# Analysis of Alternative Fuel Vehicles For the Port Authority of New York & New Jersey

CEE 5910
Engineering Management Project
Spring 2013

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Advisor: Dr. Francis Vanek

# Project Advisor's Preface

The report that follows is the result of a one-semester project conducted by a team of Master of Engineering (M.Eng) students in the School of Civil & Environmental Engineering at Cornell University, and advised by me, during the Spring 2013 semester, on behalf of the Port Authority of New York and New Jersey.

The project is the third in a series of one-semester projects conducted by the M.Eng program in collaboration with the Port Authority. Two previous projects in 2011 looked at green building opportunities for the Port Authority to improve building performance or install alternative energy and water technology. The final reports from the earlier projects are available at www.lightlink.com/francis/.

The parameters of the current project were agreed between the representatives of the Port Authority and myself prior to the launch of the project. The Port Authority own over 2,000 light- and heavy-duty road vehicles spread across facilities in the states of New York and New Jersey in and around metropolitan New York City. In keeping with their commitment to improve their sustainability, the Port Authority has upgraded this vehicle fleet in recent years been to incorporate a number of alternative fuels and alternative vehicle technologies. Along with ecological benefits, they were especially interested in the impact on maintenance costs.

At the beginning of the 2012-2013 academic year, students who joined this team chose from among a menu of projects offered by the M.Eng program. Once the team had formed, however, the project was very much run by the student team themselves, with my role being one of advisor rather than leader. The students had wide latitude to create a project proposal with scope of work (which was then approved by me), divide up tasks and create a team structure, carry out each element of the work breakdown structure, and finally create an oral presentation and written report as the deliverable for the project. Indeed, one of the goals of this project, and also of others that preceded it, is to let the team function as a small business or consulting firm, with each member having a research role but also varying degrees of leadership responsibility.

In closing, I would like to express my thanks to the Port Authority, and in particular to contacts Jim Reinish, Jeff Trilling, Jessica Levine, Andres Crespo, and Bernice Malione, for providing this insightful and rewarding opportunity, and to the students for their hard work.

Respectfully submitted,

Francis M Vanek, PhD
Senior Lecturer and Research Associate

# Executive Summary

The Port Authority of NY/NJ (henceforth referred to as the Port Authority) asked a group of 15 masters of engineering students from Cornell University's School of Civil and Environmental Engineering to complete an analysis of their fleet of vehicles. The Port Authority has a diverse fleet of vehicles in terms of functionality, size, and fuel type. The fleet contains over 2,000 vehicles that serve a range of functions from airport runway snow removal, to law enforcement, to carrying construction materials. Additionally, the fleet contains a number of fuel types including: B-20 biodiesel, compressed natural gas (CNG), gasoline, hybrid, hydrogen, bi-fuel and flex fuel. The group of 15 students from Cornell broke up into 5 sub-teams based on fuel type. The first 4 groups were titled: biodiesel, CNG, hybrid and hydrogen. The fifth group focused its analysis solely on the Port Authority's snow removal vehicles. The first four sub-teams each set out to complete three different things: (1) an analysis of the Port Authority's data relating to maintenance costs and fuel costs; (2) a scenario case study comparing the total cost of each team's own fuel type to either diesel or gasoline; and (3) an environmental impact analysis of the fuel type each sub-team was assigned to. The total cost of the scenario case study includes maintenance costs, fuel costs and capital costs. The environmental impact analysis we completed focuses solely on $CO_2$ emissions.

The analysis of the Port Authority's dataset was very difficult because of the large number of erroneous data entries. We fail to make any definitive conclusions about the benefits of individual fuel types from just analyzing the Port Authority's dataset. For the scenario case study, when possible the maintenance cost data was obtained from the Port Authority's dataset. When that was not possible, maintenance cost data was obtained from Edmunds.com. The capital and fuel costs of vehicles were found using reputable online resources such as the EPA's fueleconomy.gov. The annual total cost of using B-20 biodiesel in vehicles is only slightly higher than using diesel fuel in the same vehicles – less than 1%. CNG vehicles appear to be similar in total annual cost to equivalent gasoline vehicles but it is hard to know for sure because of the lack of information on maintenance costs. Using a discount rate of 5%, as requested by the Port Authority, the total annual cost of hybrid vehicles is noticeably cheaper than similar gasoline vehicles. Hydrogen vehicles have relatively low fuel costs compared to gasoline vehicles, but like CNG vehicles maintenance data is not conclusive. Additionally, hydrogen vehicles are not available for purchase; therefore it was impossible to complete a capital cost comparison.

Each of the four fuel types reduced $CO_2$ emissions compared to their fossil fuel counterparts but at differing levels. Biodiesel reduces emissions by 15% compared with pure diesel. CNG and Hybrid vehicles reduce emissions by 25% and 32% respectively compared to equivalent gasoline vehicles. Despite the fact that Hydrogen is produced in a natural gas steam process, hydrogen vehicles reduce $CO_2$ emissions by nearly 65% when compared with equivalent gasoline vehicles.

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# Acknowledgement and Disclaimer

The project team would like to express its sincere gratitude to Doctor Francis Vanek who provided invaluable support, supervision, encouragement and constructive critiques as an advisor throughout the semester.

The project team would also like to thank members of the Port Authority of New York and New Jersey: James Reinish, Jeff Trilling, Bernice Malione and Jessica Levine for their input into and support of this project.

While their contribution is gratefully acknowledged, the contents of this report do not reflect the official position of PANYNJ, or of Cornell University, and responsibility for any and all errors rests with the authors.

# Part I

# Project Background

# Port Authority Background

The Port Authority was established on April 30th, 1921, and it is the first bi-state agency created by a clause of the constitution permitting compacts between states with congressional consent. It builds, operates and maintains transportation infrastructure in the New York/New Jersey region including: America's busiest airport system, shipping docks and terminals, a transit system, tunnels and bridges, and the Port Authority Bus Terminal in Manhattan. The Port Authority is a self-supporting entity; its revenue includes rents, user fees, rail transit fares, bridge and tunnel tolls and other facility operation revenues.

The Port Authority is committed to improving sustainability and applying green technology to its vehicle fleet through its Central Automotive Division (CAD). Several alternative fuels and platforms such as biofuels, compressed natural gas, hybrids, hydrogen and electric vehicles have already been implemented by the CAD.

# Team Background

**Bahadir Beyazoglu** has a bachelor's degree in Civil Engineering from University of Buffalo, and is pursuing a Masters in Engineering Management at Cornell University to be completed in May 2013. Before he joined Cornell University, he worked both in Kazakhstan and Turkey as a civil engineer. His area of focus was planning and field engineering. During this short work experience, he generally worked with computer based scheduling and drawing programs such as MS Project and AutoCAD. The reason he came to Cornell University was to improve his managerial and technical skills by joining simulation projects at Cornell University.

**Christine Curtis** received her Bachelor of Science in Biological Engineering from Cornell University in May 2012. As an undergraduate, she was involved in AguaClara – a small-scale water supply development project – and was a member of the Cross Country and Track and Field teams. She is now pursuing a Master of Engineering degree in Engineering Management with a focus in water resources.

**Xiao Cui** received a bachelor's degree in environmental engineering from the Harbin Institute of Technology in China. He is currently pursuing a Master of Engineering degree in Environmental and Water Resource Systems Engineering (EWRS). He was a member of Floc Filtration Team for the Aguaclara Project. He is fluent in using MathCAD, AutoCAD, Solver/ Risk Solver Platform for Excel (RSPE).

**John Dean** is co-leader of the project and sub-team leader of the CNG team. He holds a B.S. in Mechanical Engineering from Cornell University focused in solid mechanics and is currently studying to receive his Master of Engineering degree in Engineering Management. His past experience includes entrepreneurship, venture capital, and signal processing. John has relevant skills with MatLAB, Excel modeling, and interests in renewable and clean energy alternatives.

**Zuo Du** is the co-leader of the project with bilingual language skills. She is skilled in using Solver for data optimum, Excel and other office software. She has a background in both Environmental Engineering and Science at the University of Waterloo in Canada. Now she is pursuing a Master of Environmental Engineering, concentrating in Environment and Water Resource Systems.

**Addisu Gebre** is the project team's co-liaison to the client's representative. He was born and raised in Ethiopia where he received his bachelor's degree in Hydraulic Engineering at the Arbaminch University, Arbaminch. He comes to this team with a background in Hydraulic Engineering and is currently pursuing a Masters of Engineering degree in Engineering Management. He has +6 years of experience working in the field of Civil and Hydraulic Engineering both in the United States and Ethiopia.

**Hongyi Guo** is now a Master of Engineering candidate majoring in Environmental and Water Resources System Engineering (EWRS). He obtained his bachelor's degree in environmental engineering from Dalian Maritime University, China. Hongyi worked on the sedimentation hydraulics sub-team in AguaClara last semester. He has skills using AutoCAD, MathCAD, Microsoft Office Suite, Excel Solver & Risk Solver Platform for Excel (RSPE), and Lyx.

**Michael Hyland** is the project team co-leader and a member of the Bio-diesel sub-team. He obtained his undergraduate degree from Cornell University in the field of Civil Engineering with a focus in transportation systems. He is currently a Masters of Engineering student in transportation systems engineering at Cornell. Mike completed research as an undergraduate in the field of location modeling that involved a significant amount of data analysis work. Additionally, he worked with the city of Ithaca's department of Public Works (DPW) office for 6 months. The DPW works in conjunction with the city's vehicle maintenance department. Mike also took several courses at Cornell as an undergraduate that focused on new transportation technologies including alternative fuel vehicles. For one class his junior year, he completed a project in which he analyzed whether Ithaca Carshare should implement hybrid vehicles, plug-in hybrid vehicles or keep their existing fleet of gasoline fueled vehicles.

**Tianyu Hu** obtained her bachelor degree in Environmental Science from University of Xia'men. She is pursuing a master's degree in Environment and Water Resource System in Environmental Engineering. She has experience in Data analysis using Excel, Solver and communication with team members.

**Jia Lu** obtained a bachelor's degree in Civil Engineering with a concentration in Bridge

Engineering from Tongji University, Shanghai, China. And she is now working on a Master of Engineering degree in Transportation Systems Engineering. Jia has been involved in bridge engineering projects as an undergraduate, and she has taken classes at Cornell University relating to transportation systems as well as sustainable transportation. She has completed data analysis work using R studio, EXCEL Solver, and also has interests in project management.

**Qiao Xing Liu** is the sub-team leader of the hydrogen team. He comes to this team with a background in civil engineering from Cornell University and will complete his Master of Engineering in Transportation System Engineering in 2013. He has work experience in engineering management. He also has research experience in transportation engineering. His interests include tennis, volunteering, and alternative energy.

**Xingjian Wu** has bachelor's degrees in environmental engineering and chemical engineering from East China University of Science and Technology and Fachochschule Luebeck in Germany. She is currently a Masters of Engineering student major in Environmental and Water Resource Systems at Cornell. She has experience with Solver for data optimum, Excel and other Office software.

**Mengyi Xu** got her bachelor's degree in Material Science from Sichuan University. Right now she is pursuing Master of Engineering Management. She has a good understanding of the different kinds of energy involved in this project, especially the diesel and biofuels. She is capable of doing an environmental analysis of the petrochemical industry. After reviewing the background material, she believes that this project will provide her with a great chance to learn the transportation energy field. She is experienced in Excel, Matlab, optimization software, and simulation methods.

**Weiling Xu** is the co-liaison of the project to the Port Authority. She got her Bachelor of Science degree in Environmental Engineering from Cornell University, and she is currently a Master of Engineering candidate concentrating on Environmental Water Resource Systems. Her previous academic education was mainly focus on environmental processes, and she was part of the Manual Pump Design team, Stacked Rapid Sand Filtration bench scale team, as well as Floc Filtration team for AguaClara Project, which is a project team that designs sustainable water treatment systems. She is very interested in drinking water, as well as sustainable development, and hoping to expand her scope of study into other fields, such as data analysis and management. She is looking forward to this project and is hoping to gain more knowledge on alternative energy. Besides her academic interests, she enjoys playing guitar and piano, cooking, skiing and hiking.

**Hongyao Zhao** has a Bachelor's degree in Civil Engineering with a concentration in Bridge Engineering from Wuhan University of Technology in Wuhan, China. He is pursuing a MEng degree in Civil Engineering with a concentration in Transportation System. He has skills in Microsoft Word, Excel and PowerPoint as well as AutoCAD and Solver in Excel.

**Qingxue Zhang** has a bachelor's degree in Civil Engineering from Zhejiang University in China, and has joined several research projects in modeling the numerical simulation, analyzing and building the evaluation system of the house products for the Chinese government. During her graduate study, she is focusing on the system modeling and decision support by using optimization tools, such as RSPE and Matlab. She finished a project last semester in heuristic optimization. She is a professional using Simulated Annealing (SA) methods and is interested in coding and data processing.

## Team Structure

| PA Project Team<br>Supervisor:<br>Dr. Francis M. Vanek | | |
|---|---|---|
| | Biodiesel | Michael Hyland (Project Team Leader) |
| | | Jia Lu |
| | | Mengyi Xu |
| | | Hongyao Zhao |
| | CNG | John Dean (Project Team Leader) |
| | | Hongyi Guo |
| | | Qingxue Zhang |
| | Hybrid | Addisu Gebre (PA Liaison) |
| | | Weiling Xu (PA Liaison) |
| | | Xingjian Wu (Final Presentation Liaison) |
| | Hydrogen | Bahadir Beyazaoglu |
| | | Xiao Cui |
| | | Qiao Xing Liu |
| | Snow Removal Equipment | Christine Curtis (Rochester Airport Liaison) |
| | | Zuo Du (Project Team Leader) |
| | | Tianyu Hu |

## Project Motivation

In June 1993, the Port Authority formally issued a policy statement recognizing its long-standing commitment to support its transportation, terminal and other facilities of commerce with environmentally friendly investments. Additionally, the Port Authority expressed its commitment to manage its activities in a manner consistent with applicable environmental laws and regulations and to deal with identified environmental concerns in a responsible, timely and efficient manner. The Port Authority has recognized the importance of alternative fuels for years, and it presently has more than 350 clean-fuel vehicles in its fleet. In order to find ways to reduce fuel costs and reduce the consumption of nonrenewable resources which produce green-house gas emissions, the Port Authority is now heavily involved in exploring alternative fuels to replace existing fossil fuel based vehicles. These alternative fuels include biofuels, compressed natural gas, and hydrogen as well as hybrid vehicles. In order for the Port Authority to determine which alternative fuel vehicle types to continue to invest in, it is necessary for them to complete an analysis of all the costs – financial and environmental – associated with each fuel type.

The Port Authority has asked our group to complete an analysis of the maintenance costs associated with each vehicle fuel type. Specifically, they are seeking a better understanding of the maintenance costs associated with each fuel type based on data from the Port Authority's Central Automotive maintenance department as well as data from external sources. The Port Authority has also given our group the go-ahead to complete a lifetime cost analysis of each vehicle fuel type to determine which fuel types are the most cost-effective. The cost associated with different fuel type vehicles includes the capital cost of each vehicle, fuel costs and maintenance costs. If the lifetime costs of "greener" vehicles are lower than that of conventional fossil fuel based vehicles, then the Port Authority will have further motivation to continue investments in "green" energy vehicles.

# Project Goals

Our goals as a team for the Port Authority Project are grounded in the supplied vehicle fleet data. Using the data, we will analyze the environmental impact of the Port Authority vehicles based on fuel consumption. The fuel consumption will give us the ability to breakdown the fleet's $CO_2$ emissions and as a result provide insight into possible changes in the fleet to minimize the carbon foot print of the Port Authority. The next level of the project is the cost efficiency of the fleet based on fuel consumption, initial costs, and most importantly, maintenance equivalents on a per vehicle basis. These results will provide insight in the weak vehicles in terms of cost efficiency. With cost efficiency established, research will be done into alternative fuel options for the fleet in order to increase cost efficiency and reduce tailpipe $CO_2$ emissions. By the end of the semester, we expect to have a current fleet status report and if results allow, an investment recommendation for replacing certain vehicles in the fleet for the Port Authority to research based on the obstacles involved in a state funded operation.

# Project Scope, Limitations, and Assumptions

The scope of this project is limited to strategies and analysis based on data, which is assumed to be given to us in good faith and with unbiased accuracy. There is no analysis of political and organizational obstacles that come with a state funded organization. Our focus is on the Port Authority fleet of vehicles; this includes maintenance and snow removal vehicles and excludes any stationary equipment such as generators and trailers. Our work is system based and does not provide any product development or product design. Analysis is based on fuel economy and maintenance records. In forecasting the economics of the fleet, all growth rates are linear unless deemed appropriate to adjust this method. We assume an inflation rate of 3% and a discount rate of 5% as provided by the Port Authority. All fuel and energy rates are based on New York state rates and taxes.

In analyzing on a vehicle basis, the fuel economy rates will be the EPA rated MPG and MPGe. For $CO_2$ emission analysis, the carbon foot print will be based on the tail pipe emission and will not include the emissions that go into generating the electricity for hybrid and electric powered vehicles. This is ignored because on a vehicle basis it is out of the project scope to find the source of each vehicle's electricity. In New York State, the energy is very wide spread in source and carbon footprint generated from coal, natural gas, and hydro.

Certain vehicles are eliminated from the data set based on outlying numbers that skewed results to an extreme levels measured by two standard deviations from the mean. This was necessary to reach results that made sense in the areas of fuel economy.

# Project Data Analysis and Methodologies

The 5910 project team received a relatively large and complicated dataset from the Port Authority. Because the Port Authority specifically requested that our group complete an analysis of maintenance costs we thought that the best place to start would be with their dataset. In addition to an analysis of maintenance costs we completed a fuel cost analysis. After parsing through the dataset it became clear that not only was it going to be very hard to work with because of how many different 'vehicles' (I put vehicles in single quotes because many of the data entries were not vehicles at all) but also because there is no way that the data accurately represented the vehicles' maintenance and fuel costs. Many of the vehicles had a value of zero in the fuel cost column despite being driven over 10,000 miles. Other vehicles had negative maintenance costs in the past 12 months.

Despite the poor quality of the Port Authority's dataset, it was the best source of maintenance costs available to our team for many of the vehicles listed. Edmunds.com also lists maintenance costs for vehicles but many of the vehicles in the Port Authority's fleet are not listed on Edmunds.com. We found that the best source for many of the vehicle fuel costs was not the Port Authority dataset (it was the EPA's fueleconomy.gov) but we still completed a fuel cost analysis using the Port Authority's data. The first step completed by our group was to eliminate the data entries that were not actual vehicles. For example, there were portable generators, cranes and non-motorized trailers among other things that were removed from the dataset for the purpose of our analysis. Secondly, we duplicated the data set so that we could do separate fuel and maintenance costs analyses. The need to duplicate the data set stems from the fact that some vehicles had semi-reliable fuel cost data with useless maintenance cost data and vice versa. After duplicating the data set, all of the vehicles with zero life to date (LTD) maintenance costs were deleted from the maintenance dataset, and all vehicles with zero LTD fuel costs were deleted from the fuel costs dataset (from this point forward one should assume that everything done to the maintenance cost dataset was also done to the fuel cost dataset).

Once all of the clearly inaccurate data was removed from the dataset, the remaining vehicles were organized by vehicle size – heavy, medium, light truck police, light truck non-police, sedan police and sedan non-police – and also by fuel type – biodiesel, CNG, hybrid, hydrogen, gasoline, flexfuel and bifuel. For each vehicle we took the LTD maintenance costs and divided by the current odometer reading. The next step was to identify outliers in each category (categories include gasoline sedan non-police, hybrid sedan non-police, biodiesel medium, gasoline light truck police, etc.). For example some gasoline sedan non-police vehicles had maintenance costs per mile less than $0.10/mile while other vehicles in the same category had fuel costs per mile over $2.00/mile. These values which deviate from the average significantly are almost certainly the result of poor data collection as opposed to simply being statistical anomalies; hence, the values that were extremely far from the mean (approximately 3 standard deviations away) were removed from the dataset. However, in order to not unfairly shift the mean by removing only the values that were uncharacteristically high or low we made sure that if we removed the X largest values we also removed the X smallest values in the same category even if they would not be considered extremely low.

After removing the vehicles that appear to have impossibly high or low maintenance cost values, the average maintenance cost per mile was calculated for each category by taking the sum of all maintenance costs per category and dividing by the sum of all of those vehicles' miles in the same category. This method was used to calculate the average maintenance cost per mile in order to prevent new vehicles that have accurately low maintenance costs from shifting the average maintenance cost per mile too much. The older vehicles with more miles and higher maintenance costs should carry greater weight in the maintenance cost analysis than the new vehicles with fewer miles and smaller maintenance cost values.

In a final effort to add value to the analysis's results despite the poor data collection methods, the group took the median maintenance cost per mile for each category and compared it with the average maintenance cost per mile calculated as described in the previous paragraph. If the number varied considerably – they rarely did – more outliers were removed.

# Case Scenario

In order to analyze the benefits and disadvantages of each of the different fuel types we completed a standardized case scenario. In the case scenario, a total cost analysis was completed based on: fuel, maintenance and capital costs. Additionally, the case scenario includes the amount of $CO_2$ saved by switching from gasoline to an alternate fuel. We standardized the analysis by setting: the number of miles driven per year at 5,000, the number of vehicles at 10, the lifetime of the vehicle at 10 years with $0 salvage value, and a discount rate of 5%. The fuel costs were obtained from the EPA's fueleconomy.gov website as opposed to the Port Authority's dataset because of the dataset issues enumerated in the previous section. Maintenance costs were calculated from the Port Authority's dataset; hence the results of our analysis are limited because of the poor quality of the information given to us. The capital cost, obtained from Edmunds.com, was annualized over 10 years at a discount rate of 5%.

Because our group was split into sub-teams based on fuel types each sub-team compared their assigned fuel type to gasoline vehicles – except the biodiesel sub-team which compared B-20 biodiesel with 100% Diesel. We assumed that the fuel cost for a gallon of gasoline was $4.00. Additionally, each sub-team completed a $CO_2$ emissions analysis between their fuel type and gasoline or diesel. We assumed that 19.6lbs of $CO_2$ are emitted per gallon of gasoline burned. To see how $CO_2$ emissions were calculated for the alternative fuels, please see the $CO_2$ emissions analysis done by each sub-team further on in the paper.

# Part II

# Sub-team Results

# 1. <u>Biodiesel</u>

## 1.1 Literature Review

Biodiesel is described as a fatty acid methyl or ethyl esters from vegetable oils or animals fats. Currently, it is mainly produced from soybean and rapeseed oils in a process depicted in Figure 1.1. The most common blend is a mix of 20% biodiesel with 80% petroleum diesel. It is a renewable, sustainable and alternative fuel for compression ignition engines. It affects engine power, economy, and durability.

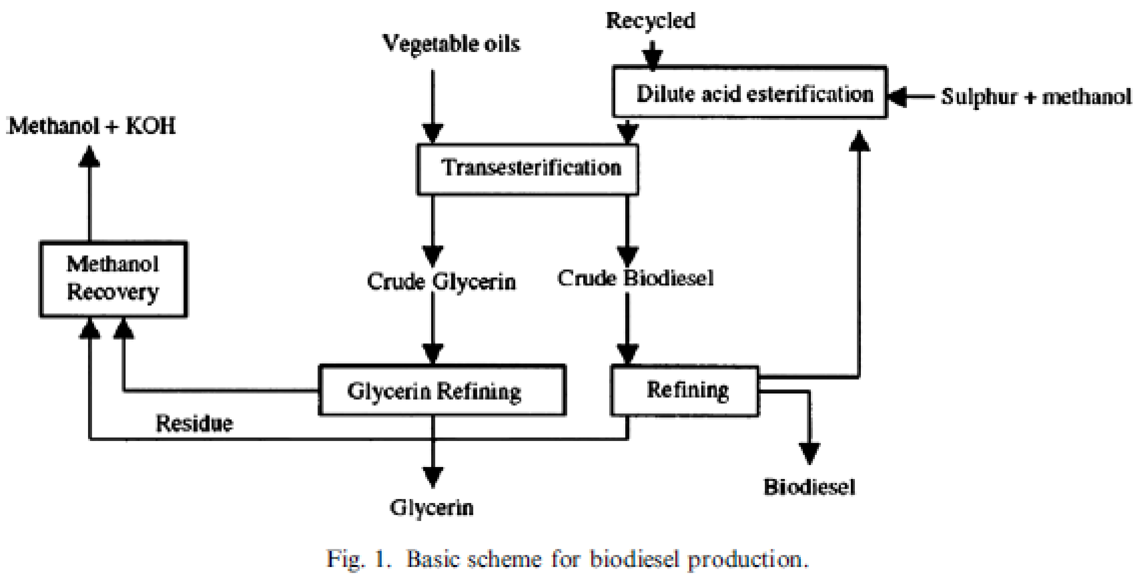


**Figure 1.1.** Basic scheme for biodiesel production. Reference: Y.C. Sharma and S.N. Upadhyay Singh, "Advancements in development and characterization of biodiesel: A review", Electronic reference, Banaras Hindu University, 20 February 2008.

<u>Power Performance</u>

The biodiesel content in a diesel blend may result in differences in engine performance. Carraretto et al. found that an increase in biodiesel percentage in the blends resulted in a decrease of both power and torque over the entire speed range for different blends on a 6-cylinder DI engine [1]. However, others found that the power increased with the addition of biodiesel content in the blend up to B-20 [2]. The properties of biodiesel also have an effect on engine power. The lower heating value of biodiesel reduces engine power. The higher viscosity of biodiesel enhances fuel spray penetration and thus improves air-fuel mixing. High lubricity of biodiesel leads to reduced friction losses and thus improves the brake effective power.

<u>Fuel Economy</u>

Most researchers found that the fuel consumption of an engine fueled with biodiesel becomes higher because of the need to compensate for the loss of heating value [3, 4, 5]. Others found that the difference in fuel consumption between diesel and pure biodiesel was 18.5% by mass, and was reduced to 13.5% in volume because of higher density of biodiesel. The department of energy [22] among other sources [23] states that fuel economy for B-20 biodiesel is 2% lower than pure diesel. Biodiesel reduces greenhouse gas emissions; it helps to reduce a country's reliance on crude oil imports and supports agriculture by providing new labor and market opportunities for domestic crops.

## Emissions

Combustion of pure biodiesel provides over a 90% reduction in total unburned hydrocarbons (HC), and a 75-90% reduction in polycyclic aromatic hydrocarbons (PAHs) [6]. Biodiesel provides further reduction in particulate matter (pm) and carbon monoxide over petroleum diesel fuel. PM emissions of biodiesel are reduced by 53-69% on average compared with conventional diesel fuel [7]. Concerning NOx emission, it is widely reported that NOx will increase when using biodiesel due to higher oxygen content for biodiesel; this is attributable to the difference in engine geometry, compression ratio, reaction time and temperature. Because of the little nitrogen in biodiesel, the reduction of $N_2O$ is attractive for using biodiesel. In addition, biodiesel contains only trace amounts of sulfur; therefore, $SO_2$ emissions are reduced significantly when compared with petro-diesel. Also, Krahl et al. research showed about a 50% reduction in CO emissions for biodiesel [8]. A higher reduction in CO emissions of 73-94% for karanja methyl ester and its blends was shown by Raheman and Phadatare [9].

Since $CO_2$ emissions from transportation represent 23% of total U.S. $CO_2$ emissions, the reduction of $CO_2$ emissions from biodiesel is extensively studied [10]. Because biodiesel is made from renewable sources, it presents a convenient way to provide fuel while protecting the environment from unwanted emissions. It is reported that biodiesel resulted in fewer $CO_2$ emissions than diesel during complete combustion due to the lower carbon to hydrogen ratio [11]. Along with the observed remarkable decrease in the emission of un-burnt hydrocarbon, 40% reduction in $CO_2$ emission was observed for B-20 and B100 biodiesel [12]. Lin C-Y et al. compared the $CO_2$ emission between three kinds of biodiesel and ASTM NO.2D diesel using $CO_2$ emission index, which is defined as the $CO_2$ emission (%) divided by the corresponding fuel consumption rate (g/h) [13]. Three kinds of biodiesels have lower $CO_2$ emission indices than ASTM NO.2D diesel. Biofuel is a low carbon fuel and has a lower element carbon to hydrogen ratio than diesel fuel.

