Energy Policy 98 (2016) 149–159

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The market and consumer welfare effects of mid-level ethanol blends in the US fuel market

Paul W. Gallagher*, Daniel Sleper

Department of Economics, Iowa State University, United States

HIGHLIGHTS

- Competiveness of 20% ethanol blends replacing gasoline is examined.
- Households can reduce costs by $1000 over vehicle life with ethanol blend.
- Blended fuel could gain a 60% share in a voluntary US gasoline market.
- US ethanol supply in a voluntary market would match current mandated output.

ARTICLE INFO

Article history:
Received 16 November 2015
Received in revised form
18 August 2016
Accepted 22 August 2016
Available online 30 August 2016

Keywords:
Ethanol-blended fuel
Substitution
Consumer demand
Competitive market

ABSTRACT

This study examines the prospect that a consumer-driven market could eventually replace the myriad regulations and demand quotas in the US ethanol and gasoline fuel market. Given efficient households that minimize the cost of operating automobiles, recent vehicle technology that improves blended fuel substitution, and typical market conditions of the last five years, blended fuels with 20% ethanol concentration could occupy a volume of 82.2 billion gallons in a 138.3 billion gallon gasoline market. The consumer welfare gain associated with blended fuel is $15.9 billion annually for US consumers, or about $1000 over the life of a vehicle.

The ethanol demand associated with a voluntary blended fuel market is 16.4 BGY, slightly more than the conventional component of the Renewable Fuels Standard. It is time to replace the corn RFS with a free market. But an active competition policy in the fuel marketing system may also be required. Intervention for the impending Biomass Ethanol Industry, such as a subsidy or an exemption a carbon tax, may also be in order.

1. Introduction

Global warming is a serious environmental problem, and complete international participation in a well-designed policy will be required for a solution. Ethanol's contribution to the mitigation of global warming may be limited according to some estimates, because carbon emissions are only reduced by 10–20% when ethanol fuel replaces pure gasoline fuel (Sinn, 2012, p. 98; Congressional Record, 2007, p. 121). However, ethanol assessments are typically based on fuels like E85, which has a concentration of 70% ethanol and 30% gasoline – some consider ethanol an inferior fuel due to the 25% reduction in fuel economy when E85 substitutes for gasoline (US EPA and US DOE Staff, 2015). Indeed, E85 has struggled in the US marketplace. Economic incentives for E85 adoption are limited (Consumer Reports Staff, 2011. p. 4). Further, demand has not grown-only about 12.0 million US cars and light trucks (6.8%)

Abbreviations: RFS, Renewable Fuel Standard; BGY, Billion Gallons per Year; EIA, Energy Information Agency; FFV, Flexible-Fuel Vehicle; EPA, U.S. Environmental Protection Agency; DOE, U.S. Department of Energy; FSR or $f\alpha_i$, Fuel Substitution Rate; BMEP, Break Mean Effective Pressure; E10, ten percent ethanol in gasoline blended fuel; E20, twenty percent ethanol in gasoline blended fuel; HWEET, EPA highway drive cycle; E0, zero percent ethanol in gasoline fuel; GLS, Generalized least squares; OLS, Ordinary least squares; GEEG, Gasoline Energy Equivalent Gallons; DOT, U.S. Department of Transportation; IDALS, Iowa Department of Agriculture and Land Stewardship; AMS, U.S. Dept. of Agriculture, Agricultural Marketing Service; BAR, A unit of pressure in multiples of standard atmospheric pressure; CRC, Coordinating Research Council; OPIS, Oil Price Information Service; NACS, fifteen percent ethanol in gasoline blended fuel E15, thirty percent ethanol in gasoline blended fuel E30, National Association of Convenience Stores

* Correspondence to: Department of Economics, Iowa State University, 481 Heady Hall, Ames, IA 50010, United States.
E-mail address: paulg@iastate.edu (P.W. Gallagher).

http://dx.doi.org/10.1016/j.enpol.2016.08.025
0301-4215/

are flex-fuel vehicles(FFVs) equipped for E85 (EIA Staff, 2015b, Table 46).

Mid-level blends with ethanol concentrations from 15% to 40% may be more effective at competing in the marketplace and improving the carbon balance for biofuels. Indeed, blender pumps offering 15%, 20%, 30%, or 50% ethanol concentrations of FFVs are available in the central US (Elesland, 2015). And the EPA has authorized sales of E15 (15% ethanol) for some vehicles manufactured since 2001 U.S. Environmental Protection Agency, 2015). The adoption of intermediate blends will also depend on relative fuel economy of intermediate blends and gasoline, and economic incentives.

This paper examines the consumer market for fuel with intermediate ethanol concentrations and evaluates the consumer welfare gain associated with adoption. We show that intermediate blends could effectively substitute for gasoline, occupy a substantial segment of the fuel market, and also yield a moderate welfare gain for US consumers. First, we introduce the economic model. Second, estimates of the technical fuel substitution rate for gasoline to ethanol blend are presented. Next, we report demand and welfare estimates. Finally, we review current US ethanol policy in light of mid-level blend potential, generally suggesting more market reliance and less government intervention.

2. Methodology

2.1. Consumer equilibrium, demand, and price relationships

Household models of consumer behavior distinguish between household goods, whose quantities are arguments in the utility function, and household inputs, whose quantities are arguments of the household production function. In the short run, inputs include the household's capital stock of appliances, such as clothes washers, automobiles, and housing (Bryant and Zick, 2006, p. 133). Then the household spends time and money operating its capital stock in the production of household goods, in this case transportation services and housing services. The takeaway is that transport services and housing services are the inputs in the consumers' utility function. In contrast, the automobile capital stock and the fuel used to maintain and operate the automobile are inputs to the household production function. Transport services and housing services are also outputs of the household production function.

We consider a simplified case of two substitute operation-input fuels for an appliance. That is, a blended fuel with ethanol concentration, α, substitutes for straight gasoline, which is indicated by the subscript g. The competiveness of blended fuel can be determined in this fashion. Also, a range of blended fuel concentrations is possible under this approach.[1]

The equilibrium requires that the input price ratio equals the technical rate of substitution between the two operation-inputs (Appendix A). The same equilibrium condition holds for a constant-output firm minimizing the cost of inputs (Perloff, 2011, p. 221). For the case of the automobile where a blended fuel with ethanol concentration, α, and retail price $P\alpha^r$ (in $/gal α) substitutes for gasoline with retail price Pg^r (in $/gal g), equilibrium requires that

$$-\frac{\Delta Q_{gi}}{\Delta Q_{\alpha i}} = \frac{P_\alpha^r}{P_g^r}, \tag{1}$$

where $\Delta Q_{gi}/\Delta Q_{\alpha i}$ is the technical substitution rate of gasoline for blended fuel (in gal g/gal α). In words, the equilibrium condition defines the cost minimizing combination of fuels for a given level of transportation service output.

Previous empirical studies of household models are incomplete for our purposes. Transportation service expenditures were measured as the rental rate for transport capital plus purchased transport services (taxis and subways) plus fuel for appliances and vehicles (Huffman, 2011, p. 469). But the input allocation of time and money associated with alternative transport methods and fuels was not included. So consider the short run-a household's transport technology (automobile), housing stock and location, and employment location are all given. Then the allocation of purchased (public) and owned (automobile) transport services is determined by relative money, time, and congestion costs.

Thus, our short-run analysis of fuel substitution technology and costs can start with a given distance traveled using an automobile. This does not mean that miles traveled is fixed in the intermediate or long run – consumer preferences could indicate another consumption and household production level for transportation services. Then the allocation of inputs to public and private transport services would change, and miles driven would change.

In the short run with a given vehicle, household i maintains a given distance traveled, M, using gas (Q_{gi}), and blended fuel ($Q_{\alpha i}$) purchases: $M = e_\alpha Q_{\alpha i} + e_g Q_{gi}$, where e_j is fuel economy with fuel type j. The cost of maintaining the given level of transport services is $C = P_\alpha^r Q_{\alpha i} + P_g^r Q_{gi}$. Fig. 1 shows the technically based fuel-substitution constraint and a set of iso-cost curves. The fuel-substitution constraint is , $Q_{gi} = M/e_g - f_{\alpha i} Q_{\alpha i}$, where $f\alpha_i$ is the technical substitution rate of gasoline for blended fuel (in gal g/gal α). Each iso-cost curve, $Q_g = (C/P_g^r) - (P_\alpha^r/P_g^r)\, Q_\alpha$, is defined by a given level of cost, C. Household i chooses the minimum-cost solution with all blended fuel in Fig. 1, because the slope of the iso-cost line, (P_α^r / P_g^r), is less than the slope of the fuel-substitution constraint, $f_{\alpha i}$.

