Hindawi
Journal of Renewable Energy
Volume 2018, Article ID 7350715, 9 pages
https://doi.org/10.1155/2018/7350715

*Research Article*

# Impacts of Biodiesel Applied to the Transportation Fleets in the Greater Houston Area

**Hongbo Du,[1] Ziaul Huque,[1,2] and Raghava R. Kommalapati[1,3]**

[1] *Center for Energy & Environmental Sustainability, Prairie View A&M University, Prairie View, TX 77446, USA*
[2] *Department of Mechanical Engineering, Prairie View A&M University, Prairie View, TX 77446, USA*
[3] *Department of Civil and Environmental Engineering, Prairie View A&M University, Prairie View, TX 77446, USA*

Correspondence should be addressed to Raghava R. Kommalapati; rrkommalapati@pvamu.edu

Received 6 March 2018; Revised 17 April 2018; Accepted 24 April 2018; Published 3 June 2018

Academic Editor: Wei-Hsin Chen



Houston, the fourth largest metropolis in the US, currently experiences severe air pollution. Major pollutants, such as VOCs, CO, $NO_x$, PM, $SO_x$, $CH_4$, and $CO_2$, are released from the transportation fleets. To decrease fossil fuel use and greenhouse gas emissions from fleet vehicles, more and more biodiesel is used in vehicles in the Houston metropolis. The GREET model was used for simulating the fuel cycle emissions of diesel vehicles using different biodiesel blends in Houston. The fuels examined were diesel-biodiesel blends of B0, B5, B20, B50, B80, and B100. The energy and water use and emissions from vehicles fueled with the blends were investigated. The study shows that the reductions in GHG emissions are significant at the Well-to-Pump stage, and all the emissions, except GHGs and $NO_x$, reduce at the Pump-to-Wheel stage. The overall Well-to-Wheel analysis shows that biodiesel is beneficial for both passenger cars and heavy duty trucks. However, the benefits are more pronounced for passenger cars compared to heavy duty vehicles. When 50% of diesel passenger cars and HDDTs are switched to B20 in the Greater Houston area in 2025, the daily GHG emissions will be reduced by 2.0 and 712.1 $CO_2$-equivalent tonnes, respectively.

## 1. Introduction

Dependence on imported crude oil and concerns of global climate change due to greenhouse gas emissions from fossil fuels are increasingly impacting the national security strategy and economic and environmental plans of many countries. With the increase in the world population, the demand for transportation vehicles is increasing, which leads to the increased use of fossil fuels. Some of the estimates suggest that there is about a 10% annual increase in vehicle population in some developing countries and even more (15%) in China [1]. Another study indicated that world energy demand would rise by about 60% by 2030, and fossil fuel would continue to dominate energy supplies in the coming decades [2]. Transportation fleets using fossil fuels release a large amount of greenhouse gases (GHGs) and other harmful air pollutants, which prove being hazardous to the environment and human health. The study of global energy consumption trends showed that CO emissions from fossil fuel-driven vehicles contribute to more than 70% of the total emissions from all the sources, and the corresponding $CO_2$ emissions contribute to 19% [3]. As the fossil fuels are exhausted every day, there is a great need to find alternative fuels to satisfy the energy demand of the world and reduce the GHGs and pollutant emissions.

Biodiesel is one of the best developed biofuels, which can replace diesel fuel used in internal combustion engines equipping the transportation vehicles and boilers [4]. Houston, the fourth largest city in the US, has a very heavy transportation load. It is known to experience severe air pollution episodes due to these automobile emissions in addition to oil refineries and other industries that support these petrochemical businesses. Regarding biodiesel development, Houston owns the largest biodiesel production facility in North America, RBF Port Neches Facility [5]. In order to decrease the amount of fossil fuel use and greenhouse gas emissions from fleet vehicles in the Greater Houston area, biodiesel derived from resources, such as soybean, rapeseed, animal fat, and kitchen fat waste. The biodiesel is not only blended into the regular diesel, but also has been directly tested in diesel engines [6].

Among the available bioresources for biodiesel production, soybean is abundant in Texas [7].

With the increasing use of biodiesel in transportation, the impacts of biodiesel on combustion characteristics, engine performance, and exhaust emissions were widely studied based on passenger cars, light duty trucks, and heavy duty vehicles [8–15]. Kousoulidou et al. investigated the emissions of different biodiesel blends used in different types of passenger cars and found that the influence of biodiesel on tailpipe emissions primarily depends on the biodiesel blend ratios and secondly on the engine technology [11]. The vehicle tests demonstrated that the use of biofuel in the transportation sector can reduce the GHG emissions from the diesel vehicles. Additionally, the impacts of biodiesel can be evaluated by environmental life cycle assessment (LCA), which is outlined by the International Organization of Standardization's 14040 series [16]. Most LCA studies of biodiesel have focused on environmental impacts of biodiesel derived from different bioresources, e.g., soybean, rapeseed, and algae [17–21]. The effects of algae-derived biodiesel used in the passenger cars could be net positive or negative, depending on the algae cultivation and conversion processes from algae to biodiesel [18]. Some researchers quantified the regional impacts of soybean-derived biodiesel for transportation fleets in Pennsylvania by using the real fleet data and pointed out that only the in-state produced B5 is preferable with its lowest environmental impacts due to the state's limited area of farmlands [21].

Recently, we have studied the impacts of bioethanol on the Houston's transportation sector, focusing on light duty vehicles such as gasoline passenger cars and gasoline light duty trucks 1 and 2 [22]. To further investigate the impacts of biofuels on the metropolitan environment, we conducted LCA of biodiesel applications in diesel vehicles in the Greater Houston area. The biodiesel can be derived from locally produced soybean in Houston's neighboring counties with the mature production procedures. The study examined the emissions of GHGs, VOCs, $SO_x$, $NO_x$, CO, $PM_{10}$, and $PM_{2.5}$ from the production of biodiesel fuels and their use in vehicles. Furthermore, various blends of biodiesel and diesel used in the vehicles were analyzed to study the environmental influence of higher blending ratios. The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Fuel-Cycle software was used to simulate the GHGs and pollutant emissions. The Vehicle Miles Traveled (VMT) for the Greater Houston area were obtained from the reports of the US Department of Transportation [23].

