Integrating Life Cycle Assessment and Choice Analysis for Alternative Fuel Valuation

By

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Working Paper 13 - 01

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ABSTRACT

We develop a framework for modeling the technological, economic, environmental, and social impacts of the life cycle of seven transportation fuels (Corn, Stover, Switchgrass, Yellow Poplar, Newsprint and Municipal Solid Waste Ethanol Blends, as well as Gasoline), by linking engineering based life cycle analysis of transportation fuels with choice analysis techniques for eliciting and understanding the social preferences for multi-attribute consumption vectors. The use of life-cycle data allows us to account for a broad range of environmental, natural resource, and health effects over the entire production and consumption life cycle of each fuel. Combining these life cycle and stated choice analyses allows for social preferences to be established for the externalities resulting from the use of the different transportation fuels. This results in a unique physical-economic feedback model allowing for improved design and evaluation of transportation policy. Our results indicate first generation biofuels, such as Corn E10 and Corn E85, actually result in a net increase in the value of environmental damage, natural resource use and human health risk relative to gasoline. After accounting for life cycle costs, these popular “alternative” fuel options offer little apparent environmental or health benefits, calling into question policies encouraging their adoption as “green” fuels. For policies with the intent of reducing foreign oil dependency and encouraging resource conservation, these same fuels may have merit. Most of the cellulosic, or second generation, biofuels have the potential to create a net improvement in environmental, natural resource, and human health impacts. Our results indicate significant trade-offs between environmental damage, human health risks and resource depletion rates will have to be made in any attempt to implement alternative fuel policy at a national level.

Submitted: 2012-05-16

Revised: 2013-08-02

Keywords: Life Cycle Impact Assessment, Choice Analysis, Fuel Valuation, Integration Techniques

JEL: Q42, Q48, Q51, Q53

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Highlights

- Corn ethanol fuels offer no benefit in environmental or health outcomes over gas
- Policies encouraging corn ethanol blends are likely inefficient.
- Cellulosic ethanol blends appear to offer potential improvements over gas
- Integrating LCIA and valuation techniques can lead to more comprehensive analysis

Introduction

Over the last two decades, the external impacts associated with the production and consumption of gasoline have gained increasing attention. This is in part due to the growing awareness of serious health effects resulting from its use, the environmental destruction often resulting from its extraction, national security issues and more recently, the role these fuels play in global climate change (Murphy and Delucchi 1998, Parry et al. 2007). Over the same time span, motor vehicle ownership and vehicle miles traveled in the United States have averaged annual increases of 1.8% and 2.5% respectively. These have, in part, contributed to the 32% increase in fuel consumption that has occurred since 1990 (BTS 2008, FHWA 2009). The serious side effects associated with gasoline consumption, combined with its increased use have subsequently generated significant interest in finding feasible alternative forms of fuel for gasoline's replacement.

Popular alternatives proposed as potential replacements include different ethanol fuel blends. Ethanol blends can be created from a number of different types of feedstock. In this study, several of these are examined including corn starch, corn stover, switchgrass, yellow poplar, newsprint and municipal solid waste. Most of these fuels are extolled as offering significant improvements over gasoline in regards to health, environmental, national security and/or climate change outcomes. Europe and the U.S. have mandated significant use of biofuels in part because they are seen as reducing greenhouse gas emissions (Melillo et al. 2009). In response, policy makers have offered generous incentives to aid in their development and production (Yano, Blandford and Surry 2010).

Yet evidence increasingly indicates these fuels may actually result in worse outcomes in many or all of these areas of concern. Analyses employing life cycle impact assessment (LCIA), in particular, have offered dissent about the positive impacts generated by these alternative fuels

(Baral and Bakshi 2010, Fargione et al. 2008, Hill et al. 2009, Kuusima and Powers 2009, Melillo et al. 2009, Searchinger et al. 2008, Tilman et al. 2006). For example, Hill et al. (2009) quantify and monetize the life cycle of a subset of impacts from transportation fuels, including climate change and health effects of greenhouse gases and particulate emissions. They estimate the total external costs to be 0.71 (\$2009) per gallon for gasoline and between 0.47 and 1.45 (\$2009) per gallon for corn starch ethanol. They also estimate external costs to be between 0.19 (\$2009) and 0.25 (\$2009) for cellulosic ethanol blends. Their analysis does not include certain key environmental impacts such as the effects from hazardous air emissions (NO_x, SO_x, and VOC), acidification, eutrophication, or habitat quality and quantity.

Kuusima and Powers (2010) build on this work by quantifying and monetizing the production life cycle of a larger set of impacts, including some of those missing from the analysis in Hill et al. (2009). They estimate the average external cost of corn starch ethanol to be 2.15 (\$2008) per gallon. They also estimate corn stover's external costs at 0.76 (\$2008) and switchgrass impacts at 0.37 (\$2008). Their analysis excludes the use phase of the life-cycle as only ethanol blends are compared and the use phase would be the same for each. Both of these previous studies utilized LCIA data combined with economic valuation to estimate the external impacts associated with fuels. They both valued component impacts individually and summed the results to arrive at an estimate for the external cost of the fuel. But, this sort of valuation is known to overestimate total economic value (Randall 1991).

In addition, neither analysis incorporated estimates on the impacts that indirect land use change (ILUC) from biofuel production may create. Indirect releases of greenhouse gases caused anywhere on the planet should be included in any analyses, because releases everywhere are mixed, and their warming effects are diffuse. They are caused by predictable responses of the

world's production system to the change in fuel demand and use (Hertel et al. 2010). Among the most important of these is the release of carbon dioxide when biofuels' demand for feedstock triggers a succession of land-use changes that cause forest and other ecosystems with high carbon stocks to be converted to cultivation (Searchinger et al. 2008).

Recent work in this area has shown ILUC impacts could be substantial. For example, Searchinger et al. (2008) find that corn starch based ethanol nearly doubles the impacts of greenhouse gas emissions, relative to gasoline, once ILUC emissions are taken into account. Hertel et al. (2010) similarly find that greenhouse gas emissions increase, but only by one-fourth the amount estimated by Searchinger et al. (2008) once market-mediated responses are taken into account (still enough to negate any greenhouse gas benefits associated with biofuels). Melillo et al. (2009) also find increases in greenhouse gas emissions from corn starch and sugarcane ethanol, as well as that additional pressure is put on biodiversity hot spots around the world as deforestation and land clearing occur to bring more land into biofuels production. These studies provide evidence of the importance of including ILUC values into any study assessing changes to fuel policy and associated environmental impacts, even though the exact nature of ILUC changes is still subject to a great deal of uncertainty. The primary focus of these studies was on the nature and magnitude of ILUC changes from biofuels production and did not incorporate the social preferences of individuals or how they value changes in the fuel mix as impacts of concern (such as changes in greenhouse gas emissions from ILUC) occur.

