Environmental Consequences of Ethanol from Corn Grain, Ethanol from Lignocellulosic Biomass, and Conventional Gasoline

Lawrence D. Mapemba, Francis M. Epplin, and Raymond L. Huhnke

Lawrence D. Mapemba is a research assistant, Francis M. Epplin is a professor Department of Agricultural Economics, and Raymond L. Huhnke is a professor, Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater. Professional paper AEP-0603 of the Oklahoma Agricultural Experiment Station, project H-2574.

Selected paper prepared for presentation at the American Agricultural Economics Association Annual Meeting, July 23-26, 2006, Long Beach, California

Contact author:
Francis M. Epplin
Department of Agricultural Economics
Oklahoma State University
Stillwater, OK 74078-6026

Phone: 405-744-6156
FAX: 405-744-8210
E-mail: f.epplin@okstate.edu

Environmental Consequences of Ethanol from Corn Grain, Ethanol from Lignocellulosic Biomass, and Conventional Gasoline

Abstract

The Energy Policy Act of 2005 includes a provision designed to double the production and use of ethanol in fuels by 2012, and that beginning in 2013, a minimum of 250 million gallons per year of ethanol be produced from lignocellulosic sources such as corn stover, wheat straw, and switchgrass. This study was conducted to determine the environmental and health consequences of using ethanol as an additive to gasoline. Comparisons are made among conventional gasoline (CG), a blend of 10 percent corn-ethanol and 90 percent CG (E10-corn), and a blend of 10 percent ethanol produced from lignocellulosic biomass (LCB) and 90 CG (E10-LCB).

Key words: lignocellulosic; biomass; ethanol; GREET; E10

Introduction

The Energy Policy Act of 2005 includes a provision designed to double the production and use of ethanol in fuels by 2012. The 2005 Act also provides that beginning in 2013, a minimum of 250 million gallons per year of ethanol be produced from lignocellulosic sources such as corn stover, wheat straw, and switchgrass. In 2005, approximately four billion gallons of ethanol were produced in the U.S. Most was produced from corn grain and blended with gasoline. The resulting 10% ethanol and 90% gasoline blends are referred to as E10. The industry benefits from a variety of federal and state subsidies and tax credits. The blenders credit of $0.51 per gallon provided a federal subsidy of more than $2 billion for the four billion gallons of ethanol.

Proponents of the ethanol fuels program proclaim that it is (a) good for energy security, (b) good for rural (economic development) America, and (c) good for the environment. The objective of the research reported in this paper is to determine the environmental costs of four billion gallons of ethanol from corn grain, and the environmental costs of four billion gallons of ethanol from lignocellulosic sources, when used as E10 in U.S. passenger cars and light-duty trucks, and to compare these costs with the environmental costs of conventional gasoline.

Air pollution from both natural and man-made sources is harmful to human health, crops and forests, damages building materials, and impairs visibility (Delucchi, Murphy and McCubbin; Hall et. al.; Krupnick and Portney; Murphy et. al.; Small and Kazimi). The transport sector contributes a substantial amount of air pollutants including volatile organic compounds (VOCs), carbon monoxide (CO), and nitrogen oxides (NO_x). VOCs react with NO_x in the atmosphere to form damaging oxidants such as ozone (O_3) (Small and Kazimi).

Health costs are considered one of the largest external costs of motor vehicle use. Air quality standards around the world are primarily set to protect human health (Neidell). A number of studies have attempted to value the health costs associated with air pollution from motor vehicles (Delucchi, Murphy and McCubbin; Delucchi; Hall, Brajer and Lurmann; Hall et. al.; McCubbin and Delucchi; Neidell; Rozan; Small; Small and Kazimi). Research shows that air pollution causes eye and throat irritation, headaches, acute and chronic respiratory illness, asthma, chronic lung disease and heart failure. The most dangerous emitted particles to human health are particulate matter of 10 microns or less in diameter (PM_{10}) and ozone (McCubbin and Delucchi; Hall et. al). PM_{10} is believed to cause the most damage since the tiny particles are inhaled deep into the lungs (Neidell). Carbon monoxide has a significant effect on hospitalizations for asthma among children ages 1-18 (Neidell). Motor vehicles are a major source of PM_{10}, nitrogen dioxide (NO_2), and carbon monoxide (CO). In cities 90 percent of CO is from motor vehicle exhaust. There is a significant correlation between ozone levels and school absences (Hall, Brajer and Lurmann). Air pollution also causes damage to building materials, vegetation including agricultural crops and impairs visibility.

Pollution exposure induces physical effects to human, animals and the environment. There is an implicit monetary value associated with these physical effects (McCubbin and Delucchi). Small and Kazimi (p. 13-14) wrote that "…a pollutant emitted into the atmosphere changes the spatial and temporal patterns of ambient concentrations of that pollutant and perhaps others. These patterns are determined by atmospheric conditions, topographical features and the presence of other natural and man-made chemicals in the air. The resulting ambient concentrations then interact with people, buildings, plants and animals in a way that depends on their locations and activity levels. The results may be physical and/or psychological effects:

coughing, erosion of stone, retarded plant growth, injury to young, loss of pleasurable views, and so forth. Finally, these effects have an economic value…”

Due to the environmental and health damages attributable to conventional gasoline use, public policy debates have centered on evaluating alternative sources of energy that are both renewable and environmentally acceptable. Ethanol has been widely recognized as an acceptable substitute for gasoline or as an additive to gasoline. Henry Ford designed the Ford Model T, introduced in 1908, to run on either ethanol or gasoline. Since ethanol is produced from plants, its use enhances the natural cycling of carbon dioxide resulting in little or no net addition of carbon dioxide to the atmosphere.