## 2. Materials and Methods

The GREET model [24] was developed by the Argonne National Laboratory and is regularly updated. It currently includes three major components: Fuel Cycle Model GREET 1, Vehicle Cycle Model GEET 2, and an app version GREET .net. GREET 2 is specially used for the life cycle assessment of vehicles from materials manufactured for vehicles to disposal of vehicles. GREET 1 is perfect for fuel cycle used in different vehicles and the 2017 Excel-based version was used in our study. The fuel cycle emissions were analyzed using three phases: Well-to-Pump, Pump-to-Wheel, and Well-to-Wheel. Low-sulfur diesel (B0) and five fuel blends of the low-sulfur diesel and biodiesel derived from soybean were used, including B5, B20, B50, B80, and B100 (where the number indicates the percentage of biodiesel in the blend). Diesel vehicles equipped with compression ignition direct injection (CIDI) engines including passenger cars, light duty trucks (LDT1 and LDT2), and heavy duty trucks (long-haul) were taken into account in this study. The emissions of $CO_2$-equivalent greenhouse gases, primarily $CO_2$, methane ($CH_4$), and nitrous oxide ($N_2O$), and other pollutants such as VOCs, CO, $NO_x$, particulate matter (PM) including $PM_{2.5}$ and $PM_{10}$, and $SO_x$ were analyzed with respect to the above-mentioned three pathways, and the targeted years were 2018 and 2025 for running the simulations.

The daily VMT records for Houston, Texas, can be downloaded from the US Department of Transportation/Federal Highway Administration [23] for the years of 2014–2016. However, the VMT reports of the years 2017 and 2018 and the future year 2025 are not available. The VMT data for the years 2018 and 2025 in Houston are estimated based on the economic conditions, the rise in population, and vehicle demands in Houston. The daily VMT mix [25] is taken into account for the various vehicle classes. According to the different ratios of vehicle classes in the vehicle population in the Greater Houston area [25], the VMT of the different types of diesel-based vehicles including passenger cars, LDT1, LDT2, and long-haul heavy duty diesel trucks (HDDTs) are calculated for the Greater Houston area and are listed in Table 1. The statistical data of the daily VMT mix showed that the long-haul HDDTs were the majority, and the diesel passenger cars took the second place in the diesel-powered transportation fleet of Houston. Houston is located in the subtropical zone, which makes it much easier to use high-blend biodiesel in vehicles compared to the north region of the US throughout the whole year.

The default emission rates for B0 (i.e., the regular diesel), provided by the GREET model, were used in the simulations. The relative emission rates for B5, B20, B50, B80, and B100 during vehicle operation were determined based on the experimental emission reports of diesel engines using biodiesel blends [12, 26]. With respect to MPG (mile per gallon) in the GREET model, the base vehicles of the simulated light duty diesel vehicles including passenger cars, LDT1, and LDT2 using the biodiesel blends are the corresponding light duty gasoline vehicles using regular gasoline. The relative MPG of the light duty diesel vehicles using regular diesel is expressed as 120% in the GREET model because the MPG of regular diesel is 1.2 times the regular gasoline. The relative MPG at B5, B20, B50, B80, and B100 for the light duty diesel vehicles were adjusted based on the engine experiments fueled with different biodiesel blends [12, 26]. The relative emission rates of passenger cars, LDT1, and LDT2 during operation were determined from the same experimental results. In the GREET model, for heavy duty vehicles fueled with the biodiesel blends including long-haul heavy duty trucks, short-haul heavy trucks, and school buses, their base vehicles are themselves using B0 when the relative MPG are calculated. The relative emission rates of HDDTs during vehicle operation were also directly determined from the

Table 1: Daily VMT of four types of diesel vehicles in the Greater Houston area (units: km).

| Vehicle Type | 2014 | 2015 | 2016 | 2018 | 2025 |
|---|---|---|---|---|---|
| Passenger Cars | 100,147 | 112,929 | 125,835 | 139,958 | 165,430 |
| LDT1 | 188 | 212 | 237 | 263 | 311 |
| LDT2 | 126 | 142 | 158 | 175 | 207 |
| Long-haul HDDTs | 6,535,230 | 7,369,307 | 8,211,508 | 9,133,122 | 10,795,350 |

*Note.* LDT: light duty truck. HDDTs: heavy duty diesel trucks.

Table 2: The MPGs and emission rates of diesel vehicles.

| Fuel | MPG | VOCs | CO | NO$x$ | $PM_{10}$ (Exhaust) | $PM_{10}$ (TBW) | $PM_{2.5}$ (Exhaust) | $PM_{2.5}$ (TBW) |
|---|---|---|---|---|---|---|---|---|
| B0 | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| B5 | 99.5% | 94.6% | 96.8% | 100.0% | 96.9% | 100.0% | 96.9% | 100.0% |
| B20 | 98.5% | 79.9% | 87.7% | 100.0% | 88.0% | 100.0% | 88.0% | 100.0% |
| B50 | 96.2% | 57.1% | 72.0% | 105.0% | 72.7% | 100.0% | 72.7% | 100.0% |
| B80 | 93.9% | 40.8% | 59.2% | 108.2% | 60.0% | 100.0% | 60.0% | 100.0% |
| B100 | 92.4% | 32.6% | 51.9% | 110.3% | 52.8% | 100.0% | 52.8% | 100.0% |

*Note.* MPG: mile per gallon. TBW: tire and brake wear.

same experimental reports. The electricity grid involved in this study is specified as the mixed electricity generation in Texas Regional Entity.

