 8.01 percent. Thereby, the renewable volume obligation (RVO) for each obligated party is calculated by multiplying this percentage standard with the annual volume of gasoline and diesel produced or imported [20].

To administer the compliance of the mandate, EPA designed the Renewable Identification Number (or RIN) to track the production and use of the renewable fuel. A RIN is a 38-digit number which contains the information of the year of production, company ID, facility ID, batch number, the renewable fuel category, start of RIN block, and end of RIN block, etc. Thus, every RIN is unique and traceable. When one gallon of renewable fuel is produced, a RIN is generated and it will remain with the renewable fuel through the distribution system, until the renewable fuel is blended into the fossil fuels. Each year, the obligated parties have to fulfill the required blending quota and submit the amount of RINs to EPA for record. The RIN can only be used to fulfill the mandate requirement when it's separated from the underlying renewable fuel. The separation event is triggered by the blending of the renewable fuel to fossil fuels. In additional to using the RINs to meet the yearly requirement, the obligated parties can also store the RINs according to predefined rules or trade the RINs with other parties registered in EPA.

The longest possible life time of RINs is two years. If not used, the RINs will expire two years after the date they are generated. Since RINs have this characteristic, EPA allows for obligated parties to borrow RINs from future periods or to bank RINs to use in the following year, up to 20% of their own mandates. Another important characteristic of RINs is that it's tradable. EPA developed a system called the EPA Moderated Transaction System (EMTS) to manage RIN transactions. Once you are registered in and approved by EPA, even if you are not an obligated party, you can trade RINs.

Each calendar year, if an obligated party has acquired more than enough RINs, it can either bank the excess RINs to the next calendar year, or sell it in the RINs market. On the other hand, if an obligated party has not acquired enough RINs, under certain conditions, it can carry a deficit to the next calendar year or purchase RINs from the market. Due to the tradability of RINs, the obligated parties do not have to blend renewable fuels physically. If blending is not making profit, the party can choose to buy RINs to meet the mandate rather than purchase the renewable fuel and blend it physically.

While the RINs transaction is managed by EPA, the RIN prices are determined by the market. There are various factors impacting the price of RINs, including the core value of RINs, transaction cost and/or a speculative component. "The core value of a RIN is the gap, if positive, between the supply price and the demand price for biofuels at any given quantity. The supply price is the price that allows biofuel producers to cover the cost of producing at that output level. Similarly, the demand price is the price that consumers (blenders) would be willing to pay for that volume of biofuels without the mandates." [20] Figure 4 demonstrates the biofuel markets with a non-binding mandate and a binding mandate. The left hand side graph shows the situation when a mandate is not binding. Sometimes, the equilibrium production amount determined by the market supply and demand already exceeds the mandate level, and in such case, the RINs core value is zero. The right hand side graph shows the situation when a mandate is binding. In this case, the equilibrium production quantity is less than the mandated level. To achieve the mandated level, the suppliers would request a higher supply price and the demanders would ask for a lower price thus there is a gap between the supply price and the demand price, which represents the RIN core value.

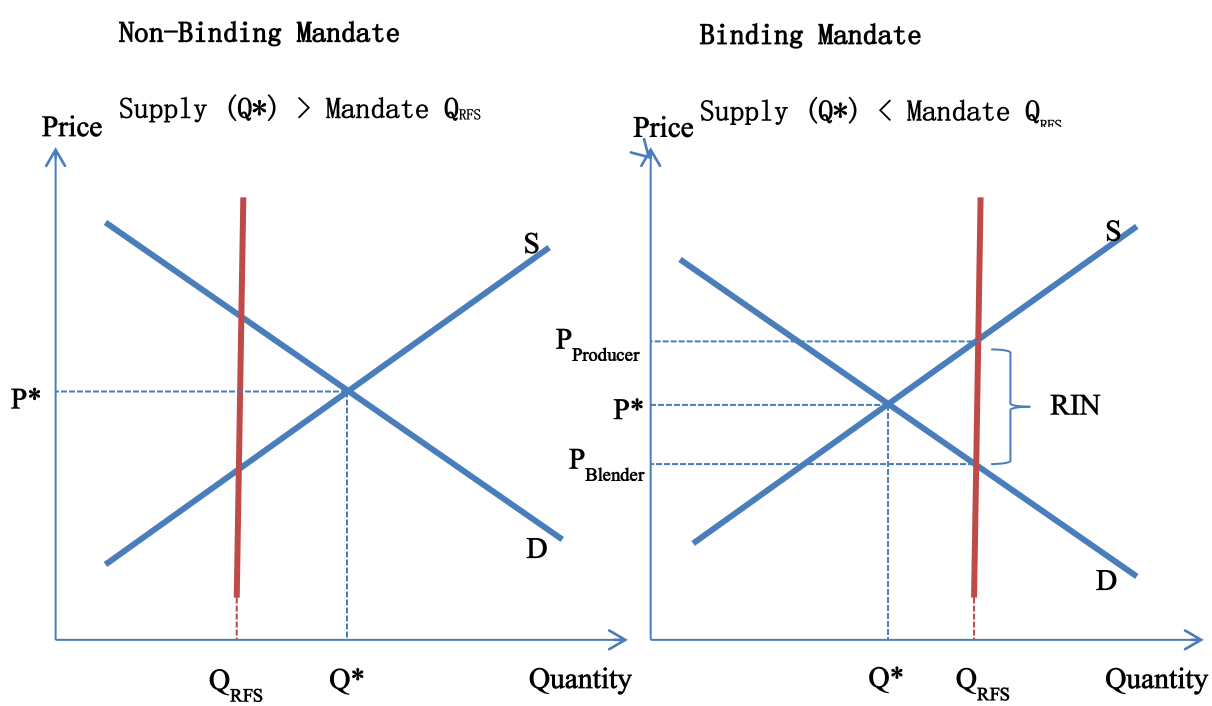

Figure 4. Biofuel markets with mandate [21]

The core value of RINs is affected by the feedstock price, the crude oil price, and the tax credits. We briefly explain these in the binding mandate scenario here. Feedstock price accounts for a large proportion of the production cost of biofuels. When the feedstock price increases, at the same price, the producers will produce less biofuels, so the supply curve will shift upward resulting in an increase of the RINs core value. This is intuitively easy to understand. When the price of feedstock for producing biofuels increases, the price of biofuels usually increases so the stakeholders will have less motivation to buy and blend biofuels physically, instead they are more likely to buy RINs to complete the mandate, which will result a RINs price increase. On the contrary, when the crude oil price increases, blenders are more willing to blend more biofuels which shift the demand curve upward and result in the decreasing of the RIN core value. The influence of tax credits on the RINs core value will be discussed later in the tax credit section.

The RINs market plays an important role in implementing the RFS2 mandate, however, in recent years, the conventional ethanol RIN prices averaged at a very low level. In 2010, the conventional ethanol RIN prices stay below 1 cent per gallon and in 2011, the prices stay around 3 cents [20], implying a low probability that the implicit mandate is blinding.

2.5 TAX CREDIT

Tax credit was another important policy to promote the production and blending of biofuels. Due to the opposition of many policy analysts, the 45 cents/gallon tax credit for conventional ethanol finally expires in the end of 2011 after three decades. Tax credits to support biofuels date back to 1970s and the latest tax credit was based on Energy Policy Act of 2005, Food, Conservation, and Energy Act of 2008, and Energy Improvement and Extension Act of 2008. Different types of biofuels have been granted different tax credits, and for ethanol, blenders could receive a tax credit of 45 cents per gallon of ethanol they blend to gasoline. Tax credit is among the factors affecting the RINs core value: when there is a tax credit, the blenders become more willing to blend ethanol, and this shifts the demand curve upward in the graph on the right of figure1 which results in the decreasing of RINs core value. In addition, this brings the equilibrium production quantity closer to the mandated quantity, which helps the mandate to be met.