In the U.S., ethanol is largely (>95%) produced from cornstarch. But the cost of corn grain and the limits to U.S. corn production has led to increased interest in lignocellulosic biomass (LCB) as feedstock for ethanol production (O’Brien et al.). Corn is an annual crop. The production of corn grain is machinery intensive. Fossil fuels are used to fuel diesel powered tractors and to produce nitrogen fertilizers. The production of ethanol from corn is not environmentally benign. On the other hand, LCB that requires less fossil fuel to produce than corn grain, such as crop residues including wheat straw and corn stover, and perennial grasses such as switchgrass could be used as feedstock. However, since LCB is bulky, it could require a substantial quantity of fuel to transport from production fields to biorefineries.

Farrell et al. reported that ethanol from LCB offers the potential for large reductions in GHG emissions. Ethanol production from LCB feedstock has more potential for efficiency gains in conversion since LCB cultivation and processing is not a mature industry. LCB-to-ethanol production is undergoing major technological development.

The aim of this research is to determine the monetary cost of the environmental and health consequences of using ethanol as an additive to gasoline. Comparisons are made among conventional gasoline (CG), E10 produced with corn-ethanol (E10-corn) and E10 produced with 10% LCB ethanol (E10-LCB).

Procedure

Environmental damages of air pollution vary spatially and temporally (Delucchi). In general, damages due to air pollution are higher in urban areas than in the rural areas due to motor vehicle traffic concentration and population density. The effects of air pollution are determined by type and age of car, atmospheric conditions, topographical features and the presence of other natural and man-made chemicals in the air (Small; Small and Kazimi).

Miller and Theis analyzed and compared three life-cycle inventory (LCI) models: the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model developed at the Center for Transportation Research, Argonne National Laboratory (Wang, 2005); the economic input-output life cycle assessment (EIO-LCA) model (Hendrickson, Lave, and Matthews), and the SimaPro model (PRé Consultants). Miller and Theis found discrepancies across model estimates resulted from "…inconsistent boundary definitions, disagreements in source assumptions regarding material and energy use, or fundamental differences in the assumed emissions associated with upstream processes…" (Miller and Theis, p. 134). This study uses the GREET model because it is readily available, fits well with the objective of analyzing emissions in the transportation sector, and because it focuses on air emissions and energy use in the transportation sector.

Quantity of Pollutants

GREET was used to estimate air pollutants emitted per mile of vehicle travel. The model calculates the full fuel-cycle (well-to-wheels) emissions including upstream operations such as feedstock production and harvesting as well as ethanol production from corn or LCB. In the case of fossil fuels, upstream operations include fuel extraction, production, refining, storage, distribution, and dispensing.

GREET 1.6 is a spreadsheet-based fuel-cycle model. The model separately calculates the fuel-cycle consumption of total energy, fossil fuels and petroleum. It also calculates fuel-cycle emissions of greenhouse gases (GHGs), primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). It calculates the fuel-cycle emissions of five criteria pollutants – volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter with a diameter measuring 10 micrometers or less (PM_{10}), and sulfur oxides (SO_x). The model allows the user to input assumptions and generate fuel-cycle energy and emissions results for specific fuel/technology combinations (Wang, 1999). GREET gives the level of pollution for each of the GHGs and five pollutants in grams per mile. Pollutants were calculated for passenger vehicle and light-duty trucks that use either gasoline or E10.

GREET allows simulation of three different vehicle types, i.e. passenger cars, light-duty trucks 1 and light-duty trucks 2. Passenger cars range from small to large and include station wagons but not minivans. Light-duty trucks 1 include those with gross weight of 6000 pounds or less (e.g. small pickups, minivans, and small sport utility vehicles). Light-duty trucks 2 include those vehicles with gross weight between 6,001 and 8,500 pounds (e.g. large pickup trucks, large vans and large sport utility vehicles). Average emissions were calculated between emissions from light-duty trucks 1 and 2 to obtain one value for each pollutant for light-duty truck emissions. Contribution of highway miles covered by passenger cars and light-duty trucks, emissions from passenger cars, and the average emissions of light-duty trucks were used to calculate weighted averages of emissions of each pollutant from passenger cars and light-duty trucks. This method provides a point estimate of the level of pollution for both passenger cars and light-duty trucks that use either CG, or E10-corn, or E10-LCB.

In 2005 over four billion gallons of ethanol were produced in the U.S. (Renewable Fuels Association (RFA)). An E10 mixture that included four billion gallons of ethanol would produce 40 billion gallons of E10. An estimate of the emissions from the use of 40 billion gallons of E10 in passenger cars and light trucks requires an estimate of the miles fueled by 40 billion gallons of E10. A gallon of gasoline contains 125,000 BTUs (Shapouri, Duffield and Wang) and a gallon of ethanol contains 76,000 BTUs (Shapouri, Duffield and Wang; Wang, Saricks and Santini). Therefore, E10 contains 120,100 BTU per gallon or 96 percent as much as CG.

The average fuel economy in 2002 was 22.1 miles per gallon (mpg) for passenger cars and 17.6 mpg for light-duty trucks (Transportation Energy Data Book, Table 4.1 and 4.2)). In 2002 U.S. passenger cars traveled 1,658,640 million miles. Light-duty trucks traveled 966,184 million miles. The total miles traveled by both passenger cars and light-duty trucks were 2,624,824 million. Passenger cars accounted for 63.2 percent of the miles. Light-duty trucks accounted for the remaining 36.8 percent. Based upon these proportions of miles traveled, the weighted average of mpg for both passenger cars and light-duty trucks is 20.4.

Given that in 2002 the vast majority of the fleet was fueled with CG, 20.4 is assumed to be the fleet average mpg for CG. Since E10 has 96 percent as much energy as CG, the estimated passenger car and light truck fleet average mpg for E10 is 19.6. By this measure motor vehicles using 40 billion gallons of E10 as fuel could travel a distance of 784 billion miles. These miles represent about 30 percent of the total miles traveled by passenger cars and light-duty trucks in 2002.

