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Assessment of Bioethanol Applications on Transportation Vehicles in Houston

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Abstract

A large amount of emissions from area industry and transportation causes severe air pollution problems in the Houston metro area in Texas. Bioethanol has been added in gasoline for many years in the US and the aim is to not only reduce the consumption of the fossil fuels, but also to improve air quality. Life cycle assessment is carried out to evaluate energy and water use, and emissions from transportation vehicles fueled with gasoline and blended fractions of bioethanol in Houston metro area. The emissions examined include greenhouse gases (GHG), VOC, SOx, CO, NOx and PM2.5 and PM10. Some blends of gasoline and bioethanol derived from corn, such as E0, E10, E20, high octane fuel (HOF) E25, HOF E40, E50, E85 and E100 were investigated to study the effects of the blends on the criteria emissions. The emissions were analyzed for three pathways, well-to-pump, pump-to-vehicle and well-to-wheel using the GREET 1 2015 model. The well-to-pump analysis generally showed that only GHGs emissions reduce with the increase of bioethanol blend rates, not other pollutants. The pump-to-vehicle study verified that HOF E25 and HOF E40 are excellent for the vehicles equipped with traditional SI engines and E85 is better for Fuel flexible vehicles (FFV). The well-to-wheel study showed that GHG and CO emissions are reduced with the increase of the bioethanol in the fuel blends; the use of energy and water increases at higher bioethanol ratios; and HOF E25 and HOF E40 are competing fuels to E10 with excellent performance, lower CO_2 emissions and slightly increase of other emissions.

Keywords: Life cycle assessment; Transportation vehicles; Bioethanol; Emissions

Abbreviations

FCV: Fuel Cell Vehicle; FFV: Flexible Fuel Vehicle; GHG: Greenhouse Gas; HOF: High Octane Fuel; LDT1: Light Duty Truck 1; LDT2: Light Duty Truck 2; PC: Passenger Car; PM: Particulate Matter; P-V: Pump-to-Vehicle; SI: Spark Ignition; TBW: Tire and Brake Wear; W-P: Well-to-Pump; W-W: Well-to-Wheel; VMT: Vehicle Miles Travelled; VOC: Volatile Organic Carbon

Introduction

Bioethanol is the most widely used renewable transportation fuel in the world, especially in the US and Brazil, and can be produced from corn, sugarcane, potato, sweet sorghum and cellulosic feedstocks. Besides the renewability, bioethanol has some advantages for use as a transportation fuel, e.g. energy independence from non-renewable crude oil, clean-burning in vehicles and less toxicity. Compared to the complicated emissions of burning gasoline in vehicle engines, bioethanol is a particulate-free burning fuel and its emissions are only carbon dioxide, carbon monoxide, water and aldehydes. Houston, the fourth biggest city in the U.S., is considered one of the most polluted cities in the US due to its heavy transportation and industrial emissions. The increasing emissions of VOCs and NOx from transportation vehicles are even affecting the air quality in Houston because VOCs and NOx are precursors for ground level ozone generation. Thus, the use of bioethanol will have a great impact on improving the air quality in Houston due to fewer emissions, especially much lower VOCs and NOx pollutants emitted from burning bioethanol in vehicles.

Although many technologies for bioethanol productions are currently being developed based on different biomass resources [1-3], the derivation technologies for the first generation bioethanol production are the most mature. Based on the mature technologies, the first generation bioethanol is bulkily produced from starchy biomass such as corn, milo, wheat, rice, potato, cassava, sweet potato and barley, and sucrose containing biomass such as sugarcane, sugar beet, sweet sorghum and fruits. The second generation bioethanol can be produced from lignocellulosic biomass such as wood, straw, and grasses, however, the technical efficiency of the second generation bioethanol production is still low and the cost is relatively high [4]. The third generation bioethanol made using non-arable land is under development [5]. With consideration of corn abundancy around Houston, the mature process of bioethanol produced from corn is applied to our current study to avoid some uncertainties of the second and third generation technologies.

Many studies and practices have shown that ethanol is partially acceptable as a fuel for the popular gasoline SI engines, and fully acceptable in dedicated ethanol engine and FCV. However, the relatively high production cost of the ethanol from food crops hinders its regular use. In the US market, E10 and E85 are the two most popular bioethanol fuel blends with gasoline, where E10 means that 10% bioethanol in volume exists in the fuel, and E85 means 85%

bioethanol in the fuel. E10 can be used in traditional gasoline vehicles without any engine modification and E85 is widely provided for FFVs and dedicated ethanol vehicles. Different high octane HOFs, especially HOF E25 and HOF E40 were recently developed and tested in Brazil and the US [6,7], and the emissions from HOF E25 and HOF E40 are comparable to E10 [8].

The objective of this study is to analyze emissions from bioethanol derived from corn feedstock used in the transportation fleet in Houston by carrying out a life cycle assessment. The pathway of bioethanol production from corn with mature technologies is chosen without any parameter change in GREET model. Bioethanol can be practically mixed with regular gasoline in any blend ratio. Various emissions of gases, including GHGs, VOC, CO, NOx, SOx, PM10 and PM2.5 were analyzed for the production of fuels and vehicle usage. Furthermore, different blends of gasoline and bioethanol by volume were simulated, and the emissions trends were analyzed. The fuel-cycle software package of GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) [9] was used to simulate the fuel use in vehicles and assess vehicle emissions using the VMT reported for Houston.

Methodology

The Excel-based GREET version, GREET 1 [9], was developed by the Argonne National Lab, and the current version is the 2015 version, which was used to simulate the fuel life cycle for transportation vehicles in our study. The software is excellent for analyzing energy and water use, emissions of GHGs and other criteria pollutants for vehicle/fuel system. In our study, various fuel blends of gasoline and bioethanol by volume were analyzed and compared with the conventional unleaded gasoline (E0). Fuel blends include E10, E20, HOF E25 and HOF E40, E50, E85 and E100, where the number is the volumetric percentage of bioethanol in the blends. The vehicle engine types chosen for the study are the most popular SI engine, widely used FFV and the most efficient FCV. The vehicles equipped with SI engine are filled with E0, E10, E20 HOF E25 and HOF E40, FFVs are filled with E50 and E85, and FCVs are filled with E100 according to the commercially available vehicle technologies. The simulations were run for the target years 2012, 2015 and 2020, where the past year 2012, the current year 2015 and the future year 2020 were chosen to examine the effects of the technological development of fuel production and vehicles. Three vehicle types, passenger cars (PC), light duty trucks 1 (LDT1) and light duty trucks 2 (LDT2), which are 5 years earlier than the simulated target year, were included in the simulations. LDT1 refers to a gross weight of the vehicle greater than the passenger car and less than 6000 lbs, and LDT2 is greater than 6000 lbs and less than 8500 lbs [9].

