# 100% Biodiesel Vector Technology and Fuel Dispensing Solution —
# A CTECH live lab pilot project for the implementation and evaluation of the 100% biodiesel technology on identified equipment within Cornell's fleet operations

Center for Transportation, Environment, and Community Health
Final Report

*by*
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16. Abstract

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# Contents

**Abstract**
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## Background

Introduction to Biodiesel & Applications

Biodiesel is often a more environmentally friendly fuel option compared to petroleum diesel[1]. It is chemically similar to petroleum-derived diesel and therefore compatible with most diesel engines, making it possible to run diesel vehicles on biodiesel with limited to no modifications. One of the advantages of biodiesel is its lower net carbon footprint compared to diesel. Biodiesel is derived from oil or fat, typically soybean oil in the US[2]. Plant-based feedstocks are more widely used as soybeans and other crops are not only grown widely in the Midwest, but animal fat feedstocks frequently contain contaminants that need to be removed before combustion in an engine. The plants that are used as the feedstocks for producing biodiesel fixate CO2 during their growth and photosynthetic processes, which partially offsets emissions associated with biodiesel production and combustion. This results in a lower net carbon footprint compared to petroleum-derived diesel. Thus, the widespread use of pure biodiesel, also known as B100, in campus vehicles can help Cornell meet its 2035 carbon neutrality goals.

Currently, biodiesel is primarily used as a transportation fuel, serving as an alternative for diesel vehicles and sold most commonly in blends with petroleum-derived diesel. The main limitation for biodiesel usage in diesel engines is its cloud point. Cloud point is a concept used to measure a diesel fuel's cold-weather characteristics as it refers to the temperature at which crystals start to form when a fuel cools. Biodiesel has a higher cloud point than petroleum diesel, causing it to congeal and solidify more readily in the fuel tank and engine during the winter.

Overview of Vector System

Pittsburgh-based company, Optimus Technologies, has developed the Vector System (VS), a technology that enables a vehicle to run on biodiesel year-round. This system requires the installation of a manifold consisting of a heat exchanger and a second fuel tank for B100. When starting up the vehicle, the engine burns traditional diesel first, and the excess heat from the engine heats up the B100 in the manifold. When the B100 reaches a certain temperature and the viscosity is low enough, the engine switches to running on B100. When it is time to shut off the engine, the system switches back to diesel to purge and clean out the engine.

The VS has been successfully installed on several medium- and heavy-duty (HD) diesel vehicle fleets throughout the country. Most notably, the Washington, D.C. Department of Public Works equipped 23 trucks with the VS in the city's effort to reduce greenhouse gas (GHG) emissions. Fuel suppliers such as Star Oilco and Renewable Energy Group have also successfully integrated Optimus' VS into their fleets of heavy-duty haulers. Our study analyzes Cornell's estimated environmental and economic impact for installing and operating a VS.

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[1] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." Biodiesel and the Environment - U.S. Energy Information Administration (EIA).

[2] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." Soybean Oil Comprises a Larger Share of Domestic Biodiesel Production - Today in Energy - U.S. Energy Information Administration (EIA).

LCA Introduction
We conducted a life cycle analysis (LCA) of both B100 and ultra-low sulfur diesel (ULSD) to fully assess the environmental impact for Cornell to operate vehicles with VS installed. An LCA involves an evaluation of the energy and resources used in all stages of the life cycle of a product, from raw material extraction and manufacturing to consumption and disposal. For fuels like diesel, the LCA process is divided into two stages: Well-to-Pump (WTP) and Pump-to-Wheels (PTW). A WTP analysis explores the environmental impact and resource consumption of the production of the fuel, accounting for all processes leading up to the direct use of the fuel in a vehicle. Whereas the PTW focuses on the combustion of the fuel in the engine. Combining the WTP and PTW stages together provides a complete Well-to Wheel (WTW) analysis of the overall life cycle of the fuel.

Tractor as a Case Study
We installed the VS onto a John Deere tractor with a 6068 series engine operated by Cornell Agricultural Services (Ag Services) to evaluate the functionality and operability of the VS during the Ithaca winter. The original plan was to use the funding to install the VS onto three heavy-duty trucks. However, since these trucks are used for snow removal, there was a concern that the modifications might fail in the winter leaving Cornell without one of its snowplows. Our partners at the Center for Transportation, Environment, and Community Health (CTECH) suggested installing the VS onto a tractor as a lower stakes option. The results collected from the tractor can be expanded and applied to a Cornell fleet for economic and environmental analysis.

**Objectives**

There were four key objectives of the Biodiesel Engine Project (BEP):

- Providing a “Living Laboratory” for members of Engineers for a Sustainable World: Biofuels (ESW: Biofuels), the student working group formed from the engineering project team.
    - Gain hands-on engineering experience throughout the entirety of this project, including using CAD to design the bracket and fittings for the VS and assist Optimus Technologies’ Lead Engineer for the VS installation.
    - Provide ESW: Biofuels members with project management and execution experience.
- Install the VS onto the farm tractor.
- Evaluate the efficacy of the VS for the Ithaca winter.
    - Assess the effectiveness of this technology in Ithaca’s winter climate
- Assess the economic and environmental impact of installing the VS onto a fleet of Cornell Grounds vehicles.
    - Assess the overall economic and environmental impact of this technology to make an informed recommendation to CTECH and Cornell’s Climate Action Committee about whether the VS should be installed on other vehicles around

campus.

**Methodology**

Brief Description of Methodology

Our data analysis is divided into two parts: environmental and economic. The objective of our environmental analysis was to estimate the expected change in emissions for Cornell if they operated vehicles with installed VS. For this analysis, we calculated the WTP and PTW emissions for both diesel and B100 to obtain a full WTW life cycle for both fuels. We then analyzed the VS log to determine the average time the tractor spent on diesel vs. biodiesel.

Lastly, we combined the life cycle emissions for diesel and biodiesel, and the Optimus Portal data to derive an equation that calculates the reduction in emissions associated with VS operation. The goal of our economic analysis was to evaluate the economic feasibility of installing the VS onto vehicles, using metrics such as the ROI and payback period.

Well-to-Pump Emissions - GREET Software

We used the Greenhouse Gases, Regulated Emissions, and Energy use in Technologies Model (GREET), a software package for estimating emissions developed by Argonne National Laboratories (ANL), to calculate the WTP emission values for B100 and diesel. ANL's model uses a collated database of literature emissions data to calculate average emissions for refining, transporting, and processing various fuels.

We began with the default soy B100 and diesel pathways in the database. Then, we used information obtained by researching the fuel supply chains to customize the pathways and processes to match the logistics for the B100 and ULSD that Cornell procures for campus and better reflect the real-life emissions associated with our fuel sources. For more detail, see the appendix.

*Biogenic $CO_2$ Fixation*

We incorporated an additional stage into the B100 PTW modeling to account for the upstream biogenic CO2 fixation. This refers to the carbon in the biodiesel that comes from CO2 that was absorbed from the air by the plant feedstock during photosynthesis. Equation 1 shows how we calculated the carbon fixation for a gallon of B100.

$$Carbon\ Dioxide\ Fixated\ in\ Biodiesel = (\%\ Carbon\ in\ Biodiesel) \times (\%\ Biogenic\ Carbon\ in\ Biodiesel) \times \left(\frac{1}{\rho Biodiesel}\right) \times \left(\frac{1}{MM_c}\right) \times \left(\frac{mol\ CO2}{mol\ C}\right) \times MM_{CO2}$$

Equation (1)

Where:

% Carbon in Biodiesel = the weight fraction of the biodiesel that is from just carbon atoms [unitless]

% Biogenic Carbon in Biodiesel = fraction of the carbon in the biodiesel that is sourced from biological carbon fixation [unitless]

$\rho Biodiesel$= density of biodiesel [g/gal]
$MMx$ = molar mass of either carbon or carbon dioxide [g/mol]

The biogenic carbon comes from $CO_2$ in the air. The soybean plant fixates the $CO_2$ into carbohydrate sugars which are then refined into hydrocarbons in the biodiesel plants, thus each atom of carbon in the fuel comes from one atom of carbon from $CO_2$ in the air. The mass-balance-molar ratio, (mol $CO_2$)/(mol C), term in Equation 1 is equal to unity and represents 1 mole of biogenic carbon coming from 1 mole of $CO_2$.

Pump-to-Wheel tailpipe emissions

We originally intended to construct the PTW results by measuring the tractor's tailpipe emissions in real-time using a portable emissions monitoring system (PEMS) provided on-loan from Optimus Technologies. However, due to technical limitations we had to replace this process with a literature review. Our PEMS unit was over 15 years old. The age and unreliability of the unit meant that we were unable to confidently collect and save emissions data. Moreover, we were not able to purchase the correct internal sensors replacement as they had not been produced in over 5 years. Lastly, even if the PEMS had worked for the tractor, the tractor is an off-road vehicle, so its emissions might not have accurately represented the on-road fleet vehicles' emissions.

Instead, we conducted a comprehensive literature review comparing the tailpipe emissions in on-road medium and heavy-duty vehicles for five key pollutants: hydrocarbons (HCs), $NO_x$, CO, particulate matter (PM), and $CO_2$. In our report the term 'PM' is additive and is the sum of $PM_{2.5}$ and $PM_{10}$.

Throughout the body of this report, we assess the environmental impact of the VS based on four pollutants: CO, PM, $NO_x$, and $CO_2$. The focus of the Climate Action Plan (CAP) is on achieving carbon neutrality so measuring $CO_2$ is a paramount variable in our study. Aside from that, the other three pollutants all pose significant hazards to the environment and human health. CO is poisonous to humans and contributes to indirect radiative effects in the atmosphere, increasing global warming. High levels of NOx lead to eutrophication and increases the risk of respiratory disease in humans. Lastly, PM acts as a respiratory irritant and can cause health effects.