GREET was used to obtain emission rates in grams of pollutants per mile for vehicles that use CG, E10-corn and E10-LCB. To determine the relative pollution consequences of 40 billion gallons of E10 the grams of pollutants per mile were multiplied by the 784 billion miles.

Marginal Cost of Pollutants

A number of studies have estimated the economic costs of air pollution (Delucchi; Hall, Brajer and Lurmann; Hall et. al.; Ogden, Williams and Larson; Small; Small and Kazimi). Most of these studies have estimated economic costs at a regional level. Some have estimated economic costs of motor-vehicle-related emissions for the entire U.S. Small used the direct estimation of damages approach to estimate the health and material damage costs of motor vehicle emissions for the U.S. This method has also been applied by Small and Kazimi and Daniels and Chiabai. Links between emissions and adverse consequences are traced and economic values are placed on those consequences. Small reported costs of U.S. urban emissions from motor vehicles but only included damage to human health and building material. Other estimates of damage costs of U.S. air pollution have been reported by Delucchi, Delucchi, Murphy and McCubbin, McCubbin and Delucchi, and Murphy et al.

Delucchi includes estimates derived from a multi-step damage-function. Delucchi estimates the relationship between change in motor vehicle use and emissions, emissions and air quality, air quality and exposure, exposure and physical damage, physical damage and monetary value. He provides estimates of the marginal external costs of motor-vehicle-related air pollution to human health, agricultural crops and visibility. He also provides estimates of the total material and forest damage costs from motor vehicle air pollution. Total material damage from motor-vehicle air pollution ranged from $1.0 billion to $8.0 billion in 1991 dollars. Forest damage from motor-vehicle air pollution ranged from $0.2 billion to $2.0 billion in 1991 dollars.

The data given in Table 1 show reported marginal costs of motor-vehicle air pollutants as reported by Delucchi, Small and Kazimi, and Small. These marginal costs can be applied to any emission rates from any type of vehicle and fuel since they are independent of the rate of emissions (McCubbin and Delucchi; Murphy et. al).

McCubbin and Delucchi reported that the dollars-per-kilogram factors were proportional to the exposed population and should be scaled by population. The estimates by Delucchi were scaled by the percentage increase in population from 1990 to 2004. Percentage change in population was calculated using population estimates from the U.S. Bureau of Census. The dollar costs per gram of pollutants were then updated to 2004 prices by using the change in GDP per capita from 1991 to 2004. Estimates of GDP per capita were obtained from the Bureau of Economic Analysis online publications. These marginal pollutant cost estimates were multiplied by the total grams of pollutant estimates from GREET for CG, E10-corn and E10-LCB and summed across all the air pollutants to find the total cost to health, visibility and crop loss for each of the fuel types.

The estimates for material and forest damage given by Delucchi were scaled to 2004 prices using the GDP inflator. It was assumed that these estimates applied to vehicles that use CG. Crop losses due to pollutants are attributed to nitrogen oxides, sulfur oxides and ozone (Delucchi). Similarly, the three pollutants were assumed to cause forest damage. The sum of the individual pollution costs of these three pollutants was obtained for costs due to use of CG, E10-Corn and E10-LCB. Using these sums, the ratios of forest damage for E10-corn to CG and E10-LCB to CG were obtained. These ratios were used to obtain estimates of forest damage from passenger cars and light-duty trucks that use E10-Corn and E10-LCB by multiplying them by Delucchi's forest damage estimates.

This study accounts for only 30% of the 2002 highway vehicle-miles traveled and 91.9% of all the vehicles in 2002 were passenger cars and light-duty trucks. Consequently, Delucchi's estimates of forest damage due to motor-vehicle pollution as well as our estimates of forest damage by cars and trucks that use E10-Corn and E10-LCB were adjusted by multiplying them by 30% and 91.9%. A similar approach was followed to obtain estimates the pollution cost of material damage. Adding up all these values provides an estimate of the cost of VOCs, CO, NO_x, PM_{10}, SO_x, and ozone air pollution resulting from passenger cars and light trucks that traveled a total of 784 billion miles (approximately 30% of the annual miles in the U.S). The estimates are in 2004 prices. Figure 1 includes a flow chart of the procedure used.

Results

The data given in Table 2 show the results from the GREET model. For a given transportation fuel/technology combination, GREET separately calculates the fuel-cycle (well-to-wheel) energy consumption for each vehicle type. The GREET model calculates the fuel-cycle (well-to-wheel) emissions of three GHGs including CO_2 with a global warming potential (GWP) of 1, methane (CH_4) with a GWP of 21, and nitrous oxide (N_2O) with a GWP of 310. GREET calculates fuel-cycle (well-to-wheel) emissions of the following six criteria pollutants: VOCs, CO, NO_x, PM_{10}, SOx, and ozone. The cost of the six criteria air pollutants is estimated for U.S. emissions of CG and E10 for the number of miles that could be traveled if four billion gallons of ethanol were produced and consumed as E10 by passenger cars and light-duty trucks.

The GREET model fuel-cycle analysis (or well-to-wheel analysis) includes the feedstock, fuel, and vehicle operation stages. Energy use and emissions are presented separately for each of the three stages. The feedstock stage includes recovery, transportation and storage. For E10 the feedstock stage also includes either corn (for E10-corn) or LCB (for E10-LCB) production and harvest. The fuel stage includes production, transportation, storage, and distribution. The third stage is for vehicle operation (Wang). The feedstock and fuel stages together make up the well-to-pump (WTP) or upstream stages. The vehicle operation stage makes up the pump-to-wheel or downstream stage (Wang).

Three fuel types chosen in this GREET model are CG, E10-corn and E10-LCB. The data provided in Table 3 show a summary of U.S. externality costs by pollutant from using motor vehicles for the three fuel types for 30% of the 2002 total miles traveled by passenger cars and light-duty trucks, in 2004 dollars. The first part of the table gives the air pollution cost estimates to health, visibility and crop damage by each of six pollutants from motor vehicle use and a sum of the costs. Estimates of total material and forest damage due to motor vehicle air pollution are added in the second part of the table giving the externality costs due to air pollution from motor-vehicle operations including upstream production of fuels. The cost estimates are given as a range from low to high.