The opponents of ethanol tax credits have listed several disadvantages of tax credits. The first one is that tax credits for ethanol production imposed extra burden on the federal finance and taxpayers paid too much for the cost of producing ethanol. In 2009, it cost taxpayers $4.8 billion to replace 7.2 billion gallons of gasoline with 10.6 billion gallons of ethanol. Between 2005 and 2009, taxpayers spent more than $17 billion on tax credits for ethanol production and usage. In 2011, the tax credit cost the government nearly $6 billion to support ethanol production [22]. The second disadvantage is that the tax credit boosted the production of ethanol which contributes to a higher corn price. Nearly 40 percent of the corn in U.S. goes to the ethanol industry and this directly leads to the price increase of food corn. In addition, the production of ethanol (with the use of pesticides and fertilizer and heavy industry machinery) caused soil erosion, air and water pollution so the land available for growing food is influenced and this also contributes to the price increase of food, not only the corn, but also meat and poultry.

CHAPTER 3. LITERATURE REVIEW

The literature on the competition between E10 and E85 is relatively scarce. Firstly, E85 is a relatively new transportation fuel product and it needs time to be accepted by the public. In addition, E85 has strict requirement on the vehicles that only FFVs can run on it, so it is not so widely used as E10. Currently the proportion of E85 on the U.S. fuel market is still low so it does not appear to be so competitive compared to E10 at this stage.

Nevertheless, there are some studies that helped shape the ideas of the market structure and the competition between E10 and E85. In addition, there are relatively abundant literature about the policies' impact on ethanol production and ethanol fuel market.

Anderson (2010) has estimated the demand for ethanol as a gasoline substitute [23]. The household preference for ethanol (E85) as a gasoline (E10) substitute was estimated by developing a model linking the shape of the ethanol demand curve to the underlying distribution among the households of the willingness to pay for ethanol. The instrumental variables techniques were used and data were acquired from many retail fueling stations. The main result is that a $0.01-per-gallon increase in ethanol's price relative to gasoline leads to a 12-16% decrease in the quantity of ethanol demanded. This implies that the preferences for ethanol are heterogeneous and that a substantial fraction of households are willing to pay a premium for the fuel.

Tatum (2010) has investigated the economic sustainability of E85 [24]. The author used an empirical model and conducted an econometric analysis of the E85 market using demand and supply analysis. The main result is that the reduced form price equation estimates indicate that the cross elasticity of E85's price with respect to the price of gasoline does not differ significantly from unity, so that any rise in the gasoline prices will be matched by a corresponding rise in the price of E85. Thus, the authors draw the conclusion that given the current market (which includes significant government subsidy) the prospect that E85 will ever be price competitive with gasoline is indeed dim.

Greene (2008) has studied on the market environment for promoting the consumption of ethanol fuel and claimed that flexible-fuel vehicles and E85 stations are needed to achieve ethanol goals [25]. A model of consumers' decisions to purchase E85 versus gasoline based on prices, availability, and refueling frequency is derived, and preliminary results for 2010, 2017 and 2030 consistent with the president's 2007 biofuels program goals are presented. The analysis results show that to meet a 2017 goal of 26 billion gallons of E85 market sale, on the order of 30% to 80% of all fuel stations in the U.S. may need to offer E85 and that 125 to 200 million flexible-fuel vehicles will need to be on the road.

There is a rich literature on on the ethanol industry which is part of what we want to address in this study. Gorter and Just (2009) has studied on the economics of a blend mandate for biofuels [26]. They built separate models to analyze the economics of a biofuel mandate and the economics of a mandate and a tax credit combined. They found that if tax credits are implemented along with the mandates, then tax credits subsidize gasoline consumption instead of the biofuels industry. This contradicts the goal of energy policy since it increases oil dependency and social costs. The authors provided some policy implications for various scenarios and showed that a mandate is a better choice. Babcock (2010) also pointed out that the biofuel industry does not need all of the mandates, tax credits and tariffs in one of the CARD policy briefs [27]. He examined how the new mandates will be implemented and the result shows that the biofuel producers will receive little or no additional benefit from tax credits while import tariffs will continue to provide U.S. corn ethanol producers a cost advantage over imported ethanol.

CHAPTER 4. MODEL FORMULATION

4.1 INTRODUCTION TO THE COURNOT MODEL

Cournot model is one type of game theory model to study market structures for homogeneous products where firms decide on the production quantities and achieve the market equilibrium between consumers' demand and total market supply. Cournot model dates back to the first half of nineteenth century, but the equilibrium concept is based on Nash: each firm independently chooses its strategy to maximize profits taking as given the strategy of each other firm [28].

Cournot model has several assumptions:

a. There is more than one firm and all firms produce a homogeneous product, i.e. there is no product differentiation;
b. Firms have some market power, i.e. each firm's output decision affects the market price;
c. Firms make decisions on quantities independently and simultaneously;
d. The firms are rational and act strategically to achieve the objective, such as, to maximize profit given their competitor' decisions.

In this study, Cournot model is formulated to study the market competition between E10 and E85.

Here is the market scenario for a Cournot model: A single product is produced by n firms and n is fixed. The cost of producing q_i units to firm *i* is $C_i(q_i)$, where C_i is nonnegative and increasing. All the output is sold at a single price, determined by the demand for the good and the form's total output. If the total output is Q, then the price is $P(Q)$, where P is a non-increasing function of Q [20]. P is called the "inverse demand function". Thus, for firm i, the profit, equal to its revenue minus its cost, is

$$\pi_i(q_1,\ldots,q_n) = q_i P(q_1+\ldots+q_n) - C_i(q_i).$$

The objective of all firms is to maximize their own profit. In order to achieve this goal, they should first take the derivative of π_i with respect to q_i,

$$\frac{\partial \pi_i(q_1,\ldots,q_n)}{\partial q_i} = \frac{\partial P(q_1+\ldots+q_n)}{\partial q_i} q_i + P(q_1+\ldots+q_n) - \frac{\partial C_i(q_i)}{\partial q_i}, i = 1,2,\ldots,n.$$

Setting this to zero for maximization:

$$\frac{\partial \pi_i(q_1,\ldots,q_n)}{\partial q_i} = \frac{\partial P(q_1+\ldots+q_n)}{\partial q_i} q_i + P(q_1+\ldots+q_n) - \frac{\partial C_i(q_i)}{\partial q_i} = 0, i = 1,2,\ldots,n.$$

The values set of q_i that satisfy this equation are the best responses for the firms, and this is called equilibrium.

Cournot competition may not have unique equilibrium which depends on the type of demand function. It is well known that the Cournot model may have multiple equilibriums if the demand function is sufficiently convex [29]. A simplest situation is that if the demand function is linear, there will be a valid unique equilibrium, as long as the equilibrium quantity and the corresponding product price are all positive.

There are many types of demand functions for retail gasoline. A very commonly used demand function is the linear log function. In Hughes's paper [30], the demand function is modeled as $\ln G_{jt} = \beta_0 + \beta_1 \ln P_{jt} + \beta_2 \ln Y_{jt} + \varepsilon_j + \varepsilon_{jt}$ (j as a month index and t as a year index, G as the demand quantity, P as the price and Y as the income) to estimate the short-run price elasticity of gasoline demand. In the article on how to measure price elasticity by Chamberlain Economics, L.L.C. [31], the author says that in the simplest case, the demand of gasoline should be driven by two things, the price of gasoline and how much income people have. If gas prices rise, consumption should fall; conversely, if income goes up, gas consumption should rise also. So if we ignore the seasonal variation, we can write the demand function as $G = a * P + b * Y$, where G denotes the gallons of gas demanded per year, P denotes the price of gas, Y denotes the average income in the economy and a, b are coefficients for the magnitudes of the impacts of prices and income on the gasoline demand.

