DEVELOPMENT OF A CALCULATOR FOR ESTIMATION AND MANAGEMENT OF GHG EMISSIONS FROM PUBLIC TRANSIT AGENCY OPERATIONS

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DEVELOPMENT OF A CALCULATOR FOR ESTIMATION AND MANAGEMENT OF GHG EMISSIONS FROM PUBLIC TRANSIT AGENCY OPERATIONS

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PREFACE

Portions of this thesis consist of text from the author's Transportation Research Board conference paper and *Transportation Research Record* journal paper "Calculators for Estimating Greenhouse Gas Emissions from Public Transit Agency Vehicle Fleet Operations" (*1*, *2*).

ACKNOWLEDGEMENTS

The generous assistance of my advisor Dr. Meyer has been essential to my completion of a thesis that is on-target and on-time. Dr. Meyer’s dedication to my learning and success has been invaluable in helping me navigate the research process. Working with Dr. Meyer and Dr. Southworth on the *Transit Greenhouse Gas Emissions Management Compendium* has helped me to develop as a researcher and has given me the special opportunity to pursue my work on this thesis. I am very grateful for Dr. Southworth’s guidance and insight on academic research in general, and public transit research in particular.

The amount of time and energy that I have been able to invest in this thesis is very much a product of the support of my wife Tanya. Tanya’s encouragement and help at home have helped me to see this work through.

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LIST OF SYMBOLS AND ABBREVIATIONS

AFV	Alternative Fuel Vehicle
APTA	American Public Transportation Association
BTU	British thermal unit
B100	100 percent biodiesel
CAP	Criteria air pollutant
CCAR	California Climate Action Registry
CFL	Compact fluorescent light
CH_4	Methane
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DGE	Diesel gallon equivalent
DOE	U.S. Department of Energy
DOT	Department of transportation
DR	Demand response
EIA	U.S. Energy Information Administration
EIO-LCA	Economic Input-Output Life Cycle Assessment
FTA	Federal Transit Administration
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GRP	General reporting protocol

GUI	Graphical user interface
GWh	Gigawatt-hour
HFC	Hydrofluorocarbon
HHV	Higher heating value
HR	Heavy rail
ICLEI	International Council for Local Environmental Initiatives
ISO	International Organization for Standardization
KWh	Kilowatt-hour
LCA	Life cycle analysis (or life cycle assessment)
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LEM	Lifecycle Emissions Model
LHV	Lower heating value
LR	Light rail
N_2O	Nitrous oxide
MARTA	Metropolitan Atlanta Rapid Transit Authority
MB	Motor bus
MMBtu	10^6 British thermal units
MWh	Megawatt-hour
NTD	National Transit Database
NY MTA	New York Metropolitan Transportation Authority
PFC	Perfluorocarbon
PMT	Passenger miles travelled (or, passenger miles of travel)

RITG	Radiatively important trace gas
SCF	Standard cubic foot (of natural gas)
TCR	The Climate Registry
TCRP	Transit Cooperative Research Program
TTW	Tank-to-wheels
VMT	Vehicle miles travelled (or, of travel)
WRI	World Resources Institute
WTP	Well-to-pump
WTT	Well-to-tank
WTW	Well-to-wheels

SUMMARY

As managers of extensive vehicle fleets and transportation infrastructures, public transit agencies present unique opportunities for reducing greenhouse gas (GHG) emissions from the transportation sector. To achieve substantial and cost-effective GHG emissions reductions from their activities, public transit agencies need tools and resources that enable effective GHG emissions management. This research thesis presents the background, methodology, and results of the author's development of a public transit agency-level life cycle GHG emissions calculator.

The development of the calculator involved a series of research efforts aimed at identifying and addressing the needs of transit agency GHG emissions management: a review of background information on climate change and public transit's role in mitigating climate change; a review of existing GHG emissions calculators for public transit agencies, a review of the methodologies for life cycle GHG emissions analysis; integration and adaption of existing calculation resources; development of calculator spreadsheets for estimating relevant lifecycle GHG emissions and quantifying GHG emission reduction cost-effectiveness; application of the developed calculator to a carbon footprint analysis for a typical mid-size to large-size transit agency; and application of the developed calculator to the evaluation of the cost-effectiveness of various potential strategies for reducing transit agency GHG emissions.

The developed calculator provides an integrative resource for quantifying GHG emissions and costs of public transit agency activities, including GHG emission reduction strategies. Further research is needed to calibrate the estimation of upstream life cycle GHG emissions, particularly for vehicle manufacture and maintenance.

CHAPTER 1

INTRODUCTION

This thesis presents the development of a calculator for the estimation and management of greenhouse gas (GHG) emissions from public transit agency operations. This introductory chapter provides an overview of the motivation, research need, and objective of the research, as well as background information on the context and importance of GHG emission reductions from public transportation.

1.1. Thesis Overview

1.1.1. Motivation

Public transportation systems offer unique and significant opportunities for mitigation of transportation sector GHG emissions. Effective management of GHG emissions associated with public transportation systems is important for several reasons. As operators of major vehicle fleets and extensive infrastructure systems, public transit agencies have an opportunity to demonstrate and highlight the benefits of a wide range of GHG emission reduction practices through both their day-to-day operations and their capital programs. Since the 1970 Clean Air Act the nation's transit agencies have served as test beds for emissions reducing vehicle technologies. In the current context of climate change mitigation, transit agencies can provide expanded leadership in society's efforts to develop more environmentally benign transportation systems (*3*). In addition to providing energy and emissions efficiency benefits to society at large, successful carbon management practices can bring some immediate rewards to the transit agency itself by helping to market services to environmentally conscious riders, reducing the costs of purchased energy, making the agency more attractive to federal grant programs (*4, 5*), and preparing the agency for participation in climate change registries (*6, 7*) and carbon trading schemes (*8*), which offer funding opportunities for GHG emissions reductions. Finally, the need for GHG emissions management will likely increase as transit agencies face impending U.S. federal or state regulations and/or legislation.

Many stakeholders concerned with climate change, transportation sustainability, and energy efficiency are looking to public transportation as a means for reducing transportation GHG emissions and energy consumption. Public transportation can reduce GHG emissions and energy consumption through its accommodation of mode shift, congestion relief, and more travel-efficient land use (*9, 10*). It should be noted that the potential magnitude of GHG emissions reductions *from* public transportation is limited. Transportation GHG emissions are generally proportional to vehicle miles of travel (VMT), and in the U.S. in 2007, public transportation VMT was approximately 0.1 to 0.2 percent of all highway VMT (*11*). The limited total impact of GHG emissions reductions through public transportation is reflected in the much discussed and debated *Moving Cooler* report, which indicates that between 2010 and 2050 "transit capital investments, such as urban transit expansion and intercity and high-speed rail, could produce cumulative GHG reductions ranging from 0.4 to 1.1 percent of baseline emissions" (*12*).

Despite limitations in total impact, the unique efficiencies of public transit vehicle capacities and alternative fuel technologies represent considerable opportunities for improving transportation GHG emissions performance. By managing the procurement, maintenance, and operation of extensive vehicle fleets and infrastructures, public transit agencies provide an ideal test bed for implementing and evaluating more carbon efficient passenger transportation systems.

It is likely that transportation system GHG emissions performance standards (measured in terms of GHGs/passenger-mile) will be imposed through federal legislation, regulation, and/or public funding eligibility requirements. As highly subsidized enterprises, public transit agencies may be required to evaluate and report their GHG emissions performance.

Public transit agencies are faced with the challenge of meeting increasing public demands with, in many cases, resources constrained by decreasing revenues. Therefore, a framework for evaluating and managing cost-effective public transit GHG emissions reductions must not only help agencies identify economically viable opportunities, it must also be easily implemented by personnel who have limited time and resources available for additional management responsibilities. To improve the GHG emissions performance of transit agencies, transit agency personnel need effective tools for managing their emissions. The managerial adage “You can’t manage what you can’t measure” is no less true in the context of GHG emissions management. *Measurement of transit agency GHG emissions requires tools for the quantification of GHGs from transit agency activities, and such tools should be appropriate to the unique context and needs of public transit agencies.*

1.1.2. Research Objective

The purpose of this research is to develop an integrative calculation tool for the estimation and management of public transit agency-level life cycle GHG emissions. An “integrative” calculation tool is one that consolidates calculation data and methods into a single resource and the intent of this research is to integrate calculation resources for the estimation of direct GHG emissions, life cycle GHG emissions, and the costs associated with GHG emission reductions.

The primary function of the calculation tool is to quantify the GHG emissions associated with consumptive agency activities. In broad terms, these activities include the provision of mobility services and the use of supporting services and facilities. The calculator may be applied to any scale of agency activity, from the operation of a single vehicle, to a complete footprint of an agency's GHG emissions. At the very least, the calculator is intended to help transit agencies quantify and evaluate the GHG emissions impact of core activities, such as the use of various types of vehicles and fuels.

Additionally, the calculator is intended for the quantification of life cycle GHG emissions of agency activities. Although upstream and downstream supply-chain GHG emissions are generally not the responsibility of transit agency managers, it is important for agency managers to quantify and thus better understand the impact of their resource consumption decisions. Quantification of life cycle GHG emissions enables accounting and management of the broader supply-chain impacts of agency activities. Quantification of displaced emissions (through mode shift, congestion relief, and land use change) is beyond the scope of this research.

An important objective of this research is to develop a calculation tool for managing cost-effective reductions in GHG emissions from public transportation. The tool is designed to help agencies identify strategies that have the most GHG reduction impact, and that are the most cost-effective. By helping agencies to identify the most cost-effective GHG emission reduction strategies, the calculator will support the management of not only GHG emissions, but also the associated asset costs. The quantification of cost-effectiveness will be based on the practice of incremental GHG emissions reduction – emission reduction strategies that provide marginal benefits relative to a baseline.

Transit agency managers have a multitude of tasks and responsibilities beyond the management of GHG emissions. This research aims to provide a GHG emissions estimation and management tool that is easy to use and understand. In the interest of transparency and accessibility, the calculation tool is a spreadsheet-based model developed for use in Microsoft Office Excel®. The calculation tool is intended to help agencies calculate their emission baseline and identify the best use of available funds for the reduction of GHG emissions from agency assets and activities.

1.1.3. Methodology

The development of the public transit GHG emissions calculation tool employed a methodological approach consisting of research need identification and objective definition, literature review, design and synthesis, and finally assessment.

The research need and objective of the research were explained in this chapter. The research literature review, which is detailed in the following chapter, investigated methods, studies, and data related to public transit agency GHG emissions estimation and cost evaluation for vehicles, fuels, and infrastructure. Based on findings in the existing literature, the relevant existing or yet to be developed evaluation capabilities were identified for integration into the calculation tool. The calculation tool was then created to accommodate life cycle assessment and cost-effectiveness evaluation of agency GHG emissions – accounting for needed outputs and available data inputs. Upon creation of the calculation tool, the calculator was applied to an annual GHG emissions inventory of a medium- to large-size public transit agency to assess the calculator, both as an estimator of annual GHG emissions and as a tool for GHG emissions management. The calculator was then also applied to case studies of public transit agency GHG emission reductions. The results of the GHG inventory and the case study calculations provide for a discussion of opportunities for improving the management of public transit agency GHG emission reductions.