Vector System Warmup Time Analysis

The VS-engine complex first starts by running on diesel, and then when the biodiesel is warm and fluid enough to be pumped, the system switches over to burning biodiesel. Therefore, understanding the warmup time of the Vector System was a crucial part of the emissions analysis because the longer it takes for the B100 to heat up to an operable temperature, the more time the tractor will spend running on petroleum-derived diesel. As a result, we needed to factor the warmup time into calculating how much B100 would actually be combusted during standard operation of a vehicle with an installed VS. This warmup time varied based on the ambient surrounding temperature, which is particularly relevant for the frigid winter months in Ithaca. In the case study of the tractor, the operators reported that on some sub-freezing days, the system was unable to switch over to B100 because the tractor did not run for a sufficient period of time and the operable temperature was never reached.

We analyzed the VS operational data that was collected and stored in Optimus' VS web portal to establish a correlation between the outside temperature and the B100 warmup time. The portal has been monitoring and logging the system since it was installed on the tractor in March 2020. We looked solely at engine cold start data when building our mathematical model to obtain the most accurate correlation of the warmup time. Turning the tractor on and off multiple times in the same day warms up the system and the fuel throughout the day. These warm and hot starts are not representative of starting an engine cold and can therefore lead to shorter and less accurate warmup times compared to cold starting.

For each cold start run in the dataset, we used the time log information to calculate how long the tractor spent running on diesel to warm up the biodiesel and how long the tractor spent running on B100. On some colder days, the system was unsuccessful in heating up the B100 to a usable temperature before the tractor turned off, resulting in no time spent burning biodiesel. These incomplete data points are not an accurate representation of the warmup time, so they were omitted from our analysis. We plotted the warmup time as a function of the ambient outside temperature (Figure 2). After removing some outliers, we fit a trendline to the data to build our correlation between B100 warmup/switching-over time and the ambient temperature.

We also produced an operator log for our partners at Ag Services to fill out each time they used the tractor to verify the effectiveness and reliability of the VS. This log provided us with information on the weather conditions, temperature, observed biodiesel warmup time, any issues with the VS during daily operation, and how the tractor was being used. This also enabled us to corroborate the Optimus Portal VS data.

<u>Environmental Emissions Impact Assessment for Vector System</u>

We derived Equation 2 to calculate the expected change in emissions associated with operating a vehicle with an installed VS. This equation takes into account the life cycle emissions of diesel and biodiesel, VS warm up time, vehicular fuel consumption, and average vehicular trip length.

$$\begin{aligned} Monthly\ Change\ of\ Pollutant\ x &= [Emissions\ with\ VS] - [Emissions\ without\ VS] \\ &= \left[f_D \times LCE_{x,D} + f_B \times LCE_{x,B}\right] - \mathrm{f} \times\ LCE_{x,D} \end{aligned}$$

Equation (2)

where:

fD = monthly diesel usage for vehicle with VS [gal/month]

fB = monthly biodiesel usage for vehicle with VS [gal/month]

f = current fuel usage by vehicle without VS [gal/month]

$LCE_X$ = life cycle emissions for pollutant x per gallon of diesel or biodiesel [kg x/gal of fuel]. This is the sum of the WTP and PTW emissions for the fuel, For $CO_2$, this takes into account $CO_2$ fixation during photosynthetic plant growth.

Using the expression for the VS warm up time, $\tau$, as a function ambient temperature, as described in the previous section, and the average trip length for the vehicle, $t$, we calculated percentage of the vehicle trip where the VS is warming up, and thus the percentage of the trip where the engine is running on diesel. Equation 3 uses this relation to calculate what the new diesel fuel usage, $fD$, would be when a VS is installed.

$$f_D = \frac{\tau}{t} \times f \qquad \text{Equation (3)}$$

Where:
$f_D$ = monthly diesel usage for vehicle with VS [gal/month]
$\tau$ = monthly average warm up time for VS [min]
t = average trip length for vehicle [min]
f = current monthly diesel usage by vehicle without VS [gal/month]

Biodiesel is used for the rest of the vehicle operation after the VS warms up. However, the energy density of biodiesel is between 8 and 10% lower than that of diesel. In other words, a gallon of diesel can output more work than a gallon of biodiesel in an engine application, so more biodiesel is required to replace the same amount of diesel. We scaled the amount of biodiesel used in a vehicle trip by the heating value ratio of diesel and biodiesel to determine $f_B$:

$$f_B = [f - f_D] * \frac{LHV_D}{LHV_B} = \left[f - \left(\frac{\tau}{t} * f\right)\right] * \frac{LHV_D}{LHV_B} = \left(\left(1 - \frac{\tau}{t}\right) * f\right) * \frac{LHV_D}{LHV_B} \qquad \text{Equation (4)}$$

Where:
$f_B$ = monthly biodiesel usage for vehicle with VS [gal/month]
$LHV_D$ = lower heating value for diesel [mmBTU/gal]
$LHV_B$ = lower heating value for biodiesel [mmBTU/gal]
The lower heating values (LHV) were obtained from GREET to be consistent with the values we used in the life cycle emissions.
Substituting Equations 3 and 4 into Equation 2, we derived the Monthly Reduction of Pollutant x:
Monthly change of pollutant x:

$$= \left[\left(\frac{\tau}{t} * f\right) * LCE_{x,D} + \left(\left(1 - \frac{\tau}{t}\right) * f * \frac{LHV_D}{LHV_B}\right) * LCE_{x,B}\right] - f * LCE_{x,D}$$

$$= \frac{\tau}{t} * f * LCE_{x,D} - \left(\frac{\tau}{t} - 1\right) * f * \frac{LHV_D}{LHV_B} * LCE_{x,B} - f * LCE_{x,D}$$

$$= \left(\frac{\tau}{t} - 1\right) * f * LCE_{x,D} - \left(\frac{\tau}{t} - 1\right) * f * \frac{LHV_D}{LHV_B} * LCE_{x,B}$$

$$= \left(\frac{\tau}{t} - 1\right) * f * LCE_{x,D} - \left(\frac{\tau}{t} - 1\right) * f * \frac{LHV_D}{LHV_B} * LCE_{x,B}$$

$$= \left(\frac{\tau}{t} - 1\right) * f * \left(LCE_{x,D} - \frac{LHV_D}{LHV_B} * LCE_{x,B}\right)$$

$$= \left(1 - \frac{\tau}{t}\right) * f * \left(LCE_{x,B} * \frac{LHV_D}{LHV_B} - LCE_{x,D}\right) \qquad \text{Equation (5)}$$

As mentioned above, $\tau$ is dependent on ambient temperature. Thus, we used the average monthly ambient temperature to derive the average $\tau$ for each month. The *Monthly Change of Pollutant X* varies for each month because $\tau$ is different from month-to-month. We summed the *Monthly Change of Pollutant X* value for each month in a year (12 months) to derive the *Annual Change of Pollutant X:*

$$Annual\ Reduction\ of\ Pollutant\ x = \sum_{n=12\ months}^{\tau} Monthly\ Reductions\ of\ Pollutant\ x$$

$$= \sum_{n=12\ months}^{\tau} \left(1 - \frac{\tau_n}{t}\right) * f * \left(LCE_{x,B} * \frac{LHV_D}{LHV_B} - LCE_{x,D}\right) \qquad \text{Equation (6)}$$

The only term that varies over the 12 months is $\tau_n$. The other terms are constant over every month and can be factored out of the summation term.

$$Annual\ Reduction\ of\ Pollutant\ x = f * \left(LCE_{x,B} * \frac{LHV_D}{LHV_B} - LCE_{x,D}\right) * \sum_{n=12\ months}^{\tau} \left(1 - \frac{\tau_n}{t}\right) \qquad \text{Equation (7)}$$

Equation 7 is the primary equation used for our environmental analysis. These formulas were inputted into an Excel spreadsheet to calculate the expected *Annual Change of Pollutant X* for any given vehicle if a VS is installed. It is important to note that *f* in Equation 6 is the current average *monthly* usage of diesel for a vehicle without the VS.

We used the following equation to calculate the current emissions of pollutant x for a diesel-engine vehicle:

Current Annual Emissions of Pollutant X= 12 * $f * LCE_{x,D}$ Equation (8)

We defined *f* as the average monthly usage of diesel for a vehicle without the VS, thus we need to multiply by 12 months to achieve annual emissions. We then divided *Annual Change of Pollutant X* by *Current Annual Emissions of Pollutant X* to obtain the annual change in emissions for a vehicle if a VS were installed. We also added the results from Equation 7 and 8 to obtain the annual emissions for a VS-installed vehicle.

Economic Analysis for Vector System

Our three measures of economic analysis are Return on Investment, Payback Period, and Capital Cost per Ton of $CO_2$ Reduced. According to Optimus Technologies' records, the average capital cost of purchasing and installing a VS onto a vehicle is between $12,000 and $15,000. We conservatively assumed a capital cost of $15,000 for purchasing and installing a VS onto a vehicle.

Federal tax incentives such as the $1 per gallon biodiesel mixture credit[3] places the cost of biodiesel lower than that of diesel. According to NYSERDA[4], as of April 5, 2021, the cost of On-Highway diesel in the New York Surrogate Region was $3.27/gal. We currently source our biodiesel from local supplier Mirabito, and according to their owner, Phil Mirabito, as of March 11, 2021, the cost of biodiesel excluding shipping costs was $2.57/gal. Shipping costs for both fuels vary to the same degree depending on the quantity of fuel purchased, so it was omitted from our analysis, and it was impractical for us to estimate.

*Return on Investment*

We calculated Return on Investment (ROI) based on the savings in annual fuel purchasing divided by the capital cost:

$$ROI = \frac{(Current\ Annual\ Cost\ of\ Diesel\ -\ Annual\ Cost\ of\ Fuel\ with\ VS)}{Capital\ Cost} = \frac{f * CostD - (fB * CostB + fD * CostD)}{Installation\ Cost\ of\ VS} \qquad \text{Equation (9)}$$

Where:

$f$ = current annual diesel usage for vehicle without VS [gal]
$f_D$ = annual diesel usage for vehicle with VS [gal]
$f_B$ = annual biodiesel usage for vehicle with VS [gal]
$Cost_x$ = cost of fuel X [$/gal]

We calculated $fD$ and $fB$ using Equations 3 and 4, respectively, and multiplying them by 12 months to achieve annual fuel usage.