The consumer is indifferent between inputs when the ethanol blend and blend-equivalent gasoline price are equal because variable travel costs are the same with either fuel:

$$P\alpha^r = Pg^r * f\alpha_i. \tag{2}$$

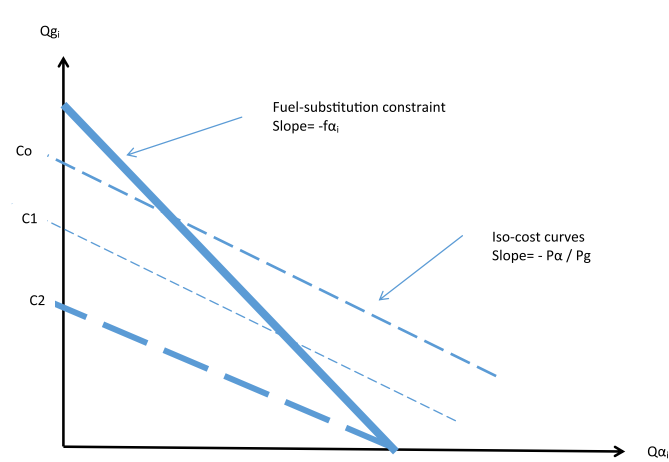

Fig. 1. Household fuel choice in short run.

[1] Most gasoline stations actually offer about six products, and restaurant menus have about 50 items. The replacement of retail products is an interesting economic problem concerning new customer attraction versus existing customers' losses and substitutions. Such an analysis would go beyond our more modest concern with the competitiveness of blended products.

When $P\alpha^r > Pg^{r*} f\alpha_i$, α is more expensive than g after adjusting for fuel economy, and the consumer chooses the corner solution with all g. When $P\alpha^r < Pg^{r*} f\alpha_i$, α is cheaper than g after adjusting for fuel economy, and the consumer chooses the corner solution with all α. Hence, Eq. (2) also defines an individual consumer's demand price for α.

Subsequent empirical analysis builds on the assumption that individual consumers can correctly access the tradeoff defined by (2) for minimum cost of household operation. Every consumer has the necessary price information posted on retail pumps. Knowledge of the distinct FSR by each consumer for her auto technology and driving condition is also plausible; records and ratios from five standard cycles, such as a week's commuting or trips to visit relatives, even satisfy a statistician. Consumers at Minnesota's blender pumps make similar calculations now.

2.2. Market relationships for blended fuels

Empirical market analysis for a new product cannot proceed with statistical demand estimation using data because there is no history. Instead, we rely on the equilibrium condition from economic theory, and estimates of the underlying physical relationship for $f\alpha_i$. Now we explain the basic assumptions and data requirements for blended fuel demand and supply estimation.

Our retail demand estimation for blended fuel concerns the short run. First, the distance traveled is taken as given. Second, each household has a distinct fuel substitution rate, $f\alpha_i$, that is defined by its automobile model, engine size, and use pattern. So there is a distribution of fuel substitution rates across consumers-we will estimate the fuel substitution rate distribution. There is also a corresponding distribution of individual demand (entry) prices for the blended fuel, α. Third, we combine for a demand curve estimate—individual vehicle entry prices are ranked, assigned a share of total demand, and cumulated for a demand estimate. The demand function, obtained with quantitative methods, is summarized by a price dependent function:

$$P\alpha^r = f(Q\alpha; Pg^r, T), \tag{3}$$

where Qα is the retail quantity of blended fuel with concentration α. Also T is the automobile technology, which defines the set of fuel substitution rates.

The retail supply analysis for blended fuel has two main assumptions. First, the retailer sells blended fuel in the retail market. In the wholesale market, he buys component fuels and blends them. The products purchased by the retailer on the wholesale market are straight gasoline, g, with price Pg, in \$/gal g, and nearly pure ethanol, e, with price Pe, in \$/gal e. Then the fuels are blended with α units of pure ethanol and 1-α units of straight gasoline. Hence, the retailer pays

$$P\alpha = \alpha\, Pe + (1-\alpha)\, Pg \tag{4}$$

in the wholesale market for a gallon blended fuel with concentration α.

Second, the blended-fuel supply price on the retail market is the sum of the implied wholesale price plus the margin for gasoline (M)

$$P\alpha^r = P\alpha + M \tag{5}$$

In effect, we invoke the small firm assumption for blended fuel in both the gasoline and ethanol market. As a first approximation, we use the gasoline retailing margin because the products are similar regarding handling and tax treatment.

Summarizing, Eqs. (3)–(5) combine for a market model with three endogenous variables: the wholesale price of blended fuel, Pα, the retail supply price of blended fuel, $P\alpha^r$ and the demand for blended fuel, Qα. For empirical analysis, data for exogenous variables, wholesale ethanol price (Pe), wholesale gasoline price (Pg), and the fuel marketing margin (M), are also required.[2] Finally, blended-fuel demand estimates require a distribution of fuel substitution rates across consumers, and the corresponding break-even entry prices into the blended fuel market.

3. Results and discussion

3.1. Fuel substitution rate estimation

Estimation of the technical rates of substitution of blended fuel for gasoline, or the fuel substitution rates (FSRs), requires an explanatory variable specification and an appropriate data set. First, the technical characteristics of vehicles and vehicle uses impinging on FSRs are identified. Second, a cross-section data set collected from public agency experiments with gasoline and blended fuel in several vehicles is reviewed. Third, results are presented and the properties of the FSR distribution are summarized.

3.1.1. Specification

Increasing ethanol content in a gasoline engine causes offsetting effects. On one hand, fuel economy tends to fall, owing to ethanol's lower heat content, but there is an offsetting increase in thermal efficiency (Stein, 2013, p. 484). Hence, the FSR regressions include three technical explanatory variables: ethanol concentration in the fuel, the engine's Break Mean Effective Pressure (bmep) with the baseline straight gasoline fuel, E0 or α=0, and the engine's displacement per cylinder ratio. bmep, which is proportional to the torque: displacement ratio, typically increases when ethanol is added because knock resistance improves (Stein, 2013, p. 475). A higher displacement per cylinder ratio is a means of increasing compression, an engine design modification that complements improved knock resistance (Stein, 2013, p. 476). Hence, existing engines with a higher displacement per cylinder ratio would likely perform relatively better than other vehicles with ethanol.

Also, we constructed an indicator of the driving conditions in a particular vehicle's test. Specifically, the ratio of a vehicle's fuel economy (miles/gallon) test result with the baseline E0 gasoline relative to the EPA's estimate for typical combined city and highway driving serves as a proxy for the extent of highway driving in a particular vehicle test. Values of unity likely reflect typical combined city/highway driving, values less than unity should occur when a particular vehicle is used mostly in an urban setting, and values greater than 1 occur when most driving occurs on a highway. Other results suggest that ethanol may perform better under engine load conditions typical in urban areas (Roberts, 2008, p. 1235). A typical specification is:

$$f\alpha_i = a - b\,\alpha_i + c\,E_i - d\,R_i + \varepsilon_i, \tag{6}$$

where

$f\alpha_i$ is the fuel substitution rate, in gal g/gal α,
α_i is the fraction of ethanol in the blended fuel, $0 \le \alpha_i \le 1$.

[2] The three equation model will likely result in a conservative assessment of market penetration by blended fuel and associated consumer benefit, compared to a large model with upward sloping supply schedules for ethanol and gasoline. The baseline prices for wholesale ethanol and gasoline used in Section 3 simulations reflect a high demand quota for ethanol. If a voluntary blend market cannot fully replace the mandated market, prices from the model with endogenous factor supplies would be lower for ethanol and higher for gasoline—both price adjustments would further encourage expansion of blended fuels.

E_i is an engine or vehicle characteristic
R_i is the ratio fuel economy of the baseline fuel to EPA city-highway fuel,
ε_i is a random disturbance term.

