A Scenario for a Secure Transportation System Based on Fuel From Biomass

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This article presents a scenario to meet the future fuel needs of the U.S. ground transportation system that does not require hydrogen, can use existing technology, and eventually transition to ethanol from biomass. This scenario is based on a combination of the reduction of liquid fuel use by means of plug-in hybrid electric vehicles and generation of ethanol from biomass. The article also demonstrates the reduction in CO_2 *generation with this technology and the urgency of initiating a strategy for reducing gasoline consumption as soon as possible.* [DOI: 10.1115/1.2855951]

Introduction

An efficient and economically viable transportation system is an essential part of a modern industrial society. In a previous article, the authors presented an approach to meet future demands of the U.S. ground transportation system that does not require hydrogen or oil and can use existing technology [1]. The approach combines a demand-side strategy based on energy efficient plug-in hybrid electric vehicles (HEVs) that could be fueled from existing power generation during off-peak hours with a synthetic fuel generation based on coal. It was pointed out, however, that the overall scheme could eventually transition to the use of renewable biomass that would also utilize existing technologies and drastically reduce carbon dioxide emissions. This article is a continuation of Ref. [1] and presents a scenario that combines plug-in hybrid electric vehicles (PHEV) with ethanol made from corn or cellulosic biomass.

Literature Survey

There have been numerous efforts to evaluate the potential of utilizing biomass to produce a liquid fuel to substitute for gasoline. The most successful effort to achieve that goal has been the Proalcool program in Brazil, which uses sugar cane to produce ethanol that can be burned in flex-fuel vehicles designed to use either gasoline or ethanol [2,3]. The preferred mixture in an economy based largely on ethanol would be 85% ethanol and 15% gasoline that could be used in flex-fuel automobiles. In the United States, ethanol is currently widely used as E10, a mixture of 90% gasoline and 10% ethanol, with the ethanol produced from corn [4].

Hammerschlag [5] recently analyzed the ethanol energy-return-on-investment literature. He showed that, based on the higher heating value of ethanol, the energy output per unit of fossil-fuel-energy input for corn-derived ethanol reported by various authors varied from 0.84 to 1.65 with an average of 1.26. In his article, he also explained why there exist discrepancies between the various studies. They are mainly the result of how much energy output is attributed to by-products and what assumptions are made regarding the production of electricity needed in the process. Hammerschlag also showed that the energy output per unit of fossil-energy input for producing ethanol from cellulosic biomass is approximately four times higher than the ethanol production from corn. This result is in agreement with a study at NREL [6], which concluded that, “there is consensus that the ratio of output energy to fossil fuel inputs is about 5 for lignocellulosic crop conversion to ethanol.”

Analysis

A detailed study on the energy required to produce ethanol [7] was published after the authors’ previous paper [1] had been sent to the printer. In this study, Farrell et al. provided a careful breakdown of all of the energies needed to produce ethanol from either corn or cellulosic material. Using these most recent data, which the authors consider to be the most reliable, an analysis has been made to estimate the mileage, as well as the reduction in carbon dioxide (CO_2) emissions possible with various mixtures of gasoline and ethanol, and four types of vehicle drive that are currently available: a conventional spark ignition (SI) engine, a HEV such as the Toyota Prius, and a PHEV with a 20 mile electric-only range (PHEV20) or a 30 mile electric-only range (PHEV30), for which demonstration models are presently on the road and have been tested by several organizations, including the EPRI [8].

Methodology

The performance of the four vehicle types combined with various fuel options has been calculated. The fuel choices are gasoline only: E10 with ethanol made from either corn or cellulosic materials and E85 with ethanol from either corn or cellulosics. In order to utilize E85 fuel, all vehicles, including hybrids, would need engines designed for that purpose, either flex-fuel (operable on gasoline or E85) or E85 only.

Since there are four different vehicle types and five different fuel choices in our model, there are 20 cases in all. For each case, three different performance parameters are calculated. These are the mileage, the relative amount of petroleum used, and the relative carbon dioxide emissions. The mileage is expressed as miles/gal of gasoline in the fuel (including the petroleum products, generally gasoline and diesel fuel, used in producing ethanol as though they are all gasoline). The relative petroleum consumption is expressed as a percentage of the gasoline consumption by a SI fleet with gasoline as the only liquid fuel (gasoline only). The carbon dioxide emission rate is expressed as a percentage of that for the SI+gasoline-only case. The methods of calculation are described in detail in the Appendix.