1.2. Background

1.2.1. Climate Change

The Earth's climate is changing, and societies, nations, communities, corporations, and individuals around the world are looking for ways to manage this change. The most prevalent change, both measured and predicted, in the Earth's climate system is an increase in the global average surface temperature. This change is commonly referred to as "global warming" – a term that both clarifies and obscures the issue of climate change. In one sense, "global warming" is a more precise characterization of the issue of climate change, in that it identifies the primary intrinsic variable (temperature or heat) and defines the positive direction of an otherwise ambiguous change. Yet "global warming" as a term ignores the array of significant climatic changes that are expected to occur as global average surface temperatures increase. Such changes include but are not limited to more extreme high and low seasonal temperatures, more frequent and more intense storm systems, and more intense droughts. In addition to these climatic changes are other significant Earth system changes, such as the melting of glacial ice, the rising of sea levels, watershed flooding, the drying and erosion of soils, and a vast and largely uncertain array of associated ecological impacts. New extremes in the climatic and natural environment bring considerable threats to humanity, such as flooding of communities, accelerated degradation of critical infrastructure, reduced access to freshwater, reduced agricultural productivity, and the loss of many important ecosystem services that sustain humanity. Although the negative impacts of climate change will vary significantly across different geographies, the overall extent of the impacts is generally global in scale.

Most climate scientists today support the theory of anthropogenic, or human-induced, climate change. Although Earth's climate systems are naturally in a continuous state of flux, there is a significant body of evidence indicating that human activities are altering the otherwise natural state or flux of Earth's climate system (*13*). Figure 1 below shows the historical global mean surface temperatures in the modern industrial era.

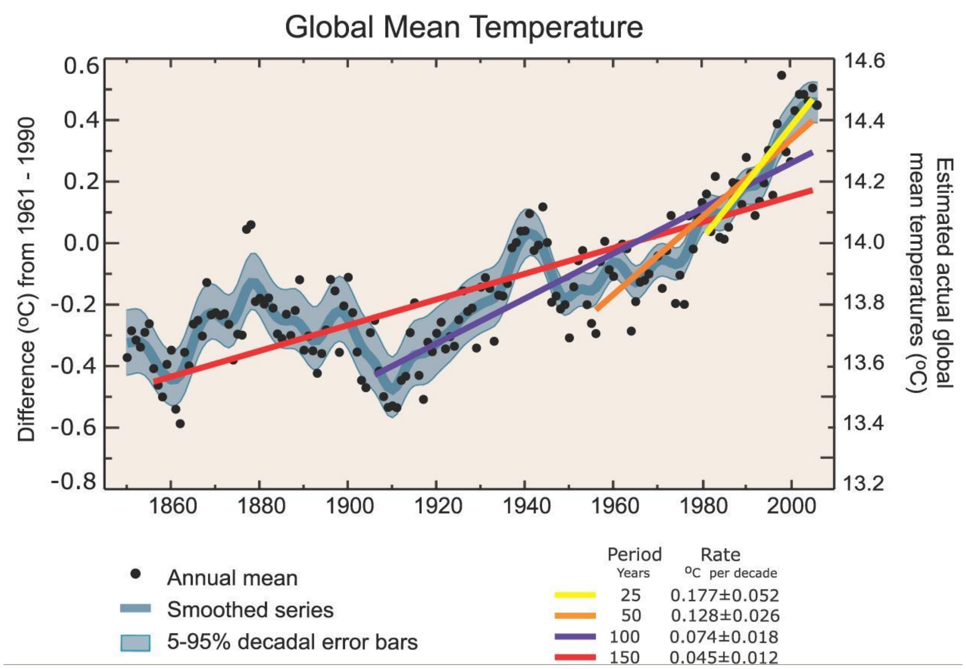

Figure 1: Historical global mean surface temperatures in the modern industrial era (*13*).

Although considerable variability exists in annual global mean temperatures, and despite various sub-cycles of increasing and decreasing trends, it is apparent that the annual global mean temperatures have been increasing since the beginning of the modern industrial era. The modern industrial era has been of period of intense industrial activity, powered largely by the combustion of fossil fuels. The combustion of fossil fuels, and other industrial practices, affect the climate system primarily by altering the quantity of greenhouse gases (GHGs) in the atmosphere. GHGs are radiatively important trace gases (RITGs) that trap solar heat in the Earth's atmosphere. Figure 2 below illustrates the historical atmospheric concentration of GHGs from 0 to 2005 CE.

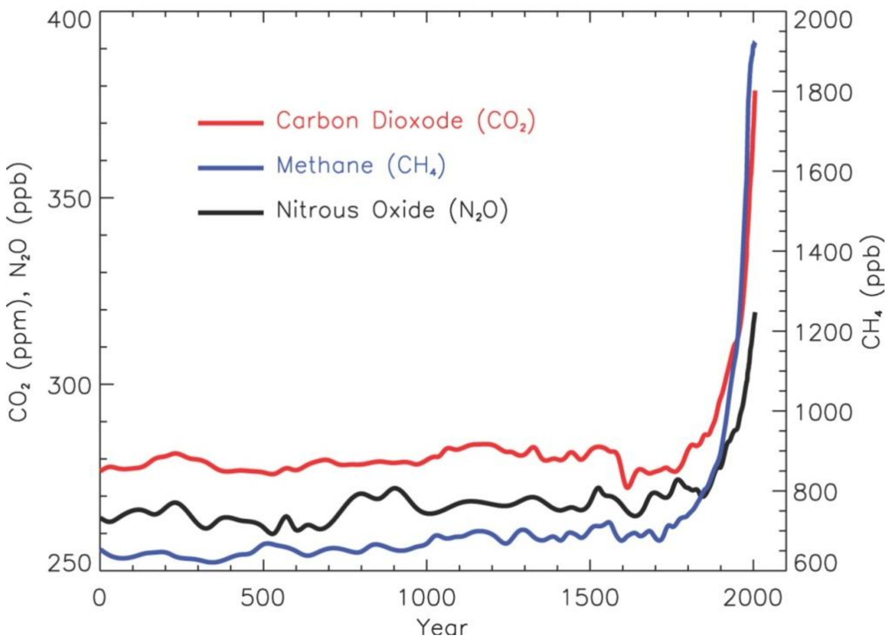

Figure 2: Atmospheric concentrations of GHGs from 0 to 2005 CE (*13*).

Figure 1 and Figure 2 provide a basic illustration of the correlation between the rise in atmospheric concentrations of GHGs and the rise in global mean surface temperatures (global warming). There are many diverse factors affecting global warming, and there are many impacts resulting from global warming. Nevertheless, atmospheric emissions and concentrations of anthropogenic GHGs have been identified by the climate science community as a critical factor affecting climate change.

The United Nations Framework Convention on Climate Change and the Kyoto Protocol define six major types of GHG emissions: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (*14*). Carbon dioxide constitutes the largest proportion of GHG emissions, yet the other five Kyoto Protocol GHGs have a higher global warming potential (GWP). The GWP measures the warming effect relative to CO_2 over a 100 year period. The weighted emissions of various types of GHGs may be expressed by multiplying the total mass of each emission type by the respective GWP. The result is the GHG emissions expressed in carbon dioxide equivalents (CO_2e).

Climate science has introduced to the world a new paradigm for interpreting, evaluating, and improving modern industrial activities. Increasingly, existing and planned activities are assessed in terms of their impact on the climate system. The process of reducing human impact on the climate system is referred to as "climate change mitigation". Mitigation primarily involves the reduction of GHG emissions and the preservation of carbon sinks, such as forests. Alternatively, the process of managing the negative impacts of the changing climate system on society is referred to as "climate change adaptation". Adaptation primarily involves making necessary infrastructure and development changes in response to more hostile environmental conditions. The mitigation/adaptation dichotomy provides a simplified categorization of society's responses to the challenges of climate change. It should be noted that this dichotomy obscures mitigation and adaptation synergies that may exist for particular development activities. For example, the development of advanced biofuel feedstocks aimed at mitigating GHG emissions from the transportation sector may (or *should*) be especially adaptable to a changing climate, thereby addressing both mitigation and adaptation concerns. Nevertheless, the mitigation/adaptation dichotomy is a well-established framework used in climate change literature. In terms of this established dichotomy, this thesis is focused on activities pertaining to climate change mitigation.

There is a general understanding in the climate science community, as well as in many political circles, that major reductions in anthropogenic GHG emissions will be necessary to forestall devastating changes in the Earth's climate system. A comprehensive, legally binding international agreement has yet to emerge, yet many local, state, and even national governments are enacting climate change mitigation requirements. These requirements are typically structured on an overall mitigation goal of reducing annual GHG emissions 80 percent below 1990 levels by the year 2050 (commonly referred to as "80 in 50" reductions). Achievement of such goals invariably involves significant changes to existing behavior and technologies within and across multiple economic sectors. The transportation sector in particular presents unique challenges for achieving climate change mitigation goals.

1.2.2. Climate Change Mitigation and Transportation

The transportation sector is a major part of the climate change mitigation challenge. First and foremost, the transportation sector as a whole is a major source of GHG emissions, accounting for approximately 28% of all annual GHG emissions in the U.S. (*15*). Figure 3 below shows the 2007 U.S. GHG emissions (CO_2e) allocated to economic sectors.

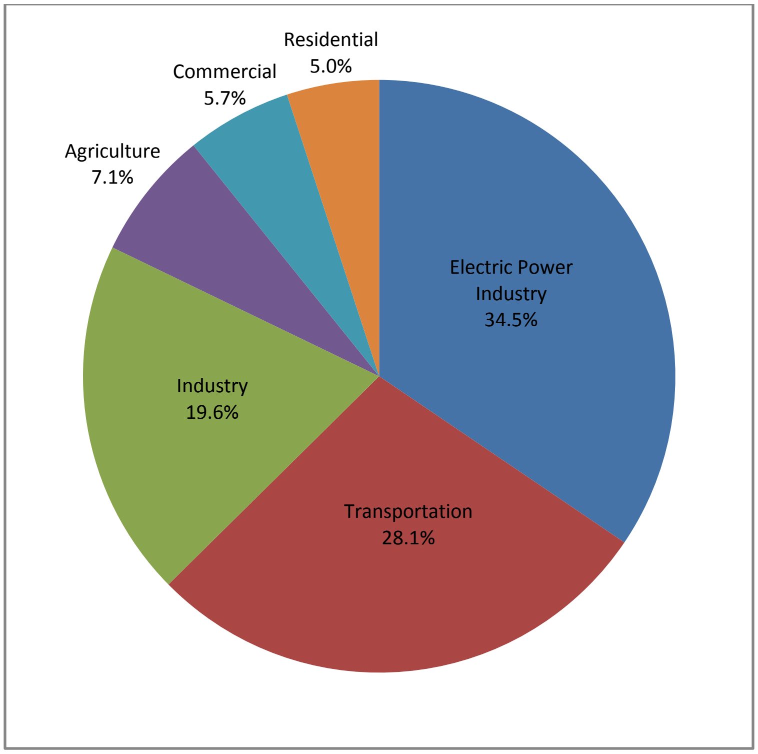

Figure 3: 2007 U.S. GHG Emissions (CO_2e) Allocated to Economic Sectors. Based on (*16*).

Due in large part to its large proportion of GHG emissions in modern industrial economies, the transportation sector is being called upon to achieve major reductions in GHG emissions. A national climate change mitigation framework has yet to emerge from the federal legislative or executive branches, but it is reasonable to expect that major reductions on the order of "80 in 50" will be required from the U.S. transportation sector (*17*).