The relative emission rates of E20, E50 and E85 during vehicle operation were determined based on the recent publications and experimental reports for bioethanol effects on the emissions of light duty vehicles [10-14]. Other default emission rates for E0, E10, HOF E25, HOF E40 and E100 provided by the GREET model were used in the simulations. Table 1 shows the relative emission rates of E20, E50 and E85 used in the simulations for the target years 2012, 2015 and 2018. The emission rates of baseline gasoline (E0) were expressed as 100% for all the emissions and the relative emission rates of E20, E50 and E80 were calculated compared to the baseline. Because the real emission rates of baseline gasoline vehicles are improved in the future years, the absolute emissions of different vehicles calculated based on the baseline vehicles are also expected to be improved. The VMT daily records for Houston, Texas for the years 2002-2013 are available and downloadable from the U.S. Department of Transportation/Federal Highway Administration [15]. However, the VMT reports of the current year 2015 and the further year 2020 aren't available. The miles traveled for the years 2015 and 2020 in Houston were estimated based on the economic conditions, the rise in population and vehicle demands in Houston [16,17]. According to the different rates of vehicle classes, PC, LDT1 and LDT2, the VMT of the three types of gasoline-based light duty vehicles were calculated for Houston and are listed in Table 2.

Fuel	Engine type	MPG	VOC (Exhaust)	VOC (Evap.)	CO	NOx	PM10 (Exhaust)	PM10 (TBW)	PM2.5 (Exhaust)	PM2.5 (TBW)
E0	SI	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
E20	SI	90.00%	108.00%	108.00%	86.00%	112.00%	86.00%	100.00%	86.00%	100.00%
E50	FFV	94.30%	75.00%	85.00%	82.00%	23.00%	80.00%	100.00%	80.00%	100.00%
E85	FFV	83.00%	57.00%	85.00%	82.00%	46.00%	66.00%	100.00%	66.00%	100.00%

Table 1: The relative emission rates of vehicle engines fueled with E20, E50 and E85.

Year	Passenger cars	LDT1	LDT2
2012	65,602,554	21,336,753	9,447,617
2015	66,364,548	21,584,586	9,557,354
2020	67,053,618	21,808,701	9,656,589

Table 2: VMT of three types of gasoline-based light duty vehicles in the years 2012, 2015 and 2020 (Units: mile).

Pollutants (2012)	E0 SI	E10 SI	E20 SI	HOF E25 SI	HOF E40 SI	E50 FFV	E85 FFV	E100 FCV
Energy	75,508,638	86,567,657	109,358,303	100,524,487	116,546,781	148,170,320	244,119,863	179,975,250
Water	10,822	20,130	33,453	32,161	48,147	68,792	141,937	99,831
GHGs	5,996,183	5,356,630	5,190,062	4,121,332	2,930,810	2,420,482	-1,632,233	-1,445,665
VOC	8,856	9,544	11,423	10,162	11,335	13,626	20,192	12,844
CO	5,558	6,814	9,067	8,650	10,740	13,627	24,087	17,218
NOx	15,185	16,756	20,489	18,147	20,771	25,778	40,053	26,606
PM10	1,260	1,592	2,163	1,701	2,266	3,377	6,107	4,319
PM2.5	901	1,010	1,251	1,010	1,172	1,625	2,592	1,903
SOx	12,199	13,574	16,719	14,269	17,102	21,402	33,737	21,713
Pollutants (2015)	**E0 SI**	**E10 SI**	**E20 SI**	**HOF E25 SI**	**HOF E40 SI**	**E50 FFV**	**E85 FFV**	**E100 FCV**
Energy	70,839,617	79,715,003	99,143,394	91,560,516	104,145,445	129,773,043	208,255,540	134,129,060
Water	8,928	17,066	28,654	27,527	41,507	59,576	123,447	86,012
GHGs	5,793,412	5,135,457	4,922,395	3,995,278	2,792,859	2,092,140	-2,131,371	-2,659,808
VOC	7,998	8,600	10,272	9,141	10,169	12,186	17,967	11,180
CO	4,833	5,733	7,441	7,097	8,582	10,664	18,279	12,046
NOx	10,743	12,098	15,055	14,167	16,489	19,734	31,703	20,433
PM10	699	982	1,428	1,299	1,794	2,485	4,763	3,248
PM2.5	560	649	827	780	929	1,141	1,904	1,243
SOx	9,156	10,308	12,826	11,857	14,404	16,805	26,990	17,365
Pollutants (2020)	**E0 SI**	**E10 SI**	**E20 SI**	**HOF E25 SI**	**HOF E40 SI**	**E50 FFV**	**E85 FFV**	**E100 FCV**
Energy	65,579,742	71,211,193	87,519,110	81,811,990	91,463,424	111,444,646	174,915,845	104,452,734
Water	6,940	14,862	24,820	23,715	3,579	51,307	106,077	69,051
GHGs	5,476,612	4,692,570	4,434,761	3,638,370	2,453,883	1,641,580	-2,617,599	-2,727,396
VOC	7,221	7,714	9,190	8,184	9,071	10,827	15,860	9,201
CO	4,230	4,773	6,086	5,820	6,895	8,413	14,063	8,591
NOx	8,029	8,532	10,717	10,426	12,238	14,342	23,413	14,194
PM10	548	774	1,156	1,071	1,506	2,086	4,070	2,608
PM2.5	446	476	615	605	729	873	1,486	912
SOx	6,478	5,895	7,590	8,312	10,171	10,702	18,141	11,123

Table 3: Well-to-pump daily total energy and water use, and emissions of pollutants for passenger cars in Houston. Energy units: kilo Btu; water units: kilogallon; pollutant units: kg.