The gasoline-only mileage for conventional SI vehicles was estimated by dividing the total U.S. light-vehicle fleet miles driven divided by the total gallons of gasoline consumed by the fleet [9], giving a value approximetely 21 miles/gal. The gasoline-only mileage of HEVs was estimated based on data for the Toyota Prius, at 45 miles/gal. [9]. The gasoline-only mileage of PHEV20s was estimated to be 65 miles/gal from the information used by EPRI in their calculations for plug-in hybrids [8] and 85 miles/gal for HEV30s [10]. When an ethanol-gasoline blend is used as fuel, it is assumed that gasoline and ethanol are utilized with the same efficiency, i.e., that the mileage per unit of fuel energy is the same for gasoline as for ethanol. No direct supportive or contradictory evidence for this was found, but it seems to be a reasonable assumption. In fact, some claim that for high-ethanol-content fuels (e.g., E85), the efficiency would be higher than for gasoline if the car were to be properly tuned for the mixture. Based on this assumption, we have calculated the following:

1. the miles/gal gasoline in fuel, including gasoline used to make ethanol (miles/gal).
2. the petroleum required to drive a particular distance for a

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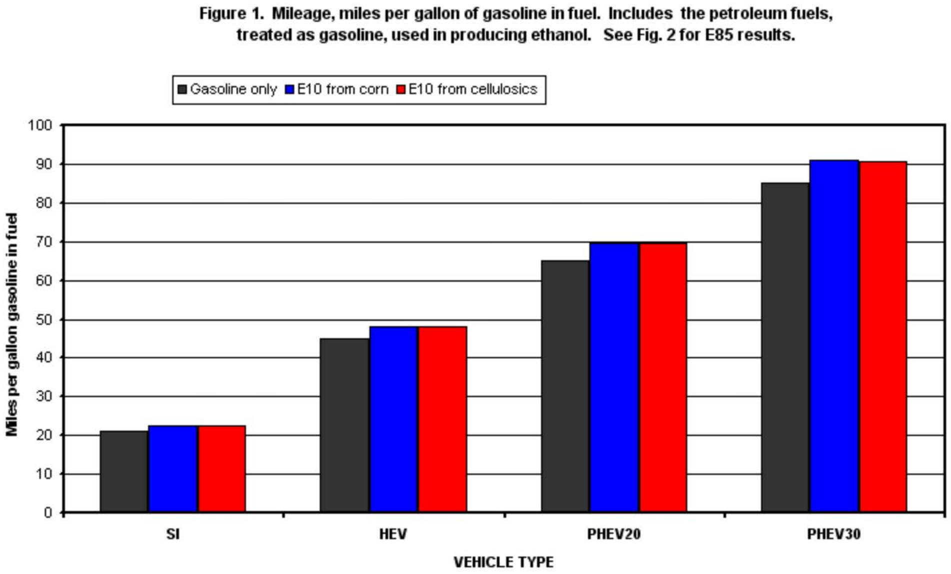

Fig. 1 Mileage, miles/gal of gasoline in fuel. Includes the petroleum fuels, treated as gasoline, used in producing ethanol. See Fig. 2 for E85 results.

case vehicle, as a percentage of the petroleum requirement to drive the same distance by a SI vehicle fueled by gasoline only

3. the carbon dioxide emission rate for case vehicles, as a percentage of that for a SI+gasoline-only case the development of these equations, as well as the values of the parameters used, may be found in the Appendix.

Results and Discussion

The results of this analysis are summarized in Figs. 1–4. Figure 1 shows the estimated miles/gal of gasoline in the fuel for various vehicle-fuel combinations. Mileage results for vehicles using E85 are shown in Fig. 2 on a different scale. These results show that, roughly, for a particular fuel, HEVs double the mileage, PHEV20s triple the mileage, and PHEV30s quadruple the gasoline mileage as compared to the present gasoline-only fleet.

