Life-Cycle Cost Model and Pollutant Emissions Estimator

Greenhouse Gas and Criteria Pollutant Emissions Estimator

Prepared for:
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1.0 Introduction

In January 2008, Westport Innovations Inc. and Clean Energy Fuels Corp. commissioned TIAX LLC[1] to develop a Life-Cycle Cost and Emissions Estimator for the comparison of current and future heavy duty engines fueled by either diesel or natural gas. The model includes three different heavy-duty applications for California: heavy heavy-duty trucks (HHDT), urban buses (UB) and refuse haulers (RH) and was developed to determine the emissions of both greenhouse gases (GHG) and criteria pollutants including oxides of nitrogen (NOx) and particulate matter (PM).

This report details Phase 1 of the project, developing a GHG and criteria pollutant estimator to be subsequently integrated into Westport's life-cycle cost model. The estimator is set-up as a lookup table for various emission factors based upon fuel type, fuel pathway and type of vehicle. Well-To-Tank (WTT) upstream emission factors are determined with the California modified GHGs Regulated Emissions and Energy in Transportation (CA-GREET) Model Version 1.7. This model was originally developed by Argonne National Laboratory (ANL) and modified by TIAX during the development of full fuel cycle emissions of transportation fuels for the California Energy Commission (CEC)[2]. CA-GREET includes California specific inputs ranging from natural gas pipeline losses to electricity distribution factors.

The Tank-To-Wheel (TTW) emission factors are determined from the EMission FACtors (EMFAC) 2007 model created by the California Air Resources Board (CARB) version 2.30.3.501 and the CARB certification values for diesel and natural gas fueled heavy-duty engines. EMFAC calculates grams per mile emission factors that incorporate deterioration of the engine and aftertreatment devices to estimate in-use exhaust emissions. The resultant well-to-wheel (WTW) emissions metrics—in the form of tons per year—are determined by using estimated annual vehicle miles traveled (VMT) and fuel economy (miles per gallon, mpg).

1 TIAX LLC is one of the world's foremost technology, product development, and technology-based consulting firms. TIAX performs assessments, feasibility analyses, and demonstrations of pre-commercial transportation technologies for clients ranging from federal government agencies (the U.S. Department of Energy) to state and local agencies (California Air Resources Board, the California Energy Commission, South Coast and Sacramento Metropolitan AQMDs) and the ports of Los Angeles and Long Beach. TIAX has also helped to develop policies such as California's Alternative Fuels Plan and the DOE's EPAct Program.

2 "Full Fuel Cycle Assessment: Well-To-Wheels Energy Inputs, Emissions, and Water Impacts," Prepared by TIAX LLC for the California Energy Commission, Revised 8/1/2007, CEC-600-2007-004-REV.

2.0 Methodology

In Phase 1 of the project, TIAX was tasked with performing the following items to develop the emission factors lookup table:

a) Create a biogas (BG) scenario in the GREET model to accurately represent CNG and LNG from BG;

b) Develop WTT emission factors for various scenarios using the CA-GREET model for diesel, biodiesel, CNG and LNG. All of the scenarios that were modeled can be found in Section 2.3;

c) Develop TTW emission factors using a combination of EMFAC and CARB certification values; and

d) Create a look-up table to be incorporated into the larger life-cycle cost model.

2.1 Creation of BG Scenario

BG is produced through the anaerobic digestion of organic materials such as municipal solid waste, wastewater sewage, and animal waste. BG can be used for transportation and other energy uses. It contains on average, an estimated 50-80% by volume methane gas (CH_4), 20-50% carbon dioxide (CO_2), and the balance nitrogen (N_2), water, oxygen and trace compounds[3]. Before the BG can either enter the pipeline and become CNG or be liquefied onsite to LNG, the gas must be purified with the removal of CO_2, N_2, water, and trace compounds. For pipeline gas, CO_2 and N_2 must be removed to create a high energy gas. For LNG, the gas must be refrigerated and condensed, in the process removing water, CO_2 and N_2.

TIAX developed a BG emission scenario in GREET that allows for the conversion of various sources of BG, including landfill and anaerobic digesters, into either CNG or LNG. The feedstock to anaerobic digesters can vary from wastewater sludge and cattle manure to agricultural waste and biomass. TIAX used current assumptions in the GREET model related to flare gas and made necessary assumptions and changes to create representative BG scenarios. By using the flare gas scenario, the baseline assumption is that BG is flared and not just vented, and therefore emissions credits are given for the exact amount of BG used (in grams of CO_2) either in the onsite process which uses BG as a fuel or in the final transportation fuel. If the baseline were vented natural gas, then the amount of gas used would be multiplied by the global warming potential (GWP) of methane to determine the amount of CO_2 credits for the pathway.

