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Impact of Ethanol Blending Policies on U.S. Gasoline Prices

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Abstract:
This paper investigates the impact of ethanol blending mandates on retail fuel prices in the United States. It uses the modifications of three microeconomics models - partial equilibrium theoretical model by de Gorter and Just, partial equilibrium simulation model of Drabik et al. and Wu and Langpap general equilibrium model - on historical data from 2009 to 2022 and predictive data from 2023 to 2030, sourced from the U.S. Energy Information Administration (EIA) and the United States Department of Agriculture (USDA), to simulate scenarios involving various ethanol blend rates. The findings reject the hypothesis that increasing ethanol blend rates always lead to higher fuel prices.

JEL: D61; H23; L71; Q42; Q48;
Keywords: biofuels; ethanol; fuel prices; renewable fuel standard

1 Introduction

The aim of this paper is an examination of how the compulsory ethanol blending under the U.S. Renewable Fuel Standard (RFS) policy influences the prices paid by U.S. consumers at the gas pump. We start with a basic intuition that with increased level of ethanol blended into gasoline, the fuel price for consumers at the pump increases as well because the production costs for ethanol are higher than for gasoline. When blending more ethanol into gasoline, these higher costs are then transmitted to end users at the pump. Based on this intuition our research hypothesis is: "The RFS ethanol mandates always lead to an increase in the end user fuel prices".

Partial or general equilibrium effects may significantly modify the results suggested by this simple intuition. In academic community, there is consequently no clear consensus on the validity of this hypothesis. However majority of authors (Khanna et al., 2021) agree that ethanol blending leads to lower U.S. gasoline prices. As de Gorter and Just (2009) write in their seminal article on the economics of a blend mandate for biofuels, a biofuel blend mandate could potentially increase or decrease the consumer price of fuel, depending on the relative supply elasticities of ethanol and gasoline. They suggest that in cases where ethanol supply demonstrates lower elasticity relative to gasoline, consumer fuel prices might increase due to an increment in the gasoline price relative to ethanol and vice versa.

Lapan and Moschini (2012) in their paper on welfare implications of biofuel policies, specifically focusing on the effects of quantity mandates and subsidies in the biofuels sector within a second-best policy framework, conclude that one might logically speculate that increasing a binding ethanol blend mandate would result in a growth in blended fuel prices, thereby reducing overall consumption. However, they continue with an important note that the outcome of such particular comparative statics scenario cannot be conclusively determined - it is possible that if ethanol sup-

ply exhibits greater elasticity compared to gasoline supply, increasing the ethanol blend requirement might actually decrease fuel prices and unintentionally increase overall fuel consumption within certain limits.

Pouliot and Babcock (2014) examine the same research question with an important change in assumptions. In their study, ethanol and gasoline are treated as imperfect substitutes, meaning that the value of ethanol can vary greatly depending on consumer preferences, especially for those consumers buying higher ethanol blends. If there's a limit to how much of the high-blend fuel can be distributed, its demand becomes less responsive, making ethanol seem less valuable and its demand more fixed compared to gasoline. From that viewpoint, their study identifies several factors that play a role in how ethanol mandates affect fuel prices. These include how responsive the supply of ethanol is to price changes, how consumers react to changes in ethanol prices, and how these dynamics influence the cost of renewable fuel credits (RINs).

Janda and Kristoufek (2019) show in their review that there exist a large number of papers investigating the price transmission in the food/biofuels/fuels consumption chain. However a systematic review of Janda et al. (2022) documents that numerical estimates of impact of ethanol blending on U.S. gasoline prices are quite rare. Overwhelming majority of a few papers identified by Janda et al. (2022) as providing exact numerical quantification of influence of RFS mandates on gasoline price reports that higher level of ethanol blending leads to lower gasoline prices. So while there are several meta-analyses on impact of RFS mandates on corn prices (Hochman and Zilberman, 2018), there is not enough data to do sufficiently authoritative quantitative meta-analysis (meta-regression) on impact of RFS mandates on U.S. retail fuel price. While (Hochman and Zilberman, 2018) show that ethanol blending decreases U.S. gasoline by about 5 percent, their meta-analysis has rather low number of source estimates and consequently is less reliable than their meta-analysis of impact of ethanol

on corn price.

Also we are not aware of any recent U.S. results similar to Lundberg et al. (2023) who investigate impact of biofuel blending mandates on fuel prices on EU data up to 2020. They find negligible effect of biofuels blending on fuels prices in EU. They argue that this may be due to low blending ratios in Europe (lower than 5 percent for ethanol).

2 Methodology

We investigate our hypothesis using slight modifications of the models introduced by de Gorter and Just (2009), Drabik et al. (2016) and Wu and Langpap (2015). All these three models are microeconomics models based on microeconomics theory.

The de Gorter & Just model is a theory based partial equilibrium (PE) model. It is widely cited with more than 400 Google Scholar citations as a foundational original model of ethanol impact on fuel price. Many of the papers published in the past 15 years on the topics associated with modelling of biofuels, in most cases focusing on ethanol and its policy and economic impacts such as Pouliot and Babcock (2016), Drabik et al. (2016), Drabik et al. (2014), Drabik et al. (2015), de Gorter et al. (2013), de Gorter et al. (2015), or Bento et al. (2015), are based on the framework and model introduced by de Gorter and Just (2009). When analyzing the economics of a blend mandate and deriving implications of introduced policies, the authors develop a conceptual framework that studies the effect of a change in the level of ethanol blended into gasoline on the resulting blended fuel price, as well as the effect of combining the binding blend mandate with an ethanol tax credit. The framework has served as an important basis for further analysis and derivations concerning the topic within the academic community.

An important simplification of de Gorter and Just (2009) model is that it does

not account for energy equivalence of ethanol as compared to gasoline. Since ethanol contains around 70% of effective gasoline energy all values associated with ethanol should be adjusted and divided by 0.7 - approximate estimate reported by both the Energy Information Administration (2024b) and U.S. Department of Energy (2024). As presented in the Table 1, the average wholesale price of gasoline for the period 2009-2022 is \$2.15 per gallon. A gallon of ethanol is then cheaper at an average wholesale price of \$1.91. However, after the energy density correction for comparison purposes, a gallon of ethanol results with an average wholesale price of \$2.73. The energy-efficient adjusted price of a gallon of ethanol is then more expensive than the price of a gallon of gasoline - in other words, it is technically less expensive to obtain energy from crude oil than from corn.

This energy density correction is incorporated in the two following models by Drabik et al. (2016) and Wu and Langpap (2015). The Drabik et al. model is a simulation PE model based on de Gorter & Just model, substantially extending and enlarging the original model. The Wu & Langpap model is a general equilibrium (GE) model, chosen for its similarity and direct comparability to the first two PE models. The basic models of all three papers including our extensions are briefly described in the appendix of this paper.

Our analysis is identical for all these three models. First, a proper understanding and decomposition of each model into its base variables is conducted in order to gain the ability of rebuilding each model from the ground up. After the reconstruction, all of the initial original values from the respective years are put into the original models and the results were carefully compared with the numerical results obtained in those original models. Our replication process produces identical results to the original models, confirming the accuracy of the approach. This verification allows for further extensions and development of our adjusted, derived fuel price models as our source models were not primarily focused on the same research question as this

paper. Subsequently we collect most recent data, both historical and predictions up to 2030 and we use all three models for simulations of impact of ethanol blending on U.S. consumer prices of gasoline.

3 Data

This paper uses historical data from 2009 to 2022 and predictive data from 2023 to 2030.

3.1 Prices

Ethanol Prices The wholesale ethanol prices are each year reported in The Annual Energy Outlook (AEO), published by U.S. Energy Information Administration (2024). The study offers a comprehensive evaluation of the long run energy trends in the United States, delving into future projections of energy markets up to the year 2050. The AEO explores various aspects of the energy landscape, including the shifts in energy sources and consumption patterns, technological advancements and the impact of legislation on energy production and usage. The retail prices are then computed according to Pouliot and Babcock (2016) who define the wholesale-to-retail markup of \$0.75/gal.

Gasoline Prices Both wholesale and retail gasoline prices are obtained from the detailed EIA dataset in the *Petroleum and Other Liquids* section. These prices represent the prices of gasoline before blending with ethanol. The source of the wholesale price is the U.S. Total Gasoline Wholesale/Resale Price by Refiners table which dates back to 1978, while the source for retail gasoline price is the U.S. All Grades All Formulations Retail Gasoline Price table from 1994.

Fuel Price The fuel price is the sales to end users gasoline price as reported by the U.S. Energy Information Administration (2024) - it is a price of blended gasoline, already including ethanol. It does not include taxes. Additionally to sales through retail outlets, the metric also includes all direct sales to end users that were not made through company-operated retail outlets, e.g. sales to agricultural customers, commercial sales and industrial sales. For its comprehensiveness, the variable is used further on in this paper as a comparison benchmark for the simulated fuel prices resulting from models.