3.1.2. Data

Four sets of vehicle tests are combined in our sample. These tests represented technology and use conditions for the United States.[3] Combined, there is a cross-sectional sample with fuel substitution rates of blended fuel for gasoline with 182 observations: 48 from West et al. (2008); 25 from Shockey and Aulich (2007); 14 from Duddy (2012); and 35 from Kittelson et al. (2007). Manufacturers' technical data on engine characteristics with standard equipment for each vehicle tested was added. Also, fuel economy ratings with standard vehicle use and the baseline E0 fuel taken from EPA reports were included. Otherwise, regression variables and procedures account for differences among sample segments. For example, the mileage ratio variable can account for FSR differences between the combined city/highway cycle in some tests and/or the highway cycle in others.[4]

3.1.3. Results

The estimations suggest that ethanol concentration and the mileage ratio do explain variation in the fuel substitution rate. Furthermore, the engine characteristics variables, the displacement size ratio, and bmep, both had statistically significant effects. A typical result taken from several preliminary regressions is

$$f\alpha_i = \underset{(12.2)}{1.262} - \underset{(9.7)}{0.184}\,\alpha_i + \underset{(2.2)}{0.1463}\,\mathrm{dcr}_i - \underset{(2.5)}{0.0244}\,\mathrm{bmep}_i - \underset{(2.0)}{0.1209}\,\mathrm{mr}_i$$
$$R^2 = 0.236 \qquad \bar{s} = 0.0943 \qquad \bar{f}\alpha_i = 0.9406 \quad N = 182 \tag{7}$$

where

$f\alpha_i$ is the substitution rate of blended fuel, α, for gasoline $(0 < f\alpha_i < 1)$, in gal g/gal α,
α_i is the fraction of ethanol in the blended fuel, $0 \le \alpha_i \le 1$,
dcr_i is the displacement per cylinder ratio, in liter/cylinder,
$bmep_i$ is the break mean effective pressure, in BAR/liter[5]
mr_i is the ratio of fuel economy for the baseline fuel to EPA's city-highway fuel,
ε_i is a random disturbance term with zero mean,

and numbers in parentheses are t-values .[6]

Generally, the results suggest that engine design characteristics associated with improved mechanical efficiency, vehicle use, and (the heat content associated with) alternative ethanol concentrations all have an effect on the FSR. First, ethanol concentration (α) has a negative effect. Also, higher displacement per cylinder increases fuel substitution, possibly due to reduced friction. Apparently, engines with low bmep tend to have high fuel substitution using blends because they benefit more from ethanol's torque-increasing properties. Lastly, the vehicles tested with a low mileage ratio (baseline/EPA) have a high fuel substitution rate, because ethanol performs better under high-load urban driving conditions, which confirms other empirical results for fuels with higher ethanol concentrations (Roberts, 2008, p. 1235).

3.1.4. Testing Heat Content as the sole determinant of the Fuel Substitution Rate

Most economic market analysis assumes that relative heat content determines the FSR, and ignores mechanical efficiency of engines and vehicle use. One study assumed that the FSR between pure ethanol and the typical gasoline-based fuel in Brazil should be 0.7 gal fuel/gal pure ethanol (Salvo and Huse, 2013, p. 252).[7] (We calculate 0.74 for the Brazil fuel comparison.) Another recent study of fuel substitution in Brazil converted all variables into Gasoline Energy Equivalent Gallons (GEEGs) using relative heat content (Drabik et al. 2015, p. 1436). Roberts (2008), in a comparison of straight gasoline substitution for E85 in the US, noted that the average FSR is 0.734 with a range of 0.683–0.810 in their 24 observation sample. So far, all of these studies have compared straight gasoline or fuel with low ethanol concentration to pure ethanol or E85. The effects of engine heterogeneity and improving technology(mechanical efficiency) is not included in market analysis.

The purpose of this section is to test the validity of the GEEGs assumption for FSRs for the mid-level range of blended fuels. An F test based on Eq. (7) is workable, because the GEEG assumption leads to a constrained form of Eq. (7). Specifically, the heat content of ethanol is he=21.1 MJ/L of pure ethanol and the heat content of gasoline is hg=31.5 MJ/L of gasoline (Stein, 2013, p. 472). Then the FSR is:

$$f_{\alpha i} = \left[\left(\mathrm{he}\,\alpha + \mathrm{hg}\,(1-\alpha)\right)\mathrm{m_g}\right] / \left[\mathrm{hg}\,\mathrm{m_g}\right], \text{ or } f_{\alpha i} = 1 - 0.33\,\alpha. \tag{8}$$

We consider the null hypothesis of a heat-content-based FSR using a standard F test (Greene, p. 2774). Eq. (7) is the unconstrained regression. And Eq. (8) is a constrained form of (7), assuming that the heat content hypothesis holds, (i.e., there are five constraints: a=1, b=−0.33, c=0, d=0, and e=0). The calculated statistic is F=13.8, while the critical values for a 5% and a

[3] Two sets of the experiments are based on laboratory simulations of engine performance. And two sets of experiments compare actual road use with gasoline and ethanol in the same vehicle over time.

The laboratory experiments use test procedures from the DOE and EPA fuel economy ratings. A first set of tests span existing Auto technology (West et al., 2008). Simulations used the unified drive cycle (LA92) of the (EPA) using a dynamometer and equipment that monitors the chemical composition of emissions. Further, experiments include results for gasoline without ethanol (E0), 10% ethanol blend (E10), and 20% ethanol blend (E20). A second set of lab tests use EPA's highway drive cycle (HWEET) (Shockey and Aulich, 2007). Results are reported for a few recent popular car models. Also, experiments for each vehicle include a wide range of blends ranging from E0 to E40.

Both road tests compare E0 and E20 performance for fleet vehicles at a public institution. In particular, actual road tests are reported for Monroe County, NY's car, van, and light truck fleet (Duddy, 2012, p.20). Also, road performance for the vehicles used by the University of Minnesota in the Twin Cities is also reported (Kittelson et al., 2007, p. 44). The U of M sample extends the range of light trucks. A wide range of driving conditions is also likely included in the U of M sample, by including intermediate-size single unit trucks, city intensive driving, and low temperature driving.

[4] In the past, some have questioned the accuracy of laboratory tests. But now lab tests are reasonably accurate and suitable for comparisons across straight gasoline and blended ethanol fuel. See Appendix B.

[5] A standard formula computes BMEP from available engine specifications (RETM Staff, 2012). Specifically, bmep=(150.8 torque)/displacement)/14.5, where torque is measured in lb-feet, and displacement is measured in cubic inches. Division by 14.5 converts the BMEP value to BAR, or number of standard atmospheres of pressure.

[6] The t-values in Eq. (7) are heteroscedasticity corrected values. We used a standard correction procedure (White, 1980). The SAS regression procedure provided calculations. In general, least squares estimates with adjusted standard errors are preferable because there is a risk of taking a step backwards with a misspecification (Greene, 2000, p. 522). Results that are similar to Eq. (7) with heteroscedasticity correction are discussed in Appendix C. However, these estimates placed less weight on the actual road test observations and more on the simulation observations. Thus, Eq. (7) is used in further analysis.

[7] They also assumed that the ethanol fuel quantity is an argument in the consumer's utility function. We disagree, unless she drinks pure ethanol instead of putting denatured ethanol in the fuel tank. Generally, fuel is a means to an end for a household. Consumer behavior can be more usefully explained as cost management. Fig. 1 is a good place to start an analysis.

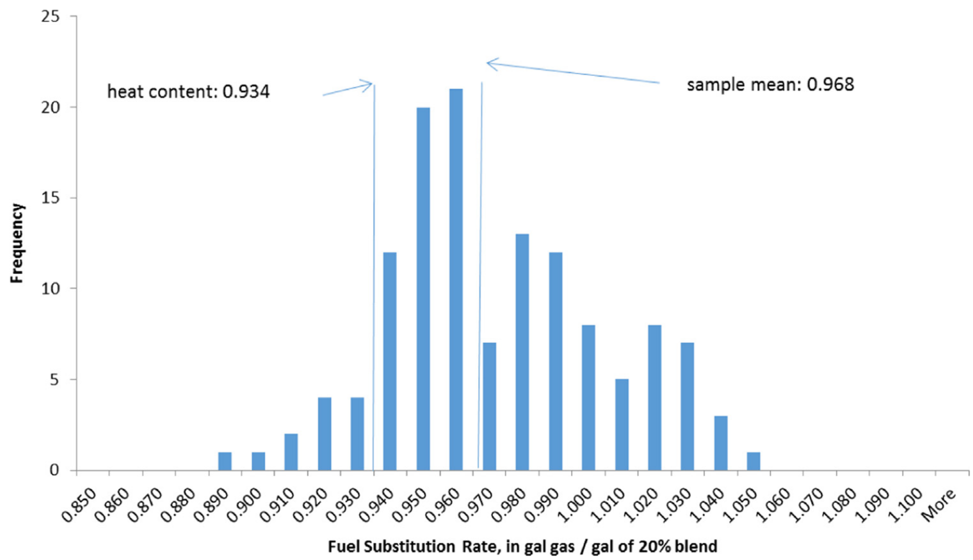

Fig. 2. Histogram for fuel substitution rate estimates($f\alpha_i{}^*$).