Due to more efficient combustion of fuel, $CO_2$ emission was reported to rise and keep similar [14]. Of course, it was pointed out in the literature (Labeckas G et al. 2006) that, in the case of biodiesel, the higher carbon dioxide emission should cause concern because of nature's recovery by raising biodiesel crops [15]. Carraretto C et al. (2004) also evaluated the effect of biodiesel on global greenhouse gas emissions through the life circle of $CO_2$ emission [16]. They found that biodiesel will cause a 50-80% reduction in $CO_2$ emission compared to petroleum diesel.

Research completed by Pimental and Patzek shows that energy outputs from ethanol produced using corn, switch grass and wood biomass were each less than the respective fossil energy inputs [17]. The same was true from producing biodiesel using soybeans and sunflower; however, the energy cost for producing soybean biodiesel was only slightly negative compared with ethanol production. According to their research, biodiesel production using soybean requires 27% more fossil fuel energy than the biodiesel fuel produced. The authors question numerous other net energy balance reports. Specifically they question whether or not previous analyses included all of the relevant inputs that go into producing ethanol and biodiesel. It is important to note that Pimental and Patzek's research contradicts numerous other fuel lifecycle analyses which conclude that biodiesel produced from soybeans or sunflowers has a positive net energy balance.

## 1.2 Cost Analysis

The methods used to complete the maintenance and fuel cost analysis are described in the "Data Analysis Methodologies" section of the report. Figure 1.2 shows the breakdown of biodiesel vehicles into size categories. The 48% "Other" category is mainly Snow Removal Equipment vehicles, which are mainly heavy duty vehicles. We can see that there are few light duty vehicles that run on biodiesel – and many of them are large SUVs as opposed to sedans.

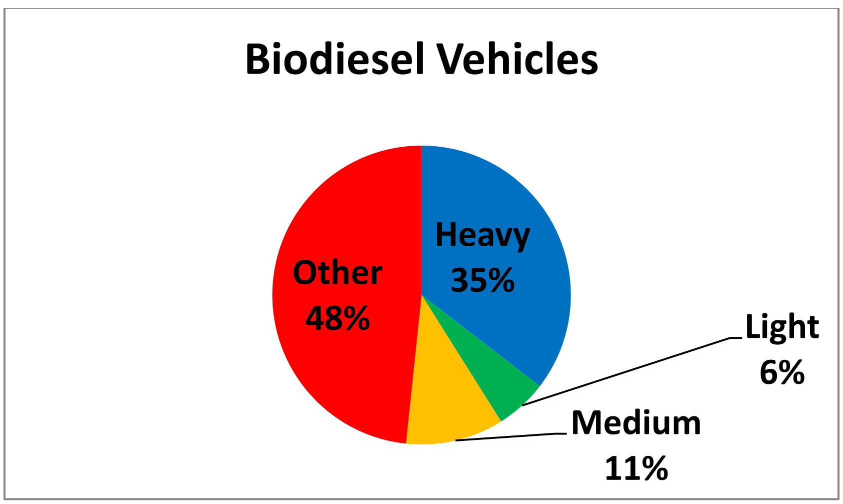


**Figure 1.2.** Breakdown of Port Authority biodiesel vehicles by size category.

Figure 1.3 shows the maintenance and fuel costs in the heavy, medium and light duty classes. The figure shows that maintenance costs in the heavy duty category are significantly higher than in the medium and even more so than in the light duty category. One can only speculate why the difference in maintenance costs per mile are so much higher for the heavy duty class but we assume that the heavy duty vehicles are: (1) less common and therefore parts and service are not standardized like with commercial light duty vehicles, (2) more likely to be used for carrying heavy equipment or being used in poor meteorological conditions (e.g. snow storms) and therefore experience considerably higher maintenance costs per mile, and (3) the heavy duty vehicles simply have more parts that can and do fail and those parts are generally bigger and more expensive than light duty vehicles.

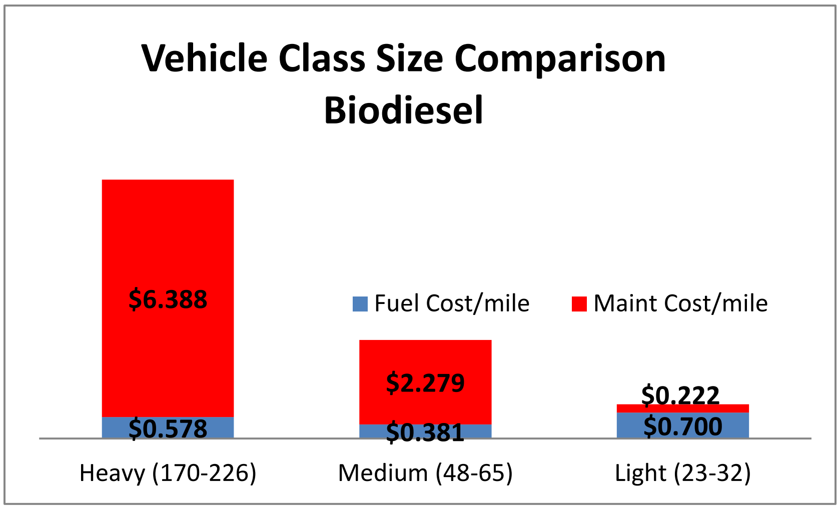


**Figure 1.3**. Maintenance and fuel costs for the heavy, medium and light duty class biodiesel vehicles.

Figure 1.3 also shows that the fuel cost data from the Port Authority should not be the final source of information on fuel costs. There is no explanation for why the fuel costs are lower for heavy duty vehicles than the light duty vehicles. It is clear that fuel dollars are not being recorded properly. Hence, our group decided to use fueleconomy.gov's fuel cost per mile as opposed to the data from the Port Authority to complete the case scenario.

Another important thing to note from Figure 1.3 is that maintenance costs per mile are significantly higher than fuel costs per mile. Therefore, when one is considering purchasing vehicles it is important to consider future maintenance costs if finances are an important factor in one's decisions.

Figures 1.4 and 1.5 display the fuel and maintenance costs of biodiesel vehicles next to different fuel types in comparable heavy and light duty non-police vehicles respectively. In the heavy class it is obvious that the maintenance costs for biodiesel are significantly higher than the hybrid vehicles. However, there are only 10 heavy hybrid vehicles with reliable maintenance cost data (and only 6 with reliable fuel data – see paranthetical values on x-axis). The small number of hybrid vehicles prevents us from making any definitive conclusions in our maintenance and fuel cost analysis.

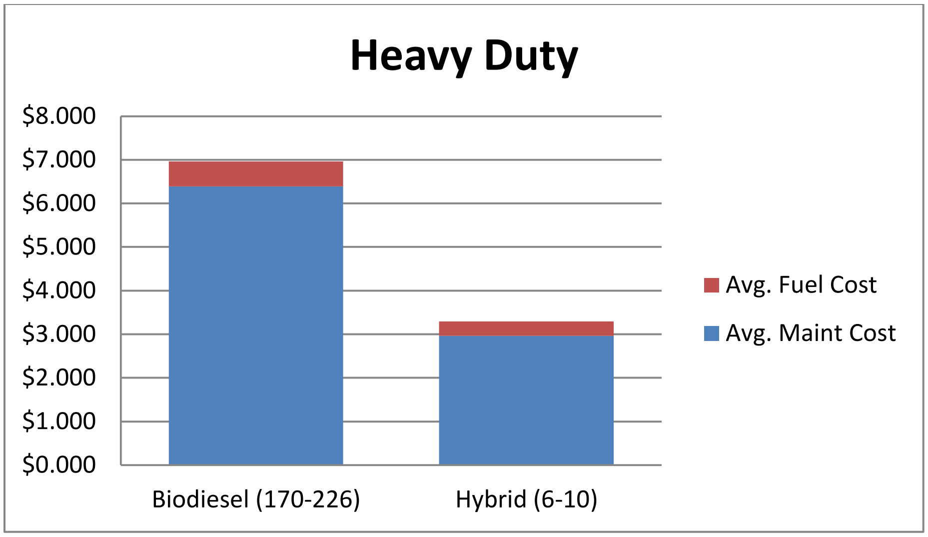


**Figure 1.4**. Average fuel and maintenance costs for heavy duty biodiesel vehicles.

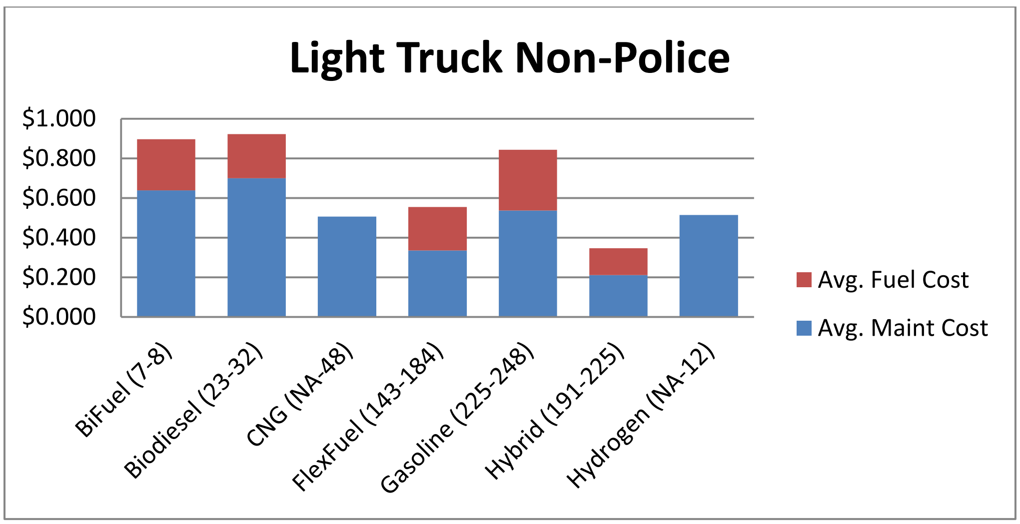


**Figure 1.5.** Average fuel and maintenance costs for light truck non-police vehicles.

Figure 1.5 shows that the maintenance costs for biodiesel vehicles in the light truck non-police category are slightly higher than all of the other fuel types. One reason is that biodiesel is an expensive fuel. Another reason is that even though these vehicles are in the same class they serve different purposes. The biodiesel vehicles in this light truck non-pollice category are large vans and pick-up truck (e.g. Ford F-350s) whereas the hydrogen and hybrid vehicles are Toyota Highlanders – much smaller vehicles. Moreover, the Ford F-350 is a construction vehicle, whereas the Toyota Highlander is a passenger vehicle.

## 1.3 Analysis of Greenhouse Gas Reduction

Engines running on biofuels emit carbon dioxide ($CO_2$), the primary source of greenhouse gas emissions, just like those running on diesel. However, because plants and trees are the raw material for biofuels, and, because they need carbon dioxide to grow, the use of biofuels does not add $CO_2$ to the atmosphere; it just recycles what was already there. The use of fossil fuels, on the other hand, releases carbon that has been stored underground for millions of years, and those emissions represent a net addition of $CO_2$ to the atmosphere. Because it takes fossil fuels – such as natural gas and coal – to make biofuels, they are not quite "carbon neutral" [18].

In this section we will present the environmental advantages of using B-20 biodiesel as opposed to pure diesel. We will begin by referencing some outside sources that display the differences in emissions between pure diesel, B-20 biodiesel and B-100 biodiesel. In our case scenario we will only consider $CO_2$ emissions but Table 1.1 shows that there are many environmental advantages of using biodiesel. The chart below comes directly from the EPA:

**Table 1.1.** Average biodiesel emissions compared to conventional diesel
Reference: http://www.biodiesel.org/docs/ffs-basics/emissions-fact-sheet.pdf

**AVERAGE BIODIESEL EMISSIONS COMPARED TO CONVENTIONAL DIESEL, ACCORDING TO EPA**

| Emission Type | B100 | B20 |
|---|---|---|
| **Regulated** | | |
| Total Unburned Hydrocarbons | -67% | -20% |
| Carbon Monoxide | -48% | -12% |
| Particulate Matter | -47% | -12% |
| Nox | +10% | +2% to -2% |
| **Non-Regulated** | | |
| Sulfates | -100% | -20%* |
| PAH (Polycyclic Aromatic Hydrocarbons)** | -80% | -13% |
| nPAH (nitrated PAH's)** | -90% | -50%*** |
| Ozone potential of speciated HC | -50% | -10% |

* Estimated from B100 result
** Average reduction across all compounds measured
*** 2-nitroflourine results were within test method variability

According to many different sources [19, 20, 21], using B-20 biodiesel as opposed to 100% diesel reduces $CO_2$ emissions by approximately 15%. This 15% is the result of a life cycle analysis. The amount of $CO_2$ emitted from tailpipes – 20% - is the same as the amount used by biodiesel producing plants to produce biodiesel; however, there are other energy consuming parts of the biodiesel production process that emit $CO_2$ including: growing and harvesting the plants, transporting the fuel, etc.

Using the 15% reduction in $CO_2$ emissions and the common value of 22.4 lbs. of $CO_2$ emitted per gallon of pure diesel we know that approximately 19.6 lbs. of $CO_2$ are emitted per gallon of B-20 biodiesel. Given this information we are able to complete a comparison of $CO_2$ emission between B-20 biodiesel and pure diesel vehicles. Another important assumption that we made in the $CO_2$ emissions analysis displayed in Table 1.2 is that a gallon of B-20 biodiesel contains 98-100% of the energy in a gallon of pure diesel [22, 23]. Some sources have slightly lower values, 90-95% [3, 4, 5], but the most recent and updated sources seem to show that the percentage is very close to 98%.

**Table 1.2.** Emissions analysis for diesel and biodiesel vehicles

| $CO_2$ Analysis | Ford F-350 for Diesel | Ford F-350 for B20 |
|---|---|---|
| Miles per Gallon | 14.5 | 14.2 |
| lbs $CO_2$ per Gallon | 22.4 | 19.0 |
| Miles Driven per Year | 5,000 | 5,000 |
| Annual lbs $CO_2$ Emissions | 7,724 | 6,690 |

Table 1.2 shows that switching from pure diesel to B-20 biodiesel reduces annual $CO_2$ emissions by 1034 lbs. or up to 14%.

## 1.4 Case Scenario Study

We know that using biodiesel can reduce $CO_2$ emissions, but whether it is economically worthwhile to replace diesel vehicles with biodiesel vehicles is also important to consider. In order to analyze whether or not it is a good idea to use B-20 biodiesel we constructed a scenario case study. We assumed the Port Authority wants to purchase 10 new Ford F-350 vehicles, which can use either petroleum diesel or B-20 biodiesel. In the scenario, the annual cost (which includes fuel cost, maintenance cost and capital cost) of the new fleet using diesel and biodiesel are compared and analyzed. We standardized the miles driven by each vehicle at 5,000 miles per year.

Using Fuelly.com we found that fuel economy for a Ford F-350 is between 14 and 15 miles per gallon (MPG); hence we used an MPG value of 14.5 [24]. Because B-20 biodiesel gets slightly lower MPG's than diesel we will set the B-20 biodiesel MPG equal to 14.2. It is important to note that B-20 biodiesel can be safely used in any diesel engine manufactured after 1993 (however, most vehicle warranties only allow for up to 5% biodiesel in their engines). For our analysis we calculated the average fuel costs per gallon of B-20 biodiesel and pure diesel between the years of 2005 and 2012. The figure and table below show that diesel and B-20 prices fluctuate from year to year but that on average diesel is slightly cheaper than B-20. The average cost of diesel between 2005 and 2012 is $2.67/gal and the average cost of B-20 is $2.72/gal.

While our group used a higher B-20 biodiesel cost value ($2.72) than diesel ($2.67), the Port Authority actually purchased B-20 biodiesel fuel at a lower average cost in the month of March ($3.52/gal), for the 22,865 gallons of B-20 it used, than it purchased for the 1,359 gallons of diesel it used ($3.67/gal). However, the Port Authority receives B-20 biodiesel in large quantities from a direct supplier; whereas, it only purchases diesel from commercial gas stations.

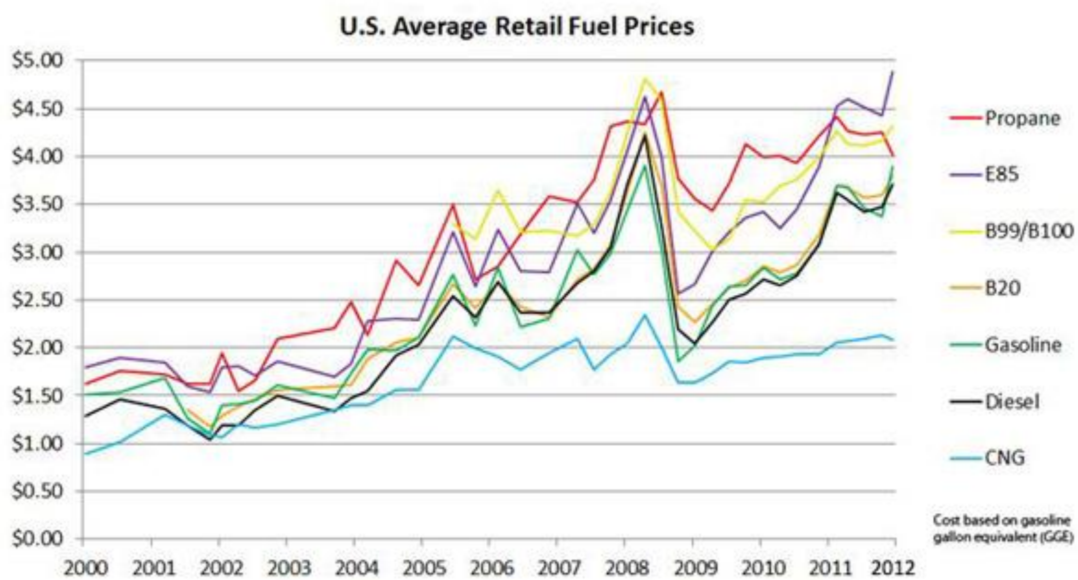


**Figure 1.6:** U.S. Average Retail Fuel Prices.
Reference: http://www.afdc.energy.gov/fuels/prices.html

**Table 1.1:** U.S. Average Fuel Prices of Diesel and B-20 Biodiesel

| Fuel Cost per Gallon | Diesel | B-20 Biodiesel |
|---|---|---|
| **2005** | 2.00 | 2.10 |
| **2006** | 2.50 | 2.50 |
| **2007** | 2.45 | 2.43 |
| **2008** | 3.50 | 3.52 |

| | | |
|---|---|---|
| **2009** | 2.10 | 2.35 |
| **2010** | 2.505 | 2.62 |
| **2011** | 2.70 | 2.80 |
| **2012** | 3.60 | 3.50 |

For annual maintenance costs, we calculated the average maintenance cost per mile based on the Port Authority dataset for FORD F-350s using the method described in the "Data Analysis Methodologies" section. For biodiesel we found that the average maintenance cost per mile is \$0.81 which is equivalent to \$4,050 per year. Because all of the Port Authority's diesel is mixed with biodiesel there is no data from the Port Authority on maintenance costs for diesel vehicles. Figures 1.7 and 1.8 below show that using B-20 biodiesel does very little to increase maintenance costs when compared with using straight diesel.

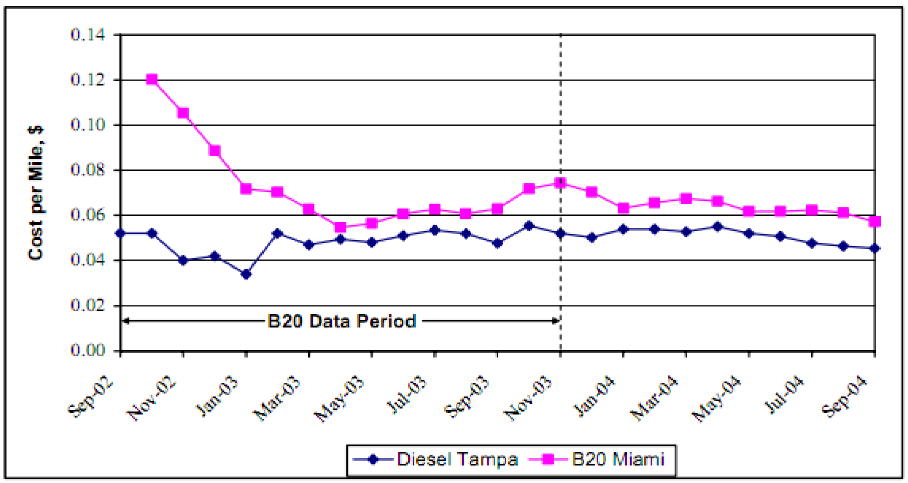


Figure 15. Cumulative Running Average Engine- and Fuel-Related Maintenance Costs per Mile for the Ford Vans. Higher costs to maintain the B20 vehicles are probably not attributable to the fuel, as discussed in the text.

**Figure 1.7**. Total costs for B-20 biodiesel and diesel vehicles.
Reference: http://www.nrel.gov/docs/fy06osti/38509.pdf

Figure 1.7 shows that Ford Vans using B-20 diesel have slightly higher maintenance cost than using regular diesel [25]. While in another case of implementation of B-20 biodiesel in transit buses, Figure 1.8 shows that B-20 and diesel have almost the exact same maintenance costs [26]. Additionally, some theoretical studies conclude that B-20 vehicles should have lower maintenance costs due to the fact that B-20 biodiesel contains a lubricant that can extend an engine's lifetime. In our case scenario analysis we assumed that vehicles using diesel and B-20 biodiesel have the same maintenance cost, which is \$4050/yr.

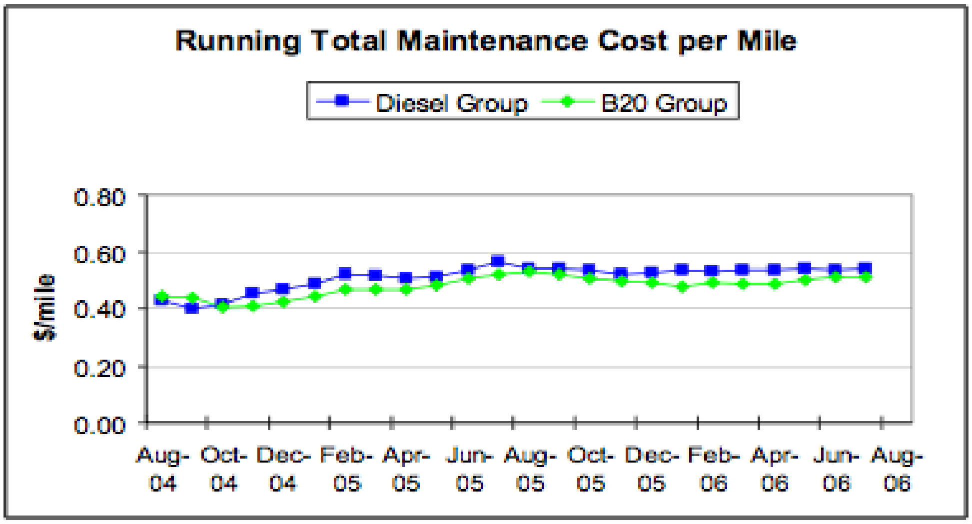


**Figure 1.8:** 100,000-Mile Evaluation of Transit Buses Operated on Biodiesel Blends. Reference: http://www.nrel.gov/docs/fy07osti/40128.pdf)

For the capital cost, the vehicle price (A) is $30,000, which we found at Edmunds.com. We also assumed a discount rate(r) of 5%, and lifetime value (N) of 10 years. The annual buying cost of a FORD F-350 can be calculated as follows:

$$A = B \times r \times (1 + r)N/(1 + r)N - 1$$

The result: an annual capital cost per vehicle of $3,885/yr.
The annual total cost comparison per vehicle is shown in the following table.

**Table 1.2.** Annual Total Cost Comparison

| Cost **Analysis per Vehicle** | **Ford F-350 for Diesel** | **Ford F-350 for B-20** |
|---|---|---|
| Miles per Gallon | 14.5 | 14.2 |
| Miles per Year | 5,000 | 5,000 |
| Fuel Cost per Gallon | $2.67 | $2.72 |
| Fuel Cost per Year | $920 | $957 |
| Maintenance Cost per year | $4,050 | $4,050 |
| Annual Capital Cost | $3,885 | $3,885 |
| Total Cost per year | $8,855 | $8,892 |

Table 1.4 shows that B-20 biodiesel is only $37/yr more expensive than using pure diesel. $37 is a 0.4% increase in cost from the annual total cost per year of a pure diesel vehicle. If the cost difference of B-20 and diesel fuel is larger than $0.05/gal, like in the table above, then the spread in total costs will be larger. However, even if the difference in fuel costs is $0.15/gal the difference in annual costs will still be quite low. Figure 1.9 shows the total cost per year,

between the years 2005 and 2012, of purchasing 10 vehicles using B-20 biodiesel or using straight diesel. Figure 1.10 shows the cost savings of using pure diesel compared with B-20 biodiesel for 10 vehicles.

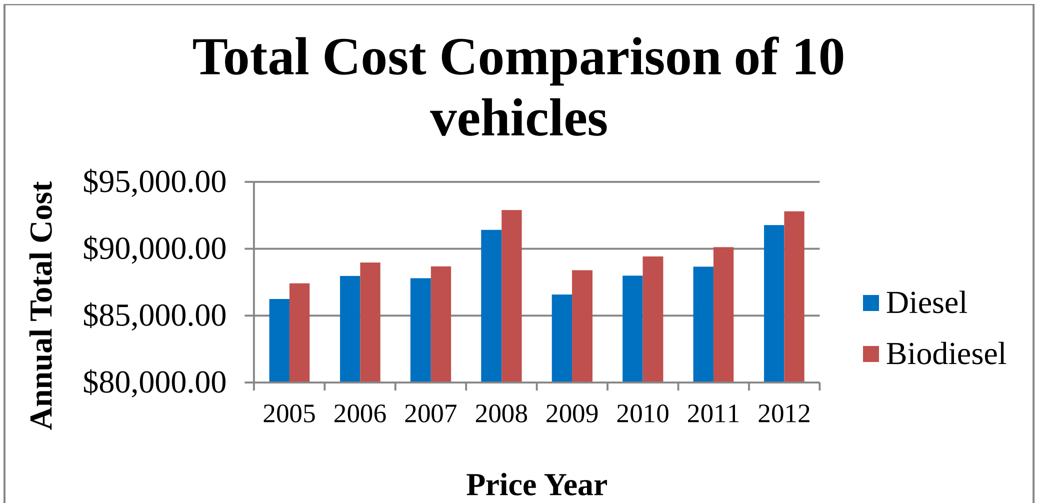


**Figure 1.9**

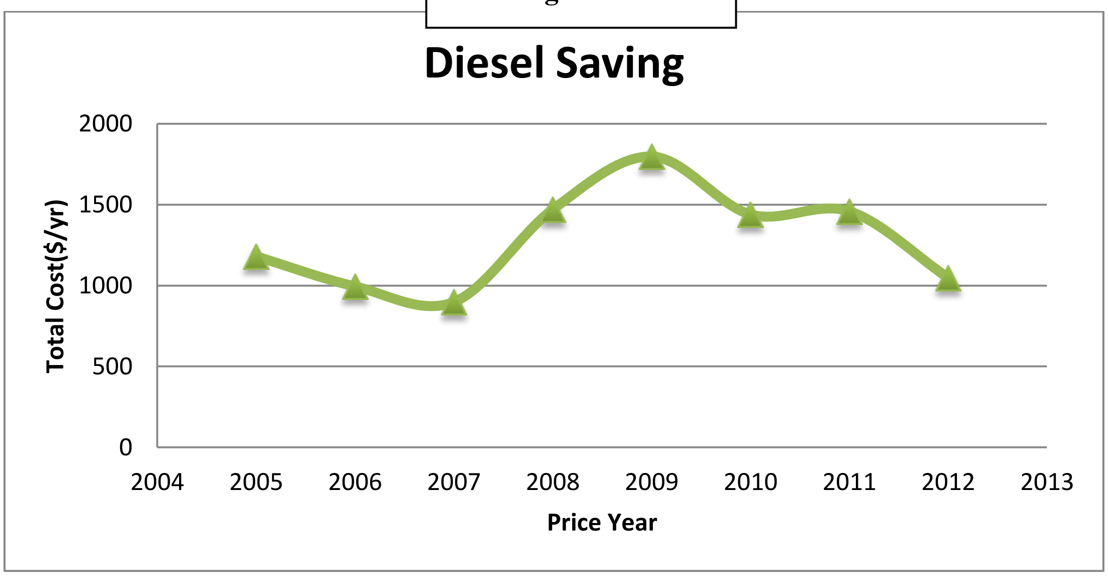


**Figure 1.10**

## 1.5 Conclusions and Recommendations

It is well known that transportation is almost totally dependent on fossil fuels. Biodiesel is one feasible alternative to fossil fuels. Biodiesel has not been widely accepted because it is currently more expensive than petroleum fuel. With recent increases in petroleum prices and uncertainties concerning petroleum availability, there is renewed interest in biodiesel fuels for diesel engines.