*Payback Period*

The Payback Period (PBP) is the amount of time it takes to recover the capital cost of installing the VS and is equal to the investment of a project divided by the cash inflow. In this case, the investment of the project is the capital cost of the VS and the annual savings in fuel costs is used instead of a cash flow. Fuel prices of diesel and biodiesel are volatile and unpredictable in the short term; thus, we assume a constant annual savings in fuel costs in the near future as a simplification.

$$PBP = \frac{Capital\ Cost\ of\ VS}{f * Cost_D - (f_B * Cost_B + f_D * Cost_D)} \qquad \text{Equation (10)}$$

[3] Hanson, Steve. "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." *U.S. Energy Information Administration (EIA)*, 28 Jan. 2020, www.eia.gov/todayinenergy/detail.php?id=42616.
[4] "Weekly On-Highway Diesel Prices." The New York State Energy Research and Development Authority, www.nyserda.ny.gov/researchers-and-policymakers/energy-prices/on-highway-diesel/weekly-diesel-prices

As our model assumes that the annual savings in fuel cost remain constant, PBP reduces to the 1/ROI.

*Capital Cost per Ton of $CO_2$ Reduced*

Capital Cost per Ton of $CO_2$ Reduced is the combination of both the environmental and economic analyses. This metric calculates the capital cost over the lifespan of a project and divides it by the total tons of $CO_2$ reduced over the VS life. This estimates how much money we would have to spend in installing a VS on a vehicle to reduce one ton of $CO_2$.

According to Optimus, the lifespan of the VS is 10 - 20 years. We chose the lifespan of the VS to be 10 years as a conservative estimate. We derived the Capital Cost per Ton of $CO_2$ Reduced with the following equation:

$$Capital\,Cost\,per\,Ton\,of\,CO2\,Reduced = \frac{\text{CAPEX}}{T * AER_{CO\,2}} = \frac{\$15{,}000}{10\;yrs\; * AER_{CO\,2}} \qquad \text{Equation (11)}$$

Where:

*CAPEX* = capital cost of installing a VS = $15,000
$T$ = lifetime of VS = 10 yrs.
$AER_{CO2}$ = annual emission reduction of $CO_2$ for the vehicle [tons/yr]

We determined $AER_{CO2}$ using Equation 6 from our environmental analysis.

<u>Application to a Larger Cornell Fleet</u>

To model the emissions impact of installing the VS onto other Cornell operated fleets we applied our environmental and economic analyses to two separate diesel fleets – a Cornell Grounds (Facility and Campus Services) fleet consisting of dump trucks, UTVs, and tractors and a TCAT fleet. The Grounds fleet provides us with a realistic assessment of the VS' utility across a wide range of vehicle types, while the TCAT fleet is an optimal candidate for alternative fuels due to its high usage and fuel consumption rates.

For the Grounds vehicles, we used fuel consumption and operating time data provided to us from Facilities and Campus Services (FCS) to predict the annual B100 consumption if the aforementioned fleets were equipped with the VS. Per FCS' suggestion, we assumed an average trip length of 2 hours in our calculations (Table 1).

*Table 1: Summary of diesel vehicles in the Cornell Grounds Fleet*

| Vehicle type | No. of vehicles in Grounds fleet | Time of each trip (hr) | Annual diesel consumption per vehicle (gal) |
|---|---|---|---|
| Large trucks (dump trucks, flatbeds, etc.) | 7 | 2 | 310 |
| UTVs | 8 | 2 | 140 |
| Tractors | 8 | 2 | 210 |

For the TCAT buses at Cornell, we calculated the average trip length and operating time based on published route data. We used Route 30[5], which runs regularly through the Cornell campus, as our model for TCAT trip length.

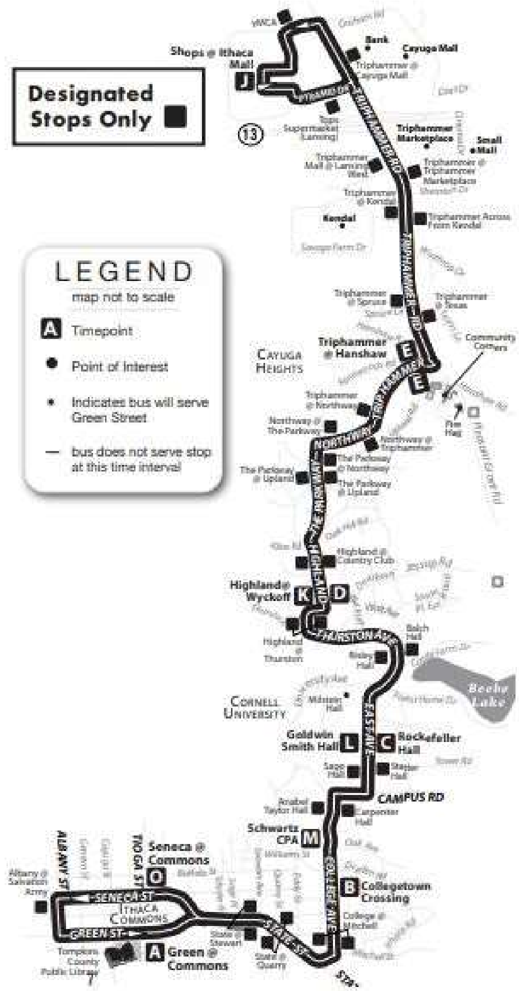



*Figure 1: TCAT Route 30*

We also assumed the buses were Gillig Advantage T40s, the predominant diesel bus employed by TCAT, to calculate operating data. We used literature values for the fuel economy of this bus

[5] https://tcatbus.com/wp-content/uploads/2020/08/30_Fall2020.pdf

model in our calculations[6]. The assumptions for this fleet are listed in Table 2 below, which allowed us to later calculate the annual fuel consumption and the impact of installing the VS.

*Table 2: Assumptions for the fleet of diesel TCAT buses*

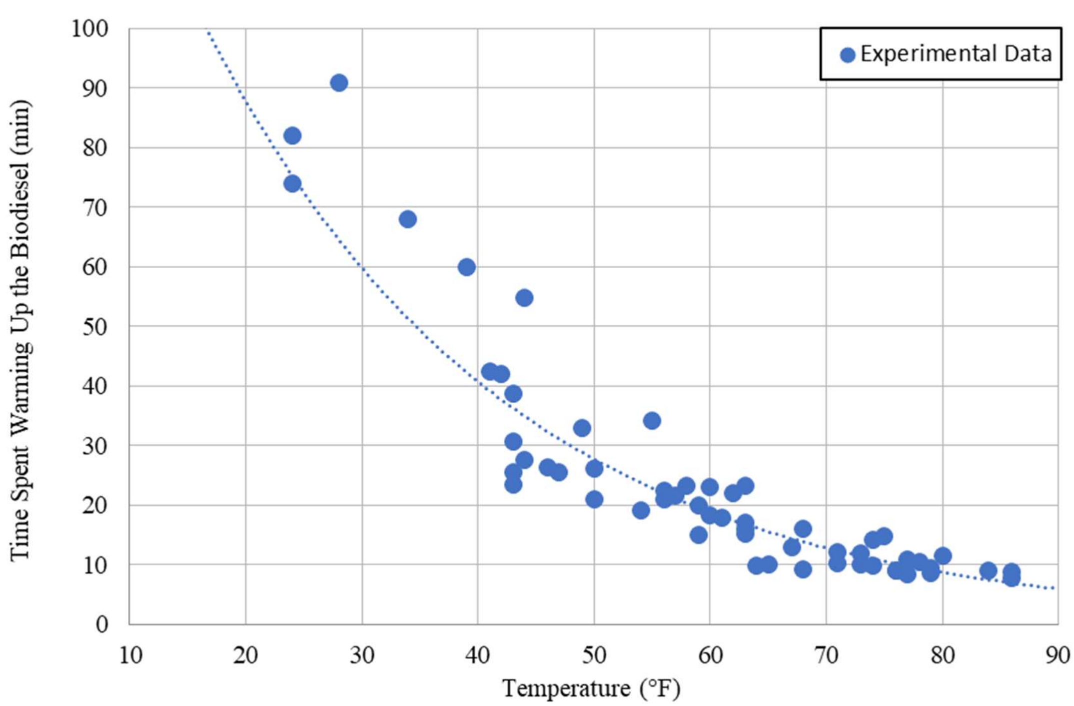
| Bus Model | Number of vehicles in fleet | Fuel economy (mpg) | Distance of each round trip (miles) | Rounds trips per day | Operating days per year |
|---|---|---|---|---|---|
| Gilling Advantage T40 (Diesel) | 34 | 4.5 | 14 | 10 | 360 |

**Results**

Tractor Case Study

The qualitative data from the operator log indicated that Ag Services has not faced any problems with operating the VS in the past year. In other words, the VS does not reduce vehicle operability. However, on some of the colder winter days the logs indicated that the VS never switched over to biodiesel. This typically occurred on shorter trips (< 1 hour). After plotting the warmup time and temperature data for the tractor (Figure 2), we developed an exponential correlation to predict the time a vehicle equipped with the VS would spend burning diesel, represented as $\tau$ (minutes), for a given ambient temperature $T$ (°F):

$$\tau = 191e^{-0.038T} \quad \text{Equation (12)}$$




[6] Hallmark, Shauna L, et al. “Evaluation of In-Use Fuel Economy for Hybrid and Regular Transit Buses.” *Journal of Transportation Technologies*, vol. 3, no. 1, Jan. 2013, pp. 52–57., doi:10.4236/jtts.2013.31006.

*Figure 2: Correlation between biodiesel warmup time and ambient temperature*

We retrieved historical weather data from the National Climatic Data Center to determine the average monthly temperatures in Ithaca, NY,[7] and used the correlation above to calculate the estimated biodiesel warmup time, $\tau$, for each month (Table 3). It is important to note that while the temperatures recorded in Figure 2 and those use to calculate $\tau$ in Table 3 are the ambient outside temperatures, during the winter months the tractor was stored inside a heated garage. Hence, there may be some discrepancies between the ambient outside temperature and the vehicle's actual startup temperature.