The majority of GHG emissions from the transportation sector are produced from the combustion of petroleum fuels. This fact helps to explain not only why the transportation sector is a major emitter of GHGs, but also why mitigating GHG emissions from the transportation sector is so challenging. The transportation sector, an enormous element and enabler of modern industrial economies, is almost completely dependent upon petroleum fuels as an energy source

– approximately 95 percent of transportation sector energy consumption in the U.S. is supplied by petroleum fuels (*18*).

The transportation sector's heavy consumption of petroleum fuels directly influences the types and proportions of GHG emissions. Figure 4 shows the 2007 U.S. transportation sector's direct GHG emissions.

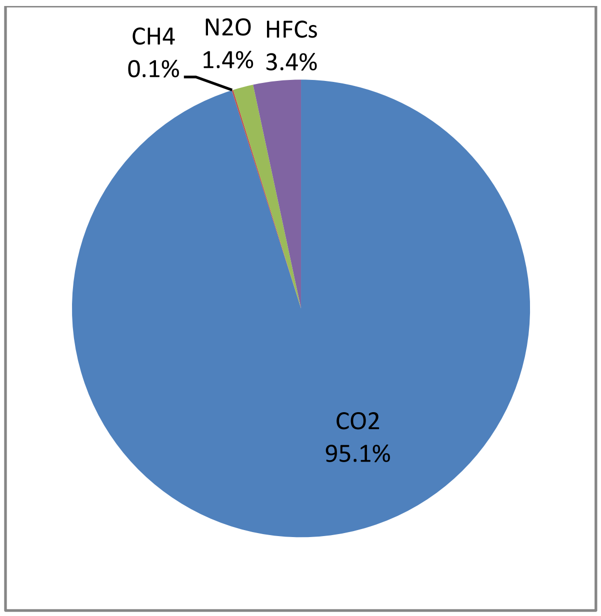

Figure 4: 2007 U.S. transportation sector direct GHG emissions, CO_2e. Based on (*16*).

The proportions of GHG emissions shown in Figure 4 are expressed in terms of CO_2e; thus the higher GWPs of non-CO_2 GHGs are accounted for in the percentages shown. Given that CO_2 is a primary product of complete combustion of hydrocarbons, Figure 4 underscores the role of the combustion of hydrocarbons, notably petroleum fuels, in the production of GHG emissions from the transportation sector.

Given that the transportation sector is a major source of GHG emissions, and that much of these emissions are produced from the combustion of petroleum fuels, it is clear that aggressive reductions in GHG emissions will necessitate substantial reductions in petroleum combustion. Yet the path toward realization of a low-carbon (or low petroleum) future is not entirely clear. No single technological development has yet emerged that can achieve "80 in 50" GHG emission reductions from the transportation sector. In fact, reductions in GHG emissions from the transportation sector are widely regarded as a multi-pronged effort. Figure 5 below shows the "4-legged stool" – a popular metaphor for the categories of GHG emission reduction strategies in the transportation sector.

Figure 5: The 4-legged stool of GHG reductions from transportation (*19*).

The "4-legged stool" is derived from the "3-legged stool", which consisted of the vehicle, fuel, and VMT legs. Figure 5 shows the introduction of vehicle/system operations as a category of GHG emission reductions (reducing emissions by reducing fuel wasted in congested or otherwise slow-moving traffic). The philosophy behind the original "3-legged stool" is that vehicles, fuels, and VMT represent the primary opportunities for reducing GHG emissions and that GHG emission reductions in only one or two area(s) (or legs) are insufficient for supporting major GHG emission reductions from transportation (analogous to the stability of a circular platform supported by three equally-spaced, equally-long circumferential columns). The strength of the analogy is weakened by the reality that GHG emission reductions in each of the three main categories will likely be unequal in degree. For example, state departments of transportation (DOTs) in the U.S. expect (or favor) GHG emission reductions primarily from improved vehicle and fuel technologies (*20*). For each of the legs of "the stool," behavior change, not just technological change, is necessary for the successful implementation of GHG emission reduction strategies. Specifically, the use of improved vehicles and fuels will require both advanced technological development and a shift in consumer behavior; reductions in VMT and system inefficiency will require both behavior that is less consumption and technology that supports the selection of more efficient modes or means of accessing goods, services, and activities.

The feasibility of a panacea (or more informally, a "silver bullet") for major GHG emission reductions in the transportation sector is hindered not only by the limited degree of reductions possible within each of the legs of the stool, but also by the diversity of transportation modes. Different types of modes in the transportation sector are each comprised of unique types of vehicle, fuel, and infrastructure systems that are not amenable to a one-size-fits-all approach to transportation GHG emission reductions. A picture of this modal diversity is illustrated by Figure 6 below, which shows the proportion of U.S. transportation GHG emissions by various mode sources.

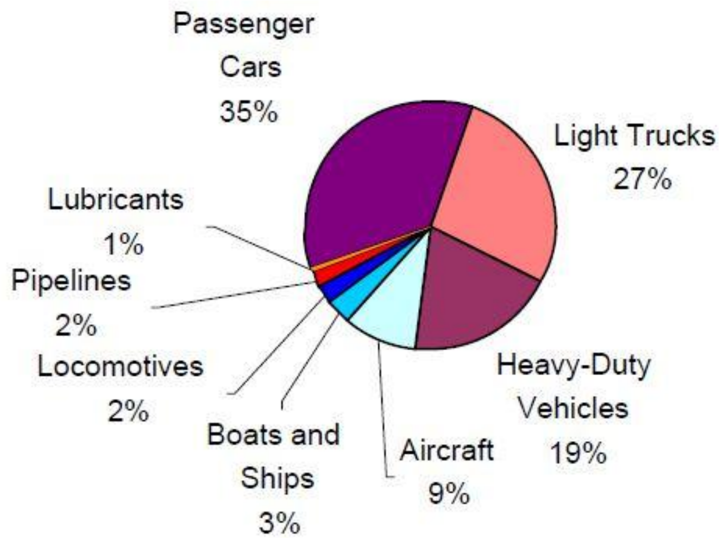

Figure 6: 2003 U.S. transportation GHG emissions, by source (*21*).

The emission sources included in Figure 6 encompass the full spectrum of transportation modes: on-road, rail, aviation, maritime, and pipeline. The above figure shows that on-road vehicles are the dominant source of GHG emissions from the transportation sector. This dominance in the proportion of GHG emissions is mostly explained by the large proportion of vehicle miles of travel (VMT) associated with on-road vehicles. Thus, there is little doubt that major reductions in GHG emissions from transportation must include a significant proportion of reductions from on-road vehicles. This is not to say that modes with lesser levels of VMT do not (or will not) play in important role in climate change mitigation. The public transportation sector, which includes several of the source types in Figure 6, provides unique and arguably essential opportunities for successful climate change mitigation.

1.2.3. Public Transportation's Role in Climate Change Mitigation

Public transportation plays a particularly unique role in mitigating climate change. Public transportation can help to mitigate climate change by reducing GHG emissions in one of two very different ways: 1) reducing the emissions produced by public transit agency (and supporting) operations and infrastructures; and 2) displacing the emissions produced by private automobile trips. Figure 7 below provides a visual representation of this typology, as advocated by the American Public Transportation Association (APTA).

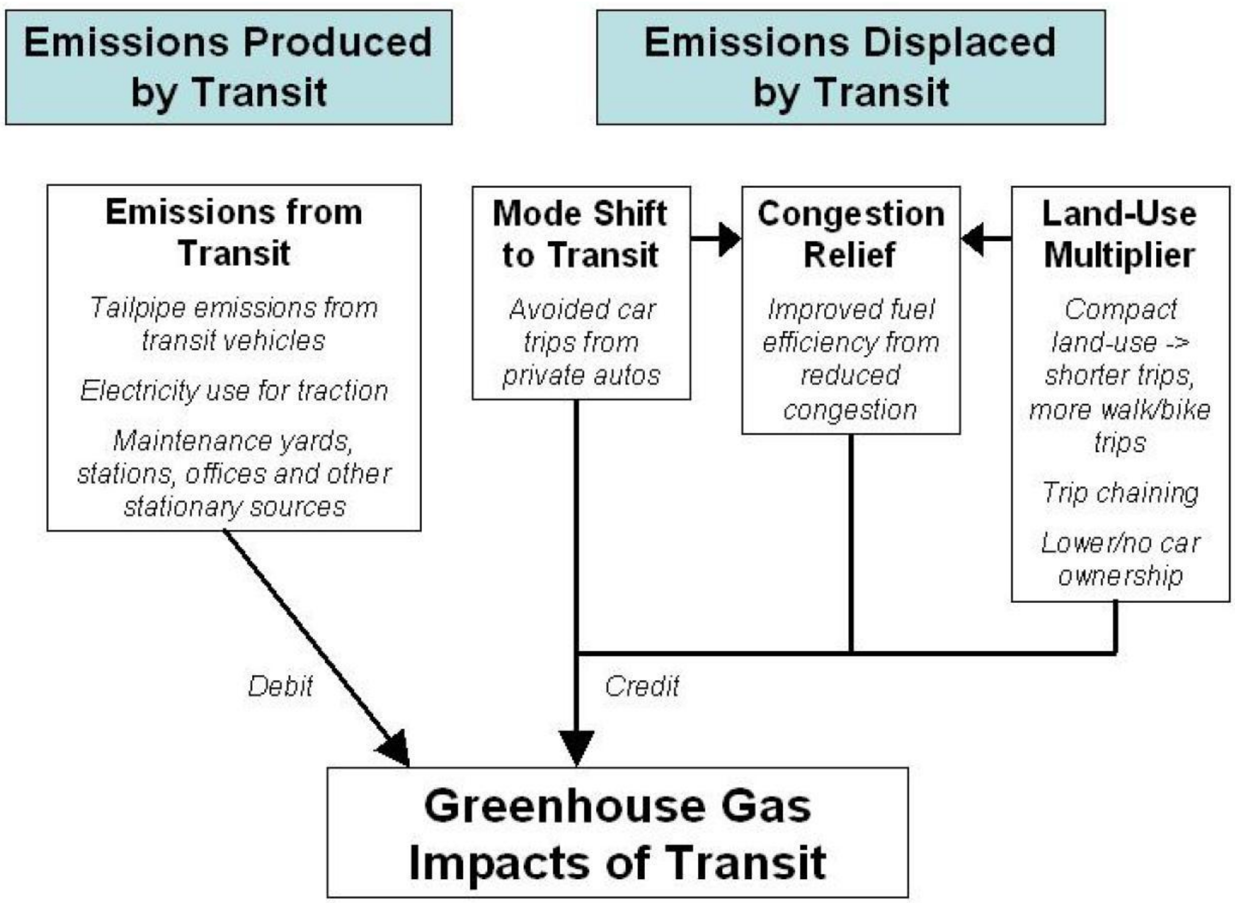

Figure 7: Typology of GHG impacts of public transportation (*9*).

1.2.3.1. Emissions Displaced by Transit

Public transit agencies can play a role in climate change mitigation by displacing GHG emissions produced by private automobile trips. GHG emissions displacement is essentially the estimated quantity of private automobile GHG emissions avoided by the provision of public transportation services. Several studies have explored how public transportation may reduce energy consumption and GHG emissions by reducing private vehicle activity (*10, 22, 23*). Referring back to Figure 7, APTA estimates displaced GHG emissions under three main categories: 1) Mode shift to transit; 2) Congestion relief; and 3) Land use multiplier effect. Mode shift to transit accounts for the trips taken by transit that would have otherwise been taken by private automobile. Congestion relief accounts for the benefit that public transit may provide by reducing on-road congestion levels and the associated wasteful emissions produced by congested traffic conditions. The land use multiplier effect is a quantification of how public transit supports more efficient land use in terms of shorter and fewer private automobile trips.