For CG, the estimated air pollution cost of 30 percent of U.S. passenger cars and light-duty truck miles ranges from $6.6 to $68.0 billion. For E10-corn, the estimated air pollution costs for the equivalent number of miles ranges from $7.0 to $72.2 billion. For E10-LCB, the estimates range from $6.0 to $62.0 billion. By this measure, four billion gallons of ethanol produced from LCB and used in motor vehicles as E10-LCB would reduce pollution costs from $1.0 to $10.2 billion relative to four billion gallons of ethanol produced from corn grain and used as E10-corn. However, four billion gallons of corn ethanol, if used to produce E10-corn, causes from $0.3 to $4.3 billion more damage in terms of air pollution than CG. This result follows because pollution resulting from the production of corn grain is allocated to the feedstock stage of E10-corn. The feedstock stage of E10-corn produces greater quantities of CO, NO_x, PM_{10}, and ozone than the feedstock stage of CG. The feedstock stage of E10-corn also produces greater quantities of CO, NO_x, and PM_{10} than the feedstock stage of E10-LCB. Much of the additional cost in the feedstock stage for E10-corn results from PM_{10}. Pollutants from the corn grain feedstock stage can only be eliminated if the crop land used to produce the corn was idled. This is not likely. It is more likely that the land used to produce corn would be farmed in the absence of a corn-ethanol industry. For example, it is likely that the land would be used to produce corn or other crops such as soybeans for other uses and for export.

Similar results have been reported by other authors. Delucchi reported total air pollution damage from motor-vehicle use of $32.4 to $493.1 billion in 1991 dollars. These estimates are smaller than Delucchi's because they include only 30 percent of 2002 vehicle-miles for passenger cars and light-duty trucks that use gasoline. A study conducted by Small reported total air pollution damage from motor-vehicle use of $2.07 billion in 1974 dollars. But Small's estimates only included damage costs to human health and building materials.

Figure 2 gives estimated emission levels for five of the six pollutants from gasoline-powered motor-vehicle operations and upstream production of fuels for vehicles that use CG, E10-corn, and E10-LCB. The figure shows that gasoline has the highest emissions in all pollutants except for SO_x and PM_{10}. Of the three fuel types E10-corn emits the most SO_x and PM_{10}. Consequently, E10-corn has the highest air pollution costs for SO_x and PM_{10} of all three fuel types (Figure 3). Figure 2 does not include emissions of CO. With the exception of CO, most of the pollutants are emitted in fractions of grams per mile for all fuel types. A vehicle that uses CG emits about 8.2 grams of CO per mile while a vehicle that uses E10-corn or E10-LCB emits about 6.2 grams of CO per mile.

Concluding Remarks

This study provided cost estimates of air pollution from motor-vehicle operations and upstream production of fuels (i.e. conventional gasoline and gasohol). The results are based upon 786 billion miles, which represents about 30 percent of the distance traveled by U.S. passenger cars and light-duty trucks in 2002. This is the approximate distance fueled by the four billion gallons of ethanol produced in 2005 if mixed with gasoline and used as E10.

Damages to human health and the environment as well as impaired visibility will continue because of the rising demand in the use of fossil fuels. Use of gasoline in motor-vehicles is damaging to human health, agricultural crops, forestry, building materials, and impairs visibility. Producing ethanol from lignocellulosic biomass has the potential to reduce the cost of damage to the environment as well as human health and visibility. National policies that encourage continued research in the feasibility of producing ethanol from lignocellulosic biomass could be worthwhile in the near-term and long-term. Additional research will be required to determine the relative differences in cost of greenhouse gas emissions.

References

Bureau of Economic Analysis. Gross Domestic Product: Current Estimates and Percentage Change. Accessed in January 10, 2006. Available online at http://www.bea.gov/bea/dn/home/gdp.htm)

Cline, W. R. “The Economics of Global Warming.” Institute for International Economics, Washington, DC, 1992.

Daniels, R. and Chiabai, A. “Estimating the Cost of Air Pollution from Road Transport in Italy.” *Transportation Research-D* 3(1998): 249-258.

Davis, S. C. and S. W. Diegel. “Transportation Energy Data Book: Edition 24.” Center for Transportation Analysis Engineering Science & Technology Division, Oak Ridge National Laboratory, 2004. Accessed November 2005. Available online at http://cta.ornl.gov/data/download24.shtml

Delucchi, M. A. “Environmental Externalities of Motor-Vehicle Use in the U.S.” *Journal of Transport Economics and Policy* 34 (2000): 135-168.

Delucchi, M. A., J. J. Murphy and D. R. McCubbin. “The Health and Visibility Cost of Air Pollution: A Comparison of Estimation Methods.” *Journal of Environmental Management* 64 (2002): 139-152.

Epplin, F. M. “Cost to Produce and Deliver Switchgrass Biomass to an Ethanol-Conversion Facility in the Southern Plains of the United States.” *Biomass and Bioenergy* 11 (1996): 459-467.

Fankhauser, S. “The Social Costs of Greenhouse Gas Emissions: An Expected Value Approach.” *Energy Journal* 15 (1994): 157-177.

Fankhauser, S. “Valuing Climate Change, The Economics of the Greenhouse.” Earthscan Publication Limited, London, England, 1995.

Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O`Hare, D. M. Kammen. “Ethanol Can Contribute to Energy and Environmental Goals.” *Science* 311 (2006):506-508.

Hall, J. V., V. Brajer, and F. W. Lurmann. “Economic Valuation of Ozone-Related School Absences in the South Coast Air Basin of California.” *Contemporary Economic Policy* 21 (2003): 407-417.