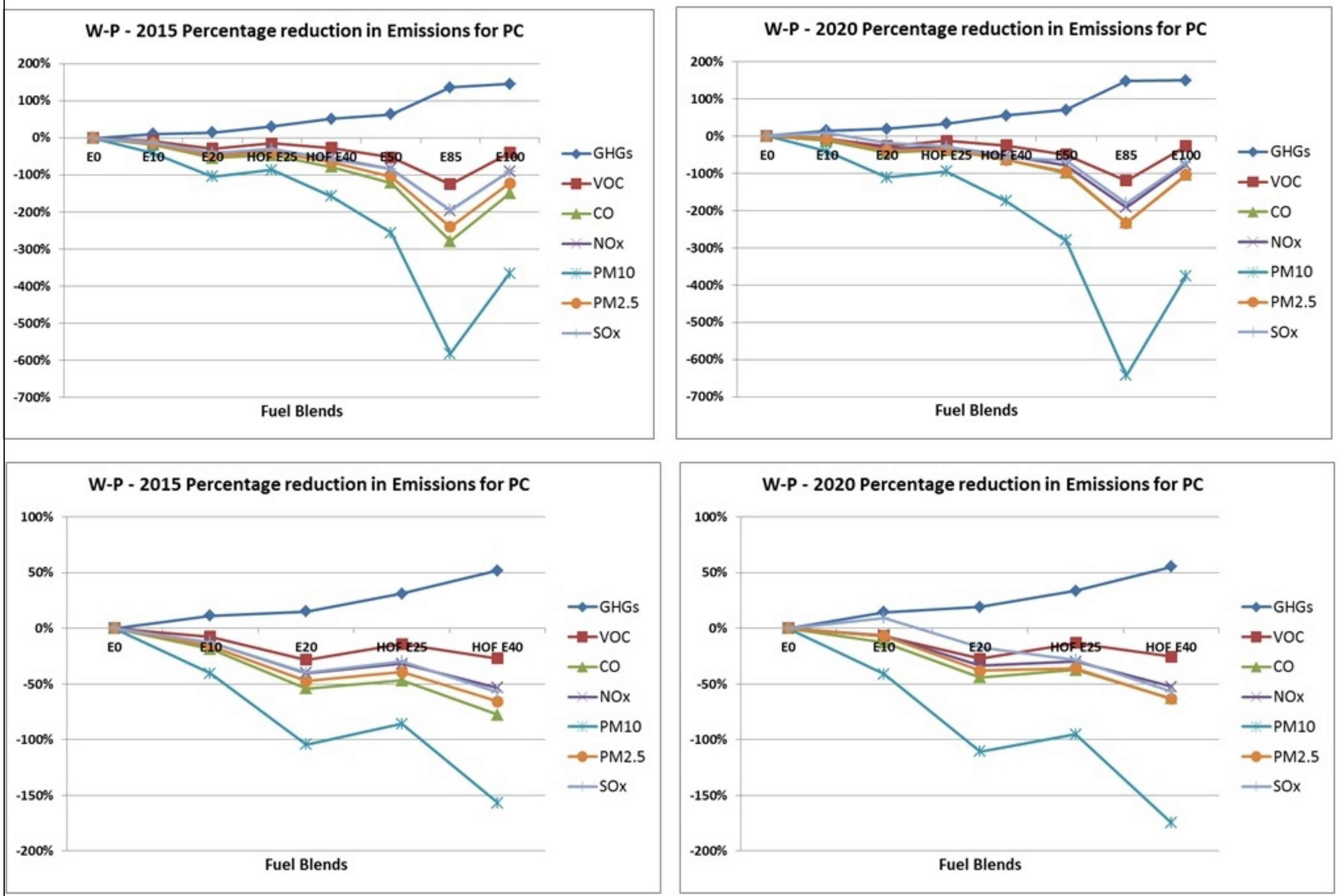

Figure 1: Percentage reduction in Emissions for passenger cars at the stage of well-to-pump (W-P).

Results and Discussion

The life cycle assessment of emissions associated with the blended fuels was performed by the GREET model for the following three pathways: well-to-pump, pump-to-vehicle and well-to-wheel. In all three pathways, the functional units of energy are Btu/mile, the functional units for water are gallon/mile, and the functional units for the different emissions are g/mile. First, the well-to-pump analysis focuses on the feedstock and fuel selections associated with the fuel use in different vehicles. The feedstock stage addresses the energy and water use, and pollutant emissions released in corn farming, corn transportation from field to biofuel refinery, corn fermentation, well mill ethanol production and ethanol transportation. The fuel stage analyzes the energy and water use, and different emissions in developing the specific fuel blends, such as E0, E10, E20, HOF E25, HOF E40, E50, E80 and E100 through the combined processes of ethanol denaturation, conventional gasoline production, a blend of bioethanol and gasoline, and transportation of the blended fuel to gasoline stations. Second, the pump-to-vehicle emissions analysis focuses on studying the energy and water use, and pollutant emissions during vehicle operation. The well-to-wheel analysis adds up the first and second analyses to evaluate the overall energy and water consumption, and emissions from corn planting and production of crude oil to the burnup of the fuel blends in vehicles. The calculated results of the first analysis associated with the VMT report in Houston are listed in Table 3 for the target years 2012, 2015 and 2020, where the bioethanol fuel blends will be individually fueled into vehicles equipped with SI, FFV and FCV engines in the second analysis of pump-to-vehicle.