We will use linear demand function similar to Chamberlain Economics in our model. Also, since we only investigate the competition in a short period, we set the average income as fixed, so the second term on the right side of the demand function can be denoted by a constant. It must be noted that in this study, the Cournot model was extended to include two products, E10 and E85 in the competition.

4.2 Model Formulation

Notations:

q_k^G, q_k^E : the supply quantities of E10 (Gasohol) and E85 by blender k;

Q^G : the total supply of E10 in the market, where $Q^G = \sum_{i=1}^{s} q_i^G$;

Q_{-k}^G : the total supply of E10 in the market excluding the supply from blender k, where $Q_{-k}^G = Q^G - q_k^G$;

Q^E : the total supply of E85 in the market, where $Q^E = \sum_{i=1}^{s} q_i^E$;

Q_{-k}^E : the total supply of E85 in the market excluding the supply from the blender k, where $Q_{-k}^E = Q^E - q_k^E$;

c^G, c^E : unit production cost of E10 and E85, respectively; (The production cost contains several components such as crude oil, federal and state taxes, refinery, and distribution and marketing. We will talk about this in detail later.)

ρ^G, ρ^E : retail unit prices of E10 and E85, respectively;

λ^G, λ^E : emission cost of E10 and E85, respectively;

p^G, p^E : unit prices (that consumers consider when they make consumption choices, including their consideration of the effect of fuels on the environment) of E10 and E85, respectively;

TC : tax credit the blender would get through ethanol purchasing;

p_r : unit price of RINs in the RINs market;

M_k : ethanol purchasing mandate for blender k;

s : the total number of blenders in the market;

4.2.1 DEMAND FUNCTIONS

We assume the inverse demand functions of E10 and E10 in the following form:

$$\begin{bmatrix} p^G \\ p^E \end{bmatrix} = \begin{bmatrix} a \\ a \end{bmatrix} - b \begin{bmatrix} 1 & \theta^E \\ \theta^G & 1 \end{bmatrix} \begin{bmatrix} Q^G \\ Q^E \end{bmatrix},$$

Here, it is important to note that E10 was abbreviated as G since it's also called Gasohol. Similarly, we abbreviate E85 as E when we use then as superscripts and subscripts. The prices p in the demand functions are unit prices that consumers consider in their purchasing process which consists of two components, the retail prices ρ and the emission costs λ .

Then the corresponding demand functions are:

$$\begin{bmatrix} Q^G \\ Q^E \end{bmatrix} = \frac{a}{b(1-\theta^G\theta^E)}\begin{bmatrix} 1-\theta^E \\ 1-\theta^G \end{bmatrix} - \frac{1}{b(1-\theta^G\theta^E)}\begin{bmatrix} 1 & -\theta^E \\ -\theta^G & 1 \end{bmatrix}\begin{bmatrix} p^G \\ p^E \end{bmatrix},$$

Here, $\theta^G, \theta^E \in (0,1)$ are the substitutability parameters, indicating how substitutable one product to another. Generally, a negative value of the substitutability parameter indicates the complementarity of the two products which is not the case for E10 and E85, since they are two competing products in the transportation fuel markets. If θ^G (θ^E) equals 0, it means E10 (E85) cannot substitute E85 (E10) at all and they do not affect each other in the market, which is obviously not true for the two products. If θ^G (θ^E) equals exactly 1, it means E10 (E85) is a complete substitute to E85 (E10) and consumers can flexibly switch between the two fuels. This is also not true in reality. Though almost all vehicles on road are able to run with E10, some Fuel-Flexible Vehicles (FFV) owners prefer to use E85, which is believed to be greener, to protect the environment or to help the biofuel industry so they would stick to E85 rather than E10. On the other hand, since FFV is still a small part of all vehicles, E85 can only substitute a limited part of E10, which made θ^E very small. Hence, θ^G and θ^E should lie between 0 and 1. The estimated values will be discussed in the numerical example part.

4.2.2 Market Indices

We use the following three market indices to measure the performance of the two types of fuel in the market. The first two market indices are easy to measure and are good indicators of E85's performance on the market. Generally, a higher market share and a lower price premium indicate a greater acceptance. The third market index is total social welfare which may provide some insights for the government and policy makers to maximize the wellbeing of the entire society.

4.2.2.1 Market share of E85

The market share of E85 is defined as the percentage of products in the market:

$$\beta^E = \frac{Q^E}{Q^E + Q^G}.$$

4.2.2.2 Total and Upfront Green Price Premium

From the inverse demand functions, we can derive the total green price premium:

$$\Delta p = \alpha p^E - p^G = \alpha\left[a - b\left(\theta^G Q^G + Q^E\right)\right] - \left[a - b\left(Q^G + \theta^E Q^E\right)\right],$$

where $\alpha = \frac{127.56}{95.38}$ is a coefficient to transform the price of E85 to a unit price for a gasoline-equivalent gallon. Here, 95.38 and 127.56 (in MJ/gallon unit) are the energy contents of E85 and E10 respectively. The energy content of E85 is only about 75% of that of E10, which results in a lower fuel efficiency. Here, we propose to adjust the prices to an energy equivalent basis. Thus, the adjusted price for E85 is 127.56/95.38 times the retail price of E85.

Intuitively, a higher price premium will cause more demand of E10 and a low price premium will cause more demand of E85. It should be noted that consumers' choices will involve more than the price premium.

Similarly, the upfront green price premium can be derived from total green price premium incorporating the gas emission costs of the two fuels:

$$\Delta \rho = \alpha\rho^E - \rho^G = \alpha\left[a - b\left(\theta^G Q^G + Q^E\right)\right] - \left[a - b\left(Q^G + \theta^E Q^E\right)\right] - \alpha\lambda^E + \lambda^G.$$

4.2.2.3 Social Welfare

Government policies could impact all stakeholders along the biofuel supply chain, including farmers, the gasoline and ethanol industry and the fuel market. Typically, the goal of the government is to maximize the well-being of the entire society, which we define as social welfare. Thereby, the government wants to implement policies that can increase social welfare.

The welfare is defined as the summation of the consumers' surplus and the producers' surplus. Consumers' surplus is the difference between the total amount that consumers are willing to pay for a good or service (indicated by the demand curve) and the total amount that they actually pay (the market price). Similarly, producers; surplus is the difference between what producers are willing and able to supply a good for and the price they actually receive. Thus, the social welfare, the sum of the consumer surplus and producer surplus, is the difference between what the consumers willing to pay and what the producers willing to supply a good for. In another word, it's what the consumers willing to pay minus the total producing cost of the good.