Since the early 1990's, methods have been continuing to develop that allow comparison between different products' life cycle environmental and economic impacts in a more integrated fashion. Frameworks such as EPS (Steen 1999), ExternE (EC 1995), LIME (Itsubo et al. 2004) and Eco-Indicator 99 (Goedkoop and Spriensma 1999), were created to aid in production process

decisions while taking into account the environment¹. The frameworks are all similar in nature, but aspects such as goal and scope of a study may make one more tractable for an analyst over another. Other characteristics that may influence the choice of methodology include its use of midpoint versus endpoint indicators, impact valuation technique (revealed versus stated preference), timeframe of analysis and the types of impacts to be examined in the study.

Itsubo et al. (2004), using the LIME framework, first demonstrated the capability of LCIA methods being coupled with conjoint analysis for valuation purposes. Their results show the feasibility of establishing weights across impact categories in an LCIA and generating reliable welfare results through the application of conjoint analysis as a means of establishing economic value. Their main objectives were to develop a damage-oriented impact assessment method for Japan, derive weights for indexes representing different social impacts and ultimately establish a willingness-to-pay (WTP) value for a unit change in the indexes on a national scale (without focusing on an individual product or service).

This study employs a similar approach to Itsubo et al. (2004) utilizing the Eco-Indicator 99 framework to couple LCIA and economic value analysis for six ethanol fuels, as well as gasoline. This framework is chosen over others for a number of reasons: first, it utilizes endpoint indicators that can be constructed from any LCIA and who's impacts are personally relevant to respondents; second, it has the flexibility to incorporate damage categories on the types of external impacts created by transportation fuels over their life cycle; and third, it allows valuation of fewer total endpoint indicators than other frameworks which reduces cognitive burden on respondents (three here as opposed to four in LIME and more in others).

This study aims to analyze a more comprehensive set of fuel damages than previously done, evaluate the entire life cycle of each fuel, allow tradeoffs between fuel attributes and

¹ For a complete description of the differences between these and other LCIA techniques see ILCD (2010).

between fuel types, as well as incorporate estimates of the indirect land use change impacts associated with biofuel production to establish the total economic value of external impacts associated with various ethanol feedstocks relative to gasoline. It contributes to previous cost estimates through use of a stated-choice analysis to estimate society's preferences regarding multiple types of environmental, natural resource, and health impacts caused over the production and consumption life cycle of fuels. It evaluates the external environmental, natural resource, and health impacts for each fuel, allowing for derivation of marginal prices (MP) for each category of impact. This benefit estimation is then directly linked to a scientifically constructed LCIA for the fuel types, preventing overestimation of the total economic value of the fuels' externalities. A benefit analysis is performed and WTP estimates for switching fuel mixes from society's perspective are calculated for the six alternative fuels relative to gasoline.

The results indicate that after accounting for life cycle costs, many popular first generation alternative fuel options offer no improvement in environmental and health benefits. This calls into question policies encouraging the adoption of these alternatives as "green" fuels. For policies with the intent of reducing foreign oil dependence and encouraging resource conservation, these alternative fuels may have merit. Overall, environmental damages, natural resource use, and human health risks increase significantly relative to gasoline under implementation of any of the currently popular corn starch ethanol derived blends, as well as for one of the cellulosic blends. Other cellulosic blends appear to offer potential improvements in decreasing net environmental damage, natural resource usage and human health risk. The results also indicate significant trade-offs between environmental damage, human health risks and resource depletion rates will have to be made in any attempt to implement alternative fuel policy at a national level. The paper is structured as follows: the first section overviews and reproduces

the LCIA results, the second section explains the stated preference study, section three details the integration of the LCIA and conjoint choice experiment, section four derives the welfare results and the fifth section concludes.

1.) Life Cycle Impact Assessment

The aim of LCIA is to enumerate the resources consumed, energy inputs required and wastes generated throughout the life cycle of a product or material. The analysis begins at extraction of raw materials and continues through final use and disposal of the product, material or service (Vigon and Jensen 1995). This sort of accounting is intended to identify opportunities for reductions in emissions and resource consumption. In this study, a previously developed life cycle inventory on fuels done by Baral and Bakshi (2006)² is utilized.

Reproducing the tiered hybrid life cycle inventory from Baral and Bakshi (2006) for each transportation fuel (gasoline, corn starch, corn stover, switchgrass, yellow poplar, newsprint, and municipal solid waste) yields the quantities reported in Table 01. Each row of Table 01 is an inventory vector of impacts corresponding to a transportation fuel.³ The functional unit of study is taken to be a distance driven basis in a representative gas-powered vehicle, thus the emissions and resource consumption reported are expressed as impacts per mile travelled using a particular fuel. The final category, ILUC, contains estimates of indirect land use changes that occur from biofuels production (specifically from corn starch, corn stover, and switchgrass) developed by the Environmental Protection Agency and augments the original inventory (EPA 2010). The remaining feedstocks are based on waste products and are deemed to have zero or trivial impacts regarding ILUC (EPA 2010). From a more exhaustive list of emissions and resources consumed

² For a detailed explanation of their methodology, assumptions, and results reference Baral and Bakshi (2006). For a good overview of LCIA reference (ISO 2006).

³ Each ethanol blend was calculated at both the 10% and 85% blend levels but only E85 results are reported here.

ten emissions and two fossil fuel resources are used in the construction of Eco-indicator 99 categories for an LCIA.