## 3. Results and Discussion

The relative MPG and emission rates of diesel vehicles using different biodiesel blends were determined from the above-mentioned experimental results reported in the literature [12, 26] and integrated to the GREET model. Table 2 shows the relative mile per gallon (MPG) and emission rates of B0, B5, B20, B50, B80, and B100 for passenger cars, LDT1, and LDT2, which were used in the simulations for the target years 2018 and 2025. The MPG slightly decrease with the increase of biodiesel in the blends. VOCs, CO, $PM_{10}$, and $PM_{2.5}$ emissions significantly decrease with the increase of biodiesel in the blends. $NO_x$ emissions have slightly increased up to 10.3% for B100.

The life cycle assessment of energy and water use and emissions associated with the different biodiesel blends was performed using the GREET model following the three phases: Well-to-Pump, Pump-to-Wheel, and Well-to-Wheel. First, the Well-to-Pump analysis mainly focuses on the feedstock of soybean and production of biodiesel from soybean. The first stage addresses the energy and water use and pollutant emissions released in soybean farming, transportation from field to biofuel refinery, biodiesel production, and biodiesel transportation. Second, the Pump-to-Wheel emissions analysis was used to address the energy and water use and pollutant emissions during vehicle operation fueled with the different biodiesel blends. The Well-to-Wheel analysis adds up the first and second analyses and thus provides the overall estimates.

Tables 3 and 4 list the daily energy and water use and emissions of pollutants from diesel-powered passenger cars and long-haul HDDTs during the stage of Well-to-Pump for the years 2018 and 2025. Based on the calculations evaluated per km, all of the energy and water use and the pollutant emissions significantly decrease for all the biodiesel blends in the future year 2025 for both passenger cars and long-haul HDDTs compared to those in 2018. The improvements in energy efficiency and emission rates can be attributed to continuous improvement in the process of low-sulfur diesel and biodiesel production in the future. However, in Tables 3 and 4 there exist some increases in these terms of energy, water, and emissions, more often for the long-haul HDDTs, because of the increasing VMT in the future year. Figure 1 shows the percentage reductions of energy use and pollutant emissions from passenger cars during the Well-to-Pump stage in Houston for the target year 2018. The results obtained for B0 are used as the base to estimate other blends. The positive values show the reductions of GHG emissions and the negative percentages show the increases in the particular pollutant emissions and energy use compared to the corresponding base values. The GHG emissions significantly reduced with the increase of biodiesel percentage in the blends, and other emissions VOCs, CO, $NO_x$, $SO_x$, $PM_{10}$, and $PM_{2.5}$ and energy use increased as the biodiesel proportion increased in the blends. The increases in energy use and pollutant emissions are associated with the biodiesel production which consumes more energy and resources than the production of conventional diesel, and more emissions would be released when the fuel blends containing more biodiesel are produced. The study shows that the different emissions have different trends for the years 2018 and 2025. The simulations applied to the LDT1 and LDT2 show the same trends of energy use and emissions as those of the passenger cars during the Well-to-Pump stage. Our study also shows that the energy use and emission trends for the long-haul HDDTs are almost the same as those for passenger cars. Figure 2 shows the increase in water consumption during Well-to-Pump for long-haul HDDTs in Houston for the target years 2018 and 2025. The water use significantly increased with the increase of biodiesel percentage in the blends, even higher in the future year compared to each baseline. The tremendous increase of water use [27, 28] for high biodiesel ratio in the blends is related to the increased

Table 3: Well-to-Pump daily energy and water use and emissions of pollutants associated with passenger cars.

| 2018 | B0 | B5 | B20 | B50 | B80 | B100 |
|---|---|---|---|---|---|---|
| Energy (MJ) | 70,037 | 74,610 | 89,893 | 122,095 | 157,296 | 182,609 |
| Water (t) | 29 | 62 | 164 | 383 | 623 | 797 |
| GHGs (t) | 6.1 | 5.1 | 2.2 | −4.2 | −11.3 | −16.4 |
| VOCs (kg) | 2.55 | 2.73 | 3.35 | 4.66 | 6.09 | 7.12 |
| CO (kg) | 4.53 | 4.65 | 5.08 | 5.99 | 6.97 | 7.68 |
| $NO_x$ (kg) | 10.15 | 10.25 | 10.73 | 11.68 | 12.70 | 13.42 |
| $PM_{10}$ (kg) | 0.68 | 0.68 | 0.70 | 0.74 | 0.78 | 0.80 |
| $PM_{2.5}$ (kg) | 0.57 | 0.57 | 0.59 | 0.62 | 0.65 | 0.67 |
| $SO_x$ (kg) | 5.89 | 6.09 | 6.79 | 8.25 | 9.83 | 10.97 |
| 2025 | B0 | B5 | B20 | B50 | B80 | B100 |
| Energy (MJ) | 70,414 | 74,903 | 89,929 | 121,577 | 156,169 | 181,044 |
| Water (t) | 24 | 56 | 158 | 377 | 616 | 789 |
| GHGs (t) | 5.2 | 4.3 | 1.8 | −3.6 | −9.6 | −13.9 |
| VOCs (kg) | 2.48 | 2.67 | 3.26 | 4.52 | 5.90 | 6.90 |
| CO (kg) | 4.26 | 4.30 | 4.51 | 4.91 | 5.34 | 5.65 |
| $NO_x$ (kg) | 8.27 | 8.25 | 8.32 | 8.39 | 8.46 | 8.50 |
| $PM_{10}$ (kg) | 0.60 | 0.60 | 0.60 | 0.60 | 0.59 | 0.59 |
| $PM_{2.5}$ (kg) | 0.50 | 0.50 | 0.50 | 0.49 | 0.48 | 0.47 |
| $SO_x$ (kg) | 5.11 | 5.26 | 5.81 | 6.94 | 8.17 | 9.06 |