Figure 1 shows the percentage reductions of pollutant emissions from well to pump in Houston for the target years 2015 and 2020. The two upper panels in Figure 1 show the overall results for all the fuel blends, the two bottom panels show the results for E0, E10, E20, HOF E25 and HOF E40 in detail. The positive values show the reductions of GHGs emissions and the negative percentages show the increases in the particular pollutant emissions, compared to the baseline which is E0 fuel. The results show that GHG emissions are reduced when using higher blends of bioethanol in feeding fuels at the first stage. Compared to the regular gasoline E0, reductions of 11%, 15%, 31%, 52%, 64% and 137% of GHG emissions are estimated when producing E10, E20, HOF E25, HOF E40, E50 and E85 fuel blends respectively for the target year 2015. Similarly, the corresponding reductions of 14%, 19%, 34%, 55%, 70% and 148% of GHG emissions are estimated for the target year 2020. The GHG emissions reduction reaches the maximum with E100 for FCV cars in all three target years 2012, 2015 and 2020. However, the pollutants VOC, CO, NOx, SOx, PM10 and PM2.5 have their emissions increased for all the fuel blends and the highest

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emissions are for E85 used with FFV cars in 2015. This is mainly due to the emissions from the activities associated with bioethanol production and transportation. These emissions dramatically reduce at E100 when used with FCV cars. The emission reduction at E100 from E85 is mostly attributed to the advances of engine technologies for FCV vehicles compared to the SI and FFV engines. Interestingly, the VOC, CO, NOx, PM 2.5 and PM 10 emissions of HOF E25 are lower than those at E20, which are mainly attributed to the refinery advantages of HOF E25 above E20. In 2020, the percentage increase trends of VOC, CO, NOx, SOx, PM10 and PM2.5 are similar to those in 2015 except a 9% emission decrease of SOx at E10. The 9% emission decrease is attributed to the predation of the SOx emission decrease based on the improvement of regular gasoline refinery technology in 2020, which is considered in the LCA study for the future years in the GREET modeling. The emission analyses of LDT1 and LDT2 at the stage of well-to-pump show the same trend as that of passenger cars, although each vehicle of LDT1 and LDT2 consume more fuel than a passenger car.

The pump-to-vehicle analysis includes the energy and water use and emissions from vehicle operation fueled with the different fuel blends. The VMT reports for Houston were also used to determine the absolute daily emissions. Gasoline vehicles including passenger cars, LDT1 and LDT2 are the most driven vehicles in Houston. Thus, they are responsible for the most emissions of pollutants. Table 4 lists energy and water use, and pollutant emissions for passenger cars in Houston for the target years 2012, 2015 and 2020 at the pump-to-vehicle stage. The pump-to-vehicle stage is crucial in the sense that it accounts for about three quarters of the total emissions in the fuel life cycle from well to wheel. The vehicle emissions were also simulated with the three engine types including SI, FFV, and FCV and various fuel blends.

Figure 2 shows the percentage reductions of pollutant emissions from pump to vehicle for the target years 2015 and 2020. The two upper panels in Figure 2 show the overall results for all the fuel blends, the two bottom panels show the results for E0, E10, E20, HOF E25 and HOF E40 in detail. Unlike the clear trends of all the emissions during the well-to-pump stage, most emissions vary for the different fuel blends during the pump-to-vehicle stage. At the pump-to-vehicle stage, the GHGs are of more concern because they are the major gases emitted from vehicles directly into the atmosphere. From E0 to HOF E40 the GHGs emissions vary. As the blends E50, E85 and E100 are introduced, the emissions of GHGs seem to increase from HOF E40 to E85, and then drop at E100 by about 50% relative to the GHG emissions for E85. There is almost no reduction achieved in GHGs for E10 and there is an 11% increase for E20 used in the SI engine cars. Surprisingly, the GHGs reductions are 5% for HOF E25 and 6% for HOF E40 fueled into the SI cars. The advanced refining technical development of crude oil for HOF blend stock mainly contributes to the reduction. The increase of GHG emissions reaches the maximum at about 18% for E85 with the FFV cars for both of the target years 2015 and 2020, and the greatest reductions of GHGs are achieved using E100 with the FCV cars by 36% for the year 2015 and by 40% for the year 2020. Like the GHG emissions from E0 to HOF E40, other pollutant emissions VOC, CO, NOx, SOx, PM 10 and PM2.5 also vary for the different fuel blends. For the fuel blends of E0, HOF E25 and HOF E40, all the other emissions keep at the same level. For E20, the emissions of VOC and NOx increase and the other emissions CO, SOx, PM 10 and PM2.5 decrease compared to those at E0. The emissions of VOC, CO, SOx, PM 10 and PM2.5 are mostly reduced with the increase of bioethanol ratios from E50 to E100 and the greatest emission reductions occur for E100. The VOC emissions reduce at the rate of about 20% for E50, about 30% for E85 fueled into FFV, and about 71% for E100 fueled into FCV. The PM10 and PM2.5 follow similar trends to VOC with smaller reduction percentages. The CO emissions reduce at the rate of about 18% for E50 and E85 fueled into FFV and about 80% for E100 fueled into FCV. The emissions of SOx slightly increase for E20 compared to E10, keep the same for HOF E25 and HOF E40, and then further decrease for FFV vehicles using E50 and E85, and for FCV vehicles using E100. The emissions of NOx increase by 12% for E20 with SI engines, stay the same for HOF E25 and HOF E40, and then also decrease by 77% for E50 and 54% for E85 and reach the maximum reduction of 79% for E100. All the operation emissions of passenger cars in 2012 have similar trends to those in 2015. The emission investigations from pump to vehicle for the other two vehicle types LDT1 and LDT2 show the same trend to those of passenger cars.

The total energy and water use, and emissions of the well-to-wheel life cycle analysis associated with VMT in Houston are listed in Table 5 for the fuel blends in the target years 2012, 2015 and 2020. A well-to-wheel analysis is excellent for making a direct comparison between the total energy costs and emissions for the different vehicle technologies taking into account fuel blend aspects. It covers all the energy use and emissions from the whole pathway, including corn farming, crude oil refinery, fuel transportation, fuel blending and vehicle operation, etc.

