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Using GREET to analyze natural gas usage in municipal fleets

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ABSTRACT

GREET was used to calculate energy consumption and pollutants emitted from specific fuel/vehicle types when given a specific set of parameters. In this case, the parameters were the type of fuel mix from TVA, the selected vehicle year of 2015, the vehicle weight specified in the heavy-duty vehicle range, and type of simulation technique, which was the Hammersely Sequence Sampling. These inputs, along with seventeen fuel/vehicles mixes, specific pollutants, and cost considerations, were used to investigate the environmental impact of the transition from petrol diesel to natural gas in the municipal fleets of Chattanooga, Tennessee.

The energy consumption included coal, petroleum, natural gas, and other power generating sources like electricity and biomass/bio-diesel. The pollutants investigated included greenhouse gases (GHGs), carbon monoxide (CO), nitrous oxides (NO_x), sulfur oxides (SO_x), and particulate matter ($PM_{2.5}$). The pollutant of particular importance to the city of Chattanooga is $PM_{2.5}$ since the city is designated a Nonattainment Area by the EPA and is looking to be re-designated as a Maintenance Area.

Natural gas vehicles emitted the lowest amount of GHGs, NO_x, and $PM_{2.5}$, only receiving competition from the standard electric vehicle with slightly lower emissions. Overall, Well-to-pump emissions were the lowest for vehicles that used pure natural gas. To summarize, compressed natural gas seems like the best option for a fuel because it is cheap, fueling the vehicle is easy, there is an unlimited hold time for the fuel, GHG and $PM_{2.5}$ emissions are lower, compressed natural gas prices fluctuate less in the current market, and the engine for the vehicle is quieter, especially when compared to diesel trucks.

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LIST OF ABBREVIATIONS

ANL	Argonne National Laboratory
BD20	Bio-diesel Soybean 20%
BTU	British Thermal Unit
CIDI	Compression-Ignition Direct Injection
CNGD	Compressed Natural Gas Dedicated
CO	Carbon Monoxide
CSI	Conventional Spark Ignition
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EV	Electric Vehicle
GCCIDIHEV	Grid Connected Compression-Ignition Direct Injection Hybrid-Electric Vehicle
GCSIHEV	Grid Connected Spark-Ignition Hybrid-Electric Vehicle
GHG	Greenhouse Gas
GICIDIHEV	Grid Independent Compression-Ignition Direct Injection Hybrid-Electric Vehicle
GISIHEV	Grid Independent Spark-Ignition Hybrid-Electric Vehicle
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use In Transportation Model
LNGD	Liquefied Natural Gas Dedicated
LSDCD	Low-Sulfur Diesel/Conventional Diesel
NO_x	Nitrous Oxide
PM	Particulate Matter
RFGCG	Re-Formulated Gasoline/Conventional Gasoline
SIDI	Spark-Ignition Direct Injection
SO_x	Sulfur Oxide
WTP	Well-to-Pump
WTW	Well-to-Wheel

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I. Introduction

Natural Gas: An Introduction

Because of hydro-fracking, a higher supply, and local markets, the price of natural gas is approximately 70% of the cost of diesel fuel. Consequently, the incentive to alter municipal fleets' fuel choice is increased due to economic reasons. Furthermore, most of the natural gas consumed in the United States is domestic[1], which decreases our country's and city's foreign dependence on fuel. Therefore, natural gas is good for the bottom line, supports the United States' energy independence, and may be beneficial for the environment and subsequently human health. For these reasons, many municipalities are considering the use of natural gas in large fleet vehicles, such as dump trucks, which currently use diesel fuel[2]. The primary purpose of this research is to investigate the environmental impact of the transition from petrol diesel to natural gas in municipal fleets.

When compared to other fuels, natural gas also has numerous other benefits other than their reduction in GHGs, NO_x, and $PM_{2.5}$. Natural gas vehicle operations also decreased noise emissions since they don't emit the same degree of high energy sound waves as do gasoline and diesel engines[3]. This is a detail not to be overlooked since garbage trucks and other urban fleets are operated when some residents of the city are still asleep. When spills and leaks of most petroleum products occur, it can affect the groundwater and residential water supplies. On the other hand, when natural gas is emitted, it is vaporized into the atmosphere causing less of an environmental concern. Lastly, compressed natural gas (CNG) vehicles save time for drivers because fueling is done overnight with automated time-fill systems instead of constantly re-fueling on a route[2].

As mentioned above, the incentive for using natural gas in municipal fleets in largely due to the increased production of natural gas inside of the United States. The U.S. is now the leading producer of natural gas in the world with 20.2% of the market with Russia in second and the European Union in third with 18.2% and 8.6% as shown in Table 1[4].

Table 1. Natural Gas Production by Country in 2012

Production of Natural Gas in 2012			
Rank	Country/Area	Billion Cubic Feet	Percentage of World's NG Production
1	United States	24058	20.2%
2	Russia	21685	18.2%
3	Europe	10183	8.6%
4	Iran	5649	4.8%
5	Qatar	5523	4.6%

Figure 1 below reveals that our production of natural gas has almost increased by 50% in the last decade. Due to the hydraulic fracturing technique, the price has decreased from the increased supply providing an incentive to purchase fuel inside our own borders[5].

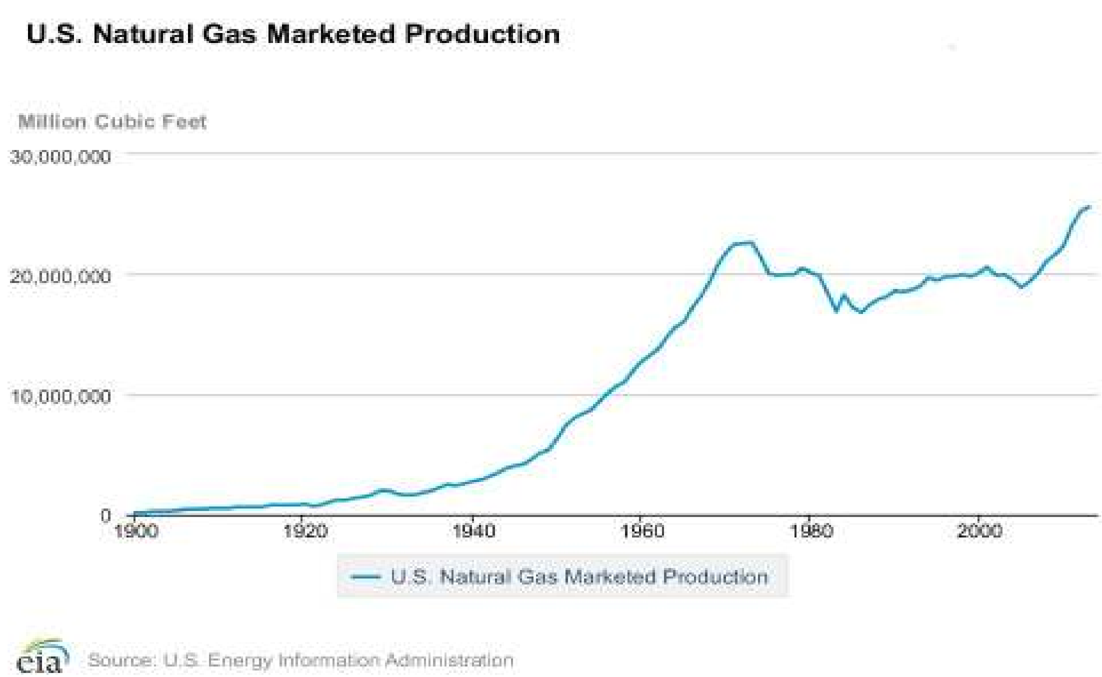

Figure 1. United States Historical Natural Gas Production

Clean Air Act and Transportation

The Clean Air Act (CAA), amended 1990, required the EPA to set National Ambient Air Quality Standards (NAAQS) for certain pollutants that are harmful for the general public and the environment[6]. The six criteria pollutants are carbon monoxide, lead, nitrogen dioxide, ozone, sulfur dioxide, and particulate matter 2.5 and 10 microns. Each of these pollutants are “primary” and have an level of contamination in parts per million, parts per billion, or micrograms per cubic meter that are permitted to be emitted for only a certain amount of time before fines and other legislative punishment are put into place[7].

The pollutant of particular importance to the city of Chattanooga is $PM_{2.5}$. $PM_{2.5}$, or fine particulate matter, includes airborne particles that have an aerodynamic diameter of 2.5 micrometers or less. Although listed and monitored as a single air pollutant, it is actually various compounds from several sources such as sulfates, nitrates, ammonium, carbon, dust, metals, and other primary organic compounds from combustion. $PM_{2.5}$ causes chronic respiratory and cardiovascular health effects. Older adults and children are especially sensitive to $PM_{2.5}$ exposure[8].

$PM_{2.5}$ is easily transported over long distances from fuel combustion sources, industrial processes, and most importantly for this research, motor vehicles. The concentration levels in the air are influenced heavily by geographic factors; since Chattanooga is in a valley, $PM_{2.5}$ is emitted and settles like a fog over the city[8].

In 1997, the EPA set a Final Rule for $PM_{2.5}$ (62 FR 38652). These standards put Chattanooga out of conformity and labeled the city as a “Nonattainment Area”. This means that the city could lose forms of federal financial assistance, such as funding for increasing manufacturing, bringing companies into our city, or funds for economic development and tourism[9]. The area is shown below in Figure 2[9].