Table 4: Well-to-Pump daily energy and water use and emissions of pollutants associated with long-haul heavy duty trucks.

| 2018 | B0 | B5 | B20 | B50 | B80 | B100 |
|---|---|---|---|---|---|---|
| Energy (MJ) | 22,613,897 | 24,457,487 | 29,025,250 | 39,409,083 | 50,788,639 | 58,961,935 |
| Water (t) | 9,387 | 20,269 | 52,985 | 123,657 | 201,278 | 257,182 |
| GHGs (t) | 1,977 | 1,684 | 701 | −1,368 | −3,642 | −5,283 |
| VOCs (kg) | 822 | 896 | 1,082 | 1,504 | 1,967 | 2,299 |
| CO (kg) | 1,462 | 1,523 | 1,642 | 1,933 | 2,251 | 2,479 |
| $NO_x$ (kg) | 3,277 | 3,361 | 3,466 | 3,770 | 4,100 | 4,334 |
| $PM_{10}$ (kg) | 219 | 223 | 226 | 238 | 251 | 260 |
| $PM_{2.5}$ (kg) | 183 | 187 | 189 | 199 | 210 | 217 |
| $SO_x$ (kg) | 1,902 | 1,995 | 2,192 | 2,662 | 3,175 | 3,543 |
| 2025 | B0 | B5 | B20 | B50 | B80 | B100 |
| Energy (MJ) | 25,564,708 | 27,608,648 | 32,649,919 | 44,124,896 | 56,699,537 | 65,730,589 |
| Water (t) | 8,591 | 20,770 | 57,480 | 136,729 | 223,775 | 286,468 |
| GHGs (t) | 1,880 | 1,600 | 663 | −1,311 | −3,481 | −5,046 |
| VOCs (kg) | 902 | 982 | 1,185 | 1,642 | 2,144 | 2,504 |
| CO (kg) | 1,546 | 1,586 | 1,637 | 1,782 | 1,940 | 2,052 |
| $NO_x$ (kg) | 3,003 | 3,042 | 3,020 | 3,047 | 3,072 | 3,087 |
| $PM_{10}$ (kg) | 219 | 222 | 218 | 217 | 215 | 213 |
| $PM_{2.5}$ (kg) | 183 | 185 | 181 | 178 | 175 | 172 |
| $SO_x$ (kg) | 1,857 | 1,941 | 2,110 | 2,520 | 2,967 | 3,288 |

water consumption for agricultural production of soybean and biodiesel derivation from soybean in the biorefinery.

Tables 5 and 6 list the energy and water use and emissions of pollutants from diesel passenger cars and long-haul HDDTs during the Pump-to-Wheel stage for 2018 and 2025. During the Pump-to-Wheel stage, all of the energy use and the pollutant emissions significantly will decrease at all the biodiesel blends in the later year 2025 for both passenger cars and long-haul HDDTs compared to those in 2018. The improvements in energy efficiency and emission rates are attributed to the enhancement of vehicle fuel efficiency in the future. Figure 3 shows the percentage reductions of pollutant emissions from pump to wheels in Houston for the target years 2018 and 2025. Similar to the Well-to-Pump stage, the positive values show the reductions of the exhaust emissions and the negative percentages show the increases

Table 5: Pump-to-Wheel daily energy and water use and emissions of pollutants from passenger cars.

| 2018 | B0 | B5 | B20 | B50 | B80 | B100 |
|---|---|---|---|---|---|---|
| Energy (MJ) | 328,930 | 328,930 | 333,939 | 342,042 | 350,298 | 355,985 |
| Water (t) | 0 | 0 | 0 | 0 | 0 | 0 |
| GHGs (t) | 24.9 | 24.9 | 25.3 | 26.0 | 26.8 | 27.3 |
| VOCs (kg) | 10.7 | 9.5 | 8.0 | 5.8 | 4.1 | 3.3 |
| CO (kg) | 244 | 236 | 214 | 176 | 144 | 127 |
| $NO_x$ (kg) | 11.43 | 11.43 | 11.43 | 12.00 | 12.36 | 12.61 |
| $PM_{10}$ (kg) | 2.05 | 2.03 | 1.99 | 1.92 | 1.85 | 1.82 |
| $PM_{2.5}$ (kg) | 0.84 | 0.83 | 0.79 | 0.72 | 0.67 | 0.63 |
| $SO_x$ (kg) | 0.17 | 0.16 | 0.14 | 0.09 | 0.04 | 0.00 |
| 2025 | B0 | B5 | B20 | B50 | B80 | B100 |
| Energy (MJ) | 327,808 | 327,808 | 332,800 | 340,875 | 349,103 | 354,770 |
| Water (t) | 0 | 0 | 0 | 0 | 0 | 0 |
| GHGs (t) | 21.2 | 21.2 | 21.5 | 22.1 | 22.7 | 23.1 |
| VOCs (kg) | 7.5 | 7.0 | 6.0 | 4.3 | 3.0 | 2.4 |
| CO (kg) | 142 | 137 | 124 | 102 | 84 | 74 |
| $NO_x$ (kg) | 6.05 | 6.05 | 6.05 | 6.35 | 6.54 | 6.67 |
| $PM_{10}$ (kg) | 2.20 | 2.19 | 2.16 | 2.11 | 2.06 | 2.04 |
| $PM_{2.5}$ (kg) | 0.80 | 0.79 | 0.76 | 0.71 | 0.67 | 0.64 |
| $SO_x$ (kg) | 0.17 | 0.16 | 0.14 | 0.09 | 0.04 | 0.00 |

Table 6: Pump-to-Wheel daily energy and water use and emissions of pollutants from long-haul heavy duty trucks.