1% test are Fc=2.21 and Fc=3.04, respectively. Hence, the strict heat content hypothesis should be discarded for analyses that focus on mid-level blends and account for variation in engine efficiency and vehicle use.

Hence, the design of a specific vehicle, its driving conditions, and the blend choice determines the FSR value for a particular household. Further, an FSR estimate from an individual experiment also represents the average FSR when many vehicles with the same design in several households face similar driving conditions and make the same ethanol blend choice.

The histogram in Fig. 2 uses regression predictions, $f\alpha_i{}^*$, for the sample to indicate the range and frequency of FSR outcomes in the automobile fleet of the US. The substitution rates for E20 are shown in Fig. 2. About 10% (20/129) of the experiments tested at or below the heat content value of 0.934 gal g/gal E20. The remaining 80% of experiments tested better than heat content. And 19% of vehicles had FSR's that were slightly better than 1.0. The FSR histogram can approximate the range and frequency of fuel substitution possibilities when there is large scale substitution of intermediate blends, because the vehicles and driving conditions in the experiment represent US households.

3.2. Market adoption of mid-level ethanol blends

Consider simulation of cost-minimizing consumers in a voluntary market adopting mid-level ethanol blend fuel instead of straight gasoline when given favorable prices and substitution rates. We use the market model described by Eqs. (3)–(5). The demand and price curve combines FSR estimates with a recent baseline of US market conditions.

Blended fuel demand curves are calculated in four steps. First, the gasoline-blend breakeven point is calculated for each vehicle. Second, the breakeven points are ranked from highest to lowest according to their blended fuel price. Third, vehicle miles traveled for each vehicle is divided by its fuel economy for the fuel demand that enters the E20 market at a particular price. Fourth, the entry prices are cumulated, thus including the E20 entry at or above a particular price.

Our simulation compares E20 (20% ethanol, $\alpha=0.2$), to straight gasoline ($\alpha=0$). As a practical matter, most of publicly available experiments underlying Eq. (7) included an E20 vs. straight gasoline, or E0, comparison, so the E20 comparison is solidly within the range of the FSR estimations.[8] As a policy matter, the range of E0 to E20 extends well beyond the existing demand quota for ethanol at about 10% of fuel use defined by existing US policy.[9] Hence, simulations allow for the possibilities of declining, maintaining, or growing beyond the 'blend wall' in a voluntary market.

Recent Iowa market conditions define the baseline for fuel prices and margins. Iowa is the largest ethanol-producing state. Consequently, wholesale prices for denatured ethanol represent supply point prices. Also, local Iowa regulations allow consumers to choose straight gasoline or ethanol blended fuels.[10] Consequently, retailers offer two types of regular grade (87 octane) gasoline: one without ethanol and one with 10% ethanol. The no-ethanol regular grade of gasoline is the reference price for straight gasoline in the simulation experiment. Finally, Iowa uses conventional fuel, so prices and margins are not distorted by the blending regulations associated with the reformulated fuel program of highly populated urban areas.

Estimated fuel substitution rates, on par or slightly below gasoline, are a very conservative representation of existing technology. Most of the cars in the publicly reported experiments were produced between 2000 and 2007. But operating cars older than 15 years represent only 8% of today's US fleet, and cars older than 10 years represent only 35% of the fleet. Newer cars likely have FSR's towards the top of our estimated

[8] In the engineering literature, an optimal ethanol blend is discussed, and some believe that it is about 30% ethanol. We tested the hypothesis in preliminary analysis, but did not find evidence supporting it. Our sample only included a few observations in the $\alpha=0.3$ neighborhood—perhaps our sample was not good enough to uncover an optimum.

[9] Mandatory minimum ethanol blending proportions in gasoline from the Renewable Fuel Standard (RFS) require 15.0 Billion gallons for 2015 (Congressional Record, 2007, p. 1522). Further, US gasoline fuel consumption in 2014 was 136.7 BGY (EIA Staff, 2015a). Manufacturers' 10% limit on ethanol in gasoline for most automobiles may soon define an ethanol blending requirement below 15.0 billion gallons.

[10] Regulations vary from state. In Minnesota, for instance, a 10% ethanol blend is required for all automobile road use fuel. But straight gasoline is available at a few stations—use of this fuel is limited to lawn mowers, outboard motors, and chain saws.

Table 1
Data for the US fuel and vehicle baseline for 2013.

Item [Symbol]	Units	By vehicle size		Total US
		Small	Large	
(1)Fuel Use [Qα]	billion gallons	88.611	46.659	138.270
(2) Fuel economy [e]	miles/gallon	23.411	14.295	
(3)Miles Traveled [M]	billion miles	2074.458	709.895	2784.353
(4)Number of Vehicles [V]	billion vehicles	0.185[Vs]	0.059[Vl]	0.244
(5)Average Distance Traveled [T]	miles/vehicle	11,213 [Ts]	12,032 [Tl]	

range. For instance, one 2015 model car gets the same mileage when ethanol blend concentration is increased twenty percentage points (Appendix D). Furthermore, the straightforward redesign of existing automobile engines for mid-level blend use can be taken into account. Specifically, a 2013 model Ford Eco-Boost engine redesigned with increased compression improves the FSR for E20 (Jung, 2012. p. 431). Accordingly, we also present a demand curve that is associated with engine redesigns for improved FSR.

3.2.1. Baseline

3.2.1.1. Quantity. An identity combines vehicle use patterns for the US with corresponding FSR's for blended fuel:

$$Q\alpha_i = T_i V_i / e_i \tag{9}$$

where $Q\alpha_i$ is the quantity of blended fuel used by vehicles of type i (in bill. Gallon), T_i is the average distance traveled (in miles per car) for vehicles of type i, V_i is the number of vehicles of type i on the road (in billions), and e_i is fuel economy (in miles per gallon)

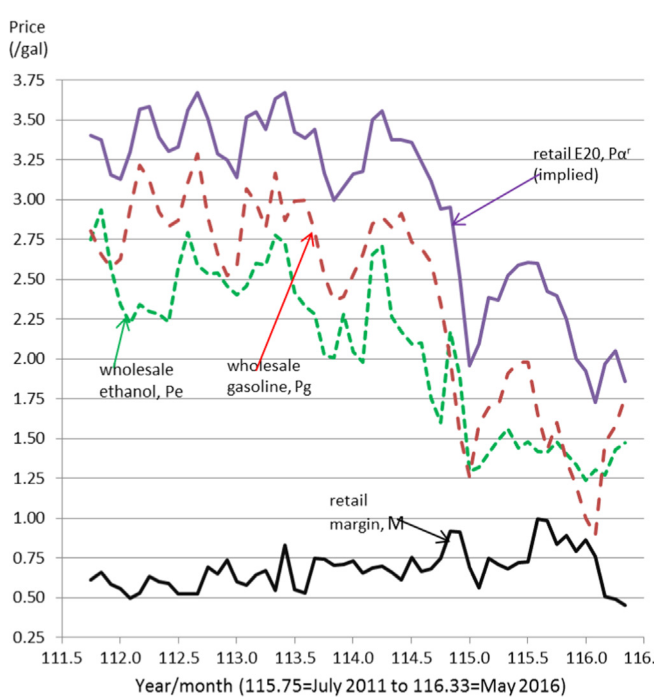

Fig. 3. Iowa fuel prices and margins, Oct 2011 through May 2016.

for vehicle type i when using blended fuel. First, we assume that the vehicles in our sample are representative of the vehicles on the road in the US, and assign each vehicle type an equal share of vehicle numbers in the US. Second, we assume that miles traveled per vehicle are the same for all vehicles in the same group. Third, we calculate fuel use for each vehicle type with an experiment's fuel economy result, adjusting for blended fuel using the FSR regression.

To arrive at the quantity of fuel used in the United States, we also distinguish between two vehicle types. We included 129 vehicle types from the FSR study, classifying 85 as small and 44 as large. We distinguish between large vehicles and small vehicles because the fuel economy and miles traveled per vehicle differs widely between these two groups. Hence, the baseline quantity of fuel for the US is

$$Q\alpha = \Sigma_{i=1}^{44} T_l V_i / e_i + \Sigma_{j=1}^{85} T_s V_j / e_j (10), \text{ where } V_j = V_l/44 \text{ and } V_j = V_s/85$$

The first set of terms refers to large vehicles and the second set of terms refers to small vehicles. Vehicle miles and miles per vehicle are assigned from the DOT data by defining short-wheelbase light vehicles as small. Large vehicles included long-wheelbase light vehicles, and single unit intermediate size trucks. However, combination trucks were excluded because they use mostly diesel fuel and were not in the FSR estimation.