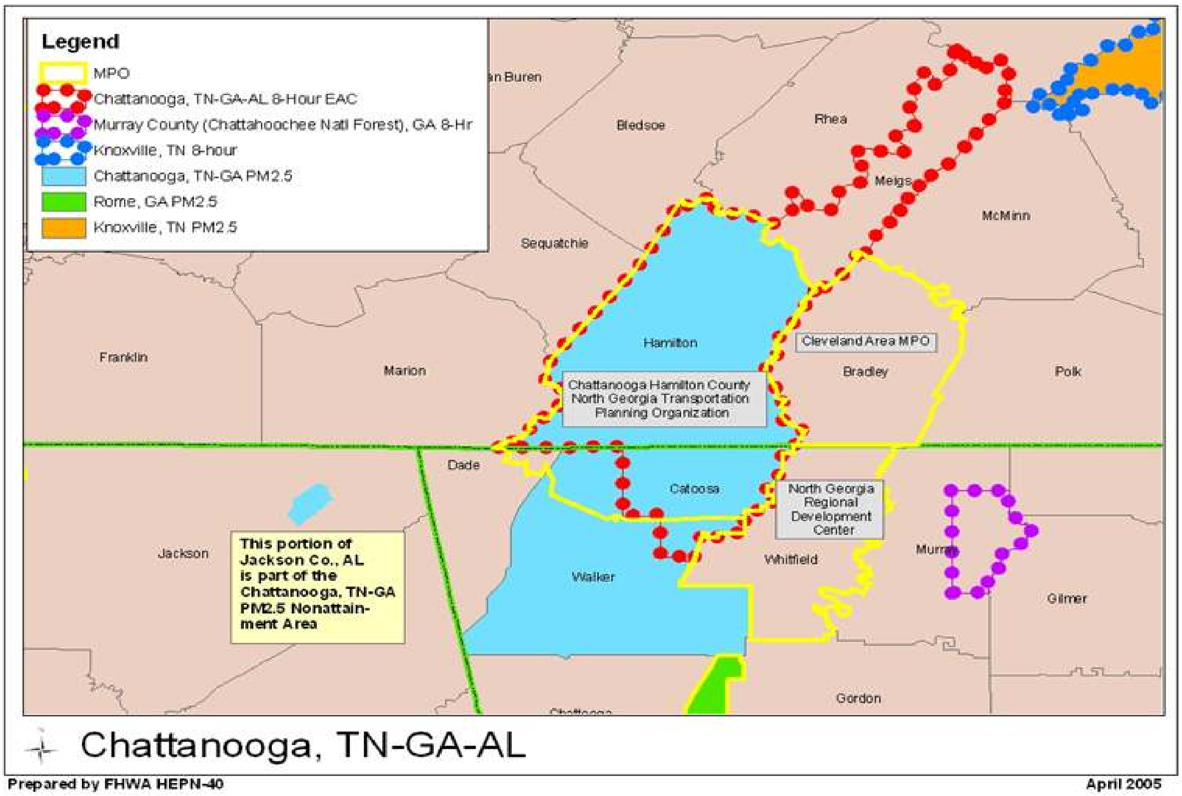

Figure 2. Non-Attainment Area

In response to this designation, the Chattanooga-Hamilton County Air Pollution Control Bureau has recently submitted a Redesignation Request and Maintenance Plan for the $PM_{2.5}$ Nonattainment Area. This would change the designation of the city to a "Maintenance Area" until air quality measurements have been met for at least seven consecutive years. After that, Chattanooga would be in attainment. From 2007-2009, Chattanooga was granted "clear data determination" by the EPA for meeting the 1997 NAAQs for $PM_{2.5}$, which made this Redesignation Request reasonable. The Maintenance Plan included with the request includes motor vehicle emissions budgets, and that's where municipal fleet's fuel choice becomes very important since the City of Chattanooga can actually control that variable[8]. Furthermore, the EPA estimates that 28% of GHGs come from transportation, so changing the fuel choice could actually make an impact on the future of this city[10].

GREET

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) is sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) and developed by Argonne National Laboratory. It is a full life-cycle model that allows researchers to evaluate vehicle and fuel combinations on a full fuel-cycle and vehicle-cycle basis. GREET simulates vehicle classes and vehicle/fuel systems and calculates emissions of pollutants[11].

GREET calculates the total energy consumption, energy consumption of fossil fuels, petroleum, coal, and natural gas associated with the production, distribution, and use of the chosen transportation fuels and vehicle types[11]. These are the fuel types chosen: compressed natural gas (CNGD), liquefied natural gas (LNGD), low-sulfur/conventional diesel (LSDCD), re-formulated/conventional gasoline (RFGCG), bio-diesel including 20% soybean and 80% diesel (BD20), and electricity. The following are the vehicle options: conventional spark-ignition (CSI), spark-ignition direct injection (SIDI), compression-ignition direct injection (CIDI), spark-ignition hybrid-electric grid independent (GISIHEV) or grid connected (GCSIHEV), compression-ignition direct injection hybrid-electric grid independent (GICIDIHEV) or grid connected (GCCIDIHEV), and electric (EV) [12]. Therefore, there were seventeen specific vehicle/fuel mixtures analyzed.

GREET has been used here to compare the use of natural gas, diesel fuel, bio-diesel, and other alternative fuels in large vehicles such as garbage trucks. The scenarios given to GREET, the results predicted by GREET, and the direction that the results give municipalities as they make their decisions about fuel choices have been outlined. The multi-dimensional Excel spreadsheet models have been provided along with all other information including costs, economic tradeoffs, and other alternatives. Initial cost estimates to help municipalities decide if it would be better financially to retrofit their current vehicles to use natural has been developed.

II. Methods

Stochastic Simulation

The stochastic module can be used in order to take uncertainties into account. This means the state of the system is non-deterministic. In other words, the system will not always produce the same output for an initial starting condition so that the next state of the system is determined by probability alone[13]. Consequently, all the variables analyzed can change with a certain probability. The stochastic simulation is a Microsoft Add-In file created GREET that assigns probability distributions and performs the sampling of all the inputs. The output reflects the range of variance for the different pathways.

Once the inputs have been decided, a sampling technique and number of iterations is chosen. The number of iterations chosen and preferred was one thousand. The sampling technique chosen for this research was the Hammersley Sequence Sampling (HSS). It ensures that the sample set is more representative of the population, showing uniformity properties more clearly in multi-dimensions. It is three to one hundred times faster than the other methods given; therefore, it is quicker and preferred for uncertainty analysis and optimization[13].

Once the stochastic simulation was completed, an Excel spreadsheet displayed the results for the one thousand sample iterations for all of the forecast options that were chosen, which were the fuels, vehicles, and sampling method. The data were analyzed by producing bar graphs to visually and statistically compare the fuel/vehicle mixes to each other. The means of the set of iterations for each fuel/vehicle mix was calculated for the area of each bar graph, and the standard deviations were used for the error bars.

TVA Mix & Inputs

The basic inputs for the GREET model was the vehicle year simulation, generation mix, and vehicle weights. The vehicle year chosen was 2015 since it is the most recent year. The generation mix chosen was TVA's own generation mix for stationary and transportation sources, and includes the following shown in Table 2: coal 37.5%, nuclear 36.5%, others (hydro,etc.) 15.5%, natural gas (9.2%), and biomass (1.3%)[14,15]. The heavy duty truck was chosen for the weight since large municipal vehicles are being analyzed for this research instead of passenger vehicles.

Table 2. TVA Electric Generation Mix

	User Defined	
	Transportation	Stationary
Residual oil	0.0%	0.0%
Natural gas	9.2%	9.2%
Coal	37.5%	37.5%
Nuclear power	36.5%	36.5%
Biomass	1.3%	1.3%
Hydro	15.5%	15.5%

Pollutants Emphasized

The pollutants investigated include: greenhouse gases (GHGs), carbon monoxide (CO), nitrous oxides (NO_x), sulfur oxides (SO_x), and particulate matter ($PM_{2.5}$). Greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases[16]. CO_2 enters the atmosphere through burning fossil fuels, solid waste, wood, and chemical reactions in nature and industry. It is the main greenhouse gas emitted through human activity[10]. CH_4 is emitted during the production and transport of coal, natural gas, and oil. It is also very efficient at trapping radiation, which causes global warming[10]. N_2O Is emitted during the combustion of fossil fuels. It stays in the atmosphere for an average of 120 years before being removed through natural processes[10]. Fluorinated gases come only from human-related activities, and have little effect on this research since it is focused on transportation and not on manufacturing or industrial activities[10].

Carbon monoxide is the product of incomplete combustion. In this study, we will see it appear from spark-ignition vehicles since they use catalytic converters to decrease NO_x emissions, but consequently CO emissions are not reduced since not all of the CO is converted to CO_2 at the outlet of the catalytic converter[17]. NO_x is a generic term used for NO and NO_2, which are produced from the reaction of nitrogen and oxygen gases during combustion at high temperatures. Spark-ignition vehicles will decrease NO_x emissions, especially in urban areas, because of their use of catalytic converters. SO_x gases are normally SO_2 and SO_3. They are produced during gas processing, oil sand production, coal combustion, and fossil fuel processing and burning. All of these are being analyzed in this study. Lastly, $PM_{2.5}$ has been described in detail and will be a main focus.

Vehicles Analyzed

There were seventeen fuel/vehicle mixes chosen. Some of the types of vehicles need to be explained more extensively and expanded upon. Conventional spark-ignition (CSI) vehicles have a system where the air-fuel mixture in the combustion chamber of the internal combustion engine is ignited by a spark. CSI vehicles use catalytic converters. Spark-ignition direct injection (SIDI) vehicles also use catalytic converters, but the highly pressurized fuel is injected directly into the combustion chamber in two or four stroke engines. This increases fuel efficiency and reduces emission levels in most cases. Compression-ignition direct injection (CIDI) vehicles lack a catalytic converter and have diesel engines. These vehicles have the highest thermal efficiency of any engine due to a high compression ratio, and they have less CO_2 emissions than other vehicles[12].

Well-to-Wheel, Well-to-Pump, and the Urban Share

When analyzing the results of this study, Figures 3-24 will have certain terms in their titles that need to be clarified in order to gain a full understanding of what GREET has output. “Well-to-pump” (WTP) refers to the energy use and emissions associated with the production and distribution activities of the different transportation fuels chosen. “Well-to-well” (WTW) includes WTP, but also includes the energy use and emissions associated with the actual operation of the different vehicles chosen in order to provide a full life-cycle analysis with all the pathways included. WTP graphs have been compiled in order to see how much of a factor the vehicle operations play in the energy and emission factors. If the vehicle operations don’t play a major factor, then the WTW analysis will not be as valuable. Finally, the Urban Share is the emissions that would be released among a dense population where urban sprawl and industry are concentrated[11]. This is important because the emissions problems and violations occur in regions where many vehicles are driven with the rural areas extracted from the equation.

III. Results

Well-to-Wheel

Figure 3 simply reveals that HEVs and EVs have lower energy consumption than the other types. Electric Vehicles have the lowest energy consumption at approximately 4000 BTUs/mile compared to the CSI gasoline vehicles at 9000 BTUs/mile. Most HEVs and EVs eliminate the internal combustion engine and fuel/exhaust systems. Instead, an electric motor and battery system added, which decreases the amount of energy consumed from fuel production and addition[18]. Natural gas vehicles have lower total energy consumed than gasoline vehicles in all applicable areas.