TIAX contacted and received operational information from Prometheus Energy, who has multiple landfill gas to LNG installations for transportation uses[4]. Their current installations operate completely on BG, using 25% of the gas flow in either turbines or internal combustion engines to produce electricity to operate the refrigeration processes to convert BG to LNG. In addition to the process energy, there is a small amount of grid electricity required to run the pumps and blowers to recover the BG from the landfill. At their Bowerman facility, they required an estimated 37.5 hp for the blowers to remove 770 scfm of landfill gas (50% methane), which is an estimated 375 scfm of natural gas. This equates to a 99.6% operational efficiency on the recovery side and 75% efficiency on the processing side for LNG. We assume that these same efficiencies are valid for CNG as a final product from BG. Also, for this analysis, landfill gas was used as a surrogate for all BG. In addition, as supplied by Prometheus Energy, the methane content of the LNG product is 97–98.5% with the balance being nitrogen and trace oxygen.[5]

3 "Alternative Fuels and Advanced Vehicle Data Center," US DOE Energy Efficiency and Renewable Energy http://www.eere.energy.gov/afdc/fuels/emerging_biogas_what_is.html

4 http://www.prometheus-energy.com/news/Bowerman%20Production--1-22-07.pdf

5 Email communication with Prometheus Energy representative

The GREET model scenarios assume that for CNG applications, BG is refined to pipeline quality and enters the distribution system and is then compressed onsite, while for LNG the BG is liquefied at the BG production location and trucked to the final destination.[6]

2.2 WTT GREET Pathways

TIAX, with the use of the CA-GREET Model, determined the necessary and applicable WTT emission factors for the emissions estimator based upon the fuel type and feedstock. Table 2-1 lists the possible fuel types and the pathways for the fuels.

Table 2-1. Fuel Types and Pathways

Fuel	Pathway
Diesel	ULSD Biodiesel—soy derived
CNG	Pipeline NG compressed Onsite LNG (NNA) introduced to Pipeline, compressed onsite BG (Landfill) introduced to Pipeline compressed onsite
LNG	NA NG liquefied onsite INL/PGE scale liquefaction NA NG liquefied onsite traditional liquefaction LNG (NNA) introduced to Pipeline, liquefied onsite INL/PGE scale LNG (NNA) introduced to Pipeline, liquefied onsite traditional liquefaction LNG (NNA) trucked from terminal onsite NA NG liquefied at plant (Boron, CA) trucked onsite LNG (NNA) introduced to pipeline, liquefied at plant (Boron, CA) and trucked onsite BG (landfill) liquefied at location and trucked onsite

NA – North American, NNA – Non-North American

The feedstock determines the distance and mode of transportation each fuel must follow before arriving at the pump. From the table, TIAX evaluated the fuel scenarios for California. For ULSD, TIAX evaluated the marginal ULSD WTT emissions, not the California average ULSD WTT emissions. TIAX had to perform additional research to determine the assumptions necessary to accurately model small scale liquefaction and the specific operating conditions at the Clean Energy Plant in Boron, CA.

In determining the specific distances and modes of transportation for each fuel pathway, TIAX contacted SEMPRA Energy[7], which operates the LNG Terminal in Baja, CA, to gather specific LNG shipping and re-gasification operating conditions. Before this project, CA-GREET did not support fuel pathways that required re-gasification at an LNG terminal for NNA NG. TIAX added the re-gasification step, with the help of operating conditions from SEMPRA, to CA-GREET.

The Baja Terminal currently has a natural gas usage rate of 0.6%, or an operational efficiency of 99.4%. In addition, the CA-GREET default values for LNG shipping include a 0.1% boil off rate per day, with only 80% of the boil-off being captured. According to SEMPRA Energy LNG ships captures all of the boil-off gases and these gases are used in dual-fuel engines that create electricity, which power the ship's propellers and all necessary controls.

Table 2-2 shows the major inputs for the pathways listed in Table 2-1 including means of transportation, distances, and operational efficiencies.

6 The assumption is made that the energy required to refine and liquefy biogas is the same to refine and compress to pipeline quality.