| 2018 | B0 | B5 | B20 | B50 | B80 | B100 |
|---|---|---|---|---|---|---|
| Energy (MJ) | 106,207,131 | 107,824,498 | 107,824,498 | 110,402,423 | 113,106,635 | 114,942,782 |
| Water (t) | 0 | 0 | 0 | 0 | 0 | 0 |
| GHGs (t) | 8,016 | 8,142 | 8,155 | 8,377 | 8,611 | 8,771 |
| VOCs (kg) | 2,357 | 2,229 | 1,884 | 1,347 | 963 | 769 |
| CO (kg) | 8,092 | 7,831 | 7,097 | 5,829 | 4,788 | 4,199 |
| $NO_x$ (kg) | 19,818 | 19,818 | 19,818 | 20,813 | 21,433 | 21,857 |
| $PM_{10}$ (kg) | 666 | 659 | 639 | 603 | 574 | 557 |
| $PM_{2.5}$ (kg) | 325 | 318 | 299 | 267 | 239 | 224 |
| $SO_x$ (kg) | 55 | 53 | 45 | 30 | 12 | 0 |
| 2025 | B0 | B5 | B20 | B50 | B80 | B100 |
| Energy (MJ) | 119,015,433 | 120,827,851 | 120,827,851 | 123,716,667 | 126,747,000 | 128,804,581 |
| Water (t) | 0 | 0 | 0 | 0 | 0 | 0 |
| GHGs (t) | 7,603 | 7,722 | 7,734 | 7,945 | 8,167 | 8,319 |
| VOCs (kg) | 2,769 | 2,618 | 2,213 | 1,582 | 1,131 | 904 |
| CO (kg) | 9,552 | 9,244 | 8,378 | 6,881 | 5,651 | 4,957 |
| $NO_x$ (kg) | 23,380 | 23,380 | 23,380 | 24,554 | 25,286 | 25,786 |
| $PM_{10}$ (kg) | 787 | 778 | 754 | 712 | 677 | 658 |
| $PM_{2.5}$ (kg) | 383 | 375 | 353 | 314 | 282 | 264 |
| $SO_x$ (kg) | 61 | 59 | 51 | 33 | 14 | 0 |

in the particular pollutant emissions and energy use. The $SO_x$, VOCs, CO, $PM_{2.5}$, and $PM_{10}$ emissions reduced with the increase of biodiesel percentage in the blends. The emission reductions for $SO_x$, VOCs, and CO are more significant at higher blend ratios. However, the emissions of GHGs and $NO_x$ and energy use slightly increased with the increase of biodiesel percentage in the blends. The emission trends of passenger cars, LDT1 and LDT2, and HDDTs are mostly similar, and the deviations are insignificant. The study also shows that the emission trends for different biodiesel blends are the same for the target years 2018 and 2025.

Figure 4 shows the percentage reductions of pollutant emissions for the passenger cars and long-haul HDDTs during the Well-to-Wheel stage in the Houston metropolis for the target years 2018 and 2025. For the passenger cars, the GHG, VOCs, and CO emissions reduced with the increase

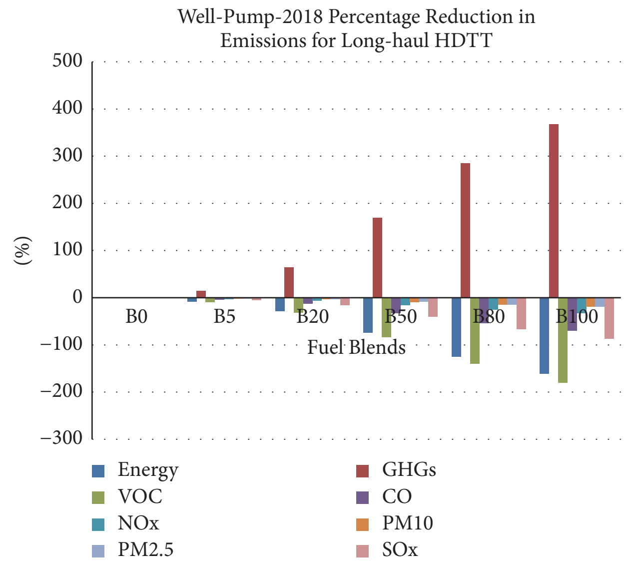


Figure 1: Percentage reductions in energy use and emissions at the Well-to-Pump stage in 2018.

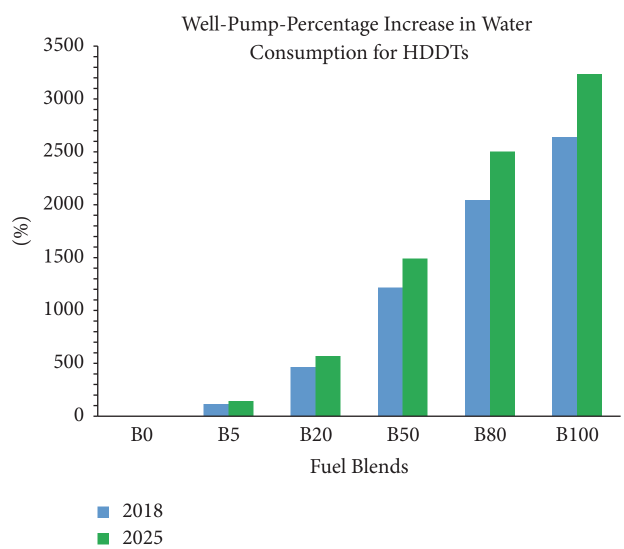


Figure 2: Percentage increases in water consumption for 2018 and 2025 during the Well-to-Pump stage.

of biodiesel percentage in the blends; energy use and the emissions of $NO_x$ and $SO_x$ increased; and the emissions of $PM_{10}$ and $PM_{2.5}$ did not change significantly for the different blends. The percentage increases of $SO_x$ emissions are much more in the future year at the higher blend ratios compared to the B0 emissions for the same future year. The emission trends have slight differences for different years. For the long-haul HDDTs, significant reductions of GHG and CO emissions were observed at the higher blend ratios; the reduction degrees of CO emissions were slightly lower than those of passenger cars; VOC emissions varied with the biodiesel blend ratio; the energy use and the emissions of $NO_x$ and $SO_x$ increased similarly to those of the passenger cars with the increase of biodiesel percentage in the blends. The $SO_x$ emissions of HDDTs share the same trend as that for passenger cars. The emission reductions for VOCs of HDDTs are relatively obvious at B20, B50, and B80 in 2018 and at B20, B50, B80, and B100 in 2025. The emissions of $PM_{10}$ and $PM_{2.5}$ reduced with the increase of biodiesel percentage in the blends, and this would show more reductions at higher blends in 2025. Based on two types of passenger cars and HDDTs, the Well-to-Wheel analysis also reveals that biodiesel has more emission reductions for passenger cars than HDDTs at the higher biodiesel blend ratios per km because of higher MPG of passenger cars.