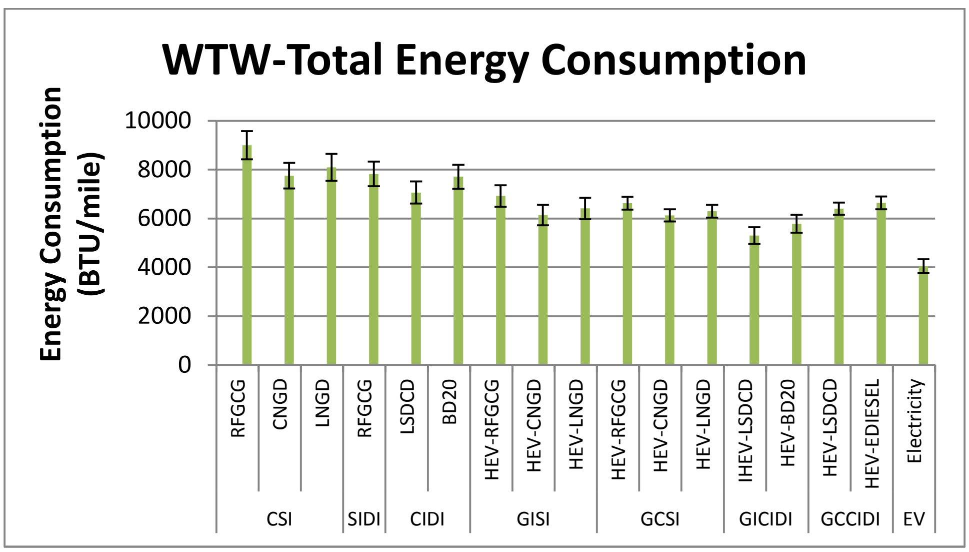

Figure 3. WTW Total Energy Consumption vs. Vehicle Type

Figure 4 shows basically the same pattern as Figure 3 besides a few exceptions. The GICIDI bio-diesel vehicle uses less fossil fuel than most other vehicles since most of the fossil fuels consumed are replaced by renewable organic material. Also, LNGD vehicles consume more fossil fuels than their conventional gasoline counterparts when transportation is taken into account.

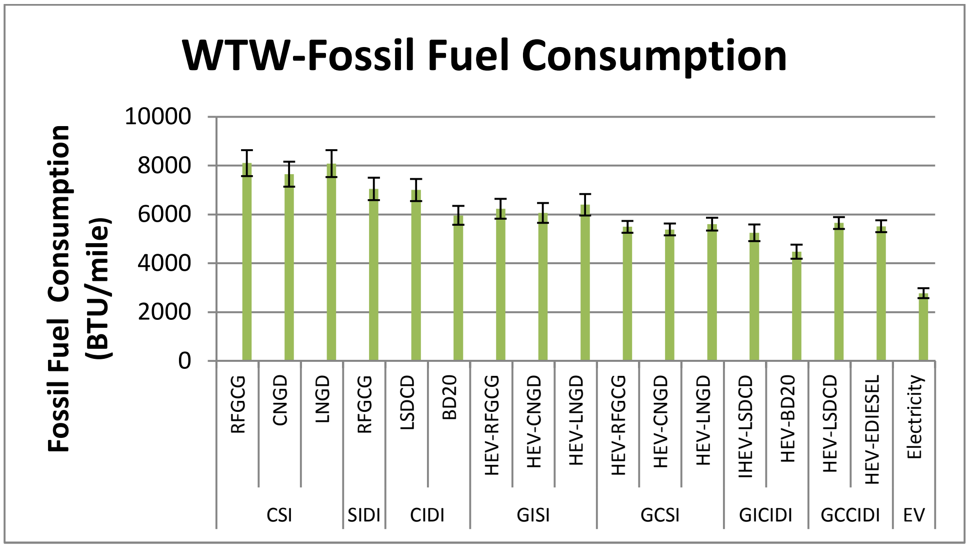

Figure 4. WTW Fossil Fuel Consumption vs. Vehicle Type

Figure 5 indicates that natural gas vehicles seem to be a great alternative when compared to diesel and gasoline. This is mostly because less petroleum is used over their life cycle when compared to gasoline and diesel vehicles. Even when compared to most HEVs, natural gas emits less GHGs except for the bio-diesel and electric vehicles since bio-fuel replaces fossil fuels for bio-diesel vehicles and the internal combustion engine is replaced with an electric motor for electric vehicles.

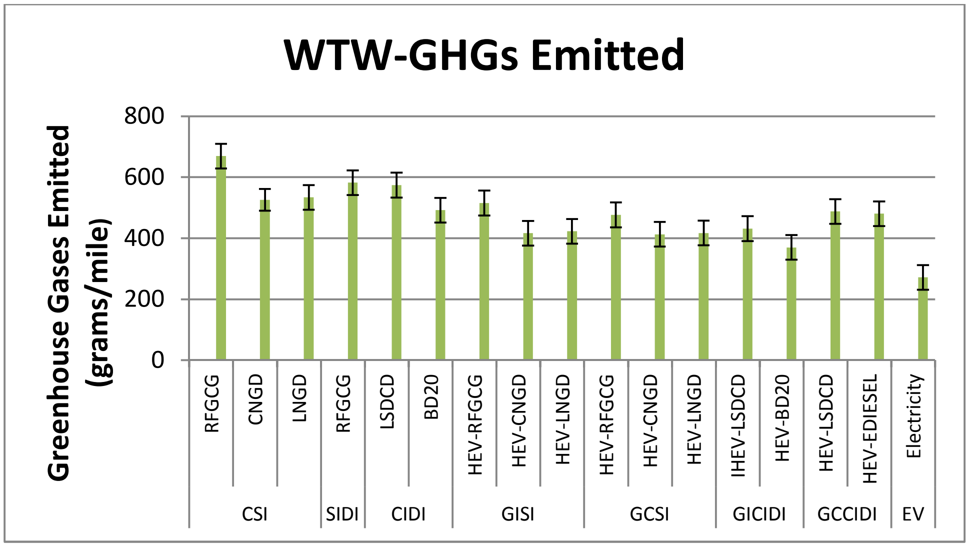

Figure 5. WTW Greenhouse Gases Emitted vs. Vehicle Type

Figure 6 outlines what most already know: spark-ignition vehicles use catalytic converters. These operate at the stoichiometric ratio where there is barely enough oxygen for combustion. CO is the product of incomplete combustion, which causes the emission of CO to be the highest for all the SIDI, GISI, and GCSI vehicles[17].

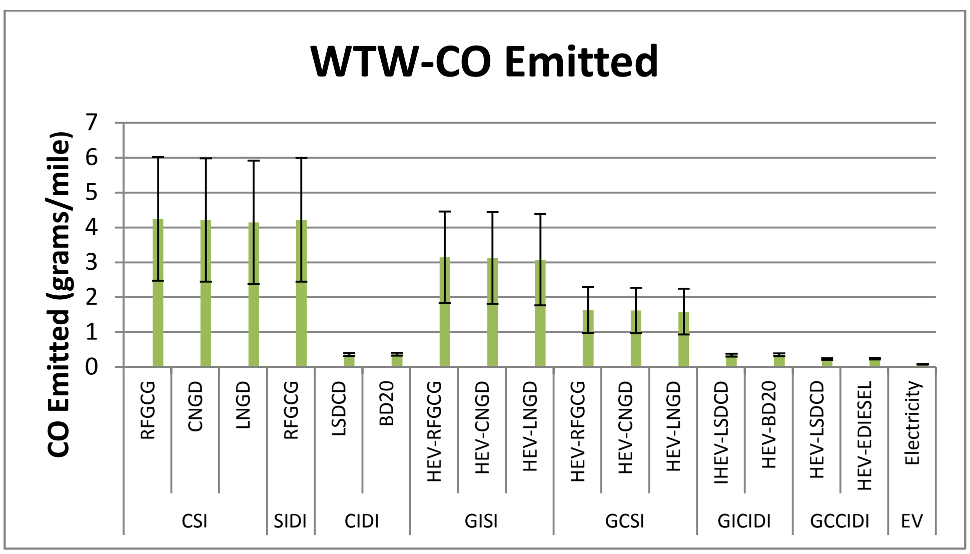

Figure 6. WTW Carbon Monoxide Emitted vs. Vehicle Type

Figure 7 illustrates another principal most already know: spark-ignition vehicles decrease NOx emissions as long as temperature and combustion standards are met[17]. LNG vehicles, CSI or GISI, seem to reduce the emissions. Catalytic converters' purpose was to decrease NOx and smog; however, Figure 7 reveals that they do their job only relatively well when compared to the other vehicle types.

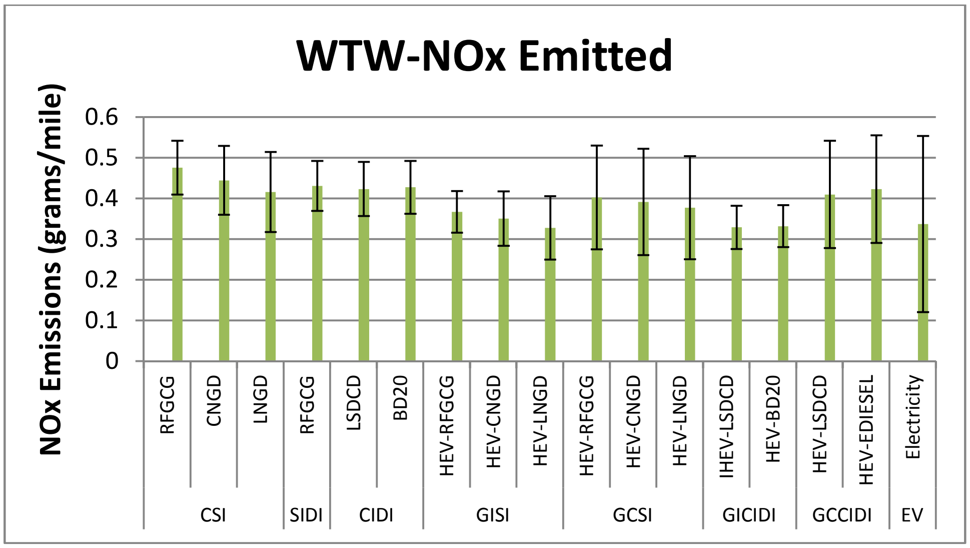

Figure 7. WTW Nitrous Oxides Emitted vs. Vehicle Type

Figure 8 reveals that grid connected and electric cars have higher SOx than other vehicles. This is because the TVA mix includes a substantial amount of coal, and the use of the batteries (if not recharged from a renewable resource) transfers pollution from the tail pipes to the smoke stacks[19]. All other vehicles are below 0.2 grams/mile.