*Table 3: Estimated monthly B100 warmup times for a VS-equipped vehicle in Ithaca, NY*

| Month | Average Temperature (°F) | $\tau$ (minutes) |
|---|---|---|
| January | 22 | 82 |
| February | 24 | 75 |
| March | 33 | 55 |
| April | 44 | 36 |
| May | 56 | 22 |
| June | 63 | 17 |
| July | 68 | 14 |
| August | 66 | 15 |
| September | 60 | 19 |
| October | 50 | 29 |
| November | 38 | 45 |
| December | 29 | 63 |

Life Cycle Analysis Results

*WTP Results - GREET*

We modified the two default pathways for diesel and biodiesel on GREET with the parameters detailed in the appendix section *GREET Pathways*. Below are the WTP emissions for $CO_2$, $NO_x$, PM, and CO from Cornell's B100 and USLD.

*Table 4: Upstream Life Cycle Emissions for $CO_2$, NOx, PM, and CO Associated with the Fuel Production Stages*

| Fuel | $CO_2$ [g/gal] | $NO_x$ [g/gal] | PM [g/gal] | CO [g/gal] |
|---|---|---|---|---|
| ULSD | 1540 | 2.47 | 0.30 | 1.49 |
| Biodiesel | 2960 | 3.74 | 0.45 | 2.49 |

[7] "Climate Data Online." *National Climatic Data Center (NCDC)*, National Oceanic and Atmospheric Administration, www.ncdc.noaa.gov/cdo-web/.

These upstream emissions do not account for the carbon fixation via photosynthesis from the soybeans during the farming stage. We refer to this carbon fixation as biogenic $CO_2$ in the biodiesel.

*Biogenic $CO_2$*

We calculated the biogenic $CO_2$ in biodiesel using values from GREET and Equation 1. According to GREET, 77.6% of the soybean-based biodiesel in our pathway is carbon by mass and 94.77% of this carbon comes from biogenic sources. Using Equation 1, uptake for biodiesel is 9.06 kg of $CO_2$/gal of biodiesel. We calculated the net WTP emissions of $CO_2$ for biodiesel by adding the carbon uptake and the upstream life cycle emissions (LCE) for $CO_2$ as shown in Table 4 above.

*Table 5: Net WTP Life Cycle Emissions for $CO_2$, NOx, PM, and CO*

| Fuel | $CO_2$ [g/gal] | $NO_x$ [g/gal] | PM [g/gal] | CO [g/gal] |
|---|---|---|---|---|
| ULSD | 1540 | 2.47 | 0.30 | 1.49 |
| Biodiesel | -6100 | 3.74 | 0.45 | 2.49 |

Our GREET model calculated all emissions using the Lower Heating Values (LHV) of diesel and biodiesel shown below:

$$LHV_D = 0.129\ \frac{mm\ BTU}{gal}$$

$$LHV_B = 0.120\ \frac{mm\ BTU}{gal}$$

*PTW Results - Literature Review for Tailpipe Emissions*

As indicated by the literature review results in Table 6, the average tailpipe PM and $CO_2$ emissions are lower for B100, whereas the average B100 emissions are higher for NOx and CO.

*Table 6: Average PTW tailpipe emissions for HD and MD on-road vehicles running on B100 and ULSD*

| Fuel Type | $CO_2$ [g/gal] | $NO_x$ [g/gal] | PM [g/gal] | CO [g/gal] |
|---|---|---|---|---|
| B100 | 8240 | 61.5 | 1.39 | 22.4 |
| ULSD | 9520 | 48.6 | 1.98 | 14.8 |
| % Change from ULSD to B100 | -14% | +26% | -30% | +51% |

It is crucial to remember that these values are the averages of PTW emissions values from different research papers. In Figure 3, each point for B100 and ULSD represents one research paper from which an emissions value was obtained. The dotted line represents the average of all of the different literature review emissions sources. Some of the pollutant graphs have more points than others, indicating that there was more emissions data available in literature. These graphs for the other pollutants can be found in the appendix.

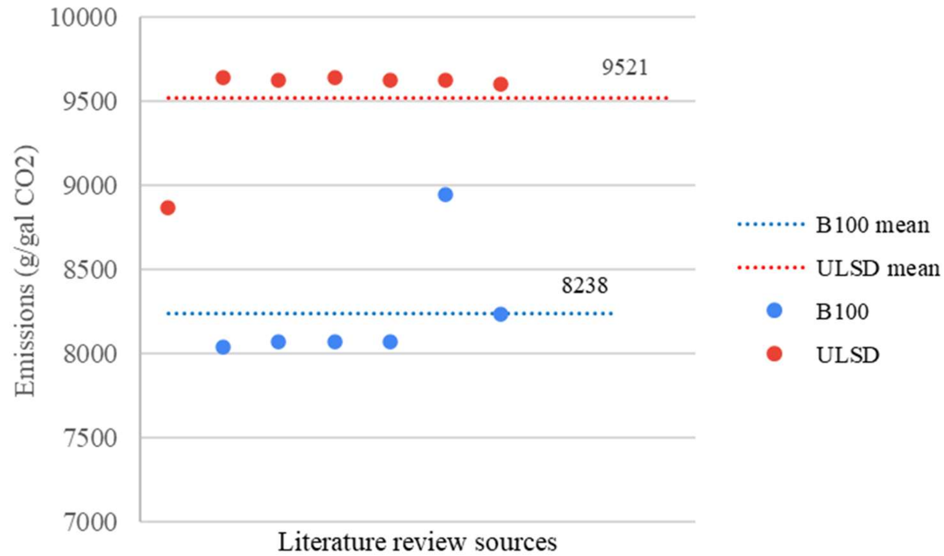



*Figure 3: Graph showing the $CO_2$ tailpipe emissions for B100 and ULSD*

Life Cycle Emissions for Each Pollutant for Diesel and Biodiesel

We calculated the Life Cycle emissions for each pollutant by adding their respective WTP emissions from GREET and average PTW emissions from tailpipe emission literature values.

*Table 7: Average LCE for $CO_2$, NOx, PM, and CO for Diesel and Biodiesel*

| Fuel | $CO_2$ [g/gal] | NOx [g/gal] | PM [kg/gal] | CO [kg/gal] |
|---|---|---|---|---|
| Diesel | 11,100 | 51.1 | 2.3 | 16.3 |
| Biodiesel | 2,140 | 65.2 | 1.8 | 24.9 |

The life cycle $CO_2$ emissions are lower for biodiesel than for diesel because of the biogenic carbon uptake that occurs during photosynthesis in soybeans. These LCE values for each fuel are used in Equation 7 to calculate the impact in pollutant quantities if we were to install a VS onto a vehicle.

Error Analysis for the Grounds & TCAT Fleets

We added error bars to Figures 4 and 5 to better show the variability of emissions data around the mean result for each pollutant. To construct these error bars, we found the maximum and minimum percent impact of installing the VS onto the Grounds and TCAT fleets for each pollutant. Due to the large variability in the literature review PTW data, the error bars for NOx, CO and PM are extremely large, indicating a wide spread of data around the mean. We will discuss the implications of this later on.

Cornell Grounds Fleet Analysis

*Environmental Analysis*

We evaluated the environmental impact of converting Cornell's FCS fleet to run on biodiesel using the VS, as shown in Table 8 and Figure 4 below.

*Table 8: Average Emissions Impact for Cornell Grounds Fleet if VS is Installed on All Vehicles in Fleet.*

| Pollutant | No-VS Current Annual Emissions [tn/yr] | VS Annual Emissions [tn/yr] | Annual Emissions Change |
|---|---|---|---|
| CO2 | 61 | 29 | -53% |
| NOX | 0.28 | 0.35 | +26 % |
| PM | 0.013 | 0.012 | -8.5% |
| CO | 0.090 | 0.13 | +0.44% |

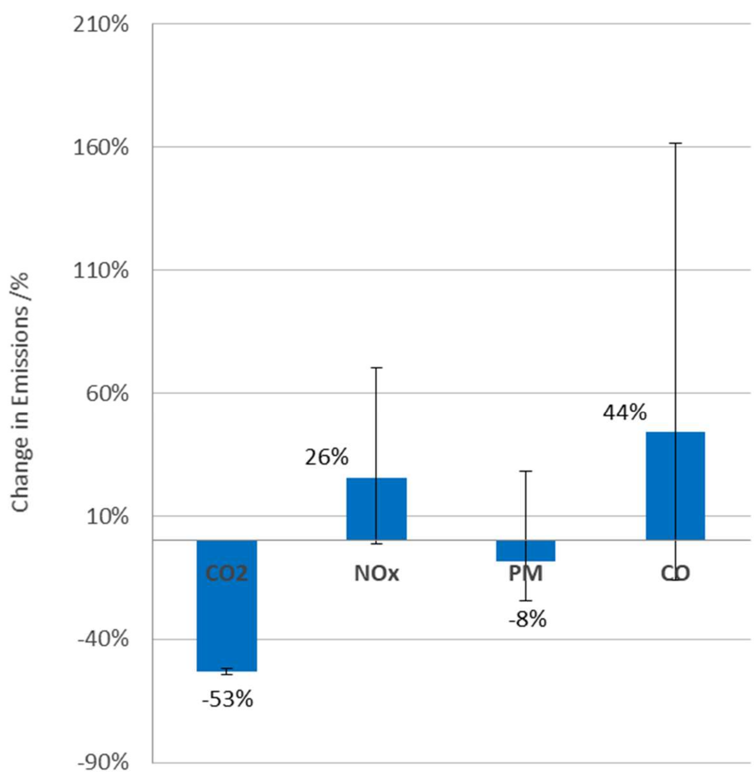



*Figure 4: Grounds Fleet - emissions impact*

As seen in Figure 4 and Table 8, $CO_2$ and PM are the only pollutants which experience a reduction in emissions when operating a VS. Their emissions decrease by 53% and 8.5%, respectively. On the other hand, NOx and CO emissions increase by 26% and 44%, respectively. However, the error bar for $CO_2$ is the only one that is sufficiently small, indicating a low variability in data around the mean. The error bars for the other three pollutants are all significantly larger than the actual % change in emissions, indicating a high variability in data around the mean.