To define social welfare for the transportation fuel market, we construct two non-decreasing functions $f_G(t)$ and $f_E(t)$ to represent the process of price discrimination, though which the producers can maximally exploit consumers' willingness to pay. The two functions are continuously differentiable in (0, 1) and that $f_G(0)=0,\ f_G(1)=Q^G$, and $f_E(0)=0,\ f_E(1)=Q^E$. Then consumers' willingness to pay can be expressed as:

$$\begin{aligned}\Upsilon &= \int_0^1 \left\{a - b\left[f_G(t) + \theta^E f_E(t)\right]\right\} df_G(t) + \int_0^1 \left\{a - b\left[f_E(t) + \theta^G f_G(t)\right]\right\} df_E(t) \\ &= a\left(Q^G + Q^E\right) - \frac{b}{2}\left[\left(Q^G\right)^2 + \left(Q^E\right)^2\right] - b\theta^E \int_0^1 f_E(t) df_G(t) - b\theta^G \int_0^1 f_G(t) df_E(t) \\ &= a\left(Q^G + Q^E\right) - \frac{b}{2}\left[\left(Q^G\right)^2 + \left(Q^E\right)^2\right] - b\theta^E Q^G Q^E + b\left(\theta^E - \theta^G\right)\int_0^1 f_G(t) df_E(t)\end{aligned}$$

By the definition of $f_G(t)$, we have

$$\int_0^1 f_G(t) df_E(t) \geq \int_0^1 0\, df_E(t) = 0 \text{, and}$$

$$\int_0^1 f_G(t) df_E(t) \leq \int_0^1 Q^G df_E(t) = Q^G Q^E .$$

Since we want to maximize Υ, it becomes

$$\Upsilon = a\left(Q^G + Q^E\right) - \frac{b}{2}\left[\left(Q^G\right)^2 + \left(Q^E\right)^2\right] - b\min\left\{\theta^G, \theta^E\right\} Q^G Q^E .$$

Subtracting total cost from Υ , we get the social welfare function:

$$\Psi := \left(a - \lambda^G - c^G\right)Q^G + \left(a - \lambda^E - c^E\right)Q^E - \frac{b}{2}\left[\left(Q^G\right)^2 + \left(Q^E\right)^2\right] - b\min\left\{\theta^G, \theta^E\right\} Q^G Q^E$$

Here, we assume $a - \lambda^G - c^G > 0$ and $a - \lambda^E - c^E > 0$ so that a positive social welfare is achievable.

4.3 ANALYSIS OF THE MODEL

In this model, we assume there are s symmetric blenders in the market which produce both E10 and E85 and their products are homogeneous: same E10 and same E85, respectively. Their profits come from the sale of both E10 and E85. The Cournot competition model is used to analyze their competition, in which a single firm has to decide its supply quantities of E10 and E85 to maximize its profit.

Given the total supply quantities of E10 and E85 excluding the supply of firm k can be written as:

$$Q^G_{-k} = Q^G - q^G_k \text{ and } Q^E_{-k} = Q^E - q^E_k$$

Therefore, the profit function of firm k becomes,

$$\begin{aligned}
&\pi_k\left(q^G_k, q^E_k; Q^G_{-k}, Q^E_{-k}\right) \\
&= \left(\rho^G - c^G\right)q^G_k + \left(\rho^E - c^E\right)q^E_k \\
&= \left[\left(p^G - \lambda^G\right) - c^G\right]q^G_k + \left[\left(p^E - \lambda^E\right) - c^E\right]q^E_k \\
&= \left[a - c^G - \lambda^G - b\left(Q^G + \theta^E Q^E\right)\right]q^G_k + \left[a - c^E - \lambda^E - b\left(Q^E + \theta^G Q^G\right)\right]q^E_k \\
&= \left[a - c^G - \lambda^G - b\left(Q^G_{-k} + \theta^E Q^E_{-k}\right)\right]q^G_k + \left[a - c^E - \lambda^E - b\left(Q^E_{-k} + \theta^G Q^G_{-k}\right)\right]q^E_k \\
&-b\left(q^G_k\right)^2 - b\left(q^E_k\right)^2 - b\left(\theta^G + \theta^E\right)q^G_k q^E_k + \left(0.1q^G_k + 0.85q^E_k - M_k\right)p_r
\end{aligned}$$

,

and its best response is:

$$\begin{bmatrix} (q_k^G)^* \\ (q_k^E)^* \end{bmatrix} = \frac{\begin{bmatrix} 2 & -(\theta^G+\theta^E) \\ -(\theta^G+\theta^E) & 2 \end{bmatrix} \begin{bmatrix} a-c^G-\lambda^G-b\left(Q_{-k}^G+\theta^E Q_{-k}^E\right)+0.1p_r \\ a-c^E-\lambda^E-b\left(Q_{-k}^E+\theta^G Q_{-k}^G\right)+0.85p_r \end{bmatrix}}{b\left[4-(\theta^G+\theta^E)^2\right]}.$$

Here, the last term in the profit function represents the profit from the RINs market. $0.1q_k^G + 0.85q_k^E$ is the number of gallons of ethanol the blender blend into gasoline and it is also the number of RINs the blender could obtain. M_k is the mandated volume. The difference (if positive) between the obtained RINs number and the mandated volume is the excess RINs number, which the blender could sell in the RINs market. Conversely, if the difference is negative, then the blenders need to purchase RINs from the market. Here we assume the blenders have no RINs from previous year and they do not bank RINs to the next year, and also the market is large enough so they can always sell the RINs out or purchase RINs in on the market.

Proposition 1 Supply quantities under Nash equilibrium with s symmetric firms are

$$(q_k^G)^* = \frac{(s+1)(a-c^G-\lambda^G+0.1p_r)-(s\theta^E+\theta^G)(a-c^E-\lambda^E+0.85p_r)}{b\left[(s+1)^2-(s\theta^G+\theta^E)(s\theta^E+\theta^G)\right]}, \forall k=1,2,\ldots,s,$$

$$(q_k^E)^* = \frac{(s+1)(a-c^E-\lambda^E+0.85p_r)-(s\theta^G+\theta^E)(a-c^G-\lambda^G+0.1p_r)}{b\left[(s+1)^2-(s\theta^G+\theta^E)(s\theta^E+\theta^G)\right]}, \forall k=1,2,\ldots,s.$$

Proposition 2 Under Nash equilibrium, market share of E85 fuel is

$$\beta^E = \frac{(s+1)(a-c^E-\lambda^E+0.85p_r)-(s\theta^G+\theta^E)(a-c^G-\lambda^G+0.1p_r)}{(s+1-s\theta^G-\theta^E)(a-c^G-\lambda^G+0.1p_r)+(s+1-s\theta^E-\theta^G)(a-c^E-\lambda^E+0.85p_r)},$$

Proposition 3 Under Nash equilibrium, the total ethanol fuel price premium is

$$\Delta p = (\alpha - 1)a + \frac{s\left[s+1-\alpha\theta^G+\alpha\theta^E - s\theta^G\theta^E - \left(\theta^E\right)^2\right]\left(a - c^G - \lambda^G + 0.1p_r\right)}{(s+1)^2 - \left(s\theta^G+\theta^E\right)\left(s\theta^E+\theta^G\right)}$$

$$- \frac{s\left[\alpha s+\alpha-\theta^E+\theta^G - \alpha s\theta^G\theta^E - \alpha\left(\theta^G\right)^2\right]\left(a - c^E - \lambda^E + 0.85p_r\right)}{(s+1)^2 - \left(s\theta^G+\theta^E\right)\left(s\theta^E+\theta^G\right)}$$

, and

$$\Delta \rho = (\alpha - 1)a + \frac{s\left[s+1-\alpha\theta^G+\alpha\theta^E - s\theta^G\theta^E - \left(\theta^E\right)^2\right]\left(a - c^G - \lambda^G + 0.1p_r\right)}{(s+1)^2 - \left(s\theta^G+\theta^E\right)\left(s\theta^E+\theta^G\right)}$$

$$- \frac{s\left[\alpha s+\alpha-\theta^E+\theta^G - \alpha s\theta^G\theta^E - \alpha\left(\theta^G\right)^2\right]\left(a - c^E - \lambda^E + 0.85p_r\right)}{(s+1)^2 - \left(s\theta^G+\theta^E\right)\left(s\theta^E+\theta^G\right)} - \alpha\lambda^E + \lambda^G,$$