Quantification of the emissions displaced by transit has become a major focus for public transportation advocates, but the quantification methods are still in their infancy and subject to considerable uncertainty. Due in part to the methodological challenges facing the quantification of GHG emissions displaced by public transit, this thesis focuses on the emissions produced by public transit.

1.2.3.2. Emissions Produced by Transit

The GHG emissions produced by transit arise from a considerably wide spectrum of activities supporting the provision of mobility services. The majority of agency GHG emissions are produced from the combustion of fuels for vehicle propulsion. These fuels include both on-board liquid and gaseous fuels typically used to power buses, vans, commuter locomotives, ferry boats, and non-revenue vehicles, as well as electrical power generation fuels typically used for heavy rail and light rail vehicles. In addition to operating extensive fleets of various types of vehicles, public transit agencies also typically manage extensive infrastructures that support agency operations, such as stations, maintenance facilities, administrative offices, and so on. The operation of agency infrastructures involves the consumption of considerable amounts of energy for heating, ventilating, air conditioning, lighting, and other processes, which in most cases produce (directly or indirectly) GHG emissions. Altogether, the opportunities for transit agencies to reduce GHG emissions from their operations are quite numerous if the diverse array of transit agency activities is considered.

The array of opportunities for reducing GHG emissions produced by transit grows larger with consideration of the upstream and downstream GHG emissions associated with transit agency activities. In other words, a life cycle perspective on the vehicle, fuel, and infrastructure systems that support agency activities captures a broader set of opportunities for managing GHG emissions from public transportation. A life cycle perspective accounts for the cradle-to-grave supply chain activities related to a particular product or service. For example, the provision of mobility services by bus involves many upstream and downstream processes with GHG emission implications, including but not limited to: the extraction, refining, distribution, storage, and dispensing of the fuel; the material extraction, parts manufacture, assembly, and delivery of the vehicle; the maintenance of the vehicle; the disposal of the vehicle and vehicle parts; and even the construction and maintenance of the roadway. The life cycle perspective offers an integrative analysis of GHG emission reduction strategies, and life cycle analysis has become an established framework for evaluating GHG emission performance and reductions in transportation (*24*).

Understanding the potential for reducing GHG emissions produced by public transportation requires consideration of the potential efficiencies of public transportation. Public transit modes are capable of higher levels of vehicle occupancy than are most other competing surface modes. Higher vehicle occupancies enable more efficient energy use on a per passenger mile basis. Thus, when considering the productive output of public transit (passenger miles of mobility) public transit can provide improved GHG emissions performance. Figure 8 below shows a general comparison of estimated CO_2 emissions per passenger mile for transit and private automobiles.

Figure 8: Estimated CO_2 emissions per passenger mile for transit and private autos (*23*).

The above figure is based on average transit vehicle occupancies, and it should be emphasized that the actual GHG emissions performance of a given transit vehicle or operation is sensitive to ridership and vehicle occupancy.

In addition to the inherent vehicle capacity efficiencies of public transit modes, public transit agencies have helped to play a leading role in field testing alternative fuel vehicles

(AFVs). Since the 1970 Clean Air Act, U.S. transit agencies have served as test beds for emissions reducing vehicle technologies. Several of these technologies tested in public transit applications, such as diesel hybrid-electric and hydrogen fuel cell propulsion (*3*), show that public transit agencies can play a leading role in the development and application of technologies that help to mitigate climate change in the transportation sector. This role has recently been expanded by public transit energy efficiency and GHG reduction grants awarded through the American Recovery and Reinvestment Act (*5*).

CHAPTER 2

LITERATURE REVIEW

This chapter presents a literature review of previous reports, frameworks, guides, and calculation tools relevant to the development of a transit GHG emissions estimation and management tool. This literature review is organized into key categories of GHG emissions estimation and management literature: 1) the author's work on a transit GHG emissions management compendium; 2) environmental management systems; 3) life cycle analysis of GHG emissions; 4) studies of transit GHG emissions and costs; 5) and GHG emissions calculators.

2.1. Transit GHG Emissions Management Compendium

Considerable attention and support exists for reducing GHG emissions from public transportation, yet managing GHG emission reductions is nonetheless a challenge for public transit agencies. Public transit agency managers have many responsibilities and tasks, and incorporating GHG emissions management into agency activities inevitably brings new responsibility and complexity to agency management. The Federal Transit Administration (FTA) recognizes this fact and has thus contracted the development of a *Transit Greenhouse Gas Emissions Management Compendium* – an informational guidebook designed to assist transit agencies with managing their GHG emissions (*25*). The forthcoming compendium will include information on potential GHG emissions reduction strategies, case studies of successful GHG emission reduction practices, and information on emissions quantification methods (*26*).

2.1.1. Decision-Making Contexts for Managing Public Transit GHG Emissions

The Compendium's approach to GHG emissions management is structured on four main decision making contexts:

1. Planning for System Expansions and Major Construction Projects;
2. Fleet Procurement Practices;
3. Fleet Operations and Maintenance Practices; and
4. Other Activities (including green building retrofit practices for support facilities and employee commuting programs)

Figure 9 below details the decision-making contexts for managing GHG emission reductions from public transit agencies.

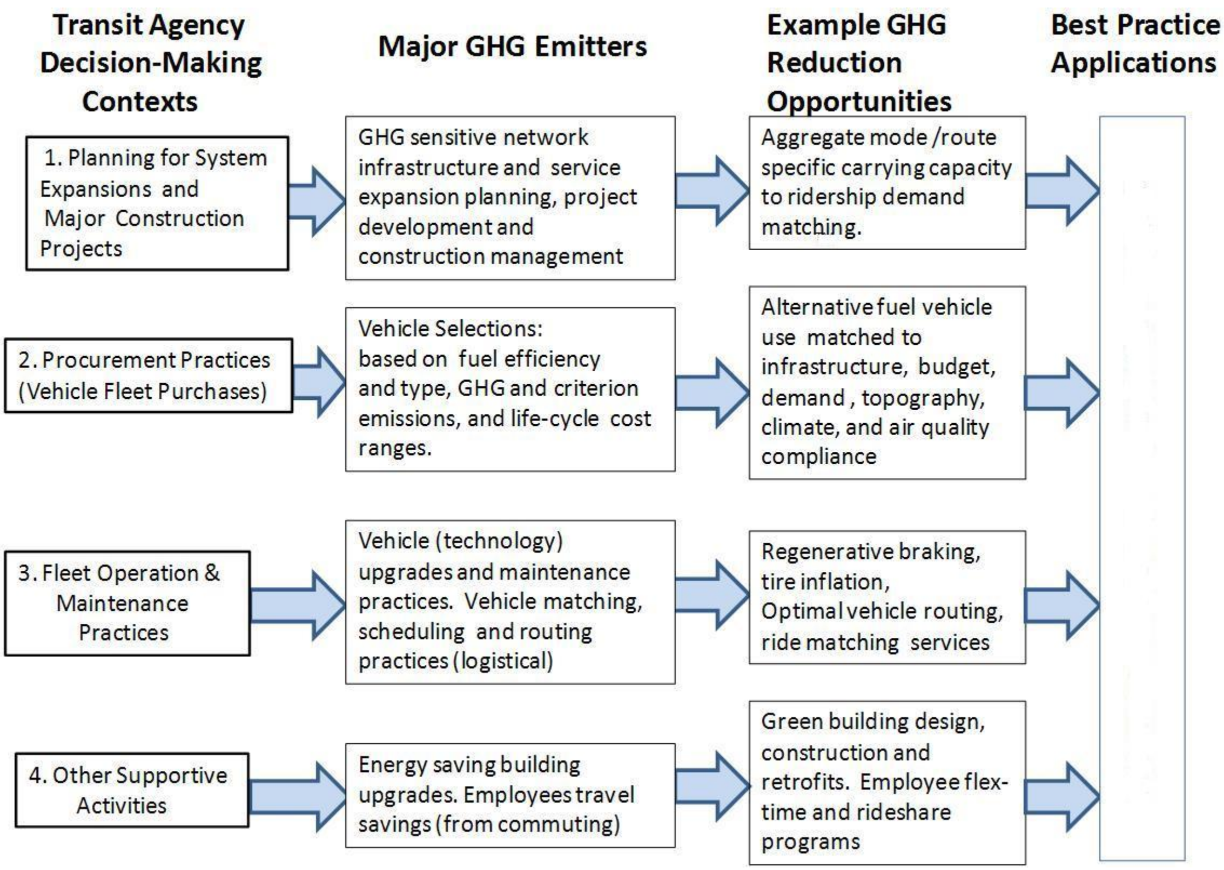

Figure 9: Decision-making contexts for managing GHG emission reductions from public transit agencies (*26*).

2.1.1.1. Planning for System Expansions and Major Construction Projects

Transit agencies are responsible for the planning and construction of major capital projects. Example projects include fixed-guideway infrastructure expansion, park-and-ride lots, bus or rail terminals, maintenance garages, vehicle or fuel storage facilities, and administrative offices. Many capital project infrastructures involve considerable life cycle GHG emissions over multi-decadal service lives. Therefore, accounting for GHG emissions in the planning of system expansions and major construction projects can help an agency manage its GHG emissions over the long term. An example scenario is the evaluation of a light rail transit (LRT) expansion vs. an alternative bus rapid transit (LRT) expansion. Taking into account the unique infrastructures, fuels, vehicles, and planned operation of each of the mode technologies, these system expansion projects would most likely have different GHG emissions performance. GHG emissions reduction is certainly not an overriding consideration in the planning of major capital projects, but unique and significant opportunities for GHG emission reductions may be realized by targeting reduction opportunities during system planning.

2.1.1.2. Fleet Procurement Practices

In general, the combustion of fuels for the propulsion of transit vehicles constitutes the greatest source of GHG emissions from transit agencies. Improvements in the GHG emissions performance of transit vehicle fleets may be realized through the procurement of more carbon efficient vehicles and fuels. For example, many agencies have recognized the improved fuel efficiency of diesel hybrid-electric buses vs. conventional diesel buses, which equates to improved carbon efficiency. The fleet procurement process represents a critical opportunity for reducing much of the day-to-day energy consumption and GHG emissions of transit agencies.

2.1.1.3. Fleet Operations and Maintenance Practices

Agency fleet operations and maintenance practices affecting GHG emissions encompass a variety of activities, including but not limited to vehicle capacity/demand matching, route restructuring, “eco-driving”, tire inflation programs, engine/drivetrain tuning, and vehicle idling reduction (through transit signal priority, passenger boarding/alighting efficiency improvements, auxiliary power systems for hotel loads, and vehicle operator shutdown policies). Operation and maintenance practices can help to improve GHG emission performance by either: 1) Maximizing the productive service output per unit of energy; or 2) Minimizing energy losses. Fleet operation and maintenance practices can offer opportunities to reduce GHG emissions without major financial investments in new vehicle or infrastructure systems.

2.1.1.4. Other Activities

The “Other Activities” in the decision-making context framework include some of the most promising strategies for reducing agency GHG emissions, most notably the retrofit of buildings in accordance with “green” or LEED® (Leadership in Energy and Environmental Design) building practices. In the U.S., buildings account for approximately 38 percent of direct domestic CO_2 emissions (*27*). Agencies that manage extensive built infrastructures may substantially reduce their carbon footprint through retrofits that improve building energy efficiency. The “Other” category also includes employee commute programs, such as flex scheduling, ridesharing, and transit pass subsidies that can help to reduce the carbon footprint of employee commuting.