*Economic Analysis*
Installing the VS onto the diesel vehicles in the Cornell Grounds fleet requires a total capital cost of $345,000 for the 23 vehicles. Since B100 is cheaper than petroleum diesel, this results in total fuel savings of around $1,300 annually. The ROI for this scenario is 0.367%, with a payback period of 273 years. While these numbers are not insignificant, the most important aspect of the Vector System is the environmental impact, and from an emissions perspective, Cornell would be spending $1,070 per ton of $CO_2$ emissions reduced for the entire fleet (over a 10-year VS lifetime).

<u>Cornell TCAT Fleet Analysis</u>
*Environmental Analysis*
Following a similar approach to the FCS fleet analysis, we studied the impact of installing the VS on a fleet of 34 TCAT buses. Since the TCAT vehicles operate for longer periods of time, they spend proportionally more time on biodiesel compared to conventional diesel. As a result, we see a larger reduction in $CO_2$ emissions compared to the FCS fleet.

*Table 9: Emissions impact for TCAT fleet if VS is installed on all TCAT buses in the fleet*

| Pollutant | No-VS Current Annual Emissions [tn/yr] | VS Annual Emissions [tn/yr] | Annual Emissions Change |
|---|---|---|---|
| **$CO_2$** | 4,640 | 1210 | -74% |
| **$NO_X$** | 21 | 29 | +36% |
| **PM** | 0.96 | 0.85 | -12% |
| **CO** | 6.8 | 11 | +61% |

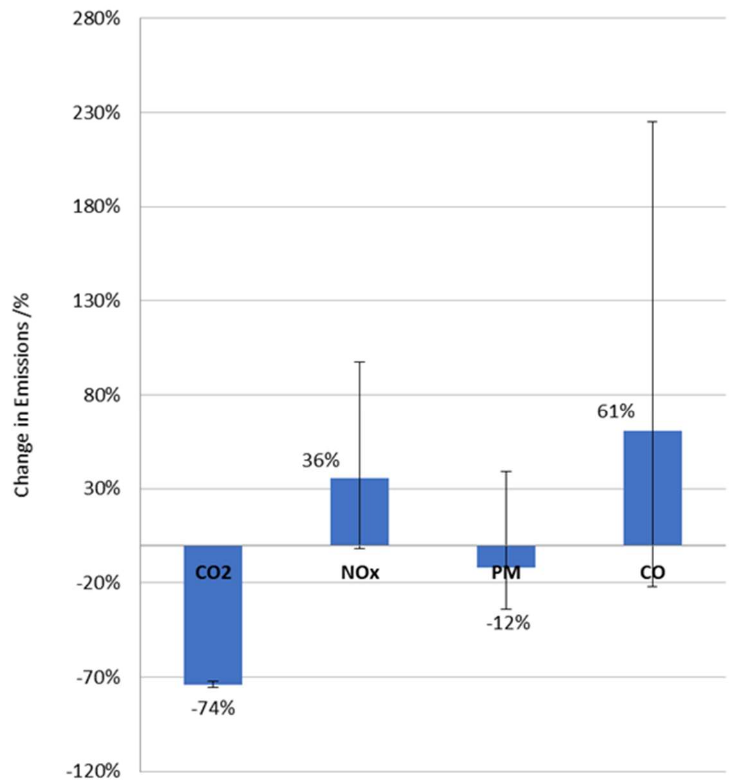



*Figure 5: TCAT Fleet – emissions impact*

As seen in Figure 5 and Table 9, $CO_2$ and PM are the only pollutants which experience a reduction in emissions. Their emissions decrease by 74% and 12%, respectively. On the other hand, NOx and CO emissions increase by 36% and 61%, respectively. However, the error bar for $CO_2$ is the only one that is sufficiently small, indicating a low variability in data around the mean. The error bars for the other three pollutants are all significantly larger than the actual change in emissions which suggests that these results are extremely uncertain.

*Economic Analysis*
Switching 34 TCAT diesel buses to the Vector System will require an estimated capital cost of $510,000 but would result in potential fuel savings of $104,000 per year for the entire fleet. In this scenario, TCAT can recover the total capital cost of installation in approximately 4.9 years with an ROI of 20.3%. This compares favorably to the ROI for the Grounds fleet, mainly due to the significantly higher fuel consumption and vehicle usage for the TCAT buses. From an environmental perspective, TCAT would be spending $14.90 per ton of $CO_2$ reduced for the entire fleet, assuming a 10-year VS lifetime.

**Discussion**
<u>Vector System Discussion</u>
The qualitative data from the tractor operator log and the warmup time correlation that we

derived both indicate that the Vector System is capable of performing as expected during warmer months. For most days in the spring, summer, and fall, the system should successfully transition to B100 within 30 minutes, resulting in measurable environmental benefits for trips of sufficient length. However, during the winter months, the VS may take over an hour to warm up the B100, making the system effective only for vehicles that operate for longer than a couple of hours, such as TCAT buses.

Economic Results

The unfavorable ROI (0.367%) and payback period for the Grounds fleet would normally indicate a poor investment. However, the environmental impact of the VS was the main focus of this study, and any economic benefits of switching to biofuels, i.e., cheaper fuel costs, are secondary. Therefore, the critical metric for this study is the capital cost per amount of $CO_2$ reduced. For the Grounds fleet, Cornell would be spending a total of $1,070 for every ton of $CO_2$ that would be reduced by installing the VS. The main advantage of the VS is that it facilitates impactful emissions reductions on existing vehicles, which is significantly less costly than purchasing new vehicles, electric or otherwise. As a result, though the financials do not seem favorable, the VS may still be a cost-effective solution to reduce campus vehicle emissions, and at the very least, will bridge the temporary gap between current petroleum-burning campus vehicles and future electrified fleets.

Since the TCAT buses operate consistently for long periods of time, the amount saved on fuel by using B100 is significant. As a result, the installation costs for this fleet can be recuperated within 5 years. Furthermore, the higher vehicle usage yields greater $CO_2$ emissions reductions and the cost of reducing each ton of $CO_2$ emissions is significantly lower. TCAT would only have to spend $14.90 per ton of $CO_2$ reduced by installing the VS on buses. High-use diesel vehicles like the TCAT buses tend to result in the largest benefits, both environmental and economic, thus making them ideal candidates for the Vector System.

Environmental Results

As noted in the economic discussion section, there is a clear GHG emissions advantage from installing the VS for both the Cornell Grounds and TCAT fleets.

*Life Cycle Results*

While the PTW emissions for B100 are higher for NOx and CO, 26% and 51%, respectively, the results also indicate that there are significant reductions in other key pollutants, such as PM and $CO_2$, 30% and 14%, respectively. However, these tailpipe emissions only represent one component of the total life cycle of these fuels. The most notable reductions in emissions for B100 occur upstream of engine combustion in the WTP processes. In the case of $CO_2$, a significant reduction in emissions can be attributed to the biogenic $CO_2$ fixation associated with soybean crop photosynthesis.

The limited data for certain pollutants, especially CO, is attributed to the fact that while there are many research papers that have compared diesel and biofuel emissions, many papers use a different feedstock (e.g., beef tallow or corn instead of soy), blend ratio (e.g., B20), or vehicle/engine type, and are therefore inapplicable to this analysis for soy B100. It is also important to note that biodiesel produced from corn or soy have an additional environmental cost of production associated with the harmful land usage, pesticide and herbicide usage practices of industrial agriculture. While it is possible to produce biodiesel from waste cooking oil and more sustainable sources, these types of biodiesels are not as widely available and there was not enough literature reviewed data to investigate them in this study. For readers interested in the upstream environmental costs of production associated with biodiesel produced from soybeans or tallow, we recommend looking into the GREET 2020 model.

*$CO_2$ Results*

The average $CO_2$ reduction estimates for the Grounds and TCAT Fleet are 53% and 74%, respectively, which results in reductions of 32 tons $CO_2$ and 3,430 tons $CO_2$, respectively. The difference between the life cycle $CO_2$ emissions for biodiesel and diesel is mainly because of biogenic $CO_2$ fixation in soybeans, the biodiesel feed stock. For both fleets, $CO_2$ emissions were reduced when the VS was used, and the error bar size is significantly shorter than the percent change in emissions, indicating a low level of variability and a high level of accuracy in these results. The difference between $CO_2$ emissions for biodiesel and diesel is of a larger magnitude than the other pollutants because the feed source for B100 fixes carbon dioxide, so the variability in tailpipe emissions has a smaller effect on the absolute change in emissions.

The TCAT fleet experiences a larger reduction in emissions because it runs for a longer time, meaning that the proportion of time it spends on B100 compared to ULSD is greater. The main obstacle for the VS to switch to biodiesel is the warm-up time, thus vehicles with a longer run time would run on biodiesel for a larger portion of their trip. This results in less $CO_2$ because the $LCE_{CO2}$ for biodiesel is much lower than it is for diesel. The maximum $CO_2$ reduction benefits of the VS occur when the VS is installed onto long run time vehicles, like the TCAT buses, which continuously run for 6+ hours a day.

The difference between $CO_2$ emissions for biodiesel and diesel is of a larger magnitude than the other pollutants because the feed source for B100 fixes carbon dioxide, so the variability in tailpipe emissions has a smaller effect on the absolute change in emissions.

*NOx, CO, and PM Results*

Both the Grounds and TCAT fleets exhibit an increase in NOx and CO and a decrease in PM emissions. Between the two fleets, the percentage change in emissions for the TCAT vehicles is higher across the board by a constant factor because of the TCAT's longer running time. While the increases in NOx and CO may appear concerning, these levels are still under the EPA imposed limits on vehicle emissions[8].