7 Phone conversations with SEMPRA Energy in February 2008.

Table 2-2. Pertinent Inputs for Fuel Pathways

Fuel	Pathway	Inputs								
		Pipeline to LNG/BG Plant (mi)	Ocean Vessel (mi)	NA Pipeline (mi)	Rail (mi)	Transport truck (mi)	Regasification Efficiency	NNA Liquefaction Efficiency	NA Liquefaction Efficiency	BG Processing Efficiency
Diesel	ULSD	-	3,550*	50*	-	50*	-	-	-	-
	Biodiesel—soy derived	-	-	-	1,400*[A]	140*[B]	-	-	-	-
CNG	Pipeline NG compressed Onsite	-	-	1,000*	-	-	-	-	-	-
	LNG (NNA) introduced to Pipeline, compressed onsite	50*[D]	7,200*[C]	200	-	-	99.4%	91%*	-	-
	BG (Landfill) introduced to Pipeline compressed onsite	1	-	50*	-	-	-	-	-	75%
LNG	NA NG liquefied onsite INL/PGE scale liquefaction	1,000*	-	-		-	-	-	100%	-
	NA NG liquefied onsite traditional liquefaction	1,000*	-	-	-	-	-	-	91%	-
	LNG (NNA) introduced to Pipeline, liquefied onsite INL/ PGE scale	50*[D]	7,200*[C]	200	-	-	99.4%	91%*	100%	-
	LNG (NNA) introduced to Pipeline, liquefied onsite traditional liquefaction	50*[D]	7,200*[C]	200	-	-	99.4%	91%*	91%*	-
	LNG (NNA) trucked from terminal onsite	50*[D]	7,200*[C]	-	-	170	-	91%*	-	-
	NA NG liquefied at plant (Boron, CA) trucked onsite	1,000*	-	-	-	135	-	-	90.335%	-
	LNG (NNA) introduced to pipeline, liquefied at plant (Boron, CA) and trucked onsite	50*[D]	7,200*[C]	225	-	135	99.4%	91%*	90.335%	-
	BG (landfill) liquefied at location and trucked onsite	1	-	-	-	50	-	-	-	75%

* – CA-GREET default values
A – Soybeans from Nebraska
B – GREET combination of GREET default of 50 miles total for soy bean transport and 90 miles for biodiesel final product transport
C – From Borneo, Southeast Asia
D – Pipeline distance in Borneo from natural gas producing well to LNG plant
E – More work needs to be done to confirm the assumption that the energy required to clean and liquefy biogas is the same to clean and compress to pipeline quality

Table 2-2 shows the modes of transportation and distances for each of the fuel pathways in first five columns. In the first column, the 50 and 1,000 mile values are current CA-GREET values based upon previous analysis by TIAX and ANL. The one (1) mile is an estimate of the distance from the landfill to the BG processing facility, and in most cases an overestimate. In the third column, the 200 mile pipeline distance in CNG and LNG NNA NG processed onsite pathways is an estimated of the pipeline distance from the Baja LNG terminal to the San Pedro Bay ports. The 225 mile pipeline distance is from the Baja Terminal directly to the Clean Energy LNG Plant in Boron, CA. This estimate was made using California pipeline maps used in a presentation by SEMPRA Energy[8].

The ocean vessel distances are the current CA-GREET values determined by TIAX in the Full Fuel Cycle Analysis (FFCA) performed for the CEC.

8 Keller, Bill. "Energia Costa Azul LNG Terminal," Presentation made to the CEC LNG Working group, July 25, 2006 http://www.energy.ca.gov/lng/documents/costa_azul/2006-07-25_Keller_Costa_Azul_LNG_Interagency.PDF

The transport truck distances for ULSD and biodiesel are CA-GREET values. The 130 mile trucking distance is from the Clean Energy Plant to the San Pedro Bay Ports and the 170 mile distance is from the Baja Terminal to the Ports. These distances were determined using Google Maps. The 50 mile distance for either the pipeline or the trucking distance for the BG is an estimate of the distance for BG sources, either from landfill, dairy farms or wastewater treatment plants to the final destination.

We have assumed for the pathways shown in Table 2-2, three different LNG efficiencies. The CA-GREET default is a 91% operational efficiency with 98% of the energy being supplied by natural gas and 2% from grid electricity. For the INL/PGE scale liquefaction, the process is 100% energy efficient, since the energy required for liquefaction is supplied by the drop in pressure from the main natural gas pipeline to the local natural gas pipeline. Traditionally this energy loss would not be captured, but through technology created by INL and PG&E, it now can be harnessed and be used to produce LNG. Although not all of the energy from the drop in pressure is harnessed to produce LNG, the process is 100% efficient because it is using energy that otherwise would have been lost and no additional energy source (i.e. electricity, natural gas) is required.

The third operational efficiency assumed is for the Clean Energy Plant in Boron, CA. The plant has a 91% efficiency of converting the incoming natural gas to final product LNG. The 9% LNG loss results from boil off and emissions throughout the process including storage and trucking filling. This 9% is piped to the adjacent natural gas combined cycle power plant and used to created electricity. The electricity from the power plant is then used in the liquefaction process. The reason for the reduction from 91% efficient to 90.335% is because electricity used at the Clean Energy Plant is greater than the electricity produced from the 9% natural gas recovered from liquefaction operations. Although there is more process energy required at the Clean Energy Plant than the GREET default, Clean Energy decreases the GHG emissions by capturing 100% of the boil-off emissions (as CH_4) from liquefaction process, storage, and filling of trucks. This results in lower overall GHG emissions. Table 2-3 shows the GREET boil-off assumptions and the Clean Energy assumptions used in the WTT pathways for LNG. GREET assumes that no boil-off loses occur during the liquefaction process, only during the storage process.