The E10 blend (Fig. 1) only increases the mileage per gallon of gasoline by about 8% compared to gasoline only, and this is virtually the same irrespective of whether the ethanol is from corn or cellulosic materials. Almost all of these changes result from the reduction of the amount of gasoline in the fuel. The miles/gal of fuel for ethanol-gasoline mixtures are actually less than for the corresponding gasoline-only case because ethanol contains only about two-thirds as much energy per gallon. For E10, the mileage is about 0.96 of that of gasoline only, while for E85, the mileage per gallon fuel is about 0.71 of that of gasoline only. The extraor-

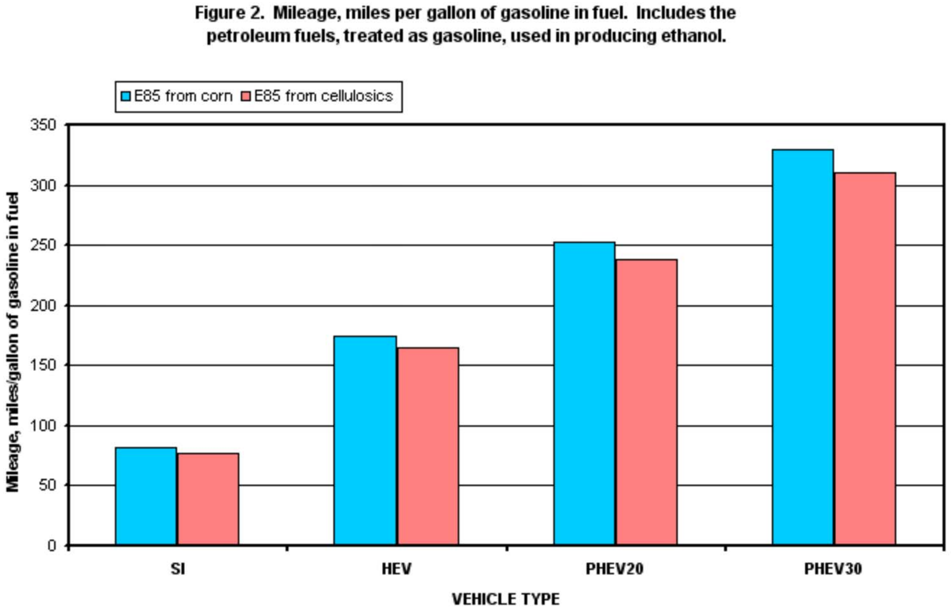

Fig. 2 Mileage, miles/gal of gasoline in fuel. Includes the petroleum fuels, treated as gasoline, used in producing ethanol.

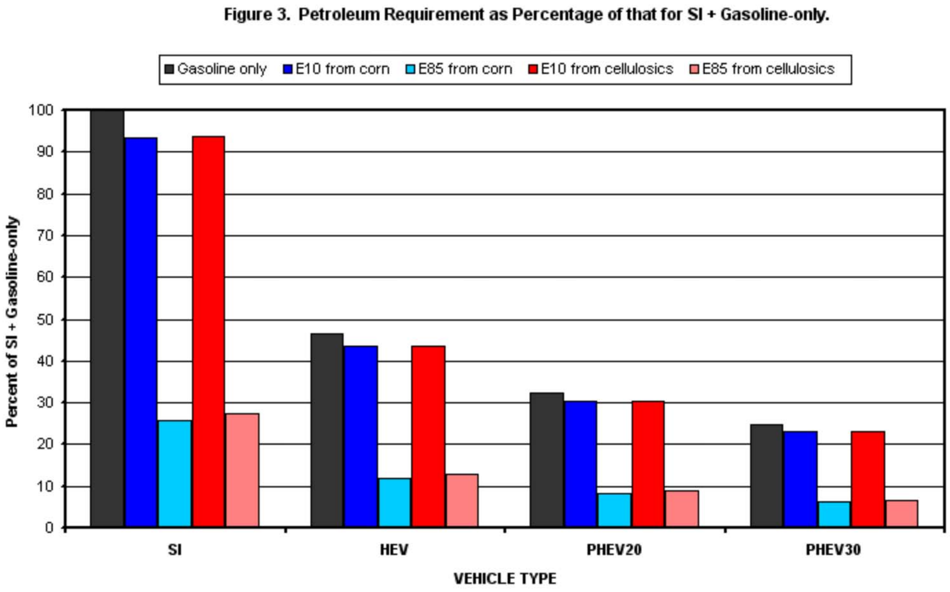

Fig. 3 Petroleum requirement as percentage of that for SI+gasoline only

dinarily high values of miles/gal gasoline for E85, (see Fig. 2) result from that fact that there is only 15% gasoline in the blend, plus the equivalent of an additional 4% when the gasoline used to produce the petroleum is included. This is partially offset by the fact that it takes 1.4 gal of E85 to supply the same energy as 1 gal of gasoline due to the lower energy content of ethanol.