Variable	**Unit**	**Mean**	**Max**	**Min**	**Range**
Corn price	$/gal	4.63	6.89	3.36	3.53
Crude oil price	$/gal	1.68	2.33	0.93	1.40
Ethanol price	$/gal	1.91	2.58	1.38	1.20
Gasoline price	$/gal	2.15	2.93	1.33	1.60
Fuel price	$/gal	2.43	3.15	1.73	1.42
Ethanol production	Mgal/d	39.40	44.09	29.97	14.12
Ethanol consumption	Mgal/d	36.93	39.87	30.24	9.63
Ethanol exports	Mgal/d	2.79	4.68	0.00	4.68
Motor fuel consumption	Mgal/d	376.76	392.26	342.25	50.01
Fuel tax	$/gal	0.46	0.49	0.45	0.05
Corn yield	bu/acre	164.36	176.70	123.10	53.60
Blend rate	%	9.80	10.43	7.95	2.49

Table 1: Summary statistics for the U.S. ethanol fuel market during the years 2009-2022

*Mgal/d stands for million gallons per day

3.2 Quantities

Quantities of crude oil, corn, ethanol and gasoline enter into the models mainly through supply and demand - production and consumption. Table 1 displays the summary statistics of the U.S. ethanol related market for the time period of 2009-2022 with a focus on prices and quantities, the main inputs of the models.

Crude Oil and Gasoline Quantities All crude oil and gasoline quantities are taken from the EIA. The world crude oil production is reported in the *Petroleum and other liquids, International* data section. The U.S. crude oil imports and demand of finished motor gasoline (already blended with ethanol) are taken from the *This Week in Petroleum* summary. Finally, the U.S. crude oil supply is obtained from the *Short-term Energy Outlook (STEO)* report, which provides a comprehensive overview of the near-term trends and projections in the energy sector for commodities such as crude oil, natural gas, electricity, coal, and renewables.

Corn Quantities The data on U.S. corn demand as food or feed are obtained from *The World Agricultural Supply and Demand Estimates (WASDE)* report, released on a monthly basis by the World Agricultural Outlook Board of the USDA. The extensive forecast reports projections for major crops and livestock products, such as wheat, rice, coarse grains, oilseeds, cotton, sugar, meat and milk, on a global scale with a more detailed focus on the U.S. market. The domestic demand of corn as food or feed is computed based on the data from the WASDE as the difference between the total production of corn and the amount of corn used for production of ethanol and other by-products.

The remaining corn variables - the U.S. production of yellow corn, U.S. corn

exports and corn yield - are taken from the Feed Grains Database of the Economic Research Service (ERS) of USDA. The database aggregates data on four principal feed grains (corn, grain sorghum, barley and oats), foreign coarse grains (inclusive of feed grains in addition to rye, millet, and assorted grains), hay, and associated commodities. The data spectrum comprises of supply metrics, demand indicators, pricing information and feed-price ratios. The statistical compilation consists of data published in the monthly editions of the Feed Outlook as well as the annual Feed Grains Yearbook tables. The primary objective of the Feed Grain Database is to furnish a comprehensive array of both contemporary and historical time-series data.

Ethanol Quantities Both the U.S. ethanol production and consumption values are from the *Monthly Energy Review (MER)* by EIA. The U.S. exports of fuel ethanol are then obtained through the *Petroleum and other liquids, Ethanol* data section.

3.3 Elasticities

Important factor of the models are various elasticities, in the models usually utilized as weights of other base variables. The variables for demand and supply elasticities distinguish between values for the United States and for the rest of the world. As Drabik et al. (2016) notes, the demand and supply curves exhibit constant price elasticities, therefore all of the presented estimates are ensured to represent the long-run data. The summary of elasticities chosen for this paper, their values and sources is presented in Table 2.

Gasoline Demand Elasticity The price elasticity of demand for gasoline in the United States has been historically one of the most prevalent subjects of examination within the energy economics. Hausman and Newey (1995) examine the household pooled data through nonparametric estimation and find the long-run price elasticity

Elasticity	Value	Source
Gasoline demand - U.S.	-0.37	Coglianese et al. (2017)
Gasoline demand - foreign	-0.40	Galindo et al. (2015)
Gasoline supply - U.S.	0.20	de Gorter and Just (2009)
Gasoline supply - foreign	0.71	de Gorter and Just (2009)
Corn supply - U.S.	0.20	de Gorter and Just (2009)
Nonethanol corn demand - U.S.	-0.20	de Gorter and Just (2009)
Ethanol supply - U.S.	0.26	Luchansky and Monks (2009)
Output elasticity of fuel	0.85	Wu and Langpap (2015)
Output elasticity of food	0.07	Wu and Langpap (2015)
Output elasticity of other goods	0.0004	Wu and Langpap (2015)

Table 2: Elasticities, values and sources used in models

of -0.81. Such result indicates high responsiveness of consumers to changes in gasoline prices. Later, Hamilton (2009) reports more plausible level of price elasticity to those presented in the 90s at estimate of -0.26 for the U.S. price elasticity. Another study by Havranek et al. (2012) uses mixed-effects multilevel meta-regression method to find the average long-run elasticity estimate of -0.31. Lin and Prince (2013) define static reduced-form demand model and dynamic partial adjustment model to determine long-run estimate at the level of -0.29. More recently, Coglianese et al. (2017) find the elasticity of -0.37 using the instrumental variable (IV) model regression adjusted by a lead and a lag, studying monthly data from January 1989 through March 2008. Comparing this result with other studies from 2008 to 2015, where many use completely different approaches and estimation methodologies, the authors confirm the validity and relevance of the result. The -0.37 value of U.S. price elasticity of demand for gasoline is therefore used in models of this paper.

The literature on elasticity of world demand for gasoline does not provide such an extensive research as compared to the United States demand. The assumption is that there should not be significant differences between the US and world elasticity values. The chosen value of -0.40 follows findings presented by Galindo et al. (2015) and Drabik et al. (2016).

Gasoline Supply Elasticities Both price elasticities of gasoline supply for the United States as well as for the rest of the world are taken from de Gorter and Just (2009) as they provide an in-depth framework for supply curves and prices in the biofuels market. The authors report a value of 0.20 for the price elasticity of gasoline supply for the United States and 0.71 for foreign countries, specifically for The Organization of the Petroleum Exporting Countries (OPEC). Later on, papers by Cui et al. (2011) and Drabik et al. (2016) refer to de Gorter and Just (2009) values as well. The elasticity of gasoline supply refers to pure gasoline before ethanol blending.

Corn Elasticities de Gorter and Just (2009) are also the source for some of the corn related elasticities, namely the United States corn supply elasticity and nonethanol corn demand elasticity with reported values of 0.20 and -0.20, respectively.

Rest of the elasticities concerning the share of corn input in the production costs of fuel, food and other consumption goods, as presented in Wu and Langpap (2015) are kept the same as in Wu and Langpap (2015): 0.85 for the output elasticity of fuel, 0.07 for the output elasticity of food and 0.0004 for the output elasticity of other consumption goods. As these parameters are narrowly focused, Wu and Langpap (2015) calculate these elasticities due to the lack of quantitative assessment of these particular elasticities within the academic community.

Ethanol Supply Elasticity The price elasticity of ethanol supply was studied by Rask (1998) through Tobit and Probit models, reporting a value of 0.75 based on data for the time period January 1988 - May 1993. Later, Luchansky and Monks (2009) update Rask's models and results through two-stage least squares (2SLS) model regression and argue for a lower elasticity value of 0.26. McPhail and Babcock (2012) use stochastic partial equilibrium simulation to define the elasticity of ethanol supply at even lower level of 0.13.

3.4 Technical Parameters & Other Values

Besides the already mentioned parameter for the wholesale-to-retail constant markup of \$0.75/gal, our dataset includes other additional technical parameters. Probably the most important is the level of ethanol blended into gasoline, obtained from the Renewable Fuels Association (RFA). The content of ethanol in blended fuel has been slightly above 10% in the past few years. The RFA reports the ethanol blend rate as the share of the total fuel ethanol consumption and total motor fuel consumption.

The lower energy efficiency of ethanol as compared to pure gasoline is expressed through the amount of miles a vehicle is able to travel per gallon of ethanol relative to the gasoline. The parameter is assigned a value of 0.7 as the average energy content of ethanol per gallon is around 30% less than gasoline. (U.S. Department of Energy (2024)) The parameter for the ethanol-corn yield is set to 2.8 gallons of ethanol per one bushel of corn, following Eidman (2007). EIA reports 19-20 gallons of gasoline produced per barrel of crude oil, which converts to approximatelly 0.5 gallons of gasoline obtained from a gallon of crude oil.