Proposition 4 Under Nash equilibrium, the social welfare is

$$\Psi = \frac{s\left(a - c^{G} - \lambda^{G}\right)\left[\left(s+1\right)\left(a - c^{G} - \lambda^{G} + 0.1p_{r}\right) - \left(s\theta^{E} + \theta^{G}\right)\left(a - c^{E} - \lambda^{E} + 0.85p_{r}\right)\right]}{b\left[\left(s+1\right)^{2} - \left(s\theta^{G} + \theta^{E}\right)\left(s\theta^{E} + \theta^{G}\right)\right]}$$

$$+ \frac{s\left(a - c^{E} - \lambda^{E}\right)\left[\left(s+1\right)\left(a - c^{E} - \lambda^{E} + 0.85p_{r}\right) - \left(s\theta^{G} + \theta^{E}\right)\left(a - c^{G} - \lambda^{G} + 0.1p_{r}\right)\right]}{b\left[\left(s+1\right)^{2} - \left(s\theta^{G} + \theta^{E}\right)\left(s\theta^{E} + \theta^{G}\right)\right]}$$

$$- \frac{s^{2}\left[\left(s+1\right)\left(a - c^{G} - \lambda^{G} + 0.1p_{r}\right) - \left(s\theta^{E} + \theta^{G}\right)\left(a - c^{E} - \lambda^{E} + 0.85p_{r}\right)\right]^{2}}{2b\left[\left(s+1\right)^{2} - \left(s\theta^{G} + \theta^{E}\right)\left(s\theta^{E} + \theta^{G}\right)\right]^{2}}$$

$$- \frac{s^{2}\left[\left(s+1\right)\left(a - c^{E} - \lambda^{E} + 0.85p_{r}\right) - \left(s\theta^{G} + \theta^{E}\right)\left(a - c^{G} - \lambda^{G} + 0.1p_{r}\right)\right]^{2}}{2b\left[\left(s+1\right)^{2} - \left(s\theta^{G} + \theta^{E}\right)\left(s\theta^{E} + \theta^{G}\right)\right]^{2}}$$

$$+ \frac{\min\left\{\theta^{G}, \theta^{E}\right\} s^{2}\left(s+1\right)\left(s\theta^{G} + \theta^{E}\right)\left(a - c^{G} - \lambda^{G} + 0.1p_{r}\right)^{2}}{b\left[\left(s+1\right)^{2} - \left(s\theta^{G} + \theta^{E}\right)\left(s\theta^{E} + \theta^{G}\right)\right]^{2}}$$

$$+ \frac{\min\left\{\theta^{G}, \theta^{E}\right\} s^{2}\left(s+1\right)\left(s\theta^{E} + \theta^{G}\right)\left(a - c^{E} - \lambda^{E} + 0.85p_{r}\right)^{2}}{b\left[\left(s+1\right)^{2} - \left(s\theta^{G} + \theta^{E}\right)\left(s\theta^{E} + \theta^{G}\right)\right]^{2}}$$

$$- \frac{\min\left\{\theta^{G}, \theta^{E}\right\} s^{2}\left[\left(s+1\right)^{2} + \left(s\theta^{G} + \theta^{E}\right)\left(s\theta^{E} + \theta^{G}\right)\right]\left(a - c^{G} - \lambda^{G} + 0.1p_{r}\right)\left(a - c^{E} - \lambda^{E} + 0.85p_{r}\right)}{b\left[\left(s+1\right)^{2} - \left(s\theta^{G} + \theta^{E}\right)\left(s\theta^{E} + \theta^{G}\right)\right]^{2}}.$$

CHAPTER 5. NUMERICAL EXAMPLES

In this section, numerical examples are presented to illustrate how to find the market equilibrium for E10 and E85, and analyze the sensitivity of the market equilibrium with respect to the production cost, the proportion of FFVs on road, the number of firms in the market and various government policies. Wherever possible, real world data are utilized supplemented with reasonable assumptions. This case study focuses on the national level around year 2011.

5.1 ASSUMPTIONS ABOUT THE PARAMETERS

First, we assume that there are only two types of transportation fuels in the market, E10 and E85, and there are two types of consumers: one that drives regular cars and the other that owns FFVs. The regular cars can only use E10 while FFVs can run both E10 and E85. FFVs currently only counts for a small proportion of all the light-duty vehicles registered in USA. As mentioned, till 2011, there are 10 million of FFVs sold, which represents about 4% of the U.S. total vehicles on the road.

Since the regular cars can only run on E10, we say $\theta_R^G = 1$ and $\theta_R^E = 0$. The FFVs group can run on either E10 or E85, so E10 and E85 are perfect substitutes to each other for this group, which means $\theta_F^E = \theta_F^G = 1$. Then we can use the two separated substitutability parameters to calculate the weighted substitutability parameter for the entire market, and we have $\theta^G = 96\%\theta_R^G + 4\%\theta_F^G = 1$, and $\theta^E = 96\%\theta_R^E + 4\%\theta_F^E = 0.04$.

As mentioned, the social carbon cost for 2005 had an average value of \$12/tCO_2, and from Table 1 we have the carbon density of gasoline as 96gCO_2e/MJ and corn ethanol as 69gCO_2e/MJ (We don't include the indirect emission here). We assume the carbon density of E10 to be 10% of that of ethanol and 90% of that of gasoline, so the carbon density of E10 is 93.3gCO_2e/MJ, and similarly, the carbon density of E85 is 73.05gCO_2e/MJ. Also, we have the energy content of E10 and E85 to be

33.18MJ/L and 25.65 MJ/L, respectively. Having this information, we can calculate the social carbon cost for per gallon of the fuels. Here is the social carbon cost for E10: $\$12/tCO_2 \times *\left(93.3gCO_2e/MJ/10^6\right)\times\left(33.18MJ/L*3.79L/gallon\right)=\$0.14/gallon$, and for E85: $\$12/tCO_2\times\left(70.05gCO_2e/MJ/10^6\right)\times\left(25.65MJ/L*3.79L/gallon\right) = \$0.08/gallon$. Thus we have $\lambda^G = 0.14$ and $\lambda^E = 0.08$.

Although the tax credit of $0.45/gallon of ethanol expired at the end of 2011, it would be of interest to policy makers to compare the scenarios with and without the tax credit. We will include the tax credit in the baseline scenario.

As discussed, the RINs price for ethanol was at a low level of 3 cents/gallon in 2011. Since it's not easy to model the RINs price in the market, we assume the RINs price to be 3 cent/gallon during a short period. Therefore, p_r =$0.03/gallon.

We need to determine the values of a and b in the demand function. Since b is related to the price elasticity of demand, it can be estimated based on existing literature on gasoline price elasticity. Based on Hughes [30], the short-run price elasticity of gasoline in U.S. ranges from -0.034 to -0.077 between 2001 and 2006. It is assumed that the elasticity in the model is about -0.05. We know that $E_d = \frac{p}{Q}\cdot\frac{dQ}{dp} = -\frac{1}{b}\cdot\frac{p}{Q}$, and the average price of gasoline in 2010 was $2.78/gallon and the total consumption of gasoline during the year was about 138,496million gallons [32]. Therefore, the parameter of b is estimated to be around 4e-10. From the demand function, the parameter a can be viewed as the price when the demand is zero which is not easy to estimate. From the simplified inverse demand function $p = a - b\cdot Q$, we can see that parameter a can be estimated with historical price and production quantity data. Therefore, $a = p + b\cdot Q = 2.58 + 4e-10\times 1.38496e11 \approx 58$.