Figure 3 shows the petroleum consumption for various cases as a percentage of the consumption by a gasoline-only SI fleet. If E10 were to be used in the conventional SI fleet, the total petroleum consumption, including that used to make ethanol, would only be 6% less than that for gasoline alone. Although the reduction is slightly less for ethanol made from cellulosics compared to ethanol made from corn, the difference is trivial. For SI-E85 vehicles, the petroleum consumption is about 27% of that for SI-gasoline vehicles. For HEVs, the petroleum consumption is about 46% of that for the corresponding SI vehicle. For a PHEV20, it is only about one-third that of the corresponding SI vehicle, and for PHEV30s about 25% of that for SIs. Again, there are only trivial differences in petroleum consumption caused by whether ethanol is made from corn or cellulosics. HEVs and PHEVs using E85 fuel result in the greatest reductions in petroleum usage, less than 12% and less than 8% of the corresponding SI vehicle, respectively.

Figure 4 compares the carbon dioxide emissions from various options to the SI gasoline-only case. The use of E10 in SI vehicles hardly reduces carbon dioxide emissions for ethanol from corn, and by 6% for ethanol from cellulosics, as compared to gasoline only.

E85 reduces CO_2 emissions by only about 6% when made from corn, but drastically to about 1/3 of that for gasoline only if the ethanol was made from cellulosics. For HEVs, emissions are

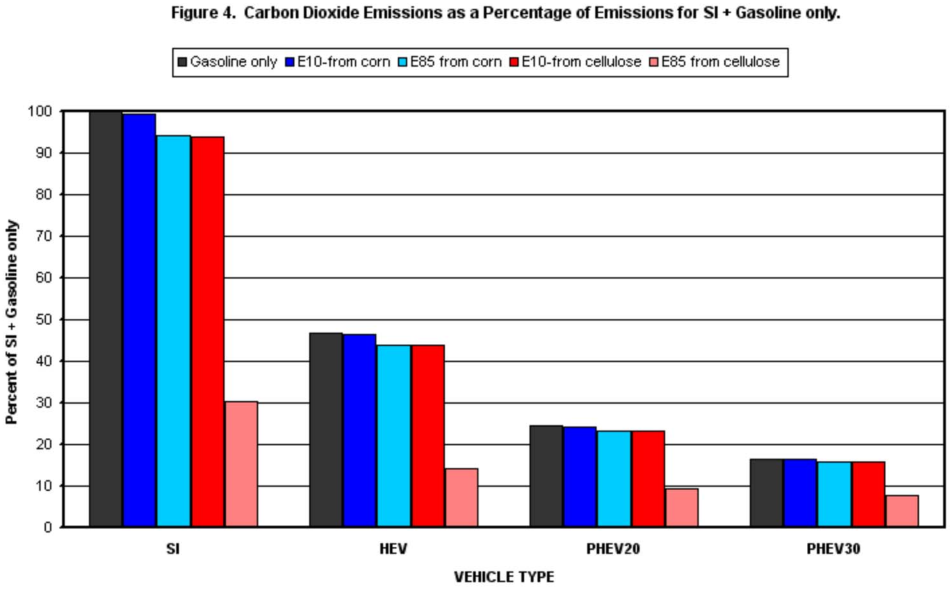

Fig. 4 Carbon dioxide emissions as a percentage of emissions for SI+gasoline only

about 45% of those from SI vehicles using the same fuel. For PHEV20s with gasoline, E10 from corn or cellulosics, emissions are about 25% of those from SI vehicles with the same fuel. For PHEV20s with E85 fuel from cellulosics, carbon dioxide emissions are about one-third of those from SI vehicles. PHEV30s show carbon dioxide emissions about 18% of those for SIs for each fuel except E85, for which PHEV30 emissions are about 9% of SI vehicles with gasoline only, which is equivalent to one-fourth of those from SIs using E85.

From the results in Fig. 4, it is clear that HEVs and PHEVs of a successively greater all-electric range can progressively reduce the emissions of carbon dioxide substantially. Gasoline, E10 from corn or cellulosics, and E85 from corn each give about the same carbon dioxide reduction for each vehicle type. E85 from cellulosics promises greater carbon dioxide reductions than any other fuel type for a given vehicle type. However, interestingly, gasoline only with PHEV20s or PHEV30s reduces carbon dioxide more than E85 does with a SI vehicle. These results show that a mix of flex-fuel SIs, HEVs, and PHEVs in combination with gasoline, E10, and E85 can reach significant reductions of carbon dioxide. This multiplicity of pathways is a distinct advantage, as it is not necessary to depend solely on a particular vehicle type and a particular fuel type to achieve significant reductions in CO_2 emissions.