Alternative fuels for compression ignition engines (CIEs) have become increasingly important due to increased environmental concerns. Additionally, diesel engine exhaust emissions have the potential to cause a range of health problems. In this sense, biodiesel derived from vegetable oils and animal fats represents a promising alternative to conventional diesel fuel (Dorado et al., 2003). Table 1.5 below displays numerous environmental advantages of using biodiesel fuel. The exhaust emissions of carbon monoxide (CO) from biodiesel were 50% lower than CO emissions from straight diesel. The exhaust emissions of particulate matter (PM) from biodiesel were 30% lower than overall PM emissions from straight diesel.

| Cost of Reducing $CO_2$ Emissions | |
|---|---|
| lbs. $CO_2$ saved | 1034 |
| Difference in Cost | $37 |
| Cost per lb. of $CO_2$ | $0.036 |
| Cost per ton of $CO_2$ | $71.6 |

**Table 1.5**

From the case scenario analysis, the fuel cost of biodiesel is a little higher than traditional diesel while the emission of $CO_2$ is reduced by 15%. The total cost per year for a Ford F-350 running on pure diesel is $8855 while the total cost per year for a Ford F-350 running on biodiesel is $8892.

## Recommendations

Our sub-team strongly believes that the environmental benefits of using B-20 biodiesel significantly outweigh the increased fuel costs of using diesel instead of B-20. Table 1.5 above shows that the Port Authority basically only paying $71.6 per ton of $CO_2$ saved. It is also important to mention that reduced $CO_2$ emissions are far from the only environmentally benefit of using biodiesel. Hence, we strongly encourage the Port Authority to continue to use B-20 biodiesel to fuel it vehicles with compression ignition engines.

Regarding regular maintenance and repair, biodiesel vehicles are very similar to conventional vehicles—they are basically standard diesel engine vehicles that can burn biodiesel fuel. In fact, biodiesel vehicles are next in line after flex-fuel vehicles (FFVs) regarding their similarity to conventional gasoline-powered cars. However, these cars do have a few more potential maintenance “gotchas” to watch out for:

**Algae**

Algae growth in the fuel tank and lines is a potential problem. Indeed, it may seem odd at first—how can anything grow and live in diesel fuel—but it is true, especially in warm and humid climates. And algae can live in petro diesel as well as biodiesel.

To Avoid Algae Problems:

- Top Off Your Tank. Keep your fuel level topped off to prevent moisture build-up from condensation in the tank.
- Use Algicides. Added to the fuel to control algae build-up, algaecides are vital in hot, humid climates.
- Change that Filter Regularly. Algae will grow in minute concentrations no matter the climate conditions—so keep the fuel filter changed on a regular basis, and it'll never have a chance to clog.

**Sludge**

Sludge tends to be a problem that is mostly limited to older diesels that have accumulated years and miles. It's a "blackish" substance similar to algae—though it's not living. Sludge builds up in the fuel system over time. Basically, it's "dirt" that settles to the bottom of the fuel tank. While it is generally harmless settled at the bottom of the fuel tank, when biodiesel is added to the mix, the sludge can be loosened and suspended in the fuel, causing the fuel filter to clog more quickly. Is biodiesel the bad guy here? Not really, actually it's a good thing—biodiesel acts as a detergent and will eventually clean out most of the sludge that has built up in the fuel system. The Port Authority reported to the team that they have been running B-20 for long enough that transition problems with sludge have worked themselves out, but we include this information here as a precaution.

To Avoid Sludge problems:

- Regular Fuel Filter Changes. When first switching to biodiesel in older vehicles, it may be necessary to change the fuel filter more frequently to remove the purged sludge.
- If you suspect your very old vehicle has severe sludge build-up—say you've changed out several filters and they're continuing to clog, you may want to consider having the fuel tank removed and pressure cleaned by a shop.

Overall, as the purpose is to reduce greenhouse gas emissions, if we maintain biodiesel cars properly, it will be a good alternative fuel. The execution of the change in fuels needs the regulations in policies. The government should address more and encourage the use of biodiesel fuels.

## 1.6 Areas of Further Research

In recent years car manufacturers have begun to implement compression ignition engines on much smaller vehicles than in the past. Diesel fuel previously fueled only large vehicles in the United States but it appears that vehicles as small as mid-sized sedans are beginning to use diesel engines. While our group did not consider B-20 biodiesel as a fuel alternative for the Port Authority's smaller vehicles, it is a possibility that would be valuable to examine.

Another area of research that would be worth looking into would be the primary drivers of biodiesel's cost fluctuations. We know that the cost of biodiesel fluctuates, but what is causing it to fluctuate? Additionally, what technological advancements may develop that would decrease the cost of biodiesel production? These are areas that I am sure the Port Authority would be very interested in.

# 2. Compressed Natural Gas

## 2.1 Introduction

Natural gas, a fossil fuel comprised mostly of methane, is one of the cleanest burning alternative fuels. It can be used in the form of compressed natural gas (CNG) or liquefied natural gas (LNG) to fuel cars and trucks.

There are three types of natural gas vehicles:

- Dedicated: These vehicles are designed to run only on natural gas.
- Bi-fuel: These vehicles have two separate fueling systems that enable them to run on either natural gas or gasoline.
- Dual-fuel: These vehicles have fuel systems that run on natural gas and use diesel for ignition assistance.

Light-duty vehicles typically operate in dedicated or bi-fuel modes, and heavy-duty vehicles operate in dedicated or dual-fuel modes. On the vehicle, natural gas is stored in tanks as CNG. LNG, a more expensive option, is used in some heavy-duty vehicles. The form of natural gas chosen depends on the range a driver needs. The energy density of LNG is greater than for CNG so more fuel can be stored onboard. This makes LNG well-suited for Class 7 and 8 trucks that need a greater range.

In general, dedicated NGVs demonstrate better performance and have lower emissions than bi-fuel vehicles. Because dedicated NGVs only have one fuel tank, they aren't as heavy as bi-fuel NGVs and offer more cargo capacity. The driving range of NGVs generally is less than that of comparable conventional vehicles because of the lower energy density of natural gas. Extra storage tanks can increase range, but the additional weight may displace payload capacity.

## 2.2 Literature Review

Bashar and Rahman (2012) enumerate the advantages of using Compressed Natural Gas (CNG) as a fuel for automobiles as opposed to petroleum based fuels in Bangladesh. Bashar and Rahman state that CNG is safer, less costly, more environmentally friendly (resulting in lower emissions and a decreased number of pollution related health problems), it reduces dependency on imported fuel and it improves engine output and engine life. In Bangladesh, CNG costs up to 80% less than petroleum based fuels because it does not need to be refined. Additionally, in cities throughout Bangladesh, including Dhaka, urban pollution is a serious concern and CNG produces a much smaller amount of particulate matter than gasoline or diesel. The authors also list the disadvantages, or more accurately called “obstacles”, of using CNG instead of petroleum based fuel. There are far fewer CNG refueling stations than gasoline and diesel refueling stations, and it takes longer to refuel a CNG vehicle than a gasoline powered vehicle [27].

Christopher Knittel (2012) explains that despite the technological advancements made in drilling for natural gas, numerous policy initiatives must be taken to level the playing field for natural gas in the transportation sector of the economy. The rise in oil prices and the advances in horizontal drilling have led to a large difference in the cost of oil and natural gas, with natural gas being much cheaper. The author believes that if efforts are made to improve natural gas fueling infrastructure in homes, at local distribution companies and along long haul trucking routes, natural gas will be able to compete with petroleum based vehicles. The author also believes that it is necessary for natural gas to be promoted by public officials the same way that ethanol and electric powered vehicles have been in the past [28].

## 2.3 Cost Analysis

CNG Fleet Data

For our study, we focused on Port Authority's dedicated CNG fleet and the fleet has three vehicle categories: Pick-up Trucks, Full Size Vans, and Sedans.

Table 2.1 and Figure 2.1 show vehicle models and the number of vehicles in each vehicle category.

**Table 2.1**

| Vehicle Category | Vehicle Models |
|---|---|
| Flat Bed Trucks | Ford F250 CNG, Ford F150 CNG |
| Full Size Vans | Ford E350 CNG, Ford E150 CNG, Dodge B2500 CNG |
| Sedans | Honda Civic CNG |

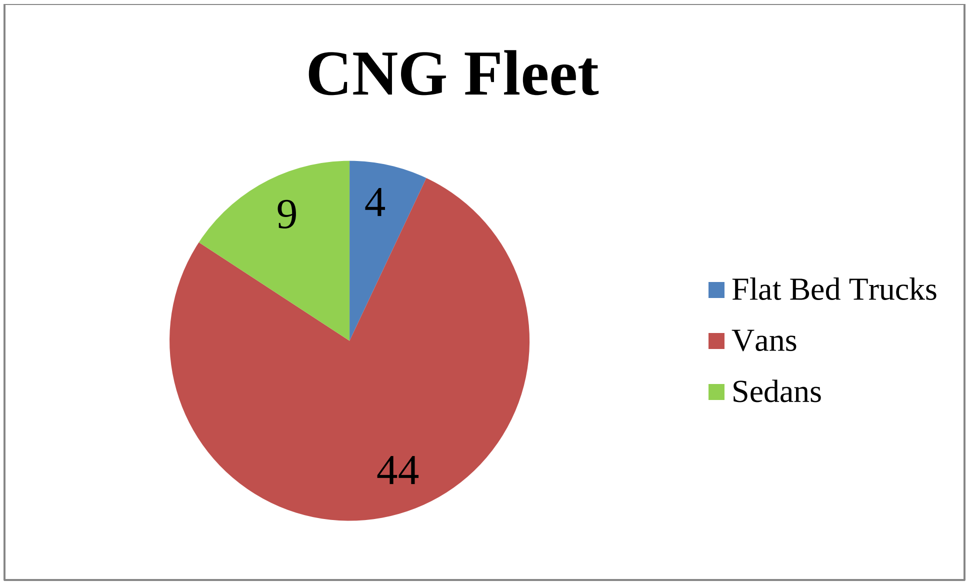


**Figure 2.1**

## Annual Cost Calculation

**Fuel Cost/Mile**

In our data set, we do not have LTD Fuel Dollars and LTD Fuel Quantity. In order to calculate Fuel Cost/Mile, we looked up the MPGGEs of vehicles in our fleet and the average CNG price ($2.80/MPGGE for New York City) from U.S. Dept. of Energy's website (http://www.afdc.energy.gov). Then we calculated Fuel Cost/Mile by:

$$\text{Fuel Cost per Mile} = \frac{CNG\ Price}{MPGGE}$$

**Maintenance Cost/Mile**

Since we are doing fuel economy analysis for CNG vehicles, we excluded accident cost from maintenance cost and calculated Maintenance Cost/Mile by:

$$\text{Maintenance Cost per Mile} = \frac{LTD\ Maintenace\ Cost - LTD\ Accident\ Cost}{Current\ Odometer}$$

**Annualized Capital Cost**

$$Annualized\ Capital\ Cost = \frac{B \times r \times (1 + r) \times N}{(1 + r) \times N - 1}$$

Where:
Discount Rate(r) = 5%
Years in Service (N) = 10
Buying Cost (B) = LTD Depreciation + Book Value

**Total Annual Cost**

- We assume annual mileage is 5,000 per vehicle
- We divided Vans into New Vans and Old Vans for Annualized Capital Cost calculation because of the initial buying cost disparity for vans 2004 and older being significantly cheaper than the 2010 and younger models. These initial buying costs come from the Port Authority data. It is assumed that between the years of 2004 and 2010 the price point for the vans changed due to market value and possible discounts.
- Total Cost/yr = Fuel Cost/yr + Maintenance Cost/yr + Annualized Capital cost

$$\begin{aligned} Total\ Annual\ Cost &= 5000mi \times Fuel\ Cost\ per\ mi + 5000mi \times Maintenance\ Cost\ per\ mi \\ &+ Annualized\ Capital\ Cost \end{aligned}$$

Figure 2.2 shows comparison of annual total cost by vehicle category.

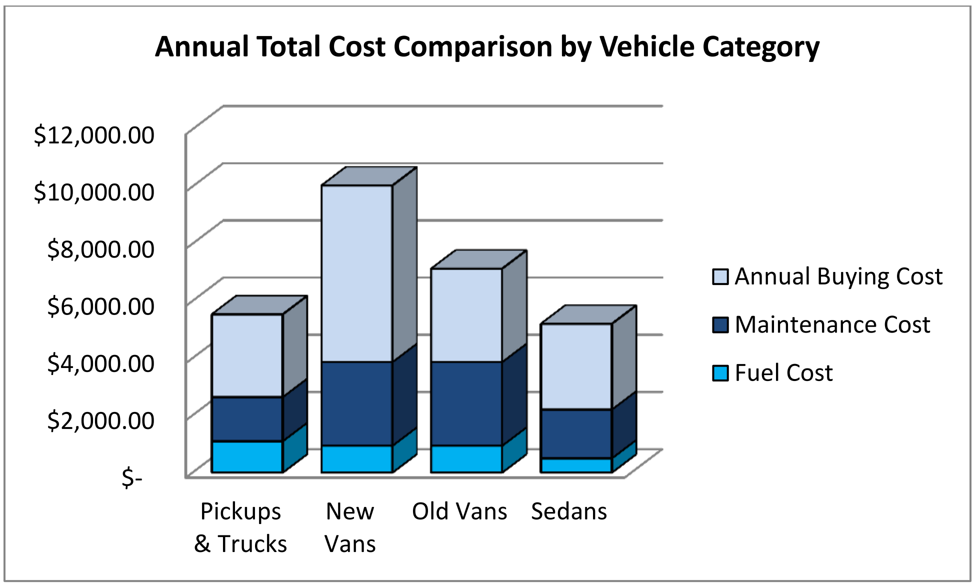


**Figure 2.2**

## 2.4 Analysis of Green Gas Reduction

The calculation of CO2 emission

In comparing compressed natural gas to gasoline, the units used by the EPA are gasoline gallon equivalent (GGE). They are used to compare fuel economies of gasoline and CNG vehicles [29].

1 GGE = 33.40 kWh = 120.24MJ

So in the CNG fleet, MPG means "mile per GGE" and the main $CO_2$ chemical formula for CNG is:

$$CH_4 + 2O_2 = 2H_2O + CO_2$$

Thus, the calculation of the emission of the $CO_2$ from CNG uses the following formula:

$$Total\_GGE = \frac{miles}{MPG};$$

$$CO2 = Total\_GGE \times 33.41\frac{Kwh}{GGE} \times 3.6 \times \frac{Mj}{kwh} \times A \times \frac{CO2\_lbs}{Mj}$$

$A$: The certain parameter of how many pounds of $CO_2$ generated by 1 MJ contained in the CNG. $A$ is an experimental constant and is not based on the simple chemical formula.

Based on the "Natural Resources Canada" [30], we got the practical value of $A$.
$A = 0.056$ kg CO2 / Mj = 0.1232 lbs CO2 / Mj
Thus, the $CO_2$ emission formula is

$$CO2 = Total\_GGE \times 120.24\frac{MJ}{GGE} \times 0.1232\frac{lbs}{MJ}$$

$$= Total\_GGE \times 14.8\frac{lbs}{GGE}$$

From this formula, we calculated the emissions of CO2 per mile:

$$CO2\_lbs/mile = 0.123\frac{lbs}{MJ} \times \frac{120.24MJ}{GGE} \times \frac{1}{MPG} = \frac{14.8lbs/GGE}{MPG}$$

From this the $CO_2$ emissions per mile can be calculated. The results are shown in Table 2.2 and Figure 2.3. Figure 2.3 clearly shows that Honda Civic has the lowest CO2 emission rate, which is only the half of Ford and Dodge. This is the same proportion as the fuel economy because the fuel economy determines the $CO_2$ emission.

**Table 2.2**

**CO2lbs emission per mile**

| **Makers** | DODGE | FORD | | | | HONDA |
|---|---|---|---|---|---|---|
| | | E150 | E 350 | F-150 | F-250 | |
| **CO2 lbs./mile** | 1.134 | 0.988 | 0.988 | 1.140 | 1.235 | 0.529 |

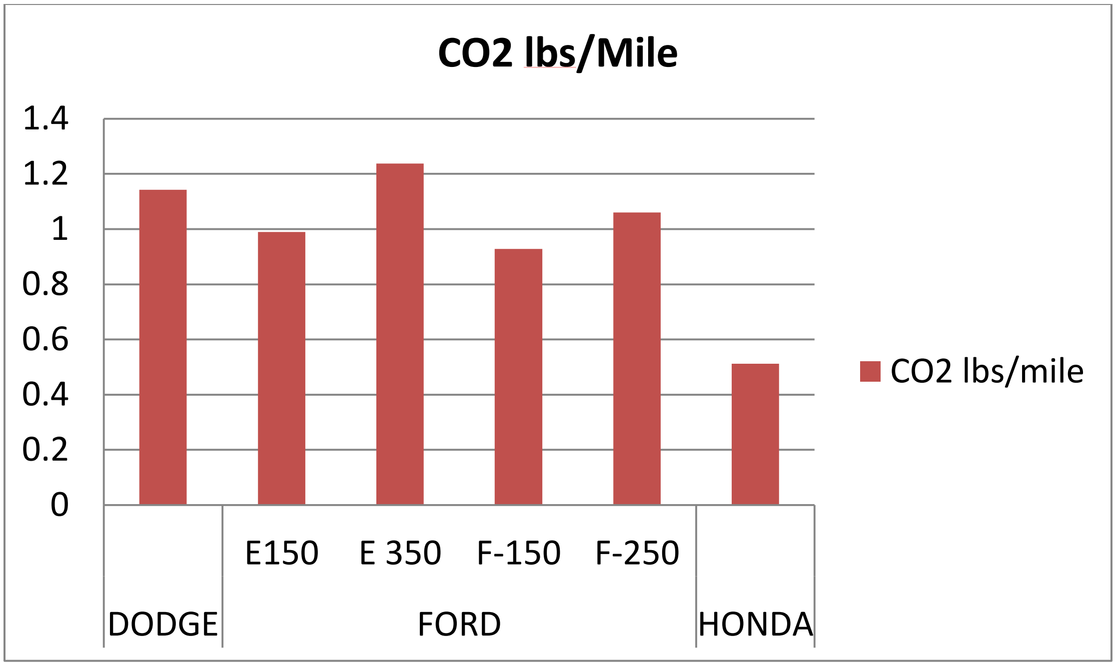


**Figure 2.3**

<u>Comparison between CNG and Gasoline</u>

CNG beats gasoline on two fronts. The price per GGE of CNG is about $2.80 compared to the $4.00 price per gallon of gasoline. Not only is CNG cheaper, but it is also cleaner. The $CO_2$ emission for gasoline is 19.6 lbs./gallon compared to the 14.8 lbs./GGE for CNG. This ratio reduces $CO_2$ emissions by 25%. CNG, purely by fuel analytics, is better than gasoline in the area of economic and environmental impact. Table 2.3 tabulates these results and Figure 2.4 shows the model by model CNG and gasoline $CO_2$ emission rates.

**Table 2.3**

| CO2 emission calculation (lb/mil) | | |
|---|---|---|
| CNG | $= 0.123\frac{lbs}{MJ} \times \frac{120.24MJ}{GGE} \times \frac{1}{MPG}$ | $= \frac{14.8\ lbs/GGE}{MPG}$ |
| Gasoline | $= 19.6\ lbs/gallon \times \frac{1}{MPG}$ | $= \frac{19.6\ lbs/gallon}{MPG}$ |

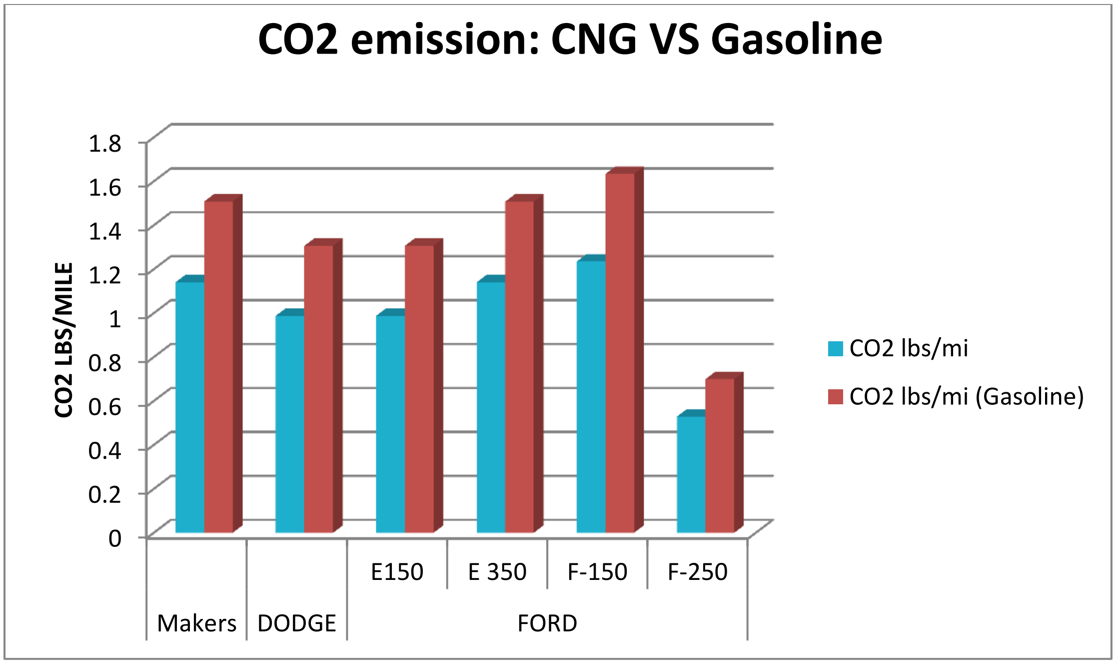


**Figure 2.4**

## 2.5 Case Scenario

A side by side cost scenario between Honda 2008 Civic Gasoline and Honda 2008 Civic CNG, Honda 2013 Civic Gasoline and Honda 2013 Civic CNG shows that the capital cost is greater for the CNG model on an annual basis. The comparison is based on the following assumptions:

1. Assume annual mileage is 5,000 per mile per vehicle.
2. Fuel cost(Gasoline) =(5,000mile/MPG)*$4.00/gallon.
3. Fuel cost(CNG)=(5,000mile/MPG)*$2.80/gallon.
4. Maintenance cost is based on the current PA's fleet for the 2008 CNG civic and from edmunds.com for the other Civic [31].
5. Annualized capital cost is based on the vehicle's capital cost (edmunds.com).
6. Total cost per year = Fuel Cost per Year + Maint. Cost per year + Annualized Capital cost.

Using the similar methods in "Cost Analysis" and "Analysis of green gas reduction", we got the results shown in Table 2.4.

**Table 2.4**

| | 2008 Gasoline Civic | 2008 CNG Civic | 2013 CNG Civic | 2013 Gasoline Civic |
|---|---|---|---|---|
| Fuel Cost /yr | $678.00 | $500.00 | $452.00 | $625.00 |
| Maintenance Cost/yr | $1,144.80 | $1,705.82 | $958 | $643 |
| Annual Capital Cost | $2,849.10 | $2,994.23 | $ 5,293.00 | $ 3,793.00 |
| Total Annual Cost | $4,671.10 | $5,200.05 | $6,703 | $5,061 |
| CO2 lbs./mile | 0.68 | 0.53 | 0.48 | 0.61 |
| CO2 lbs./year | 3379.31 | 2642.86 | 2,387 | 3,063 |

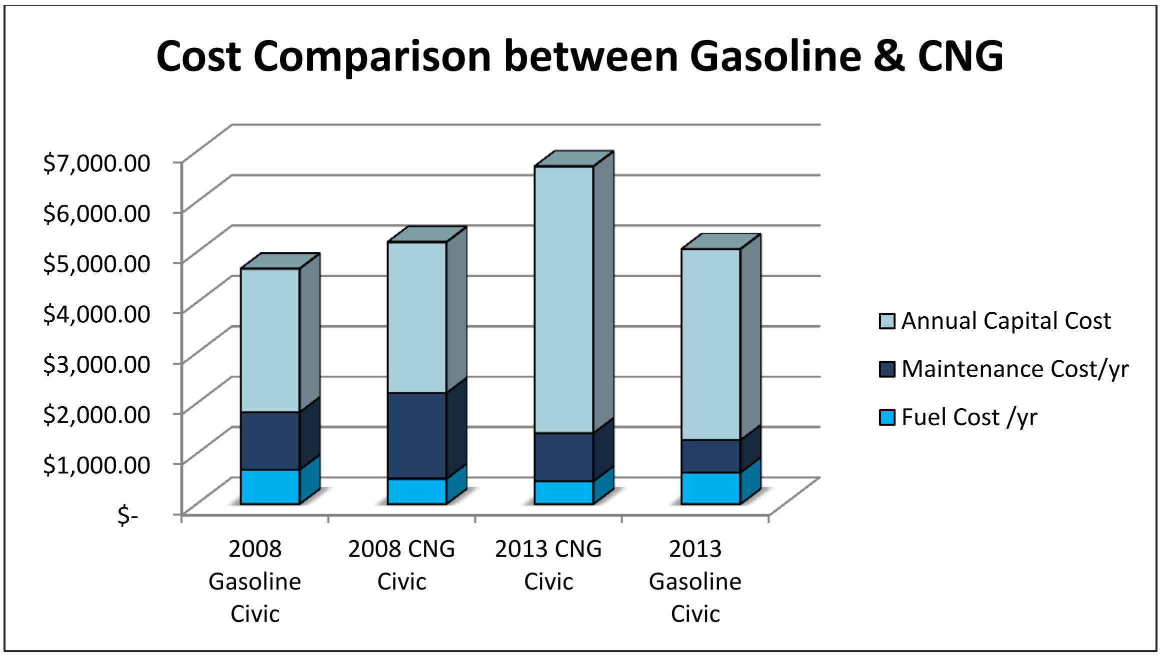


**Figure 2.5**

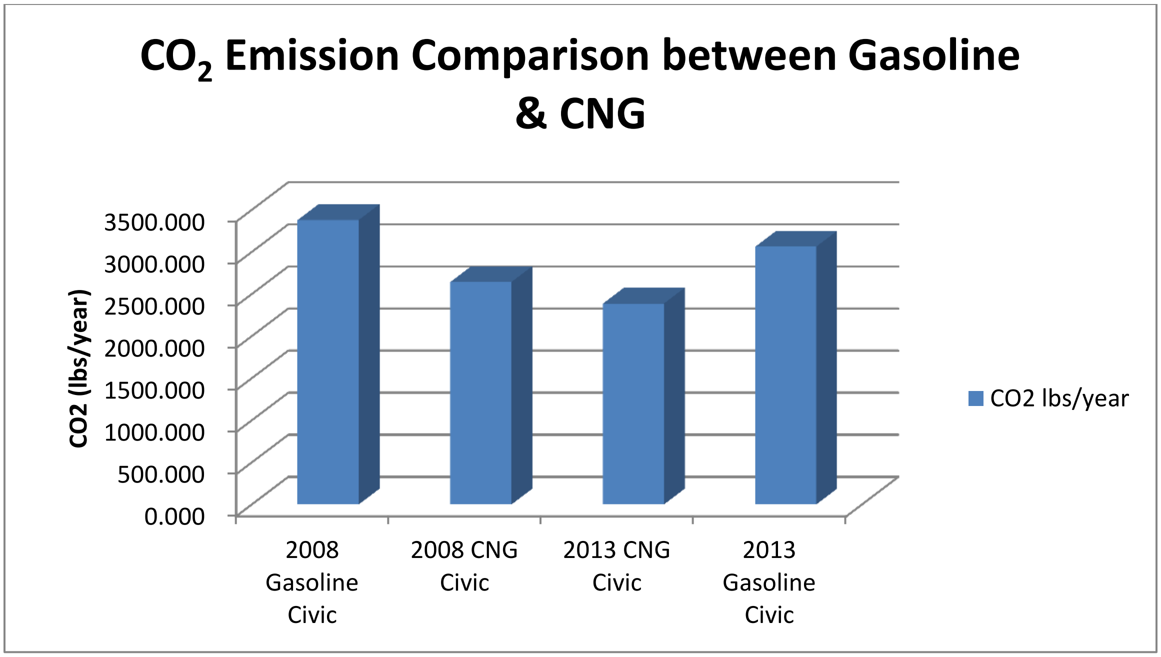


**Figure 2.6**

From Figure 2.6, it is clear to tell that the 2013 CNG has the lowest CO2 emission because of its highest MPG. 2007 CNG has lower emission than 2007 Gasoline because CNG has lower CO2 emission parameter. Compare 2013 CNG Civic and 2013 Gasoline Civic, it is clear that 2013 CNG has higher annual maintenance cost and capital cost, and lower annual fuel cost than 2013 Gasoline. If we just consider about the CO2 emission, 2013 CNG is the best choice.