2.2. Environmental Management Systems

Anthropogenic GHGs are essentially environmental pollutants, not in the sense that they are toxic, but in the sense that they engender changes in the climate that are harmful to human-Earth systems. The human-controlled and –induced processes that produce GHG emissions, such as the combustion of fossil fuels, are very often the same processes that produce toxic emissions, such as criteria air pollutants (CAPs). The close relationship between the production of GHG emissions and other regulated emissions suggests a common management framework. Frameworks addressing the management of emissions or pollutants from organizational activities are referred to in the literature and in industry as Environmental Management Systems (EMSs).

The International Organization for Standardization (ISO) offers a robust EMS framework for the management of environmental emissions from commercial or industrial organizations – the ISO 14000 management standard. ISO 14000 is a "management tool enabling an organization of any size or type to:

- Identify and control the environmental impact of its activities, products or services, and to
- Improve its environmental performance continually, and to
- Implement a systematic approach to setting environmental objectives and targets, to achieving these and to demonstrating that they have been achieved" (*28*).

APTA has incorporated the use of ISO 14000 EMS in its recently developed "Sustainability Commitment" for transit agencies (*29*). The APTA Sustainability Commitment is a framework available for transit agencies to define and track progress toward sustainability initiatives such as reducing water usage, CAPs, GHGs, energy use, and material waste (*29*).

The ISO 14000 management standard by itself does not provide specific guidance on managing GHG emissions, but it does provide “a framework for a holistic, strategic approach to the organization's environmental policy, plans and actions” (*28*). Specific guidance on how to estimate and report GHG emissions from an organization is provided by the ISO 14064 Greenhouse Gases series of standards – a GHG emissions inventory protocol similar to those covered in Section 2.5 “GHG Emissions Calculators.”

2.3. Life Cycle Analysis of GHG Emissions

The environmental management of GHG emissions is meaningful for organizations like transit agencies; however, the GHG emissions implications of organizational activities oftentimes extend beyond the control boundary (financial or managerial) of a given organization. Expressed another way, transit agencies may do well to manage emission produced directly from their consumptive activities, but these activities likely result in upstream or downstream emissions in material and energy supply chains. Thus, the identification of an appropriate system boundary for agency GHG emission impacts is essential for emissions management. Since GHG emissions have a global-scale impact, management of only local emissions may neglect potentially relevant system effects.

A life cycle analysis perspective is becoming the viewpoint of choice among researchers interested in comprehensive quantifications of GHG emissions from products and services (*24, 30, 31*). The term “life cycle analysis”, as it is used in this thesis, is inclusive of both life cycle inventory (LCI) and life cycle assessment (LCA). Life cycle inventory is the quantification of a metric of concern (e.g. GHG emissions) over a product or service lifetime. Life cycle assessment is the characterization of the impact(s) of the inventoried metric, and involves the incorporation of value judgments in assessing the impact(s). The calculator developed in this thesis is focused on the LCI aspects of life cycle analysis.

Despite considerable popularity and technical complexity in the life cycle analysis of products and services, there exists no standard methodology for quantifying life cycle GHG emissions. However, the literature does include a schematic framework for developing a life cycle analysis for a product or service: ANSI/ISO 14040 *Environmental management – Life Cycle Assessment – Principles and framework* (*32*). This standard provides a methodological framework that directs users to define the goal and scope of their assessment. The scope includes the product system to be studied, the product system boundaries, and the functional unit (*32*). "A functional unit is a measure of the performance of the functional outputs of the product system. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related" (*32*). For assessment of GHG emissions produced by transit APTA has established the following functional units (referred to as "performance metrics"): GHGs per vehicle mile, GHGs per revenue vehicle hour, and GHGs per passenger mile (*9*). With respect to analysis boundaries, APTA recommends that transit agencies focus their GHG emissions analysis within the organizational boundaries of the agency (*9*). This focus is consistent with GHG emissions reporting protocols, which are discussed in the section "GHG Emissions Calculators."

In the research literature, life cycle assessments follow one of three main calculation approaches (*33*):

1. Process-based life cycle assessment;
2. Economic Input Output life cycle assessment (EIO-LCA); or
3. Hybrid life cycle assessment.

A process-based LCA is a method of modeling each of the “smallest portion[s] of a product system for which data are collected” (*33*). For some product systems that contain a plethora of parts and components, (e.g. a transit bus), calculation data on the GHG emissions of each portion of the product system may not be available. In such a case, an EIO-LCA approach may be used. EIO-LCA uses economic input tables to link the money spent on a given product system with the industrial sectors that played a role in creating or delivering the product system. Average reported GHG emissions of the supporting sectors are used to allocate and aggregate the GHG emissions for the given product system. This approach offers a convenient alternative for products or services that lack adequate data for a process-based LCA; however, the use of industrial sector average emissions limits the utility of comparing materially different products classified under the same sector. For example, the manufacture of a diesel bus and a diesel electric hybrid bus would reasonably result in different levels of GHG emissions, since the hybrid bus has a much larger large mass of batteries (typically lead-acid or Li-ion). Yet, the EIO-LCA-estimated difference in GHG emissions between the manufacture of a hybrid bus and the manufacture of a conventional diesel bus is a function of only the difference in purchase cost, not the difference in material types or quantities.

Complex life cycle assessments, such as a GHG footprint of a transit agency, may have data available for process-based calculations for some but not all portions of the system. In such cases, a hybrid life cycle assessment approach may be used – an approach utilizing process-based life cycle assessments that are augmented by EIO-LCA calculations

2.4. Studies of Transit GHG Emissions and Costs

An example in the literature of a complex life cycle assessment using a hybrid LCA approach, and one of the most extensive studies of transportation life cycle emissions (but not costs), is the *Environmental Life-cycle Assessment of Passenger Transportation* by Chester and Horvath (*24*). This study used a hybrid approach for a cross-modal GHG emissions performance life cycle assessment, which included bus, heavy rail, and light rail transit modes. The analysis boundary of the study was quite large, encompassing vehicle operation, manufacturing, maintenance, and insurance, as well as the construction, operation and maintenance of right-of-way infrastructure. The study used national-level and agency-level data to calculate direct and indirect emissions and utilized many calculation assumptions regarding various GHG emission producing processes, from vehicle idling to the vacuum cleaning of vehicle interiors. The results indicate that the relative GHG emissions performance of public transit is dependent upon mode, fuel/energy supply chain, and ridership. The study contributes a holistic perspective and framework to the literature on estimating GHG emissions from passenger transportation, but the applicability of the study's findings for managing GHG emissions is limited. The study's assumptions and data are not representative of the diversity of operational contexts among all transit agencies, and thus the study's estimated GHGs per mile for transit modes are very likely not applicable to agencies with vehicle and fuel systems that differ from those included in the study. The calculation methodology/data for "operation" emissions (GHGs produced from the combustion of fuels for vehicle propulsion) does not follow APTA Recommended Practices (*9*) For example, the study's calculation of the electrical energy supply chain emissions associated with heavy and light rail transit propulsion does not account for emissions generated for non-useful heat energy (electrical generation plant efficiencies are not accounted for).

Both emissions and costs are a concern for transit agency managers, and the Federal Transit Administration (FTA) has conducted a detailed study of the life cycle costs and emissions of public transit bus technologies (*34*). This report evaluates compressed natural gas (CNG), ultra low sulfur diesel (ULSD), biodiesel (B20), and diesel hybrid bus life cycle cost and emissions using 2007 national-level data (and predictions) on costs and efficiency. The costs considered include: "capital costs (bus procurement, infrastructure, and emissions equipment) and operation costs (fuel, propulsion-related system maintenance, facility maintenance, and battery replacement)" (*34*). Fuel-cycle GHG emissions are evaluated on both a well-to-tank and tank-to-wheels basis. The report indicates that for a 12-year life cycle, hybrid diesel buses produce the least GHG emissions, but are most expensive. The national-level analysis does not account for local variations in cost and efficiency, i.e. the results are specific to the contexts for the cost data sources. Thus, the inputs and results may not be applicable to the unique operational context of a given agency seeking to identify the most cost-effective bus (or non-bus) alternative.

More recently, the Transit Cooperative Research Program (TCRP) of the Transportation Research Board (TRB) has provided an assessment of hybrid-electric transit bus technology (*35*), one of the more popular bus technologies for reducing fuel costs and emissions. This report evaluates CNG, diesel, diesel hybrid, and gasoline hybrid life cycle costs, using national-level data and agency case study data, and provides estimated defaults for both historical and projected costs. With federal funding and low-speed duty cycles, hybrid buses are found to have the lowest life-cycle cost to the agency. The report provides a robust LCCA calculation methodology for transit buses and a spreadsheet-based calculation tool is provided in the appendix. The calculation tool includes many cost, activity, and efficiency inputs and allows users to modify the default inputs. The model provides only an LCCA, and thus emissions performance is neglected.

Table 1 below provides a summary of the main studies of transit GHG emissions and costs. Overall, these findings in the literature indicate that generalized studies of the GHG emissions performance of various modes of public transit provide limited utility for the management of specific public transit agency activities.

Table 1: Studies of Transit GHG Emissions and Costs

Study	**Purpose / Methods**	**Findings / Synthesis**
FTA 2006 (*36*)	Compiles quantitative and qualitative data on costs, emissions, and implementation barriers of AFVs for transit.	Recognizes importance of lifecycle analysis of costs (LCCA) and total fuel cycle emissions (WTW), but no such analysis is provided.
U.S. DOT 2005 (*37*)	Assesses GHG emissions benefits of heavy duty NG vehicles in the U.S. using test data from WVU	Emissions benefits vary depending upon vehicle wt., model year, and drive cycle. Data support only highly aggregated emission factors. Universal conclusions on relative benefits of NG vs. diesel are limited.
FTA 2007 (*34*)	Evaluates CNG, ULSD, B20, and diesel hybrid bus life cycle cost and emissions using 2007 national-level data (and predictions) on costs and efficiency.	For a 12-year life cycle, hybrid diesel buses produce the least GHG emissions, but are most expensive. The national-level analysis does not account for local variations in cost and efficiency.
Hodges 2009 (*23*), Chester & Horvath 2008 (*24*)	Evaluates GHG emissions performance of transit relative to other commuter modes. Uses national and agency-level data.	Relative GHG emissions performance is dependent upon mode, fuel/energy supply chain, and ridership. Cost of alternatives not assessed.

2.5. GHG Emissions Calculators

The literature contains a variety of publicly available GHG emissions calculators that may be utilized for the estimation of transit agency emissions. The literature search presented here recognizes a "calculator" as a calculation guidance report, spreadsheet, online application, or downloadable software tool. The guidance reports typically provide instructions on how to perform GHG emission calculations for various combinations of input data. These instructions normally include guidance on the preferred hierarchy of calculation methods; calculation formulae; default emissions factors by vehicle and fuel technology; and example calculations. Spreadsheet resources, such as the U.S. EPA's Simplified GHG Emissions Calculators (*38*), generally enable calculations through built-in formulae and default or user-entered emission factors. Online calculators, for example The Climate Registry Information System (*39*), provide similar functionality through an internet web browser, while downloadable software programs typically provide a calculation capability based on a significantly larger number of user inputs, selections, or reference data sets.