Data for 2013 summarized in Table 1 is used for the quantity baseline. It gives miles traveled, vehicle numbers, fuel consumption, and fuel economy by vehicle size (DOT Staff, 2013). From row 4, 0.185 billion small vehicles (Vs) used 88.611 billion gallons (row 1) and 0.0596 billion large vehicles (Vl) used 49.61 billion gallons of fuel. The total of 138.3 billion gallons (Qα) roughly corresponds to recent estimates of gasoline consumption in the United States. From row 5, small vehicles traveled an average of 11,213 miles/vehicle (Ts) and large vehicles traveled an average of 12,032 miles/vehicle (Tl). From row 2, average fuel economy differs significantly, 23.4 miles/gal for small vehicles and 14.3 miles/gal for large vehicles. For calibration, a proportional correction factor was applied to fuel economy observations for individual experiments within a group (large or small) that aligned the average from experiments with aggregate data in Table 1. Then subsequent simulations rank blended fuel by vehicle type, $Q\alpha_i$, according to FSR's and breakeven entry points into the blended fuel market.

3.2.1.2. Prices. In Iowa wholesale markets, ethanol prices have usually been less than straight gasoline prices (Fig. 3), a preliminary indication that blended fuels are competitive. The blended fuel supply price for the simulation baseline combines average prices and marketing margins from the last five years, October 2011 to September 2015.

Iowa Fuel Price data comes from several sources. Retail and wholesale fuel prices are published by the Iowa Department of Agriculture and Land Stewardship (IDALS Staff, 2015). Wholesale gasoline (spot) prices are reported by the EIA (EIA Staff, 2015c). Wholesale Ethanol prices from Iowa are reported by the US Dept. of Agriculture (AMS Staff, 2015).

The retail supply price for blended (E20) fuel is $P\alpha^r$=$3.18/gal. One component is the weighted average wholesale price of blended fuel, $P\alpha$=$2.48/gal, which is calculated as the blend-weighted average of wholesale prices for ethanol, Pe=$2.18/gal and gasoline, Pg=$2.55/gal, and α=0.2.

The retail gasoline price of regular gasoline for simulation, the breakeven point reference for blended fuel, is Pg^r=$3.22/gal. It is calculated as the five-year average of published retail gasoline price data for regular gasoline without ethanol. Also, the gasoline marketing margin is the difference between the retail price and

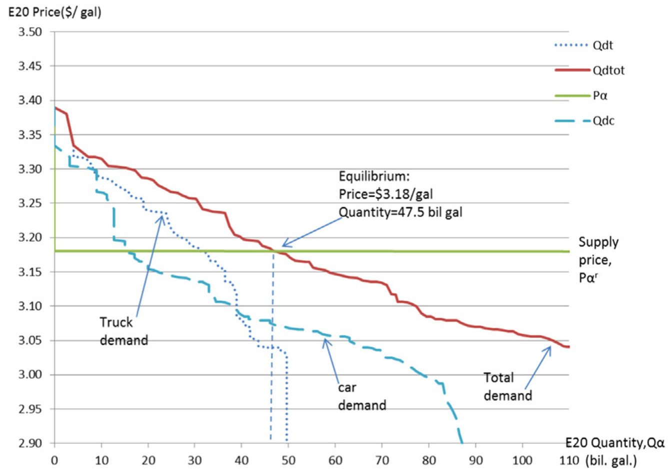

Fig. 4. Demand and supply price for E20 (α=0.2): baseline for market conditions and technology.

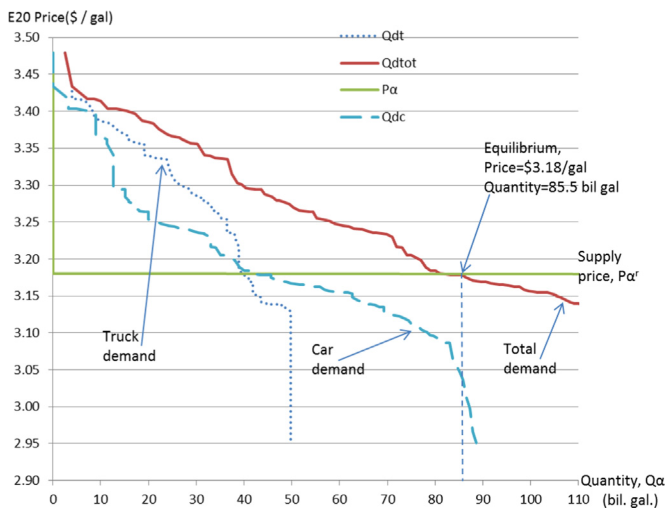

Fig. 5. Demand and supply price for E20: baseline market conditions and newest technology.

the wholesale price of straight gasoline. The five-year average value for the gasoline margin is $0.67/ gal.

The marketing margin for E20 includes an allowance for the amortized cost of new pumps for blended fuel. First, a new pump and tank would cost $97,935 (Moriarty et al., 2014, p.viii). Second, a typical gasoline retailing station sells 1.46 mill. Gallons of fuel/ year (NACS Staff, 2013, p. 2). So the capital outlay is $.54/gallon, for a typical gas station with eight pumps.

Amortizing over a 30-year equipment lifetime, and using current interest rates of 4% for an equipment loan, gives an annual equipment loan payment of $.03/ gallon. Hence, our estimate of the retail margin for a new blended fuel is M=$0.70/ gal.[11]

[11] If interest rates doubled to 8%, then the annual equipment payment would increase to $.0503/gallon, from$.0344/gallon. So the blended fuel supply price in Fig. 5 increases to $3.20/gallon instead of $3.18/gallon. In turn, total market demand declines somewhat to 77.0 billion gallons instead of 82.2 billion gallons. Similarly, total market demand declines by 4.5 billion gallons in Fig. 4.

3.2.2. *Engine redesign*

In the intermediate run, auto manufacturers could revise engine specification for performance with higher ethanol concentrations. We estimate more favorable FSR's for blended fuel. Specifically, we adjusted the engine design variables one standard deviation in the direction of reduced fuel economy loss. The variable dcr was increased by 0.754 l/cylinder. Also, the variable bmep was reduced by 0.621 bar.[12]

3.2.3. *Market effects*

Fig. 4 summarizes the results for typical market conditions. Demand by large vehicles or trucks (Qdt), by small vehicles or cars, (Qdc), and combined demand (Qdtot) are given. The large vehicles enter first at prices slightly above the gasoline price. With a blended-fuel supply price of $3.18/gal, total market demand is 46.7 billion gallons of blended fuel, about 15.8 billion from the car market and 30.9 billion from the truck market.

In the intermediate run, auto technology would likely adapt to blended fuel. Fig. 5 depicts the gasoline market with the technology improvement. With a blended-fuel supply price of $3.18/ gal, total market demand is 82.2 billion gallons of blended fuel, about 42.3 billion from the car market and 39.9 billion from the truck market.

3.2.4. *Welfare gain*

Surpluses calculated as the area below the demand curves of Figs. 3 and 4 and above the supply price line indicate US consumers' stake in intermediate ethanol blends and related technology. If an E20 price of $3.18/gallon prevails, the demand for E20 is 46.7 billion gallons with existing technology. The consumer surplus for the total demand of Fig. 4 is $1.8 billion. In the longer run, the demand will shift to 82.2 billion gallons if technology adapts to blended fuels. Then the consumer surplus for the total demand curve of Fig. 5 is $15.9 billion. The technology change is worth the change in surplus to consumers: $14.1 billion.

3.2.5. *How long will these adjustments take?*

Generally, fuel qualities and material characteristics of vehicles must change simultaneously. For instance, catalytic converters in autos required a lead ban in fuel because leaded fuel wrecks the converter. After a decade, most autos had converters and used unleaded fuel. Before then, both types of fuel were available-leaded fuel for old cars and unleaded fuel for new cars.

In the case of E15, an industry study found that most vehicles manufactured before the regulation were compatible with E15. However, a few engines had problems such as pitted valves due to relatively lower grade metal (CRC Staff, 2012, p. 11). Several auto manufacturers opposed intermediate blends at that time (Sensenbrenner, 2011). But major American manufacturers approved E15 for warranty coverage on new vehicles—Ford beginning in 2010, GM beginning in 2012 (OPIS Staff, 2012). Some other major manufacturers have followed.