## 2.6 Recommendations

The CNG alternative sedan sized vehicles are a very viable option compared to the gasoline standard. With an initial investment, the CNG vehicles will decrease the $CO_2$ emissions by 25% compared to the gasoline equivalent. The comparison will be true across all models because the 25% reduction is based on the chemical equation and is exact in theory for all dedicated CNG vehicles. Over the course of an expected life of 10 years for a CNG vehicle, the expected extra cost for any CNG vehicle relative to the gasoline equivalent is about $17,000. This price is subject to change with more research, because there is such limited data on the costs of the dedicated CNG vehicle market. PA should choose CNG only if it is worth this much to PA to save $CO_2$ or achieve other benefits of CNG. As of now we would not recommend purchasing CNG vehicles based on a cost basis.

## 2.7 Further Research

From our analysis of the Port Authority dedicated CNG data, we were able to see that there is a need for more data regarding the maintenance costs of CNG vehicles. Because the CNG Honda Civic fleet has relatively low maintenance costs compared to the expected maintenance costs of a gasoline version of the Honda Civic, we can conclude that more data is needed to back up this maintenance cost savings. If this cost savings could be proven consistent through all CNG vehicles, an investment in CNG would prove to be a less of an investment than currently expected. Another factor in the investment in dedicated CNG vehicles is the fuel savings. Currently CNG is significantly cheaper than gasoline on a per mile basis. However, this cost savings could fluctuate significantly in the near future given the New York State effort to tap the natural gas resource in New York.

# 3. Hybrid Electric Vehicles

## 3.1 Literature Review

### Introduction

Hybrid technology has gained popularity in the new car market because it reduces emissions and improves fuel economy through features such as hybrid assist, regenerative braking and engine auto-stop. Two teams within the Port of New York/ New Jersey have also been formed to research the opportunities and challenges associated with applying hybrid technology to cargo handling equipment, and the potential for its commercialization [32]. Our team has investigated the technology of hybrid vehicles in order to find the possibility of replacing the conventional vehicles with HEV or PHEV by calculating the cost analysis and CO2 emission.

### Technology for hybrid vehicles

According to Taylor &Francis Group, LLC. (2008), a hybrid vehicle is any kind of vehicle that uses two or more propulsion systems. Possible combinations of power (energy) sources include diesel/electric, gasoline/fly wheel, and fuel cell/battery. Typically one energy source is storage and the other is conversion of a fuel to energy [33].

Hybrid Vehicles utilize small internal-combustion engines (ICE) and an electric motor. The control system of hybrid engine regulates engine's performance depending on driving conditions. One more advantage is possibility to recharge a battery on the move by a process of kinematical energy recuperation during braking [34].

### HEVs

Hybrid-electric vehicles (HEVs) combine the benefits of gasoline engines and electric motors. An alternate arrangement is a diesel engine and an electric motor. HEVs can be configured to obtain different objectives, such as improved fuel economy, increased power, or additional auxiliary power for electronic devices and power tools [35]. An HEV is formed by merging components from a pure electrical vehicle and a pure gasoline vehicle.

Table 3.1: Table of electric vehicles and their performance

| Car | Chevy Volt | Ford Focus Electric | Mitsubishi i-MiEV | Nissan Leaf | Toyota RAV4 EV | Tesla Model S |
|---|---|---|---|---|---|---|
| Year | 2013 | 2013 | 2013 | 2012 | 2013 | 2013 |
| Fuel Type | Electric + gas recharge | Electric | Electric | Electric | Electric | Electric |
| Range (miles) | 38 + 242 gas | 76 | 62 | 73 | 103 | 208 |
| Charge Time (hours) | 4 | 4 | 7 | 8 | 6 | 10 |
| Top Speed | 100 | 84 | 81 | 90 | 100 | 120 |
| Drive Type | Front-wheel | Front-wheel | Front-wheel | Front-wheel | Front-wheel | Rear-wheel |
| 0-60MPH (sec) | 9 | 10 | 15 | 7.5 | 7 | 5.9 |
| Base MSRP | $31,645 | $39,200 | $21,625 | $35,200 | $49,800 | $59,000 |
| Battery Type | Lithium Ion | Lithium-Polymer | Lithium Ion | Lithium Ion | Lithium Ion | Lithium Ion |
| Seats | 4 | 5 | 4 | 5 | 5 | 5 |

**Typical Technology in HEVs**

- **Regenerative Braking.** The electric motor applies resistance to the drivetrain causing the wheels to slow down. In return, the energy from the wheels turns the motor, which functions as a generator, converting energy normally wasted during coasting and braking into electricity, which is stored in a battery until needed by the electric motor.
- **Electric Motor Drive/Assist.** The electric motor provides additional power to assist the engine in accelerating, passing, or hill climbing.
- **Automatic Start/Shutoff.** Automatically shuts off the engine when the vehicle comes to a stop and restarts it when the accelerator is pressed [35].

**Main Components in HEVs**

- **Battery.** Batteries are one of the most important parts of a hybrid vehicle. When the driver uses the brakes, this sends a charge to the car's battery. Some hybrids garner energy from the gasoline engine by attaching a spinning electrical generator on the device. Since the battery helps power the vehicle, it is larger and holds much energy than batteries used to start conventional vehicles.

- **Gasoline Engine.** The gasoline engine is the part of the hybrid that resembles its traditional counterpart, the gas-powered vehicle. It's just like one you would find on a traditional car, except that it usually much smaller and more efficient.

- **Electric motor.** Before hybrids, electric motors were typically used to power smaller devices such as fans, computer equipment and printers. Through what is known as "regenerative braking," braking and accelerating create a steady stream of energy. With the assistance of the car's wheels, the motor functions as a generator, and energy normally wasted from braking and coasting are harnessed. . It also tarts the gasoline engine instantly when needed [36].

## PHEVs

Plug-in hybrid electric vehicles combine operational aspects of both battery electric vehicles (BEVs) and power-assist hybrid electric vehicles (HEVs). A PHEV, like a BEV, can be recharged from the electric grid, stores significant energy in an onboard battery, and then uses this energy, depleting the battery, during daily driving [37]. However in hybrids, the electric power for the motor is generated from regenerative braking and from gasoline engine, so the hybrids don't have to be "plugged in" to an electrical recharge.

**Basic PHEV configurations**

- **Series PHEVs (EREVs).** Only the electric motor turns the wheels; the gasoline engine is only used to generate electricity. Series PHEVs can run solely on electricity until the battery needs to be recharged. Therefore, for shorter trips, these vehicles might use no gasoline at all.

In a series hybrid vehicle, the internal combustion engine is not directly connected to the drive train at all; rather it powers an electrical generator instead. Separate small electric motors (in – wheel motor) installed at each wheel are featured in some prototype and concept cars. This allows the possibility of easily controlling the power delivered to each wheel, and therefore simplifies traction control, all-wheel drive and similar features.

The advantage of this type of hybrid is the flexibility afforded by the lack of a mechanical link between the internal combustion engine and the wheels. A weakness of a series hybrid system is that series hybrids require separate motor and generator portions which can be combined in some parallel hybrid engines; the combined efficiency of the motor and generator will be lower than that of a conventional transmission thereby offsetting the efficiency gains that might otherwise be realized. However, series hybrids are the most efficient in driving cycles that incorporate many stops and starts such as for delivering vehicles, urban buses or stop and go city driving [34].

- **Parallel or Blended PHEVs.** Both the engine and electric motor are mechanically connected to the wheels, and both propel the vehicle under most driving conditions.

Parallel hybrid systems connect both the electrical and internal combustion systems to the mechanical transmission. They can be sub – classified on the bases of the ratio of contribution to the motive power of the different component or portion. In some cases the internal combustion engine is the dominant component and is used to supply power primarily with the battery supplying power only when a boost is needed. Others can run with just the electric system operating alone. Most designs combine a large electrical generator and a motor into one unit often situated between the internal combustion engine and the transmission replacing both the conventional starter motor and the alternator. A large battery pack is needed [34].

**Environmental benefits of PHEV**

A number of significant environmental benefits accompany the use of grid electricity in a plug-in hybrid. Electricity is produced largely from diverse domestic resources, in contrast to the high level of dependence on imported petroleum in the transportation sector. PHEVs can reduce direct emissions at the vehicle, with positive implications for transportation-dense urban areas that suffer from poor air quality due to mobile-source emissions. PHEVs recharged by electricity produced by efficient combustion, non-emitting, or renewable generation technologies will emit significantly lower fuel-cycle greenhouse gas emissions than either conventional or hybrid vehicles [37].

## Maintenance and Repair Costs

According to a study done by Jeffrey Kosub, there will be an oil change every 3,000 miles driven for the hybrid vehicle, and at 60,000miles of the vehicle life, there will be a major tune-up which includes: oil, all fluids, plugs, inspection of belts and hoses, filters replaced, transmission inspected, and engine timing inspected. At the fourth year of regular service, the front and back break system needs a repair, as well as the four tires will be needed for replacement.

As for the battery system, as Jeffrey Kosub mentioned, large battery is a major factor in determining repair costs since the cost to replace can range from $5,500 to $7,000 to replace after 10 years. Furthermore, the batteries in the hybrid vehicle that drive the electric motor are warranted for 100,000 miles and will not need service or maintenance since they are a sealed battery system [38].

### Fuel Economy

According to a recent paper published by United States Environmental Protection Agency (EPA): Office of Transportation and Air Quality (2008),Traditional hybrid vehicles are powered by both an internal combustion engine and a rechargeable battery, yielding fuel economy improvements up to 30-60 percent over conventional gasoline-only models. Plug-in hybrid vehicles come with the added feature of a plug that allows the vehicle to be recharged through a conventional electrical outlet. By shifting the automobile’s energy source from conventional fuels to electricity, plug-in hybrids offer potential for a number of environmental and energy security benefits, such as: Reducing U.S. consumption of petroleum; Reducing greenhouse gas emissions; and Advancing battery and other technologies that could ultimately make 100% electric vehicles commercially viable.

Plug-in hybrids have a larger up-front cost than current hybrid vehicles because of their larger battery, motors, and power electronics. However, fuel costs are lower for plug-in hybrids because per-mile electricity costs are lower than those for gasoline. This is especially true in areas where electricity rates are lower at night when most plug-in hybrids will be recharged. Over time, research and mass production will likely improve the cost-effectiveness of plug-in hybrids. Moreover, an article by John Voelcker (2009) states that plug-in vehicles including plug-in hybrids and purely electric cars, will make up almost a third of new-car sales in the United States. And by 2050, plug ins could account for most of China's burgeoning vehicular travel. But the environmental implications of such a massive shift are hardly straightforward [37].

Greenhouse Gas Emission

A recent study by Omonowo D. Monoh and Michael O. Omoigui (2009) describes that conventional vehicles operate on the principle of internal combustion engine (ICE) that runs on fossil fuels (gasoline or diesel) from oil deposits that are millions of years old. ICE vehicles emit carbon dioxide, hydrocarbon, sulphur oxides, carbon monoxide and hydrocarbon through their tailpipes. These gases result in global warming through greenhouse gas effects and pollution effects which are harmful to both environment and lives [37]. Since the better fuel economy and the lower GHG emission for both Hybrid and Plug-in hybrid, there exhibits a market potential for both HEVs and PHEVs, which will decrease the GHGs emissions, as well as petroleum consumption. Therefore, a lot of researchers have done study on GHG emission and compared with the conventional vehicles. According to Samaras and Meisterling, PHEVs could reduce use phase GHG emissions by 38 – 41% compared to conventional vehicles under the U.S. average GHG intensity of electricity, and by 7 – 12% compared to HEVs. Samaras and Meisterling also argue that the "GHG emission reduction is highly dependent on the energy sources of electricity production", such as under the carbon-intensive scenario, life cycle PHEV impacts are 9-18% higher than those of HEVs, while under low-carbon scenario, 51-63% of life-cycle reductions compared with Conventional Vehicles, and 30-47% compared to HEVs [34]. Therefore, both Hybrid vehicle and Plug-in hybrid have a lower life cycle GHGs compared to Conventional Vehicles [39].

## 3.2 Cost Analysis

In our data analysis, we compare the cost efficiency of hybrid vehicles and gasoline vehicles.

Each fuel type of vehicles is categorized by the weight of vehicles.

- Light vehicles (<10,000 pounds)
- Medium (10,001~19,500 pounds)
-

In addition, for each of the vehicles, we have calculated

- Fuel cost per mile (LTD Fuel Dollars/Current Odometer),
- Fuel cost per gallon (LTD Fuel Dollars/LTD Fuel Quantity),
- Maintenance cost per year (LTD Maintenance Cost/ Year in Service),
- Maintenance cost per mile (LTD Maintenance Dollars/Odometer),
- Total cost per year ((LTD Fuel Dollars + LTD Maintenance Cost)/Year in Service),
- Total cost of time in service (LTD Fuel Dollars + LTD Maintenance Cost).

The passenger sedan is included in the "light" category in both hybrid and gasoline fuel analyses.

<u>Hybrid Fuel</u>
The figure below shows the percentage of types of vehicles (categorized by the weight) among hybrid vehicles according to PA data.

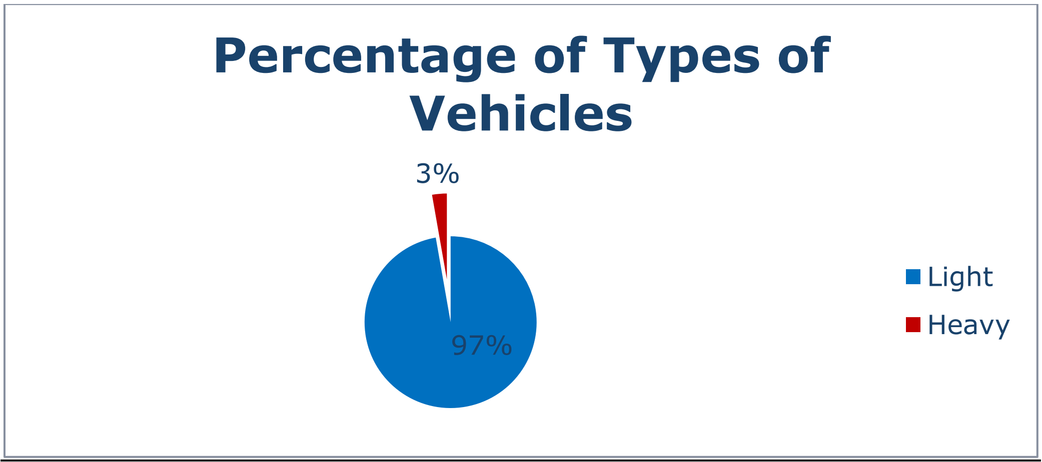


**Figure 3.1**

There are 265 vehicles that are using hybrid as their fuel source, out of the 265 vehicles, there are 256 vehicles are categorized as light vehicles (weight less than 6000 pounds), while the remaining 9 are categorized as heavy vehicles (weight greater than 19,500 pounds).

Table 3.2 below has summarized the result for vehicles using hybrid fuel.

**Table 3.2**

| Type of Vehicle | Fuel Cost per Mile | Fuel Cost per Gallon | Maint Cost per Year | Maint Cost per Mile | Total Cost per year | Total Cost of Time in Service | Count | Data Used Count |
|---|---|---|---|---|---|---|---|---|
| Light | $0.17 | $3.04 | $ 1,727 | $0.26 | $3,235 | $ 9,104 | 256 | 176 |
| Heavy | $0.34 | $3.37 | $ 3,513 | $5.43 | $3,962 | $12,196 | 9 | 5 |

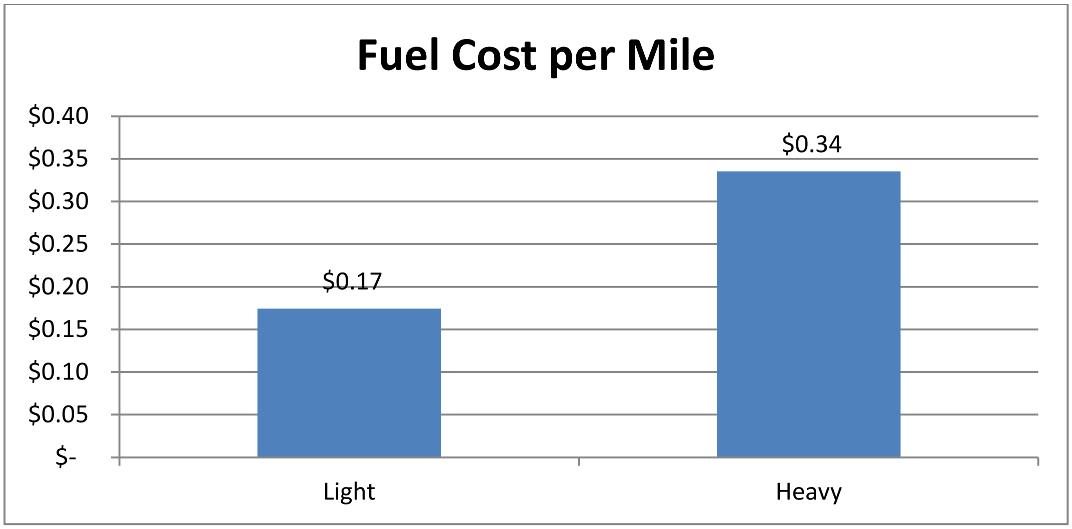


**Figure 3.2**

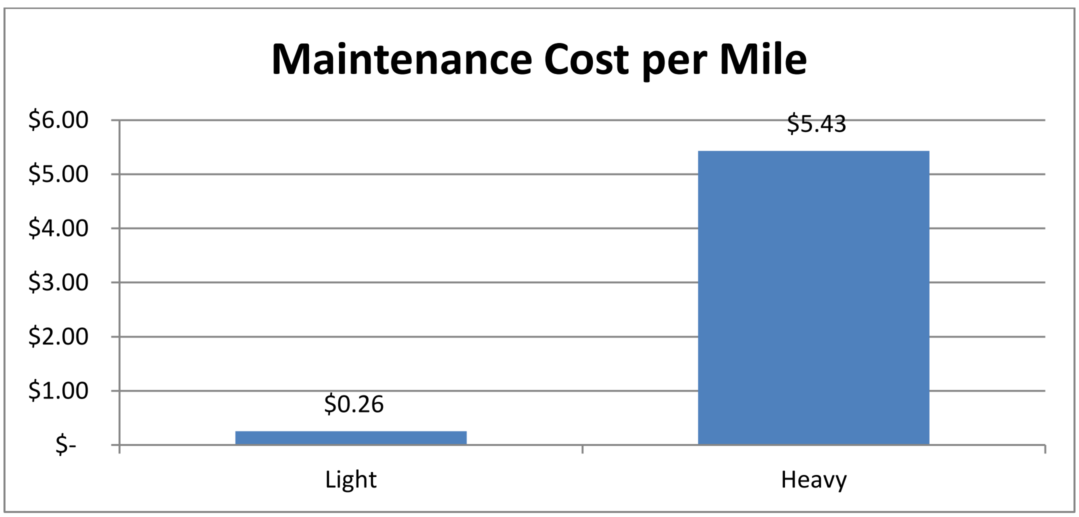


**Figure 3.3**

<u>Gasoline Fuel</u>

The figure below shows the percentage of types of vehicles (categorized by the weight) among gasoline vehicles according to PA data.

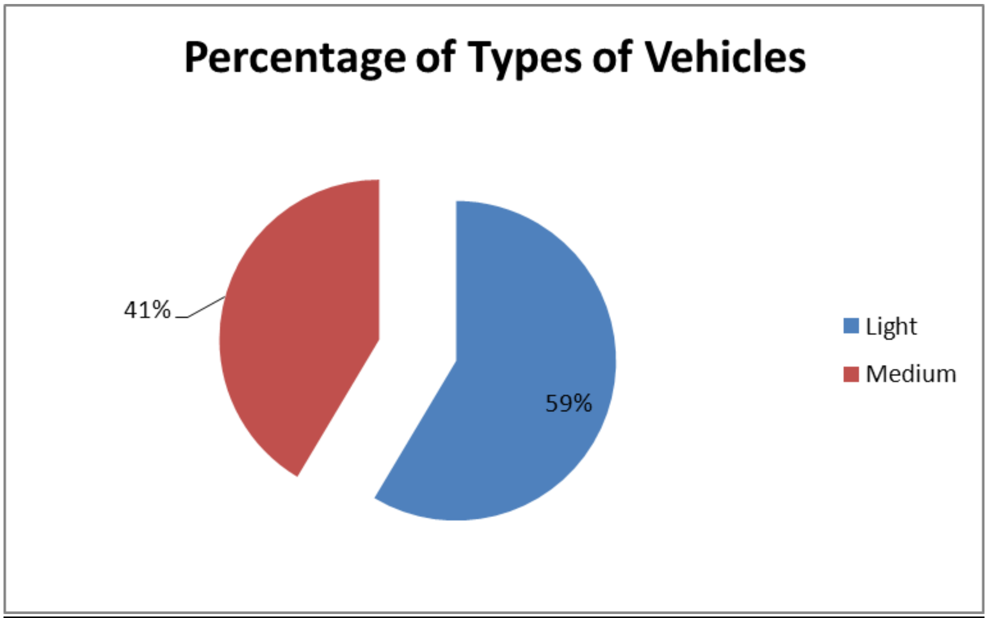


**Figure 3.4**

There are 350 vehicles that are using gasoline as their fuel source, out of the 350 vehicles, there are 217 vehicles categorized as light vehicles (weight less than 6000 pounds) and 127 vehicles categorized as medium vehicle (weight between 60001 pounds to 19,500 pounds),

Table 3.3 below has summarized the result for vehicles using gasoline fuel.

**Table 3.3**

| Vehicle Type | Fuel Cost /mi. | Fuel Cost /gal. | Maintenance Cost /YR. | Maintenance Cost /mi. | Total Cost / yr. | Total Cost of Time in Service | Total Count | Data Used Count |
|---|---|---|---|---|---|---|---|---|
| Light | $0.26 | $2.58 | $3,196.65 | $ 0.41 | $ 5,585.49 | $ 38,887.81 | 217 | 171 |
| Medium | $0.41 | $2.61 | $4,377.04 | $ 0.77 | $ 7,115.61 | $ 50,454.96 | 127 | 121 |

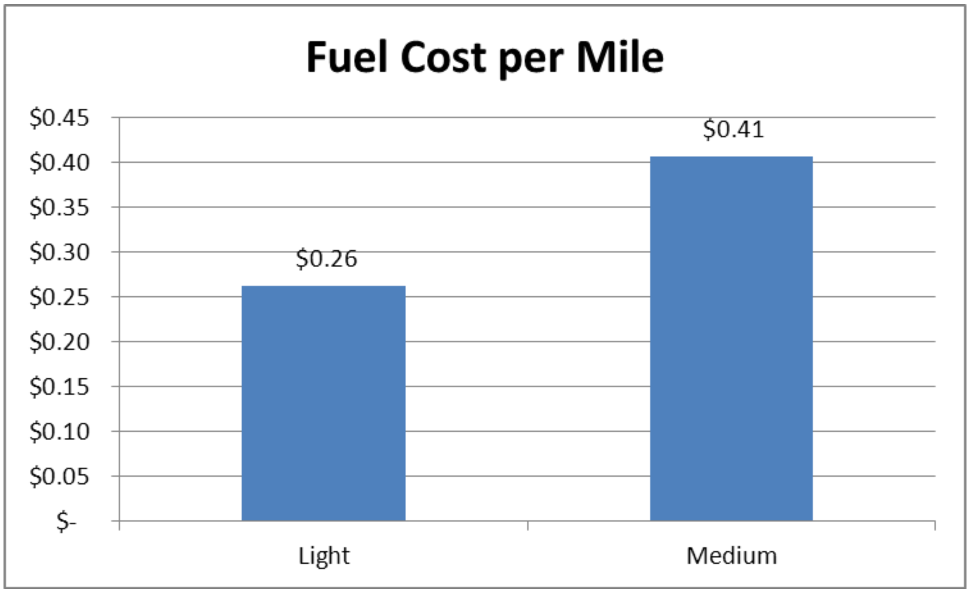


**Figure 3.5**

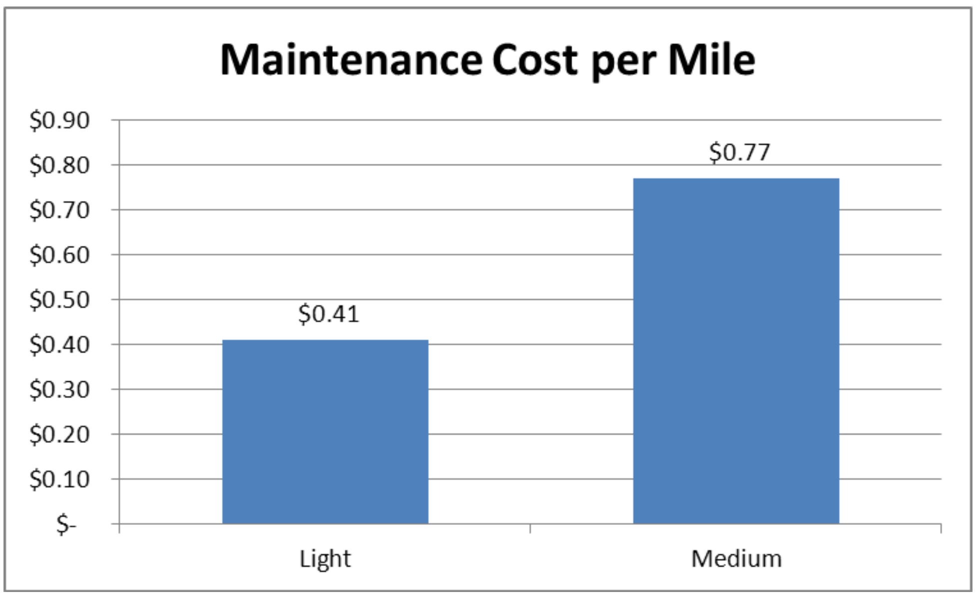


**Figure 3.6**

According to the above comparison figures, for light fleet category (weight less than 6000 pounds), we get the table below based on the PA data.