One key feature to note is the large error bar sizes for these 3 pollutants compared to $CO_2$. This indicates high levels of variability among the different tailpipe emissions data from the PTW literature review stage. This variation in tailpipe emission data is due to the limitation of the secondary data we collected. While we tried to filter the different literature review papers to only collect emissions data on HD/MD on-road vehicles, there were still other variables at play which would lead to variations in emissions levels, such as engine and vehicle type. Ultimately, the size of the error bars for these 3 pollutants means that we cannot confidently conclude whether the VS reduces or increases NOx, PM, and CO emissions. We will expand more upon this in our conclusion.

Alternatives to the Vector System

The advantage of the VS is that it enables existing vehicles to still be used while also reducing the carbon dioxide footprint of the vehicle by as much as 60-80%. Hence, the VS acts as a bridge technology enabling us to reduce emissions without needing to replace fleet vehicles. However, other alternative modifications for fleets can also reduce emissions, such as switching the fuel to renewable compressed natural gas, purchasing new vehicles that are hybrid electric, plug-in hybrid electric, hydraulic hybrid or fully electric. Alternatively, driver competency and training can also impact emissions. According to the Department of Energy, "fuel economy is reduced by idling, speeding, shifting gears frequently or improperly, accelerating or braking aggressively or frequently." While this report evaluates and discusses the VS, other alternatives do exist.

Living Laboratory

Since the onset of this project, it has been a priority to treat it as a living laboratory and give student members of the project an opportunity to apply the material they have learned in classes to real-world engineering problems and gain hands-on experience. Student involvement began back in 2019 with defining project scope.

During the fall of 2019, we designed and engineered modifications to the VS, so it could fit on the tractor. We first traveled to the farm to measure the tractor dimensions, so we could CAD the mounting brackets for the VS manifold, selector valves, and biodiesel fuel tank. After completing our initial design, we sent it to the engineers at Optimus Technologies for review.

Taking their suggestions into consideration, we updated the design and prototyped the bracket out of acrylic sheets in the Rapid Prototyping Lab (RPL). We then traveled back to the farm to test the fit of these brackets before making further modifications and sending the designs off to be fabricated from metal plates.

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[8] https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-smog-soot-and-other-air-pollution-commercial

After we designed and fabricated the mounting brackets, Optimus Technologies' Chief Engineer came up to Cornell in March 2020, and Biofuels members assisted him in installing the VS to the Ag Service's tractor. Once the VS was installed, the Biofuels members focused on troubleshooting the system and interfacing with Ag Services.

We then pivoted to focusing on validating the VS and designing experiments to evaluate its operability. The student team also collected data and modeled the biodiesel and diesel life cycles to assess the environmental and economic impact of expanding the VS to additional vehicles.

**Assumptions and Sources of Error**

There are a few sources of error that could have impacted the validity and reliability of our results. Most notably, due to technical difficulties, we were unable to follow our original plan of collecting real-time data and measuring the tractor's tailpipe emissions with the PEMS unit lent to us by Optimus Technologies. As a substitute we collected secondary tailpipe data through a comprehensive literature review process. However, even if the PEMS unit had worked, we would have been using tailpipe data from the tractor, a heavy-duty off-road vehicle, to approximate the exhaust emissions of the Grounds and TCAT fleets which both predominately consist of on-road vehicles. In order to accurately gauge the tailpipe emissions of the different vehicles in this study, we recommend installing a PEMS unit onto each vehicle type and measuring the exhaust emissions in each case.

Another potential source of error was the lack of specificity in the GREET life cycles. At some stages of the LCA, the data we needed to approximate emissions were not publicly available, such as the emissions associated with the refinery process of B100 at HeroBX (the biodiesel refinery where our B100 was sourced from). In these cases, we used the default average values in the GREET databases. Looking forward, we suggest using other life cycle analyses tools in conjunction with GREET to ensure that emission values are as accurate as possible.

When deriving the environmental impact equation, we made two key assumptions – 1) that there would be no seasonal difference in tractor use and 2) that the total LCA emissions of winter diesel (cut with 40% kerosene) would be approximately the same as the LCA emissions for regular ULSD (no kerosene). For the first assumption, although we assumed in our model that vehicle use would be constant year-round, there likely is some seasonal variation in vehicle use, especially for the HD vehicles used to plow snow. Nonetheless, we felt justified in this assumption as only some of the vehicles in our fleet have seasonal variability in their use and that in many cases these differences would have a negligible impact on emissions. For instance, there is limited seasonal variation in the TCAT bus use as it has pre-set routes and the difference in load carried, i.e., passengers, is more trivial. Integrated into these assumptions, we also surmised that the load carried by the tractor and the tractor's specific tasks would not affect start-up time.

For the second assumption, we were unable to conduct a literature review on kerosene-cut diesel emissions due to a lack of available data since studies that looked at kerosene emissions did so in jet engines, not on-road vehicles. Nevertheless, we felt justified in assuming that its emissions were the same as regular ULSD, because kerosene is a more refined fuel. While it does have higher upstream WTP emissions, it also burns more cleanly in the tailpipe, yielding lower PTW emissions. Moreover, kerosene only accounts for ~10% (3/12 months using 40% kerosene) of the total fuel the fleet vehicles use per year, indicating that it would have a small impact on the tractors' net emissions.

A final source of error in this experiment was the limited winter testing data. Although the Optimus portal provided us with VS data from March 2020 onwards, there was a lack of data for temperatures below 30 °F. There were also inconsistencies in the temperature threshold for when the system switched over to biodiesel as there are some data points when the system switched to biodiesel and other points when it did not at the same temperature. To rectify this, we recommend increasing tractor use to collect more data so that the threshold temperature is clearer. Additionally, previous case studies conducted by Optimus indicate that correlating the average ambient temperature as a clear gauge for warmup time may not be the most accurate portrayal of how the engine heats up. Moving forwards, greater thought and studies into the accuracy of the data may be required.

## Conclusion

### Vector System Feasibility

We confidently recommend the VS as a means of helping Cornell achieve its carbon neutrality goals. For both vehicles with short and long run times, installing the VS would decrease $CO_2$ emissions, and for longer running time vehicles, there are clear economic benefits. For shorter running vehicles, there are clear environmental benefits, but no major economic advantages, just a minor reduction in operating cost from using a less expensive fuel.

While the VS has a definitive impact on reducing $CO_2$ emissions, its impact on NOx, PM and CO are more nuanced. As shown in Figure 4 and Figure 5, the large error bar sizes for NOx, PM and CO impacts indicate that we cannot confidently endorse this technology as a means of reducing (or increasing) the levels of these pollutants. Mitigating climate change is more complicated than just reducing $CO_2$ – other pollutants like NOx, CO and PM have their own associated hazards and exacerbate global warming. Before the VS is installed onto Cornell vehicles, we strongly recommend installing a PEMS unit onto other vehicle types to measure the exact tailpipe emissions of these pollutants.

Ultimately, the Vector System, and biodiesel as a whole, can serve as a feasible and impactful bridge solution to achieve Cornell's carbon neutrality goals. Compared to other alternatives, the VS is a relatively economical technology with immediate environmental benefits. Since the VS enables the existing fleet to be converted to biodiesel, the transition will be far quicker and simpler, requiring little infrastructural development and no need to dispose of current vehicles.

Certainly, we envision a future of zero-emissions, electric-powered vehicles to service Cornell's transportation needs. However, such an undertaking would require far more time and resources, and the VS can be an effective bridge to this future by reducing greenhouse gas emissions in the present. Biodiesel should be seen as a complement, and not a rival, to carbon-free technologies, and will hopefully ease the transition to a cleaner Cornell.

Living Laboratory

This project provided us with ample opportunities to work on real engineering problems. We worked collaboratively to troubleshoot issues, designed our own testing plan for the VS on the tractor, and took charge of operating the VS. Ultimately, this project was full of rich opportunities for us to gain hands-on engineering experience and develop into competent engineers prepared to tackle real-word problems.

## Appendix

GREET Pathways

We created our fuel pathways for ULSD and biodiesel by modifying the default *Low-Sulfur Diesel from Crude Oil* and *Biodiesel Production from Soybeans* pathways in the GREET database, respectively. These pathways are presented in Figure 6 and Figure 7 below. After contacting suppliers and researching about relevant refineries and transesterification plants, we modified the two default pathways on GREET to customize them to provide the specific LCAs of the fuels used by Cornell.

Cornell procures both diesel and biodiesel from local fuel supplier Mirabito; however, the logistics for the two fuels differ. The diesel supplied by Mirabito is ULSD produced at the Bayway Refinery in Linden, NJ. The refinery obtains its crude oil from imported crude at New York Harbor and domestic Bakken Shale from North Dakota. The ULSD produced at the Bayway Refinery then is transported via the Buckeye Pipeline to a terminal in Binghamton, NY. The pipeline goes from Linden, NJ to Whitehall, PA, then to Binghamton, NY. A Mirabito tanker truck transports diesel from the Binghamton terminal to a local terminal at Ithaca, NY. Lastly, another truck transports the diesel from the Ithaca terminal to Cornell University. Quantitative details of these logistics are listed below:

- Bayway Refinery – processing capacity of 238,000 bbl crude/day
    - 90,000 bbl/day of domestic Bakken Shale is transported via rail to Bayway Refinery (~1,250 mi. distance)
    - 148,000 bbl/day of imported crude oil is transported via a 10 mi. pipeline from NY Harbor to Bayway Refinery.
    - Two primary sources of imported crude oil at NY Harbor
        - Nova Scotia, Canada – imported via pipeline. Accounts for roughly 91% of imported crude at NY Harbor (~730 mi. distance).
        - Nigeria – imported via tanker ship. Accounts for roughly 9% of imported crude at NY Harbor (~7,620 mi. distance).
- Buckeye Pipeline – the route from the Linden, NJ terminal to the Binghamton, NY terminal goes through Whitehall, PA (~230 mi. distance).
- ULSD is transported from the Binghamton, NY terminal to Cornell via heavy-duty tanker truck. (~55 mi. distance)