The fraction of E15-compatibile vehicles indicates the share of the fuel market with the potential to substitute between gasoline

[12] The hypothetical redesigned engines increase estimated FSRs by an average of 3.0%. For comparison, we calculated the implied increase in the FSR from an experiment with a 2013 model Ford, increasing the ethanol concentration and increasing the compression at the same time (from 10:1 to 11.9:1) – we obtained a FSR increase of 3.7%. Hence, the hypothetical engine redesign may be a conservative assessment of the potential to adapt the technology to mid-level blends.
For sensitivity analysis, we adjusted the engine design variables two standard deviations (instead of one) in the direction of reduced fuel economy loss for the redesigned engine scenario, giving an average FSR increase of 6.2%. Then the total market for blended fuel would be 109.0 bill gallons (instead of 85.5 in Fig. 5). Also, the consumer welfare increase is $20.7 billion (instead of $15.9 billion).

and blended fuel, possibly defining the length of the transition period. For an estimate, we used a recent vehicle age distribution estimate (Davis, et al., 2012, p. 3-12). Thus, 84% of vehicles would satisfy the EPA criteria in 2015, and 100% in 2020. Using a new car warranty criteria, the adjustment process would be somewhat slower. For an initial estimate, post-2011 vehicles account for 25% of vehicles in 2015, they will account for 50% in 2020, and 80% in 2025.

But there are considerable political-economic forces influencing E15 standard setting. For instance, auto manufacturers' positions are consistent with strategic behavior for profit advantage. Major domestic manufacturers could improve sales in their main market by accommodating the E15 standard. But some foreign manufacturers may actually be concerned about the cost of meeting a strict material standard for their small share of the US market. Also, a compatibility demonstration for E15 could invite an extension of refiners' ethanol blending regulation. In fact, ethanol producers requested that the EPA consider legalizing E15. The oil industry generally opposes E15 because they may face a loss in the gasoline market.

In the event that E15 for conventional vehicles dies in a court fight , voluntary adoption of FFV's for mid-level blends, such as E20 or E30, is still possible. For an upper limit of the adoption rate in the voluntary scenario, use the age distribution estimate again; 6.8% of vehicles are FFV's in 2015, 37% of vehicles would be FFV's in 2020, and 66% of vehicles would be FFV's in 2025. However, there must be economic incentives for FFV adoption, or nothing would happen.

4. Conclusions and policy implications

Ethanol-blended fuel with intermediate concentrations such as E20 (20% ethanol concentration) is a good substitute for straight gasoline. FSR estimates suggest that E20 substitutes for gasoline above the heat-content rate of 0.934 gallons of gasoline per gallon of blended fuel for almost all (88%) of the cars in our sample representing auto technology introduced in the last decade. Further, the substitution rate is at one-for-one or higher for 20% of these vehicles, for new vehicles, and especially for redesigned vehicles with adoption potential in the near future. Vehicles with higher FSRs have engine design and vehicle use characteristics that offsets the decline in heat content associated with increasing ethanol concentration. Economic and environmental analysis of ethanol substitution for fossil fuel should focus to intermediate blends such as E20 instead of E85 or E100-substitutions are near one gallon of ethanol for one gallon of gasoline instead of 1.3 gallons of ethanol for 1 gallon of gasoline, fundamentally changing analyses of competiveness and environmental benefits.

Because there is a range of FSRs for existing vehicles, efficient households that minimize the operating cost of their vehicles will adopt blended fuels over a range of relative prices for straight gasoline and blended fuel. Simulations for the range of existing vehicles and typical market conditions of the last five years for a hypothetical E20 market suggest demand of 46.7 BGY of blended fuel with a net annual welfare gain for consumers of $1.8 billion. Further, a blended fuel demand of 82.2 BGY with consumer welfare gain of $15.9 billion with adoption of the new vehicle technology that improves the FSR. There are incentives to adopt improved blended fuel technology. The consumer saves $800 to $1200 over the life of a vehicle. Further, the manufacturer cost for ethanol-compatible equipment is only $200/vehicle (Consumer Reports Staff, 2011, p.2).

Blended fuel demand would sustain substantial ethanol input demand. Specifically, the implied ethanol demand would be 16.4 BGY, if the blended fuel demand of 82.2 billion gallons of E20 is realized. That is, ethanol market demand would be slightly larger than the RFS mandate for corn ethanol use in the US.

It is time to replace the RFS for corn ethanol with a free market. Four decades of public support are enough, especially since the industry has gained a solid competitive position now.[13] Further, standards policies that specify minimum consumption levels generally suffer from the "Green Paradox." That is, standards policies for minimum renewables accelerate fossil fuel use in the present, and offset the benefits of renewables (Sinn, p. 186–187).[14]

Some biofuels interventions are still worthwhile. First, an aggressive competition policy in the fuel marketing system is needed, or else the oil industry's control may preclude entry of ethanol blended products. Second, support for biomass power in corn-ethanol production further improves the energy and carbon balance for this established industry. Third, the possibility of reduced carbon emission and the short-sighted nature of commercial decisions justifies support for the US biomass ethanol industry. In light of the Green Paradox issues, a subsidy or exemption from a carbon tax is likely a better policy than a standard, as long as commercial production improves.

Funding

Partial financial support for this project was provided by the Agricultural Experiment Station at Iowa State University and by Cooperative Agreement #58-0111-13-005 between Iowa State University and the U.S. Department of Agriculture.

Acknowledgment

Thanks to Nathan Cook for editing the manuscript.

[13] Getting to a free market would require repeal of the RFS. Transition programs would be needed to move from the RFS to a competitive gasoline/blended ethanol free market. A gradual phase out would be least disruptive.

The first transition component would be a standard for new vehicles that can use gasoline or mid-level ethanol blends. There are three relatively low cost alternatives: (a) pre-existing E15 compatibility on new US vehicles could be required by other manufacturers; (b) Brazil's E20 compatibility standard could be extended to the US; or, (c) E85 compatibility could be the standard or a substitute standard. The standard choice should be guided by the lowest net cost for consumers after accounting for fuel cost savings and incremental capital cost for vehicle equipment.

The second component would ensure consumers have a choice between gasoline and blended fuel at retail stations. Thus far, blended fuel has been mostly limited to independents, grocery stores with fuel retailing operations, and farmer cooperatives.

A transition program may be needed to ensure availability of blended fuel and gasoline matches the growing stock of FFVs. A legal framework precluding refiners from denying blended-fuel retailers access to wholesale gasoline may be necessary, or a quota requiring retailers to provide blended fuel could be useful.

Third, consumers should have information about benefits and consequences of using blended fuels or gasolines, such as fuel economy performance reports that include a mid-level blend and fuel-based vehicle maintenance differentials published by manufacturer and model.

[14] Some recent empirical studies suggest that ethanol substitution in the US must carry a large inherent GHG reduction to offset increased petroleum production and consumption associated with the Green Paradox and market rebound effects (specifically, see Grafton et al., 2014 and Hill et al., 2016). Both studies may overestimate ethanol's GHG reduction threshold. Hill, et al. assume that ethanol substitutes on a heat content basis—inappropriate for mid-level blends—and Grafton et al. (2014) may overestimate the statistical relationship between ethanol and oil production in the US.

Appendix A

Consider a revision of Huffman's model (p. 467) to include two operation inputs for a capital good. Suppose there are household goods, Z_1 and Z_2 , and a utility function, $U=U(Z_1, Z_2, L)$, where L is hours of leisure time.

The household production function, expressed as a transformation function, defines the tradeoff between the two household goods, given the levels of purchased inputs, X_1 and X_2. The purchased inputs are transformed into household goods as :$Z_1=F[Z_2, t, , X_1, X_2)$.

Also, t represents hours of housework. For our application, one of the household goods, say Z_1 "transportation services", which requires inputs, X_1, say, gasoline, and X_2, say blended fuel.

The household's full-income-expenditure-constraint defines the household's income, housework, leisure tradeoff, $Y=W L+W t-P_1X_1-P_2X_2$, where Y is potential income, W is the market wage, and P_i are the input prices.

The Lagrangian for the household's utility maximization problem is.