Hall, J. V., A. M. Winer, M. T. Kleinman, F. W.Lurmann, V. Brajer, and S. D. Colome. “Valuing the Health Benefits of Clean Air” *Science* 255 (1992): 812-817.

Krupnick, A. J. and P. R. Portney. “Controlling Urban Air Pollution: A Benefit-Cost Assessment.” *Science* 255 (1991):522-528.

Hendrickson, C. T., L. B. Lave, H. S. Matthews. Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach. RFF Press: Washington, 2006.

McCubbin, D. R. and M. A. Delucchi. "The Health Costs of Motor-Vehicle-Related Air Pollution." *Journal of Transport Economics and Policy* 33 (1999): 253-286.

Miller, Shelie A. and Thomas L. Theis. "Comparison of Life-Cycle Inventory Databases: A Case Study Using Soybean Production". *Journal of Industrial Ecology* 10(2006): 133-147.

Murphy, J. J., M. A. Delucchi, D. R. McCubbin and H. J. Kim. "The Cost of Crop Damage Caused by Ozone Air Pollution from Motor Vehicles." *Journal of Environmental Management* 55 (1999): 273-289.

Neidell, M. J. "Air Pollution, Health, and Socio-Economic Status: The Effect of Outdoor Air Quality on Childhood Asthma." *Journal of Health Economics* 23(2004): 1209-1236.

Nienow, S., K. T. McNamara, and A. R. Gillespie. "Assessing Plantation Biomass for Co-Firing with Coal in Northern Indiana: A Linear Programming Approach." *Biomass and Bioenergy* 18 (2000): 125-135.

Nordhaus, W. D. "The Costs of Slowing Climate Change: A Survey." *Energy Journal* 12(1991): 37-65.

O'Brien, D. J., G. E. Senske, M. J. Kurantz, and J. C. Craig Jr. "Ethanol Recovery from Corn Fiber Hydrolysate Fermentation by Pervaporation." *Bioresource Technology* 92 (March, 2004): 15-19.

Ogden, J. M., R. H. Williams and E. D. Larson. "Societal Lifecycle Costs of Cars with Alternative Fuels/Engines." *Energy Policy* 32 (2004): 7-27.

PRé Consultants. SimaPro. Amersfoort, The Netherlands, 2006. Available online: http://www.pre.nl/simapro/default.htm

Renewable Fuels Association (RFA). "Building a Secure Energy Future." 2003 Available Online at http://www.ethanolrfa.org/outlook2003.PDF, Accessed 2006.

Rozan, A. "How to Measure Health Costs Induced by Air Pollution?" *Swiss Journal of Economics and Statistics,* 137(2001): 103-116.

Shapouri, H., J. A. Duffield, and M. Wang. "The Energy Balance of Corn Ethanol: An Update." United States Department of Agriculture, Agricultural Economic Report Number 813, July 2002. Available Online at http://www.transportation.anl.gov/pdfs/AF/265.pdf. Accessed January, 2006.

Small, K.A. "Estimating the Air Pollution Costs of Transport Modes." *Journal of Transport Economics and Policy* 11 (1977): 109-132.

Small, K.A. and C. Kazimi. “On the Costs of Air Pollution from Motor Vehicles.” *The Environment and Transport* (1999) pages 33-58.

Tembo, G. “Integrative Investment Appraisal and Discrete Capacity Optimization Over Time and Space: The Case of an Emerging Renewable Energy Industry.” Ph.D. Dissertation, Oklahoma State University, Stillwater, Oklahoma, 2000.

Tol, R.S.J. “The Marginal Damage Cost of Carbon Dioxide Emissions: An Assessment of the Uncertainties.” *Energy Policy* 33 (2005): 2064-2074.

U.S. Bureau of Census. Accessed in January 2005. Available online at (http://www.census.gov/Press-Release/www/releases/archives/statepop05table.xls)

Wang, M. Q. “Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies.” November 2005. Center for Transportation Research, Argonne National Laboratory. Available Online at http://www.transportation.anl.gov/pdfs/TA/153.pdf

Wang, M. Q., C. Saricks and D. Santini. “Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions.” Center for Transportation Research, Argonne National Laboratory. 1999.

Table 1. Marginal costs estimates of ambient pollution in $ per kg emitted [1]

Ambient Pollutant	United States[2]		All Urban Areas[3]	
	Low	High	Low	High
Source: Delucchi (1991 $)				
VOCs[4]	0.11	1.20	0.14	1.50
CO	0.01	0.09	0.01	0.10
NO_x	1.36	18.40	1.78	24.45
PM_{10}	10.15	137.68	14.14	191.38
SO_x	7.79	69.49	10.51	94.91
Ozone[5]	0.20	0.42	0.21	0.46
Source: Small and Kazimi (1992 $ for Los Angeles, CA)				
VOCs				2.92
NO_x				10.67
PM_{10}				102.0
SO_x				109.9
Source: Small (1974 $)				
VOCs	0.106			
CO	0.0069			
NO_x	0.35			
PM_{10}	0.206			
SO_x	0.432			

[1]Costs include cost to human health, visibility, crop damage and material damage. Crop damage is affected by ozone. Visibility is not affected by carbon monoxide and ozone. Estimates by Delucchi include damage costs to human health, visibility and crops. Estimates by Small, and Small and Kazimi include damage costs to human health and building materials.

[2]Estimated costs ($/kg) of these pollutants averaged across the U.S.

[3]Estimated costs ($/kg) of these pollutants across U.S. urban areas.

[4]VOCs = volatile organic compounds; CO = carbon monoxide; NO_x = nitrogen oxides; PM_{10} = particulate matter of aerodynamic diameter of 10 microns or less; SO_x = sulfur oxides.

[5]Ozone is formed by reaction between VOCs and NO_x. Ozone levels were calculated by combining the GREET estimates of emission levels of VOCs and NO_x because they contribute jointly to ozone production.