Table 01: *Life Cycle Inventory Results*

With the completed tiered hybrid inventories, aggregation into endpoint indicators is possible. Table 02 provides the necessary characterization factors to construct the endpoint indicators directly. The coefficients are based on those used in Eco-Indicator 99 and can also be found in a number of public references (Goedkoop and Spriensma 1999, Institute of Environmental Sciences 2010).⁴

Table 02: *Characterization Factors for Endpoint Indicators*

The inventory of emissions and resources consumed is aggregated into relevant impact categories. Whereas the original inventory is expressed in terms of units of measurement particular to each pollutant or resource (e.g. tons of carbon dioxide or tons of methane), the impact assessment is expressed in terms of an appropriate common through application of characterization factors which are determined through scientific or engineering knowledge. Though they may be subject to a higher degree of uncertainty, endpoint indicators offer a more ready interpretation and are the type of indicators employed here. The Eco-indicator 99 framework aggregates into three endpoint indicators related directly to changes in human health risks, ecosystem quality and resource depletion associated with a product. Human health can be discussed in terms of changes to disability-adjusted life years (DALY), a World Health Organization measurement incorporating years of life lost and affected by disability within a population. Resource depletion is measured through the proxy of surplus energy in mega joules (MJ) that must be expended to extract the next unit of mineral or fossil fuel resource. Finally,

⁴ For a complete explanation and description of the aggregation methods, allocation rules, and impact pathway assumptions employed in Eco-Indicator 99 for these pollutants see Goedkoop and Spriensma (1999).

potentially disappeared fraction of species (PDF) proxies for environmental damage and represents the fraction of species threatened or lost in a given region due to the life cycle emissions and resource consumption of a material. For each impact category, smaller values are desirable as they represent less severe impacts, or greater amounts of preservation of natural habitat, energy conservation and preservation of human health, respectively.

The following sections summarize Goedkoop and Spriensma's (1999) methodology report on Eco-indicator 99 endpoint construction:

Human health damages are modeled for infectious diseases, cardiovascular and respiratory diseases, climate change, cancer as a result of ionizing radiation, cancer and eye damages due to ozone layer depletion, and respiratory diseases and cancer due to toxic chemicals in air, drinking water, and food. Four steps are used to model these impacts: 1) Fate analysis, linking an emission (expressed as mass) to a temporary change in concentration; 2) Exposure analysis, linking this temporary concentration to a dose; 3) Effect analysis, linking the dose to associated health effects; and 4) Damage analysis, linking health effects to DALYs, using estimates of the number of Years Lived Disabled (YLD) and Years of Life Lost (YLL). Damage from emissions of certain heavy metals, endocrine disrupters, as well as health damages from allergic reactions, noise and odor are not yet able to be modeled in this framework.

Ecosystem quality damages are modeled for toxic emissions and those that change acidity and nutrient levels in air and soil. The models go through the procedure of: 1) Fate analysis, linking emissions to concentrations; 2) Effect analysis, linking concentrations to toxic stress or increased nutrient or acidity levels; and 3) Damage analysis, linking these effects to the increased potentially disappeared fraction of plant species. Only damages to natural systems can be modeled and only if these damages occur through airborne depositions. So far the framework

cannot model the effect of phosphate emissions to water. Climate change could also have a large impact on biodiversity and species loss (Mellilo et al. 2009), as could oil and gas production and ethanol production through indirect land use changes, but an additional limitation is that these effects cannot currently be modeled in this framework.

Resource depletion indicates the quality of the remaining mineral and fossil resources available. In both cases, the extraction of these resources will result in higher energy requirements for future extraction and is determined through 1) Resource analysis, which can be regarded as a similar step as the fate analysis, linking the extraction of a resource to a decrease in the resource concentration, and 2) damage analysis, linking lower concentration to the increased efforts to extract the resource in the future. Market forces assure that deposits with the highest concentrations of a given resource will be depleted first, leaving future generations to deal with lower concentrations. Thus in theory, the average ore grade available for future generations will be reduced with the extraction of every kilo. This decreasing concentration is the basis for the resource analysis. It is very comparable to fate analysis; instead of modeling the increase of the concentration of pollutants it models the decrease of the concentration of mineral resources. As more minerals are extracted, the energy requirements for future mining will increase. The “damage” is the energy needed to extract a kg of a mineral or fossil fuel in the future.

Table 03: *Life Cycle Impact Assessment Results*

Using Table 02 and each inventory in Table 01, the LCIA is complete for each transportation fuel and the results are summarized in Table 03. Gasoline has relatively low impacts for environmental and human health; this may be surprising at first glance, but the fuels have different emissions profiles and the emissions due to renewable fuels are deemed more harmful. For example, the renewable fuels require larger land areas to grow feed stocks, thus

potentially destroying habitats and displacing species. However, gasoline represents the most harmful fuel in terms of resource depletion as its production requires intensive extraction of resources from the environment. The information in Table 03 demonstrates that reductions in a particular impact category may come at the expense of increases in others when switching fuel types.

Given no fuel is Pareto-dominant over every impact category, preferences are necessary to determine how society trades-off among the damage types in order to assess whether changing fuels moves society in a welfare increasing or decreasing direction.

2.) Stated Preference Choice Analysis

2.1.) Survey and Choice Experiment

To determine society's preferences over the LCIA impact categories derived in the previous section, a choice experiment is conducted to elicit society's relative willingness to trade off the impacts of changing the transportation fuel mix. As individuals' choose among fuels based on the externalities generated and price, their preference relationship is established regarding those fuels and the externalities. The choice experiment is administered by Knowledge Networks, an internet-based survey research firm that has developed a fully representative panel of survey respondents who regularly participate in on-line surveys. A representative sample of licensed drivers from the state of Ohio was drawn from active members of Knowledge Networks survey panel ("KnowledgePanel").⁵

Prior to the choice experiment, respondents were asked about their fuel usage and transportation habits. They were then given information on how transportation fuels can affect three broad impact categories (whose definitions and descriptions were based on the Eco-Indicator 99 endpoints): environmental damage, natural resource use, and human health risk. It

⁵ A number of studies have tested the validity and reliability of the KnowledgePanel (Cameron et al. (2005), Viscusi et al. (2004)) and found it to meet government and academic standards.

was explained that often scientists summarize the myriad impacts of the production and consumption of various fuels through indices. Respondents were told the environmental damage index represents, for example, specific impacts on fish and wildlife populations, habitat quality, as well as air and water quality. They were also told the natural resource use index contains specific impacts on resource abundance and rates of extraction, and the human health risk index refers to effects on health outcomes, such as asthma risk, cancer incidence, and mortality rates. Figure 01 (appendix) provides the prompt given to respondents indicating the types of impacts contained within each index. The aggregation of the individually important impacts into indices creates the mechanism through which respondents compare different fuels based on the fuels' negative externalities without the mental gymnastics required to value all of the possible individual impacts simultaneously.

The attributes were described on a scale of 0 to 100, with 0 representing the most desirable outcome for each index: i.e. excellent health outcomes and little environmental damage and resource use. Similarly a level of 100 represents poor health outcomes and extensive environmental damage and resource use. The level of 50 is defined *a priori* as the currently experienced, status quo, level of each attribute to an individual. Thus, a level of 50 represents the current level of environmental damage, natural resource use, and human health risk created under the current fuel mix in the U.S. (i.e. primarily gasoline).