**Table 3.4**

| Vehicle Type | Fuel Cost /mi. | Fuel Cost /gal. | Maintenance Cost/ Yr. | Maintenance Cost/ Mile | Count | Data Used Count |
|---|---|---|---|---|---|---|
| hybrid | $ 0.17 | $3.04 | $1,727.48 | $0.26 | 256 | 176 |
| gasoline | $ 0.26 | $ 2.58 | $ 3,196.65 | $0.41 | 217 | 171 |

## 3.3 Analysis of Greenhouse Gas Reduction

$CO_2$ Emissions from a gallon of gasoline: 19.6 lb. $CO_2$/gal .This gasoline factor is from a recent regulation establishing GHG standards for model year 2012- 2016 vehicles (75 Federal Registry 25324, 2010).
According to the PA data, we calculate the fleet average $CO_2$ emission and fleet total $CO_2$ emission illustrated below.

**Table 3.5**

| Fleet Catogory | Fuel Type | Total Fleet Fuel QTY(gal) | Fleet Counts | Average Fuel QTY/Year (gal) | Fleet Average CO2 emission /Year (Lbs.) | Fleet total CO2 emission (Short Tons)/Year |
|---|---|---|---|---|---|---|
| Light vehicles (weight less than 10,000 pounds) | Gasoline Fuel | 165,427 | 217 | 762 | 14,942 | 7 |
| | Hybrid Fuel | 99,948 | 256 | 390 | 7,652 | 4 |
| Medium vehicles (weight between 10,001 pounds to 19,500 pounds ) | Gasoline Fuel | 127,208 | 127 | 1,002 | 19,632 | 10 |
| | Hybrid Fuel | 0 | 0 | 0 | 0 | 0 |

Since light vehicles cover 97% among the hybrid vehicles, we put more emphasis on the light fleet category. The figure below is the comparison of $CO_2$ emission (lb/yr) between gasoline fuel and hybrid fuel for light fleet category.

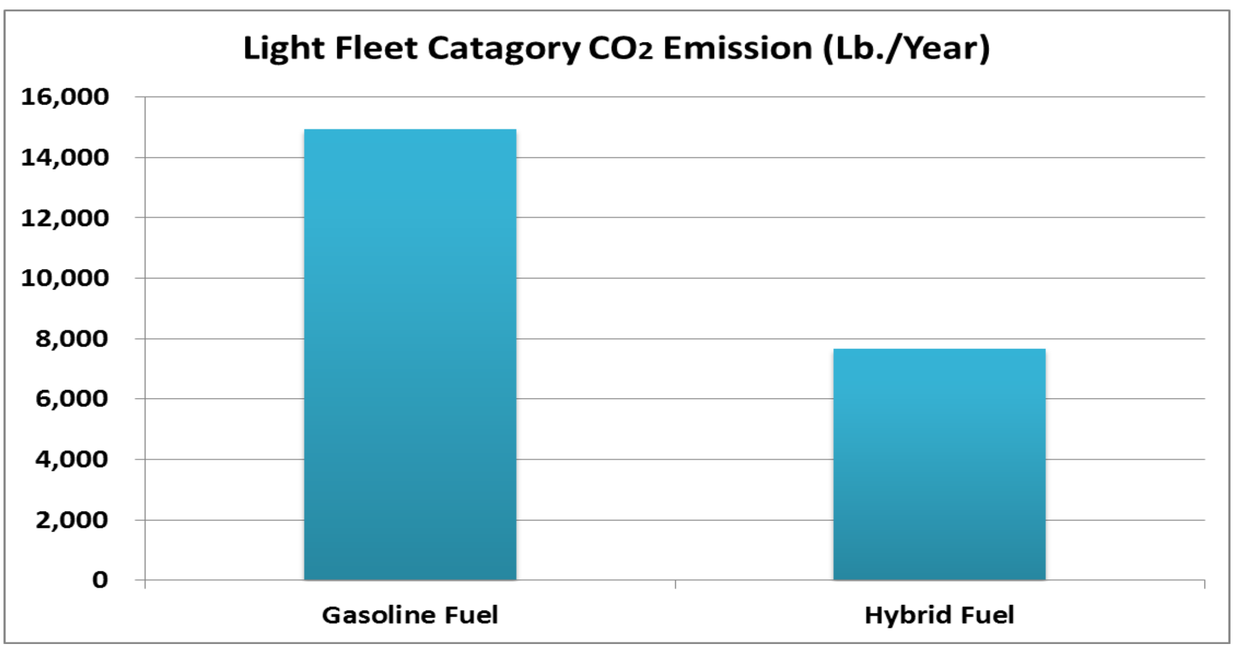


**Figure 3.7**

We also select the same brand vehicles Toyota Highlander 2010 with different fuel types to do further analysis. The result shows below we can hybrid fuel of Toyota Highlander 2010 has a higher CO2 emission per year but has a much lower CO2 emission per mile.

**Table 3.6**

| Vehicle Type | Fuel Type | Total Odometer | EPA MPG | Fuel Qty | CO2 emission /Year (Lbs.) | CO2(Lb.)/mile |
|---|---|---|---|---|---|---|
| Toyota Highlander 2010 | Gasoline Fuel | 31,090 | 19 | 1,636 | 32,072 | 1.032 |
| | Hybrid Fuel | 49,243 | 26 | 1,894 | 37,122 | 0.7538 |

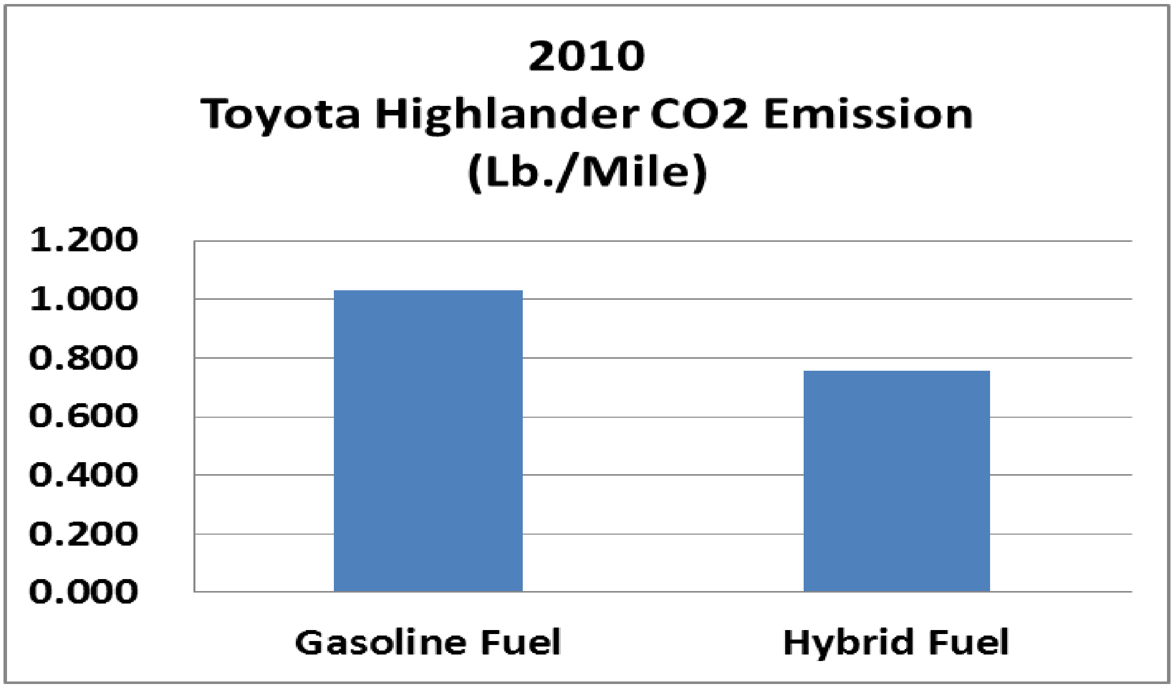


**Figure 3.8**

# 3.4 Scenario Case Study

In addition to the data analysis of the Port Authority hybrid vehicle fleets and the greenhouse gas emission, a scenario case study has been done, with the following assumptions:

- Annual mileage of the vehicle is 5000 miles
- Fuel cost is $4.0 per gallon
- Total cost per year equals to the sum of fuel cost plus maintenance cost and annualized capital cost
- Maintenance cost is based on Port Authority's data
- GHG emission is 19.6 lb per gallon
- Maintenance cost for gasoline Highlander is based on the average maintenance cost for gasoline vehicles

The vehicle models that we chose to compare are 2012 model. In addition, we have estimated the maintenance cost from Edmunds.com to compare with the Port Authority's raw data. The tables below have shown the result for the scenario case study, Prius serves as a reference for hybrid vehicle.

**Table 3.7**

| | Gasoline Highlander | Gasoline Highlander** | Hybrid Highlander | Hybrid Highlander** | Hybrid Prius | Hybrid Prius** |
|---|---|---|---|---|---|---|
| **Fuel Cost per year** | $ 1052.63 | $ 1052.63 | $ 714.29 | $ 714.29 | $ 400.00 | $ 400.00 |
| **Maintenance Cost per year** | $ 2321.89 | $ 840.20 | $ 550.00 | $ 777.20 | $ 1550.00 | $ 813.40 |
| **Capital Cost per year** | $ 3734.91 | $ 3734.91 | $ 5077.36 | $ 5077.36 | $ 4106.59 | $ 4106.59 |
| **Total Cost per year** | $ 7109.44 | $ 5627.74 | $ 6341.64 | $ 6568.84 | $ 6056.59 | $ 5319.99 |

**** Maintenance cost is estimated from Edmunds.com.**

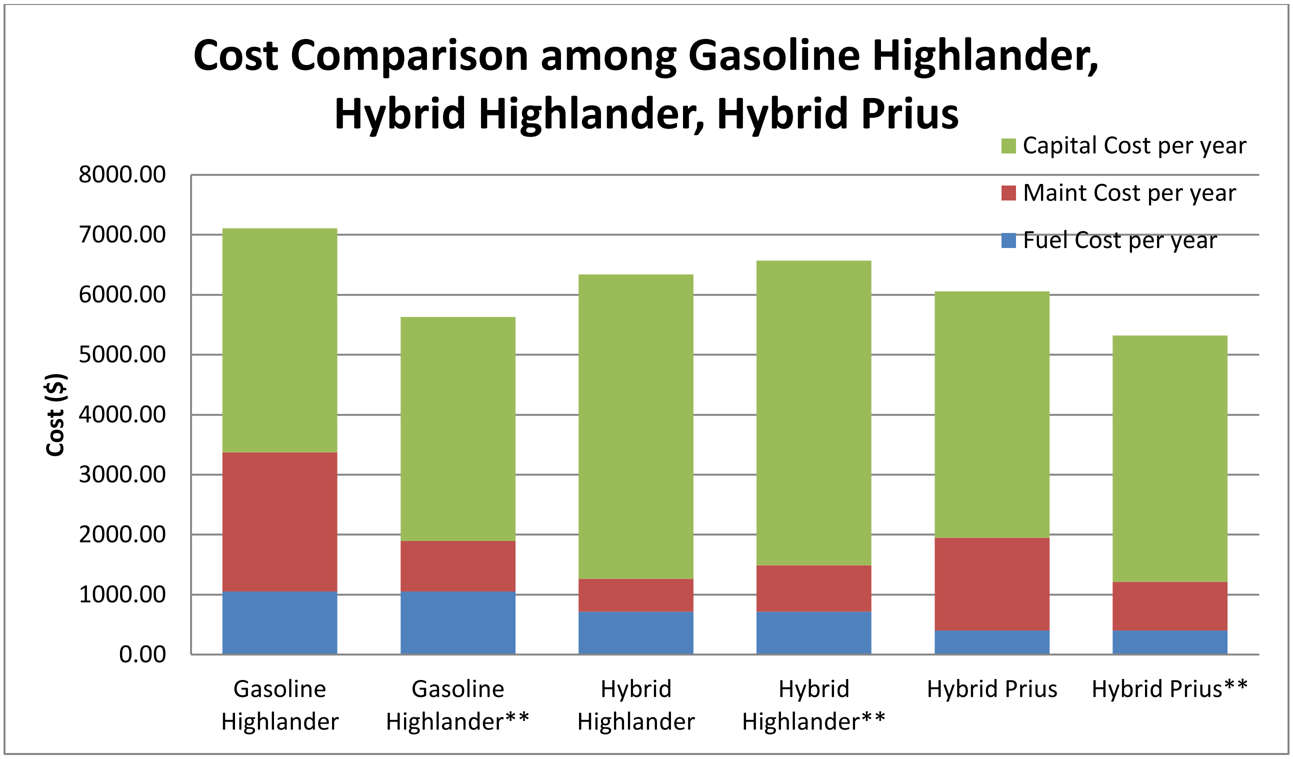


**Figure 3.9**

**Table 3.8.** CO2 Emission per Year

| | Gasoline Highlander | Hybrid Highlander | Hybrid Prius |
|---|---|---|---|
| Emission Rate (lb/year) | 5158 | 3500 | 1960 |

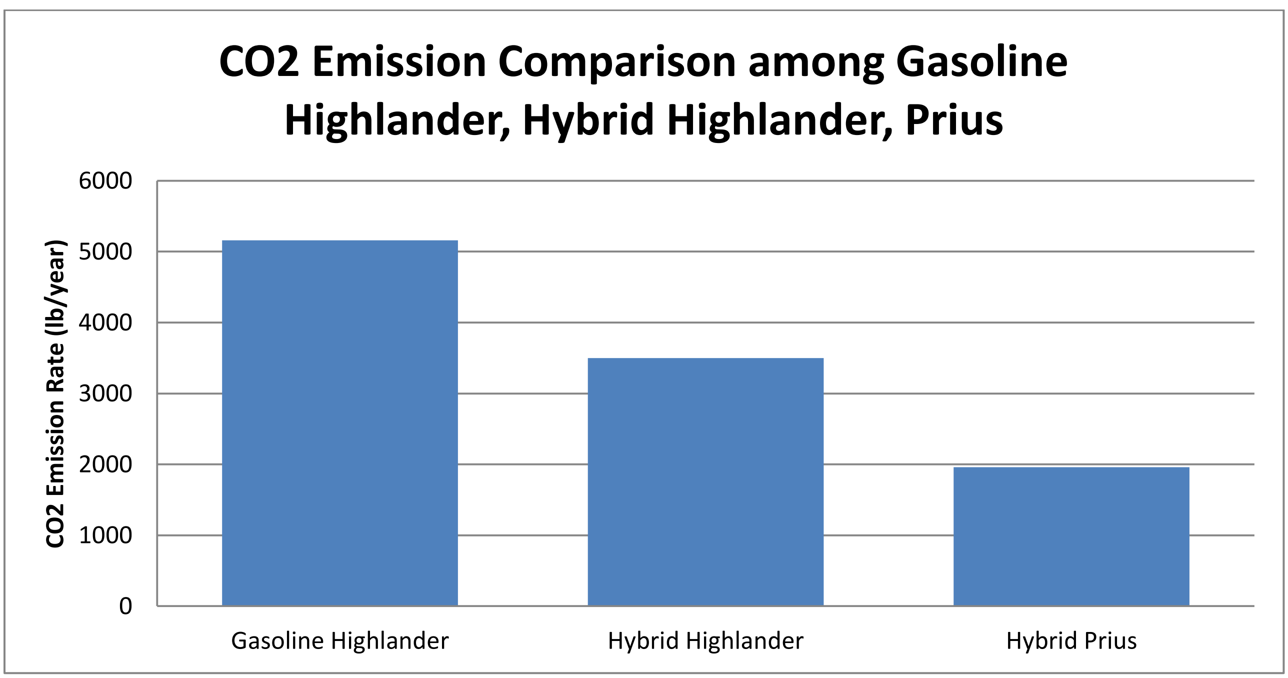


**Figure 3.10**

## 3.5 Conclusion and Recommendations

The results of the cost analysis and scenario case study indicate that hybrid vehicle is more cost effective than the gasoline vehicle. If replacing 10 gasoline Highlanders with 10 hybrid Highlanders, the Port Authority could save approximately $34,000 in fuel cost per year, and reduces carbon dioxide emission by 35,000 pounds per year (32% reduction). If a better fuel economy hybrid vehicle is introduced to the Port Authority, the saving in fuel cost per year can be potentially larger, while less carbon dioxide emission reduction per year. Furthermore, the usual life time of the hybrid vehicle is 100,000 miles, we recommend the Port Authority to replace their hybrid vehicle after 100,000 miles of usage, or resale the vehicle.

## 3.6 Future Work

Because there is variability in the maintenance cost for different types of hybrid vehicles, a further study can be done to have a better estimate for them. In addition, comparison study between more hybrid vehicle models can be done to estimate which model is more cost effective than others.

# 4. Hydrogen

## 4.1 Literature Review

Hydrogen is the simplest, lightest and most plentiful element in the universe. It is made up of one proton and one electron revolving around the proton. In its normal gaseous state, hydrogen is colorless, odorless, tasteless, non-toxic and burns invisibly. It should not be considered a "fuel," but instead, should be considered as an energy transport mechanism.

Currently, most hydrogen is made from natural gas through a process known as reforming. Reforming separates hydrogen from the methane in natural gas by adding heat. Hydrogen can also be produced from a variety of sources including water and biomass.

Hydrogen is not more dangerous than any other fuel. Hydrogen's hazards are usually managed easier than hydrocarbon fuels because hydrogen is lighter than air, and it burns upward and disperses. Hydrogen can however cause brittleness in some materials, including metals, and can generate electrostatic charges and sparks through flow or agitation [40].

**Fuel Cell**

Fuel cells generate electricity from a catalyst-facilitated chemical reaction between hydrogen and oxygen ions in a cell. Several cells combined make up a fuel cell stack. Fuel cell systems have relatively few moving parts, and their only by-products are water and heat when pure hydrogen is used as the fuel.

A fuel cell converts the chemical energy of a fuel directly into electricity without any intermediate thermal or mechanical processes. The electrical energy can be used to do useful work directly, while the heat is either wasted or used for other purposes.

A fuel cell "stack" requires fuel, oxidant and coolant in order to operate. The gases must be humidified, and the coolant temperature must be controlled. To achieve this, the fuel cell stack must be surrounded by a fuel system, fuel delivery system, air system, stack cooling system, and humidification system [41].

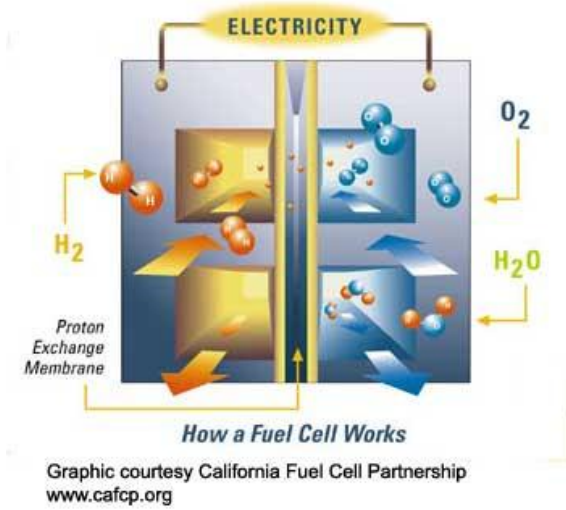


**Figure 4.1.** Diagram of a fuel cell. Reference: Detail of a hydrogen fuel cell, "Hydrogen fuel cell vehicles", Electronic reference, Dream Green, http://dream-green.org/wiki/index.php5?title=Hydrogen_fuel_cell_vehicles, 02/15/2013.

**Hydrogen in Internal Combustion Engines**

Getting an internal combustion engine to run on hydrogen is not difficult. The challenge is getting an internal combustion engine to run well on hydrogen.

The U.S. Department of Energy (DOE) tested four internal combustion vehicles using hydrogen: a Dodge Ram van and a Ford F-150 with engines designed for compressed natural gas, a Ford F-150 with a gasoline engine that was modified to run on a hydrogen/natural gas blend, and a Mercedes van with a gasoline engine modified to run on pure hydrogen.

The tests showed the hydrogen lowered emissions and increased fuel economy (as compared to the engine on natural gas or gasoline alone). Ford Motor Company has developed an internal combustion engine optimized to burn hydrogen instead of gasoline.

The engine can reach an overall efficiency of about 38 percent, about 25 percent more fuel-efficient than a typical gasoline engine with nearly zero emissions. The engine is based on Ford's 2.3 liter engine used in the Ford Ranger. Supercharging allows the engine to deliver the same power as its gasoline counterpart.

The Sun Line Transit hydrogen hybrid bus in California is in revenue service. This bus has performed well and receives better fuel economy than diesel buses [42].

**The Future of Hydrogen Vehicles**

Possible hydrogen vehicles in the future may be:

- Vehicles with internal combustion engines using pure hydrogen, or using a mix of hydrogen and natural gas.

- Vehicles with fuel cells that use hydrogen that is produced either on-board by converting liquid fuels (gasoline, ethanol, or methanol) to hydrogen, or by using direct hydrogen that has been generated off-board and stored on the vehicle in compressed or liquid form [43].

**Fundamental Technological and Economic Challenges**

Hydrogen systems must be not only cost-competitive but also safe and appealing to the customer. There are some technological and economic challenges associated with hydrogen-fuel transportation that must be considered.

The first one is developing and introducing cost-effective, durable, safe, and environmentally desirable fuel cell systems and hydrogen storage systems. This is not very easy since current fuel cell lifetimes are much too short and fuel cell costs are at least an order of magnitude too high. Another issue is developing the infrastructure to provide hydrogen for the light duty vehicle users. The cost of distributing H2 to dispersed locations is currently very high.

A third concern is reducing the costs of hydrogen production from renewable energy sources. It is known that making hydrogen from renewable energy is not cost-effective. Further breakthroughs are needed.

Finally, capturing and storing the carbon dioxide by-products of hydrogen production from coal is not easy. Coal processing generates large amounts of CO2. In order to reduce CO2 emissions from coal processing in a carbon-constrained future, massive amount of CO2 would have to be captured and safely and reliably sequestered for hundreds of years [43].

**Hydrogen Technologies for Reduction of U.S. Oil Use and $CO_2$ Emissions**

It is known that oil usage in U.S is going to be one of the most challenging issues that need to be considered in the future since oil usage has increased significantly for the last centuries. Estimating future transportation fuel use is difficult because of the complexities and uncertainties inherent in the analysis, but it is clear that hydrogen technologies are going to be very beneficial in the reduction of U.S. oil use and CO2 emission.

Fuel cell vehicles and hydrogen have the potential to become competitive with conventional vehicles and fuels, but it is far from certain that may occur. For this reason, several scenarios and analysis were developed. The main object of the scenario analysis is to estimate the maximum practicable penetration rate of fuel cell vehicles, and then to estimate the resulting reductions of petroleum use and emissions of carbon dioxide (CO2) in 2020 and beyond. The information in Table 4.1 can be used to make predictions and comparisons for the development of future guidelines [44].

**Table 4.1:** Hydrogen Scenario Analysis for Future Estimate

| | 2005 | 2020 | 2035 | 2050 |
|---|---|---|---|---|
| Total number of LDVs (millions) | 220 | 280 | 331 | 369 |
| Share of LDV fleet | | | | |
| Gasoline ICEVs | 99.8% | 96.6% | 93.2% | 91.4% |
| Gasoline hybrids | 0.3% | 3.4% | 6.8% | 8.6% |
| New LDVs sold per year (millions) | 16.2 | 18.2 | 20.8 | 22.4 |
| Share of New LDVs per year | | | | |
| Gasoline ICEVs | 98.6% | 94.7% | 91.8% | 91.1% |
| Gasoline hybrids | 1.4% | 5.2% | 8.2% | 8.9% |
| Average on-road fuel economy, new gasoline LDVs (mpg) | | | | |
| Gasoline ICEVs | 20.2 | 29.3 | 30.6 | 31.7 |
| Gasoline hybrids | 32.1 | 41.0 | 42.9 | 44.5 |
| Gasoline price ($/gallon) | 2.32 | 3.19 | 3.54 | 3.96 |
| Vehicle-miles traveled (billion per year) | 2,556 | 3,251 | 4,243 | 5,364 |
| Gasoline consumed (billion gallons per year) (includes blends of ethanol up to 10%) | 124 | 132 | 140 | 157 |
| Ethanol (billion gallons per year) consumed as: | | | | |
| Blend in gasoline to 10% | 3.4 | 12.7 | 15.6 | 21 |
| E 85 | 0.01 | 0.06 | 0.20 | |
| Greenhouse gas emissions (million tonnes $CO_2$ equivalent per year) | 1,345 | 1,442 | 1,527 | 1,710 |

Reference: Major Cost Elements for Hydrogen Fuel Vehicles, “Transitions to Alternative Transportation Technologies--A Focus on Hydrogen”, Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council, http://www.nap.edu/catalog/12222.html, 02/15/2013.

**A Budget Road Map**

Research, development, and demonstration (RD&D) funding from both the federal government and the private sector would be required for a transition to hydrogen fuel cell vehicles (HCFVs). Based on certain scenarios and predictions, a budget road map can be developed by government for hydrogen fuel cell vehicles. The major cost elements of a budget roadmap are summarized in Table 4.2 below. They include the capital requirements plus the annual operating and maintenance (O&M) costs for the two principal components of the system, namely (1) fuel cell vehicles and (2) hydrogen fuel supply for these vehicles [45].

**Table 4.2:** Major Cost Elements for Hydrogen Fuel Vehicles.

| Cost Element | Capital Costs | O&M Costs |
|---|---|---|
| Vehicle production costs | Production facilities<br>Testing facilities<br>Base vehicle costs<br>Fuel cell power train costs | Raw materials<br>Labor costs (skilled, manual, supervisory)<br>Facility operating costs (utilities, insurance, etc.)<br>Facility maintenance costs<br>Retailing costs |
| Hydrogen supply costs | Fueling station land and building costs<br>$H_2$ supply technology (SMRs; coal gasification)<br>Delivery system hardware (local or remote) | Feedstocks (natural gas, electricity, etc.)<br>Labor costs<br>Delivery costs<br>Other operating costs<br>Supply-related facility maintenance costs |

Reference: Hydrogen Scenario Analysis for Future Estimate, “Transitions to Alternative Transportation Technologies--A Focus on Hydrogen”, Committee on Assessment of Resource

Needs for Fuel Cell and Hydrogen Technologies, National Research Council, http://www.nap.edu/catalog/12222.html, 02/15/2013.

**Comparison of Fuel Types**

A comparison of operating costs for buses used in a transit system was investigated considering four alternative fuels: biodiesel, compressed natural gas, methanol, and diesel. Rust's "nested fixed point" maximum likelihood estimation algorithm was used in this comparison. The algorithm considers both tangible costs such as fuel, maintenance, and infrastructure, and intangible costs associated with different levels of bus engine operating reliability under alternative fuels. Using data on actual monthly mileage and the time the engine takes to rebuild under the four alternative fuels. The Rust algorithm is employed assuming an optimal maintenance strategy is adopted for each alternative fuel type. Results indicate that, although biodiesel and biodiesel blends have higher total costs than diesel fuel, they have the potential of competing with CNG and methanol as fuels for urban transit buses [46].

## 4.2 Cost Analysis

In the section, we will discuss the methodology of cost analysis for gasoline and hydrogen vehicles. The section begin with introduce the vehicles' model, year, and manufacture. Then, it follows by the brief description of the data given by Port Authority. The net present value will be used in calculating the total cost. The specific assumptions are included in the beginning of the model.

### Description of the Vehicles

As the beginning of the semester, our team received the data of hydrogen vehicles from the Port Authority's dataset. There are twelve specific hydrogen vehicles which will be analyzed. The manufacture of hydrogen vehicles is Toyota, and the model of the vehicles is Highlander. As shown in the data, the year of vehicles is 2009.