Table 2-3. Greet and Clean Energy Boil-Off Assumptions

	Percent Boil-Off per Day	Number of Days	Percent Recovery
Ocean Vessel	0.1	16	100%
Traditional and Small Scale Liquefaction Storage	0.1	5	80%
Clean Energy Liquefaction Storage	0.1	5	100%
Storage at Refueling Station	0.1	5	80%

2.3 TTW GREET Pathways

TIAX gathered and calculated the necessary emission factors of various fuels and engines for a variety of applications including heavy duty trucks (HHDT), urban buses (UB), and refuse haulers (RH). TIAX determined an emission factor for each type of fuel (diesel and natural gas, including CNG and LNG), for several model years (2004, 2007 and 2010), and for the three trucking applications (HHDT, UB and RH). EMFAC was used to determine the emission rates in g/mile. EMFAC estimates criteria emissions based on in-use chassis dynamometer data and estimated deterioration factors. Deterioration factors are estimated based on the emission control system employed to meet the emission standards. Thus, EMFAC can be used to estimate average in-use emissions as a function of mileage or vehicle life. Below we describe how each set of model year engine emission factors were determined. The resulting emission factors in the TTW analysis have the units of grams per unit of distance (g/mi).

2004 Model Year (MY)

For 2004 MY diesel HHDT and UB, EMFAC was used to determine the emission rates at zero miles and full vehicle lifetime miles for GHG and criteria pollutants. Deterioration of the engine and emission control devices makes it necessary to determine emissions over the useful life of the application. Deterioration factors for each pollutant were used to determine the end of life emission factors. The end of life emission rate was averaged with the zero miles emissions rate to determine the mid-life emissions factor.

For diesel RHs, an additional factor was applied to that of UB to adjust for the additional energy required for power take off (PTO) operations such as trash compaction. UB usually have the same size and type of engine as RH. Generally, the emissions of RHs are four (4) times those of heavy duty trucks per unit distance, and this factor is used in this analysis.

Since similar EMFAC emissions data are not available for natural gas engines, a slightly different (yet consistent) approach was used to estimate in-use emissions. In this case, ARB's certification database was used to convert emission factors for diesel engines to those for natural gas engines. The 2004 MY certification values for Cummins diesel engines and natural gas engines were extracted for each pollutant and the ratio of the natural gas certification factor to the diesel certification factor was applied to the diesel emission factor determined through EMFAC. The only 2004 MY certification data for both diesel and natural gas engines is for medium duty engines (around 8 L). We used this data to determine the emission ratios for various exhaust emissions. We have assumed that these estimates will also apply to the larger displacement engines. For HHDT, the ratios of CG/ISC (CNG) and LG/ISL (LNG) engines certification data for MHDD intended service class was used. For UB and RH, the certification data for UB intended service class was used for the same engine ratios.

2007 MY

The 2007 MY diesel engine emission factors were determined in the same way as the 2004 emission factors using EMFAC. The natural gas emission factors (for both CNG and LNG) were determined in the same way as previously done for 2004 MY engines using ARB's certification database, except the ratio of heavy duty engines ISX G/ISX was utilized for HHDT and ISL G/ISL for UB and RH.

2010 MY

The 2010 MY diesel engine emission factors were determined in the same way as the 2004 and 2007 emission factors with the use of EMFAC. The natural gas emission rates were assumed the same as the 2010 diesel emission rates as both will have to achieve the same extremely low emission standards.[9]

9 The smaller bore natural gas engines use stoichiometric technologies with a three way catalyst whereas the larger bore engines used in HHDT applications use Westport's HPDI system (combustion process similar to diesel combustion) coupled with NOx aftertreatment. These two technologies differ enough that the simplified analysis on emissions ratios may not be valid. Nevertheless, both engine technologies will have to meet the very stringent 2010 standards for NOx and PM.

3.0 Results and Discussion

TIAX created a look-up database to determine the WTT emission factors. This was done by determining corresponding GHG and criteria pollutant emission factors for a given fuel economy, lifetime, and annual VMT. The WTT emission factors were added to the TTW emission factors giving an overall WTW emission factors in grams per mile. The grams per mile were multiplied by the annual VMT and the conversion factor of grams to tons, to determine lifetime emissions in tons. The calculation of the emissions was determined as shown in Figure 3-1.

$$\text{WTW Emissions (tons)} = \text{Unit Conversion gms} \rightarrow \text{tons} \times \text{Annual VMT (mi)} \times \left(\text{WTT Emission (g/dge)} \times \text{Vehicle Fuel Economy (dge/mi)} + \text{TTW Emissions (g/mi)} \right)$$

Figure 3-1. WTW Emissions Calculations

Table 3-1 shows the WTT total GHG and individual urban criteria pollutants emissions from each of the fuel pathways shown in Table 2-2. The WTT emissions are shown in units of grams per diesel gallon equivalent. Figure 3-2 shows the WTT GHG emissions in graphical form.