A 'choice set' for a respondent consists of three fuel mixes: the status quo (gasoline) and two alternative fuel mixes. A fuel mix is fully described by a price per gallon of fuel and levels for each of the three indices. The price of the status quo option is the respondents' self-reported price per gallon of gas last paid. The alternative fuel mixes in the choice set are randomly

assigned a price from one of five treatments: a 10% or 5% decrease from the status quo, no change, and 5% or 10% increase from the status quo.

Indexed values in the choice experiment were used rather than the direct LCIA impact factors described in section one for two reasons: first, it improves understanding of the full range of impacts to be considered instead of only focusing on a specific sub-type (such as greenhouse gas equivalents and climate change); and second, the framework and analysis can be extended beyond the original fuel types. Referencing a common normalized midpoint allows for relative comparisons between fuel types and allows flexibility for future fuels to be compared as new life-cycle assessments become available. The index levels for the two alternative fuel mixes for each choice are randomly assigned from five possible levels: 37.5, 45, 50, 55, and 62.5 on the scale, representing decreases of 25% and 10%, no change, and increases of 10% and 25% respectively from the status quo level of 50. A fuel described with all three index levels of 37.5, would represent a fuel that decreases environmental damage, natural resource use, and human health impacts by 25% each from current levels. Similarly, a fuel with all attribute levels of 62.5 represents a fuel which increases environmental damage, natural resource use, and human health impacts by 25% each from the status quo. Both the numerical value and percentage change were presented to respondents. Table 04 summarizes the experimental levels for the attributes.

Table 04: *Experimental Levels for Attribute Types*

In an ideal setting, each respondent would face all possible choices between fuel mixes described by the attributes in Table 04. Unfortunately, a 5x5x5x5 experimental design would result in 3,125 possible combinations of attributes to describe fuel mixes. A survey representing all possible combinations is practically impossible to administer by a survey firm and presents a cognitively impossible task for respondents. To simplify the choice experiment without loss of

information, the well-established experimental design literature is drawn upon. An experimental design relates the designated attributes and their different levels in a systematic and planned process through which the attributes and their levels are pre-defined without measurement error and then varied to create choice alternatives (Louviere, Hensher and Swait 2000). Each resulting choice alternative represents a different potential type of transportation fuel.

An orthogonal fractional-factorial, generic attribute experimental design optimally derived from the full factorial experimental design is utilized. The choice sets were chosen to maintain design orthogonality and level balance between all attributes and first-order attribute interactions as best as possible. Some trade-offs were made between orthogonality and statistical efficiency in order to maximize the information obtained in each choice scenario and prevent duplicate or dominated alternatives from occurring. Inclusion of a “baseline” scenario is another necessary trade-off which allows individuals to have an “opt-out” or “no-change” option within the choice set, which is important in maintaining unbiased parameter estimates (Johnson et al. 2007).

This experimental design results in 75 choice scenarios, which is still too large to reasonably expect any individual respondent to be able to complete consistently. As such, the design was modified further by dividing it into 5 blocks, with each block containing 15 of the final 75 choice sets. Respondents were randomly assigned to one of the five blocks and then given the 15 choice scenarios corresponding to that block. Assuming a common linear additive form of utility function underlies all respondents allows for estimation of society’s preference structure regarding both main and first-order interaction effects for the impact categories.

To facilitate graphical aids, the survey was administered to respondents online. The question format and an example are seen in Figure 02 (appendix). The respondent examines the

three fuel alternatives and chooses his or her most preferred alternative, given the attribute levels and price of each (repeated 15 times for each respondent). A pretest of the survey was fielded to assess understanding and improve questionnaire design prior to implementing the main survey. The main survey was completed by 537 respondents for a completion rate of 62.5 percent. Of the 537 respondents, 532 (99%) completed all required questions and were eligible for inclusion in the analysis. The other five respondents failed to provide either their day-to-day vehicle mileage or the last price paid at the pump and were subsequently excluded from the analysis. A comparison of the pilot and main surveys is in Table 05 below.

Table 05: *Survey Completion and Incidence Rates*

Table 06 provides demographic characteristics for the sample, the state of Ohio, and the United States. The sample demographics closely mirror those of the state, although the sample mean age is higher than the state average and more likely to be a homeowner. A major difference can be seen in the state percentage of individuals with a valid driver's license versus that of the sample. This is to be expected given the eligibility requirements for survey participation and the nature of the project in general. Since the focus is on transportation fuel preferences, it must involve respondents who drive, consume the commodity, and pay for consumption. This is not to say fuel non-consumers will not have preferences over the impacts of transportation fuels on the attributes being studied, but their preferences are not currently included. As such non-drivers are underrepresented in this sample.

Table 06: *Demographic Characteristics of U.S., Ohio, and Sample*

The self-reported price variable has a mean of \$1.88, but ranges from as low as \$0.90 to as high as \$3.29.⁶ This variability can be explained by the use of coupons and discounts by some consumers, the timing of the consumer's last purchase, as well as natural variability in fuel pricing. As expected, the environmental damage, natural resource use, and human health risk variables all have means around 50, the no change level, indicating balanced attribute levels after survey responses were collected.

2.2.) *Random Utility Framework*

The statistical analysis of the responses to the choice questions yields the preference structure for the attributes and is based on the assumption that the choice between fuel alternatives is driven by the respondents' underlying utility. The utility function has two components (deterministic $\bar{V}(\mathbf{x}_{ij}, \boldsymbol{\beta})$ and stochastic ε_{ij}) and is therefore embedded in a random-utility framework⁷ denoted by (1),

$$U_{ij} = \bar{V}(\mathbf{x}_{ij}, \boldsymbol{\beta}) + \varepsilon_{ij} \quad (1)$$

where subscript i denotes the individual, subscript j denotes the alternative, $\mathbf{x}$ is the vector of attributes that vary across alternatives and ε_{ij} is a stochastic error term capturing individual and alternative specific factors influencing utility unobservable by the researcher. The model is further formalized by assuming the deterministic portion of utility can be approximated as a linear function of attributes. Within the general model, the only respondent characteristic necessarily included is residual income, denoted $(M - p)$. Thus utility can be represented by (2),

$$U_{ij} = \beta_0 + \mathbf{x}_{ij}\boldsymbol{\beta}_l + (M_i - p_{ij})\beta_M + \varepsilon_{ij} \quad (2)$$

⁶ This mean value indicates good recall of last price paid as weekly Midwest regular conventional retail gasoline averaged per gallon prices of \$1.908 the week of 03/09/09 and \$1.849 the week of 03/16/09 (EIA 2013).