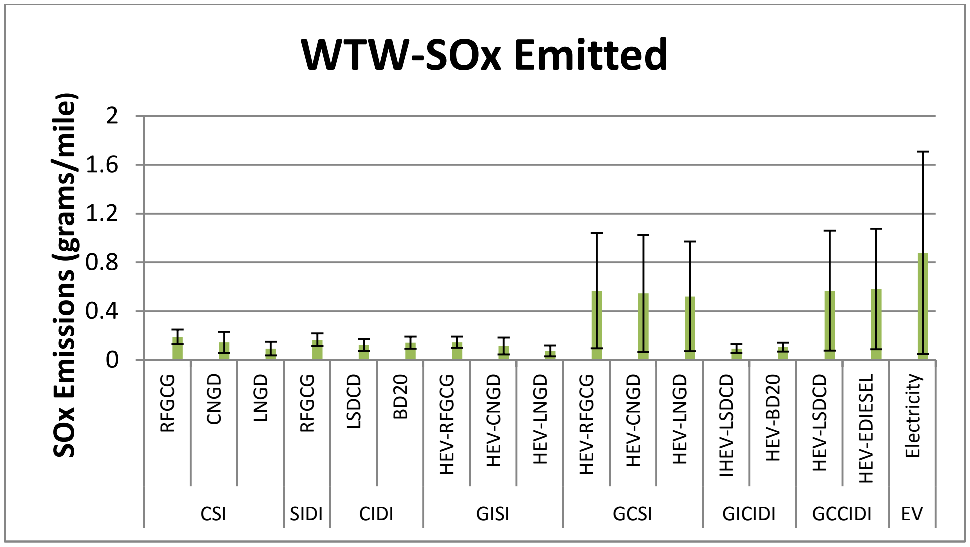

Figure 8. WTW Sulfur Oxides Emitted vs. Vehicle Type

Figure 9 shows that natural gas and electric vehicles are the best options to reduce PM2.5 emissions. To reiterate, this is important for Chattanooga since our city has been designated a “Nonattainment Area” by the EPA. The city is now trying to draft a Redesignation Plan in order to designate it a “Maintenance Area” for attainment[8]. Natural gas and electric fleets could play a big role in this.

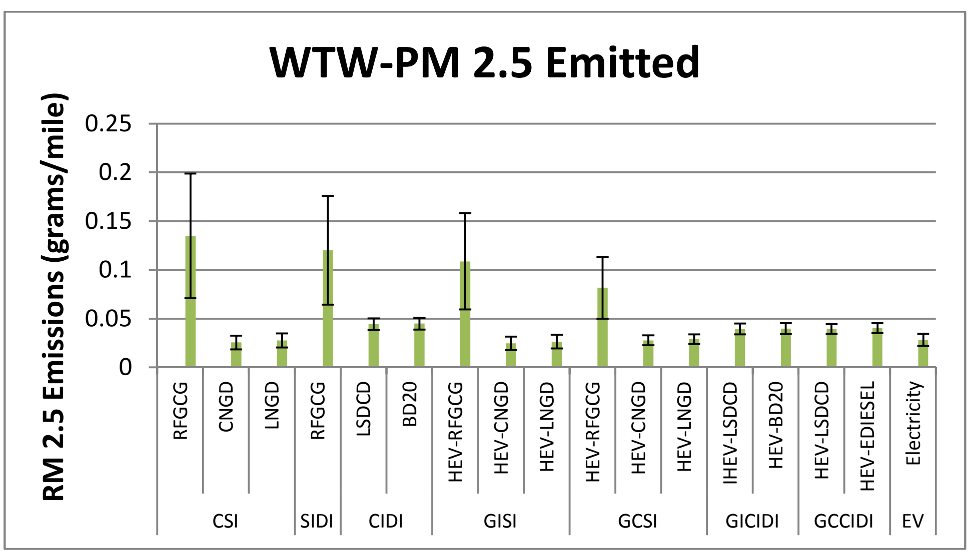

Figure 9. WTW Particulate Matter 2.5 Microns Emitted vs. Vehicle Type

Well-to-Wheel: Urban Share

Figure 10 shows the same results as Figure 6. There is therefore no difference between the carbon monoxide emissions in rural and urban areas. Since incomplete combustion is taking place in each area due to the catalytic converter, the results will not change.

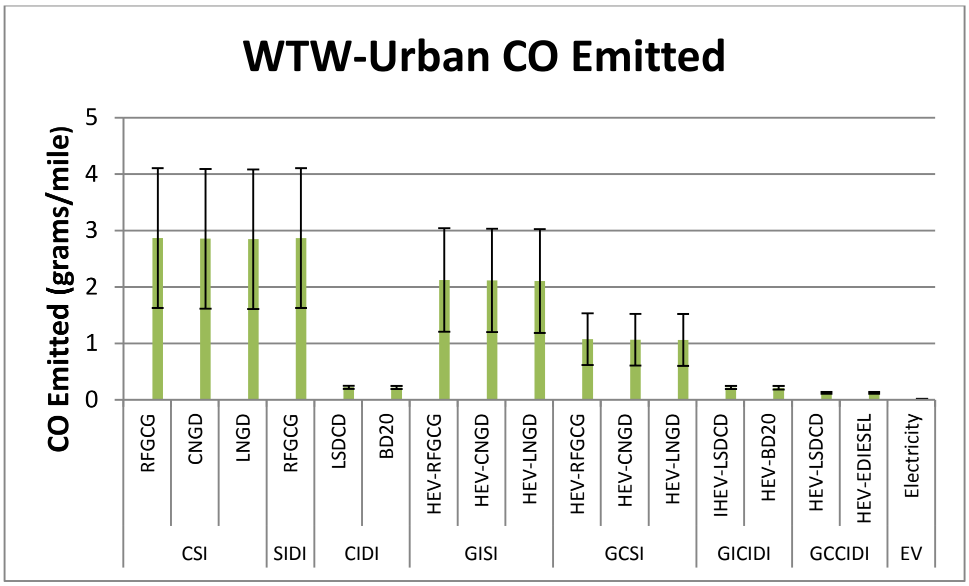

Figure 10. WTW Urban Share of Carbon Monoxide Emitted vs. Vehicle Type

Figure 11 is actually quite a bit different than Figure 7. This reveals that even though the NOx emissions for all the vehicles may be similar for the full life-cycle when rural and urban areas are combined, NOx emissions over the densely populated areas are decreased when using LNGD, CNGD, and EVs. This is because the vehicle emissions themselves, minus the production and transportation of the vehicles and fuels, are less for these types of vehicles and decrease the smog over the areas that the majority of individuals live in.

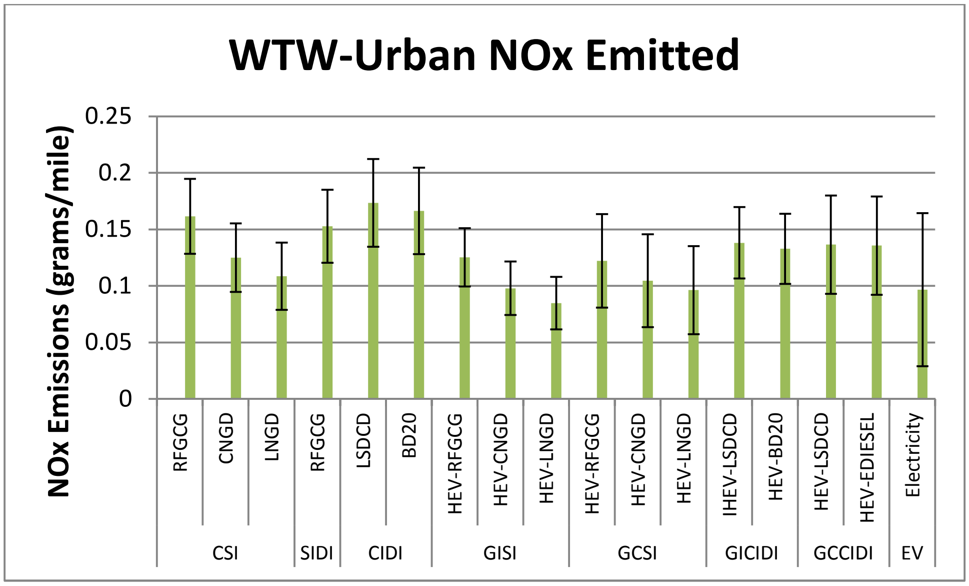

Figure 11. WTW Urban Share of Nitrous Oxides Emitted vs. Vehicle Type

Similar to CO emissions, Figure 12 produces the same results as Figure 8. This is because the TVA Mix includes 37.5% coal[14]. Since that is true, all the electric vehicles and grid connected vehicles produce SO_x at the smokestack through production at the coal-fired power plants[19].

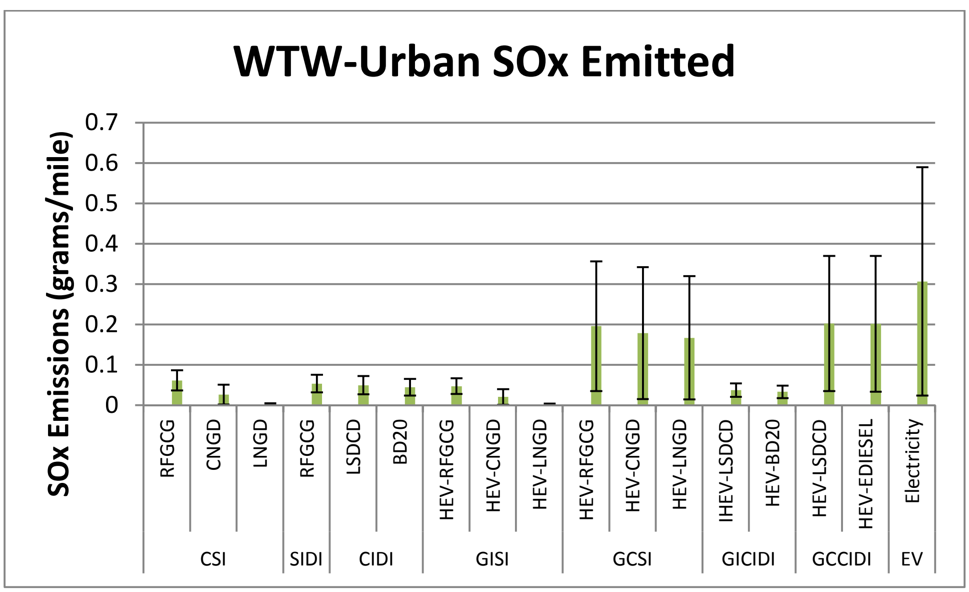

Figure 12. WTW Urban Share of Sulfur Oxides Emitted vs. Vehicle Type

Like Figure 9, Figure 13 shows us that natural gas and electric vehicles decrease $PM_{2.5}$ emissions. Figure 13 is of particular importance since the urban area of Chattanooga is the focal point of this research. Emissions from the tailpipe, brake wear, and tire wear are all decreased due to natural gas usage.