The prevalent biodiesel blend that is currently used in the Greater Houston is B5. If more biodiesel can be used in the transportation fleets, Houston can share more benefits from bioenergy to reduce metropolitan pollution. To study the real impact of biodiesel blends in the Houston metropolis, two hypothetical scenarios are taken into our calculations, where 25% and 50% of all passenger cars and HDDTs are

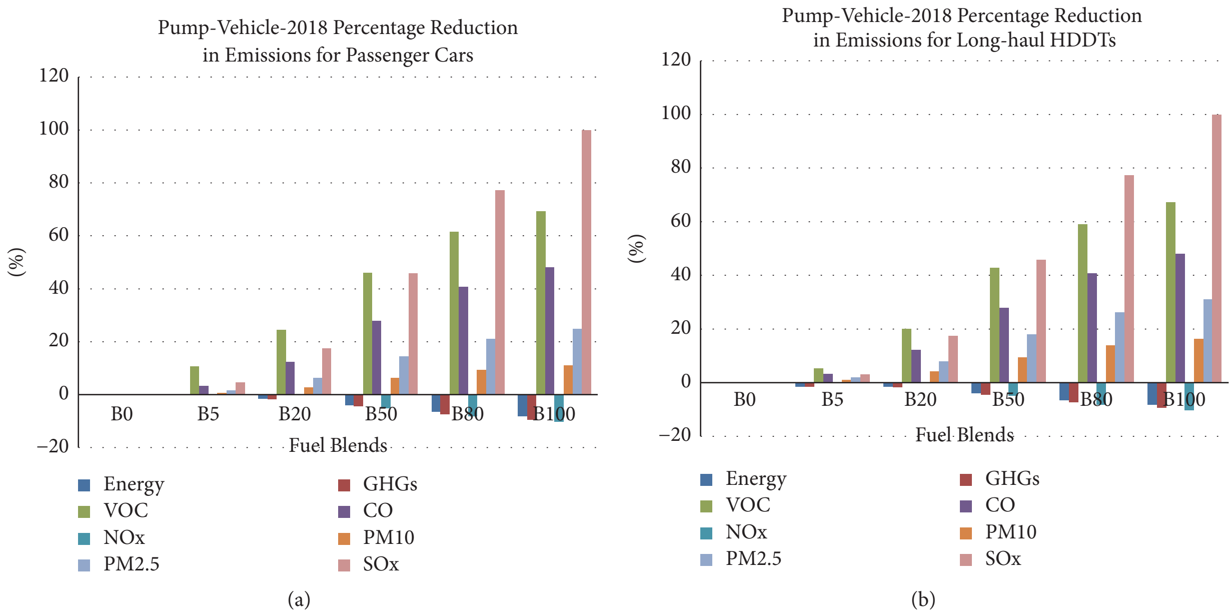


Figure 3: Percentage reduction in energy use and emissions for (a) passenger cars and (b) and long-haul HDDTs during the Pump-to-Wheel stage.

switched to the B20 and B50 fuels in 2025. Through our calculations from well to wheels, it can be found that the daily reductions of GHGs, VOCs, and CO emissions from 25% of all the possible diesel passenger cars using B20 would be 0.7 $CO_2$-equivalent tonnes, 0.2 kg, and 4.3 kg, respectively, in 2025; the corresponding emissions reductions from the HDDTs would be 271.2 $CO_2$-equivalent tonnes, 68.2 kg, and 271.3 kg in 2025. When the biodiesel blend ratio increases to 50%, the corresponding reductions would be promoted to 2.0 $CO_2$-equivalent tonnes, 0.3 kg, and 9.8 kg from the passenger cars and 712.1 $CO_2$-equivalent tonnes, 111.7 kg, and 609.0 kg from the HDDTs in 2025. It can be seen that when 50% diesel vehicles of the transportation fleet are taken into account, the daily reductions of these emissions will be more than the double of the 25% case. The emissions of $NO_x$ will slightly increase for both passenger cars and HDDTs in both 2025 scenarios. The emissions of $SO_x$ will also increase for both passenger cars and HDDTs in both scenarios, and the increases in $SO_x$ emissions during the Well-to-Pump stage will cause the overall increases of $SO_x$ emissions.