The value of consumers' time endowment is derived in Wu and Langpap (2015) as the average number of hours that every person divides between leisure and labour.

The assumed value is 16 hours as an average human sleeps for 8 hours and is productive for the rest of the day. Finally, all data for the determination of the household consumption expenditures for leisure, food, gasoline and other consumption goods are taken from the Consumer Expenditure Survey, released annually by the U.S. Bureau of Labor Statistics.

3.5 Policy Variables

The U.S. fuel tax applied in this paper is based on data provided by EIA and comprises of two components; federal and state fuel tax. The federal tax is a constant of 18.4 cents per gallon of gasoline and applies to all states. The tax has remained at the same level since its latest adjustment in 1993. The federal tax is not indexed for inflation hence in nominal terms, the tax has been gradually decreasing in its purchasing power, losing nearly half of its value since the last revision. The state fuel tax is the average state tax for a given year as the level of the tax is governed by each state separately and therefore varies across the country. The state fuel tax composes of the general sales tax and associated fees, which may include inspection fees, environmental fees, use taxes, or other charges. On January 1, 2024, the difference between the lowest and highest state taxes was 59.15 cents per gallon; Alaska with 8.95 cents per gallon and 68.1 cents per gallon in California. (Energy Information Administration (2024c)

The fuel tax in the rest of the world is taken as the 2019 average of the OECD countries, reported by the U.S. Department of Energy (DOE) at the level of 2.06 dollars per gallon of gasoline. The tax credit on ethanol, VEETC, had been effective since 1979 and was allowed to expire on December 31, 2011 at the level of 45 cents per gallon of pure ethanol.

Goulder and Williams (2003) assume a labor tax rate of 40 percent which had been the highest federal income tax bracket on ordinary income until 2018, when it

was reduced to 37 percent. Both tax rates on food and other consumption goods were obtained from the Federation of Tax Administrators (2024). The tax rate of food is the average state sales tax rate on food taken only from the U.S. states that impose a tax on food while the taxation of other consumption goods is determined by the average state sales tax based on all 51 states.

4 Empirical Results

4.1 Historical Results

4.1.1 Modelling of the Fuel Prices in 2009-2022

The replication analysis of all three source papers as described in section 2 preceded the simulation of fuel prices for the time period 2009-2022. A thorough decomposition and subsequent reconstruction of the models from the highest level to the base variables was carried out, in order to replicate the models with original variables and confirm the consistency of the models and accuracy of the analytical processes.

Since the Drabik et al. framework focuses on price-transmission elasticities and the Wu & Langpap paper is concerned with percentage changes in prices and consumer utility associated with different levels of ethanol subsidies and mandates, the replication was performed from the ground up to an appropriate level of each of the models' needed for the analysis of this paper. Therefore, the replication focused on a confirmation of the values of compound variables in each model as defined in section 2. The original data for the respective calibrated years reported in the three papers resulted in identical values of the compound variables, confirming the accuracy of frameworks and further allowing for the derivation of fuel price models. One of the contributions of this paper lies in the derivation of these fuel price models as the original papers were aimed at different research questions.

Finally, the simulation of derived fuel prices models was performed for the examined period 2009-2022 with the most current data as reported in section 3. The results obtained from the simulation are presented in Table 3. This table summarizes the simulated fuel prices, as predicted by the studied models, compared with the actual fuel prices observed in the market. The blend rate of ethanol, which is the percentage of ethanol mixed with gasoline, shows a consistent increase over the analyzed period, reflecting a policy trajectory toward greater renewable fuels utilization. The blend rate is determined each year by the RFS as an average share of the U.S. ethanol consumption in the total U.S. motor fuel consumption.

Year	**Blend rate**	**Fuel price**	**de Gorter**	**Drabik**	**Wu/Langpap**
	%	$\$/gal$	$\$/gal$	$\$/gal$	$\$/gal$
2009	7.95%	**1.89**	2.20	2.18	1.90
2010	9.22%	**2.30**	2.53	2.34	2.29
2011	9.41%	**3.05**	3.24	3.08	2.98
2012	9.72%	**3.15**	3.35	3.11	3.03
2013	9.84%	**3.05**	3.22	3.24	2.97
2014	9.90%	**2.86**	3.03	3.07	2.79
2015	9.94%	**2.00**	2.23	2.18	1.86
2016	10.04%	**1.73**	1.98	2.02	1.60
2017	10.20%	**1.98**	2.13	2.06	1.84
2018	10.10%	**2.30**	2.40	2.31	2.14
2019	10.16%	**2.25**	2.28	2.15	2.02
2020	10.15%	**1.83**	1.82	1.73	1.46
2021	10.17%	**2.57**	2.60	2.52	2.31
2022	10.43%	**3.00**	3.13	2.95	2.90

Table 3: Resulting simulated fuel prices, dollars per gallon

The fuel price is the U.S. sales to end users fuel price (excluding taxes) reported by the U.S. Energy Information Administration (2024) and serves as a chosen comparison benchmark for the simulated results, with values varying between 1.73 and 3.15 dollars per gallon. The fuel prices exhibit fluctuations that do not necessarily correlate with the increasing trend of ethanol blend rates, suggesting the presence of other influential factors in price determination. This observation is in line with the market's complexity, where variables such as crude oil prices, agricultural yields, and global economic events intertwine to shape the final cost to end-users (Janda et al., 2021).

When comparing the models' simulated prices with the actual fuel prices, the Drabik et al. model apparently adheres closest to the real-world data, indicating a possible superior calibration of this model to real market conditions. In contrast, the de Gorter & Just model and the Wu & Langpap model tend to overestimate and underestimate the prices, respectively. Each model's predictive ability varies in different contexts. For example, the Wu & Langpap (2014) model tends to yield underestimations of fuel prices during periods marked by elevated market prices, suggesting potential omissions of certain factors that catalyze price surges within its predictive framework. Conversely, the de Gorter & Just model demonstrates a tendency to overestimate fuel prices in instances where the market exhibits a downturn, such as observed in the year 2016. This pattern may imply an overemphasis on specific variables which actually exerted a diminished influence during that period.

Modeled fuel prices fluctuate around real fuel price with significant deviations in only some years. The initial year of examination, 2009, is overestimated by 15-16%, or 0.30 dollars per gallon, by both de Gorter and Just (2009) and Drabik et al. (2016) derived models. Also, all three models seemingly fail to accurately capture the reality of the simulation period around year 2016 with 8-16% divergences (in absolute terms). The highest deviation of 20%, equal to 0.37 dollars per gallon, is reported in 2020 by the model derived from Wu and Langpap (2015).

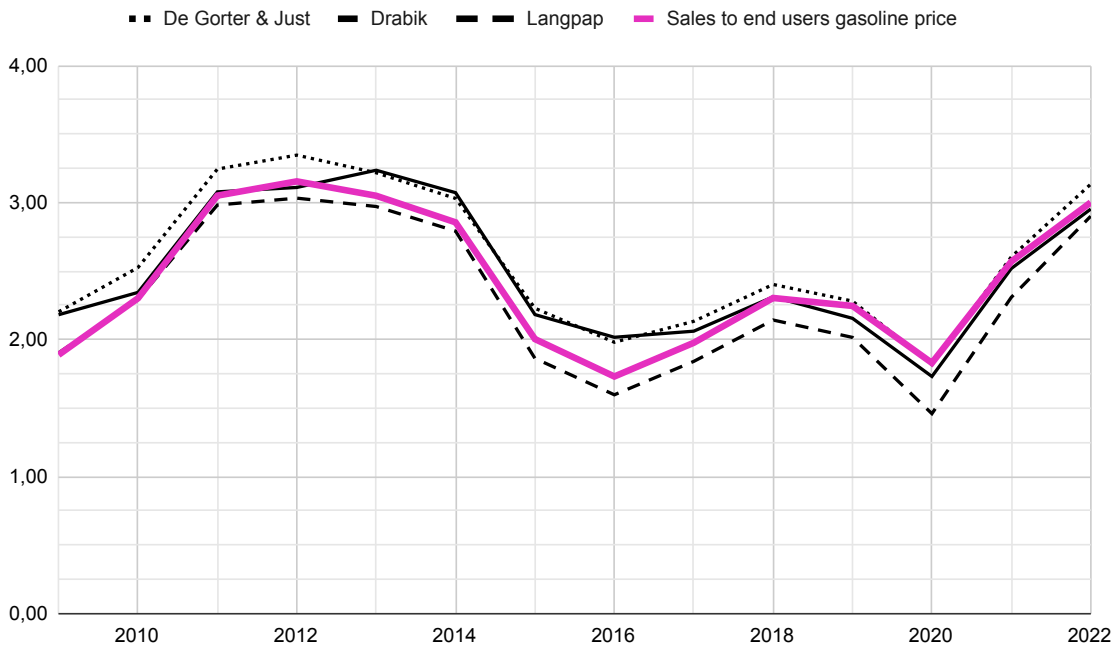

Figure 1: Comparison of simulated fuel prices obtained from the derived models and the actual sales to end users fuel price

The empirical findings are further visualized in Figure 1, which depicts the temporal evolution of the modeled prices against actual prices. The graphical representation confirms the tabular data's narrative, illustrating the relative accuracy of the Drabik et al. model and slightly greater systematic deviation of the other two models. However, all three models capture the overall trend of the fuel prices very well. It is particularly notable that despite the marginal divergence of the simulated prices from the real prices around year 2016, all three models capture the dramatic dip in prices during 2014-2016, a reflection of global crude oil price declines during that period.