The U.S. Energy Policy Act of 2005 requires that 7.5×10^9 gal of ethanol per year must be produced by the year 2012 [11]. At the present time, the U.S. uses about 140×10^9 gal of ground transportation fuel per year. The amount of gasoline required for the fleet could be reduced by a factor of about 2 with E10 HEVs or a factor of 3 with E10 PHEV20s, to about 75×10^9 gal or 50×10^9 gal of gasoline per year, or 7.5×10^9 gal and 5×10^9 gal of ethanol per year, respectively. The projected production rate of 7.5×10^9 gal of ethanol would be sufficient to meet this need for E10 fuel. Some 24×10^9 gal, 15×10^9 gal, or 11×10^9 gal of ethanol would be needed to supply the entire fleet of HEVs, PHEV20s, or PHEV30s, respectively, with E85. Thus, a substantially higher, but definitely achievable, growth in the ethanol industry would be required.

According to the Energy Information Agency, in the year 2003, at a retail price of \$1.56/gal of gasoline, 44% of the total cost came from crude oil, while 56% came from taxes, refinery costs, distribution, and profits. Since that time, the cost of crude oil has more than doubled, and this explains why the consumer currently has to pay about \$3.00/gal. According to Sanna, with the cost of electricity at \$0.085 kW h, a PHEV20 would run at the equivalent of \$0.75/gal for the electricity-only portion of its mileage [12]. Given that half of the cars in the U.S. are driven 25 miles/day or less, a plug-in with a 20 mile range battery pack could reduce petroleum fuel consumption by more than 2/3 and the cost per mile appreciably.

According to Sommerville [13], several significant problems must be overcome to make fuels from lignocellulosic biomass. Cellulose is a recalcitrant substrate for bioconversion, and at present large amounts of enzymes are required to produce sugar. Lignin occludes polysaccharides and inhibits enzymatic hydrolysis of the carbohydrates. A large amount of energy is required for its removal. A suitable procedure for converting plant lignocellulose should be a high priority of current R&D.

A recent analysis [14] has shown that the U.S. could produce 1.3×10^9 tons of biomass each year in addition to present agricultural and forested production. It is potentially possible to obtain 100 gal of ethanol from a ton of cellulosic biomass [13] Thus, the United States could sustainably produce about 130×10^9 gal of biomass-derived ethanol, which is more than the amount required if the fleet would use only HEV and PHEV vehicles.

Figures 3 and 4 show what enormous improvements could be achieved if ethanol were produced from cellulosic biomass. With an E85 with cellulosic ethanol mixture, the petroleum consumption, as a percentage of the conventional vehicle fleet, drops to 27% that of the HEV to 13% and that of the plug-in electric vehicles to less than 10% of that for the current fleet average. The greatest benefit from using cellulosic ethanol, however, is the huge reduction in CO_2 emission. The emissions, with E85 from cellulosics, as a percentage of those for the current fleet, would drop to 30% for a conventional vehicle, 15% for a HEV, and 17% for a PHEV20. The reason why the CO_2 emissions for the 20 mile plug-in hybrid are higher than that of the hybrid is that CO_2 is emitted by the largely coal energy sources in the electric power grid used in the recharging of batteries. That also explains why emissions for PHEV30s are greater than for PHEV20s. The CO_2 production from the electric power grid was obtained from current values published by the Energy Information Agency [15].

A combination of plug-in hybrid vehicles with cellulosic E85 as the fuel can lead to a sustainable transportation system based on biofuels. This combination, which is based on currently available technology, would reduce gasoline consumption to less than 10% and carbon dioxide emissions to less than 10% of the current rates.

It has also been shown that the PHEV load on the existing utility grid would not require an increase in generation capacity if the utilities have some control over when battery recharging occurs because there is currently a large amount of underutilized generation capacity [16]. This study has also shown that "the dispatchable load offered by PHEVs could increase the minimum system load, increase the utilization of base load units, and decrease plant cycling all without increasing the need for new generating assets. It is assumed that if a utility can add load to existing generators, these "marginal" sales can be made at just the variable cost of fuel and O&M, which can be quite low."