Table 3-1. Pertinent Inputs for Fuel Pathways

Fuel	Pathway	Pathway Name*	Emissions g CO_{2eq}/dge						
			GHG	ROG: Urban	CO: Urban	NOx: Urban	PM10: Urban	PM2.5: Urban	SOx: Urban
Diesel	ULSD	ULSD	2,710	0.473	0.059	0.187	0.007	0.007	0.004
	B5 5% Biodiesel by volume	B5	2,306	0.470	0.096	0.296	0.012	0.011	0.007
	B20 20% Biodiesel by volume	B20	1,081	0.463	0.207	0.625	0.026	0.024	0.016
	B100 100% Biodiesel	B100	(5,867)	0.424	0.841	2.494	0.103	0.095	0.070
CNG	Pipeline NG compressed Onsite	NA-CNG	1,283	0.019	0.072	0.082	0.005	0.005	0.000
	LNG (NNA) introduced to Pipeline, compressed onsite	NNA-CNG	2,977	0.008	0.057	0.122	0.009	0.008	0.013
	BG (Landfill) introduced to Pipeline compressed onsite	BG-CNG	(7,202)	0.002	0.048	0.007	0.005	0.005	0.000
LNG	NA NG liquefied onsite INL/PGE scale liquefaction	NA-LNG-SSI	1,153	0.019	0.040	0.081	0.002	0.002	0.000
	NA NG liquefied onsite traditional liquefaction	NA-LNG	2,004	0.019	0.040	0.081	0.002	0.002	0.000
	LNG (NNA) introduced to Pipeline, liquefied onsite INL/PGE scale	NNA-LNG-SSL	2,896	0.011	0.020	0.204	0.008	0.006	0.025
	LNG (NNA) introduced to Pipeline, liquefied onsite traditional liquefaction	NNA-LNG	3,784	0.011	0.020	0.204	0.008	0.006	0.025
	LNG (NNA) trucked from terminal onsite	NNA-LNG-TER	2,300	0.012	0.022	0.180	0.004	0.003	0.011
	NA NG liquefied at plant (Boron, CA) trucked onsite	NA-LNG-CE	2,104	0.026	0.049	0.155	0.002	0.002	0.000
	LNG (NNA) introduced to pipeline, liquefied at plant (Boron, CA) and trucked onsite	NNA-LNG-CE	3,789	0.016	0.028	0.267	0.008	0.006	0.025
	BG (landfill) liquefied at location and trucked onsite	BG-LNG	(7,305)	0.003	0.015	0.028	0.001	0.001	0.000

* NA – North America, NNA – Non-North America, BG – Biogas, SSL – Small Scale Liquefaction, TER – Trucked onsite from the LNG terminal, CE – Clean Energy