Table 2. Well-to-wheel emissions (grams/mile) for conventional gasoline, E10-corn, and E10-LCB.

	Conventional Gasoline			E10-Corn			E10-LCB		
Item	Feedstock[1]	Fuel[1]	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
CO_2[2]	25	87	454	-2	95	432	-5	74	432
CH_4	0.546	0.109	0.086	0.493	0.129	0.129	0.493	0.094	0.129
N_2O	0.000	0.001	0.031	0.015	0.001	0.031	0.011	0.005	0.031
GHGs	36	90	466	13	98	445	8	78	445
VOC	0.019	0.078	0.312	0.009	0.107	0.250	0.018	0.074	0.250
CO	0.047	0.042	8.104	0.053	0.053	6.078	0.049	0.062	6.078
NO_x	0.130	0.119	0.460	0.146	0.137	0.403	0.142	0.145	0.403
PM_{10}	0.004	0.016	0.034	0.033	0.017	0.026	0.004	0.018	0.026
SO_x	0.053	0.113	0.099	0.052	0.133	0.087	0.052	0.095	0.087
Ozone	0.149	0.198	0.771	0.155	0.244	0.653	0.160	0.219	0.653

[1] The feedstock stage includes recovery, transportation and storage. The fuel stage includes production, transportation, storage, and distribution.

[2] CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide; and GHGs = greenhouse gases. VOCs = volatile organic compounds; CO = carbon monoxide; NO_x = nitrogen oxides; PM_{10} = particulate matter of aerodynamic diameter of 10 microns or less; SO_x = sulfur oxides. Ozone is formed by reaction between VOCs and NO_x. Ozone levels were calculated by combining the GREET estimates of emission levels of VOCs and NO_x because they contribute jointly to ozone production.

Table 3. Air pollution cost of U.S. automobiles and light trucks assuming the use of four billion gallons of ethanol (40 billion gallons of E10) fueled approximately 30% of 2002 vehicle-miles (billion dollars)

Ambient Pollutant[1]	Cost of Motor Vehicle Air Pollution in 2004 (billion $)					
	LOW[2]			HIGH[2]		
	CG[3]	E10-Corn	E10-LCB	CG	E10-Corn	E10-LCB
VOCs	0.070	0.063	0.059	0.766	0.685	0.641
CO	0.128	0.097	0.097	1.151	0.869	0.869
NO_x	1.505	1.457	1.466	20.361	19.708	19.828
PM_{10}	0.857	1.197	0.770	11.629	16.231	10.450
SO_x	3.227	3.310	2.844	28.788	29.529	25.370
Ozone	0.298	0.281	0.275	0.621	0.584	0.573
Total Pollution Costs to Health, Visibility and Crop Losses	6.086	6.403	5.511	63.316	67.605	57.731
Total Material Damage[4]	0.464	0.467	0.422	3.712	3.712	3.408
Total Forest Damage[5]	0.093	0.093	0.085	0.928	0.929	0.853
Total Externality Cost due to Motor Vehicle Air Pollution	6.643	6.963	6.017	67.956	72.246	61.992

[1]The pollutants are as defined in Table 1.
[2] Low and high refer to the low and high marginal cost estimates as reported by Delucchi (Table 1).
[3]CG = conventional gasoline; E10-Corn = gasohol mixed with 10% ethanol from corn; E10-LCB = gasohol with 10% ethanol from lignocellulosic biomass. Total pollution costs to health, visibility and crop losses is the sum of the estimated costs of VOCs, CO, NO_x, PM_{10}, SO_x, and ozone.
[4]Total material damage for E10-Corn and E10-LCB were calculated by obtaining the ratio of the sum of costs due to VOCs, NO_x, and SO_x for E10-Corn to CG and E10-LCB to CG and multiplying this ratio by total material damage for CG.
[5]Total forest damage for E10-Corn and E10-LCB were calculated by obtaining the ratio of the sum of costs due to NO_x, SO_x and ozone for E10-Corn to CG and E10-LCB to CG and multiplying this ratio by total material damage for CG.

Table 4. Air pollution cost of U.S. automobiles and light trucks assuming the use of four billion gallons of ethanol (40 billion gallons of E10) fueled approximately 30% of 2002 vehicle-miles (2004 billion dollars). Feedstock production for E10-Corn is excluded.

Ambient Pollutant[1]	Cost of Motor Vehicle Air Pollution in 2004 Billion Dollars Excluding Feedstock Production for E10-Corn					
	LOW[2]			HIGH		
	CG[3]	E10-Corn	E10-LCB	CG	E10-Corn	E10-LCB
VOCs	0.070	0.061	0.059	0.766	0.669	0.641
CO	0.128	0.096	0.097	1.151	0.861	0.869
NO_x	1.505	1.146	1.466	20.361	15.508	19.828
PM_{10}	0.857	0.678	0.770	11.629	9.196	10.450
SO_x	3.227	2.682	2.844	28.788	23.927	25.370
Ozone	0.298	0.239	0.275	0.621	0.498	0.573
Total Pollution Costs to Health, Visibility & Crop Losses	6.086	4.903	5.511	63.316	50.660	57.731
Total Material Damage[4]	0.464	0.376	0.422	3.712	2.982	3.408
Total Forest Damage[5]	0.093	0.075	0.085	0.928	0.745	0.853
Total Externality Cost due to Motor Vehicle Air Pollution	6.643	5.354	6.017	67.956	54.387	61.992

[1]The pollutants are as defined in Table 1.
[2] Low and high refer to the low and high marginal cost estimates as reported by Delucchi (Table 1).
[3]CG = conventional gasoline; E10-Corn = gasohol mixed with 10% ethanol from corn; E10-LCB = gasohol with 10% ethanol from lignocellulosic biomass. Total pollution costs to health, visibility and crop losses is the sum of the estimated costs of VOCs, CO, NO_x, PM_{10}, SO_x, and ozone.
[4]Total material damage for E10-Corn and E10-LCB were calculated by obtaining the ratio of the sum of costs due to VOCs, NO_x, and SO_x for E10-Corn to CG and E10-LCB to CG and multiplying this ratio by total material damage for CG.
[5]Total forest damage for E10-Corn and E10-LCB were calculated by obtaining the ratio of the sum of costs due to NO_x, SO_x and ozone for E10-Corn to CG and E10-LCB to CG and multiplying this ratio by total material damage for CG.