Publicly available GHG emissions calculators fall under two main categories, each one reflecting different emerging needs of transit agencies for GHG reporting:

1. Registry/inventory based calculators, most suitable for standardized voluntary reporting, carbon trading, and regulatory compliance.
2. Life cycle analysis (LCA) calculators, most suitable for holistic comparisons of the advantages of one transit mode, vehicle type, or fuel type over another.

Inventory calculators are designed for a broad user-base of corporations and municipalities and support the quantification of total agency end-use GHG emissions, which may be reported to a voluntary data registry (U.S. EPA's Climate Leaders program) or a registry for carbon credit trading (such as the Chicago Climate Exchange). The inventory calculators that are based on a reporting protocol are designed to be consistent in their approach to GHG emissions estimation (*6, 38, 40, 41, 42*).

The inventory calculators that are based on a reporting protocol follow what has become a standard "three-scope" division of emissions:

1. Scope 1: Direct emissions controlled by the agency;
2. Scope 2: Indirect combustion emissions that occur outside of the agency (primarily the emissions produced from the generation of purchased electricity);
3. Scope 3: Indirect "optional" emissions produced upstream or downstream of an organization's activities or control.

With respect to revenue transit vehicle emissions, vehicle fuel combustion and refrigerant leaks fall under Scope 1, purchased electrical energy falls under Scope 2, and upstream and downstream vehicle and fuel life cycle emissions fall under Scope 3. The assumption of Scope 3 is that these emissions would be accounted for as Scope 1 emissions by the organizations or entities that directly control them. An illustration of how these three scopes relate to life cycle GHG emissions of transit agency vehicle fleet operations is provided by Figure 24 in Appendix A.

The standard approach for calculating public transit agency GHG emissions is defined by the Recommended Practice published by the American Public Transportation Association (*9*). This industry standard follows inventory protocols (*6, 40, 41*) for defining the recommended calculation and reporting methods for public transit agencies. The inventory protocols provide a comprehensive accounting framework for estimating GHG emissions from both mobile and stationary sources, however very little technical guidance is provided for estimating upstream fuel-cycle, vehicle-cycle, or infrastructure-cycle emissions (Scope 3). The APTA standard defines the preferred data and required performance metrics (functional units) for transit GHG emissions estimation and comparison. The specified performance metrics include emissions per vehicle mile, emissions per revenue vehicle hour, and emissions per passenger mile. According to the executive summary of the APTA recommended practices, APTA is currently developing an online or spreadsheet-based calculation tool, but there is no indication that the tool will account for costs or total life cycle GHG emissions.

Table 2 below shows a summary of the main GHG emissions estimation frameworks and protocols applicable to public transit agencies.

Table 2: GHG Emissions Estimation Frameworks and Protocols

Framework	Purpose / Methods	Findings / Synthesis
ANSI 1997 (*32*)	Outlines a methodological framework for performing life cycle assessment studies.	The definition of the goal and scope of an LCA is an iterative process. Key elements include the adoption of a functional unit, system boundaries, and the requirements and limitations of data.
TCR 2009 (*39*), WRI 2009 (*40*), CCAR 2009 (*41*), ICLEI 2009 (*42*), ISO 2006 (*43*)	Defines standardized methodologies for calculating organization/corporate-level GHG emission inventories.	A comprehensive framework of calculation methods, default data quality tiers and sources, and accounted categories are defined. Although life cycle upstream emissions are acknowledged, guidance is lacking.
APTA 2009 (*9*)	Follows inventory protocols for defining the recommended calculation and reporting methods for public transit agencies	Preferred data and required performance metrics (functional units) for transit are defined.

For a more detailed listing of inventory GHG emission estimation protocols and calculators, see Table 21 in the appendix. Table 21 outlines the format and outputs of the inventory calculators. For a similar outline of life cycle GHG emission estimation calculators, see Table 22 in the appendix.

For the most part, the calculation methodology and formulae of the inventory protocols adequately account for direct combustion emissions, but supplemental calculations are necessary to estimate GHG emissions in supply chains. For example, although inventory calculators account for plant efficiency losses in the production of purchased electricity, considerable upstream GHG emissions are neglected. For purchased electricity emissions, inventory calculators utilize data from the U.S. EPA's eGRID database of electrical power generation emission factors (*44*). The eGRID emission factors include neither upstream fuel extraction, refining, and transportation-related GHG emissions, nor GHG emissions associated with electrical energy transmission and distribution (T&D) losses. GHG emission registry protocols stipulate that that energy transmission and distribution losses are to be reported only if the reporting organization controls the transmission and distribution network (*6*, *40, 42*). Electrical T&D networks experience line losses on the order of 10 percent of plant generated power (*45*) and the effect is a net increase in GHG emissions per MWh of electrical energy delivered to the agency. Transit agencies have little control over T&D losses on power grids. However, the emissions associated with such losses must be understood in order to evaluate properly mode and vehicle technology alternatives during the planning of fixed guideway services or to evaluate the development of onsite power generation alternatives.

Life cycle analysis calculators account for a larger array of upstream and downstream processes and emission, and are thus considerably more complex in their calculation methodology. The pre-eminent, publicly available resources for calculating life cycle GHG emissions from U.S. on-road transportation modes are the GREET models from the Argonne National Laboratory of the U.S. Department of Energy (*46, 47, 48*) and GHGenius from Natural Resources Canada (*49*). These process-based, spreadsheet calculators enable estimation of fuel-cycle and vehicle cycle energy consumption and GHG emissions for primarily passenger cars and light duty vehicles. The models utilize national and regional data for default emission factors and consider GHG emission credits of displaced emissions. The GREET model inputs, outputs, (and fuel-cycle model user interface) provide limited functionality for emissions estimation from public transportation modes. Uniquely, the GHGenius model includes heavy duty vehicles and buses, and it provides $/tonne cost-effectiveness of GHG reductions of fuel/energy alternatives.

The cost-effectiveness of GHG reductions are calculated by dividing the capitalized additional cost per vehicle km by the GHG reductions per vehicle km. For buses, the additional costs and emissions reductions are relative to a petrol diesel baseline. The cost-effectiveness is calculated separately for the "upstream fuel cycle," the "vehicle use," and the "vehicle material/assembly/transport." Costs are categorized as vehicle purchase cost, operation & maintenance costs, fuel costs, and other/additional costs. The GHGenius model is licensed for limited personal use, and it is derived from the larger Lifecycle Emissions Model (LEM) developed by Mark Delucchi (*50*). The LEM model includes a broader range of transit modes and GHG emission processes, but the model is not publicly available.

A spreadsheet-based calculation tool for estimating both the life cycle costs and emissions of various types of transit bus propulsion technologies has recently been developed at the Chicago Transit Authority (CTA), but it is not publicly available (*51*). The costs considered in the tool include vehicle purchase costs, refueling station costs, depot modification costs, emissions equipment cost, driver cost, vehicle maintenance cost, facility maintenance cost, and fuel cost. The cost framework does not account for subsidies, and similar to FTA and TCRP research, it does not account for any equipment salvage value (*34*, *35*, *51*). Costs are reported on a per passenger mile basis and total fuel-cycle GHG emissions (WTW, WTT, and TTW) are reported, but it is unknown what emission calculation methodology is used.

Table 3 shows a sample summary of main calculation tools for GHG emissions/cost estimation that are applicable to public transit agencies.

Table 3: Example Calculation Tools for GHG Emissions and/or Cost Estimation

Tool	Methods	Findings / Synthesis
Climate Leaders 2009 (*38*)	Process-based, spreadsheet calculation of direct GHG emissions, with separate accounting for biogenic emissions	Direct emissions estimation capability for both road and non-road transit modes, however life cycle emissions and transit performance metrics are neglected.
GREET V1.0 Fleet 2009 (*48*), GREET V1.8c Fuel-Cycle (*46*), GREET V2.7 Vehicle Cycle (*47*)	Process-based, spreadsheet calculation of fuel-cycle and vehicle cycle energy consumption and GHG emissions per vehicle mile. Utilizes national and regional data for default emission factors. Considers GHG emission credits of displaced emissions.	User interface, inputs, and outputs provide limited functionality for emissions estimation from public transportation modes.
GHGenius 2009 (*49*), LEM (*50*)	Similar to GREET. GHGenius is based primarily on data from/for Canada. LEM includes a broader range of GHG emission processes and transit modes.	Similar to GREET, yet provides $/tonne cost-effectiveness of GHG reductions of fuel/energy alternatives.
Green Design Institute 2009 (*52*)	Economic Input Output-based calculation of average industrial sector GHG emissions associated with product values.	Provides results for vehicle-cycle emissions of any transit vehicle type, although data resolution is limited to industrial sector averages.
Clark et. al 2009 (*35*)	Evaluates CNG, diesel, diesel hybrid, and gasoline hybrid life cycle costs, using national-level data and agency case study data.	With federal funding and low-speed duty cycles, hybrid buses are most cost-effective. Provides a LCCA calculation methodology, but emissions performance is neglected.

Many other calculation tools, in addition to those presented in Table 3: Example Calculation Tools for GHG Emissions and/or Cost Estimation, are available for estimating GHG emissions. As part of this research, the author has conducted an extensive review of calculators for estimating GHG emissions from public transit vehicle fleet operations. Table 23 and Table 24 in the appendix provide a detailed listing of the vehicle types and fuel types covered by available GHG emissions calculators. Although a large number of vehicle and fuel types are included in these calculators, most calculators are not designed specifically for quantifying emissions from transit modes.

2.6. Synthesis of Existing Calculation Capabilities and Needs

Many calculation data sources, frameworks, and tools exist. However, no one resource provides integrative life cycle GHG emissions estimation capability that is appropriate to the context of transit agency emissions management. A number of tools are available to transit agencies for either developing a carbon emissions inventory that is consistent with the accounting standards of several carbon emissions registries, or for analyzing relevant vehicle and fuel life cycle GHG emissions. Quantifying GHG emissions that occur upstream or outside of the operations controlled by the agency is generally much more complex, and much more data intensive, than doing the same for direct emissions based only upon in-service vehicle energy consumption. To estimate upstream/downstream emissions transit agencies would need to obtain additional data on fleet vehicle technologies/components and fuel/energy feedstocks, or use national and regional defaults, which may not be representative of a particular agency's operation. Nevertheless, estimating GHG emissions from external processes like electrical power generation is vital for characterizing the emissions implications of transit agency decisions. The emissions produced by these external processes are often referred to as "indirect" emissions, but it should be understood that these emissions are in fact the direct result of transit agency activities – the boundaries of responsibility should not be confused with the boundaries of consequence.

Though many existing calculators may be drawn upon to develop vehicle and fuel GHG emissions, a fully specified transit LCA calculator that can be adapted easily to handle the wide range of transit vehicles and modes does not currently exist. An improved calculator should model and compile manufacturing, maintenance, and disposal emissions for each of the types of vehicles reported to the National Transit Database (NTD). Existing LCA calculators have made some progress, but much more capability is needed, especially for maintenance emissions and for the life cycle of non-road vehicles. A similar compilation or simplification of upstream fuel/energy feedstock data would help to distill existing process-based upstream fuel emissions calculators down to a level of complexity that is more compatible with the level of detail of fuel/energy feedstock data available to fuel procurement personnel. Compilation of life cycle emissions would reduce the data gathering burden on transit fleet managers and would develop consistency in vehicle LCA GHG emissions estimates.

Existing calculators are generally consistent in their approach to estimating emissions from purchased electricity, but the accuracy of the calculators would be much improved if they accounted for T&D losses and accounted for temporal variations in peak and off-peak emission rates. Improvements in the geographic and temporal accuracy of electrical power emissions calculations would benefit the GHG emissions estimation efforts of many organizations beyond the public transportation sector. Unfortunately, such improvements are currently limited by the aggregation of reported power generation emissions data.