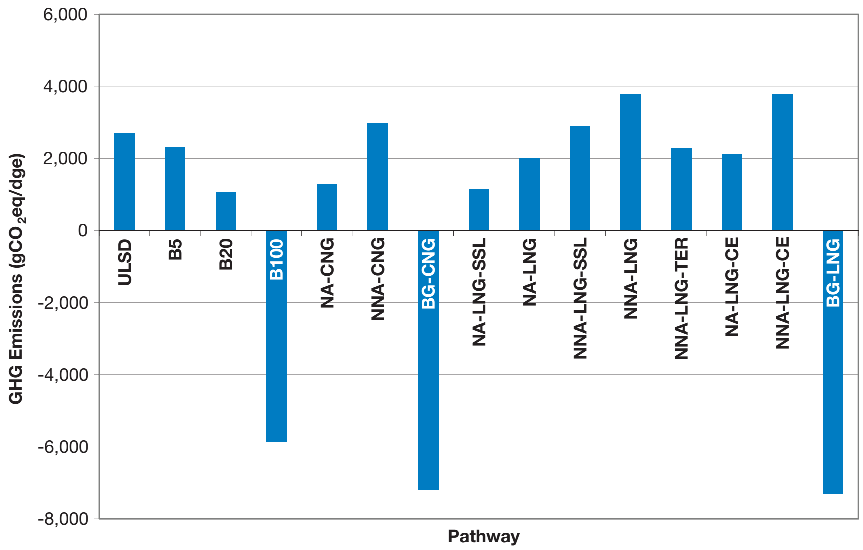

Figure 3-2. WTT GHG Emissions By Pathway

Table 3-1 shows that compared to ultra-low sulfur diesel, all forms of natural gas that originate in North America have less upstream GHG emissions. Table 3-1 also shows that all pathways using NA natural gas have less emissions of criteria pollutants, albeit the difference much smaller than GHG emissions. The NNA natural options have more emissions associated with them due to the transoceanic voyage in an LNG tanker. In addition, it can be seen that NNA-LNG-TER pathway has comparable WTT emissions to ULSD and NA LNG pathways. In addition, as expected the emissions associated with BG are negative indicating there is an upstream savings of using BG as a fuel instead of faring the gas. Biodiesel also has a negative or upstream credit due to plant recycling of CO_2 as a result of photosynthesis.[10]

To detail the components of the WTT GHG emissions, Table 3-2 shows the emissions of each stage. The emissions are those emitted in that stage, plus an escalation due to losses in subsequent stages. It must be noted that the stages do not exactly add up to the total due to rounding.

Table 3-2. GHG Emissions for Each Stage of the WTT Emissions

	Emissions g CO_{2eq}/dge		
Stages	**NA LNG**	**NA LNG CE**	**NNA LNG TER**
Recovery	449	447	459
Processing	488	486	504
Pipeline	79	78	4
Liquefaction	915	911	949
Transportation (Ocean Vessel)	-	-	173
Distribution (Truck)	-	110	140
Storage	71	71	71
Total	**2004**	**2104**	**2300**

10 There are current arguments that the benefits of biofuels are overstated since with increase use as a transportation fuel requires additional planting of crops for food. This so called "land use" effect it true can substantially reduced the benefits of biofuels. This effect was not considered in this analysis.

Tables 3-3 to 3-5 show the TTW GHG and criteria pollutant emission factors in grams per mile based upon a scenario of 10 year lifetime, 40,000 miles per year, and fuel economy of 5 miles/dge. The RH estimates were adjusted for its duty cycle using the previous mentioned correction factor of 4. For either diesel or natural gas TTW results the lifetime, annual vehicle miles traveled and fuel can be varied. The type of use (HHDT, UB or RH) and year must be specified for GHG and criteria pollutant emissions as the emissions are different for each year and engine. To determine TTW GHG emissions, the assumption was made that CNG operated in CG and ISL G engines has 6% fuel economy loss and LNG operated in LG and ISL G engines has a 5% fuel economy loss and while both natural gas fuels in ISX G engines do not have a fuel economy loss.

Table 3-3. 2010 HHDT TTW GHG Emissions for Each Fuel, with 5 mi/dge

	Carbon Content in Fuel			Methane Emissions	Total GHG Emissions
Pathways	g/MJ	g/dge	g/mile	g/mile	g CO_{2eq}/mile
USLD	74.1	9,966.5	1,993.3	0.009[11]	**1,993.5**
B5	74.18	9,977.3	1,995.5	0.009	**1,995.7**
B20	74.43	10,010.4	2,002.1	0.009	**2,002.3**
B100	75.82	10,197.8	2,039.6	0.009	**2,039.8**
CNG 1–3	55.2	7,424.4	1,484.9	3.03	**1,554.6**
LNG 1–8	56.55	7,606.0	1,521.2	3.03[12]	**1,590.9**

Table 3-4. Diesel TTW Emission Factors for a 10 yr, 400,000 mile, 5 mi/dge Scenario (g/mi)

	HHDT			UB			RH		
	2004	2007	2010	2004	2007	2010	2004	2007	2010
NMHC (ROG)	0.36	0.28	0.20	0.03	0.03	0.03	0.13	0.13	0.12
CO	1.85	1.52	1.19	0.61	0.61	0.56	2.43	2.45	2.24
NOx	9.56	5.55	1.52	0.76	0.41	0.38	3.03	1.65	1.51
PM (PM2.5)	0.46	0.06	0.06	0.02	0.02	0.02	0.09	0.10	0.09

Table 3-5. Natural Gas TTW Emission Factors for a 10 yr, 400,000 mile, 5 mi/dge Scenario (g/mi)

	HHDT			UB			RH		
	2004	2007	2010	2004	2007	2010	2004	2007	2010
NMHC (ROG)	0.15	2.84	0.20	0.01	0.12	0.03	0.05	0.49	0.12
CO	0.26	24.25	1.19	0.25	1.05	0.56	0.98	4.19	2.24
NOx	3.96	3.96	1.52	0.32	0.04	0.38	1.28	0.16	1.51
PM (PM2.5)	0.05	0.05	0.06	0.00	0.11	0.02	0.01	0.43	0.09

11 "Full Fuel Cycle Assessment: Tank to Wheels Emissions And Energy Consumption" Prepared for the California Energy Commission by TIAX LLC, June 2007, CEC-600-2007-003, Page 5-3, Table 5-2 HHDT.