## 4. Conclusions

The life cycle energy and water use and emissions of GHGs, VOCs, CO, $NO_x$, $SO_x$, $PM_{10}$, and $PM_{2.5}$ for biodiesel blends with regular diesel were studied in Houston by using passenger cars and long-haul HDDTs with the GREET model. Three major pathways, Well-to-Pump, Pump-to-Wheel, and Well-to-Wheel were used in LCA for the years 2018 and 2025. The Well-to-Pump analysis shows that only GHG emissions significantly decrease with the increase of biodiesel blends, while other emissions and water and energy use increase. The Pump-to-Wheel analysis shows that total energy use and the emissions of GHGs and $NO_x$ increase, and other emissions of $SO_x$, VOCs, CO, $PM_{10}$, and $PM_{2.5}$ decrease for higher biodiesel fuel blends. The emissions of $SO_x$, VOCs, and CO significantly reduce with the increase of the biodiesel blend ratios. Overall, the Well-to-Wheel analysis of biodiesel applications in transportation vehicles in Houston shows that an increase in the biodiesel blend results in the increases in energy and water use and all the pollutant emissions except GHGs, VOCs, CO, and PM emissions from the diesel vehicles. For the long-haul HDDTs, the reductions of VOCs emissions are not significant as those of passenger cars at the corresponding blends. It is also seen that the emission trends will change in the future year 2025. The reduction of VOCs emissions will alleviate the secondary pollutant $O_3$ which often occurs in spring and summer in Houston because VOCs are one major precursor which produce ozone. The research confirms that biodiesel applications are environment-friendly for both passenger cars and long-haul HDDTs, and the environmental impacts depend not only on the fuel blends but also on the vehicle types. The comparison of the overall energy use and emissions between passenger cars and HDDTs shows that biodiesel is more beneficial for passenger cars than HDDTs per km.

## Data Availability

Data is presented in the tables and figures in the paper; some intermediate data generated from the calculations are available upon request.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

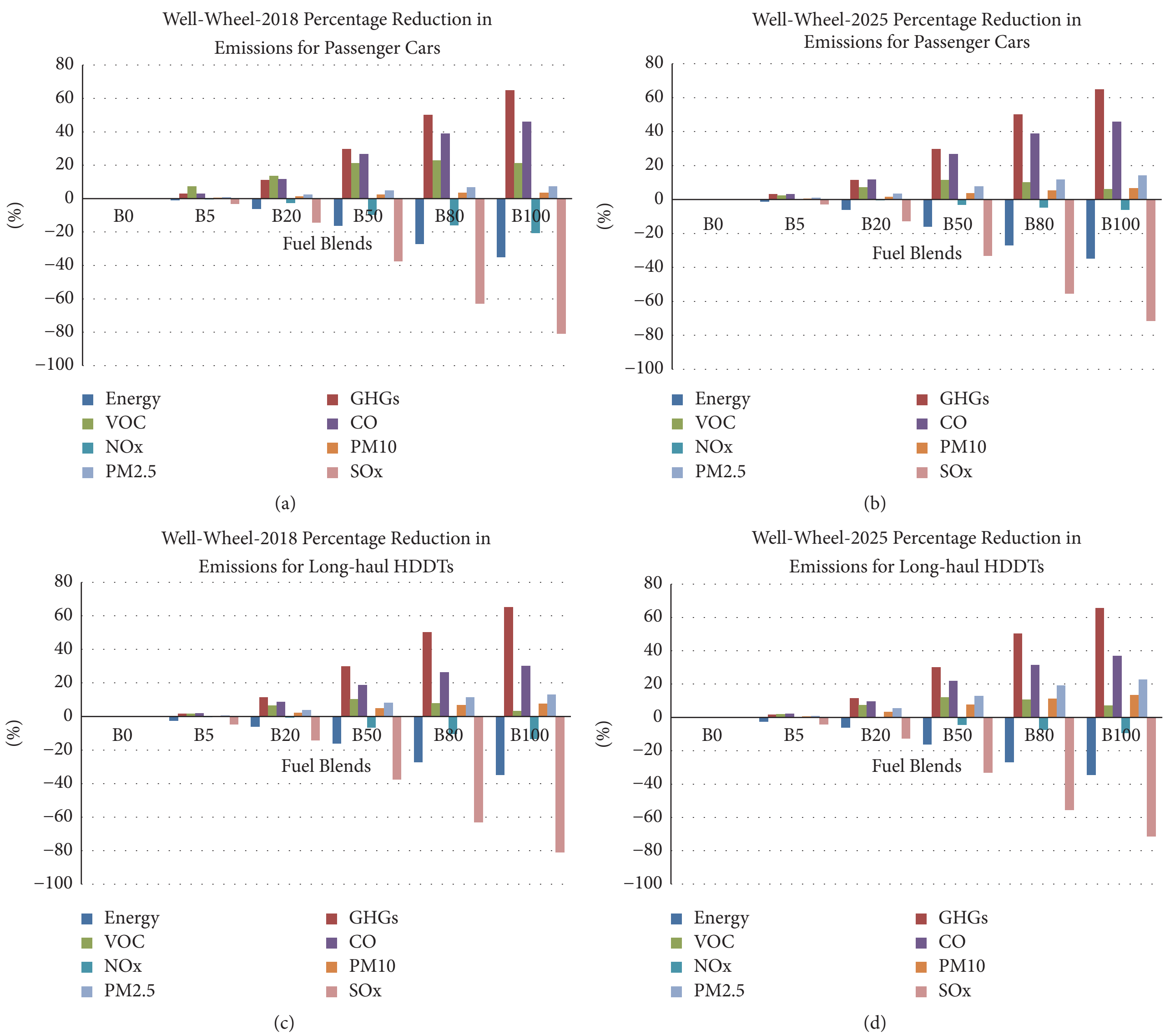


Figure 4: Percentage reduction in emissions and energy use for passenger cars and long-haul HDDTs during the Well-to-Wheel stage in 2018 and 2025.


## Acknowledgments

This work is supported by the National Science Foundation (NSF) through the NSF CREST Center for Energy and Environmental Sustainability (CEES) at Prairie View A&M University (Award no. 1036593).


## References


[1] P. Poudenx, "The effect of transportation policies on energy consumption and greenhouse gas emission from urban passenger transportation," *Transportation Research Part A: Policy and Practice*, vol. 42, no. 6, pp. 901–909, 2008.

[2] C. Bessou, F. Ferchaud, B. Gabrielle, and B. Mary, "Biofuels, greenhouse gases and climate change. A review," *Agronomy for Sustainable Development*, vol. 31, no. 1, pp. 1–79, 2011.