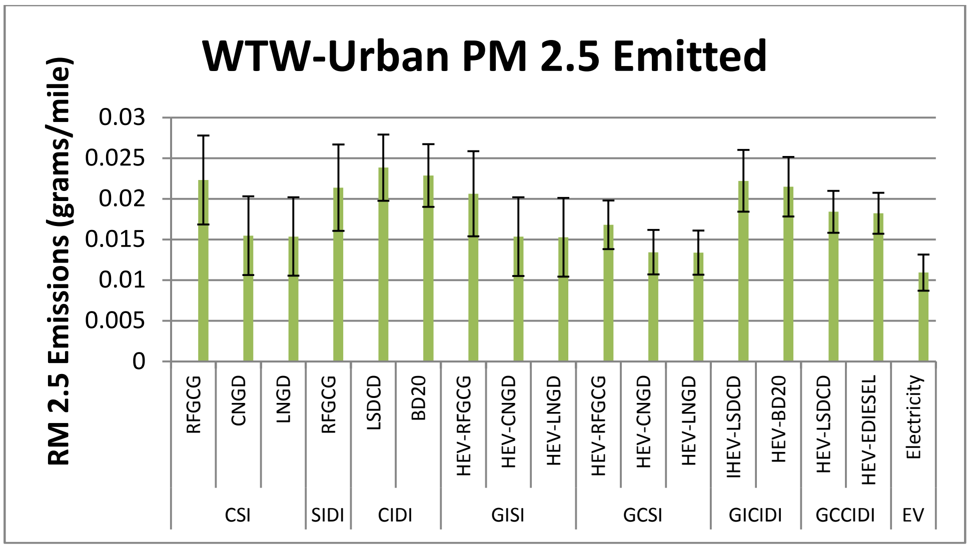

Figure 13. WTW Urban Share of Particulate Matter 2.5 Emitted vs. Vehicle Type

Well-to-Pump

Figure 14 reveals a few interesting details that the WTW results alone couldn't show us. First of all, hybrid-electric vehicles, and especially standard electric vehicles, consume the most energy when being extracted from the well, refined, and transported. This is because of the high ratio of coal in the generation mix as mentioned before. So even though the electric vehicles have the lowest total energy consumption for the full life-cycle, WTW analysis, the amount of energy consumed when their batteries are being used alone is something that needs to be taken into consideration. On the other hand, natural gas production consumes less energy since not as much coal, oil, and/or petroleum is being burned or used in the production on natural gas[20].

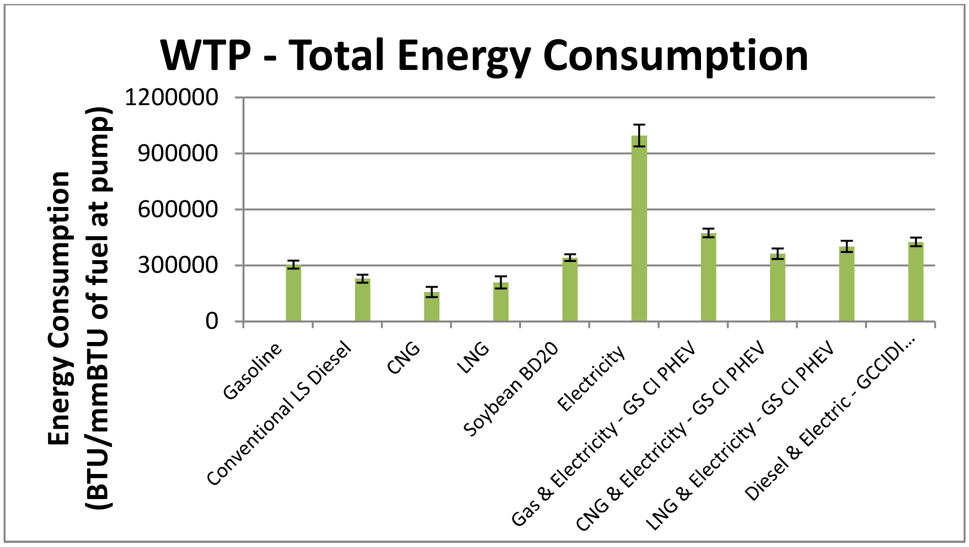

Figure 14. WTP Total Energy Consumption vs. Fuel Type

Figure 15 provides the same results as Figure 14. The vehicles' energy consumption for all factors appear to be equal across the board. Therefore, the amount of natural gas, coal, and petroleum consumed follow the same trend as the total energy consumption for each vehicle analyzed.

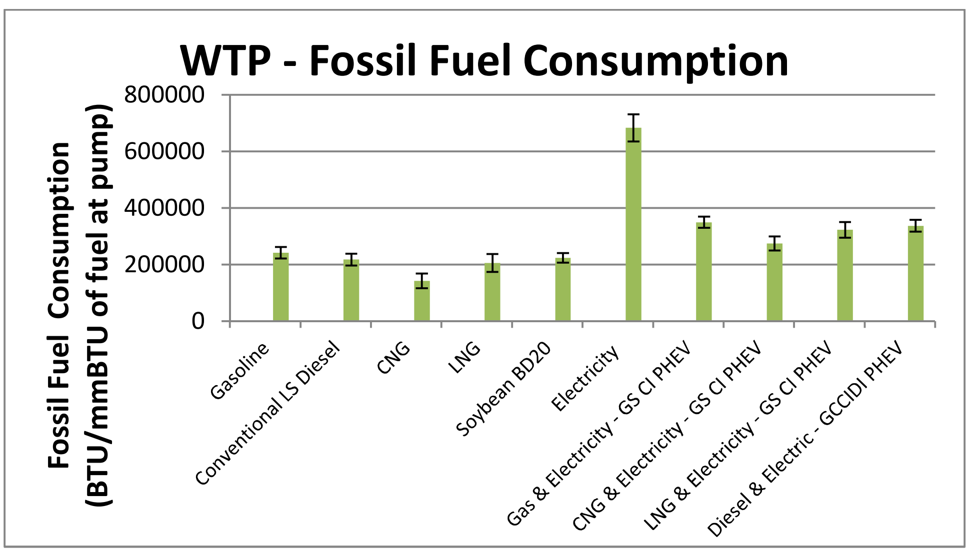

Figure 15. WTP Fossil Fuel Consumption vs. Fuel Type

Since electric and hybrid-electric vehicles consume the most fossil fuels and energy, Figure 16 confirms that they also emit the most greenhouse gases when being produced. This is due to the significant quantities of raw materials in electric vehicles systems and the manufacture of the batteries by removing nickel and other metals from the earth through mining[18]. The bio-diesel option emits the least amount of GHGs since the credit, CO_2 removal from the air, given for the growing of soybean causes the emissions to be that much lower. All of the other options (gasoline, diesel, and natural gas) have very few GHG emissions.

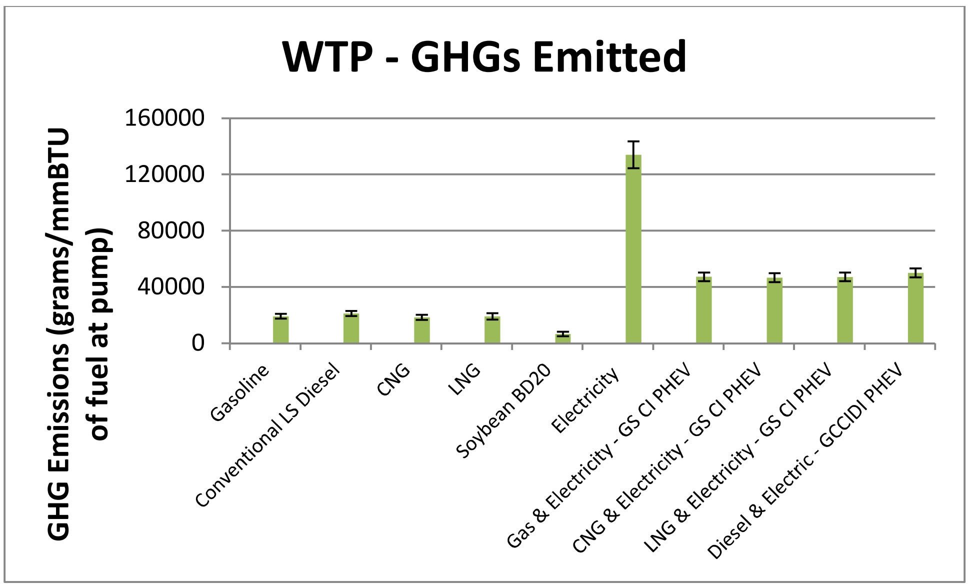

Figure 16. WTP Greenhouse Gases Emitted vs. Fuel Type

Compared to the WTW results from CO emissions where all gasoline and natural gas vehicles revealed the highest emissions because of the spark-ignition engines, the WTP results show that the standard electric, gasoline, CNG, or gasoline/CNG/electric options have the highest values. The gasoline emissions of CO are so high because of the burning of petroleum that occurs when extracting and refining the gasoline which produces CO and CO_2. The emissions of CO in CNG production are usually because of the low efficiency of the natural gas in the boilers[20]. The high emissions of the standard electric option in Figure 17 have already been explained in the discussion of Figure 16.