Figure 3 shows the percentage reductions of pollutant emissions from well to wheel in Houston for the target years 2015 and 2020. The two upper panels in Figure 3 show the overall results for all the fuel blends, the two bottom panels show the results for E0, E10, E20, HOF E25 and HOF E40 in more detail. Also, the positive values show the reductions of different emissions and the negative percentages show the increases in the particular pollutant emissions. The results show that GHG and CO emissions are reduced when using higher blends of bioethanol in feeding fuels over the whole pathway. Compared to the regular gasoline E0, reductions of 2%, 10%, 15%, 9%, and 14% of GHG emissions are estimated when fueling E10, HOF E25, HOFE 40 into SI engine cars, E50 and E85 for FFV cars for the target year 2015; for E20 used in SI engine cars, there is a 5% GHG emission increase in 2015. For the target year 2020, the GHG emissions of different fuel blends are similar to those in 2015. The reductions of GHG emissions reach the maxima with E100 for FCV cars in all three target years 2012, 2015 and 2020. From E0 to HOF E40, the CO emissions almost keep the same except a reduction of 12% for the year 2015 and 13% for the year 2020 at E20. The reduction in CO emissions is about 14% (year 2015) and 15% (year 2020) at E50 and about 10% (year 2015) and 12% (year 2020) at E85. The greatest reduction of CO emissions occurs at E100 for FCV vehicles. Similar to the pump-to-well analysis from E0 to E85, the pollutants VOC, NOx, SOx, PM10 and PM2.5 have their emissions increased and the highest emissions are noted for E85 blend used with FFV cars. These emissions reduce for E100 used with FCV cars, similar to the trend observed for the well-to-pump stage. The great emission drop at E100 from E85 is dedicated to the technological advances of higher fuel efficiency of FCV engine compared to the SI and FFV engines. The sensitivity of emission increases of VOC, NOx, SOx, PM10 and PM2.5 are very different at the higher different bioethanol blend ratios. The emission percentage of VOC increases from 3% to 21% following the blends from E10 to E85 except for the increase percentage of 14% at E20. However, the emission percentages of SOx, PM10 and PM2.5 dramatically increase following the blend from E10 to E85. The emission increase percentage varies for different blends E10, E20, HOF E25, HOF E40 and E50 and reaches the maximum for

E85. All the overall emissions of passenger cars analyzed from well to wheel in 2012 have the similar trends to those in 2015. The emission investigations for the other two vehicle types LDT1 and LDT2 also show the similar trends to those of passenger cars.

Pollutants (2012)	E0 SI	E10 SI	E20 SI	HOF E25 SI	HOF E40 SI	E50 FFV	E85 FFV	E100 FCV
Energy	314,537,669	314,537,669	349,486,299	299,559,685	299,559,685	333,550,020	378,961,047	212,525,452
Water	0	0	0	0	0	0	0	0
GHGs	24,328,936	24,288,796	26,921,949	23,077,216	23,007,340	25,557,108	28,748,119	15,952,101
VOC	21,763	21,763	23,504	21,763	21,763	17,005	14,316	3,755
CO	205,433	205,433	176,673	205,433	205,433	168,455	168,455	55,533
NOx	13,595	13,595	15,226	13,595	13,595	3,127	6,253	2,603
PM10	1,534	1,534	1,484	1,534	1,534	1,462	1,412	1,174
PM2.5	620	620	575	620	620	556	512	302
SOx	390	364	375	364	364	259	123	0
Pollutants (2015)	**E0 SI**	**E10 SI**	**E20 SI**	**HOF E25 SI**	**HOF E40 SI**	**E50 FFV**	**E85 FFV**	**E100 FCV**
Energy	287,793,234	287,793,234	319,770,260	274,088,794	274,088,794	305,189,007	346,738,836	188,977,285
Water	0	0	0	0	0	0	0	0
GHGs	22,264,566	22,227,839	24,637,101	21,119,277	21,055,343	23,383,438	26,299,631	14,189,296
VOC	15,982	15,982	17,260	15,982	15,982	12,684	11,063	4,592
CO	180,861	180,861	155,540	180,861	180,861	148,306	148,306	36,172
NOx	8,030	8,030	8,994	8,030	8,030	1,847	3,694	1,606
PM10	1,566	1,566	1,515	1,566	1,566	1,494	1,443	1,204
PM2.5	628	628	583	628	628	564	519	308
SOx	356	334	343	334	334	237	112	0
Pollutants (2020)	**E0 SI**	**E10 SI**	**E20 SI**	**HOF E25 SI**	**HOF E40 SI**	**E50 FFV**	**E85 FFV**	**E100 FCV**
Energy	261,668,919	261,668,919	290,743,244	249,208,495	249,208,495	277,485,598	315,263,758	160,622,156
Water	0	0	0	0	0	0	0	0
GHGs	20,207,818	20,174,424	22,364,986	19,166,492	19,108,361	21,225,188	23,876,710	12,054,910
VOC	14,696	14,696	15,872	14,696	14,696	11,706	10,291	4,306
CO	172,186	172,186	148,080	172,186	172,186	141,193	141,193	34,437
NOx	7,410	7,410	8,299	7,410	7,410	1,704	3,408	1,482
PM10	1,562	1,562	1,512	1,562	1,562	1,491	1,441	1,207
PM2.5	622	622	578	622	622	559	516	308
SOx	127	119	123	119	119	86	44	0

Table 4: Pump-to-vehicle daily total energy and water use, and emissions of pollutants for passenger cars in Houston Energy units: kilo Btu; water units: kilogallon; pollutant units: kg.