The biodiesel supplied by Mirabito is B100 biodiesel from a HeroBX biodiesel plant in Erie, PA. There are numerous soybean farms throughout the Midwest, so it is not possible to pinpoint where the soybean for biodiesel production comes from. However, there is a cluster of soybean processing plants in Western Ohio, which is the closest source to Erie, PA, so we assumed the soybeans were farmed in western Ohio, as well. The harvested soybeans are then transported via medium-duty (MD) trucks to nearby soybean stacks, central locations for soybean loads. The soybean loads are then transported via heavy-duty trucks to the transesterification plant, where the soybeans are converted into soybean oil. The soybean oil then is transported via rail and heavy-duty trucks to the HeroBX biodiesel plant. After the soybean oil is converted into biodiesel, it is transported via heavy-duty trucks to a terminal in Sidney, NY. Lastly, Mirabito transports the biodiesel from Sidney, NY to Cornell with medium-duty trucks. Quantitative details of these logistics are listed below:

*Table 10: Distances and Modes of Transportation for the Biodiesel Pathway*

| | **Ohio farms** | **Soybean Stacks** | **Transesterification plant (W Ohio)** | **HeroBX biodiesel plant** | **Sidney, NY Terminal** | **Cornell** |
|---|---|---|---|---|---|---|
| Distance (mi.) | Origin | 10 mi. | 30 mi. | 250 mi. | 300 mi. | 30 mi. |
| Mode of transportation | N/A | Medium-Duty Truck | Heavy-Duty Truck | Rail + Heavy-Duty Truck | Heavy-Duty Truck | Medium -Duty Truck |

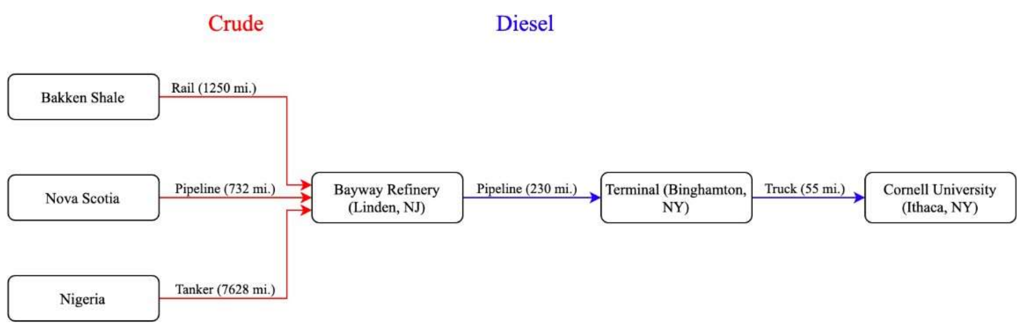


*Figure 6: Pathway for petroleum diesel. Crude oil is predominantly sourced from the Bakken Shale, Nova Scotia, and Nigeria, which make up approximately 38%, 56%, and 6% of crude imports at the Bayway refinery, respectively.*

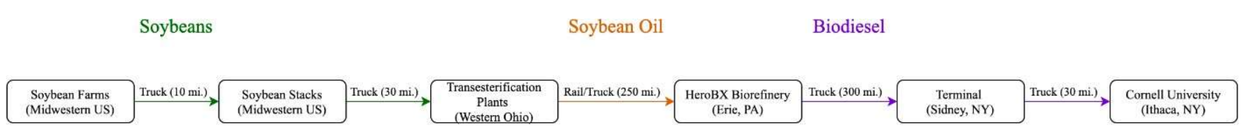


*Figure 7: Pathway for soy B100. Soybean feedstock is sourced from various farms in the general Midwestern US.*

<u>Tables</u>

*Table 11: Average PTW Tailpipe Emissions for HD and MD On-Road Vehicles Running on B100 and ULSD (Including HC Emissions)*

| **Fuel Type** | **HC [g/gal]** | **$NO_x$ [g/gal]** | **PM [g/gal]** | **CO [g/gal]** | **$CO_2$ [g/gal]** |
|---|---|---|---|---|---|
| B100 | 0.681 | 65.8 | 1.50 | 23.9 | 8823 |
| ULSD | 1.827 | 56.4 | 2.30 | 17.2 | 9722 |

| | | | | | |
|---|---|---|---|---|---|
| % Change from ULSD to B100 | -63% | +17% | -35% | +39% | -9% |

*Table 12: Maximum and Minimum PTW Tailpipe Emissions for HD and MD On-Road Vehicles Running on B100 and ULSD*

| | | **PM [g/gal]** | **$NO_x$ [g/gal]** | **CO [g/gal]** | **$CO_2$ [g/gal]** |
|---|---|---|---|---|---|
| **B100** | Minimum | 0.34 | 36.4 | 5.6 | 8040 |
| | Average | 1.39 | 61.5 | 22.4 | 8238 |
| | Maximum | 2.20 | 79.5 | 43.5 | 8945 |
| **ULSD** | Minimum | 1.44 | 31.4 | 7.3 | 8870 |
| | Average | 1.98 | 48.6 | 14.8 | 9521 |
| | Maximum | 3.00 | 70.1 | 19.3 | 9644 |

*Table 13: Complete Life Cycle Emissions Data for Grounds Fleet*

| | **No-VS Annual Emissions [tn/yr]** | | | **VS Annual Emissions [tn/yr]** | | | **Annual Emissions Change** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Min.** | **Avg.** | **Max.** | **Min.** | **Avg.** | **Max.** | **Min.** | **Avg.** | **Max.** |
| **$CO_2$** | 57 | 61 | 62 | 28 | 29 | 30. | -55% | -53% | -47% |
| **NOx** | 0.19 | 0.28 | 0.40 | 0.29 | 0.35 | 0.40 | -27% | 26% | 112% |
| **PM** | 0.010 | 0.013 | 0.018 | 0.0092 | 0.012 | 0.014 | -50% | -8% | 43% |
| **CO** | 0.048 | 0.090 | 0.11 | 0.070 | 0.13 | 0.20 | -39% | 44% | 314% |

*Table 14: Complete Life Cycle Emissions Data for TCAT Fleet*

| | **No-VS Annual Emissions [tn/yr]** | | | **VS Annual Emissions [tn/yr]** | | | **Annual Emissions Change** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Min.** | **Avg.** | **Max.** | **Min.** | **Avg.** | **Max.** | **Min.** | **Avg.** | **Max.** |
| **$CO_2$** | 4370 | 4640 | 4690 | 1130 | 1210 | 1500 | -76% | -74% | -66% |
| **NOx** | 14 | 21 | 30 | 19 | 29 | 36 | -37% | 36% | 156% |
| **PM** | 0.73 | 0.96 | 1.38 | 0.43 | 0.84 | 1.17 | -69% | -12% | 60% |
| **CO** | 3.7 | 6.8 | 8.7 | 4 | 11 | 20 | -54% | 61% | 437% |