Table 5. Air pollution cost of U.S. automobiles and light trucks assuming the use of four billion gallons of ethanol (40 billion gallons of E10) fueled approximately 30% of 2002 vehicle-miles (2004 billion dollars). Feedstock production is excluded for all three fuel types.

Ambient Pollutant[1]	Cost of Motor Vehicle Air Pollution in 2004 Billion Dollars Excluding Feedstock Production					
	LOW[2]			HIGH		
	CG[3]	E10-Corn	E10-LCB	CG	E10-Corn	E10-LCB
VOCs	0.067	0.061	0.056	0.731	0.669	0.607
CO	0.127	0.096	0.096	1.144	0.861	0.863
NO_x	1.229	1.146	1.164	16.632	15.508	15.748
PM_{10}	0.794	0.678	0.701	10.776	9.196	9.515
SO_x	2.577	2.682	2.216	22.985	23.927	19.764
Ozone	0.259	0.239	0.233	0.538	0.498	0.484
Total Pollution Costs to Health, Visibility & Crop Losses	5.053	4.903	4.465	52.805	50.660	46.981
Total Material Damage[4]	0.464	0.466	0.412	3.712	3.689	3.323
Total Forest Damage[5]	0.093	0.093	0.082	0.928	0.923	0.832
Total Externality Cost due to Motor Vehicle Air Pollution	5.610	5.462	4.959	57.444	55.272	51.135

[1]The pollutants are as defined in Table 1.
[2] Low and high refer to the low and high marginal cost estimates as reported by Delucchi (Table 1).
[3]CG = conventional gasoline; E10-Corn = gasohol mixed with 10% ethanol from corn; E10-LCB = gasohol with 10% ethanol from lignocellulosic biomass. Total pollution costs to health, visibility and crop losses is the sum of the estimated costs of VOCs, CO, NO_x, PM_{10}, SO_x, and ozone.

[4]Total material damage for E10-Corn and E10-LCB were calculated by obtaining the ratio of the sum of costs due to VOCs, NO_x, and SO_x for E10-Corn to CG and E10-LCB to CG and multiplying this ratio by total material damage for CG.
[5]Total forest damage for E10-Corn and E10-LCB were calculated by obtaining the ratio of the sum of costs due to NO_x, SO_x and ozone for E10-Corn to CG and E10-LCB to CG and multiplying this ratio by total material damage for CG.