A major part of the decrease was due to adverse demand shocks, signaling a slowdown in the global economy. Additionally, a significant portion of the price drop was expected because of optimistic projections for both current and future oil production

prior to July 2014. Besides these anticipated factors, the remaining overall drop in prices was unexpected and stemmed from a sudden change in oil price expectations, which reduced the demand for oil inventories. Moreover, a notable negative demand shock in December 2014, caused by an unpredicted downturn in the global economy, further contributed to the price decline.

Later on, all three models also depict the temporary decrease in 2020 driven by the economic impact of the COVID-19 pandemic, which led to a significant contraction in transport fuel demands, and the Russia-Saudi Arabia oil price war. The global spread of the COVID-19 pandemic in March 2020 prompted widespread government containment measures, drastically reducing outdoor activities and severely impacting sectors like tourism, airlines, and shipping. This led to an unprecedented decline in oil demand, causing a supply glut, a sharp fall in oil prices, massive inventory build-up, and limited storage capacity. The situation was worsened by a production conflict between Saudi Arabia and Russia, where both countries increased oil production, further depressing global oil prices.

4.1.2 Blending Scenarios in 2009-2022

The accuracy and consistency of studied models further allow for simulations of the fuel prices with different levels of the ethanol blend rate in the studied years 2009-2022. These scenarios offer a comprehensive outlook on the relationship between the fuel price and the level of ethanol blended into gasoline. The scenarios chosen for demonstration of the simulated fuel prices across the three studied models are 1%, 5%, 10%, 15%, 20%, 25% and 30% ethanol blend levels where the 10% is the average of the years 2009-2022 and hence serves as a benchmark for each of the models. Tables 4, 5 and 6 display the potential savings - or additional costs in case of the negative values - the customers might have faced at the pump were the blend rates at these

levels, expressed in dollars per gallon of fuel.

The savings (or costs) are computed as the differences between simulated fuel prices for each of the models where the simulation changes the level of ethanol blending. The benchmark ethanol blending level and fuel price for each model and year are the values reported in Table 3 for each particular model. The comparing price is then obtained by changing the ethanol blend rate within the setup. For each year, the base variables are kept from the dataset and kept at the same, reported real values. The simulation changes only the level of ethanol blend rate and therefore produces potential fuel price for the given - higher or lower - blend rate. This hypothetical, simulated fuel price is then subtracted from the benchmark fuel price.

For example, the Drabik et al. model reports a saving of 1.15 dollars per each gallon of fuel in 2022, were the ethanol blend rate increased from 10.43% (the real blend rate in 2022) to 25%. With the 10.43% share of ethanol in fuel, the Drabik et al. model reports a price of 2.95 dollars per gallon (Table 3, this being the benchmark price. The Drabik et al. simulation with higher blend rate of 25% then results in 1.80 dollars per gallon, which leads to 2.95-1.80=1.15 saving. The same approach was taken for scenarios with decreased levels of ethanol; reduction of ethanol content in the fuel to 5% would lead to increased price of 3.48 dollars per gallon of fuel. The consumer would therefore suffer additional cost of 0.53 dollars per gallon.

According to our results, all three models report the same trend; increasing blend rates lead to increasing savings and vice versa, lower blendings cause additional costs for the end users at the pump. For the entire studied period, both Drabik et al. and Wu & Langpap models fully reject the research hypothesis of this paper based on the economic intuition that the higher ethanol blend rates result in higher fuel prices and hence cause additional costs at the pump for the consumers. The de Gorter & Just model rejects the hypothesis to a greater extent as well, with the only exceptions being the three divergent years - 2015, 2016 and 2020.

Year	1%	5%	10%	15%	20%	25%	30%
2009	-0.01	-0.01	0.00	0.01	0.02	0.03	0.04
2010	-0.08	-0.04	0.01	0.06	0.10	0.15	0.20
2011	-0.07	-0.03	0.00	0.04	0.08	0.12	0.16
2012	-0.03	-0.02	0.00	0.02	0.04	0.05	0.07
2013	-0.04	-0.02	0.00	0.02	0.04	0.07	0.09
2014	-0.03	-0.02	0.00	0.02	0.04	0.06	0.08
2015	0.04	0.02	0.00	-0.02	-0.05	-0.07	-0.10
2016	0.07	0.04	0.00	-0.04	-0.08	-0.11	-0.15
2017	-0.01	-0.01	0.00	0.01	0.01	0.02	0.03
2018	-0.04	-0.02	0.00	0.02	0.04	0.07	0.09
2019	-0.04	-0.02	0.00	0.02	0.05	0.07	0.09
2020	0.01	0.00	0.00	0.00	-0.01	-0.01	-0.01
2021	-0.07	-0.04	0.00	0.04	0.07	0.11	0.15
2022	-0.11	-0.07	-0.01	0.06	0.12	0.18	0.24

Table 4: de Gorter model: Savings resulting from the simulated fuel prices with different ethanol blend rates, dollars per gallon

The savings from different blend rate scenarios are further summarized in Table 7. The table presents descriptive statistics of the savings resulting from the three models assessing the impact of ethanol blend rates on simulated fuel price savings in the United States for the studied time period 2009-2022. The overall narrative suggests that increasing ethanol blends tends to correlate with consumer savings, though the extent and consistency of these savings vary across different models. These differences highlight the complexities involved in making accurate forecasts and emphasize the need for a flexible approach when evaluating the economic impacts of biofuel policies.

Year	1%	5%	10%	15%	20%	25%	30%
2009	-0.42	-0.17	0.12	0.39	0.63	0.86	1.07
2010	-0.64	-0.32	0.06	0.39	0.70	0.97	1.21
2011	-0.80	-0.41	0.05	0.47	0.86	1.20	1.52
2012	-0.78	-0.41	0.02	0.43	0.80	1.15	1.46
2013	-0.85	-0.45	0.01	0.44	0.84	1.20	1.53
2014	-0.81	-0.43	0.01	0.42	0.79	1.13	1.44
2015	-0.46	-0.25	0.00	0.25	0.49	0.71	0.92
2016	-0.38	-0.21	0.00	0.21	0.41	0.61	0.81
2017	-0.54	-0.30	-0.01	0.26	0.50	0.73	0.94
2018	-0.64	-0.35	-0.01	0.31	0.60	0.86	1.10
2019	-0.61	-0.33	-0.01	0.29	0.56	0.81	1.03
2020	-0.43	-0.23	-0.01	0.21	0.41	0.60	0.77
2021	-0.75	-0.41	-0.01	0.35	0.67	0.96	1.23
2022	-0.95	-0.53	-0.04	0.40	0.80	1.15	1.47

Table 5: Drabik model: Savings resulting from the simulated fuel prices with different ethanol blend rates, dollars per gallon

The convergence of results toward the higher end of the ethanol blend spectrum across all models suggests that there is a consistent, though not linear, relationship between higher ethanol blend rates and increased fuel savings. This could be attributed to a number of factors, including but not limited to the economic efficiencies of ethanol production, federal blending mandates, and relative movements in the global crude oil market.

An examination of the range values across the models provides further insights. The de Gorter & Just model, with its smaller range, indicates more stable model pre-

Year	1%	5%	10%	15%	20%	25%	30%
2009	-0.14	-0.08	-0.03	0.08	0.15	0.36	0.42
2010	-0.17	-0.09	-0.04	0.09	0.18	0.44	0.52
2011	-0.22	-0.12	-0.05	0.12	0.24	0.57	0.68
2012	-0.23	-0.12	-0.02	0.12	0.24	0.58	0.68
2013	-0.22	-0.12	-0.02	0.12	0.24	0.58	0.70
2014	-0.21	-0.11	-0.02	0.11	0.23	0.55	0.66
2015	-0.13	-0.07	0.00	0.07	0.14	0.33	0.38
2016	-0.12	-0.06	0.00	0.06	0.12	0.28	0.33
2017	-0.13	-0.07	0.01	0.07	0.14	0.33	0.39
2018	-0.16	-0.09	0.02	0.09	0.17	0.41	0.48
2019	-0.15	-0.08	0.02	0.08	0.16	0.37	0.44
2020	-0.11	-0.06	0.02	0.06	0.11	0.26	0.30
2021	-0.17	-0.09	0.04	0.09	0.18	0.44	0.51
2022	-0.22	-0.12	0.05	0.12	0.23	0.57	0.67

Table 6: Wu and Langpap model: Savings resulting from the simulated fuel prices with different ethanol blend rates, dollars per gallon

dictions, which could be indicative of a more robust model structure or assumptions that are less responsive to market volatility. Conversely, the Drabik et al. model, with its wider range, incorporates a broader set of market variables, allowing for greater responsiveness to market shocks but also increasing the uncertainty of its predictions.