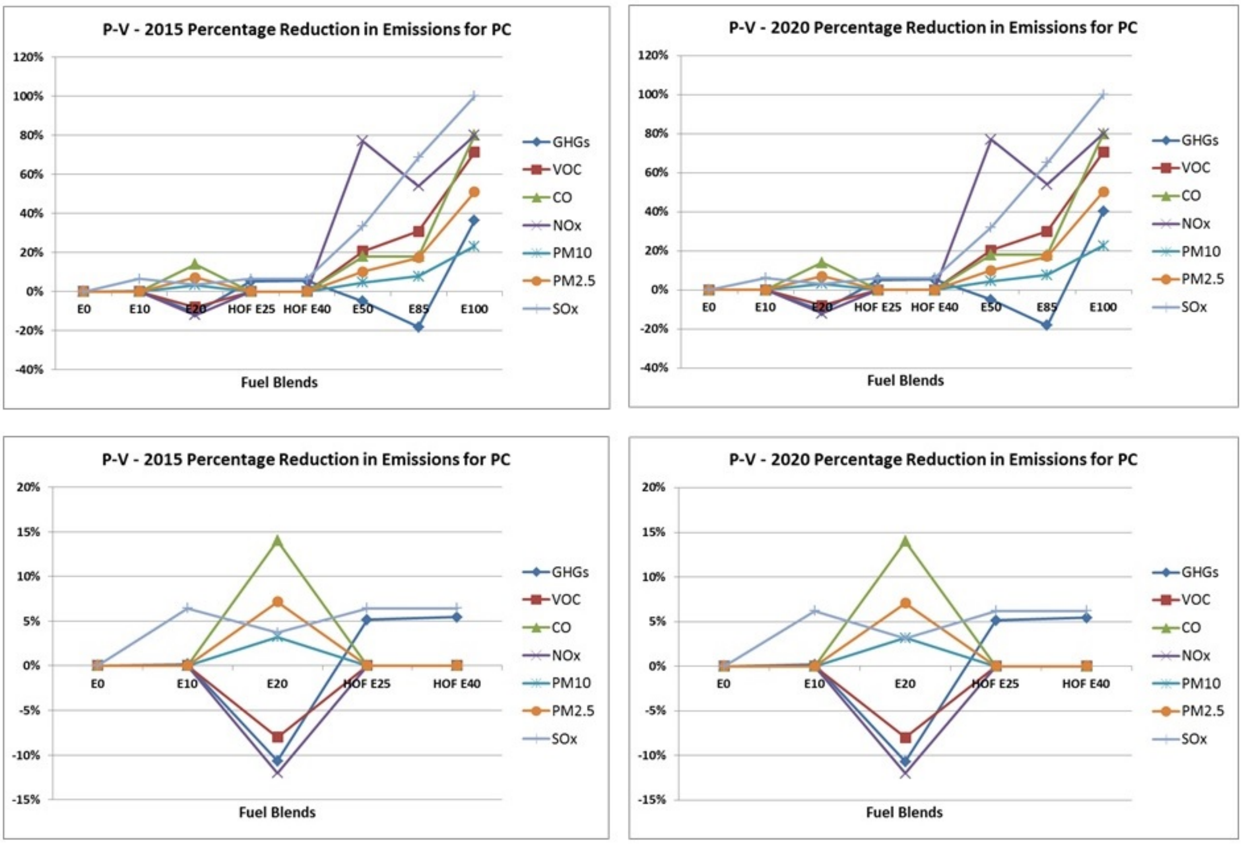

Figure 2: Percentage reduction in Emissions for passenger cars at the stage of pump-to-vehicle.

Pollutants (2012)	E0 SI	E10 SI	E20 SI	HOF E25 SI	HOF E40 SI	E50 FFV	E85 FFV	E100 FCV
Energy	390,046,307	401,105,326	458,844,602	400,084,172	416,106,466	481,720,340	623,080,910	392,500,702
Water	10,822	20,130	33,453	32,161	48,147	68,792	141,937	99,831
GHGs	30,325,120	29,645,426	32,112,010	27,198,549	25,938,151	27,977,591	27,115,886	14,506,436
VOC	30,620	31,307	34,928	31,925	33,098	30,631	34,509	16,600
CO	210,991	212,247	185,740	214,083	216,173	182,082	192,543	72,751
NOx	28,780	30,351	35,715	31,742	34,366	28,904	46,306	29,209
PM10	2,794	3,126	3,647	3,235	3,799	4,839	7,518	5,493
PM2.5	1,521	1,630	1,827	1,630	1,792	2,182	3,104	2,204
SOx	12,588	13,938	17,095	14,633	17,466	21,661	33,859	21,713
Pollutants (2015)	**E0 SI**	**E10 SI**	**E20 SI**	**HOF E25 SI**	**HOF E40 SI**	**E50 FFV**	**E85 FFV**	**E100 FCV**
Energy	358,632,850	367,508,237	418,913,654	365,649,310	378,234,239	434,962,051	554,994,376	323,106,345
Water	8,928	17,066	28,654	27,527	41,507	59,576	123,447	86,012
GHGs	28,057,978	27,363,296	29,559,496	25,114,555	23,848,202	25,475,578	24,168,260	11,529,489

VOC	23,980	24,581	27,532	25,123	26,150	24,870	29,029	15,772
CO	185,694	186,594	162,981	187,958	189,443	158,970	166,585	48,218
NOx	18,774	20,128	24,050	22,198	24,519	21,581	35,397	22,039
PM10	2,265	2,548	2,944	2,865	3,360	3,978	6,206	4,452
PM2.5	1,188	1,277	1,410	1,408	1,557	1,705	2,423	1,551
SOx	9,512	10,642	13,169	12,191	14,738	17,042	27,102	17,365
Pollutants (2020)	**E0 SI**	**E10 SI**	**E20 SI**	**HOF E25 SI**	**HOF E40 SI**	**E50 FFV**	**E85 FFV**	**E100 FCV**
Energy	327,248,662	332,880,112	378,262,354	331,020,484	340,671,919	388,930,245	490,179,603	265,074,890
Water	6,940	14,862	24,820	23,715	35,679	51,307	106,077	69,051
GHGs	25,684,430	24,866,995	26,799,748	22,752,316	21,512,562	22,866,768	21,259,111	9,327,514
VOC	21,917	22,410	25,062	22,827	23,713	22,533	26,151	13,507
CO	176,416	176,959	154,167	177,596	178,669	149,606	155,256	43,028
NOx	15,439	15,941	19,016	17,794	19,602	16,047	26,821	15,675
PM10	2,110	2,336	2,668	2,626	3,061	3,576	5,511	3,815
PM2.5	1,068	1,098	1,193	1,225	1,348	1,432	2,001	1,221
SOx	6,605	6,015	7,713	8,412	10,266	10,788	18,185	11,123

Table 5: Well-to-wheel daily total energy and water use, and emissions of pollutants for passenger cars in Houston Energy units: kilo Btu; water units: kilogallon; pollutant units: kg.

From Table 5, it can be seen that the water and energy consumption increases with the increase of the bioethanol ratio in the fuel blends. The consumption increases are mainly attributed to the production of bioethanol during the well-to-pump stage.

Figure 4 shows the energy and water consumption of the fuel blends analyzed from well to wheel for passenger cars in the different target years.

Compared to E0, the energy use for HOF E25 and HOF E40 slightly increases, the energy use of E20 and E50 respectively increases by about 16~18% and about 19~24% respectively, and the energy consumption reaches the maximum for E85 at 50~60%.