There is no public available data on the production costs of E10 and E85. EIA provides the base for the retail price of gasoline which includes the cost of crude oil, refining cost and profit, distribution cost, and marketing cost and profit. In this study, we will use similar framework to estimate the production cost of E10 and E85. In 2010, the average retail price of gasoline was $2.78 and the components for this price are: 68% for crude oil, 14% for federal and state taxes, 7% for refining cost and profit, and 10% for marketing and distribution [33]. The 2010 average crude oil price was $1.70/gallon [34], thus the estimated cost for gasoline is $(\$1.70/\text{gallon})/0.68\times 0.95 = \$2.375/\text{gallon}$. In Nov 2010, the rack price for ethanol was $2.47/gallon [35]. When the blenders buy one gallon of ethanol at the rack price, they can get a tax credit of $0.45 back, so the actual ethanol rack price is $2.02/gallon. With the production costs of gasoline and ethanol, we can calculate the production cost of E10 and E85 with the weighted sum method. Therefore, the estimated cost of E10 should be $c^G = 0.1\times 2.02 + 0.9\times 2.375 = \$2.34/\text{gallon}$ and similarly, the cost for E85 should be $c^E = 0.15\times 2.375 + 0.85\times 2.02 = \$2.07/\text{gallon}$.

The last parameter that will be used in the model is the number blenders. As of April 2011, the number of blenders in the U.S. is 141 [36], and thus we have s =141.

All the parameters that will be used are summarized in Table 2.

Table 2. Model parameters

	s	λ^G	λ^E	c^G	c^E	θ^G	θ^E	a	b	p_r
Value	141	0.14	0.08	2.34	2.07	1	0.04	58	4e-10	0.03

5.2 BASELINE SCENARIO

Now we have all the parameters for the numerical examples. In the next, various scenarios are investigated to study the impacts of policies like tax credit and RINs market, the number of refiners, and the proportion of FFVs on roads, to the competition between E10 and E85 based on the market indices defined (the market share of E85, the green price premiums, and the social welfare).

The Nash Equilibrium of the baseline scenario is shown in Table 3. As we can see from Table 3, the estimated total market supply of E10 is 1.377e11 gallons, compared to the actual consumption of 138,496million gallons in 2010. The estimated retail price for E10 and E85 are $2.733 and $2.066, compared to the actual average retail prices of $2.78 for E10 and $2.4 for E85 [5]. These similarities indicate that the model captures some key points of the real market and the estimated result matches the reality well. Under the baseline scenario, the green price premium is negative while the upfront (retail) green price premium is positive. This means if we simply look at the retail price of the two fuels, E85 has a price premium over E10 because of its lower energy content. However, when we consider the emission cost and include it into the price, the green product (E85) has a negative price premium which means it is even “cheaper” than E10. If people are aware of the environmental advantage of E85 over E10, then they will do the math and choose the “cheaper” fuel in this sense. This demonstrates the importance of public education on the green products’ environmental friendliness and green product producers’ marketing strategies.

Table 3. Nash Equilibrium in baseline scenario

	E10	E85
Production Quantity of a Single Company (Gallon)	9.769e8	1.344e7
Total Market Supply (Gallon)	1.377e11	1.895e9
Product Price (Demand Price) ($/gal)	2.873	2.146
Upfront Price (Retail Price) ($/gal)	2.733	2.066
Market Share	98.6%	1.4%
Green Price Premium ($/gal)	-3.759e-3	
Upfront Green Price Premium ($/gal)	2.925e-2	
Total Social Welfare ($)	3.954e12	

Now we will do some numerical examples and the objective of this numerical study is to answer the following questions.

5.3 ALTERNATIVE SCENARIO 1: HOW DOES THE ELIMINATION OF TAX CREDIT AFFECT THE MARKET EQUILIBRIUM?

A lot of studies expressed the perspective that the biofuel industry does not need both of the mandate and tax credit to promote the consumption of ethanol and some said that tax credit only benefit the blenders rather than the biofuel industry thus it should be eliminated. At the end of 2011, the tax credit policy expired and the government did not extend this subsidy which means that the ethanol fuels have to compete with the conventional fuels without the help from the government. We want to investigate the impacts of eliminating the tax credit on the market equilibrium between E10 and E85. Thereby, our alternative scenario 1 is that we eliminate the ethanol tax credit of 45 cents per gallon so blenders no longer get tax credit when they purchase ethanol as an E85 raw material. This increases the cost for producing E85 and the new cost is $c^E = 0.15 \times 2.375 + 0.85 \times 2.47 = \$2.46 / \text{gallon}$. The result of the Nash equilibrium for alternative scenario 1 is summarized in Table 4.

Table 4. Equilibrium result for alternative case 1 with tax credit eliminated

	E10	E85
Production Quantity of a Single Company (Gallon)	9.772e8	6.238e6
Total Market Supply (Gallon)	1.378e11	8.800e8
Product Price (Demand Price) ($/gal)	2.870	2.533
Upfront Price (Retail Price) ($/gal)	2.730	2.473
Market Share	99.4%	0.6%
Green Price Premium ($/gal)	5.167e-1	
Upfront Green Price Premium ($/gal)	5.497e-1	
Total Social Welfare ($)	3.900e12	

As we can see from Table 4, after the elimination of the ethanol tax credit, the production quantity of E10 increases slightly and the price decreases slightly as well. Meanwhile, the production quantity of E85 has a big decrease and the estimated retail price increases from $2.066 to $2.473, which yields a high positive green price premium. The market share of E85 also drops from 1.4% to0.6%. These two indices indicate that E85 is much less competitive in this case and the blenders will have to cut some of their ethanol purchasing quantity, which seems to contradict our expectation based on some literature that the ethanol industry should not be affected a lot by the elimination of the tax credit. About this contradiction, the author has some explanations. First, the amount of ethanol going into E85 is just a small fraction of the total ethanol production, so the decrease of E85 production does not has big effect on ethanol industry. Second, in this scenario we assume that the mandate is fulfilled by the blenders since the mandate is not binding due to the very low RINs price. However, in the real market, the mandate is not necessarily met and blenders may need to produce more E85 to achieve the profit optimization. Third, in our model we do not include the business between the ethanol producers and the blenders, and we just set the rack price of ethanol as a constant and cannot know how it should change with the market. There is some possibility that the ethanol industry is benefited from the elimination of tax credit though the production of E85 decreases.

We can also notice in Table 4 that the total social welfare decreases from \$3.954e12 to \$3.900e12, which means a \$54 billion loss. However, since we define the social welfare to be the sum of the producers' surplus and the consumers' surplus, we may miss some components that are external of this system but should also be included as a part of the social welfare. Once the government eliminates the social welfare, it can save a large amount from the subsidy expense, which is also paid by the taxpayers. If we include this part into the total social welfare, the welfare does not need to decrease.

5.4 Alternative scenario 2: How does the elimination of the blend mandate affect the market equilibrium?

We have an earlier guess that the ethanol mandate is not binding because the RINs price is at a very low level. In this example, we want to confirm whether this guess is correct. Thereby, our alternative scenario 2 is that we eliminate the mandate for blenders, which also means there is no RINs tool and no RINs market, and in our model, the last term in the profit function which represents the profit from the RINs market is removed. If the result shows that the elimination of the mandate has a significant impact on the market performance, it means the mandate is binding, otherwise, the mandate is not binding. The equilibrium result for alternative scenario 2 is summarized in Table 5.