4.2 Forecasting Results

Relying on the results from modelling past years based on the historic values might not be the most compelling and relevant argument for policymakers. This section

Blend	**1%**	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**
de Gorter							
Mean	-0.03	-0.02	0.00	0.02	0.03	0.05	0.07
Min	-0.11	-0.07	-0.01	-0.04	-0.08	-0.11	-0.15
Max	0.07	0.04	0.01	0.06	0.12	0.18	0.24
Range	0.18	0.10	0.01	0.09	0.19	0.29	0.39
Drabik							
Mean	-0.65	-0.34	0.01	0.34	0.65	0.92	1.18
Min	-0.95	-0.53	-0.04	0.21	0.41	0.60	0.77
Max	-0.38	-0.17	0.12	0.47	0.86	1.20	1.53
Range	0.57	0.36	0.16	0.26	0.45	0.61	0.76
Langpap							
Mean	-0.17	-0.09	0.00	0.09	0.18	0.43	0.51
Min	-0.23	-0.12	-0.05	0.06	0.11	0.26	0.30
Max	-0.11	-0.06	0.05	0.12	0.24	0.58	0.70
Range	0.12	0.06	0.10	0.06	0.13	0.33	0.40

Table 7: Descriptive statistics of simulated fuel price savings with different ethanol blend rates (studied period 2009-2022), dollars per gallon

therefore takes the analysis further in order to examine the behaviour of the fuel prices and associated policies in the future as the conceptual framework for each of the models allows for projections and hypothetical scenarios. The methodology of each of the models is suitable for a long-run examination hence the structure does not require any changes. The forecasted period is chosen for the years 2023-2030. The dataset utilizes databases from the Energy Information Administration (EIA) and the United States Department of Agriculture (USDA) as both of these institutions frequently release future projections in line with the market expectations.

The predictions of the future values of variables representing the prices and quantities of crude oil, gasoline and ethanol were obtained from EIA's *Annual Energy Outlook, 2023* which explores long-term energy trends in the United States. (Energy Information Administration (2024a) The USDA's forecast *Agricultural Projections to 2032* then provides expectations for the corn market - especially the development of corn prices, exports, production and demand. (U.S. Department of Agriculture (2024)) The technical parameters, policy variables and elasticities were with the best knowledge and conscience carried forward from the known values of 2022. Such approach was carefully considered within the frameworks of the models in order to secure the accuracy and consistency and it was concluded that most of the parameters are constant throughout time, therefore the last known values from 2022 serve as the best predictions for the near future.

Lastly, the projections are contingent upon the blend rates and all of the other predicted variables holding to the EIA's and USDA's anticipated trajectory, making the actual future prices subject to change should the real values of the variables deviate from these forecasts.

4.2.1 Projections of the Fuel Prices in 2023-2030

The Table 8 presents the projected fuel prices over the period 2023 to 2030 in the United States, based on the three distinct models: the de Gorter & Just, Drabik et al., and Wu & Langpap. These projections are premised on blend rates obtained separately for each year as the share of blended ethanol consumption in the total motor fuel consumption; both of these metrics are forecasted by the Energy Information Administration (EIA). The projections follow same approach and principles as the modelling of historic prices in section 4.1. Drabik et al. and Wu & Langpap models account for the energy content discrepancies between fuel ethanol and gaso-

line through the incorporation of the *Miles per gallon of ethanol relative to gasoline* technical coefficient. All of the base variables are integrated through same units in order to secure the consistency of the results.

Year	**Blend rate**	**de Gorter**	**Drabik**	**Wu/Langpap**
	%	$/gal	$/gal	$/gal
2023	10.13%	3.13	3.15	2.89
2024	10.30%	2.87	2.87	2.62
2025	10.37%	2.68	2.68	2.43
2026	10.44%	2.69	2.72	2.44
2027	10.51%	2.72	2.74	2.46
2028	10.57%	2.76	2.80	2.50
2029	10.63%	2.81	2.89	2.56
2030	10.70%	2.87	2.98	2.62

Table 8: Forecasted fuel prices for 2023-2030, dollars per gallon

The de Gorter & Just model forecasts a steady increase in fuel prices across the period, with the lowest price of $2.68 per gallon in 2025, gradually escalating to $2.87 per gallon by 2030. The model suggests a moderate but consistent upward trend, possibly reflecting a view that the blend rates and other market factors will contribute to incremental price rises after 2025. The Drabik et al. model mirrors the trajectory of the de Gorter & Just model with almost identical prices. Such observation is partially logical as Drabik et al. model expands the base framework introduced by de Gorter & Just, however the modelling based on historical values in section 4.1 results in fairly different prices for these two models so one would expect some degree of variation within the projections as well. Finally, the Wu & Langpap model is characterized by the lowest projected prices among the three models. Starting at $2.89 per gallon in

2023, the prices experience a gradual decrease, reaching the lowest at $2.43 per gallon in 2025, before slightly rising to $2.62 per gallon by 2030. It is generally quite difficult to determine the source of such shift as the model utilizes many different elasticities and parameters to the ones incorporated in Drabik et al. model (and de Gorter & Just as well). From an economic perspective, the variance between these models' predictions can be attributed to differing assumptions about the base variables, such as the costs of raw materials, advancements in ethanol production technologies, policy changes or market-driven supply and demand dynamics.

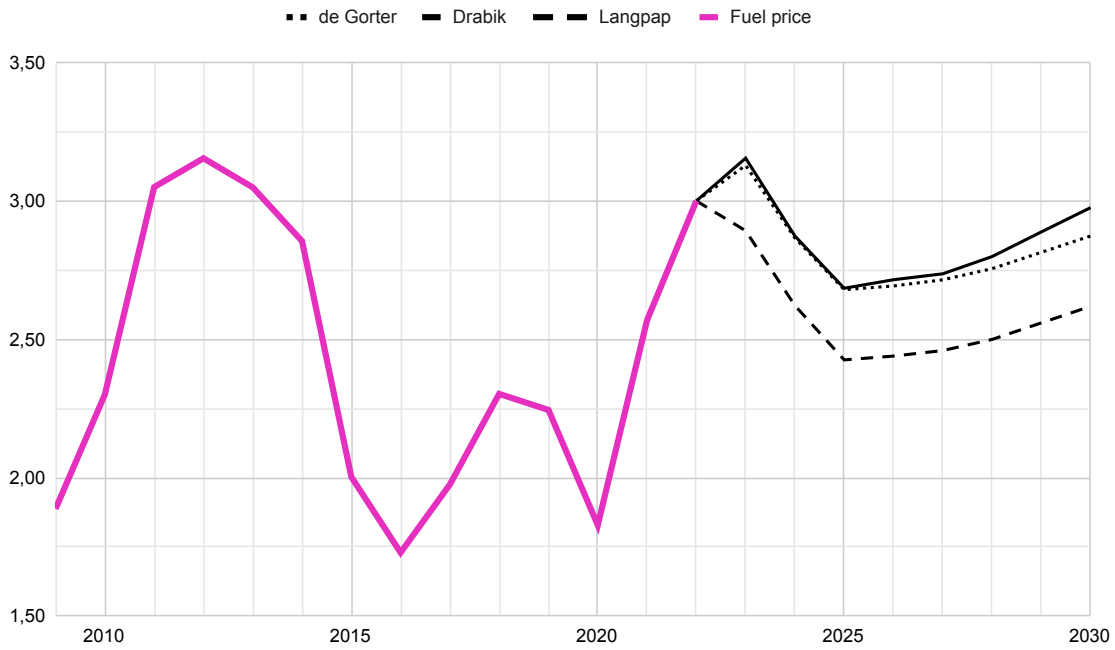

Figure 2: Projection of the fuel prices for 2023-2030

Figure 2 displays the real fuel prices reported by the EIA for the period 2009-2022, once more applying the sales to end users fuel prices as throughout the entire paper. The time period 2023 to 2030 then pictures the projections of fuel prices from the three models with a clear view on the almost identical trajectories of the de Gorter

& Just and Drabik et al. models and the downward shift of the Wu & Langpap forecast, although keeping the same trend as the other two models. When modelling the historic prices, the Wu & Langpap model results in very slight underestimations of the reality, however the pair of scissors is open fairly widely in the case of these forecasts. One of the possible reasons for the divergence might be in the volume of predicted West Texas Intermediate (WTI) crude oil price which is a corner stone of the Wu & Langpap model for the simulated fuel price, while the other two models utilize directly the predicted gasoline prices. In their predictions obtained from the *Annual Energy Outlook, 2023*, the EIA assumes crude oil prices higher by almost a one-third when comparing the average of the past ten years to the predicted average of the next ten years. Such expectations might be the explanation for the sudden shift in the model.