### Variables of Models

The data from Port Authority has different variables. The variables that will be used to calculate the total cost are: Current Odometer, Average Miles per Year, Years in Service. Maintenance Cost per Year, Miles/Kg of Hydrogen. Current Odometer is the reading of miles on odometer which can be defined as the total miles driven by a vehicle. An average mile per year is the total miles driven in a year which is calculate by Current Odometer divided by years in service. Lastly, the years in service is the vehicle's current service time.

### Total Cost Analysis

Although capital cost data for the hydrogen vehicles are not available, they are thought to cost approximately $500,000 because they are made in such small numbers.  Similarly, the Port Authority is not allowed to maintain these vehicles, but it is reasonable to think that they are quite costly to maintain because they are few in number."

## 4.3 Analysis of Greenhouse Gas Reduction

In our carbon emission analysis part, we calculated the carbon emission for PA (Port Authority of NY & NJ)'s hydrogen vehicles and compared that with the carbon emission for PA's some gasoline vehicles. As we mentioned earlier, in our carbon emission analysis, natural gas is chosen as the source of hydrogen production for hydrogen vehicles, considering of the economy and efficiency for hydrogen production.

### Calculation of Carbon Dioxide Emission

In our carbon emission calculation, we calculated the $CO_2$ emission per mile for PA's hydrogen vehicles first. According to PA's data set, there is only one model of hydrogen vehicles in PA's fleet-2009 Toyota Hydrogen Highlander. From cars.com, we got some relevant data for hydrogen vehicles that 10.5 lbs $CO_2$ emission per lb of hydrogen and that 30.84 Miles per lb of hydrogen.
Based on these data, we can calculate the carbon dioxide emission per mile for 2009 Toyota Hydrogen Highlander as below,

$$10.5/30.84 = 0.340 \text{ lb/mile}$$

Then we calculated the $CO_2$ emission per mile for PA's Toyota gasoline vehicles-2003 Toyota Camry, 2009 Toyota RAV4 and 2010 Toyota Highlander.
From EPA, we learned that the $CO_2$ emission from a gallon of gasoline is 19.60 lbs. and that the MPG (Miles per gallon) for PA's Toyota gasoline vehicles:

**Table 4.3**

| Model | MPG (miles per gallon) |
|---|---|
| 2003 Toyota Camry (Gasoline) | 28 |
| 2009 Toyota RAV4 (Gasoline) | 25 |
| 2010 Toyota Highlander (Gasoline) | 19 |

According to the data above, we can calculate the $CO_2$ emission per mile for 2010 Toyota Highlander (Gasoline) as below,

$$19.60/19 = 1.030 \text{ lb/mile}$$

Similarly, the $CO_2$ emission per mile for 2003 Toyota Camry (Gasoline) and 2010 Toyota Highlander (Gasoline) can also be calculated. The calculation results are shown as follows:

**Table 4.4**

| Model | $CO_2$ Emission per mile (lbs./mile) |
|---|---|
| 2003 Toyota Camry (Gasoline) | 0.700 |
| 2009 Toyota RAV4 (Gasoline) | 0.784 |
| 2010 Toyota Highlander (Gasoline) | 1.030 |

### Carbon Dioxide Emission Comparison

To further analyze the carbon emissions for PA's hydrogen vehicles, we made the following carbon emission comparisons:

2009 Toyota Highlander (Hydrogen) vs. 2003 Toyota Camry (Gasoline),

2009 Toyota Highlander (Hydrogen) vs. 2009 Toyota RAV4 (Gasoline), and
2009 Toyota Highlander (Hydrogen) vs. 2010 Toyota Highlander (Gasoline)

These comparisons are based on the assumptions that in one year, each Toyota Highlander hydrogen vehicle can run as much as each Toyota gasoline vehicles in PA's fleet (5,000 miles/year).

$CO_2$ emission per mile for 2009 Toyota Highlander (Hydrogen): 0.340×5,000 = 1700 lbs./year
$CO_2$ emission per mile for 2010 Toyota Highlander (Gasoline): 1.030×5,000 = 5150 lbs./year
After the calculation above, we can draw this bar chart as below, which is showing the comparison of carbon emissions for PA's 2009 Toyota Highlander (Hydrogen) and PA's 2010 Toyota Gasoline Highlander.

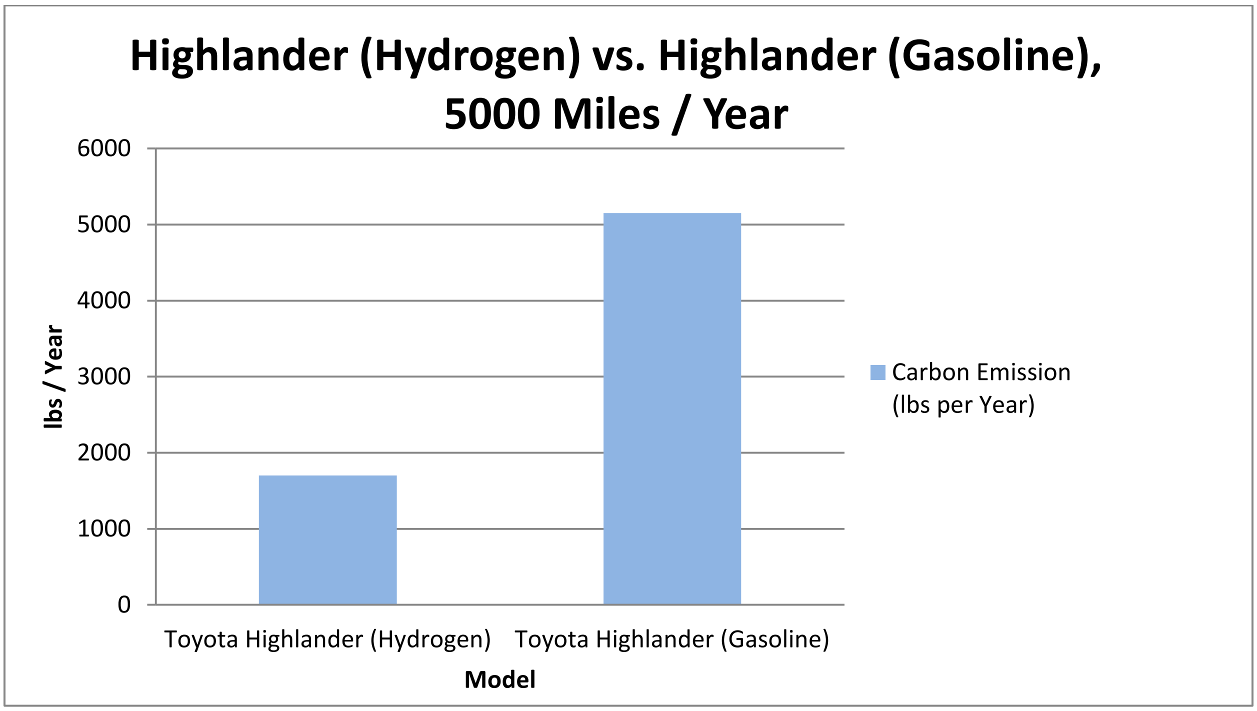


**Figure 4.2**

In the same way, we can get the comparison of carbon emissions for PA's 2009 Toyota Highlander (Hydrogen) and PA's 2003 Toyota Camry (Gasoline):

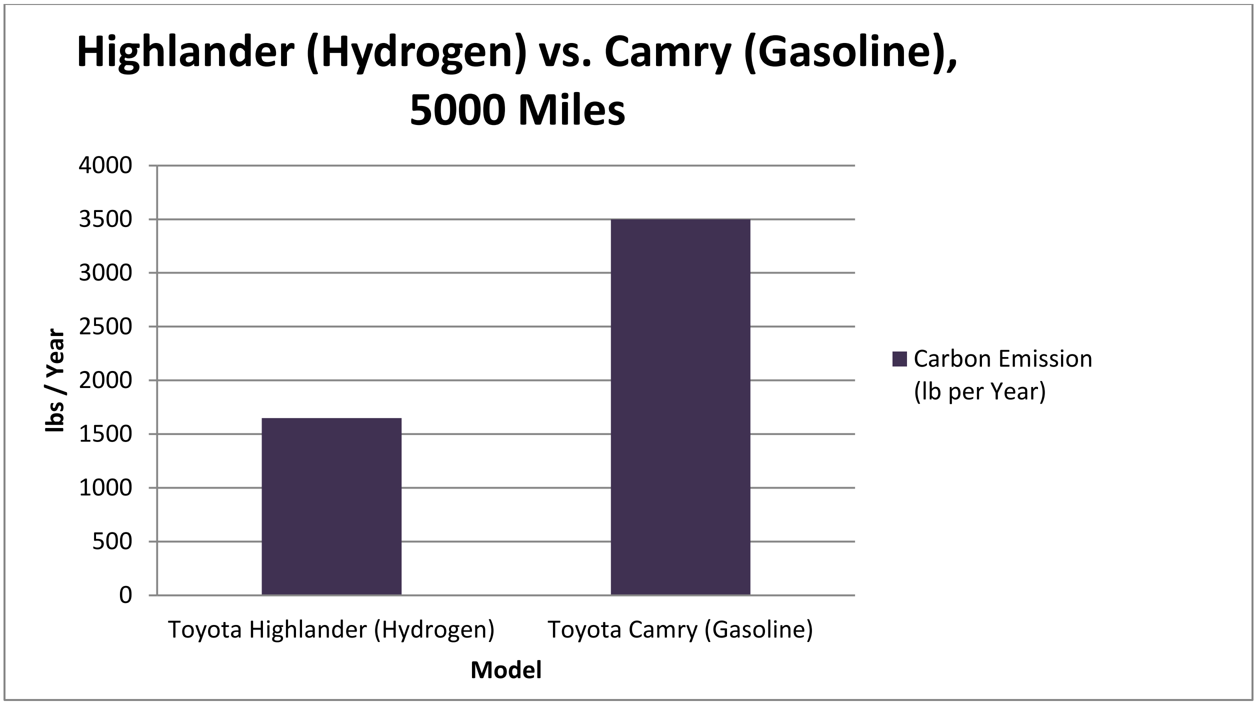


**Figure 4.3**

And the comparison of carbon emissions for PA's 2009 Toyota Highlander (Hydrogen) and PA's 2009 Toyota RAV4 (Gasoline):

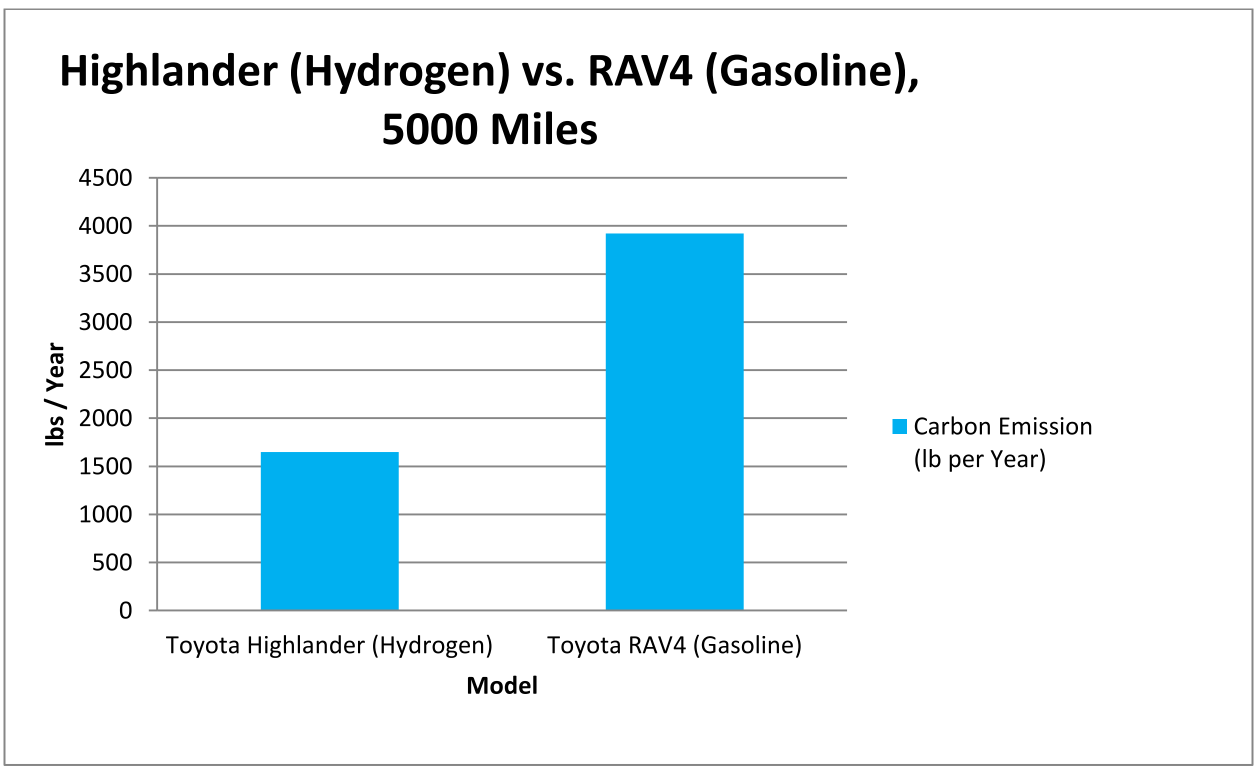


**Figure 4.4**

From the bar charts above, it is obvious that carbon emission is much lower when using hydrogen instead of gasoline as vehicle fuel. The reduction rate could be as high as 65%.

## 4.4 Fuel Cost Analysis

Assumptions for Hydrogen Vehicles and Gasoline Vehicles for Comparison:

- Hydrogen vehicles and Gasoline Vehicles will drive 5000 mi/year
- Fuel cost will be adjusted according to 5000 miles per year.
- Toyota Highlander is the only Hydrogen Vehicle that Port Authority has. For comparison 3 gasoline vehicles that are Toyota Camry, Toyota RAW4 and Toyota Highlander used.
- Fuel cost per gallon is assumed to be $4 per gallon for gasoline vehicles
- According to Port Authority refined data set, fuel cost per mile gives significantly low values for Toyota Camry, Toyota RAV4 and Toyota Highlander gasoline vehicles. For this reason we used fuel.economy.gov to calculate fuel cost per mile of each gasoline vehicle that we used for comparison;
    - TOYOTA CAMRY drives averagely 28 mi/gal
    - TOYOTA RAV4 drives averagely 25 mi/gal
    - TOYOTA HIGHLANDER drives averagely 19 mi/gal

Fuel Cost Analysis for Hydrogen Vehicles

Hydrogen team observed that there is no fuel cost per mile according Port Authority refined data set. However; our team and our advisor decided that fuel cost/mile should be taken into consideration for overall cost of the hydrogen vehicles. For this reason, we found that hydrogen vehicles can drive 68 miles per kg of hydrogen. Also, cost (in $ amount) of producing 1 kg of hydrogen depends on production process. Table 4.5 shows cost of producing 1 kg of hydrogen via different processes.

**Table 4.5. Cost for producing 1 kg of hydrogen via different resources**

| Hydrogen Source | Dollar Amount per kg of Hydrogen |
|---|---|
| Hydrogen from natural gas produced via steam reforming at fueling station | $4 - $5 |
| Hydrogen from natural gas produced via steam reforming off-site and delivered by truck | $6 – $8 |
| Hydrogen from wind via electrolysis | $8 – $10 |
| Hydrogen from nuclear via electrolysis | $7.5– $9.5 |
| Hydrogen from nuclear via thermochemical cycles | $6.5 – $8.5 |

| | |
|---|---|
| Hydrogen from solar via electrolysis | \$10 – \$12 |
| Hydrogen from solar via thermochemical cycles | \$7.5 – \$9.5 |

**REFERENCE:** http://www.h2carblog.com/?p=461, Cost of hydrogen from different sources *by* GREG BLENCOE *on NOVEMBER 9, 2009*

As it can be seen from Table 4.3, hydrogen can be produced by 4 different resources that are natural gas, wind, nuclear and solar. Additionally, hydrogen production from natural gas via steam reforming at fueling station is the cheapest way to produce hydrogen and the steam reforming process will be as follows;

$$CH4 + H20 \rightarrow CO + 3H2$$
$$CO + H2O \rightarrow CO2 + H2$$

For this reason, we used natural gas for fuel cost per mile analysis. Fuel cost per mile for hydrogen vehicles for different sources are shown in Figure 4.5:

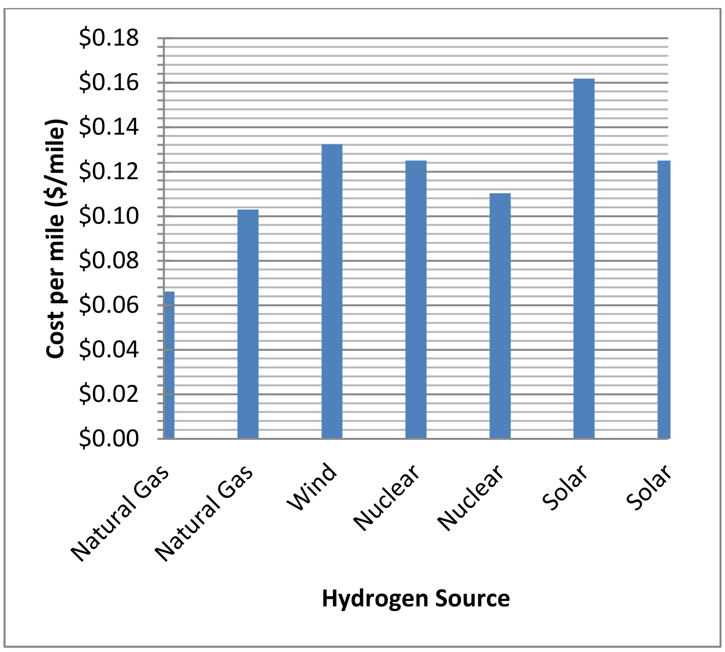


**Figure 4.5**: Fuel cost per mile for hydrogen vehicles according to different sources

- Natural gas produced via steam reforming at fueling station = 0.07\$/mile
- Natural gas produced via steam reforming off-site and delivered by truck = 0.103\$/mile
- Wind via electrolysis = 0.132 \$/mile
- Nuclear via electrolysis = 0.125\$/mile
- Nuclear via thermochemical cycles = 0.110 \$/mile
- Solar via electrolysis = 0.162 \$/mile
- Solar via thermochemical cycles = 0.125 \$/mile

To explain how we calculated fuel cost per mile, following example below will be beneficial to understand it;

- Hydrogen vehicles can drive 68 miles per kg of hydrogen
- Producing hydrogen from natural gas produced via steam reforming at fueling station is averagely 4.5$ per kg of hydrogen.
- **Fuel cost per mile for this case** = (4.5$/kg of hydrogen) / (68 miles/ kg of hydrogen)
- **Fuel cost per mile for this case** = 0.066 $/ mile (we rounded that to 0.07 for comparison)
- **Fuel Cost for 5000 miles/year =** 5000 mile x 0.066 $/ mile
- **Fuel Cost for 5000 miles/year = 330.88 $ /year**

## Cost per Ton of CO2 Reduced by Using Nuclear instead of Natural Gas

As we stated in our hydrogen fuel cost analysis, we used natural gas produced via steam reforming at fueling station that has fuel cost of 0.07$ per kg of hydrogen. To explain in a better way why we didn't continue our analysis with other hydrogen production processes, we implement cost per ton CO2 analysis. For this analysis, we selected the second cheapest hydrogen production process that is nuclear via thermochemical cycles and it has fuel cost per mile of 0.11 $/mile. Based on that calculations are going to be as follows;

$$\frac{\text{(Fuel Cost for Hydrogen)}}{\text{(Ton CO2 Emission)}} = \frac{\Delta \text{Cost}}{\Delta CO_2} = \frac{(0.11\ \$/\text{mile} - 0.07\ \$/\text{mile})}{(0\ \text{lb CO2/mile} - 0.34\ \text{lb CO2/mile})}$$

$$\frac{\text{(Fuel Cost for Hydrogen)}}{\text{(Ton CO2 Emission)}} = \mathbf{0.118\ \$/\ lb\ CO2 = 236\ \$/\ ton\ CO2)}$$

According Hansen James who gave lecture in 2010 at Cornell University, the threshold of max 100 $/ton CO2 can be assumed to be cost-effective for CO2 reduction. In our case we have 236 $ / ton CO2. This proves that even we continue our fuel cost analysis based on the second cheapest production process that is nuclear via thermochemical cycles for hydrogen, it won't be cost effective.

## Fuel Cost Analysis for Gasoline Vehicles

According to fuel economy.gov, fuel cost per gal for TOYOTA CAMRY is averagely 28 mi/gal, TOYOTA RAV4 is averagely 25 mi/gal and TOYOTA HIGHLANDER is averagely 19 mi/gal. Since we assumed fuel cost per gal is 4$/gal, calculations for fuel cost/mile is going to be as follows;

TOYOTA CAMRY = [(5000 mile/ year) x (4$/gal)] / (28 mile/gal) = **714.3 $/year**

TOYOTA RAV4 = [(5000 mile/ year) x (4$/gal)] / (25 mile/gal) = **800 $/year**

TOYOTA HIGHLANDER = [(5000 mile/ year) x (4$/gal)] / (19 mile/gal) = **1052.6 $/year**

As it can be seen from calculation according to fueleconomy.gov, Toyota Highlander is the least cost effective vehicle according to fuel cost per year.

## Comparison between Hydrogen Vehicles and Gasoline Vehicles:

As it can be seen from Table 4.6, fuel cost can be reduced significantly by using hydrogen vehicles instead of gasoline vehicles.

**Table 4.6:** Fuel Cost Comparison between gasoline vehicles and hydrogen vehicles

| **Model** | **Average Mile Driven per Year** | **Gasoline Fuel Cost per Year** | **HYDROGEN TOYOTA HIGHLANDER Fuel Cost/year** |
|---|---|---|---|
| **TOYOTA CAMRY** | **5000 mile** | **$714.3** | **$330.9** |
| **TOYOTA RAV4** | **5000 mile** | **$800.0** | **$330.9** |
| **TOYOTA HIGHLANDER (Gasoline)** | **5000 mile** | **$1,052.6** | **$330.9** |

| **Model** | **Average Mile Driven per Year** | **Gasoline Fuel Cost per Year** | **TOYOTA HIGHLANDER Fuel Cost/year** | **$ Saved by Using TOYOTA HIGHLANDER** | **PRESENT VALUE (10 Years Fuel Cost Saving)** |
|---|---|---|---|---|---|
| TOYOTA CAMRY | 5000 miles | **$714.3** | **$330.88** | **$383.5** | **$2,961.29** |
| TOYOTA RAV4 | 5000 miles | **$800** | **$330.88** | **$469.1** | **$3,622.27** |
| TOYOTA HIGHLANDER | 5000 miles | **$1,052.6** | **$330.88** | **$721.8** | **$5,573.55** |

## 4.5 Recommendations and Conclusions

As it can be seen from the above calculations, we made our comparisons based on 5000 mileage usage per year for both hydrogen and gasoline vehicles. Since fuel cost is cheaper for hydrogen vehicles than gasoline vehicles, we suggest that the Port Authority increase their driving ranges for hydrogen vehicles. We have observed that there is no range limit for hydrogen vehicles and we see no reason hydrogen vehicles cannot drive as much as gasoline vehicles. For this reason, as driving range for hydrogen vehicles increase, hydrogen vehicles will be more cost effective than gasoline vehicles due to fuel saving.

As it can be seen from Figure 4.9 below, gasoline prices continued to increase from 1979 to 2013. As gasoline prices continue to increase, hydrogen vehicles are going to be more cost effective due to fuel savings.

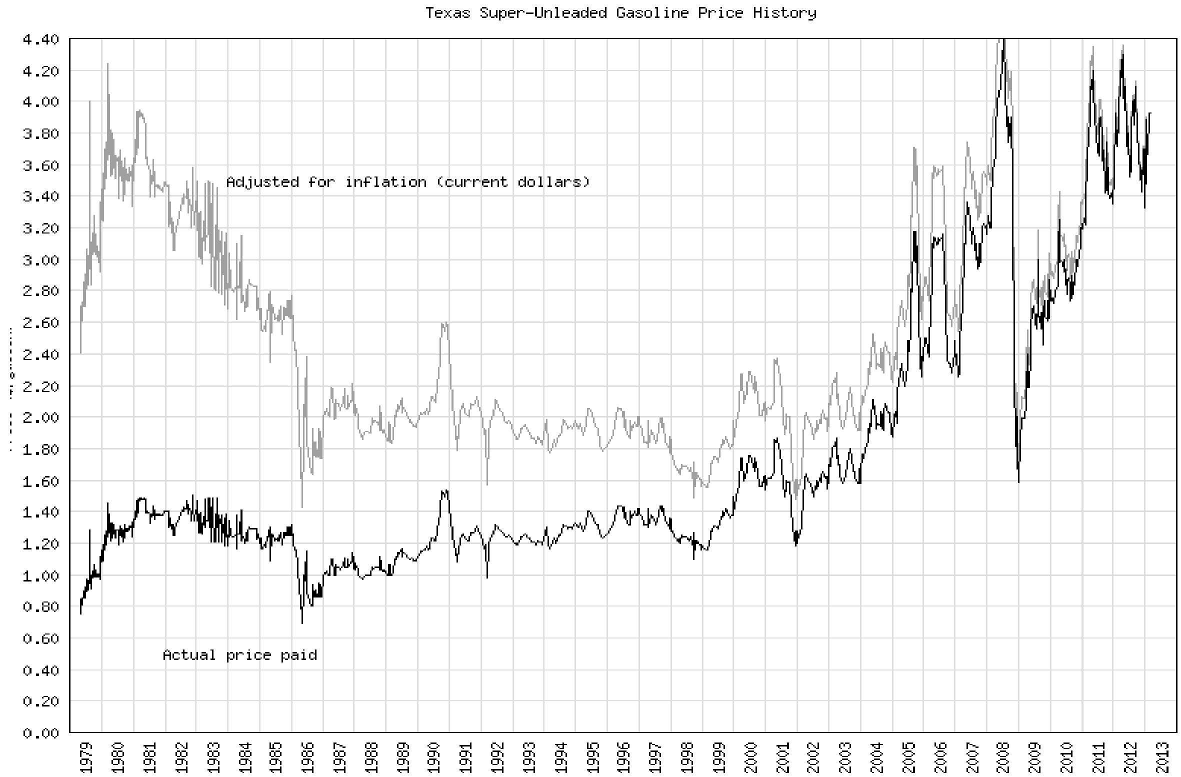


**Figure 4.9:** Gasoline Prices over Time

**Reference:** http://www.randomuseless.info/gasprice/gasprice.html, *Gasoline Price History, published April 3, 2013.*

As can be observed from our net present value analysis, we compared Toyota Highlander hydrogen vehicles with 3 different types of gasoline vehicles. Based on our calculations without considering maintenance cost, we primarily suggest Port Authority to replace their gasoline Toyota Highlander models with Toyota Highlander hydrogen vehicles for the basis of fuel saving analysis for the 10 year period if the capital cost can be sufficiently reduced to make the total cost competitive.

As we stated above, hydrogen can be produced from wind, solar or nuclear sources. For these production processes, there are zero $CO_2$ emissions. However, fuel cost per mile is going to increase significantly since producing hydrogen from renewables is more expensive than non-renewables. On the other hand, hydrogen can be produced by non-renewables- that is, natural gas production. $CO_2$ emissions will not be zero for natural gas but as it can be seen from our calculations, $CO_2$ emissions will be reduced significantly.

# 5. Snow Removal Equipment (SRE)

## 5.1 Literature Review

The Port Authority maintains a fleet of snow equipment vehicles ranging from Ford pickups fitted with snow plows and liftgates to the more specialized de-icers, friction testers, mowers, and skid-steer loaders.

**Wausau Snowblower**
A standard snowplow designed for airport runways manufactured by the Wausau-Everest ranges in weight from 3,530 to 5,300 pounds. The BlueMax BMP model has many specialized features, such as an adjustable moldboard pitch to manage varying snow depth and density, isomer cushions to protect the vehicle from damage when encountering obstacles, and heavy-duty reversing cylinders for adjustable angling [47]. This complexity likely makes maintenance on these vehicles more difficult.