The energy use in the year 2015 is lower than that in the year 2012 from E10 to E85, and even lower in 2020. In the future years, the rate of energy use is lower than the past years due to the technology developments in the future years.

Interestingly, the energy consumption of E100 fueled with FCV cars is reduced compared to E0 in 2015 and 2020, and even more reduced in future years.

In this study, the calculations for energy use for LDT1 and LDT2 show that the similar trends to those for passenger cars from E0 to E85, and that the reductions of energy use occur in all three target years.

The findings show that it is much better for E100 to be fueled into big-size vehicles. The water consumption increases from E0 to E85 except the smaller consumption for HOF E25 relative to E20.

The water use in the year 2015 is more than that in the year 2012 from E10 to E85, The water consumption reaches the maxima of 1212~1428% for E85. The water analysis here agrees with most studies that show huge water use for biofuel production when more biofuel is increasingly consumed in the world [18,19]. The water consumption drops for E100 in FCV.

The less energy and water use of E100 is attributed to the higher miles per gallon (MPG) and specific drive technology used in FCV engine which is different from the SI engine.

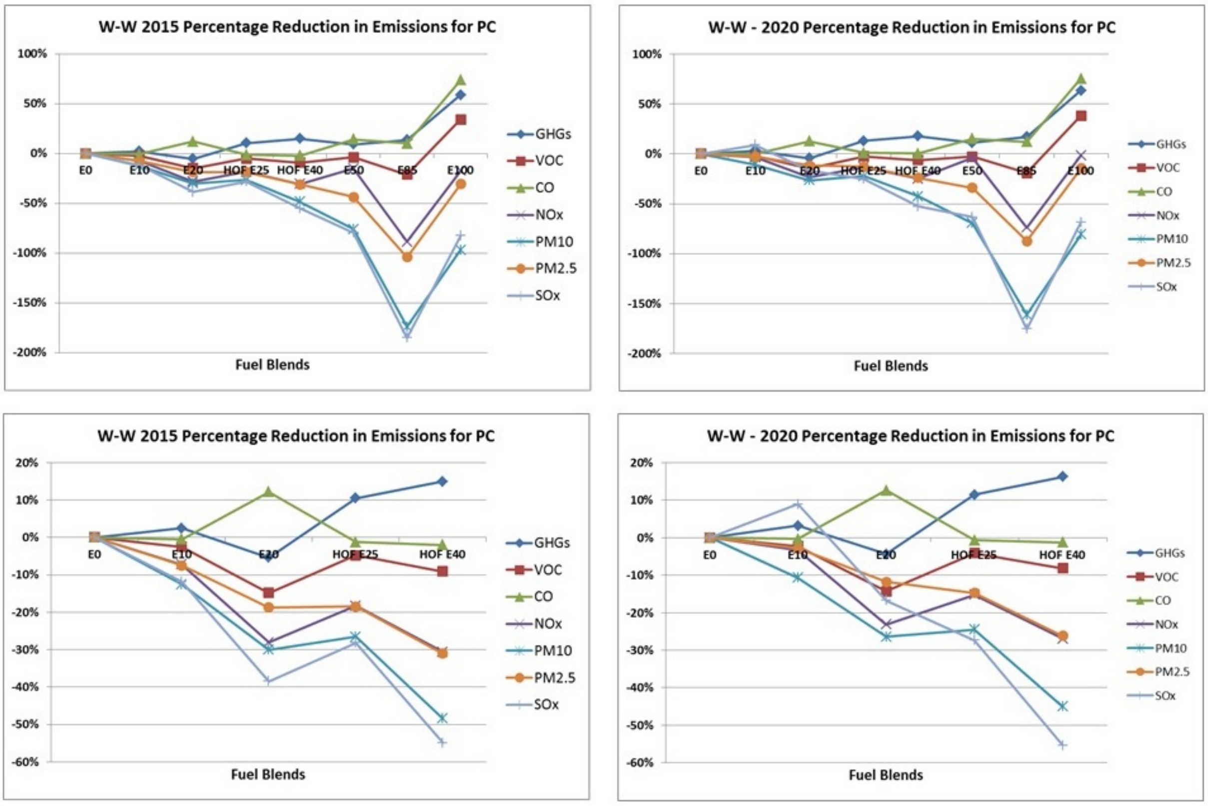

Figure 3: Percentage reduction in Emissions for passenger cars obtained through the well-to-wheel analysis.

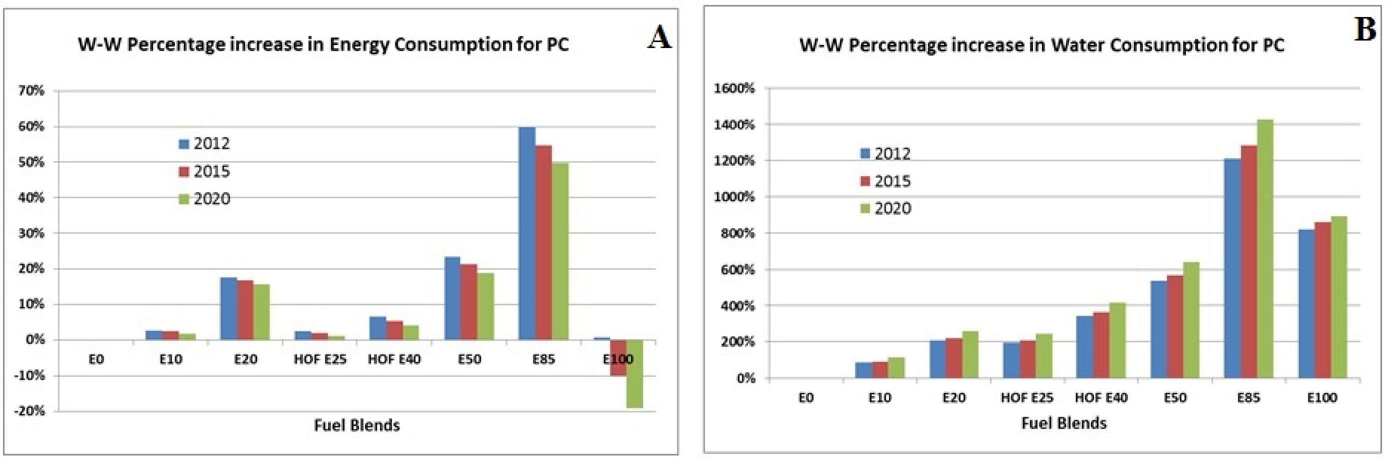

Figure 4: Percentage increase in energy **A.** and water **B.** use of the fuel blends obtained through the well-to-wheel analysis for passenger cars.