Overall, the projections imply a stabilizing effect of the RFS policy, indicating that the future fuel market may not experience the volatility seen in the historical data. The converging patterns of the models suggest a market consensus on the direction of future fuel prices, although with some divergence in the magnitude of the changes. That aligns with the economic rationale that, as the market adapts and policies evolve, the influence of ethanol on fuel prices will become more predictable and integrated into the general fuel pricing mechanism.

4.2.2 Blending Projections in 2023-2030

The scenarios of fuel prices savings or costs resulting from different blend levels projected for the period 2023 to 2030 are reported in Tables 9, 10 and 11. The methodology follows the same process as the simulations of historical prices and consequent consumer savings in section 4.1 - the savings (or costs) are computed as the differences between projected fuel prices for each of the models where the projection changes the

level of ethanol blending with the base values reported in Table 8 for each particular model. Through potential changes in levels of ethanol blended into gasoline, the comparing prices are obtained. The forecast changes only the hypothetical level of ethanol blend rate and therefore produces potential fuel price for the given - higher or lower - blend rate. This projected fuel price is then subtracted from the benchmark fuel price.

The scheme again offers the scale of blend rates from 1% up to 30% with the assumed (expected) real blend rate fluctuating between 10-11%. Similarly to the simulated historical results, the projected fuel prices clearly demonstrate the same trend: increasing the level of ethanol blended into gasoline results in lower fuel prices hence higher savings for the end users. The vice versa scenario, i.e. decreased level of ethanol blending, leads to higher prices and translates to negative values of savings, causing additional costs for the consumers. For instance, in 2025, a 1% blend rate corresponds to a \$0.06 - \$0.80 - \$0.18 per gallon additional costs resulting from the three models respectively, while a 30% blend rate predicts a \$0.13 - \$1.28 - \$0.39 per gallon savings. This pattern remains consistent through the years, with the savings for a 30% blend rate being the highest and the additional costs peaking at the 1% blend rate.

From an economic perspective, the tables suggest that there is an incentive not to decrease the blend rate of ethanol in gasoline as it may lead to consumer losses. Such outcome may influence policy decisions regarding the Renewable Fuel Standards and the encouragement of alternative fuel use. The outcomes might find important use for stakeholders in the fuel industry, including producers, retailers, and consumers, to understand how changes in ethanol blending can impact fuel pricing.

The magnitude and course of the savings from the three models are represented in Figure 3. For better portrayal, the values for each model and blend level are taken as the averages of the period 2023-2030. The curve labeled as "Equally Weighted

Year	1%	5%	10%	15%	20%	25%	30%
2023	-0.10	-0.06	0.00	0.06	0.11	0.17	0.23
2024	-0.07	-0.04	0.00	0.04	0.07	0.11	0.15
2025	-0.06	-0.03	0.00	0.03	0.06	0.09	0.13
2026	-0.06	-0.03	0.00	0.03	0.06	0.09	0.12
2027	-0.06	-0.03	0.00	0.03	0.06	0.09	0.12
2028	-0.06	-0.03	0.00	0.03	0.06	0.09	0.12
2029	-0.06	-0.04	0.00	0.03	0.06	0.09	0.12
2030	-0.06	-0.04	0.00	0.03	0.06	0.09	0.12

Table 9: de Gorter model: Savings resulting from the projected fuel prices with different ethanol blend rates, dollars per gallon

Results" is created by taking equally weighted linear combination of all three other lines (labeled as "de Gorter", "Drabik", and "Langpap"). The Drabik et al. model suggests a robust positive correlation between the blend rate and savings, implying that as the ethanol content in fuel increases, the savings on fuel prices are expected to rise. This trend could be indicative of the efficiency gains from blending ethanol, possibly due to improved production processes or better utilization within engines.

In contrast, the projections from the de Gorter & Just and Wu & Langpap models are relatively static, hinting at a prediction that changes in ethanol blend rates within the examined range might not influence savings in fuel costs that significantly as in the Drabik et al. case. Such flatter trends can be interpreted as conservative estimates, possibly factoring in market barriers like the ethanol blend wall, which limits the feasible amount of ethanol that can be mixed into fuel without necessitating engine or infrastructure modifications. The projections shed light on the intricate dynamics at play in the fuel market and highlight the importance of a multifaceted

Year	1%	5%	10%	15%	20%	25%	30%
2023	-0.97	-0.52	-0.01	0.45	0.87	1.24	1.57
2024	-0.86	-0.47	-0.03	0.38	0.75	1.09	1.39
2025	-0.80	-0.44	-0.03	0.35	0.69	1.00	1.28
2026	-0.81	-0.45	-0.03	0.35	0.69	1.01	1.29
2027	-0.82	-0.46	-0.04	0.34	0.69	1.01	1.30
2028	-0.84	-0.47	-0.05	0.35	0.70	1.03	1.32
2029	-0.88	-0.50	-0.05	0.35	0.72	1.06	1.36
2030	-0.91	-0.52	-0.06	0.36	0.74	1.09	1.40

Table 10: Drabik model: Savings resulting from the projected fuel prices with different ethanol blend rates, dollars per gallon

approach to policy-making. If the more pro-ethanol outlook of the Drabik et al. model holds true, then supportive policies towards higher ethanol blends or towards not decreasing the already achieved blending levels might yield considerable economic benefits through fuel savings. Conversely, if the market behaves as suggested by the more conservative de Gorter & Just and Wu & Langpap models, then the economic intuition for promoting higher blend rates could be less compelling.

Naturally, any policy decisions about biofuels mandates also have to take into account environmental (Langpap and Wu, 2011), land use (Taheripour et al., 2022b; Rajcaniova et al., 2014), technological (Taheripour et al., 2021), food-related (Rajcaniova and Pokrivcak, 2011; Rajcaniova et al., 2013) and other (Taheripour et al., 2022a) impacts of biofuels.

Year	1%	5%	10%	15%	20%	25%	30%
2023	-0.22	-0.12	0.00	0.12	0.23	0.34	0.45
2024	-0.20	-0.11	0.00	0.11	0.21	0.32	0.42
2025	-0.18	-0.10	0.00	0.10	0.20	0.30	0.39
2026	-0.19	-0.10	0.00	0.10	0.20	0.30	0.39
2027	-0.19	-0.10	0.00	0.10	0.20	0.30	0.40
2028	-0.19	-0.11	0.00	0.10	0.21	0.31	0.40
2029	-0.19	-0.11	0.00	0.11	0.21	0.31	0.41
2030	-0.20	-0.11	0.00	0.11	0.22	0.32	0.42

Table 11: Wu and Langpap model: Savings resulting from the projected fuel prices with different ethanol blend rates, dollars per gallon

5 Conclusions

This paper contributes to existing biofuels related price transmission literature in multiple ways. Firstly, our replication of the original well established microeconomics models of de Gorter and Just (2009), Drabik et al. (2016) and Wu and Langpap (2015) papers results in the same values of the compound variables for the calibrated years of the models as the ones obtained by de Gorter and Just, Drabik et al., Wu and Langpap. In this way we provide a replication based verification of these three models. As these models provide conceptual framework for the price-transmission elasticities and percentage changes in prices and consumer utility associated with different levels of ethanol subsidies and mandates, one of the contributions of this paper is the derivation of adjusted fuel price models based on the original models.