$L=U(Z_1, Z_2, L)+\lambda_1 [Y-(W L+W t-P_1X_1-P_2X_2)]+\lambda_2[Z_1- F(Z_2, t, , X_1,X_2)]$. The first order conditions are:

$$\frac{\partial \mathcal{L}}{\partial t}=-\lambda_1 W + \lambda_2 f_t=0 \tag{a.1}$$

$$\frac{\partial \mathcal{L}}{\partial X_1}=-\lambda_1 P_1 + \lambda_2 f_{X_1}=0 \tag{a.2}$$

$$\frac{\partial \mathcal{L}}{\partial X_2}=-\lambda_1 P_2 + \lambda_2 f_{X_2}=0 \tag{a.3}$$

$$\frac{\partial \mathcal{L}}{\partial L} = U_L - \lambda_1 W=0 \tag{a.4}$$

$$\frac{\partial \mathcal{L}}{\partial Z_1} = U_{Z_1} - \lambda_2=0 \tag{a.5}$$

$$\frac{\partial \mathcal{L}}{\partial Z_2} = U_{Z_2} - \lambda_2 f_{Z_2}=0 \tag{a.6}$$

Solving (b) and (c) for λ_1, and rearranging, yields an equilibrium condition for the substitution between X_1 and X_1 :

$$\frac{\Delta X_2}{\Delta X_1} = \frac{f_{X_1}}{f_{X_2}} = \frac{P_1}{P_2} \tag{a.7}$$

Or, substituting, $X_1=Q\alpha$, $X_2=Qg$, $P_1=P_\alpha$, and $P_2=P_g$ for the gasoline: blended fuel substitution case,

$$-\frac{\Delta Q_g}{\Delta Q_\alpha} = \frac{f_{Q_\alpha}}{f_{X_g}} = \frac{P_\alpha}{P_g} \tag{a.8}$$

In the long run, vehicle and fuel substitution is variable. Then expenditures for the marginal unit of blended fuel balances the foregone expenditure on gasoline.

Appendix B

There may be some differences between the laboratory experiments and the road tests. The experiment removes variation in a wide range of driving conditions that influence a particular fuel economy observation, such as wind speed and direction, traffic, and individual acceleration and braking habits, through the use of a standard drive cycle. So one experiment produces one fuel economy observation for typical driving conditions, and replications should reflect only measurement error. In contrast, a road test observation allows driving condition variation, and relies on the average of several observations for a measure of fuel economy with typical driving conditions. The average is a good measure of fuel economy with typical conditions, because variability declines rapidly with a small sample. Nonetheless, random variation for road tests could be higher than random variation for lab experiments, because road tests do still include driving condition variation. Subsequently, we test for heteroscedastic regression disturbances.

Early EPA-style vehicle tests had substantial bias (Lovell, 1986, p. 120). Now, however, laboratory experiments are likely suitable for fuel comparisons. Specifically, a regression of actual fuel economy (A_i) and forecast of fuel economy (F_i) for 2015 model cars gives:

$$\begin{gathered} A_i = \underset{(0.75)}{0.0698} + \underset{(30.6)}{0.9339}F_i \\ \bar{R}^2 = 0.88 \qquad \bar{A} = 22.5 \qquad s = 1.67 \\ (\text{tstatisticsinparenthesis}) \end{gathered} \tag{b.1}$$

where A_i is actual fuel economy in a road test for model i, in mi/gal, and F_i is the forecast of fuel economy for vehicle i, in mi/gal.

Road test data comes from a consumer products testing association (Consumer Reports, 2015). The simulation forecast is provided by the US Government (DOE and EPA Staff). An unbiased predictor has a zero intercept and a slope coefficient of one, and efficiency requires a high R^2. The intercept is very small and not statistically different from zero. The slope magnitude is close to one, but statistically, it is less than one. Together, these results imply that there is a moderate and constant upward bias in the forecasts of 6.4%.

Constant percentage bias is favorable for measurement of the FSR. The FSR is calculated as the ratio of two fuel economy observations. Both measurements are multiplied by the same constant bias correction. So an accurate FSR measurement is not dependent on bias in fuel economy measurement when there is constant bias.

Appendix C

Testing Heteroskedasticity:

The sample is easily partitioned into group 1 (lab tests) and group 2 (road tests). The regression has disturbance term ε_1 with standard deviation σ_1 in group 1 and disturbance ε_2 with standard deviation σ_2 for group 2:

$$Y_i = \alpha + \beta X_i + \varepsilon_{1i} \text{ for } i = 1, \ldots, n_1 Y_i = \alpha + \beta X_i + \varepsilon_{2i} \text{ for } i = 1, \ldots, n_2 \tag{c.1}$$

where $n_1$and n_2 number of observations in each group. The null hypothesis of the Goldfeld-Quandt test is H_o:$\sigma_1 = \sigma_2$. The F statistic is based on the grouped regression residuals:

$F = \frac{s_2^2}{s_1^2} = \frac{\sum_1^{n_2} u_{2i}^2 / (n_2 - k)}{\sum_1^{n_1} u_{1i}^2 / (n_1 - k)} \cap\cup F(n_2 - k, n_1 - k)$ under H_o with k regressors (Greene, p. 509). For the sample at hand, the standard deviation in group 2 is $s_2 = 0.115$, and the standard deviation in group 1 is $s_1 = 0.043$. Hence, the test statistic F=7.15 with $n_1 = 73$, $n_2 = 109$, and k=3. The null hypothesis is rejected at one percent significance (Fc=1.7), and at five percent significance (Fc=1.45). Hence, the variance of road test residuals is likely larger than the variance of lab experiment residuals.

For Generalized least squares (GLS) estimates, we apply a variability index divisor to the group 1 observations : $Y^*_i = Y_i / v_i$, $I^* = 1 / v_i$ and $X^*_i = X_i / v_i$. To see this, suppose that scaled disturbances (η_i) are obtained from the group 2 disturbances ε_{2i} with standard deviation σ_2 for group 2: $\eta_i = k\, \varepsilon_{2i}$, for i=1,…,n_2. Then the standard deviation of the scaled group 2 observations is related to the standard deviation of the group 2 observations as follows: $\sigma_\eta = k\, \sigma_2$. Now suppose k is chosen so that $\varepsilon_{1i} = k\, \varepsilon_{2i}$. Then $\sigma_1 = k\, \sigma_2$, or $k = \sigma_1 / \sigma_2$.

Multiplying both sides of the group 2 regression by k yields: $k\, Y_i = \alpha\, k + \beta\, k\, X_i + k\, \varepsilon_{2i}$ for i=1,…,n_2.

Hence, the stacked regression, $Y_i = \alpha + \beta\, X_i + \varepsilon_{1i}$ for i =1,…,n_1.

$Y^*_i = \alpha\, I^* + \beta\, X^*_i + \varepsilon^*_{1i}$ for i =1,…,n_2, where $Y^* = (\sigma_1/\sigma_2)\, Y_i$, $I^* = \sigma_1/\sigma_2$, $X^*_i = (\sigma_1/\sigma_2)\, X_i$, and $\varepsilon^*_{1i} = (\sigma_1/\sigma_2)\, \varepsilon_{2i}$, gives GLS estimates with constant disturbance standard deviation, σ_1 , for both groups. Further, the disturbance variance is the variance associated with diverse driving conditions excluded.

Then the transformed group 1 data is stacked on the group 2 data for a combined regression. The (v_i) index divisor ensures that the transformed group 1 observations and group 2 observations have the same disturbance variance. The variability index is calculated from the sample standard deviations of residuals from least squares residuals $v_i = (s_2/s_1) = 2.668$.

The stacked FSR regression has four independent variables. So each variable is divided by the variability index. The results from this estimation are:

$$f\alpha_i/v_i = \underset{(1.3)}{1.13371}/v_i - \underset{(8.7)}{0.2407}\alpha_i/v_i + \underset{(3.5)}{0.1532}\mathrm{dcr}_i/v_i - \underset{(2.0)}{0.0172}\mathrm{bmep}_i/v_i - \underset{(1.6)}{0.0600}mr_i/v_i$$

$$R^2 = 0.458 \qquad \bar{s} = 0.045 \qquad \bar{I}/\bar{v} = 0.0397 \qquad N = 182 \tag{c.2}$$

The GLS estimate still suggests that the same systematic variables, vehicle design, driving conditions and ethanol content choice, have an effect on the fuel substitution rate. The coefficients are somewhat smaller, possibly because the road test observations carry considerably less weight. Also, the road test observations may cover exactly the vehicles and conditions where the FSR is larger. Hence, the OLS estimates of Eq. (7) are used for subsequent analysis.