**Øveraasen RS 400**
Øveraasen emphasizes low operation and maintenance costs for many of its runway sweeper models, which it attributes to its "intelligent modular structure". The RS 400 model has hydraulic and diesel fuel tanks with respective volumes of 100 and 550 liters and is rated for 315 kW of power. The compact version models can reach speeds of up to 65 km/hr [48].

**Batts De-Icer**
The Batts De-Icer Pro 5000 unit can be powered by a heavy-duty truck (suggested minimum 330 hp diesel engines and minimum 86,000 lb frame). The truck engine powers the hydraulic system of the de-icer through a front-drive PTO. The hydraulic system then controls the booms, product pumping system, and spray nozzle functions [49].

**Hagie Mower**
All of Hagie Manufacturing Company's machines are powered by electronically controlled diesel engines ranging from 160 to 365 hp. The fuel capacity of the DTS 10 mower, a standard model, has two 50-gallon fuel tanks for a total fuel capacity of 100 gallons [50].

**Oshkosh H273b Blower and P2546 Runway Plow**
Oshkosh's H-Series Blower models include a Caterpillar C-18 6-cylinder blower engine capable of 575 hp at 2,300 rpm. The drive engine is EPA on-road emission compliant for green fleets. It has a 250 gallon fuel capacity [39]. Oshkosh's P-Series models feature a Cummins ISX engine that provides 320-450 hp at 2,100 rpm [51,52].

**VAMMAS PSB 4500 and 5500h Units**
VAMMAS PSB units combine the features of a snow plow, sweeper, and air-jet blower into one vehicle. The 4500 uses a Caterpillar C11 drive engine (287 kw) and aggregate engine (313 kW);

the 5500 uses a Caterpillar C15 drive engine (354 kW) and aggregate engine (354 kW) [53].

**Kodiak Cf8s Snow Blower**

Kodiak manufactures a series of mechanical blower heads suitable for highways and other non-airport applications as well as a series of hydrostatic blower heads more suitable for runway applications where variable head speeds are desired. The hydrostatic blower head is capable of moving 3,000-11,000 tons per hour and delivers horsepower at the requested level in the range of 400-1,300 hp [54].

**Grasshopper 930D Snowblower**

The Grasshopper 930D features a 30 hp, 3-cylinder, liquid-cooled Kubota diesel engine. It has a fuel capacity of 8 gallons. It is assumed that the vehicle owned by the Port Authority features the added dozer blades, rotary brooms, and snowthrowers to modify the mower for snow removal [55].

**Freightliner M2106**

The Freightliner M2106 is powered by a Cummins ISB or ISC engine. The ISB engine is the lightest engine in its class, and the Cummins ISC has the largest power/torque ratings in the medium duty market. The M2106 also is available with the Eaton parallel electric hybrid system. Powered by the Cummins ISB 6.7 liter engine with a variety of horsepower/torque ratings up to 325 hp/750 ft lb torque, the M2 106 Hybrid comes with the Eaton parallel-electric hybrid system. This system features a 6-speed Ultrashift transmission, coupled with an electric motor that provides up to an additional 60 hp and 310 ft lb torque at peak. Optional electronic power take off (ePTO) capability makes the M2 106 Hybrid ideal for high-idling applications such as utility and tree trimming. Idle time is reduced up to 87% and fuel consumption up to 60% in ePTO mode. Freightliner has embraced proven selective catalytic reduction (SCR) emissions technology for EPA 2010 and beyond. Requiring fewer changes under the hood, the after treatment system design means less stress on the engine, fewer active regenerations and improved fuel economy [56].

**How Does It Work?**

1. The Eaton parallel-electric hybrid system enables the truck to operate using the diesel engine alone, or in combination with the hybrid-electric motor.

2. The hybrid system's electric motor provides additional power (up to 60 hp) to launch the vehicle, improving fuel economy in stop-and-go operations.

3. The hybrid system's lithium-ion batteries are recharged through a process called regenerative braking. During braking, the vehicle's kinetic energy is captured and regenerated to charge the hybrid battery. Regenerative braking captures up to 44kW (or 60hp), power that normally is absorbed by the foundation brakes and lost as heat.

4. The all new engine-off-at-stop feature provides up to 8% additional fuel savings. When the

service brake is applied, at a stop light for example, the engine turns off. When the service brake is released, the engine restarts.

**GMC W5500**

The W5500 uses an inline four-cylinder engine of the 4HK1-TC series. The fuel system is turbocharged direct injection diesel. The total displacement is 5.19 liters, or 317 cubic inches. The total horsepower is 205 at 2,400 rpm and the total torque is 441 foot-pounds at 1,850 rpm. The torque ratio when the clutch becomes engaged is 265 ft-lbs while the governed engine speed is 2,800 rpm.

Total fuel tank capacity is approximately 30 gallons. The total exterior length is 200 inches, the width is 81.3 inches and the height is 91 inches. The front overhang is 48 inches and the rear overhang without the bumper is 43 inches. The front bumper to the back of the cab is 71 inches. The ground clearance is 8.3 inches while the wheelbase is 109 inches. The interior head room is 38.4 inches, front leg room is 29.5 inches, front shoulder room is 70.7 inches and front hip room is 67.7 inches. The front and rear wheel size is 19.5 by 6 inches. The front and rear tire size is 225/70R19.5F.

The front and rear wheels are made of steel and the front stabilizer bar is 1.65 inches in diameter. The front suspension design is a tapered leaf while the rear suspension type is a multi-leaf. The front brakes are discs and the rear are drum brakes. The transmission is the Aisin A465 six-speed, automatic with overdrive. The body is a tilt chassis cab and the cab can seat three. This truck uses a four-wheel anti-lock brake system and has power-steering [57].

**GMC K3500**

Performance Specifications [58]:

- 5,733 cc 5.7 liters 8 V engine with 101.6 mm bore, 88.4 mm stroke, 9.4 compression ratio, overhead valve and two valves per cylinder
- Unleaded fuel
- Multi-point injection fuel system
- 129 liter fuel tank
- Power: 190 kW , 255 HP @ 4,600 rpm; 330 ft lb , 447 Nm @ 2,800 rpm

**Ford F350**

Performance Specifications:

- Engine - 6.2L SOHC 2-valve V8 Flex Fuel engine (F-250/350)
- E85 / unleaded fuel
- Multi-point fuel injection
- 35.0 gallon fuel tank
- Power (SAE): 316 hp @ 4,179 rpm; 397 ft lb of torque @ 4,179 rpm

The E85-capable 6.2L gas V8 features a single overhead camshaft design and dual-equal variable cam timing —features that help optimize power throughout the speed range as well as fuel efficiency. For power conversion to compressed natural gas (CNG) or liquid propane gas (LPG), Ford offers the CNG/LPG Gaseous Engine Prep Package, available for F-250 and F-350 models. The Snow Plow Prep Package includes computer-selected springs for snow plow application and extra-heavy-duty alternator with Power Stroke® V8 Turbo Diesel engine or heavy-duty alternator with gas engine (not available with Heavy Service Suspension Package; requires 4x4) [59].

**Ford F550**

The Ford F550 is a class 5 Ford conventional truck. Its configuration is unique in its weight class in that the model shares fenders, hood and grille as well as the cab with a pickup model. 2005 and later models have a wide track front axle, with Gray plastic fender and bumper extensions (shared with the F450) that made the trucks much easier to maneuver in tight spots. GVW's up to 19,500# are offered, also a 35,000# GCWR towing package is offered. New for 2011 is a 6.7 liter Ford built Power stroke diesel engine. The 6.8 liter V10 gas engine is a carryover for 2011 [60].

**Oshkosh MPT**

A smaller, more economical version of the Oshkosh P-Series, the MPT-Series 4x4 chassis is built from the ground up as an all-wheel-drive truck, unlike mass-produced commercial vehicles that are converted off the assembly line [61].

**Peterbilt 320**

The Model 320 diesel engine lineup spans from the lightweight, efficient Cummins ISL9 to the powerful Cummins ISX12 with ratings up to 400 horsepower and 1,650 lb-ft. of torque. For applications requiring natural gas fuel, the Model 320 is available with the Cummins Westport ISL G rated at 320 horsepower and 1,000 lb-ft of torque. This spark-ignited engine is capable of running on either Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG), offering ultimate flexibility in fuel sources. With the flexibility to mount tanks either on the rail or integrated into the body, the Model 320 allows for maximum use of space when integrating a body for a variety of applications [62].

**Toro Groundmaster 7210**

Toro Groundmasters are new zero-radius rotary mowers with Kubota 28hp (21kW) or 35hp (26kW) 3-cylinder liquid- cooled diesel engines. While during the winter months, the Toro® Polar Trac™ System transforms the Groundsmaster® 7210 into a snow removal machine [63].

**Bobcat S185**

Bobcat S185 has a Liquid Cooled Diesel Engine that produces 75 horsepower. It is offered with a hydraulic flow of 16.9 gpm and weighs 6220 pounds. The four cylinder skid steer model has a maximum speed of 7.3 mph. The S185 Skidsteer from Bobcat comes equipped with a universal skid steer quick hitch. This allows a wide variety of skid steer attachments to be attached to this loader [64].

**John Deere 624**

John Deere 624 has interim Tier 4-emission certified engine and powershift torque-converter transmission. The EPA IT4-certified engine provides the same horsepower and torque as that of a Tier 3 engine. The IT4 engine utilizes an automatic regeneration process which periodically cleans the filter without impacting machine productivity. The cooled exhaust gas recirculation (EGR) technology is simple, fuel efficient, field proven, fully integrated, and fully supported. It features a diesel particulate filter (DPF) and diesel oxidation catalyst (DOC) to reduce particulate matter (PM) and nitrogen oxides. The DPF traps particulate matter and ash. The DPF service interval is 5,000 hours.

Excavator-style hydraulics sense the load and deliver the flow needed for smooth, combined functions and fast work cycles.The in-tank filter with large element traps that hold contamination allow for cleaner oil, a cleaner hydraulic system, and less maintenance. Service intervals are extended to 4,000 hours. The hydraulic filter is a common part for the 444K—844K. Easily accessible hydraulic diagnostic ports enable quick pressure checks and minimize the possibility of introducing contaminants [65].

**New Holland TV145**

The New Holland TV145 Bidirectional™ tractor is a versatile 105-PTO horsepower tractor. The Bidirectional lets you mount and power implements on either end to get the best combination of visibility, traction and weight balance. This machine could be multipurpose by changing to snow blower, mower, wheel loader etc.

Three-speed hydrostatic transmission provides infinite speed selection in forward or reverse. Ample hydraulic power--up to 65 gpm--provides instant response. Full-time, four-wheel drive and articulated steering provide traction and maneuverability that other tractors can't match. Servicing the TV145 is especially easy thanks to a flip-up hood and convenient fluid checks [66].

## 5.2 Cost Analysis

### Refined Data

For our analysis, we divided the data based on gross vehicle weight. The gross vehicle weight (GVW) is the maximum operating weight of a vehicle as specified by the manufacturer and includes the vehicle's chassis, body, engine, engine fluids, fuel, accessories, driver, passengers and cargo but excluding that of any trailers. Based on the data provided by Port Authority, we decided that a vehicle weighing less than 14,000 lbs. belongs to the light weight group, between 14,000 lbs. and 20,000 lbs. are in the medium weight group, and any vehicles heavier than 20,000 lbs. are heavy vehicles. The details of fuel type and number of vehicles in use for each GVW group are listed in Table 5.1 below, and Figure 5.1 depicts this information graphically.

**Table 5.1**

| GVW | Fuel Type | Fleet |
|---|---|---|
| Light (<14,000lbs) | Flex fuel | 13 |
| | Gasoline | 47 |
| Medium (14,000lbs ~ 20,000lb) | Bi fuel | 2 |
| | Bio diesel | 9 |
| | Gasoline | 3 |
| Heavy (> 20,000lbs) | Bio diesel | 35 |

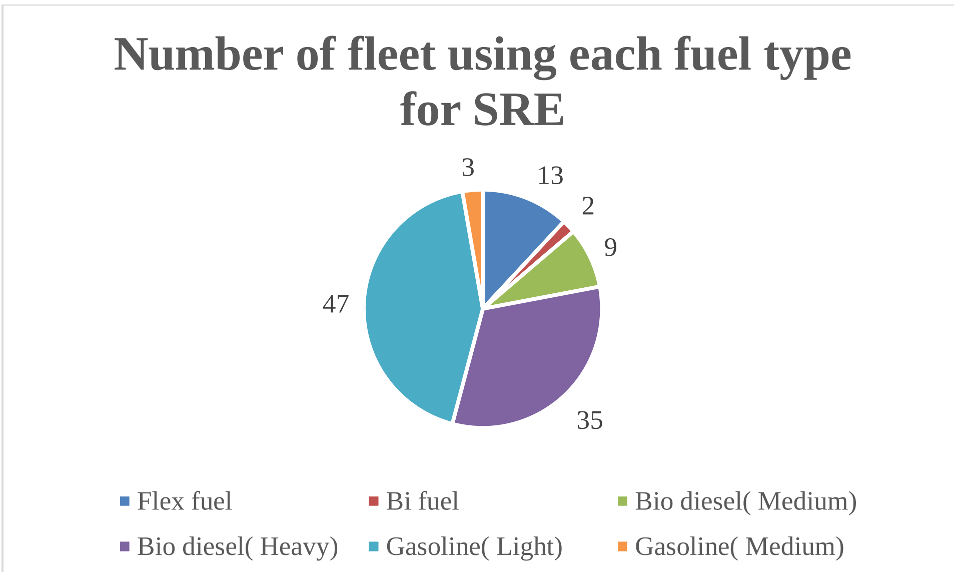


**Figure 5.1**

<u>Fuel Cost/Mile Analysis</u>

The equation used for fuel cost calculation is as follows:

$$Fuel\ cost\ per\ mile = \frac{LTD\ fuel\ cost}{Odometer\ reading}$$

Where

LTD fuel cost = life time duration fuel cost.

Using the equation above, we obtained the following results:

**Table 5.2**

| Fuel type | Cost/ mile | Cost/gal |
|---|---|---|
| **Flex fuel** | 0.397 | 3.114 |
| **Bi fuel** | 0.750 | 3.724 |
| **Bio diesel( Medium)** | 0.410 | 3.464 |
| **Bio diesel( Heavy)** | 0.356 | 2.977 |
| **Gasoline( Light)** | 0.439 | 2.626 |
| **Gasoline( Medium)** | 0.404 | 2.518 |

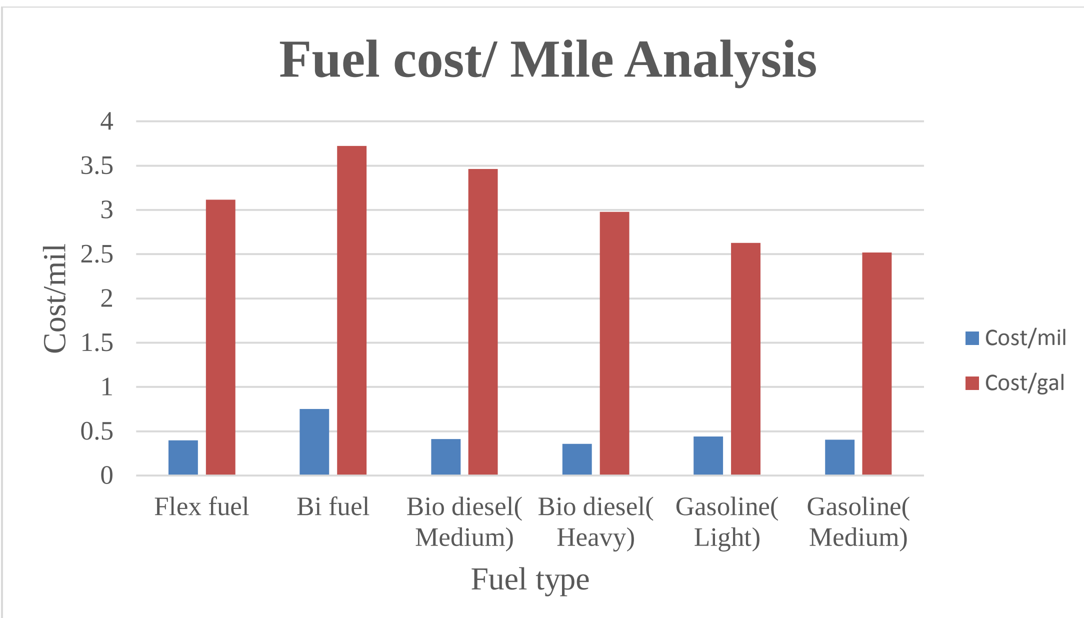


**Figure 5.2**

As Figure 5.2 shows, bi fuel, biodiesel, and flex fuel vehicles tend to have higher fuel costs per gallon than gasoline. Bi fuel vehicles had both the highest costs per mile and costs per gallon, indicating that these vehicles may not be a good investment for the Port Authority.

## Annual Cost Analysis

The equation used for annual cost analysis is as follows:

$$Annual\ cost = \frac{LTD\ fuel\ cost + LTD\ maint\ cost - LTD\ acci\ cost + LTD\ depreciation}{Service\ time}$$

Where

LTD maint cost = life time maintenance cost
LTD acci cost = life time accident cost

Based on the data provided by the Port Authority and the equation above, we obtained the following results:

**Table 5.3**

| **GVW category** | **Fuel type** | | |
|---|---|---|---|
| | Flex fuel | Gasoline | |
| **Light** | 18,390 | 12,878 | |
| | Bi fuel | Biodiesel | Gasoline |
| **Medium** | 30,647 | 24,413 | 15,988 |
| **Heavy** | Biodiesel | | |
| | 32,468 | | |

Since the light weight group contains only flex fuel and gasoline fuel vehicles, we chose the Ford F-350 as a vehicle for further analysis as shown in Figure 5.3.

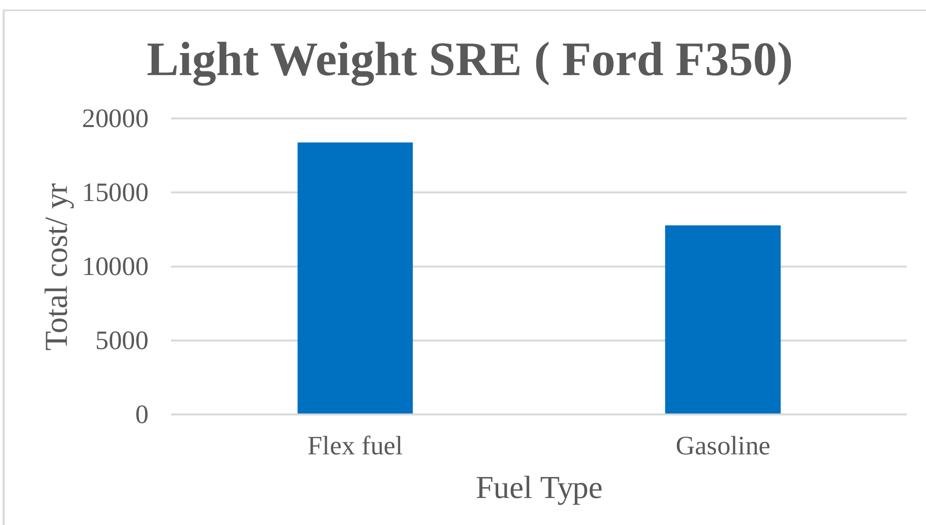


**Figure 5.3**

According to the figure above, it is true that the total cost of using flex fuel is higher than gasoline, but it is still within the acceptable range. In comparison, in the medium-duty vehicle group, the annual cost of using bi fuel was found to be almost twice as high as gasoline, with the annual cost for biodiesel lying somewhere in between.

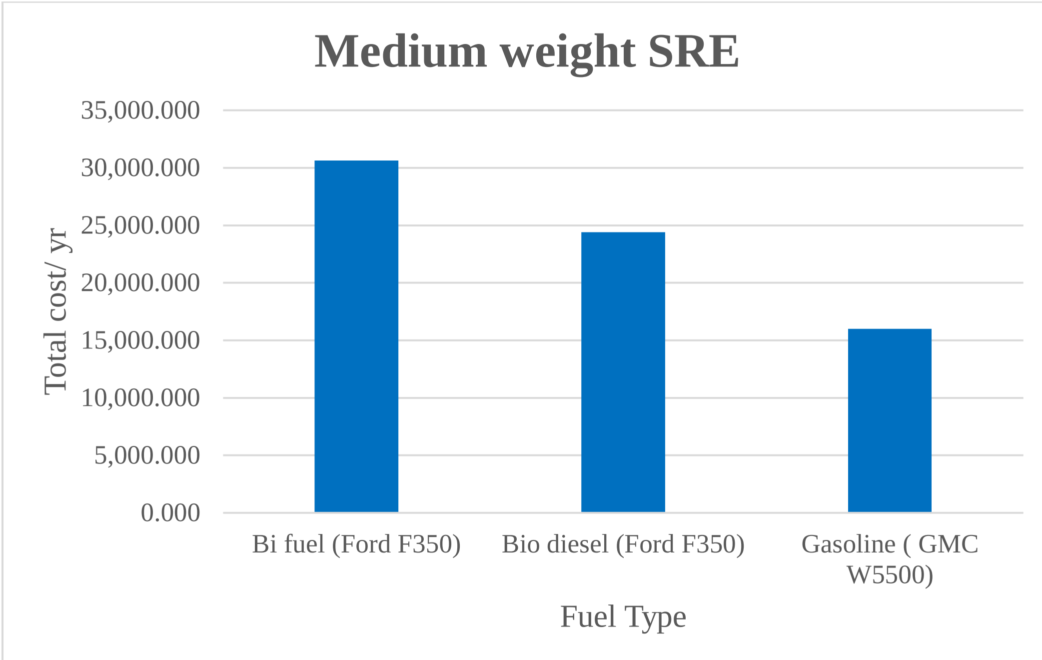


**Figure 5.4**

Biodiesel is the only fuel used for heavy snow equipment, so we made a comparison across the several makes in the Port Authority fleet:

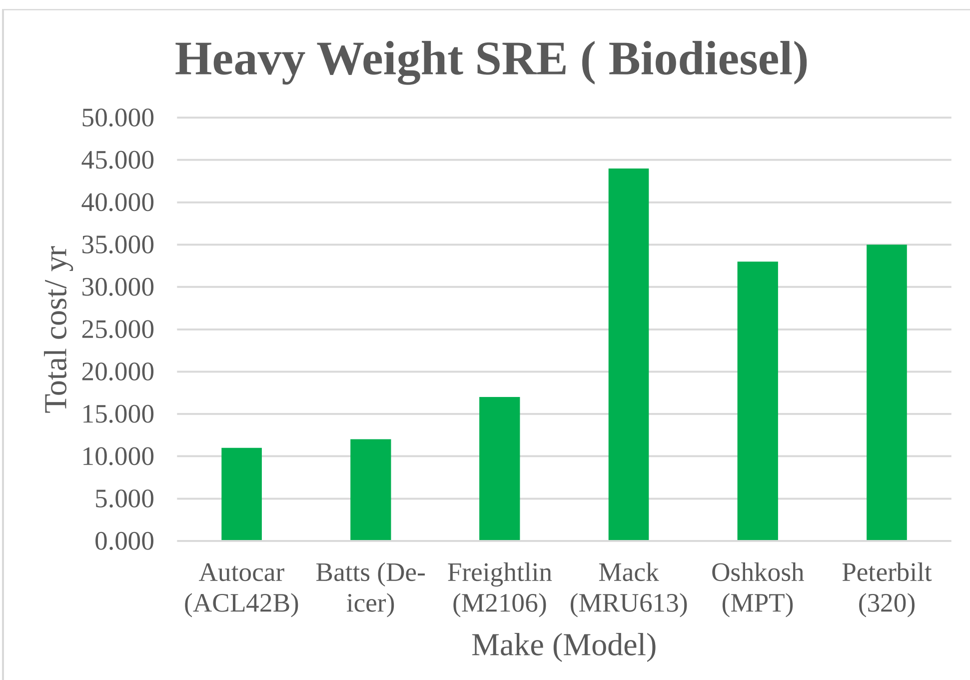


**Figure 5.5**

The total costs for each make vary greatly because they are very different in their functions, duty load and service time.

## 5.3 Greenhouse Gas Reduction Analysis

Table 5.4 shows the values we obtained from the EPA used for the CO2 emission calculation. Flex fuel is also called E85, which means it uses 85% ethanol + 15% gasoline. We did not include bi-fuel in our analysis; since bi fuel uses two fuels in separate tanks, the emissions value varies based on what kind of fuel the vehicle uses. In any case, based on the results we discussed previously, the fuel cost and annual cost for bi fuel are much higher than the other fuel types, and the Port Authority does not actually have many vehicles that use bi fuel.

**Table 5.4**

| Fuel Type | CO2 Emission lb/gal |
|---|---|
| **Gasoline** | 19.6 |
| **Bio diesel** | 18.0 |
| **Flex fuel ( E85)** | 13.99 |

The equation used for $CO_2$ Emission is as follows:

$$CO_2 emissions\ per\ mile = \frac{CO_2 per\ gallon}{mpg}$$

Based on the data provided by Port Authority and the equation above, we obtained the results as follows:

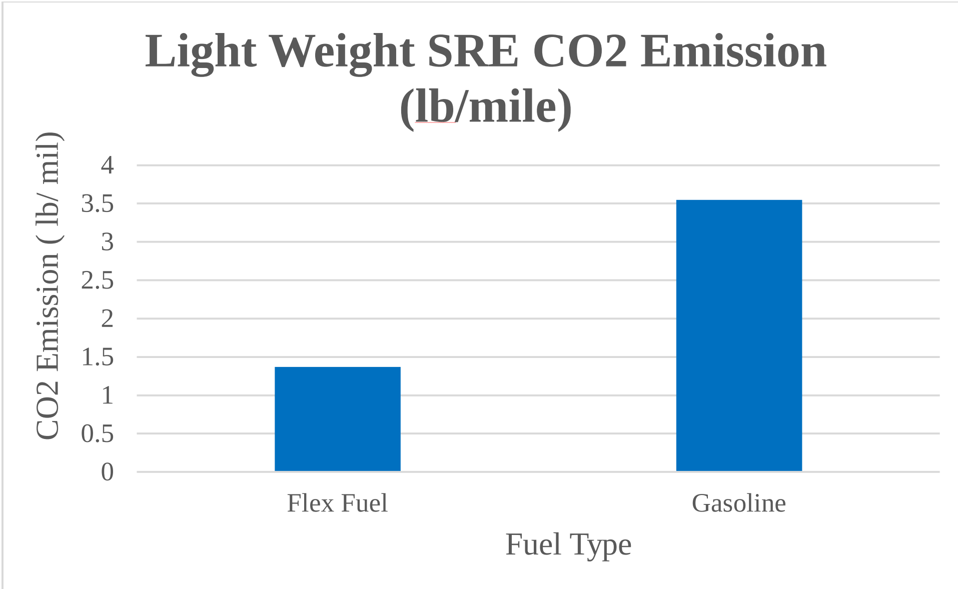


**Figure 5.6**

It is obvious that in light vehicle group, flex fuel is much cleaner than using gasoline, reducing almost 50% $CO_2$ emission.