One of the important considerations to transit officials is the cost of achieving GHG emissions reductions, which are often measured by cost effectiveness in units of $’s/tonne of CO_2e reduced. Only one of the calculators identified in this review contained an analysis or estimation of emission reduction cost effectiveness (*49*). To be more useful to agency decision makers, an improved calculator should support such considerations of cost effectiveness by either estimating cost or allowing users to input estimates of the component costs of alternative fleet management decisions.

The calculator framework developed and presented in this thesis is not (and cannot be) comprehensive for all decision alternatives and aspects. A robust management framework must account for considerations beyond the management of costs associated with GHG emission reductions, such as the realization of other system benefits that meet organizational objectives. The life cycle cost LCCA method, the method used in the recent TCRP evaluation report for hybrid buses (*35*), does not account for benefits, such as the benefits of GHG emissions reductions or the benefits of quieter bus operation. A cost-effectiveness metric merely allows agencies to identify strategies that present the lowest incremental cost for an incremental decrease in GHG emissions.

Incremental analysis requires the determination of meaningful baselines, and meaningful comparison requires normalization of emissions by a performance metric. Appropriate baselines will vary substantially between various transit agency activities. For example, in the case of cross-modal GHG emissions reduction comparison, a single occupant private automobile emission rate may serve as a meaningful baseline. For comparison of alternative bus vehicle-fuel systems, a 40 ft diesel bus emission rate may serve as a meaningful baseline. In each of these vehicle comparison contexts, the appropriate normalizing performance metric is pax-miles or vehicle miles. Normalization by pax-miles provides the most direct characterization of the emissions and cost efficiency of a given vehicle-based strategy; however, this metric makes strategy performance dependent upon ridership, which may vary between strategies that offer equivalent capacities and quality of service. In other words, strategy comparisons normalized by pax-miles are sensitive to confounding factors that cause disparate levels of ridership between the alternatives being considered. Furthermore ridership data for specific vehicles or specific vehicle types may be limited do to agency data collection or accounting methods. Alternatively, normalization by vehicle miles eliminates the confounding effect of disparities in ridership, but a vehicle-miles metric may unfairly bias evaluations in the favor of smaller lighter vehicles that provide inadequate capacity to serve ridership demand. Thus, comparisons based on vehicle-miles must represent fair comparisons of supplied capacity. For example, a comparison of 40 ft buses to 60 ft. buses should account for the higher frequency of 40 ft bus trips needed to supply the capacity of (or the demand served by) 60 ft buses.

In the context of facility-based strategies, a different performance metric and baseline is required. The architecture/engineering industry typically normalizes energy and emissions performance by facility square footage (*53*). This normalizing metric may be applied to the many fixed infrastructures that transit agencies manage: bus garages, bus maintenance facilities, railcar maintenance facilities, stations, terminals, park and ride lots and garages, administrative office buildings, etc. A per SF normalizing metric allows comparison of costs and emissions/energy across different facility types and sizes, but is does not account for the unique service benefits garnered by investments in different facility types. For example, a facility efficiency investment for a transit station may be more expensive than a facility efficiency investment for a bus garage, but the transit station may uniquely result in a positive gain in passenger satisfaction or ridership. Nevertheless, in consideration of the fact that facilities can constitute a considerable proportion of agency GHG emissions (and considerable potential for GHG emission reductions), effective management of agency GHG emissions requires an integrative GHG emissions reduction evaluation framework that accounts for per SF facility investment costs and savings.

Fair comparison of the cost-effectiveness of vehicle-based and facility-based emission reduction strategies is possible once a $/tonne cost-effectiveness for vehicle-based and facility-based strategies and their respective baselines has been established. This research aims to develop a calculation tool that allows users to enter several unique cost and activity profiles/inventories and to select their preferred baselines for vehicle-based and facility-based emission reduction strategies.

The existing literature does not offer an integrative framework or tool for managing cost-effective GHG emissions reductions from public transit; however, the literature does provide a point of departure for defining the relevant calculation capabilities needed.

CHAPTER 3

CALCULATOR DESIGN AND SYNTHESIS

3.1. Purpose and Capabilities

The general purpose of the calculator developed in this thesis is to enable quantification and management of GHG emissions from public transit activities. Toward this end, the developed calculator provides several distinct capabilities for the user:

I. Estimation and inventory of agency GHG emissions (carbon footprint) that is consistent with standard GHG inventory protocols;
    - Use of input data tiers and output scopes;

II. Estimation of upstream supply-chain GHG emissions;

III. Estimation of the cost-effectiveness of agency GHG emission reduction strategies (relative to baseline activities);
    - Accounting of costs associated with different types of vehicles and facilities.

The calculator incorporates the methodologies and data of several calculation resources identified in the literature review and thus provides an integrative calculation resource for transit agency managers. This chapter details the architecture of, and the methodologies and data used by, the developed calculator.

3.2. Calculator Architecture

The architecture of the calculator is a product of both established GHG accounting frameworks and the software platform. With respect to GHG accounting frameworks, the calculator is partitioned between the main types of GHG emission sources:

- Mobile sources;
- Stationary sources;
    - Onsite combustion;
    - Purchased electricity;

The mobile source / stationary source distinction is founded in part on the methodological differences in calculating GHG emissions from these two main types of GHG emission sources. This distinction roughly corresponds with the organizational separation between facilities management and fleet management within public transit agencies, with one notable exception – electrically powered fleets produce propulsion-related GHG emissions at stationary sources. Vehicle fleet emissions are thus associated with both mobile and stationary sources. For vehicle fleet emissions, the calculator is divided into different mode types, each of which require a slightly or substantially different calculation methodology for estimating GHG emissions. The modes currently built into calculator include:

- Bus and paratransit;
- Light rail (LR) and heavy rail (HR) transit;
- Non-revenue vehicles

Measured in terms of passenger miles of travel (PMT), bus, paratransit, LR, and HR represent over three-quarters of all public transit activity in the U.S. (*23*). Due to research time constraints, commuter rail was not included in the developed calculator – however, commuter rail GHG emissions estimation will be included in a post-thesis version of the calculator.

The calculator organizes GHG emissions into the accounting scopes (1, 2, and 3) utilized by GHG emission inventory protocols. These scopes identify the relationship between a particular GHG emission producing activity and the organizational control boundary of the agency. Table 4 below indicates the inventory scopes for each type of modal or facility activity accounted for in the calculator.

Table 4: GHG Emission Inventory Scopes and Associated Modal and Facility Activity

GHG Emission Inventory Scope	**Modal or Facility Activity**
Scope 1	Mobile combustion (direct): Bus, paratransit, non-revenue vehicles, commuter rail etc.; Stationary combustion (direct): Facility boilers and heaters; Fugitive leaks (direct): Refrigerants from air conditioning equipment, methane from refueling facilities (leaks to be included in a later version of the calculator);
Scope 2	Purchased electricity: HR and LR transit, as well as facility energy consumption
Scope 3	Upstream life cycle processes: material/energy extraction, refining, manufacturing, transportation, distribution, and storage.

The calculator is built upon a spreadsheet platform and consists of several calculation and data worksheets. Each modal or facility element of an agency inventory (bus, paratransit, facility electricity, etc.) is calculated on a separate worksheet within the calculator. Figure 10 illustrates the organization and scopes of the GHG emissions inventory worksheets.

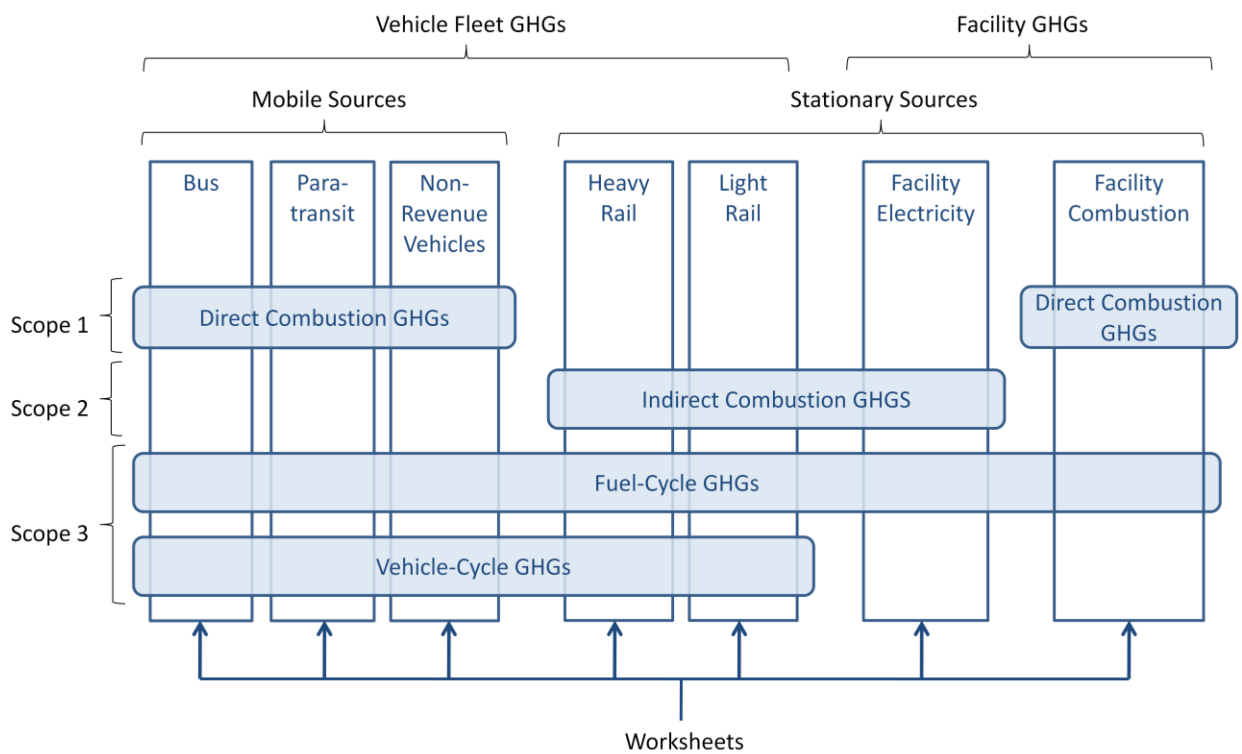

Figure 10: Organization and scopes of GHG emissions inventory worksheets.

The horizontal bands in Figure 10 indicate what type/scope of GHG emissions are calculated by the underlying worksheets. The division of inventory elements into separate worksheets accommodates a useful disaggregation of inventory record types and facilitates consistency in the columns (input, calculation, and output) in each of the worksheets. Figure 11 shows the general functional layout of an inventory worksheet.