Conclusions

The analysis presented above shows that a plug-in electric vehicle with a 20 mile electric range, which is easily within reach of current technology, could achieve more than 200 miles/gal of gasoline and reduce CO_2 emissions to less than 25% of the current emissions from the fleet on the road today. Since the transportation sector consumes nearly one-third of the total energy used by the U.S. economy, the scenario presented shows that the light-vehicle fleet could be made to reduce the total CO_2 emissions of the United States by approximately 25%. Such a reduction would represent an enormous contribution to the goals of the Kyoto Protocol and could begin to bring the United States into compliance with the Protocol.

In addition to the enormous environmental benefits from the introduction of plug-in electric vehicles fueled by E85 made from cellulosic materials, the transition to this transportation system would create many jobs in the United States, reduce or eliminate the dependence on imported oil, and insulate the U.S. economy from the threats posed by uncertainties in oil production in countries that have unstable governments or whose production is subject to interruptions. It should also be noted that in order to achieve this goal, virtually all the technologies must be available, and then the transition could begin immediately. The timing would, of course, depend on the investment strategy, but would be helped enormously by a corporate average fuel economy (CAFE) standard that would force the automobile industry to produce flex vehicles capable of hybrid electric performance with 20 miles or more all-electric capacity and a carbon tax to pay for the transition.

One of the main obstacles to a paradigm shift in the transportation sector is the availability of a fueling infrastructure. Current automobiles with SI engines could handle 10% or 15% ethanol. This step, which could be implemented immediately with the current distribution infrastructure, would reduce gasoline consumption with PHEV20s to less than 30% of the current fleet. However, more flex-fuel vehicles would have to be introduced in order to take advantage of higher ethanol content, including flex-fuel engines on hybrid vehicles. It is beyond the scope of this paper to analyze the costs and possible investment strategy. However, given the enormous advantages, it is recommended that an appropriate organization provide that type of information. However, as previously shown by the authors in Ref. [1], it will take at least ten years for a substantial impact of the transition to an energy efficient automobile fleet to be felt. It is therefore imperative that steps be taken to initiate this transition immediately.

Appendix A: Development of Equations

Here, we show the development of the equations for calculating the following: miles/gal of fuel, miles/gal of gasoline in the fuel, petroleum required as a percentage of that required for a gasoline-only fueled vehicle, and the carbon dioxide (CO_2) emissions as a percentage of those for a gasoline-only fueled vehicle.

The key assumption made in this development is that ethanol is used in each vehicle type at the same energy efficiency as is gasoline, or, stated another way, a given amount of energy produces the same miles of travel whether the energy comes from gasoline or ethanol. We have seen some indication that this is valid, though there are those who say that if a given engine were to be tuned for ethanol (or an ethanol-fuel blend), it would be more efficient than a gasoline-only engine.

Table 1 Nomenclature for vehicle index

Index i	Vehicle type	Miles/gal, of gasoline only (MGO_i)	Source
1	SI gasoline engine, current fleet average	21	[9]
2	Gasoline-HEV	45	[9]
3	Plug-in gasoline-PHEV20	65	[8]
4	Plug-in gasoline-PHEV30	85	[10]

A.1 Mileage

The mileage for each vehicle type operating on gasoline only has been taken from the literature, giving the following values.

The miles/gal of fuel is given by

$$\text{miles/gal of fuel, } MF_{ij} = (\text{miles/gal gas}) \times [(\text{gal gas/gal fuel}) + (1 - \text{gal gas/gal fuel}) \times (\text{energy, LHV/gal ethanol})/(\text{LHV/gal gasoline})] = MGO_i[FG_j + (1 - FG_j)(\text{LHV ratio})]$$

where, MF_{ij} is miles/gal of fuel for vehicles type i and fuel type j, MGO_i is miles/gal gasoline-only for vehicle i (see Table 1 above), FG_j is the volume fraction of gasoline in fuel type j $(1-FG_j)$ is the volume fraction of ethanol in fuel type j, and the ratio of lower heating values (LHVs) is LHV ratio=(LHV/gal ethanol)/(LHV/gal gasoline)=0.6625. The index i indicates the vehicle type as shown in Table 1, and the index j denotes the volume fraction of gasoline in an ethanol-gasoline blend as follows: for gasoline only, $FG_1=1$; for E10 (i.e., 10 vol % ethanol and 90 vol % gasoline), $FG_2=0.90$; and for E85 (85 vol % ethanol, 15 vol % gasoline), $FG_3=0.15$. Other ethanol concentrations could be used.