12 "Chassis Dynamometer Evaluation of Climate-Friendly Clean Air Technologies: Westport Innovations Inc. Liquefied Natural Gas Highway Project" Environment Canada, October 2006, EC-ERM Report #06-43

Tables 3-3 to 3-5 show that, with the exception of ROG and CO in the 2007 MY engines, natural gas engines have the same or less criteria pollutant emissions when compared to diesel. Table 3-3 shows the 20-22% TTW GHG reductions of either type of natural gas versus ULSD, while the reductions compared to biodiesel are even larger. This is due to the lower carbon content in natural gas.

The main inputs that could vary in the WTT analysis of natural gas pathways are the trucking and pipeline distances. In doing a sensitivity analysis on these inputs, TIAX determined the specific GHG emissions from trucking and pipeline distances. Table 3-6 below shows the g/dge of WTT, TTW, WTW and pipeline and trucking distances. It also shows the percentage of the WTW emissions come from trucking and pipeline distances. The trucking for the diesel options are done with diesel trucks while the natural gas options use natural gas trucks. See Table 2-2 for the actual trucking and pipeline miles in each pathway. Figure 3-3 shows the GHG emissions by pathway in graphical form.

Table 3-6. 2010 WTW GHG Emissions with 5 mi/dge

	GHG Emissions (g/dge)					Percentage of WTW GHG Emissions	
Pathway	Pipeline	Trucking	WTT	TTW	WTW	Pipeline	Trucking
ULSD	4	41	2,710	9,966	12,676	0.03%	0.32%
B5	3.8	43	2,306	9,977	12,283	0.03%	0.35%
B20	3.2	47	1,081	10,010	11,091	0.03%	0.42%
B100	0	74	(5,867)	10,198	4,331	0.00%	1.71%
NA-CNG	80	0	1,283	7,773	9,056	0.88%	0.00%
NNA-CNG	20	0	2,977	7,773	10,749	0.19%	0.00%
BG-CNG	4	0	(7,202)	7,773	571	0.70%	0.00%
NA-LNG-SSL	78	0	1,153	7,954	9,107	0.86%	0.00%
NA-LNG	79	0	2,004	7,954	9,958	0.79%	0.00%
NNA-LNG-SSL	20	0	2,896	7,954	10,850	0.18%	0.00%
NNA-LNG	20	0	3,784	7,954	11,738	0.17%	0.00%
NNA-LNG-TER	4	140	2,300	7,954	10,254	0.04%	1.37%
NA-LNG-CE	78	110	2,104	7,954	10,058	0.78%	1.09%
NNA-LNG-CE	22	110	3,789	7,954	11,743	0.19%	0.94%
BG-LNG	0	41	(7,305)	7,954	649	0.00%	6.32%

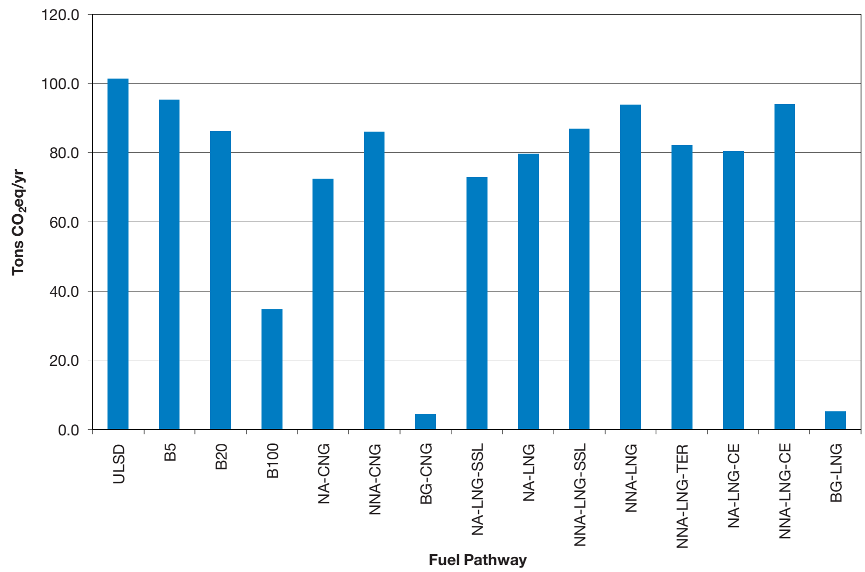

Figure 3-3. WTW GHG Emissions by Pathway for a 10 yr, 400,000 mile, 5 mi/dge Scenario

From Table 3-6, we can see that pipeline and trucking distances contribute minor amounts to the overall WTW GHG emissions. Excluding BG to LNG, the combination of pipeline and trucking contribute less than 2% of the overall GHG emissions, with many pathways less than 1%.