Appendix D

This appendix reports the fuel economy outcomes for a 2015 Chevy Equinox (4 cyl) that was driven on E10 and E30 in Minnesota between June 2015 and September 2015. The driving was split about evenly among rural highways, interstate highways and town driving. The fuel economy outcomes are:

e (mi/ gal)	Db (0/1)	Dg (0/1)
27.66	0	1
24.14	0	1
29.02	0	1
25.75	0	1
28.03	0	1
27.65	0	1
28.17	0	1
27.39	0	1
27.15	1	0
30.36	1	0
28.66	1	0
26.93	1	0

30.01	1	0
29.16	0	1
27.27	1	0
27.15	1	0
28.88	0	1
27.78	1	0

Variable Definitions:

e = fuel economy, in miles / gallon , $Db = \begin{smallmatrix}1, \text{ if E30 blended fuel is used} \\ 0, otherwise\end{smallmatrix}$

$Dg = \begin{smallmatrix}1, \text{ if E10 blended fuel is used} \\ 0, otherwise\end{smallmatrix}$

A regression from this data is $E = \underset{(.5232)}{28.164Db} + \underset{(.4680)}{27.585Dg}$, where $s = 1.48 mi / gal$

(standard errors of coefficients are in parentheses)

Under the null hypothesis that fuel economy is the same with either fuel, the statistic, $t=(27.585–28.164)/(0.52322+0.46802) = -0.579/0.4927 = -1.18$, follows the t distribution with 16 degrees of freedom. The critical values in a two tailed test are $t^{0.05}=2.12$, $t^{0.02}=2.58$, and $t^{0.01}=2.92$, at 5%, 2%, and 1% confidence, respectively. Hence, the null hypothesis is rejected for most significance levels-fuel economy is about the same with E10 and E30.

In fact, the calculated FSR for this vehicle is $f\alpha_i=28.164/27.585=1.021$ gal $\alpha=0.1$/gal $\alpha=0.3$. That is, it takes 1.02 gallons of E10 to replace 1 gallon of E30.

References

Agricultural Marketing Service (AMS) Staff, 2015. Iowa ethanol, corn and co-products processing values. USDA-MO Department of Agriculture, Market News Service, Saint Joseph, MO. ⟨www.ams.usda.gov/mnreports/NW_GR212.txt⟩.

Bryant, W. Keith, Zick, C.D., 2006. Economic Organization of the Household. Cambridge University Press, New York.

Congressional Record, 2007. Energy Independence and Security Act of 2007. 110th congress. Public Law 110-140. ⟨http://www.gpo.gov/fdsys/pkg/PLAW-110publ140/pdf/PLAW-110publ140.pdf⟩.

Consumer Reports Staff, 2015. New cars. Consumer rep. 80, pp.7–77.

Consumer Reports Staff, 2011. Ethanol (E85) fuel alternative, January. ⟨http://www.consumerreports.org/cro/2011/01/the-great-ethanol-debate/index.htm⟩,.

Coordinating Research Council (CRC) Staff, 2012. Intermediate-level ethanol blends engine durability study. CRC Project CM-136-09-1B, April, Alpharetta, GA. ⟨http://www.crcao.com/reports/recentstudies2012/CM-136-09-1B%20Engine%20Durability/CRC%20CM-136-09-1B%20Final%20Report.pdf⟩.

Davis, S.C., Deigel, S.W., Boundy, R.G., 2012. Transportation Energy Data Book, 32nd edition. Oak Ridge National Lab, Tennessee.

Drabik, D., DeGorter, H., Just, D.R., Timilsina, G.R., 2015. The economics of Brazil's ethanol-sugar markets, mandates, and tax exemptions. Am. J. Agric. Econ. 97, 1433–1450.

Duddy, B., 2012. RIT-CIMS/USDOT E-85 Fuel Economy Study, January 2011.

Elesland, S., 2015. American Coalition for Ethanol publishes map of blender pump locations. Ethanol Today, November 2, ⟨https://www.google.com/maps/d/viewer?mid=zZmWtgB0c9qM.kH3LCTH7xebc&hl=en_US⟩.

EIA Staff, 2015a. Petroleum and other liquids: supply and disposition, November 9, U.S. Energy Information Agency, U.S. Department of Energy, ⟨http://www.eia.gov/dnav/pet/pet_sum_snd_d_nus_mbbl_a_cur.htm⟩.

EIA Staff, 2015b. Annual energy outlook 2015. U.S. Department of Energy. (accessed 11.12.15), ⟨http://www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2015&subject=15-AEO2015&table=49-AEO2015&region=0-0&cases=ref2015-d021915a⟩.

EIA Staff, 2015c. Petroleum and other liquids: prices, November 2, U.S. Energy Information Agency, U.S. Department of Energy, ⟨http://www.eia.gov/petroleum/data.cfm#prices⟩.

Grafton, R.Q., Kompas, T., Van Long, N., To, H., 2014. US biofuels subsidies and CO_2 emissions: an empirical test for a weak and a strong green paradox. Energy Policy 68, 550–555.

Greene, W.H., 2000. Econometric Analysis. Prentice Hall, New Jersey.

Hill, J., Tajibaeva, L., Polasky, S., 2016. Climate consequences of low-carbon fuels: The United States Renewable Fuel Standard. Energy Policy 97, 351–353.

Huffman, W.E., 2011. Household production and the demand for food and other inputs: U.S. evidence. J. Agric. Resour. Econ. 36, 465–487.

Iowa Department of Agriculture and Land Stewardship (IDALS) Staff, 2015. Historic Fuel Price Reports, November 2. ⟨http://www.iowaagriculture.gov/agMarketing/IRFI/historicFuelPrices.asp⟩.

Jung, H., Leone, T., Shelby, M., Anderson, J., Collings, T., 2012. Fuel economy and CO_2 emissions of ethanol-gasoline blends in a turbocharged DI engine. SAE Int. J. Engines, 6. http://dx.doi.org/10.4271/2013-01-1321.

Kittelson, D., Tan, A., Zarling, D., 2007. Demonstration and driveability project to determine the feasibility of using E20 as a motor fuel Report submitted for publication to Minnesota Department of Agriculture.

Lovell, M.C., 1986. Tests of the rational expectations hypothesis. Am. Econ. Rev. 76, 110–124.

Moriarty, K., Kass, M., Theiss, T., 2014. Increasing biofuel deployment and utilization through development of renewable super premium: infrastructure assessment. National Renewable Energy Lab of the U.S. Department of Energy, Technical Report NREL/TP-5400-61684, November 2014. ⟨http://www.nrel.gov/docs/fy15osti/61684.pdf⟩.

NACS Staff, 2013. Modern gas station celebrates 100th anniversary. ⟨http://www.nacsonline.com/News/Daily/Pages/ND1126131.aspx#.VjfUiissCDk⟩.

Oil Price Information Service (OPIS) Staff, 2012. Ford and General Motors okay E15 blends for new vehicles. Oil price information service, October 2.

Perloff, J.M., 2011. Microeconomics. Addison-Wesley, Boston.

RETM Staff, 2012. Brake mean effective pressure (BMEP): the performance yardstick. Race Engine Technology Magazine. ⟨http://www.epi-eng.com/piston_engine_technology/bmep_performance_yardstick.htm⟩.

Roberts, M.C., 2008. E85 and fuel efficiency: an empirical analysis of 2007 EPA test data. Energy Policy 36, 1233–1235.

Salvo, A., Huse, C., 2013. Build it, but will they come? Evidence from consumer choice between Gasoline and sugarcane ethanol. J. Environ. Econ. Manag. 60, 251–279.

Sensenbrenner, S.J., 2011. Letter to EPA administrator Lisa Jackson, U.S. Congress, House of Representatives. ⟨http://sensenbrenner.house.gov/uploadedfiles/e15_auto_responses.pdf⟩.

Shockey, R.E., Aulich, T.R., 2007. Optimal ethanol blend-level investigation. Energy and Environment Research Center (University of North Dakota) and Minnesota Center for Automotive Research (Minnesota State University), Report 2007-EERC-11-02.

Sinn, H., 2012. The Green Paradox. MIT press, Cambridge.

Stein, R., Anderson, J., Wallington, T., 2013. An overview of the effects of ethanol-gasoline blends on SI engine performance, fuel efficiency, and emissions. SAE Int. J. Engines, 6. http://dx.doi.org/10.4271/2013-01-1635.

U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE), 2015. Fuel economy guide, November 2, 2015. ⟨http://www.fueleconomy.gov/feg/findacar.shtml⟩.

U.S. Environmental Protection Agency, 2015. E15: a blend of gasoline and ethanol. ⟨http://www3.epa.gov/otaq/regs/fuels/additive/e15/⟩.

U.S. Dept. of Transportation (DOT), 2013. Highway statistics. Office of Highway Policy, (⟨http://www.fhwa.dot.gov/policyinformation/statistics/2013/vm1.cfm⟩).

West, B., Knoll, K., Clark, W., Graves, R., Orban, J., Przesmitzki, S., Theiss, T., 2008. Effects of intermediate ethanol blends on legacy vehicles and small non-road engines, report 1. National Renewable Energy Lab and Oak Ridge National Lab, NREL/TP-540-43543 and ORNL/TM-2008/117.

White, H., 1980. A heteroscedasticity consistent covariance matrix estimator and a direct test for heteroskedasticity. Econometrica 48, 817–828.