Table 5. Equilibrium result for alternative case 2 with mandate eliminated

	E10	E85
Production Quantity of a Single Company (Gallon)	9.769e8	1.302e7
Total Market Supply (Gallon)	1.377e11	1.836e9
Product Price (Demand Price) ($/gal)	2.876	2.171
Upfront Price (Retail Price) ($/gal)	2.736	2.091
Market Share	98.7%	1.3%
Green Price Premium ($/gal)	2.730e-2	
Upfront Green Price Premium ($/gal)	6.031e-2	
Total Social Welfare ($)	3.951e12	

From Table 5 we can see that the production quantity of E10 almost remains the same and the change in the price of E10 is also very slight. At the same time, the production quantity of E85 decreases by 3% and the price increases by 1%. Besides, the market share of E85 decreases from 1.4% to 1.3%. The social welfare has a loss of $3 billion but it's only 0.07% of the original welfare. These changes are observable but not very significant. We can draw the conclusion that the elimination of mandate from the baseline scenario does not have a big effect on the market performance of E85, which means the mandate in the base scenario is not binding.

5.5 ALTERNATIVE SCENARIO 3: HOW DOES THE CHANGE OF INDUSTRY SIZE AFFECT THE MARKET EQUILIBRIUM?

This question is inspired by the idea that due to the increasing price of crude oil and the developing of the new energies, the competition between fuel firms will be fiercer and some firms may have to quit the industry. In this case, the number of fuel blender companies decreases and we want to see whether this has a significant impact on the market share of E85 and the total social welfare. The current number of blenders is 141 in U.S. and we assume that there are 100 competitive blenders left after the narrowing of the industry. The equilibrium result is summarized in Table 6.

Table 6. Equilibrium result for alternative case 3 with number of refiners decreasing to 100

	E10	E85
Production Quantity of a Single Company (Gallon)	1.373e9	2.291e7
Total Market Supply (Gallon)	1.373e11	2.291e9
Product Price (Demand Price) ($/gal)	3.035	2.156
Upfront Price (Retail Price) ($/gal)	2.895	2.076
Market Share	98.4%	1.6%
Green Price Premium ($/gal)	-1.525e-1	
Upfront Green Price Premium ($/gal)	-1.195e-1	
Total Social Welfare ($)	3.975e12	

From Table 6 we can see that the supply quantity of E10 decreases by 0.2% and the decreasing amount is about 400 million gallons while the supply quantity of E85 increases by 20.9% and the growth is about 396 million gallons. The price of E10 increases by $0.162 which can be implied from the decreasing of the E10 supply quantity. Though the supply quantity of E85 increase a lot, the price of E85 still has a small increase from $2.066 to $2.076, and this is also because of the decreasing supply quantity of E10 since E10 is a complete substitute to E85 in both groups. The market share of E85 increases from 1.4% to 1.6% and the total social welfare increases by $21 billion. Here is something seems to be counter-intuitive. In general cases, the total social welfare should increase with the increase of number of companies and decrease with the decrease of number of companies. But in this scenario, there are two competing products on the market rather than only one product in general cases, and the change of number of companies will change the share of the two products which can lead to a totally different result.

Table 6 shows that the narrowing of the blender industry size is beneficial for both the market performance of E85 and the well-being of the total society.

5.6 ALTERNATIVE SCENARIO 4: HOW DOES THE INCREASE OF FFVS AFFECT THE MARKET EQUILIBRIUM?

In one of the literature article we reviewed, Greene said that about 125 to 200 million flexible-fuel vehicles may need to be on the road in order to achieve ethanol goals. Overall there were an estimated 254.4 million registered passenger vehicles in the U.S. according to a 2007 DOT study [37]. If 125 to 200 million FFVs are indeed put on the road, then the proportion of FFVs will reach up to 30%-40%. President Obama said during the 2008 campaign that "Sustainably-produced biofuels can create jobs, protect the environment and help end oil addiction-but only if Americans drive cars that will take such fuels" and he promised to work with congress and auto companies to ensure that all new vehicles have FFV capability. If this goal is achieved, in the long run, the proportion of FFVs on road will even go up to a much higher value. In this example, we are to investigate how the increase of FFVs fraction will affect the market equilibrium between E10 and E5, and the total social welfare.

We first let the proportion of FFVs increase a little from 4% to 10% and thus ethanol's substitutability parameter θ^{E} is changed to 0.1. The Nash equilibrium for this case is summarized in Table 7. We can see from Table 7 that with the increase of FFVs proportion, the supply quantity of E10 decreases by about 0.07% while the supply quantity of E85 increases by 3.2%. The price of E10 almost stays the same and the price of E85 increases by $0.023, which is also a very small amount. The market share of E85 increases slightly (This cannot be seen from the table since the percentage is rounded to the nearest tenth). The total social welfare decreases by $4 billion. Overall, the market performance doesn't change a lot expect for a slight increase in the market share of E85.

Table 7. Equilibrium result for alternative case 4 with FFVs proportion increasing to 10%

	E10	E85
Production Quantity of a Single Company (Gallon)	9.760e8	1.387e7
Total Market Supply (Gallon)	1.376e11	1.955e9
Product Price (Demand Price) ($/gal)	2.873	2.169
Upfront Price (Retail Price) ($/gal)	2.733	2.086
Market Share	98.6%	1.4%
Green Price Premium ($/gal)	2.794e-2	
Upfront Green Price Premium ($/gal)	6.096e-2	
Total Social Welfare ($)	3.950e12	

Now we assume that in the future, the proportion of FFVs on road will reach 50% and see what will happen to the performance of E85 on the fuel market. The equilibrium result is summarized in Table 8. We can see from Table 8 that the supply quantity of E10 decreases by 0.9% and the supply quantity of E85 increases by 44.1% when the proportion of FFVs increased to 50%. The total social welfare continues to decrease with the increase of FFVs. The increase of the E85 supply quantity is large but the decrease of the supply quantity of that of E10 is small, and adding that the baseline market share of E85 is small, so the market share in this case only increases from 1.4% to 2.0%. The result shows that though the proportion of FFVs is lifted to a high level, E85 is still not competitive compared to E10 on the fuel market, which is not as what we expected.

Table 8. Equilibrium result for alternative case 4 with FFVs proportion increasing to 50%

	E10	E85
Production Quantity of a Single Company (Gallon)	9.678e8	1.936e7
Total Market Supply (Gallon)	1.365e11	2.730e9
Product Price (Demand Price) ($/gal)	2.872	2.326
Upfront Price (Retail Price) ($/gal)	2.732	2.246
Market Share	98.0%	2.0%
Green Price Premium ($/gal)	2.386e-1	
Upfront Green Price Premium ($/gal)	2.717e-1	
Total Social Welfare ($)	3.928e12	

To further explore how the market share of E85 changes with the proportion of FFVs, I drew the following Figure 5 to show the relationship between them.