Utilizing the same scenario above for HHDT TTW, Table 3-7 shows the WTW emissions in tons per year for GHGs and criteria pollutants for all pathways. In the emissions estimator, as stated above, the fuel, pathway, vehicle lifetime, annual vehicle miles traveled and fuel economy can be varied to calculate specific results.

Table 3-7. 2010 MY HHDT WTW Emissions for a 10yr, 400,000 mile, 5 mi/dge Scenario

Fuel	Fuel Pathway	Emissions (tons/yr)				
		GHG	ROG: Urban	CO: Urban	NOx: Urban	PM2.5: Urban
Diesel	ULSD	101.4	0.012	0.048	0.062	0.003
	B5	95.3	0.012	0.048	0.063	0.003
	B20	86.2	0.012	0.049	0.066	0.003
	B100	34.7	0.012	0.054	0.081	0.003
CNG	NA-CNG	72.4	0.008	0.048	0.061	0.003
	NNA-CNG	86.0	0.008	0.048	0.062	0.003
	BG-CNG	4.6	0.008	0.048	0.061	0.003
LNG	NA-LNG-SSI	72.9	0.008	0.048	0.061	0.003
	NA-LNG	79.7	0.008	0.048	0.061	0.003
	NNA-LNG-SSL	86.8	0.008	0.048	0.062	0.003
	NNA-LNG	93.9	0.008	0.048	0.062	0.003
	NNA-LNG-TER	82.0	0.008	0.048	0.062	0.003
	NA-LNG-CE	80.5	0.008	0.048	0.062	0.003
	NNA-LNG-CE	93.9	0.008	0.048	0.063	0.003
	BG-LNG	5.2	0.008	0.048	0.061	0.002

Table 3-7 shows that all natural gas pathways have less GHG emissions and comparable criteria pollutant emissions as ULSD. The most likely pathway for the Port of Long Beach and the Port of Los Angeles is NA-LNG-CE, NA natural gas liquefied at the Clean Energy Plant in Boron, CA and trucked onsite. This pathway has a GHG emissions reduction of 21%. The BG pathways could provide significant reductions in GHG emissions if an adequate quantity of BG can be obtained.

Biodiesel also shows a significant reduction in WTT GHG emissions. There are currently questions about the accuracy and current calculations of WTT GHG emissions associated with biofuels (i.e. ethanol, biodiesel, NOT BG) in GREET or any other full fuel cycle GHG model. A point that needs to be raised when considering biodiesel, or any biofuel, is the impact of the land use changes and GHGs. The GREET model does take into account the GHGs associated with direct land use changes, that is the GHGs emitted from the conversion of a specific plot of land into a fuel crop. GREET does not take into account the GHGs from indirect land use changes.

Indirect land use changes are the changes anywhere in the world (can be inside or outside U.S.) caused by the change of the specific piece of land in question to a fuel crop. One example is an acre of land that produces corn for food converts to producing soybeans for biodiesel. The direct land use change is any GHGs associated with switching from producing corn to soybeans. The indirect land use change considers there is now one acre less of corn, does somewhere else in the world convert prairie, rainforest or some other type of land to corn to make up for the deficit. What can be seen from this example, is indirect land changes are difficult to quantify, and as is the case of converting an acre of rainforest to corn production, can be quite substantial. In the future, if the quantification of indirect land use change is available, it could dramatically change the above results for biodiesel.

4.0 Conclusions

In Phase 1 of this project for Westport Innovations, TIAX developed an emissions estimator based upon CA-GREET and EMFAC model runs and assembled in a lookup table. Table 3-7 presents the results of all fuel pathways for one vehicle scenario. The results show that all natural gas pathways have less GHG emissions than ULSD, ranging from 18% to 25% reductions for NA natural gas. The NA-LNG-CE pathway of LNG trucked from the Clean Energy plant is the likeliest pathway to the South Coast Region and has a GHG reduction of 21%. Biodiesel also has less GHG emissions than ULSD, but there are still questions about biofuels and land-use changes. This is an area where the estimator can be updated in the future.

The emission estimator calculates WTT, TTW and WTW GHG and criteria pollutant annual emissions. Inputs to the emissions estimator include fuel, fuel pathway, lifetime, annual vehicle miles traveled, fuel economy, and engine model year. The life-cycle cost model, Phase 2, will incorporate the emissions estimator and supply it with the above variables.

Please contact sales@westport.com for a demonstration of the Emissions Estimator model and a quantification of the significant fleet-specific environmental benefits that can be derived from switching to low-cost, low-carbon natural gas.