⁷ For a more detailed discussion on the random-utility framework see Greene (2012) or Haab (2002).

where M_i is individual i 's income and p_{ij} is the price faced by respondent i under alternative fuel profile j . The coefficient on residual income, β_M , is the marginal utility of income.

2.3.) *Estimation*

Statistical analysis proceeds by estimating the utility difference model using a mixed logit estimator. The traditional linear-in-parameters mixed logit is chosen over more complicated nonlinear specifications, which showed no improvement in terms of statistical fit or predictive capability. The choice among alternatives is treated solely as a function of the attributes of the alternative and is estimated to determine the contribution of each attribute to the probability of choice regarding an alternative. Since the individual is assumed to possess a common functional form for utility, aggregation across respondents is possible.

The parameters are estimated through simulated maximum likelihood for the mixed logit (Haab 2002). Since global concavity is not guaranteed for the mixed logit, multiple starting values were used to test fit (Train 2009). For all four of the attributes comprising the fuel profiles, the parameters have well-defined expectations with respect to sign. Similar to price, increases in the levels of all attributes are welfare decreasing. Therefore, *ceteris paribus*, respondents are expected to prefer fuel profiles that offer lower levels of environmental damage, lower levels of natural resource use, lower levels of risk to human health, and lower prices. Table 07 lists the variables included in model estimation.

Table 07: *Variable Definitions*

The model is found to be statistically superior: The likelihood ratio test of the null that all slopes are equal to zero is 5752.64 (p value < 0.0001). Table 08 contains the parameter estimates for the model. The signs for the attributes correspond with intuition and the parameter estimates are significant at the 99% confidence level. Increases in all attributes are negatively related to

utility, showing increases in the levels of externalities are welfare decreasing for society. The marginal disutility of increases in the risk to human health attribute is largest at -0.141, indicating society gains the most from improvements in health outcomes. This is followed by the marginal disutility of increases in the environmental damage attribute at -0.120, indicating individuals next prefer improvements in environmental outcomes. These are followed last by the marginal disutility of increases in resource depletion and usage at -0.92, which indicates resource improvements are preferred, but less so at the margin than health and environmental outcomes.

Table 08: *Utility Function Parameter Estimates*

From the parameter estimates recorded in Table 08, it is possible to estimate marginal prices for the attributes. The marginal price for a specific attribute is derived solely with respect to a change in that attribute. After estimating the common utility function, marginal price for attribute l is obtained by normalizing the marginal utility estimate of attribute l by the negative inverse of the marginal utility of income to yield,

$$MP_l = - \frac{\hat{\beta}_l}{\hat{\beta}_M} \quad (3)$$

where MP_l represents marginal price of attribute l , $\hat{\beta}_l$ is the estimated coefficient on l , and $\hat{\beta}_M$ is the estimated marginal utility of income. Table 09 lists the MP estimates. These price estimates correspond to marginal changes for each attribute from the status quo level of 50, holding other attributes constant.

Table 09: *Marginal Prices of Attributes (\$/Attribute)*

Rounding to the tenth-of-a-cent shows a marginal price of 2.9¢ per gallon for a unit reduction in the environmental damage index from status quo. Reduction in natural resource usage yields 2.2¢ per gallon for a unit reduction in the index from status quo. Lowering risks to the human health index yields marginal price estimates of 3.4¢ for reductions from status quo.

All estimates are significant at the 99% level and are statistically significantly different from each other. These results broadly follow previous findings in this area, namely that health outcomes are preferred over environmental and resource use outcomes (Delucchi 2000, Goedkoop and Spriensma 1999, Itsubo et al. 2004, Murphy and Delucchi 1998). Given this preference structure, policies targeted toward improving human health through fuel changes will have the most positive impact on welfare (given the same cost of implementation), followed by changes in environmental damage and lastly natural resource depletion.

3.) Integration

Integrating the LCIA Eco-Indicator 99 impact results with the framework used in the choice analysis elicitation yields WTP values specific to each feedstock and fuel. Because the output from the LCIA is not identical in scale and unit as that used in the choice analysis, it must be appropriately combined. The integration proceeds by mapping the LCIA impact results into the same scale and units as used in the choice analysis. This creates unique choice analysis index values for each alternative fuel type based on the measured LCIA impacts. This is accomplished by computing the ratio between the value of gasoline's LCIA impact for environmental damage, natural resource use, and human health risk and the value of each alternative fuel type's corresponding impact level. This expresses the value of each alternative fuel's impacts as a percentage change from gasoline's impacts. This is important given respondents valued each fuel type based on its impacts as a percentage change from the status quo of gasoline. Next, the choice analysis index value for each feedstock can be established by expressing it as a percent change from 50 (defined as the choice analysis level for gasoline *a priori*). This yields the value of each fuel type in terms of the choice analysis index scale valued by respondents.

This process is used for both the resource depletion and human health risk indices. For the environmental damage index, a slightly modified transformation was done because additional information on the LCIA endpoints for the index was available. Since the upper and lower limits of the environmental damage index are known, this information is incorporated into the transformation. This effectively allows three corresponding points to be mapped in order to accurately place the LCIA values for the environmental damage index into their corresponding choice analysis values, instead of using just two points as in the other two impact categories. Both endpoints from the LCIA index, as well as the value for each fuel type are mapped into the choice analysis index. This modified format for transformation of the environmental damage index creates a more accurate reflection of the fuels' impacts for this category.

Since gasoline is the status quo baseline, each alternative fuel's LCIA impacts are computed as percentage changes above or below gasoline's impacts. These percentage changes can then be used to exactly locate the alternative fuel's impact values on the choice analysis indices. Once the percentage changes from gasoline are known for each LCIA fuel type, the marginal willingness-to-pay for switching to that alternative fuel type is calculated. Thus, in the WTP analysis that follows, the x_j 's are the values imputed from the integration for each alternative fuel and the x_0 's are the status quo values of gasoline.