Our empirical analysis consists of simulations and projections of the blended fuel prices, providing numerical results for the derived models. The historical simulations are run for the period 2009-2022 and results report the same trend for all three con-

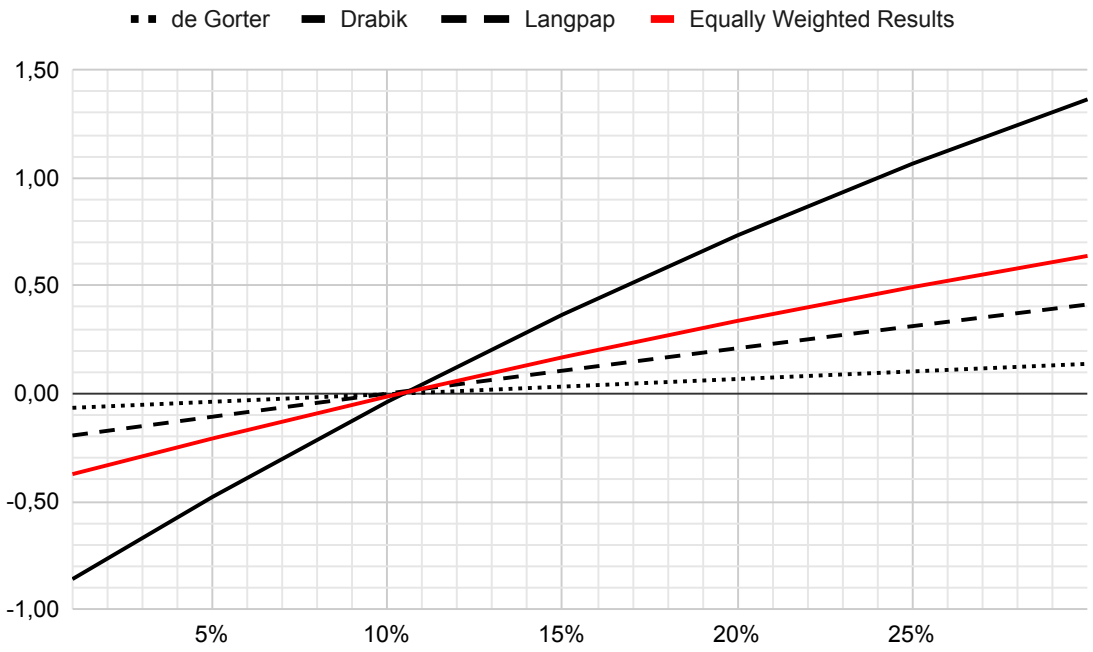

Figure 3: Projection of the savings resulting from different blend levels, averages of 2023-2030 in cents per gallon

sidered models with only minor differences from the U.S. sales to end users blended fuel price as reported by U.S. Energy Information Administration (2024). The general equilibrium Wu & Langpap model is mostly underestimating and the partial equilibrium de Gorter & Just model is, in contrast, mostly overestimating the real prices while the results of Drabik et al. model fluctuate around the U.S. sales to end users blended fuel prices inside the Wu & Langpap and de Gorter & Just band. Our analysis then simulates blended fuel prices under various ethanol blend levels, keeping other variables constant. These simulations generate new fuel prices for each scenario, which are compared to the original simulated prices. The results, presented as savings tables, show that increasing ethanol blending actually decreases fuel prices at the pump, rejecting our initial hypothesis of positive correlation between ethanol

mandates and gasoline prices paid by the consumer at the pump.

Finally we provide the long-term forecasts in the form of projections of blended fuel prices in the years 2023-2030 based on predicted values of the base variables used within the derived models. As inputs we use predictions made by the Energy Information Administration (2024a) in their *Annual Energy Outlook, 2023* and the U.S. Department of Agriculture (2024) forecast *Agricultural Projections to 2032*. Our projections suggest that higher ethanol blend rates could lead to consumer savings.

Our findings are an important contribution for policy decision making related to the Renewable Fuel Standards and alternative fuel use. Our results might be useful for stakeholders both in government and in the fuel industry, including producers, retailers, and consumers, to understand how changes in ethanol blending policies and practice can impact fuel pricing.

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Appendix A de Gorter and Just (2009) Model

In consideration of a competitive market, the de Gorter and Just (2009) model necessitates the fulfillment of three equilibrium conditions. For the first condition, the upward sloping ethanol supply curve S_E, horizontal gasoline supply curve S_G and downward sloping fuel demand curve D_F are defined. Then, all of the fuel that is being traded in the market is obliged to contain a specific level of ethanol, α, following the current mandate. The model assumes endogenous gasoline prices, zero biofuels imports and a blended fuel composed of two ingredients only - gasoline and ethanol, where both of the components are considered perfect substitutes in consumption. The weighted average consumer price of fuel including blended ethanol P_F equals the marginal cost that the customers are required to pay to the blenders for processing the blended fuel, as given by the right-hand side of the equation (1) that weighs the average prices of wholesale ethanol, P_E, and gasoline before blending, P_G, by the ethanol proportion blended into the gasoline while taking into account a volumetric tax on all fuel t and ethanol tax credit t_E:

$$P_F = \alpha(P_E + t - t_E) + (1 - \alpha)(P_G + t) \tag{1}$$

Further on, the authors determine such market prices of the blended fuel that result in equality of the total fuel supply and total fuel demand, $S_F(P_F) = D_F(P_F)$, in order to find the equilibrium prices for the wholesale ethanol and gasoline before blending, P_E and P_G respectively. The market-clearing condition is then found intuitively by setting the fuel mixture demand equal to the supply of gasoline and supply of ethanol curves:

$$D_F(P_F) = S_G(P_G) + S_E(P_E) \tag{2}$$

The third and last equilibrium assumption considers a constraint imposed by the

mandate as the consumption of ethanol must be equal to $\alpha D_F(P_F)$ for any blended fuel price P_F. The equilibrium price of wholesale ethanol, P_E, is implicitly defined as:

$$\alpha D_F(P_F) = S_E(P_E) \tag{3}$$

Appendix B Drabik et al. (2016) Model

Building up on the theoretical model introduced by de Gorter and Just (2009), partial equilibrium model of Drabik et al. (2016) focus on the implications of ethanol policies to the price transmission in corn and food markets. The model by Drabik et al. (2016) offers three different scenarios: a) the no biofuel benchmark, b) a binding blend mandate, and c) a binding blender's tax credit.

The first scenario establishes a baseline framework with absent biofuel production and hence no applicable, biofuels supporting laws. In such market, corn is being utilized in two ways only - (i) in a domestic food and feed consumption, i.e. cornstarch, corn oil, feed for hogs etc, and (ii) as an exported commodity. With that intuition, the authors define a system of equations for the total U.S. corn supply $S_C(P_C)$, total demand for food $D_f(p)$ and a profit maximizing first-order condition applicable in the corn processing industry:

$$S_C(P_C, Y_1) = x + \bar{D}(P_C, Y_2) \tag{4}$$

$$D_f(p, Y_3) = f(x) \tag{5}$$

$$pf_x = P_C \tag{6}$$

where x stands for the U.S. food and feed corn production and $\bar{D}$ is the export

demand curve facing the U.S. market. Altogether, these equations define the equilibrium in the market. After including exogenous market shocks Y_i, where $i = 1, 2, 3$ stand for the corn supply, corn export demand and food demand respectively, Drabik et al. (2016) determine the price transmission elasticities.

Biofuels are presented into the framework through a linkage between ethanol and the corn-food supply chain through a definition of the general ethanol supply curve $S_E(P_E)$. The logic behind the ethanol supply is that the ethanol plants obtain only the amount of produced corn that is left after taking care of the domestic food and feed production and exports:

$$S_E(P_E) = \frac{\lambda\beta}{1 - r\delta}[S_C(P_C, Y_1) - x - \bar{D}(P_C, Y_2)] \tag{7}$$

The complete ethanol supply curve is weighted by several conversion parameters; λ is the energy equivalent coefficient of ethanol relative to the gasoline, β denotes the amount of ethanol (in gallons) commonly obtained from a bushel of corn and δ stands for the portion of an ethanol co-product DDGS (dried distillers grains with solubles), that is restored to the market in the form of an animal feed.

The fuel market with ethanol blended gasoline then reaches its equilibrium when the blended fuel demand, $D_F(P_F)$, is set equal to the sum of gasoline supply, $S_G(P_G)$, and ethanol supply, $S_E(P_E)$:

$$D_F(P_F) = S_G(P_G) + S_E(P_E) \tag{8}$$

The binding blend mandate and binding blender's tax credit scenarios refer to the previous work of de Gorter and Just (2009) by adapting their model as presented in the section A and accounting for the energy efficiency of ethanol, exogenous market shocks and others. The full biofuels model is then able to asses the price transmission in the fuel market under different policies and market shocks.

One of the extensions of the original de Gorter and Just (2009) model made by Drabik et al. (2016) is the implementation of the energy equivalent parameter, λ, which the authors apply throughout the framework to ethanol related variables. The adjustment is crucial for a proper analysis and suggests that results from Drabik et al. (2016) model should be more accurate and reliable.

B.1 Derived Fuel Price Model

The Drabik et al. (2016) framework examines solely the price transmission in the fuel and food market and the effect of various ethanol policies and market shocks on the transmission. Our paper is, however, focused on the price effect of the ethanol policies on the prices that consumers pay at the pump. One of the contributions of our paper is therefore the derivation of the separate fuel price model in the form of a system of equations and resulting implementation of the model to the analysis while incorporating the collected dataset of base variables.