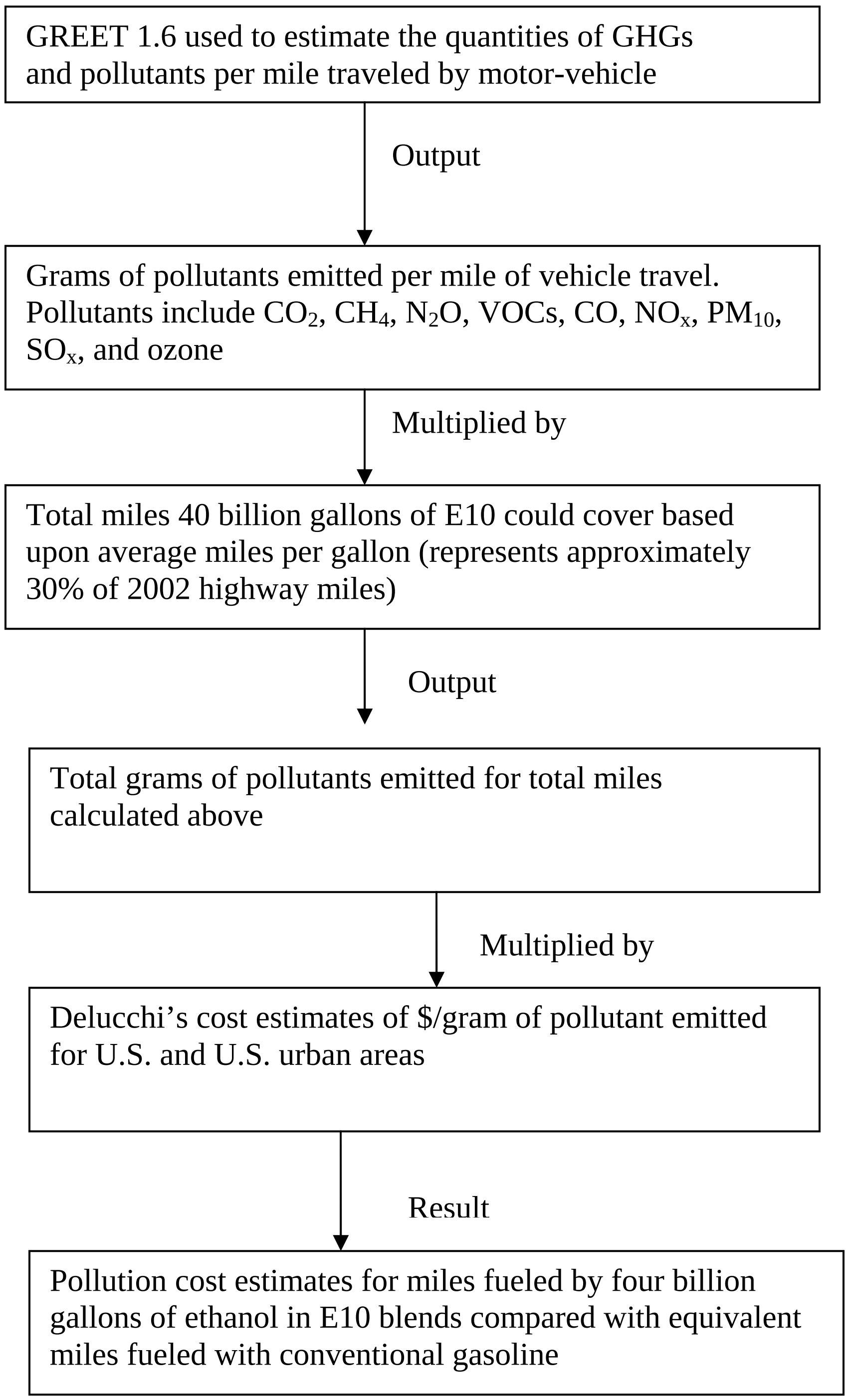

Figure 1. Flow chart of the procedure used to estimate pollution costs

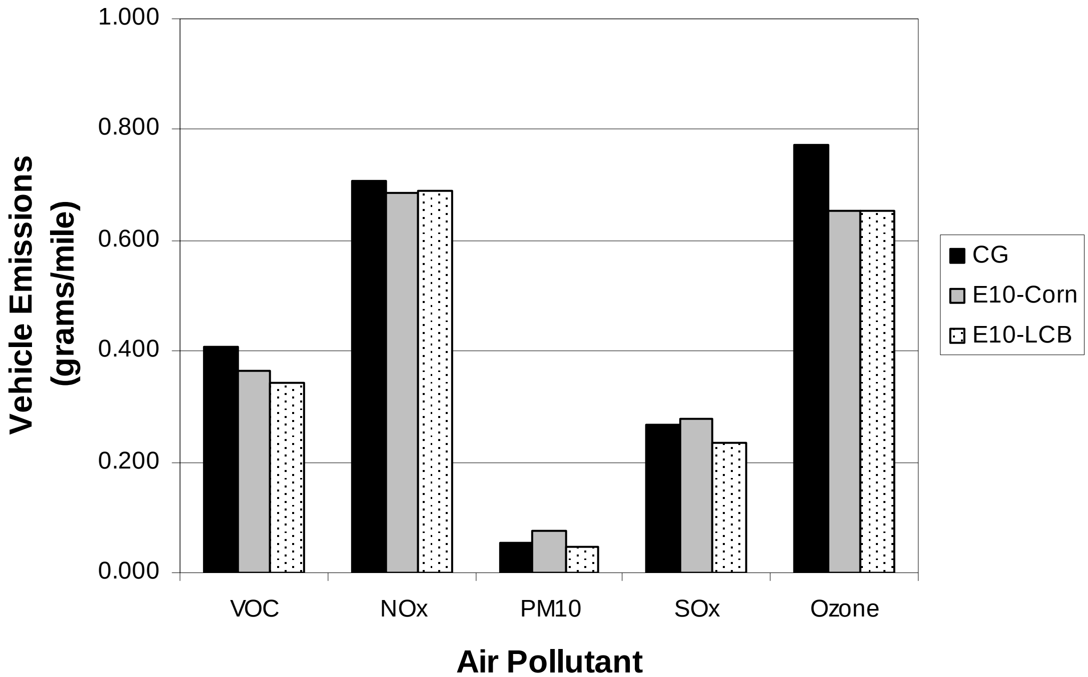

Figure 2. Estimated levels of emissions for each of six air pollutants from gasoline powered motor-vehicle operations and upstream production of fuels for conventional gasoline (CG), and E10 blends (10% ethanol-90% conventional gasoline) with ethanol from corn grain (E10-corn) and ethanol from lignocellulosic biomass (E10-LCB).

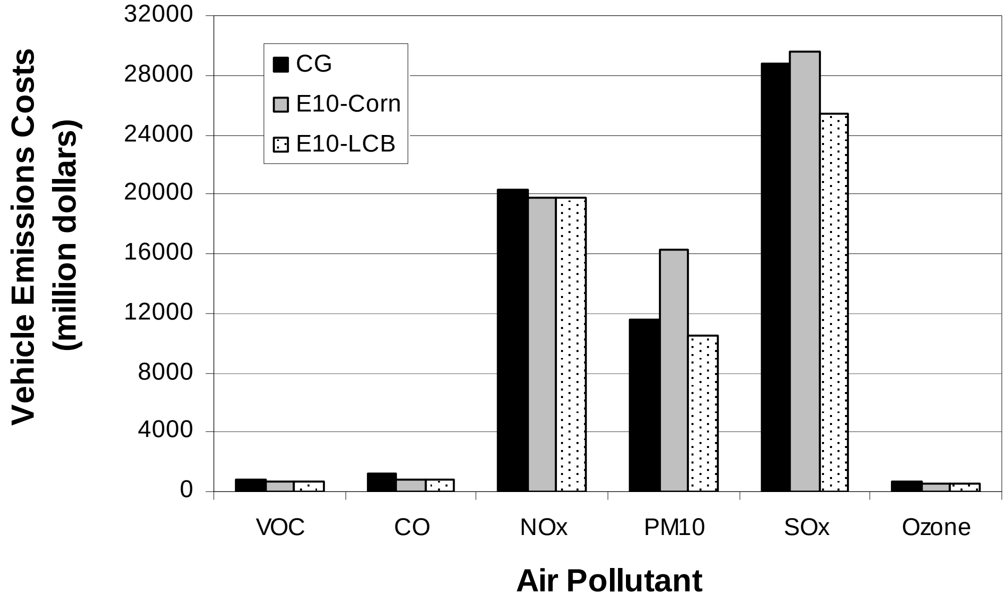

Figure 3. Pollution cost estimates for each of six air pollutants for miles fueled by four billion gallons of ethanol in E10 blends compared with equivalent miles fueled with conventional gasoline, E10-corn, and E10-LCB (in 2004 prices).