4.) WTP Results

To establish the WTP for a fuel, the indirect utility function associated with that alternative is equated to the indirect utility under the status quo option and solved for WTP as in (4) below.

$$x_j \hat{\beta}_l + (M - WTP_j) \hat{\beta}_M = x_0 \hat{\beta}_l + (M) \hat{\beta}_M \quad (4)$$

Here, $\mathbf{x}_j$ represents the vector of attribute values describing the alternative fuel j , $\hat{\beta}_I$ is the vector of estimated coefficients for the alternative's attributes, and $\hat{\beta}_M$ is the estimated marginal utility of income. Solving for WTP_j yields (5), where $\Delta\mathbf{x}$ is the difference between the status quo and alternative fuel type attribute levels.

$$WTP_j = \frac{(\Delta\mathbf{x})\hat{\beta}_I}{\hat{\beta}_M} \quad (5)$$

The differences in attribute levels for the alternative fuel types from gasoline are calculated corresponding to the $\Delta\mathbf{x}$ in equation (5) above. Inputting these $\Delta\mathbf{x}$'s and the parameters estimated in Table 08 for the betas into (5), the marginal willingness-to-pay in dollars per gallon for the change in damages associated with each alternative fuel type, relative to gasoline, are calculated and listed in Table 10.

Table 10: *Marginal Willingness-To-Pay (\$/Gallon) for Fuel Types^b*

As Table 10 details, the corn starch blend, as well as switchgrass have negative WTP relative to gasoline. This indicates the environmental, natural resource, and health outcomes are, *overall*, worse than gasoline and individuals would prefer to avoid them. As shown in the LCIA data in Table 03, natural resource usage does decline, but once combined with the preference structure of individuals, which include worsening environmental and health outcomes, these benefits are negated. Consumers would have to be compensated in order to accept the overall worse outcomes from these alternative fuels. When only examining these ethanol blends relative to gasoline, consumers are worse off. For example, switching to corn starch based E85 fuel in place of gasoline engenders net increases in environmental damage, natural resource use, and human health risk valued at nearly 64¢ per gallon, while switchgrass E85 has net increases in

environmental damage, natural resource use, and human health risk valued at 34¢ per gallon.⁸

This indicates that along these impact vectors welfare is declining with the implementation of any of these alternative fuels in place of gasoline. The improvement in natural resource usage simply does not compensate for declining environmental and health outcomes, leaving society worse off.

The remaining ethanol fuel types are all so-called “second generation” cellulosic blends and (other than corn stover which is not statistically significant)⁹ have net decreases in environmental damage, natural resource use, and human health risk associated with their consumption in place of gasoline. Overall, the environmental damage, natural resource use, and human health benefits of these blends combine to offer positive benefits relative to gasoline from society’s perspective. Importantly, these feedstocks are all generated from waste material that do not compete for land use or the food sector in the same manner as corn and switchgrass. The direct and indirect net decreases in environmental damage, natural resource use, and human health risk range from a low value of 67¢ from newsprint, to a high value of \$1.03 from yellow poplar per gallon and show certain cellulosic blends could have significant positive impacts if they are scalable to commercial levels. The study highlights the value of biofuels from waste products because they can avoid land-use change and its emissions. This follows the results and recommendations highlighted in Searchinger et al. (2008) that to avoid land use change altogether, biofuels must use carbon that would reenter the atmosphere without doing useful work that needs to be replaced, for example, municipal waste, forest residues and/or crop waste.

⁸ Taking into account the ILUC impacts and the associated greenhouse gas emissions that occur with use of these feedstocks roughly doubles the welfare values of corn starch and switchgrass, relative to their direct estimated impacts alone.

⁹ This indicates consumers would be indifferent to switching to use of corn stover relative to gasoline based on the net changes in the three indicator categories, but they would not be willing to pay or need to be compensated for the change.

5.) Conclusion

This framework more comprehensively estimates the life cycle cost of the externalities associated with fuels which can be used to adjust prices and cost-benefit analyses to reflect the true social cost of fuel use rather than just the private cost observed in markets. A main contribution of this framework to previous external cost estimates is its examination of multiple externalities imposed throughout the life cycle of a good through the use of appropriate multi-metric indicators, including indirect land use changes. Establishing marginal prices for each set of impacts represented by an indicator provides a unique way to examine how society views and trades-off between different classes of externality and provides a unique way to inform policy which will have the greatest impact on social welfare.

Many of the fuels examined here are touted as promising alternatives to gasoline that improve on foreign oil dependence, improve environmental degradation and also improve human health risks related to gasoline consumption. But, the direct LCIA results show explicitly not all of these claims are accurate and in fact, for some of the alternative fuels, the environmental and health outcomes are significantly worse. The natural resource outcomes for all of the alternative fuels do offer improvement over gasoline. But, this is a tradeoff made at the expense of increased environmental degradation and human health risk in some cases. By integrating the LCIA results with environmental valuation techniques from a conjoint choice analysis, WTP per gallon for switching to these alternatives fuels from society's perspective is estimated and shows how net environmental damage, natural resource use and human health risk change under implementation of different alternative fuel types. It also highlights the large social values placed upon avoidance of the impacts associated with greenhouse gas emissions created through indirect land use change.

The results suggest policies advocating for alternative biofuels as environmentally or health friendly alternatives to gasoline should be thoroughly examined based on exactly what type of feedstock is specifically being incentivized. If a policy is advocating for an alternative fuel type based on a desire to mitigate foreign oil dependence, conventional first generation biofuels have merit. Otherwise, subsidies, blender's credits and other incentives aimed at creating a more environmentally and health friendly fuel should be reserved for specific types of second generation cellulosics, as giving these benefits to corn based biofuels is inefficient. In the case of conventional biofuels, it should be well understood that the desire to end foreign oil dependence will come at a high cost to both the environment and to human health.

A limitation of the current study is aggregation and comparison proceeds from the bottom-up. LCIA results can be calculated, preferences established, and the goods (here fuel types) compared to determine which represents the best choice from among those presented. The framework cannot work backwards to the production process which will deliver the optimal good, given resource or cost constraints. In addition, it is important to understand the potential sensitivity of results to the specific aggregation method chosen for the life cycle inventory (here it is tiered-hybrid). In performing the LCIA, changing characterization factors and/or inventory aggregation schemes could affect the resulting indicators. Further investigation into the aggregation strategy is necessary to determine how robust the analysis and framework are to these issues. Also demanding additional investigation is the use of biometric and multi-metric indicators for valuation purposes. A clear explanation of what the indicator represents and how it is constructed are certainly prerequisites for even the most basic claim that respondents truly understand and can value changes in these devices. Yet, there is little evidence currently available examining the use of these types of devices for valuation purposes.