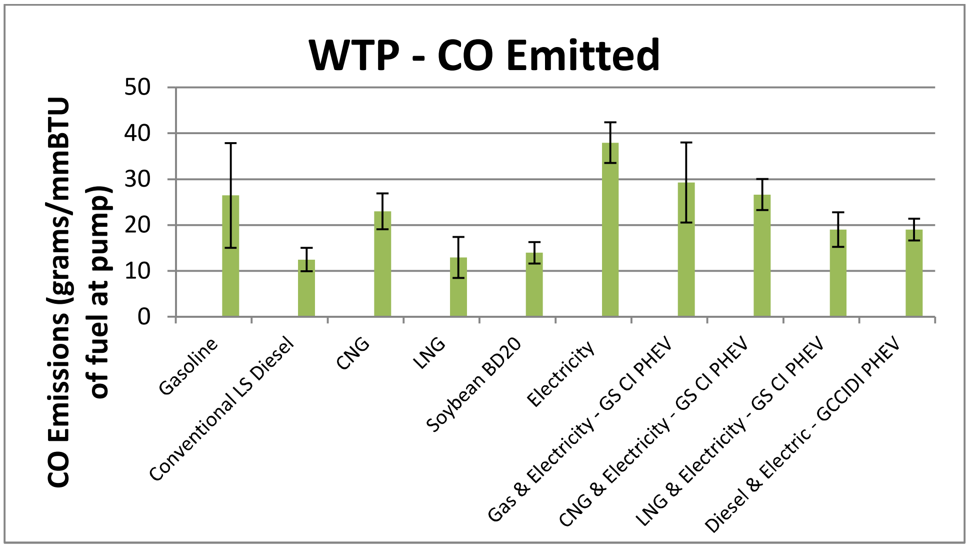

Figure 17. WTP Carbon Monoxide Emitted vs. Fuel Type

The same conclusions that were reached from the GHG emissions results in Figure 16 can be applied to NO_x emissions in Figure 18. Significant amounts of raw materials, fossil fuels, and coal go into battery use in electric vehicles, which increases the amount of NO, NO_2, and N_2O emissions. This causes these figures to have a similar trend.

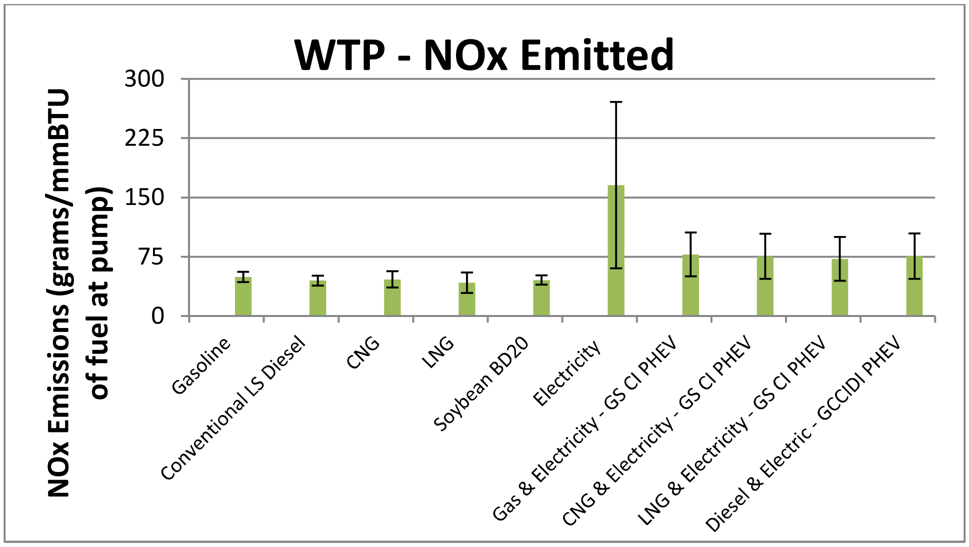

Figure 18. WTP Nitrous Oxides Emitted vs. Fuel Type

The conclusions that were reached from the GHG emissions results in Figure 16 and 18 can also be applied to SO_x emissions in Figure 19. Significant amounts of raw materials, fossil fuels, and coal go into battery use in electric vehicles, which increases the amount of SO_2 and SO_3 emissions. This causes these figures to have a similar trend. Figure 19 can also be compared to the WTW results in Figure 8, which shows the SO_x emissions being transferred from the tail pipe to the smokestack and ultimately shown here in Figure 19.

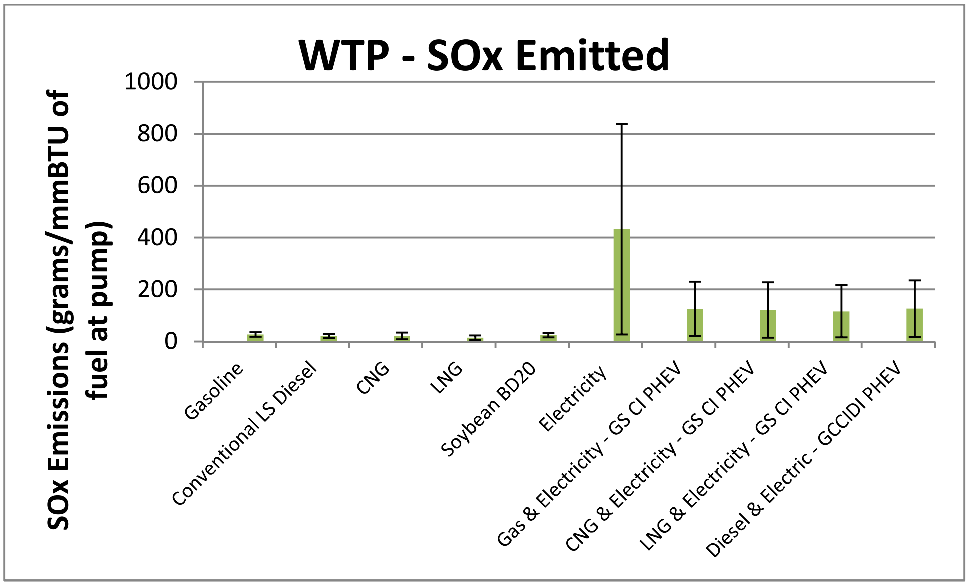

Figure 19. WTP Sulfur Oxides Emitted vs. Fuel Type

Gasoline production emits the highest amount of $PM_{2.5}$ with electric vehicle production coming in second with the gasoline/electric mix as shown in Figure 20. Since distillate and residual fuels are derived from petroleum and reformulated into gasoline, and combustion cause the release of $PM_{2.5}$ into the atmosphere[20]. Natural gas production, which primarily gives off CH_4, releases only a small amount of particulate matter in the air since the natural gas is lighter than air[21], and because it doesn't have to be burned and refined as much as gasoline does.

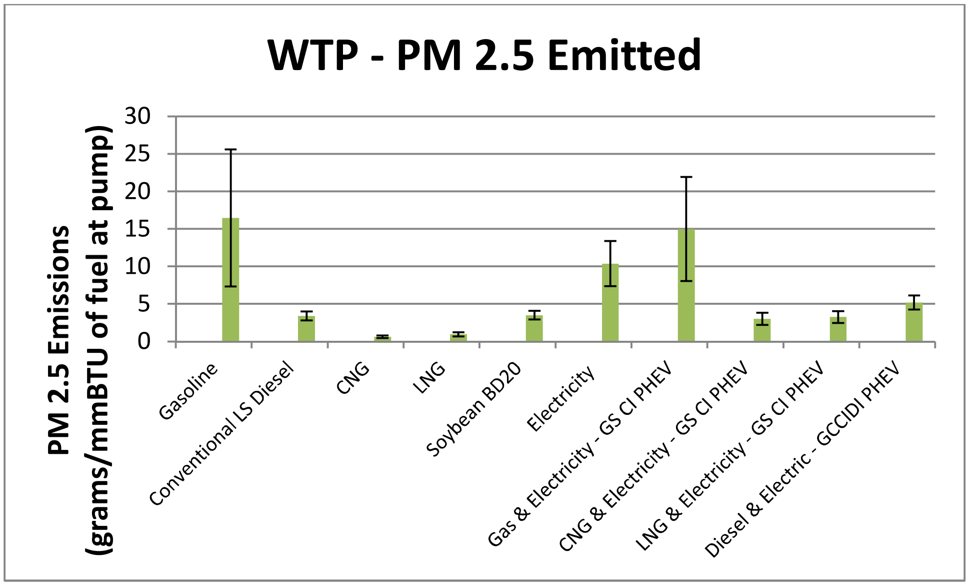

Figure 20. WTP Particulate Matter 2.5 Microns Emitted vs. Fuel Type

Well-to-Pump: Urban Share

Compared to Figure 17, the urban CO emitted for CNG and LNG is lower in Figure 21 below when conventional diesel was slightly the lower under total WTP CO emitted in Figure 17. Once again, this is important because the emissions in urban areas for these fuel types have the least environmental impact in the most densely packed areas. This is overshadowed by the WTW urban CO emissions in Figure 10, but it is still important to see how the manufacture of natural gas leaves a small eco-footprint.

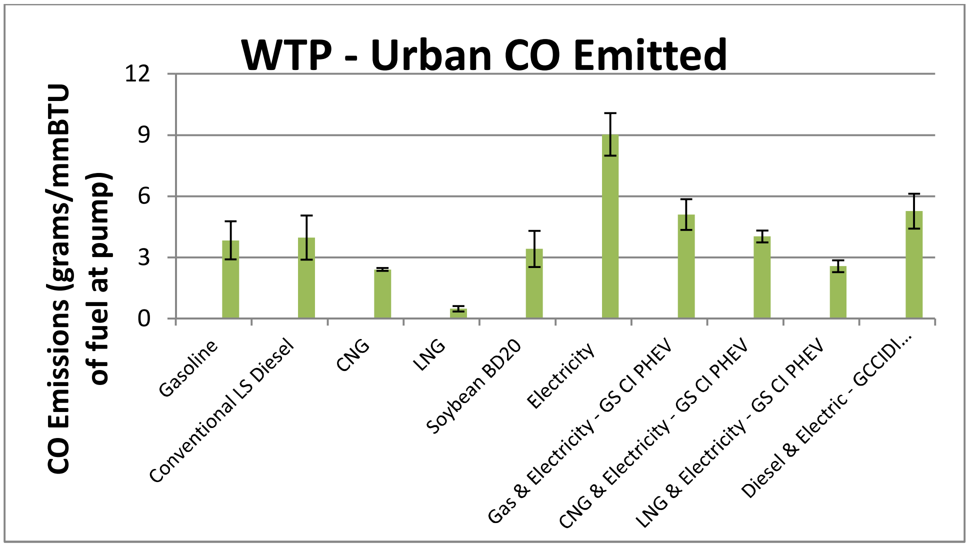

Figure 21. WTP Urban Share of Carbon Monoxide Emitted vs. Fuel Type

Figure 22 sums up another major positive for natural gas: natural gas manufacturing along with CNG and LNG vehicles plus their hybrid counterparts emit the least amount of NO_x gases. Figure 11 and 18 reveal they have the lowest WTW urban emissions and WTP overall emissions of NO_x. Of course, electric vehicle battery use emits the most NO_x gases for the same reasons mentioned before in Figure 18.