The miles/gallon of gasoline in the fuel, including the petroleum-based fuels used in making ethanol in the fuel (by counting the energy of all petroleum-based fuels as gasoline), is given by

$$\text{miles/gal of gasoline in fuel, } MG_{ijk} = \frac{MF_{ij}}{[FG_j + (1 - FG_j) \times (0.6625) \times (\text{MJ gasoline used in making 1 gal ethanol})(\text{MJ/gal ethanol})]} = \frac{MF_{ij}}{FG_j + (1 - FG_j) \times (0.6625) \times Rk}$$

where Rk denotes the MJ of gasoline used to make one MJ of ethanol. For corn-based ethanol, $k=1$, $R1=0.06$, while for cellulosic-based ethanol, $k=2$, $R2=0.08$ [7].

A.2 Petroleum Requirement

The petroleum required to produce an ethanol-gasoline blend, including the petroleum used to make the ethanol, is expressed as a percentage of the petroleum required for the same miles traveled by the same vehicle type using gasoline only. For a gasoline-only-fueled vehicle of any type, this percentage is 100%. A general equation for the percentage petroleum requirement is

$$\text{Petroleum requirement, } \% = 100 \times (MGO_i)/(MG_{ijk})$$

A.3 Carbon Dioxide Emissions

The CO_2 emissions, including those from making the ethanol and generating the electricity used from the grid by the vehicle, are expressed as a percentage of the emissions produced by the same type of vehicle fueled by gasoline only traveling the same number of miles.

$$CO_2 \text{ production, } \% \text{ of that for gasoline-only vehicle} = 100 \times [FE_m \times (\text{kW h/mile}) \times (\text{g-carbon/kW h}) + (1/MF_{ij}) \times (1 - FE_m) \times [FG_j \times (\text{g-carbon/MJ gasoline}) \times (\text{MJ/gal gasoline}) + (1 - FG_j) \times ((\text{MJ/gal ethanol}) \times (\text{g-carbon/MJ ethanol})]/[(\text{g-carbon/MJ gasoline used}) \times (\text{MJ/gal gasoline})/(MGO_1)]$$

where FE_m is the fraction of the miles driven by electricity from the grid for a plug-in hybrid vehicle. For $m=0$, any non-PHEV, $FE_0=0$; for a PHEV20, $m=1$, and $FE_1=0.327$ [8]; for a PHEV30, $m=2$, and $FE_2=0.50$ estimated by analogy with PHEV20. According to Ref. [8], the kW h/mile from the grid=0.2853, the g-carbon emitted/kW h=157 (146 average for all electricity generation [15] divided by 0.93, the average transmission efficiency), the g-carbon emitted/MJ gasoline=94 [8], the MJ/gal gasoline=121, the MJ/gal ethanol =80.2, and CE_k the g-carbon emitted/MJ ethanol. For $k=1$ (corn), $CE_1=87$, and for $k=2$, cellulosics, $CE_2=11$.

So,

CO$_2$ production as a % of that for gasoline-only vehicle

$$= \frac{100 \times \{\mathrm{FE}_m \times (0.2853) \times (157) + (1/\mathrm{MF}_{ij}) \times (1 - \mathrm{FE}_m) \times [\mathrm{FG}_j \times (94) \times 121 + (1 - \mathrm{FG}_j) \times \mathrm{CE}_k \times (80.2)]\}}{(94) \times (121)/21}$$

A.4 Example

The use of the equations is demonstrated for this case: PHEV30, E85, ethanol from cellulosics. The relevant variables are

$$\mathrm{FE}_m = 0.5$$

$$\mathrm{MF}_{ij} = 85 \times (0.15 + 0.85 \times 0.6625) = 60.61$$

$$\mathrm{CE}_k = 11$$

So, the result is

$$\mathrm{CO}_2 \text{ production, } \% \text{ of that for gasoline-only vehicle} = 100 \times \{(0.5 \times 0.2853 \times 157) + (1/60.61) \times 0.5[0.15 \times 94 \times 121 + 0.85 \times 11 \times 80.2]\}/(94 \times 21/21) = 4.13 + 2.60 + 1.14 = 7.87\%$$

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