The results highlight the difficult challenges faced ahead in attempting to find a suitable replacement for gasoline as a long-term source of mobility provision. They also highlight the difficult trade-offs that may need to be made, in both the short and long run, between environmental quality, human health, and natural resource use if a suitable fuel replacement cannot be found which improves on all three of these classes of externality over current alternatives.

Thanks to William McGuire, Brent Sohngen, H. Allen Klaiber and participants in several conferences and seminars for helpful conversations, comments and advice, as well as Anil Baral for additional consultation regarding the original life cycle inventory. A special thanks to the reviewers for their time, energy and comments which were extremely helpful and greatly improved the final work. Financial support from National Science Foundation grant #ECS-0524924 is gratefully acknowledged. The views expressed herein are those of the author(s) and do not necessarily reflect the views of the authors' institutions.

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Table 01: Life Cycle Inventory Results

	Inventory Constituents Pollutant (P) or Resource (R)											
Fuel Type (kg/mi)	VOC (P)	CO (P)	NO _x (P)	PM10 (P)	SO _x (P)	CH ₄ (P)	N ₂ O (P)	CO ₂ (P)	CFCS (P)	Crude Oil (R)	Nat. Gas (R)	ILUC (P)
Gasoline	8.48 E-05	1.09 E-03	9.04 E-05	3.33 E-05	1.05 E-04	6.86 E-04	1.06 E-05	3.19 E-01	3.71 E-08	1.49 E-01	2.38 E-03	0.00 E+00
Corn Starch	1.27 E-04	1.01 E-03	8.35 E-04	5.46 E-05	1.60 E-04	4.82 E-04	1.61 E-04	1.44 E-01	4.23 E-08	3.74 E-02	2.65 E-02	1.14 E-01
Corn Stover	2.12 E-04	1.36 E-03	8.53 E-04	1.10 E-04	-3.79 E-05	3.74 E-04	6.41 E-02	1.23 E-01	4.32 E-04	2.61 E-02	7.74 E-03	0.00 E+00
Yellow Poplar	1.09 E-04	1.08 E-03	5.62 E-04	6.76 E-05	-1.32 E-04	2.39 E-04	4.28 E-02	6.94 E-02	2.80 E-04	1.88 E-02	5.51 E-03	0.00 E+00
Newsprint	1.13 E-04	1.11 E-03	5.39 E-04	6.17 E-05	1.53 E-04	2.79 E-04	8.97 E-03	1.05 E-01	4.85 E-04	1.76 E-02	1.06 E-02	0.00 E+00
Switch- grass	2.12 E-04	1.36 E-03	8.53 E-04	1.10 E-04	-3.79 E-05	3.74 E-04	6.41 E-02	1.23 E-01	4.32 E-04	2.88 E-02	8.40 E-03	5.30 E-02
Municipal Solid Waste	8.49 E-05	9.16 E-04	4.01 E-04	4.16 E-05	1.87 E-04	3.19 E-04	3.25 E-03	1.44 E-01	4.95 E-04	2.10 E-02	3.03 E-03	0.00 E+00

LCIA is compiled assuming the use of resources and release of pollutants is linearly related to total outputs of the system. Values are for E85 blend level of fuels. International (including domestic U.S. and global) changes in indirect land use change are denoted in the column titled ILUC and are denoted in CO2 equivalent units.

Table 02: *Characterization Factors for Endpoint Indicators*

Inventory Item	PDF/kg	MJ/kg	DALY/kg
VOC			6.46E-07
CO			7.31E-07
NO_x	5.713E+00		8.91E-05
PM10			3.75E-04
SO_x	1.041E+00		5.46E-05
CH₄^a			4.40E-06
N₂O^a			6.22E-05
CO₂			2.10E-07
CFCs^a			1.79E-03
Crude Oil		4.23E+01	
Natural Gas^b		5.00E+01	
ILUC^c			2.10E-07

a) Characterization factors for CH₄, N₂O and CFCs are based on CO₂ equivalent releases. They are derived by multiplying CO₂ impacts by 23, 296 and 8500, respectively.

b) Published characterization factor is 35.7 MJ/m³ of natural gas. Factor for conversion to mass (1.40 m³/kg) assumes 1 atm pressure and temperature 0 C.
1.40 m³ /kg * 35.7 MJ/m³ = 50.0 MJ/kg c) Indirect Land Use Change

Table 03: *Life Cycle Impact Assessment Results*

Fuel Type	Environmental Damage (PDF/mi)	Resource Depletion (MJ/mi)	Human Health Risk (DALY/mi)
Gasoline	6.26E-04	6.42E+00	9.71E-08
Corn Starch	4.94E-03	2.91E+00	1.61E-07*
Corn Stover	4.84E-03	1.49E+00	1.57E-07*
Yellow Poplar	3.07E-03	1.07E+00	9.38E-08
Newsprint	3.24E-03	1.27E+00	1.06E-07
Switchgrass	4.84E-03	1.64E+00	1.68E-07*
Municipal Solid Waste	2.49E-03	1.04E+00	9.47E-08

LCIA results from sum-product of Tables 01 and 02. * Denotes fuel with human health risk values impacted by ILUC.

Table 04: *Experimental Levels for Attribute Types*

	Environmental Damage	Natural Resource Use	Human Health Risk	Price
Best Level	37.5	37.5	37.5	-10%
Better Level	45	45	45	-5%
No Change	50	50	50	0
Worse Level	55	55	55	5%
Worst Level	62.5	62.5	62.5	10%

Table 05: *Survey Completion and Incidence Rates*

	Field Dates	N Sampled	N Completed	% Completed	N Qualified	% Qualified
Pilot	3/3–3/6/09	60	35	58.3%	34	97.1%
Main	3/13–/23/09	859	537	62.5%	532	99.0%

Table 06: Demographic Characteristics of U.S., Ohio, and Sample

	Mean or Percentage		
	United States^a	Ohio^b	Sample
HH Income (\$/year)	52,175 ^c	48,023 ^c	52,290
Age (years)	36.7	37.9	48.3*
HH Members (#)	2.61	2.48	2.59
Married (%)	54.4	54.5	47.7
Female (%)	50.7	51.3	51.7
Homeowner (%)	67.1	69.6	78.4*
Bachelor's Degree or Higher (%)	27.4	23.8	21.8
White (%)	74.3	84.0	84.4
Metropolitan^d (%)	80.3	71.4	75.8
Valid Driver's License (%)	88.0 ^e	76.2	91.6*