Figures

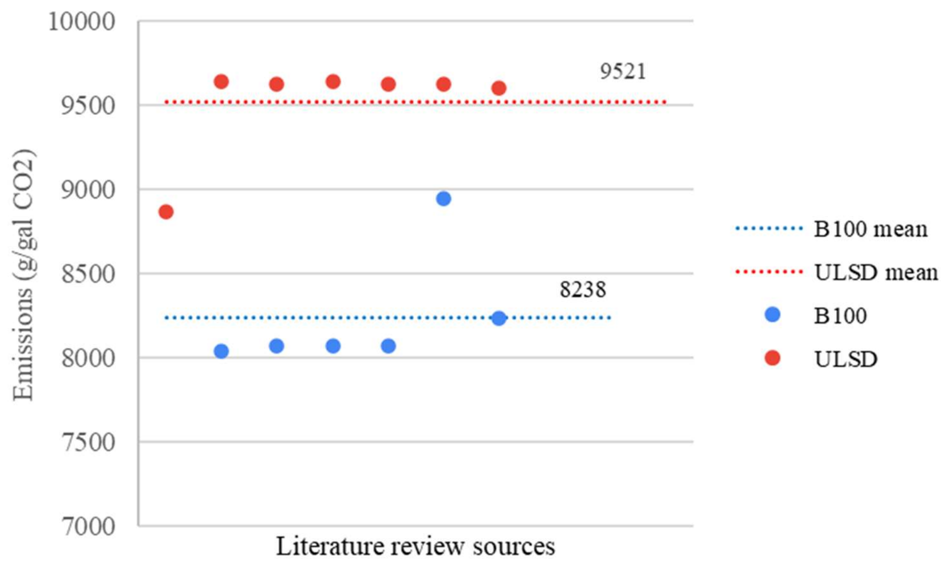


*Figure 8: Graph comparing the $CO_2$ tailpipe emissions for B100 and ULSD*

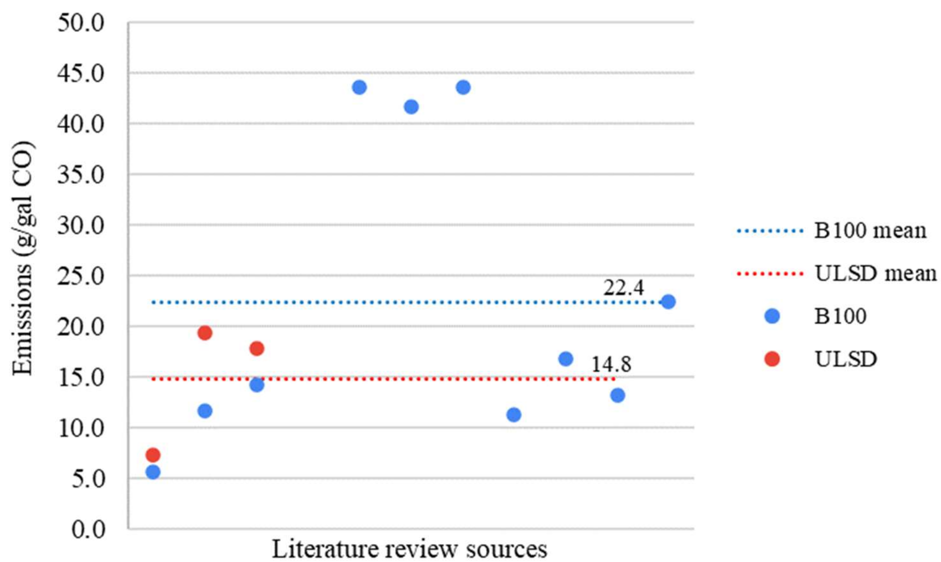


*Figure 9: Graph comparing the CO tailpipe emissions for B100 and ULSD*

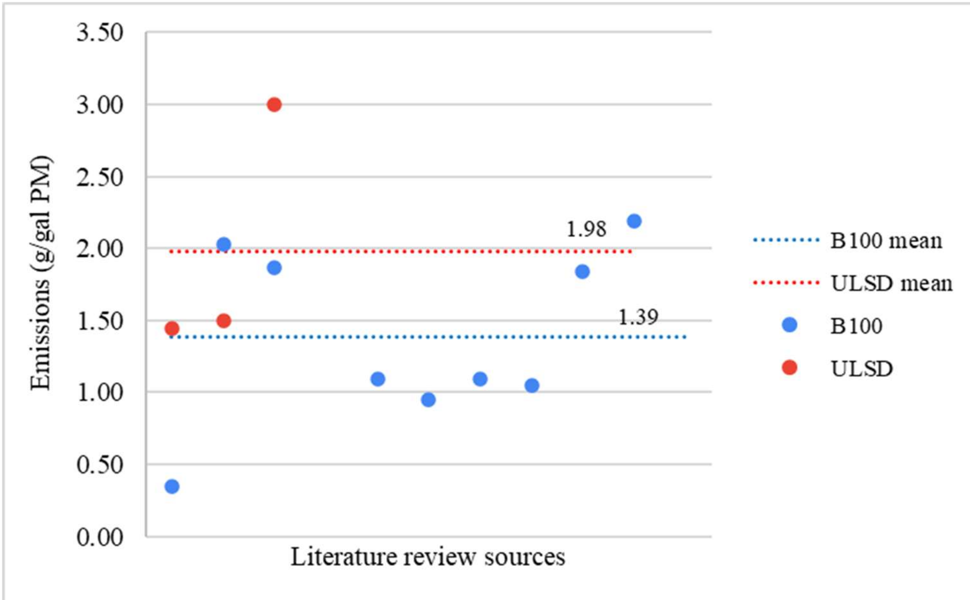


*Figure 10: Graph comparing the PM tailpipe emissions for B100 and ULSD*

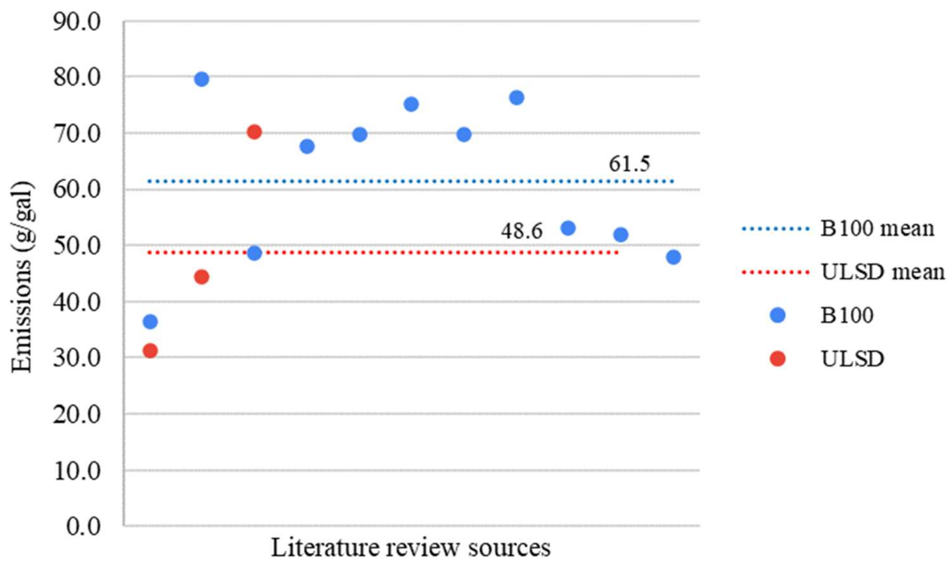


*Figure 11: Graph comparing the NOx tailpipe emissions for B100 and ULSD*

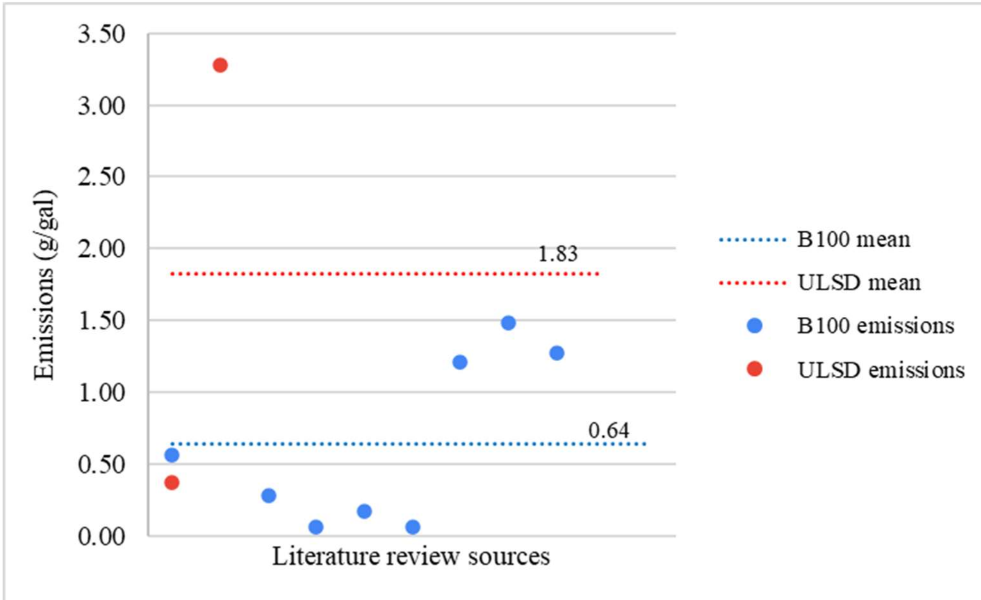


*Figure 12: Graph comparing the HC tailpipe emissions for B100 and ULSD*

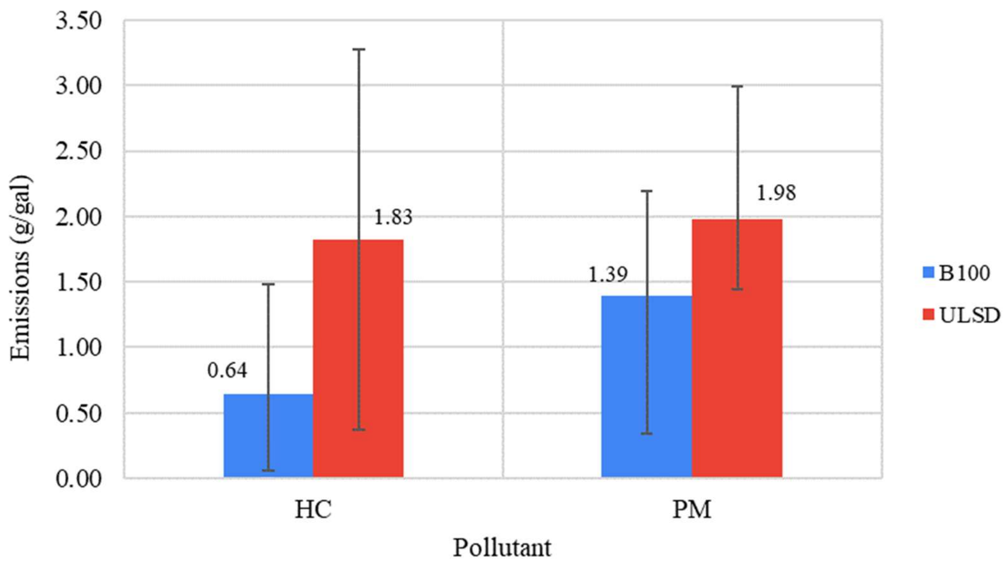


*Figure 13: Range of Literature Review Values for Tailpipe HC & PM Emissions*

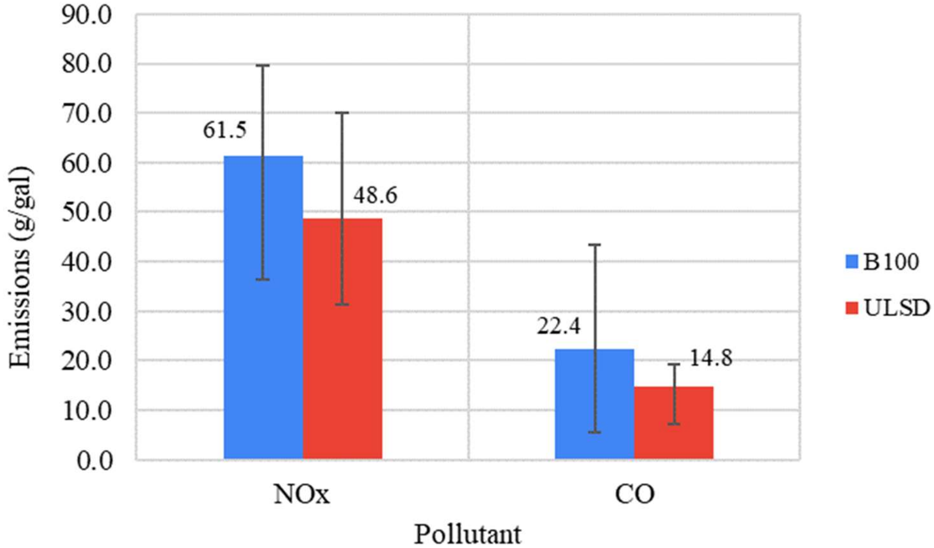


*Figure 14: Range of Literature Review Values for Tailpipe NOx & CO Emissions*