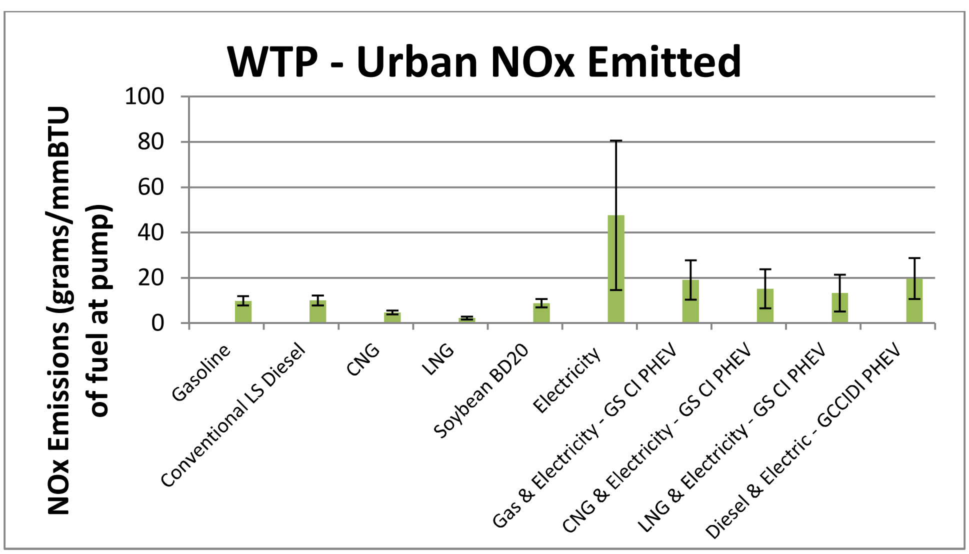

Figure 22. WTP Urban Share of Nitrous Oxides Emitted vs. Fuel Type

In the same way as the other urban emissions analyzed, electric vehicles emit the most SO_x gases and natural gas vehicles emit the least as shown in Figure 23. So not only do all the grid-connected vehicles and standard electric vehicles emit the most urban SO_x gases over the full life cycle, but they also emit the most from WTP too. The amount of SO_x gases emitted from gasoline, diesel, bio-diesel, and natural gas are negligible.

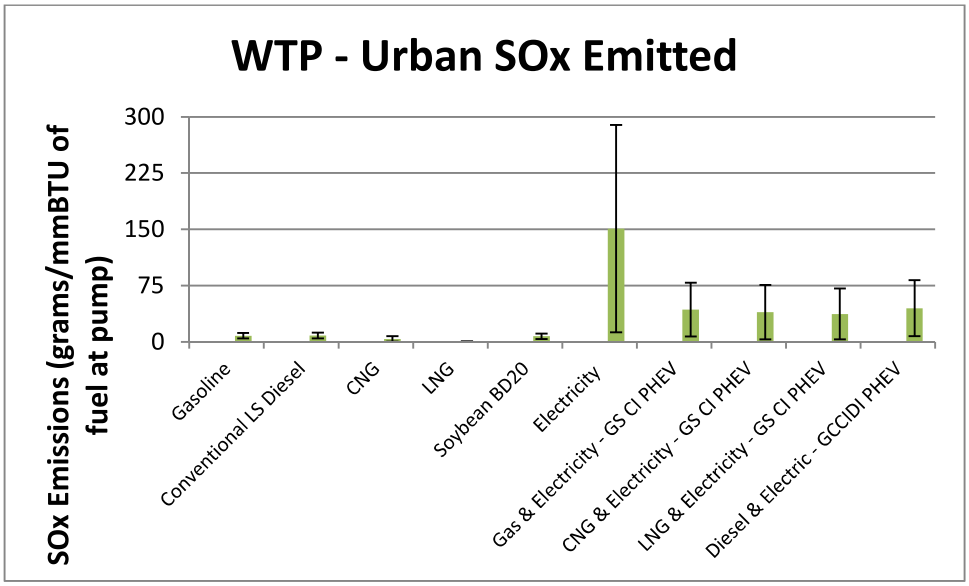

Figure 23. WTP Urban Share of Sulfur Oxides Emitted vs. Fuel Type

Lastly, Figure 24 conveys the main point all the other WTP figures: natural gas vehicles emit the least amount of pollutants, especially $PM_{2.5}$. None of the other fuel/vehicle types even compare when analyzing WTP. Only the standard electric vehicle rivals standard natural gas vehicles and natural gas hybrids.

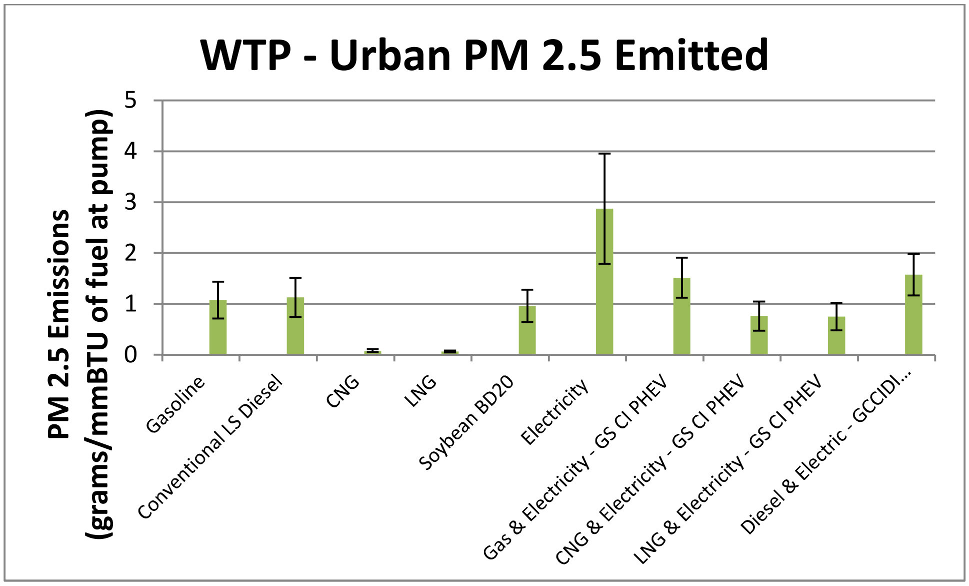

Figure 24. WTP Urban Share of Particulate Matter 2.5 Emitted vs. Fuel Type

Cost Analysis

Table 3 is a breakdown of the gallons per mile, dollars per gallon, and ultimately, the dollars per mile of each type of vehicle analyzed. All units, specifically the gas and electricity units, have been converted to gallons only in order to get cost on a more uniform, decipherable level[22,23,24,25,26]. When it comes down to cost alone, all the LNG vehicles are the lowest with costs between \$0.016/mile to \$0.024/mile. However, the hold time for LNG is limited because it will vent when not being used.

Another great option includes the grid-connected e-diesel car at \$0.069/mile. On the other hand, the environmental cost will be high since it has higher GHG, NO_x, SO_x, and $PM_{2,5}$ emissions over the full life-cycle than does natural gas vehicles. The standard electric vehicle is also cheap with \$0.045/mile, but the hidden cost of maintenance, costs to operate, costs to manufacture, and WTP emissions from coal-fired power-plants coupled with the inconvenience of a purely electric car make this option less attractive[18,19].

That leaves all the CNG vehicles ranging in cost from $0.085/mile to $0.127/mile. Refueling is easy, there is an unlimited hold time, low GHG and $PM_{2.5}$ emissions, less price fluctuation, and the engine for the vehicle is quieter especially when compared to diesel trucks[21]. For these reasons, the CNG vehicles seem like the best option when taking the environmental and economic costs each into consideration.

Table 3. Cost per Mile of Fuel for Each Type of Vehicle Analyzed

Calculated Cost of Fuel per Mile			
	gallons of gas equivalent/mile	**$/gallons of gas equivalent**	**$/mile**
Baseline Gasoline Vehicle: Gasoline	6.17E-02	3.299	$ 0.203
Dedicated CNGV	5.99E-02	2.130	$ 0.127
Dedicated LNGV	5.99E-02	0.395	$ 0.024
SIDI Vehicle: Gasoline	5.36E-02	3.299	$ 0.177
CIDI Vehicle: Conventional and LS Diesel	5.14E-02	3.733	$ 0.192
CIDI Vehicle: BD20	5.14E-02	3.966	$ 0.204
Grid-Independent SI HEV: Gasoline	4.76E-02	3.299	$ 0.156
Grid-Independent SI HEV: CNG	4.74E-02	2.130	$ 0.101
Grid-Independent SI HEV: LNG	4.74E-02	0.395	$ 0.019
Grid-Connected SI PHEV: Gasoline	4.01E-02	3.299	$ 0.132
Grid-Connected SI PHEV: CNG	3.97E-02	2.130	$ 0.085
Grid-Connected SI PHEV: LNG	3.97E-02	0.395	$ 0.016
Grid-Independent CIDI HEV: Conventional and Low-Sulfur Diesel	3.85E-02	3.733	$ 0.144
Grid-Independent CIDI HEV: BD20	3.85E-02	3.966	$ 0.153
Grid-Connected CIDI PHEV: Conventional and Low-Sulfur Diesel	4.01E-02	3.733	$ 0.150
Grid-Connected CIDI PHEV CS Mode: E-Diesel	3.69E-02	1.867	$ 0.069
	gallons/mile	**$/KWh**	**$/mile**
Electric Vehicle, w/ charger	1.81E-02	0.096	$ 0.045

IV. Discussion of Results

To summarize, after running the stochastic simulations and doing some statistical analysis, the results above could be analyzed by fuel type and vehicle type. The focus was on the vehicle/fuel mixes with the lowest amount of energy consumption and pollutants emitted. The vehicles with the lowest amount of total energy consumption over the full life-cycle were the HEVS and the standard EV, excluding the gasoline hybrid, with approximately 5000 to 6000 BTU/mile. They also consumed the fewest amount of fossil fuels. The natural gas vehicles, CNG and LNG, consumed less energy at 8000 BTU/mile than the gasoline vehicles at 9000 BTU/mile, but consumed approximately the same amount of energy as the diesel vehicle. The GICIDI bio-diesel vehicle uses less fossil fuel at 4000 BTU/mile than most other vehicles since 20% of the fossil fuels consumed are replaced by renewable organic materials.