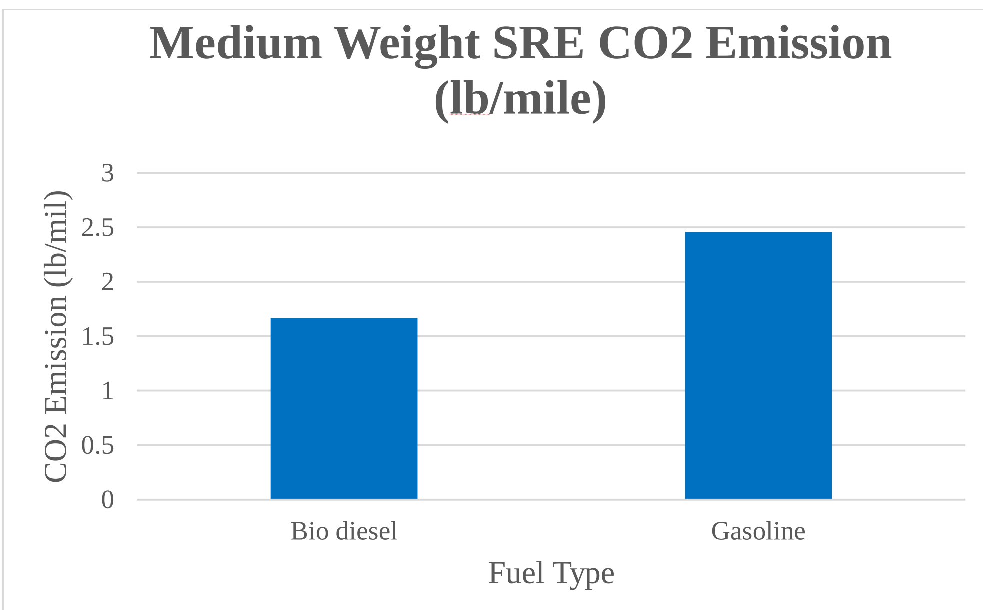


**Figure 5.7**

In the medium weight group, biodiesel is much cleaner than gasoline, reducing $CO_2$ emissions by approximately 35%.

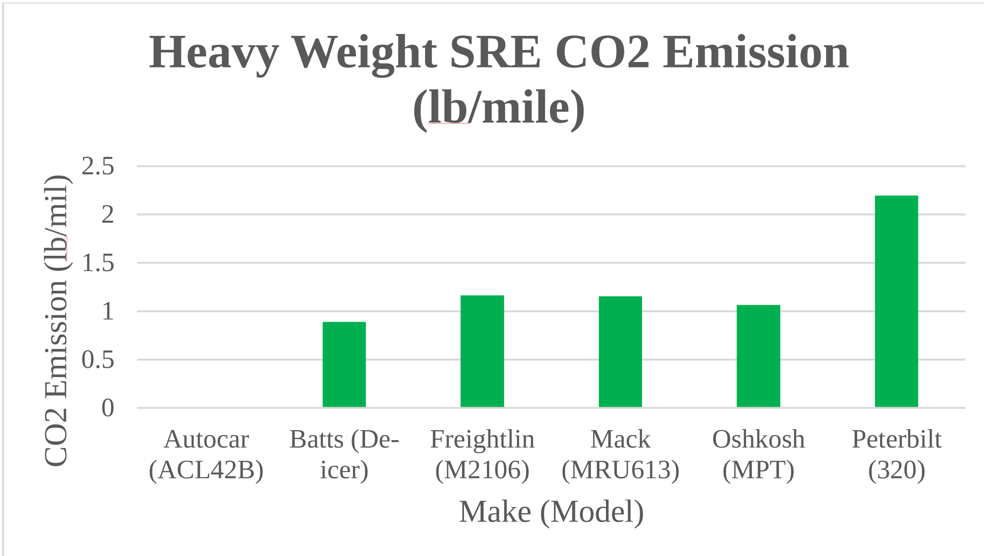


**Figure 5.8**

The emission values vary greatly among vehicles in the heavy weight group, since they have widely different functions, service times and duty load.

## 5.4 Conclusions and Recommendations

Based on the results below, there is no doubt that gasoline is the most economical option, but it also produces the most $CO_2$:

**Table 5.5**

| GVW | Fuel Type | Total cost ($/yr) | MPG | CO2 Emission (lb/mil) |
|---|---|---|---|---|
| **LIGHT** | Flex fuel | 18,390 | 10.2 | 1.37 |
| | Gasoline | 12,878 | 5.5 | 3.55 |
| **MEDIUM** | Bi fuel | 30,647 | 5.0 | N/A |
| | Bio Diesel | 24,414 | 10.8 | 1.61 |
| | Gasoline | 15,988 | 7.9 | 2.46 |
| **HEAVY** | Bio Diesel | 32,468 | 15.4 | 1.17 |

Since the Port Authority wants to diversify their fleet with “green” vehicles, we have sought to identify an alternative fuel vehicle that is best suited to replace a gasoline vehicle in each weight class. We recommend flex fuel as an alternative for their light weight vehicles and biodiesel for medium weight snow equipment. Since there are several makes with a variety of service times, functions, and duty loads in the heavy vehicle group (all of which use biodiesel), we cannot make any conclusions for the heavy weight group. However, it is worth noting that at this time, many heavy weight and medium weight SREs are only available in a diesel/biodiesel version, so the Port Authority does not have an option for replacing these vehicles. Discussions with Dave Butters of the Rochester Airport indicate that in the future, SREs that use propane as a fuel source may become more available. These vehicles reportedly do not incur noticeably higher maintenance costs than conventional vehicles [68].

## Future Work

In this project, we mainly focus on Snow Removal Equipment in New York State. Further research could be done by making a comparison between Snow Removal Equipment in New York State and other states in the US and finding out if there are other factors beyond those we have discussed in the project that might influence the cost and the performance of these vehicles.

We discovered that only flex fuel and gasoline are used in light snow removal equipment. More research could be done into the relationship between fuel type and gross vehicle weight. Data should be analyzed to make people convinced why bio-diesel and bi fuel vehicles are not utilized as light SREs. The same goes for the fuel type used in medium and heavy snow removal equipment.

Noticing that data of dedicated and part time snow equipment are given separately, no comparison has been made discussing the specific differences that exists between these two types of equipment. Comparisons could be made on fuel type or gross vehicle weight between these two types of equipment.

Furthermore, for the environmental impact analysis, $CO_2$ is the major gas we focus on. However, many other substances contained in the emissions also have negative effect on the environment. For example, nitrogen and oxygen atoms in the air react to form various nitrogen oxides, under the high pressure and temperature conditions in an engine, collectively known as NOx. Nitrogen oxides, like hydrocarbons, are precursors to the formation of ozone. They also contribute to the formation of acid rain [67]. For improvement, analysis should be done concerning the impact of other gas emissions on the environment.

# Part III

# Summary and Conclusions

# Risk Analysis

The project team used Risk Solver Platform Simulation to measures and describes various characteristic of the bottom-line performance measure of a model since our independent variables are uncertain. In this case, the team decided Fuel Cost per year, Maintenance Cost per year and Annualized Capital Cost per year as independent random variables and the Total Cost per year as dependent variable.

The objective in simulation is to describe the distribution and characteristics of the possible values of the bottom-line performance measure which is Total Cost per year, given the possible values and behavior of the independent variables Fuel Cost per year, Maintenance Cost per year and Annualized Capital Cost. For this project, our analysis focused on 2012 Gasoline Highlander and 2012 Hybrid Highlander vehicles on 5000 mile per year scenario case study.

Our first step in spreadsheet simulation was to place a random number generator (RNG) formula in each cell that contains an uncertain value. And each of these formulas generated a number that represents a randomly selected value from a distribution that these samples are taken from. And, for this analysis, we used our judgment in selecting appropriate RNGs to model the random behavior of the uncertain variables.

We have used simulation to generate 5,000 observations on our bottom-line performance measure and then calculated various statistics to describe the characteristics and behavior of the performance measure. We assumed that we can model Fuel Cost per year, Maintenance Cost per year and Annualized Capital Cost as a normally distributed random variable using their given values as means and assuming their Standard deviation as 10% of their respective mean value.
Whereas,

*Total Cost per year=Fuel Cost per year+ Maintenance Cost per year+ Annualized Capital Cost*

As a final step, after entering the appropriate RNGs, each time we pressed the recalculate key the RNGs automatically selected new values for the entire cell in the spreadsheet that represent uncertain (or random) variables which are depicted in the figures below.

Figures 6.1and 6.2 depict the approximate shapes of the probability distribution associated with Total Cost per year for 2012 Gasoline Highlander traced by Risk Solver Platform during the simulation. In these figures, the shape of the distribution associated with the total cost variable is somewhat bell-shaped and cumulative probability distribution graph respectively; with 80% confidence interval value for Total Cost per year between $6,500 and $7,700.

Figures 6.3 and 6.4 depict the approximate shape of the probability distribution associated with Total Cost per year for 2012 Hybrid Highlander traced by Risk Solver Platform during the simulation. In these figures, the shape of the distribution associated with the total cost variable is somewhat bell-shaped and cumulative probability distribution graph respectively; with 80% confidence interval value for Total Cost per year between $5,700 and $6,800.

| | Gasoline | | Hybrid | |
|---|---|---|---|---|
| **Mile per year** | 5000.00 | 5000.00 | 5000.00 | 5000.00 |
| **Miles per gallon** | 20.22 | 19.00 | 28.30 | 28.00 |
| **Cost per gallon** | $ 4.06 | $ 4.00 | $ 4.27 | $ 4.00 |
| **Fuel cost per year** | $ 1,003.18 | $ 1,052.63 | $ 754.15 | $ 714.29 |
| **Maintenance Cost** | $ 2,365.20 | $ 2,322.00 | $ 548.69 | $ 550.00 |
| **Annualized Capital Cost** | $ 4,293.21 | $ 3,735.00 | $ 5,416.11 | $ 5,077.00 |
| **Total Cost** | $ 7,661.59 | $ 7,109.63 | $ 6,718.94 | $ 6,341.29 |
| **80% Confidence interval** | $ 6,500.00 | $ 7,700.00 | $ 5,700.00 | $ 6,800.00 |

**Table 6.1: Uncertainty Analysis results for 2012 Highlander Gasoline and 2012 Hybrid Gasoline Vehicles (with and without Risk Solver Platform)**

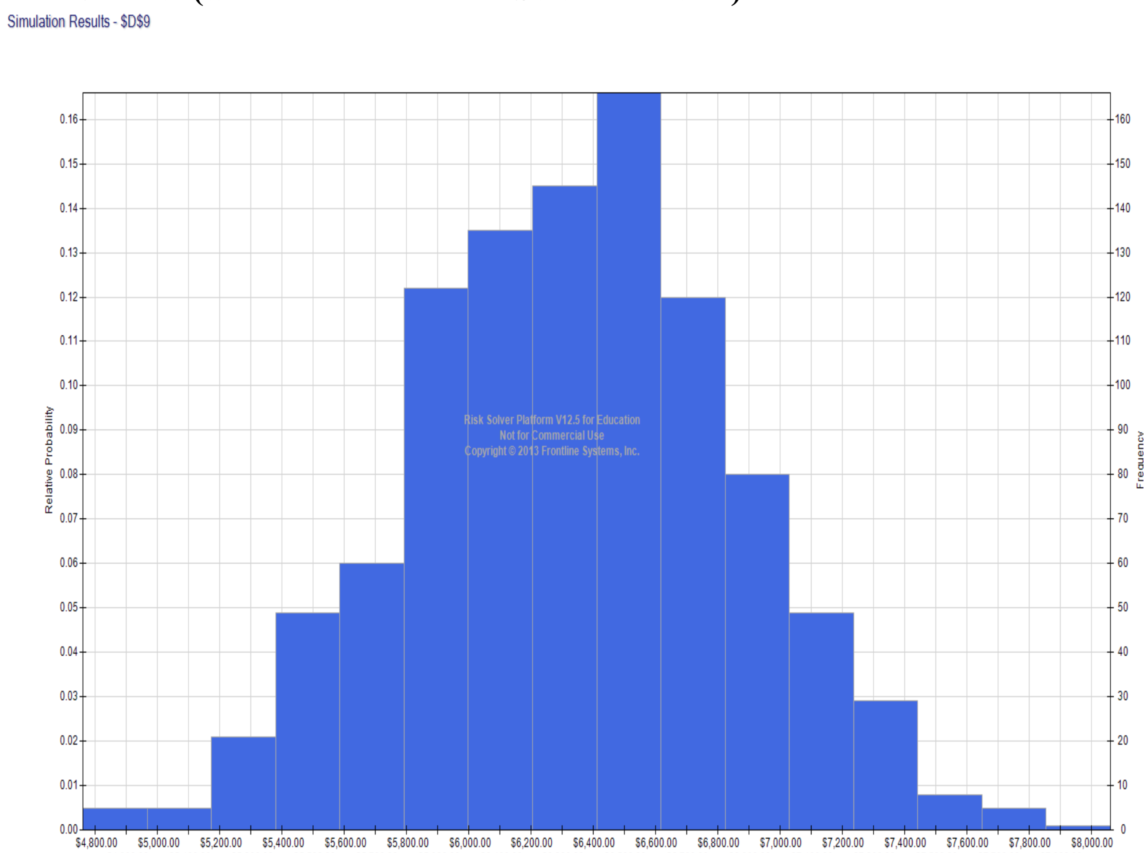


**Figure 6.1: Frequency Histogram for Gasoline Vehicle Total Cost**

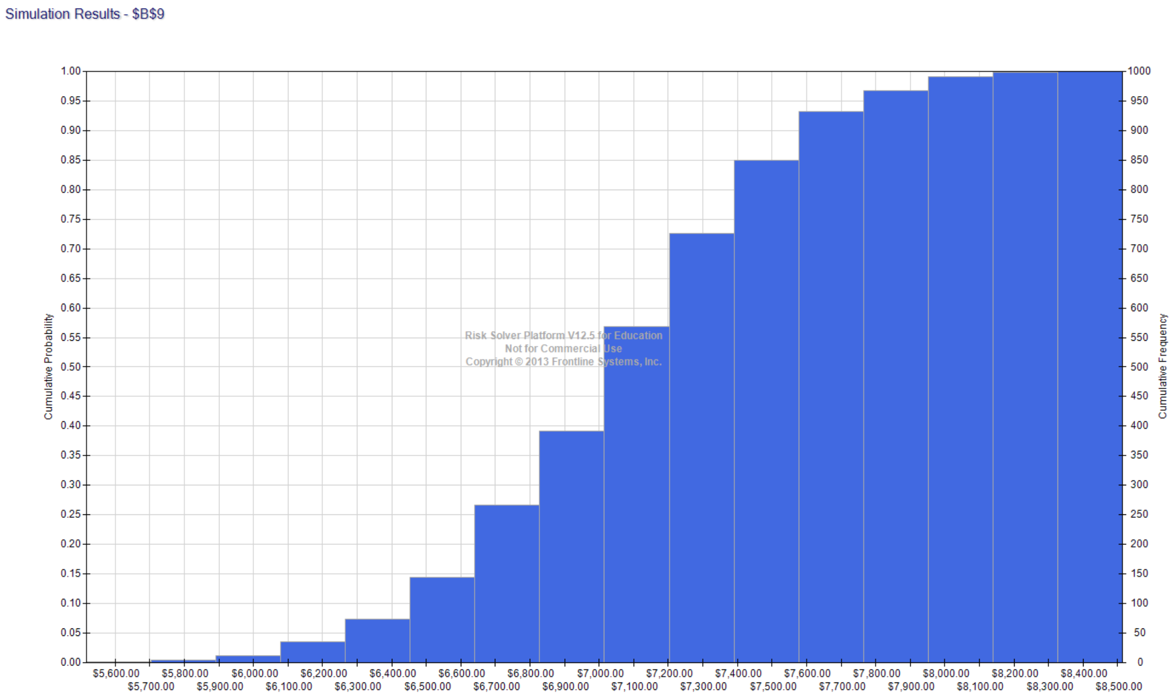


**Figure 6.2: Cumulative Frequency Histogram for Gasoline Vehicles Total Cost**

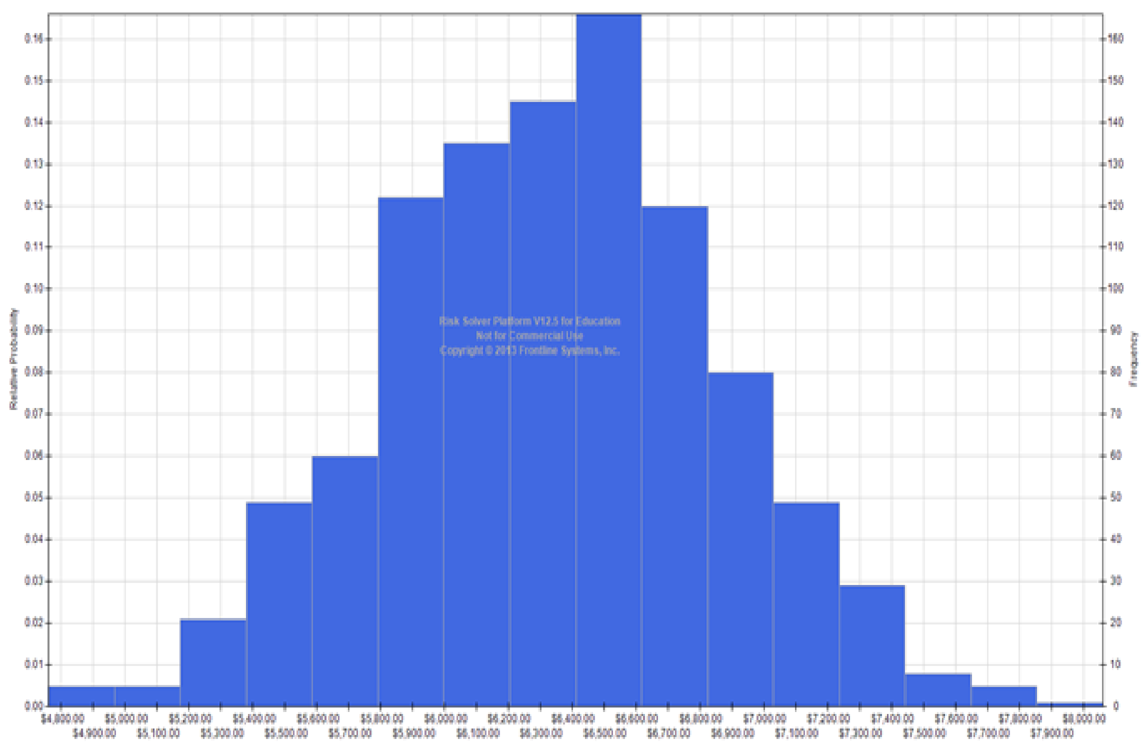


**Figure 6.3: Frequency Histogram for hybrid Vehicles Total Cost.**

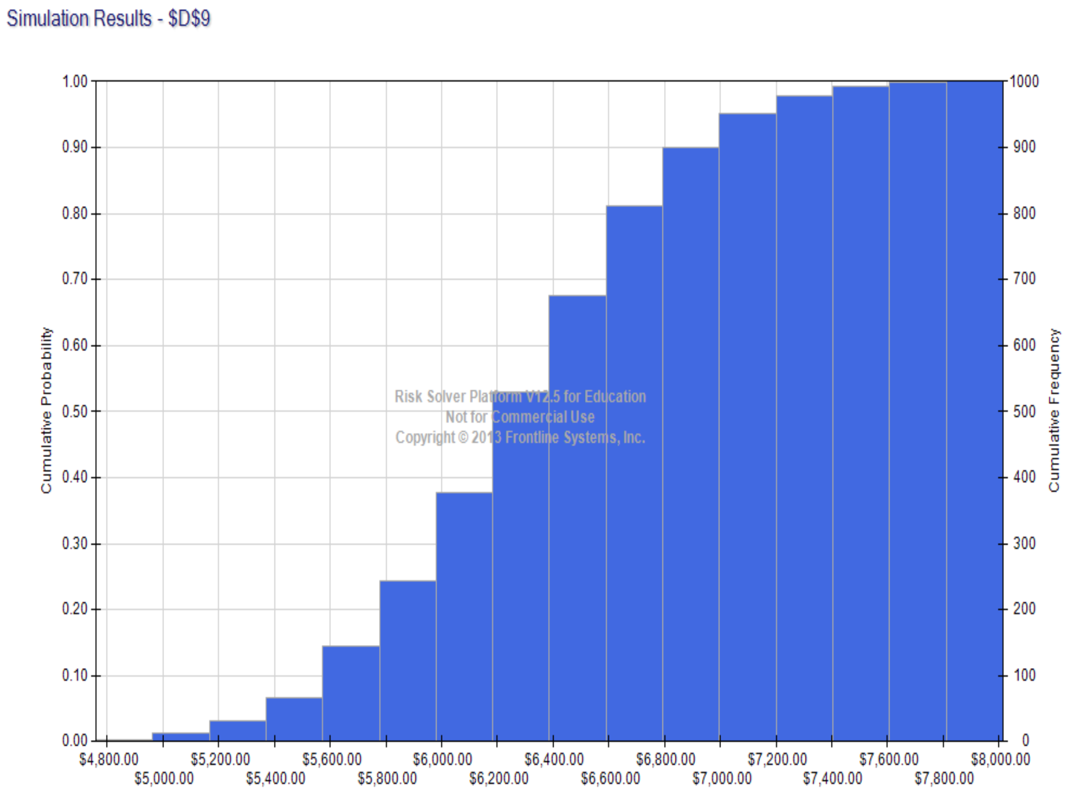


**Figure 6.4: Cumulative Frequency Histogram for Hybrid Vehicles Total Cost**

## Summary

From the case scenario analysis, it has been shown that the maintenance cost of biodiesel is slightly higher than traditional diesel while the emission of $CO_2$ is reduced by 15%. The total cost per year for Ford-F350 for diesel is $8855 while the total cost per year for biodiesel is $8892. As the price of the fuels fluctuate, the total cost will also vary but mainly the cost for biodiesel is higher than diesel. As the goal is to reduce greenhouse gas emissions, properly maintained biodiesel vehicles it will be a good alternative.

The CNG alternative sedan sized vehicles are a very viable option compared to the gasoline standard. With an initial investment, the CNG vehicles will decrease the $CO_2$ emissions by 25% compared to the gasoline equivalent. However, over the course of an expected life of 10 years for a CNG vehicle, the expected extra cost for any CNG vehicle relative to the gasoline equivalent is about $6,000. As of now we would not recommend purchasing CNG vehicles based on a cost basis.

The results of the cost analysis and scenario case study indicate that hybrid vehicle is more cost effective than the gasoline vehicle. By replacing 10 gasoline Highlanders with 10 hybrid Highlanders, the Port Authority could save approximately $34,000 in fuel costs per year and reduce carbon dioxide emissions by 35,000 pounds per year (32% reduction).

Since fuel cost is cheaper for hydrogen vehicles than gasoline vehicles, we suggest that the Port Authority increase their driving ranges for hydrogen vehicles. We have found that one major advantage of hydrogen vehicles in comparison to other alternative fuel types is that the range of a typical hydrogen vehicle is similar to that of a gasoline vehicle. For this reason, as driving range for hydrogen vehicles increase, hydrogen vehicles will be more cost effective than gasoline vehicles due to fuel saving. Based on our calculations without considering maintenance cost, we primarily suggest to the Port Authority that they replace their gasoline Toyota Highlander models with Toyota Highlander hydrogen vehicles for the basis of fuel saving analysis for the 10 year period, provided that the purchase cost is cost-effective.

We have sought to identify an alternative fuel for each size category of snow removal vehicles. We recommend flex fuel as an alternative for light weight vehicles and biodiesel for medium weight snow equipment. Since there are several makes with a variety of service times, functions, and duty loads in the heavy vehicle group (all of which use biodiesel), we cannot make any conclusions for this group.

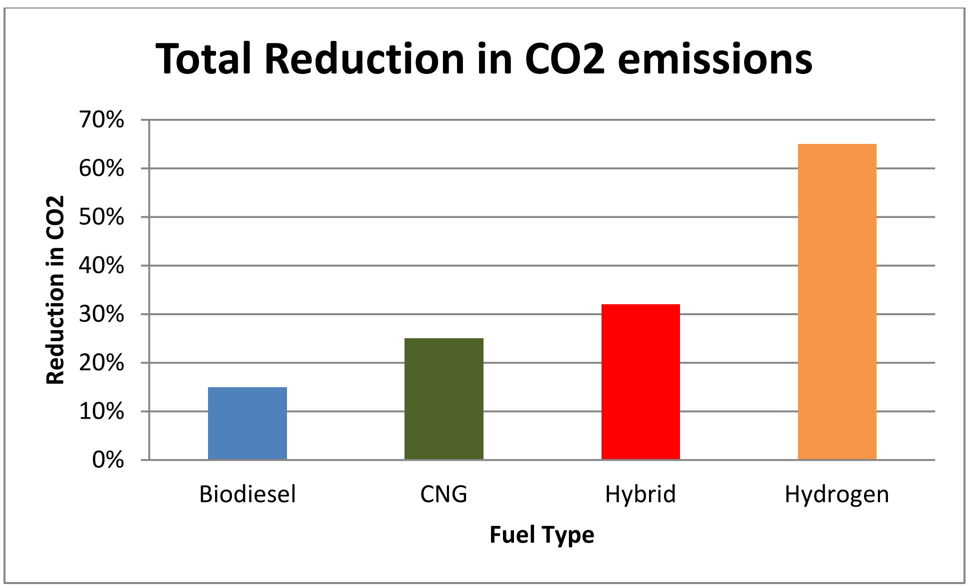


**Figure 6.5: The reduction of $CO_2$ emissions per fuel type.**

## Further Research

One area of further interest that may be of value to the Port Authority deals with the increased prevalence of smaller vehicles having compression ignition engines. The use of biodiesel in these vehicles would be an interesting topic to consider. Additionally, a more in depth study of what causes biodiesel prices to fluctuate and what future technological advancements may result in a decrease in biodiesel production costs than completed in this project may be of interest to the Port Authority.

From our analysis of the Port Authority dedicated CNG data, we were able to see that there is a need for more data regarding the maintenance costs of CNG vehicles. Because the CNG Honda

Civic fleet has relatively low maintenance costs compared to the expected maintenance costs of a gasoline version of the Honda Civic, we can conclude that more data is needed to back up this maintenance cost savings.

Because there is variability in the maintenance cost for different types of hybrid vehicles, further study can be done to have a better estimate for them. In addition, a comparison study with more hybrid vehicle models can be done to identify possible models that may be more cost effective.

Noticing that data of dedicated and part time snow equipment are given separately, no comparison has been made discussing the specific differences that exists between these two types of equipment. Comparisons could be made on fuel type or gross vehicle weight between these two types of equipment. In addition, we have found that only flex fuel and gasoline are used in light snow removal equipment. More research could be done into the relationship between fuel type and gross vehicle weight.

The last thing that we would like to discuss is the data collection and data inputting methods used by the Port Authority. As is mentioned a few times throughout the report, the quality of the data limited our ability to reach definitive conclusions in our maintenance and fuel cost analyses. If the Port Authority plans to analyze maintenance and fuel costs in the future we think it is imperative that the organization puts more emphasis on correctly and consistently inputting data accurately. The amount of fuel consumed and the total cost of fuel consumed are the two areas which need the most improvement. One way to ensure that the fuel data is more accurate is to invest in a computer system where drivers have to input their vehicle ID at the refueling station every time they refuel. The computer at the refueling station would then record the amount of fuel consumed by each vehicle, every time it refuels. The concern with this method is that some vehicles are refueled at commercial stations. However, there are a couple of methods that the Port Authority can use to ensure that fuel data is accurate. The first method is to force drivers to report the amount of fuel they added at the commercial before being refunded by the Port Authority. The second method is to force drivers to input their vehicle's odometer reading every time they fill up at the pump. A simple computer program would be able to tell if the driver refueled at a commercial station in between refueling at the Port Authority's stations. The program could then smooth the data to account for these outside fill-ups. Or the Port Authority could simply discard the fuel cost data for vehicles that consistently refuel at commercial stations, but it is imperative that this is reflected in the dataset.

According to Paul Gier, Fleet Manager at Cornell University, the university uses a program called Agile Fleet Commander to track their vehicles [69]. Each vehicle is assigned an asset number when Cornell purchases the vehicle. Each time maintenance work is performed, it is entered into the system, resulting in very detailed maintenance records for each vehicle. Cornell allows faculty to "check out" their vehicles, so each time a vehicle is returned, the updated mileage and fuel consumption are recorded. Cornell receives fuel deliveries of both gasoline and alternative fuels to its own private station twice a week, so they can easily keep iterative records of fuel costs. The Port Authority may be interested in this program or employing similar methodologies.

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