Extraction of the model as introduced by Drabik et al. (2016) with a focus on the essential components was executed through thorough examination and decomposition of the model into its prime factors and expressions. Then, a new model for simulated blended fuel price was derived. As this paper focuses on the period of the past fourteen years, 2009-2022, the effective biofuels policies had to be reviewed. The Volume Ethanol Excise Tax Credit (VEETC) expired on Dec 31, 2011 and no other U.S. policy regarding ethanol tax credit has been implemented since then. Therefore, the VEETC variable is kept in the model and its value is set to zero after year 2011. The ethanol blend mandate, as determined by the Renewable Fuel Standard, is still effective and has been slowly increasing year after year.

The resulting model for simulated blended fuel price P_F is dependent on the U.S. gasoline supply S_G, foreign gasoline supply S_{G_F}, foreign gasoline consumption D_{G_F},

an auxiliary calibrated parameter for the U.S. fuel consumption A, the level of blend mandate α and U.S. gasoline demand elasticity η_G^D:

$$P_F = \left[\frac{S_G + S_{G_F} - D_{G_F}}{A(1-\alpha)}\right]^{\frac{1}{\eta_G^D}} \tag{9}$$

with

$$S_G = \frac{D_F - D_E}{S_O + I_O} S_O \tag{10}$$

$$S_{G_F} = \frac{D_F - D_E}{S_O + I_O} (\bar{S_O} - S_O) \tag{11}$$

$$D_{G_F} = S_G + S_{G_F} - GUS \tag{12}$$

where D_F is the motor fuel consumption, D_E is the U.S. ethanol consumption, S_O is the U.S. oil supply, $\bar{S_O}$ is the world oil production and I_O is the U.S. import of crude oil.

Substituting (12) into (9), the simulated blended fuel price equation can be simplified to

$$P_F = \left[\frac{GUS}{A(1-\alpha)}\right]^{\frac{1}{\eta_G^D}} \tag{13}$$

Variable GUS determines level of the U.S. gasoline consumption by subtracting the amount of U.S. ethanol supply from the total amount of the U.S. motor fuel consumption D_F:

$$GUS = D_F - \frac{E}{\lambda} \tag{14}$$

The energetic equivalent of ethanol production, E, is equal to the ethanol consumption and was derived from raw data on variables for the U.S. production of yellow corn S_C, U.S. domestic corn demand as food/feed D_x, U.S. corn exports X and ethanol parameters.

$$E = \lambda\beta(S_C - D_x - X) \tag{15}$$

The calibrated parameter for U.S. fuel consumption A equals to the ratio of U.S. blended fuel consumption D_F and de Gorter and Just (2009) equation for price of blended fuel, adjusted by the U.S. gasoline demand elasticity η_G^D:

$$A = \frac{D_F}{[\alpha(P_e + \frac{t}{\lambda} - \frac{t_E}{\lambda}) + (1-\alpha)(P_G + t)]^{\eta_G^D}} \tag{16}$$

Here P_e is the wholesale price of ethanol expressed in energy terms, computed as the ratio of the ethanol wholesale price, P_E, and the energetic equivalent of ethanol relative to gasoline, λ: $P_e = \frac{P_E}{\lambda}$. The U.S. blended fuel consumption D_F is the sum of the ethanol production E and the U.S. gasoline consumption GUS; $D_F = E + GUS$.

Appendix C Wu and Langpap (2015) Model

Wu and Langpap (2015) define a general equilibrium framework in order to asses the interconnections between biofuel mandates and subsidies, especially focusing on their effect on crops, food and energy markets and prices, as well as the overall consumer welfare within the structure. The authors expand an original model introduced by Goulder and Williams (2003) and calibrate it to the 2011 data. The main reason for incorporating this model into our analysis is due to its ability to capture relationships among different markets. The framework distinguishes between two markets; (i) intermediate goods markets (specifically corn, C, crude oil, O and other intermediate goods markets, M) and (ii) consumption goods markets (gasoline, G, food, f, and markets with other goods, Z), with four agents in operation: consumers, producers of intermediate goods, producers of consumption goods and governments.

The authors introduce the continuous, quasi-concave household utility function,

maximized by consumers spending of their income on different consumption goods i as measured by the total consumption, C_i,

$$U(l, C_G, C_f, C_Z), \tag{17}$$

with a household time constraint $T = l + \sum_i L_i + \sum_j L^j$. The time endowment is in reality different for each consumer as every person splits their time between leisure, l, and labor, L, differently according to their possibilities. However for purposes of this paper, the time endowment is assumed a constant throughout the examined time period.

Within the context of a biofuel mandate, the United States primarily utilize corn-based ethanol for biofuels. The mandate necessitates a specific ratio of ethanol to crude oil for fuel production. A unit of ethanol, indicated by β, is defined by the amount of biofuel produced from one unit of corn, equivalent to 2.8 for corn-based ethanol with current technology. The volume of gasoline produced from one barrel of crude oil is signified by a and approximates to 0.5. The biofuel mandate, α, stipulates a minimum blend threshold and can be expressed through a and β as $\alpha \leq \beta I_F^C / (a I_F^O + \beta I_F^C)$.

The production function of fuel with a biofuel mandate is then defined:

$$C_F = F_G(L_G, a I_G^O + \beta I_G^C, I_G^M) \tag{18}$$

assuming that ethanol and gasoline are perfect substitutes below the minimum blend rate. The variable I_i^j determines the amount of intermediate good j (i.e. crude oil, corn and other intermediate goods) which is utilized in the production process of a consumption good i, in this case the fuel F. Generally, it must hold that this amount of an intermediate good j being utilized in the production process of a consumption goods i is equal to the actual produced amount of the intermediate good:

$$\sum_{i=G,f,Z} I_i^j = I^j \tag{19}$$

Concerning the amount of labor needed for the production of goods, the model by Wu and Langpap (2015) assumes normalized units where one unit of labor produces one unit of output.

C.1 Derived Fuel Price Model

The utilized model for equilibrium blended fuel price, P_F, is

$$P_F = \frac{\gamma_G^{\lambda}[(1-t_L)T + \text{GOV}]^{\lambda}[a\alpha P_{C*} + \beta(1-\alpha)P_O]^{\eta_G^C}}{\phi_G(1-t_c)^{1-\lambda}(a\beta)^{\eta_G^C}} \tag{20}$$

where γ_G is the household consumption expenditure share for gasoline, λ is the miles per gallon of ethanol relative to gasoline adjustment for energy equivalence, t_L represents the labor tax rate and t_c is the calibrated tax rate of fuel, defined as the percentage share of fuel tax t in gasoline price P_G. The model also employs a consumer time endowment, T, which is the number of hours per day that the consumer divides between labor and leisure. The parameters a and β are used for efficiency scaling of the intermediate goods, crude oil and corn; a stands for the amount of gasoline produced from a gallon of crude oil and β stands for the amount of ethanol produced from a bushel of corn. P_{C*} represents the equilibrium price of corn and P_O is the West Texas Intermediate (WTI) price of crude oil. The output elasticity of gasoline, η_G^C, indicates the share of corn input in the production costs of blended fuel.

The model also employs a government lump-sum transfer payment, GOV, that the government compensates the households with and provides biofuel subsidies to biofuel producers. It enters the model as

$$GOV = T(1-t_L)\left[\frac{\gamma}{\gamma_l + (1-t_L)\sum_i (1-t_i)\gamma_i} - 1\right] \tag{21}$$

for $i = G, f, Z$, differentiating between gasoline, food and other consumption goods variables. Here γ is the total household consumption expenditure, summing up together fractional consumption expenditures of households, and t_i are different tax rates.

The equilibrium price of corn is obtained through variables for the time endowment, various tax rates, supply of corn S_C, elasticities, household consumption expenditures, crude oil price and ethanol blend level:

$$P_{C*} = \left\{ \frac{T(1-t_L)}{S_C[\gamma_l + (1-t_L)\sum_i (1-t_i)\gamma_i]} \left[(1-t_f)\eta_f^C \gamma_f + \right.\right.$$
$$\left.\left. (1-t_Z)\eta_Z^C \gamma_Z + (1-t_c)\eta_G^C \gamma_G \frac{a\alpha}{a\alpha + \beta(1-\alpha)\tilde{P_O}} \right] \right\}^{\frac{1}{1+\eta}}$$

Output elasticities of gasoline, food and other consumption goods; η_G^C, η_f^C and η_Z^C, determine the share of corn input in the production costs of the respective consumption goods. $\tilde{P_O}$ is the share of WTI crude oil price and corn price: $\tilde{P_O} = \frac{P_O}{P_C}$.

The final term incorporated into the equilibrium fuel price model reflects the utilization of the real price of corn P_C and the wholesale gasoline price P_G:

$$\phi_G = \frac{\gamma_G^{\lambda}[(1-t_L)T + \mathrm{GOV}]^{\lambda}[a\alpha P_C + \beta(1-\alpha)P_O]^{\eta_G^C}}{P_G(1-t_e)^{1-\lambda}(a\beta)^{\eta_G^C}} \tag{22}$$

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