Conclusion

The life cycle energy and water use and emissions of GHGs, VOC, CO, NOx, SOx, PM10, and PM2.5 for bioethanol blends with gasoline were studied using passenger cars, LDT1 and LDT2 in Houston. Three stages of life cycle assessment, well-to-pump, pump-to-vehicle and well-to-wheel (total) were simulated using the GREET model. During the well-to-pump stage, all the emissions follow the same emission trend except GHG emissions. GHG emissions are reduced when using higher blends of bioethanol in feeding fuels for all three target years, 2012, 2015 and 2020. The greatest reduction of GHG emissions occurs for E100 used in FCV vehicles. The other pollutants VOC, CO, NOx, SOx, PM10 and PM2.5 increase for all the blends from E10 to E85 and the highest emissions are for E85 blend used with FFV vehicles. These emissions at E100 used with FCV cars are much lower than those at

E85, and comparable to those at E50. During the pump-to-vehicle stage, most emissions vary for different bioethanol blends for the three target years. The GHG emissions vary from E0 to HOF E40 fueled into SI vehicles, increase from HOF E40 to E85, and then significantly drop for E100 fueled with FCV vehicles. The other emissions VOC, CO, NOx, SOx, PM 10 and PM2.5 slight vary from E10 to HOF E40 and dramatically decrease from E50 to E100. The calculated results indicate that HOF 25 and HOF 40 are excellent for SI vehicles due to not only the higher bioethanol blend ratio than E10 and E20, but also some lower or comparable emissions than those at E10. E85 used with FFV is also an excellent option because it reduces VOC, CO, NOx, SOx, PM10, and PM2.5 except a slight increase of GHG emissions. The well-to-wheel analysis shows that GHG and CO emissions are reduced when using higher blends of bioethanol in feeding fuels over the pathway. From E0 to E85, the other pollutants VOC, NOx, SOx, PM10 and PM2.5 increase and the highest emissions reach for E85 blend used with FFV cars. The significant drop of the most emissions for E100 is attributed to higher MPG and specific technological aspects of FCV. Based on the results of the life cycle assessment for the different ethanol gasoline blends from 0 to 100% fueled in different vehicles, the 100% bioethanol fuel used with FCV might be the best option if the greatest reductions of all the pollutant emissions are considered. The energy and water analysis generally shows the increase of energy and water consumption with the increased bioethanol rate in the fuel blends, and dramatic increase of water use at higher rates.

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References

1. Morales M, Quintero J, Conejeros R, Aroca G (2015) Life cycle assessment of lignocellulosic bioethanol: Environmental impacts and energy balance. Renew Sustain Energy Rev 42: 1349-1361.
2. Behera S, Arora R, Nandhagopal N, Kumar S (2014) Importance of chemical pretreatment for bioconversion of lignocellulosic biomass. Renew Sustain Energy Rev 36: 91-106.
3. Srivastava N, Rawat R, Oberoi SO, Ramteke PW (2015) Review on Fuel Ethanol Production from Lignocellulosic Biomass. Int J Green Energy 12: 949-960.
4. Limayem A, Ricke SC (2012) Lignocellulosic biomass for bioethanol production: Current perspectives, potential issues and future prospects. Prog Energy Combustion Sci 38: 449-467.
5. Fasahati P, Woo HC, Liu JJ (2015) Industrial-scale bioethanol production from brown algae: Effects of pretreatment processes on plant economics. Appl Energy 139: 175-187.
6. Streva ER, Pasa VD, Sodré JR (2012) Aging effects on gasoline-ethanol blend properties and composition. Fuel 90: 215-219.
7. Cao H, Tan E, Hartley D, Snowden-Swan L (2015) Supply Chain Sustainability Analysis of Indirect Liquefaction of Blended Biomass to Produce High Octane Gasoline.
8. Han J, Elgowainy A, Wang M, Divita V (2015) Well-to-wheels Greenhouse gas emissions analysis of high-octane fuels with various market shares and ethanol blending levels.
9. Argonne National Laboratory (2015) GREET Model.
10. Karavalakis G, Short D, Vu D, Villela M, Asa-Awuku A, et al. (2014) Evaluating the regulated emissions, air toxics, ultrafine particles, and black carbon from SI-PFI and SI-DI vehicles operating on different ethanol and iso-butanol blends. Fuel 128: 410-421.
11. Karavalakis G, Durbin TD, Shrivastava M, Zheng Z, Villela M, et al. (2012) Impacts of ethanol fuel level on emissions of regulated and unregulated pollutants from a fleet of gasoline light-duty vehicles. Fuel 93: 549-558.
12. Yanowitz J, McCormick L (2009) Effect of E85 on tailpipe emissions from light-duty vehicles. J Air Waste Manage Assoc 59: 172-182.
13. Kelly K, Bailey B, Coburn T, Clark W, Lissiuk P (1996) Federal test procedure emissions test results from ethanol variable-fuel vehicle chevrolet luminas.
14. Lamberty R (2007) Optimal ethanol blend-level investigation.
15. Highway Statistics Series.
16. Texas Transportation Institute (TTI) (2009) 2008 CERR on-road mobile source CERR emissions inventories for the HGB area, Transportation Modeling Program.
17. Texas Transportation Institute (TTI) (2009) 2008 On-Road Mobile Source Actual Annual and Ozone Season Weekday Emissions Inventories For 215 Counties in Texas, Transportation Modeling Program.
18. Chiu YW, Suh S, Pfister S, Hellweg S, Koehler A (2012) Measuring ecological impact of water consumption by bioethanol using life cycle impact assessment. International Journal of Life Cycle Assessment 17: 16-24.
19. Williams PD, Inman D, Aden A, Heath GA (2009) Environmental and Sustainability Factors Associated with Next-Generation Biofuels in the US: What Do We Really Know? Environ Sci Technol 46: 4763-4775.