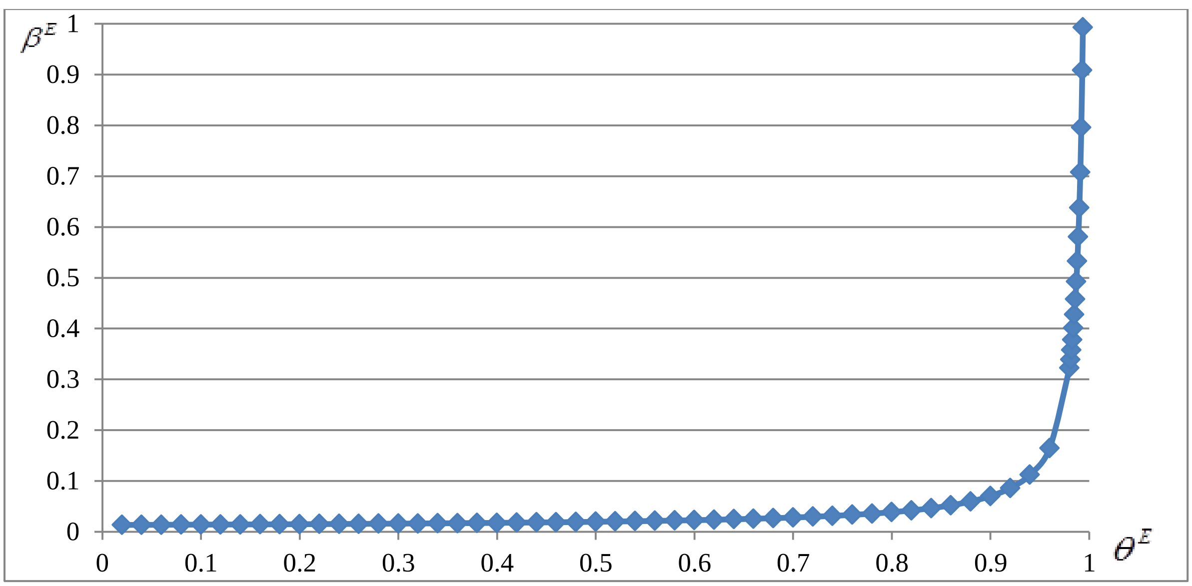

Figure 5. The relationship of market share to E85's substitutability (proportion of FFVs)

As we can see from Figure 5, the curve is very flat when the proportion of FFVs is smaller than 0.9 and becomes extremely steep when the proportion goes over 0.9 and reaches 1 when the proportion is around 0.9936. What happens at 0.9936? If we go back to check the supply quantity's equation derived from the equilibrium, we can find that the supply quantity will decrease sharply when the proportion of FFVs goes up to around 0.9, and it will become negative when the proportion is larger than 0.9937. When the equilibrium quantity becomes negative, it means the firms will not produce this product and the real supply quantity should be zero and we will need to recalculate the equilibrium quantity of the other product. However, it's not necessary for us to do this since the proportion of FFVs will not go to that high in the near future so it's not a big concern in this study.

Figure 5 gives us some insight into the effectiveness of increasing the number of FFVs in order to promote the consumption of E85 and increase its market share. If we really want to improve the market competitiveness or E85 in the competition with E10, then we have to make more than 90% of the vehicles on roads to be FFVs, otherwise, the market share is very insensitive to the change of FFVs proportion.

CHAPTER 6. CONCLUSION AND FUTURE WORK

E10 and E85 are two competing products in the transportation market. E85 contains more renewable energy and reduces more of the greenhouse gas emission, so it should be considered as a favorable substitute to conventional fossil fuels. However, E85's reality in the competing market does not match its good image. E10 still takes most majority place in the transportation market and E85 seems to act as a complementary product. There are two objective reasons for this situation. **The first one** is the limited availability of the E85 fueling. As mentioned, there are currently only about 2500 stations national wide that carry E85 fuel while there are more than 128887 gas filling stations as of 2007 and about two thirds of them sell E10 [38]. Though there are new E85 tanks and pumps being built each month, the proportion of E85 stations among all fuel stations is very small and it's not convenient for people to get reach of E85 fuel. To break this limitation for E85, there is a need for gas stations to set up pumps for E85 and the government may have to give subsidy to support this action since the investment for the pumps is a big cost for the stations. **The second reason** for the small E85 consumption is that the number of FFVs on road is still limited. Very few people have FFVs and even among them, some still use E10 as a regular fuel since they are not aware that their cars are FFVs or they do not know the difference between fuels. From our numerical example, we further know that E85 is comparable to E10 in the market share aspect only when the proportion of FFVs is higher than 90%, which is difficult to reach in the near future. These two reasons are two big obstacles for E85 to be popular.

An oligopoly Cournot model is formulated to study the competition between E10 and E85 which captures some key characteristics of the two products, the market and some government policies. Three important market indices are derived from the model equilibrium, including the market share of E85, the green price premium, and the total social welfare. The market share is defined as the percentage of sales quantity of E85 to the summation of sales quantity of E10 and E85, and it is a direct indicator of the consumer acceptance of E85. The E85 price premium is defined as the difference between the price of E85 and the price of E10 in an energy equivalent basis and it indicates the premium consumers willing to pay for E85. The total social welfare is defined as the sum of consumers' surplus and producers' surplus in the transportation fuel market. This is an important concept to measure how the entire society benefits from the market so it provides insights for relevant decision makers, such as the government, and regulatory agencies.

Numerical examples are presented to validate the model formulation and derive managerial insights for decision making for various stakeholders along the supply chain. Multiple scenarios have been investigated to demonstrate the approach. The equilibrium results derived from the baseline scenario matches the real market statistics well, which validate the model formulation.

The result from alternative **scenario 1** in which the tax credit is eliminated shows that the market performance of E85 is degraded with the market share decreasing and the price premium increasing, and the total social welfare decreases. This is intuitively easy to understand, since the cost of E85 will increase more than the increase of the cost of E10 after the elimination of ethanol tax credit, it will definitely make E85 less competitive with other conditions remain the same in the short period. However, in the long run, other conditions will change and the market will adjust itself to a new competition environment. For example, we can see from alternative **scenario 2** that the mandate is not binding, and that maybe partly because of the ethanol tax credit. When the tax credit expires, the function of mandates will recover and force blenders to buy ethanol. So we can just conclude from alternative scenario 1 that the sudden expiration of tax credit would give a shock to E85 industry but whether this will last depends. The mechanism under tax credits and mandates, especially the mandates, are more complicated than what I modeled in this study. To make the model more realistic, we will need to build sub-models for them to study the interaction between them and the market. This is one of the directions of future study.

If the blended fuel industry sizes down in the future as in alternative **scenario 3**, it will be easier for E85 to survive in the competition with E10 with the market share increasing and the price premium decreasing. The total social welfare also increases. This may happen when the transportation fuel industry faces challenges from new energies and new technologies like electric vehicles. The result from alternative **scenario 4** is not very optimistic for E85. Only when the proportion of FFVs is higher than 90%, which means most of the vehicles on roads are FFVs, will the market share of E85 increase in a considerable amount with the increase of FFVs proportion. This goal is hard to achieve in the near future so the prospect of increasing FFVs proportion to help E85 take more market share is dim.

While the literature in this area is relatively scarce, this study gives some original insights into the competition between E10 and E85. The results have some important implications for policy makers. The mandate is not binding since the market performance does not change a lot without the mandates. The elimination of tax credit will decrease the total social welfare and it also decreases the market share of E85, thus decreasing the amount of ethanol blended into gasoline fuels. These are theoretical feedbacks to the policy makers about the situation of mandates and the effect of the eliminating the tax credits. While president Obama said he would work with congress and auto companies to ensure that all new vehicles have FFV capability, the policy makers should notice from this study that to promote the consumption of E85, it is not so useful to increase the number of FFVs unless the it can make the proportion of FFVs goes higher than 0.9.

The future research in this area could go in the following directions: **First**, more sophisticated and accurate demand functions are needed to represent the demand and price relationship. **Second**, the blend mandates and the RINs market need deeper analysis and we may need to build a sub model to study the price and quantity relationship for RINs under the mandate. **Third**, the assumption that all firms are symmetric may be not valid in real market so we may need to differentiate the firms.

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