*Denotes statistically significant difference between Sample and State Means at the 0.01 level. a) U.S. demographics obtained from U.S. Census Bureau's American Community Survey 2006-2008 estimates (<http://www.census.gov>) b) State of Ohio demographics obtained from U.S. Census Bureau and Ohio Bureau of Motor Vehicles (<http://www.bmv.ohio.gov>) c) median household income in 2008 inflation adjusted dollars d) Metropolitan indicates Urban or Suburban resident. e) 2005 Carter-Baker Commission Report

Table 07: *Variable Definitions*

Variable	Definition
Choice	=1 if fuel alternative is chosen
Price	Difference in price per gallon between fuel alternatives (in dollars)
Environmental Damage	Difference in this attribute level between fuels (from baseline)
Natural Resource Use	Difference in this attribute level between fuels (from baseline)
Human Health Risk	Difference in this attribute level between fuels (from baseline)
Income	Marginal effect of income on marginal utility of attribute
ASC	Alternative Specific Constant for the status quo alternative

Table 08: Mixed Logit Estimates (N=7274)

Variables	Mean (Standard Error)
ASC	1.105 (0.069)
Price (\$/gal)	-4.177 (0.267)
Environmental Damage^a	-0.120 (0.005)
Natural Resource Use^a	-0.092 (0.005)
Human Health Risk^a	-0.141 (0.006)
McFadden's Pseudo R^{2b}	0.344
Log-Likelihood	-5487.44

All parameter estimates were significant at the 1% level.

a) Assumed parameter distribution is normal

b) See Green 2012, page 537, for a detailed discussion.

Table 09: *Marginal Prices of Attributes*

Variable	Marginal Price (\$/Attribute)
Environmental Damage	0.029 (0.002)
Natural Resource Use	0.022 (0.002)
Human Health Risk	0.034 (0.003)

Figures are estimates of marginal willingness-to-pay for the listed attribute as calculated using equation (3). Estimates for marginal 1% decrease from current, base levels. Estimated using Krinsky-Robb Simulation with 10,000 draws.

Table 10: *Marginal Willingness-To-Pay*

Fuel Type	MWTP (\$/Gallon)
Corn Starch	-0.641* (0.057)
Corn Stover	-0.015 (0.034)
Yellow Poplar	1.030* (0.088)
Newsprint	0.656* (0.061)
Switchgrass	-0.337* (0.043)
Municipal Waste	0.901* (0.078)

Figures are estimates of marginal willingness-to-pay for the listed fuel as calculated using equation (5). Estimates are for a change from gas(status-quo) to the listed alternative. They are estimated using Krinsky-Robb Simulation with 10,000 draws.

APPENDIX

Figure 01: Index Descriptions

The three index values for the Current Fuel Mix represent the impact that the current fuel mix has on the environment, natural resources, and human health.
The Environmental Damage Index
<p>An increase in the Environmental Damage Index means that there is more damage to the environment. Possible damages include:</p> <ul style="list-style-type: none">– Lower populations of various species including plants, worms, algae, amphibians, mollusks, crustaceans and fish.– Increased air, land, and water pollution creating a more toxic environment.
The Natural Resource Use Index
<p>An increase in the Natural Resource Use Index means that there is increased strain on natural resources making it more difficult to extract minerals and fossil fuels, and that there are less available for future use.</p> <ul style="list-style-type: none">– Minerals, including lead, zinc, iron, copper, limestone and clay are used in countless consumer products.– Fossil Fuels, including oil, coal, and natural gas are used as energy sources for heating and cooling homes, electricity generation, and transportation
The Human Health Risk Index
<p>An increase in the Human Health Risk Index means that there is a higher risk of harmful effects on human health. Possible health effects include increased risk of:</p> <ul style="list-style-type: none">– Cancer, including thyroid, bone, breast, and lung cancers– Leukemia– Cardiovascular and respiratory diseases– Eye damage due to ozone layer depletion

Figure 02: Prompt, Stimulus, and Choice Question Format for Conjoint Experiment

<p>[Q] Consider the following three fuel mixes. Each is characterized by different levels of the Environmental Damage, Natural Resource Use, and Human Health indices and a change in the fuel price per gallon.</p>										
<p>Current Fuel Mix</p>	<p>[\$GASPRICE] per gallon</p>	<table border="1"> <thead> <tr> <th>Index</th> <th>Value</th> </tr> </thead> <tbody> <tr> <td>Environmental Damage</td> <td>50</td> </tr> <tr> <td>Natural Resource Use</td> <td>50</td> </tr> <tr> <td>Human Health Risk</td> <td>50</td> </tr> </tbody> </table>	Index	Value	Environmental Damage	50	Natural Resource Use	50	Human Health Risk	50
Index	Value									
Environmental Damage	50									
Natural Resource Use	50									
Human Health Risk	50									
<p>Fuel Mix A</p>	<p>[\$GASPRICE] per gallon</p>	<table border="1"> <thead> <tr> <th>Index</th> <th>Value</th> </tr> </thead> <tbody> <tr> <td>Environmental Damage</td> <td>45</td> </tr> <tr> <td>Natural Resource Use</td> <td>50</td> </tr> <tr> <td>Human Health Risk</td> <td>55</td> </tr> </tbody> </table>	Index	Value	Environmental Damage	45	Natural Resource Use	50	Human Health Risk	55
Index	Value									
Environmental Damage	45									
Natural Resource Use	50									
Human Health Risk	55									
<p>Fuel Mix B</p>	<p>[\$GASPRICE] per gallon</p>	<table border="1"> <thead> <tr> <th>Index</th> <th>Value</th> </tr> </thead> <tbody> <tr> <td>Environmental Damage</td> <td>62.5</td> </tr> <tr> <td>Natural Resource Use</td> <td>37.5</td> </tr> <tr> <td>Human Health Risk</td> <td>50</td> </tr> </tbody> </table>	Index	Value	Environmental Damage	62.5	Natural Resource Use	37.5	Human Health Risk	50
Index	Value									
Environmental Damage	62.5									
Natural Resource Use	37.5									
Human Health Risk	50									
<p>Assuming you are driving the same vehicle that you currently drive, and the expected fuel mileage does not change, which Fuel Mix would you prefer?</p> <p> ☐ I would prefer Current Fuel Mix ☐ I would prefer Fuel Mix A ☐ I would prefer Fuel Mix B </p>										

Note: [\$GASPRICE] refers to the respondents reported price paid per gallon multiplied by the experimentally determined price level