Standard EVs emitted the least amount of GHGs at 300 grams/mile. The natural gas vehicles, including the hybrids, emitted approximately 400-500 grams/mile compared to the diesel vehicles with 600 grams/mile. The CSI-RFGCG had the highest emissions with 700 grams/mile with the SIDI-RFGCG vehicle emitting approximately the same amount as the CNGD and LNGD vehicles.

Spark-ignition vehicles emit the most CO because they use catalytic converters to remove NO_x gases. All the other vehicle emissions of CO hardly compare with the amount of CO released by the spark-ignition vehicles. Furthermore, the amount of NO_x removed by the spark-ignition vehicles was relatively small compared to the CO released.

Natural gas vehicles emitted the lowest amount of NO_x and $PM_{2.5}$, only receiving competition from the standard EV. The CSI-CNGD and CSI-LNGD emitted 0.4-0.45 grams/mile

NO_x and their HEV counterparts emitted 0.3-0.35 grams/mile NO_x. The entire selection of natural gas vehicles emitted only 0.025 grams/mile of $PM_{2.5}$ along with the EV. The EV had the least amount of urban $PM_{2.5}$ emissions with 0.01 grams/mile, natural gas vehicles emitted 0.015 grams/mile, and all other vehicles emitted at least 0.02 grams/mile.

Grid connected and electric cars have higher SOx than other vehicles. This is because of the high amount of coal from the generation mix. The pollutant is transferred from the tailpipe of the vehicle to the smokestack where the manufacturing of the electricity to charge the vehicle takes place. The urban SO_x emissions for natural gas vehicles are practically negligible.

Overall, WTP emissions were the lowest for vehicles that used pure CNG and LNG excluding their hybrid equivalents. Bio-diesel was slightly lower for fossil fuel consumption. In addition, diesel was slightly less than CNG for CO emissions.

CNG vehicles, ranging in cost from $0.085/mile to $0.127/mile, appear to be the best option. Refueling the vehicle is easy, there is an unlimited hold time for the fuel, low GHG and $PM_{2.5}$ emissions, less price fluctuation in the current market, and the engine for the vehicle is quieter especially when compared to diesel trucks.

V. Conclusion

In conclusion, each vehicle/fuel mix analyzed consumes a certain amount of energy and emits a quantifiable amount of pollutants when given a specific set of parameters. In this case, the parameters were the type of fuel mix from TVA, the selected vehicle year of 2015, the vehicle weight specified in the heavy-duty vehicle range, and the type of simulation technique, which was the Hammersely Sequence Sampling. These inputs, along with seventeen fuel/vehicles mixes, specific pollutants, and cost considerations, were used to investigate the environmental impact of the transition from petrol diesel to natural gas in the municipal fleets of Chattanooga, Tennessee.

The energy consumption included coal, petroleum, natural gas, and other power generating sources like electricity and biomass/bio-diesel. The pollutants investigated included greenhouse gases (GHGs), carbon monoxide (CO), nitrous oxides (NO_x), sulfur oxides (SO_x), and particulate matter ($PM_{2.5}$). The pollutant of particular importance to the city of Chattanooga is $PM_{2.5}$ since the city is designated a Nonattainment Area by the EPA and is looking to be re-designated as a Maintenance Area.

Natural gas vehicles emitted the lowest amount of NO_x and $PM_{2.5}$, only receiving competition from the standard EV with slightly lower emissions. The natural gas vehicles' emissions of GHGs, including the hybrids, emitted approximately 400-500 grams/mile compared to the diesel vehicles with 600 grams/mile, and they once again only received competition from the standard EV which emitted the least amount of GHGs at 300 grams/mile. Overall, WTP emissions were the lowest for vehicles that used pure CNG and LNG, which is important to note since the manufacture and refining of the fuel occurs in the WTP phase. Also, natural gas has shown to be a cleaner alternative than diesel fuel. Compared to diesel, it has approximately 15%

less greenhouse gases, 30% less nitrous oxides for urban environments, and 50% less $PM_{2.5}$ for combustion in a vehicle engine. To summarize, CNG seems like the best option for a fuel because it is cheap, fueling the vehicle is easy, there is an unlimited hold time for the fuel, low GHG and $PM_{2.5}$ emissions, less price fluctuation in the current market, and the engine for the vehicle is quieter especially when compared to diesel trucks.

VI. Appendix

Table 4. CSI, SIDI, CIDI Per-Mile Fuel Consumption and Emissions of Vehicle Operation

	Baseline Gasoline Vehicle: Gasoline	Dedicated CNGV	Dedicated LNGV	SIDI Vehicle: Gasoline	CIDI Vehicle: Conventional and LS Diesel	CIDI Vehicle: BD20
Urban Emission Shares	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%
MPG (per gasoline equivalent gallon)	16.2	16.7	16.7	18.7	19.5	19.5
Total fuel use (Btu/mile)	6,917	6,715	6,715	6,015	5,764	5,764
Fossil fuel use (Btu/mile)	6,456	6,715	6,715	5,614	5,764	4,683
Coal use (Btu/mile)	0	0	0	0	0	0
Natural gas use (Btu/mile)	0	6,715	6,715	0	0	0
Petroleum use (Btu/mile)	6,456	0	0	5,614	5,764	4,683
Emissions: grams/mile						
CO	4.074	4.074	4.074	4.074	0.285	0.285
NOx	0.134	0.134	0.134	0.134	0.165	0.165
PM2.5: exhaust	0.014	0.014	0.014	0.014	0.018	0.018
PM2.5: brake and tire wear	0.007	0.007	0.007	0.007	0.007	0.007
SOx	0.008	0.002	0.000	0.007	0.003	0.003
GHGs	535	406	408	465	459	460

Table 5. GISI, GCSI Per-Mile Fuel Consumption and Emissions of Vehicle Operation

	Grid-Independent SI HEV: Gasoline	Grid-Independent SI HEV: CNG	Grid-Independent SI HEV: LNG	Grid-Connected SI PHEV: Gasoline, CD Combined	Grid-Connected SI PHEV: Gasoline, CS Mode	Grid-Connected SI PHEV: CNG, CD combined	Grid-Connected SI PHEV: CNG, CS Mode	Grid-Connected SI PHEV: LNG, CD combined	Grid-Connected SI PHEV: LNG, CS Mode
Urban Emission Shares	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%
MPG (per gas equivalent gal)	21.1	21.1	21.1	41.1	16.5	42.6	16.5	42.6	16.5
Total fuel use (Btu/mile)	5,321	5,321	5,321	2,728	6,813	2,636	6,813	2,636	6,813
Fossil fuel use (Btu/mile)	4,966	5,321	5,321	2,052	6,359	1,790	6,813	1,790	6,813
Coal use (Btu/mile)	0	0	0	1,121	0	1,522	0	1,522	0
Natural gas use (Btu/mile)	0	5,321	5,321	197	0	268	6,813	268	6,813
Petroleum use (Btu/mile)	4,966	0	0	734	6,359	0	0	0	0
Emissions: grams/mile									
CO	3.015	3.015	3.015	0.343	3.015	0.343	3.015	0.343	3.015
NOx	0.105	0.105	0.105	0.012	0.105	0.012	0.105	0.012	0.105
PM2.5: exhaust	0.014	0.014	0.014	0.002	0.014	0.002	0.014	0.002	0.014
PM2.5: brake and tire wear	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
SOx	0.006	0.001	0.000	0.001	0.008	0.000	0.002	0.000	0.000
GHGs	412	321	323	61	526	47	410	48	412

Table 6. GICIDI, GCCIDI, EV Per-Mile Fuel Consumption and Emissions of Vehicle Operation

	Grid-Independent CIDI HEV: Conventional and Low-Sulfur Diesel	Grid-Independent CIDI HEV: BD20	Grid-Connected CIDI PHEV: Conventional and Low-Sulfur Diesel, CD Combined	Grid-Connected CIDI PHEV: Conventional and Low-Sulfur Diesel, CS Mode	Grid-Connected CIDI PHEV: E-Diesel, CD Mode	Grid-Connected CIDI PHEV CS Mode: E-Diesel, CS Mode	Electric Vehicle, w/ charger
Urban Emission Shares	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%
MPG (per gasoline equivalent gallon)	26.0	26.0	40.3	17.1	53.2	17.1	55.1
Total fuel use (Btu/mile)	4,323	4,323	2,784	6,562	2,109	6,562	2,034
Fossil fuel use (Btu/mile)	4,323	3,512	2,164	6,562	1,489	6,158	1,381
Coal use (Btu/mile)	0	0	1,227	0	1,227	0	1,175
Natural gas use (Btu/mile)	0	0	238	0	238	0	207
Petroleum use (Btu/mile)	4,323	3,512	699	6,562	24	6,158	0
Emissions: grams/mile							
CO	0.285	0.285	0.028	0.285	0.000	0.285	0.000
NOx	0.135	0.135	0.013	0.135	0.000	0.135	0.000
PM2.5: exhaust	0.018	0.0175	0.002	0.018	0.000	0.018	0.000
PM2.5: brake and tire wear	0.007	0.0073	0.007	0.007	0.007	0.007	0.007
SOx	0.002	0.001913	0.000	0.004	0.000	0.003	0.000
GHGs	345	346.2292	54	523	0	520	0

Table 7. Vehicle Miles Traveled Share by CD & CS Operations for GCHEV

Vehicle Miles Traveled (VMT) Share by CD and CS Operations for GC HEV					
	Grid-Connected SI PHEV: Gasoline	Grid-Connected SI HEV: CNG	Grid-Connected SI HEV: LNG	Compression Ignition PHEVs: CD and LSD	Grid-Independent CIDI HEVs: E-Diesel
Charge-Depleting (CD) Operation	56.5%	56.5%	56.5%	54.5%	54.5%
Charge-Sustaining (CS) Operation	43.5%	43.5%	43.5%	45.5%	45.5%

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