[3] M. Balat and H. Balat, "Recent trends in global production and utilization of bio-ethanol fuel," *Applied Energy*, vol. 86, no. 11, pp. 2273–2282, 2009.

[4] A. E. Atabani, A. S. Silitonga, I. A. Badruddin, T. M. I. Mahlia, H. H. Masjuki, and S. Mekhilef, "A comprehensive review on biodiesel as an alternative energy resource and its characteristics," *Renewable & Sustainable Energy Reviews*, vol. 16, no. 4, pp. 2070–2093, 2012.

[5] "The largest biodiesel production facility in the US," Accessed on June 10, 2017; http://www.rbfuels.com/company/.

[6] L. G. Schumacher, W. Marshall, J. Krahl, W. B. Wetherell, and M. S. Grabowski, "Biodiesel emissions data from series 60 DDC engines," *Transactions of the ASAE*, vol. 44, no. 6, pp. 1465–1468, 2001.

[7] X.-P. Song, P. V. Potapov, A. Krylov et al., "National-scale soybean mapping and area estimation in the United States using

medium resolution satellite imagery and field survey," *Remote Sensing of Environment*, vol. 190, pp. 383–395, 2017.

[8] E. Bakeas, G. Karavalakis, and S. Stournas, "Biodiesel emissions profile in modern diesel vehicles. Part 1: Effect of biodiesel origin on the criteria emissions," *Science of the Total Environment*, vol. 409, no. 9, pp. 1670–1676, 2011.

[9] G. Fontaras, M. Kousoulidou, G. Karavalakis, E. Bakeas, and Z. Samaras, "Impact of straight vegetable oil-diesel blends application on vehicle regulated and non-regulated emissions over legislated and real world driving cycles," *Biomass & Bioenergy*, vol. 35, no. 7, pp. 3188–3198, 2011.

[10] E. G. Giakoumis, "A statistical investigation of biodiesel effects on regulated exhaust emissions during transient cycles," *Applied Energy*, vol. 98, pp. 273–291, 2012.

[11] M. Kousoulidou, L. Ntziachristos, G. Fontaras, G. Martini, P. Dilara, and Z. Samaras, "Impact of biodiesel application at various blending ratios on passenger cars of different fueling technologies," *Fuel*, vol. 98, pp. 88–94, 2012.

[12] "Biodiesel.org," Accessed on June 10, 2017; http://biodiesel.org/using-biodiesel/handling-use/emissions-calculator.

[13] S. Oberweis and T. T. Al-Shemmeri, "Emissions and performance of a stationary diesel engine run on biodiesel blends," *International Journal of Oil, Gas and Coal Technology*, vol. 4, no. 4, pp. 375–386, 2011.

[14] J. Xue, T. E. Grift, and A. C. Hansen, "Effect of biodiesel on engine performances and emissions," *Renewable & Sustainable Energy Reviews*, vol. 15, no. 2, pp. 1098–1116, 2011.

[15] M. Gürü and A. Keskïn, "Evaluation of biodiesel production, engine performance, and emissions," *Journal of Electronic Materials*, vol. 45, no. 8, pp. 3882–3888, 2016.

[16] ISO, "Environmental management—life cycle assessment—requirements and guidelines," Tech. Rep., International Organization for Standardization, 2006.

[17] L. Panichelli, A. Dauriat, and E. Gnansounou, "Life cycle assessment of soybean-based biodiesel in Argentina for export," *The International Journal of Life Cycle Assessment*, vol. 14, no. 2, pp. 144–159, 2009.

[18] A. F. Clarens, H. Nassau, E. P. Resurreccion, M. A. White, and L. M. Colosi, "Environmental impacts of algae-derived biodiesel and bioelectricity for transportation," *Environmental Science & Technology*, vol. 45, no. 17, pp. 7554–7560, 2011.

[19] E. Gnansounou and J. Kenthorai Raman, "Life cycle assessment of algae biodiesel and its co-products," *Applied Energy*, vol. 161, pp. 300–308, 2016.

[20] J. Malça, A. Coelho, and F. Freire, "Environmental life-cycle assessment of rapeseed-based biodiesel: alternative cultivation systems and locations," *Applied Energy*, vol. 114, pp. 837–844, 2014.

[21] X. Xue, W. O. Collinge, S. O. Shrake, M. M. Bilec, and A. E. Landis, "Regional life cycle assessment of soybean derived biodiesel for transportation fleets," *Energy Policy*, vol. 48, pp. 295–303, 2012.

[22] H. Du, R. R. Kommalapati, and Z. Huque, "Assessment of bioethanol applications on transportation vehicles in houston," *Journal of Fundamentals of Renewable Energy and Applications*, vol. 6, no. 3, Article ID 1000207, 2016.

[23] US Department of Transportation Fedral Highway Administration, Accessed on June 20, 2017; http://www.fhwa.dot.gov/policyinformation/statistics.cfm.

[24] "Argonne National Laboratory. GREET Life Cycle Model," Accessed on July 10, 2017; https://greet.es.anl.gov/publication-greet-model.

[25] "Transportation Modeling Program, 2008 and On-Road Mobile Source CERR Emissions Inventories For the HGB Area, 2009," Texas Transportation Institute.

[26] "United States Environmental Protection Agency. Verified Technologies for SmartWay and Clean Diesel," Accessed on June 10, 2017, https://www.epa.gov/verified-diesel-tech/various-technology-biodiesel-1-100.

[27] P. R. D. Williams, D. Inman, A. Aden, and G. A. Heath, "Environmental and sustainability factors associated with next-generation biofuels in the U.S.: what do we really know?" *Environmental Science & Technology*, vol. 43, no. 13, pp. 4763–4775, 2009.

[28] M. D. P. Palacios-Diaz, V. Mendoza-Grimon, I. H. Brito, J. R. Fernández-Vera, and J. M. Hernández-Moreno, "Reclaimed water use in biofuel production," *Water*, vol. 7, no. 9, pp. 4848–4857, 2015.