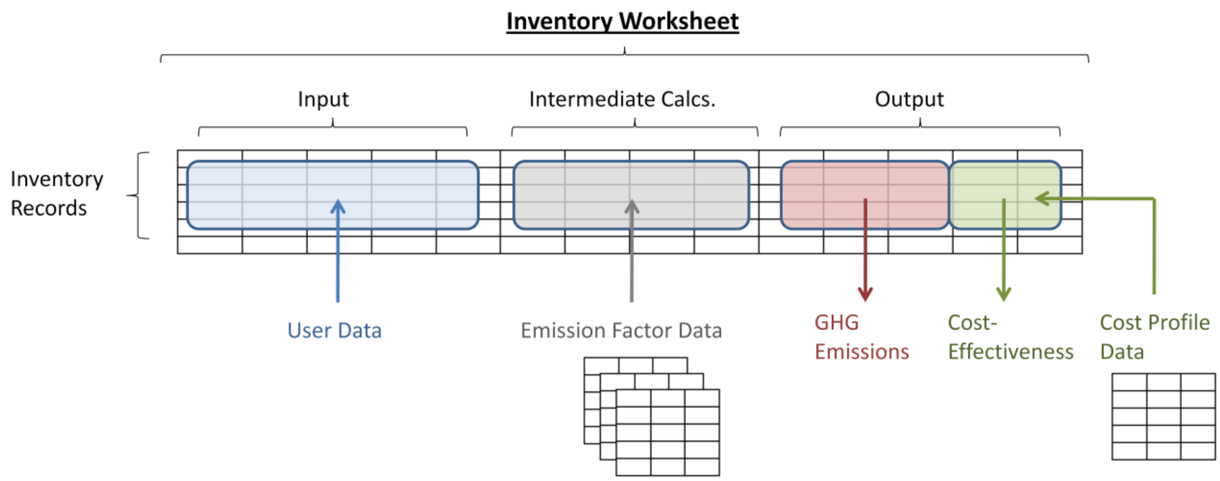

Figure 11: General functional layout of an inventory worksheet

The inventory worksheets contain rows of inventory records and columns of various input, calculation, and output data. In general, the worksheets contain most of the user input cells on the left-hand side and most of the calculation output cells on the right-hand side. Occupying many of the in-between columns are various, essential intermediate calculations. These intermediate calculations include estimations of activity (e.g. estimation of VMT from fuel consumption and fuel efficiency inputs) and queries of default emission factor data. Default emission factor data stored on other worksheets within the spreadsheet calculator are linked to the inventory calculations in response to selected user inputs. Similarly, "cost profile data" (entered by the user and explained later in this chapter) are linked to the inventory calculations and user inputs to generate cost-effectiveness outputs. The GHG emission outputs from each of the inventory worksheets are compiled on a single output worksheet containing summary tables and graphs of the GHG emissions inventory.

Appendix B contains figures of the inventory worksheets for transit buses, and shows the calculation formulae contained within the cells. Cells with a dashed or single solid outline are user inputs, hatched cells are unused inputs or outputs, as determined by initial user inputs, grey cells are intermediate outputs, and cells with a double outline are main outputs. The figures in Appendix B show the details of the calculation formulae, but some important features and functions of the inventory worksheets are not self-evident in the figures. The inventory worksheets utilize data validation for many of the user inputs, such as “fuel type” in column D, whereby the user may select the input from a drop-down list (see fuel type options listed at the bottom of column D in Figure 25). Parts of the inventory worksheets provide data validations lists that are conditional on other user inputs (see columns W, X, Y and Z in Figure 27). Also, the inventory worksheets employ conditional formatting (cell hatching) to reveal to the user which cells require input and which cells provide an optional output based on user selections. For example, if the user selects data tier A1 for a bus CO_2 emission factor (see column F in Figure 25), then the hatching on user input cells for fuel heat content and carbon content are removed (see columns AA, AB, AF, and AG in Figure 28). Default calculation data such as fuel and vehicle emission factors are stored in named ranges on other worksheets and are referenced in the formulae of the inventory worksheets. Most, but not all of the calculation input cells are located at the far left of the worksheets. The optional Scope 3 fuel-cycle and vehicle-cycle inputs are located (for convenience) near the outputs toward the right-hand side of the worksheets. Each row in an inventory worksheet may be used to record the activity and calculate the emissions associated with a particular vehicle-based or facility-based GHG emissions inventory, reduction strategy, or baseline.

3.3. Calculation Methodologies

The calculator incorporates a variety of calculation methodologies to estimate GHG emissions from direct and life cycle GHG emissions from the various categories of transit agency activities. Direct GHG emissions are estimated in accordance with APTA recommended practices (*9*) and upstream GHG missions are estimated through incorporation of the pre-eminent life cycle calculation methods and assumptions of the U.S. DOE's GREET fuel-cycle model (*46*) and the Green Design Institute's EIO-LCA model (*52*). The incorporated life cycle analysis calculations provide an increased level of sophistication and robustness to transit agency GHG emissions estimation, but interpretation of the meaning of these life cycle calculations requires a clear understanding of the methods and assumptions used.

3.3.1. Life Cycle Analysis Approach

The calculator presented in this thesis utilizes a life cycle analysis approach that attempts to capture all of the relevant and quantifiable GHG emission activities. These activities include various upstream and downstream processes in the supply chain. Figure 24 in the appendix provides a simplified diagram of life cycle GHG emissions producing activities related to transit agency vehicle fleet operations. Figure 24 depicts the many elements and processes comprising life cycle GHG emissions, and it highlights the limited focus of standard protocol GHG emission inventory calculators. The calculator presented in this thesis goes well beyond this limited focus for both transit fleet and facility GHG emissions. However, due to limitations in available research time and data, the boundary and scope of the developed calculator does not include every (all) life cycle GHG emission process(es).

3.3.1.1. Boundary and Scope

Identification of the boundary and scope is an essential step in conducting a life cycle assessment, in that it defines the processes included in the life cycle inventory (*31, 32*). The calculator is designed to estimate the six major types of GHG emissions defined by the Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (*14*). The majority of GHG emissions from transit agencies arises from fossil fuel combustion and thus is comprised mainly of CO_2, CH_4, and N_2O. For this reason, only these three types of GHGs are explicitly inventoried and totaled.

The LCA process boundary of the developed calculator is designed to capture GHG emissions directly or indirectly controlled by agency activities. Figure 12 below shows the processes included within the life cycle analysis boundary of the developed calculator.

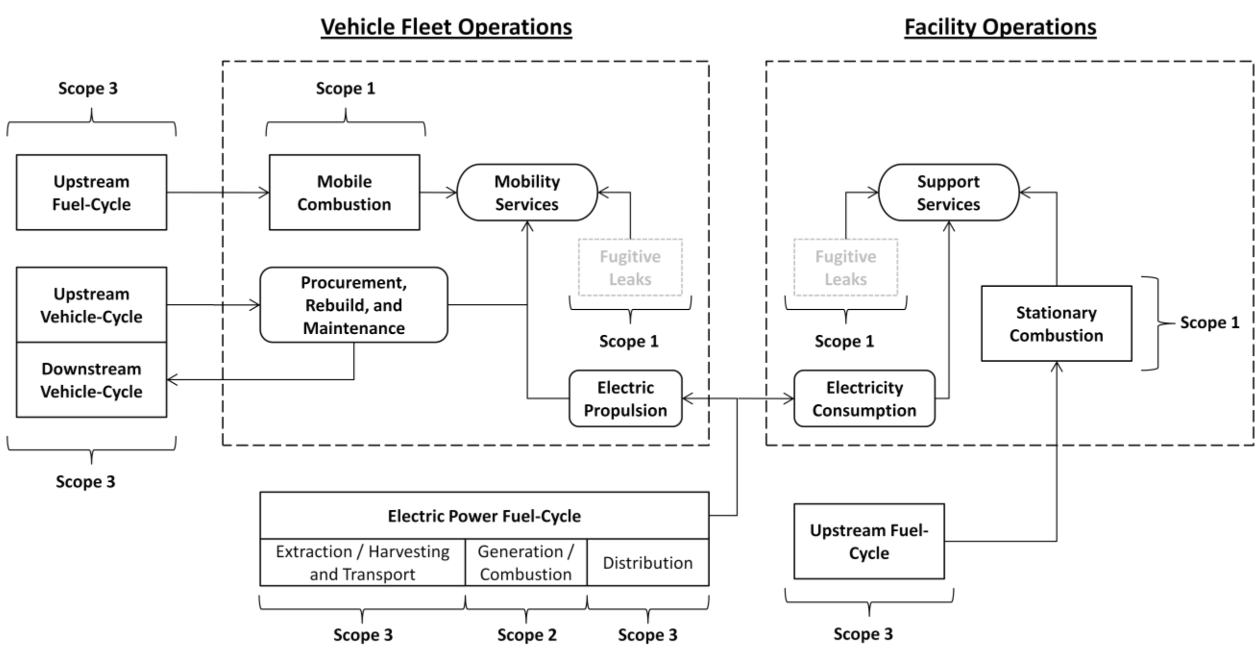

Figure 12: Processes included within the life cycle analysis boundary of the developed calculator.

The dashed line in Figure 12 encloses the activities that are directly controlled by the agency – the direct emissions arising from these activities are all counted as Scope 1 emissions. Estimation of fugitive leaks from refrigerants has not yet been included in the calculator, but will be added later. The calculation method for fugitive refrigerant leaks is rather straightforward, and in many (if not most) cases refrigerant leaks will comprise less than 5% of agency GHG emissions, in which case "simplified methods" may be used for estimation (*9*). Due to the relatively low level of fugitive leaks and more importantly the limited availability of refrigerant inventory data for applying the calculator (see Chapter 4), Scope 1 fugitive leaks have not yet been included in the calculator (although fugitive leaks are included in the Scope 3 fuel-cycle and vehicle-cycle calculations).

The availability of data plays a key role in the calculation methods used for estimating life cycle GHG emissions. For most of the direct and indirect activities, data is available to support a process-based estimation of GHG emissions. However, for the manufacturing and maintenance activities associated with the vehicle life cycle, process-level data was unavailable. This data is particularly scarce for heavy duty on-road and rail vehicles – the types of vehicles typically used by public transit agencies. These data limitations resulted in the use of a hybrid LCA approach – an approach consisting of both process-based and EIO-LCA-based calculations. EIO-LCA-based calculations were applied exclusively to vehicle-cycle manufacturing and maintenance activities.

It should be noted from Figure 12 that GHG emissions from the construction and maintenance of fixed infrastructures such as rights-of-way, stations, and other support facilities are not included in the LCA. This omission is due to a paucity of data (both emission factor data and infrastructure material inventory data) for estimating GHG emissions from capital projects.

Some basic default GHG emission factor data is available for building materials (*9, 24*) and for construction sectors (*52*), but it is very unlikely that this data is representative of the diversity of construction methods used in transit agency infrastructures. The limited availability of material inventory data (or material "take-off" data, as it is commonly referred to in the architecture/engineering industries) would have forestalled the application of an "infrastructure-cycle" calculation module within the developed calculator. These data limitation issues are not unique to the development of this transit GHG emissions calculator. The LCA and GHG emissions estimation literature does not effectively account for the emissions associated with fixed-infrastructures. For example, several calculation resources are available to estimate upstream GHG emissions in the fuel or energy supply chain (*46, 49, 50*), but these resources do not estimate the GHG emissions associated with the construction and maintenance of the supply chain infrastructure (e.g. refineries, pipelines, power plants, transmission lines, etc.). This is not to say that the literature, or the calculator developed by this research, is deficient in its GHG emissions estimation methods. Rather, the LCA boundary of this and other calculators is simply constrained by available data, and what is perhaps more important than attempting to account for all GHG emission impacts is to delineate the scope and boundary of the accounting.

3.3.1.2. Functional Units

Meaningful life cycle analysis of GHG emissions from activities requires consideration of the productive output of those activities. In the LCA literature, the productive outputs are related to emission inventories through the use of "functional units" (*32*). This calculator employs APTA's recommended functional units, or "performance metrics," outlined in Table 5 below.

Table 5: APTA Required Performance Metrics (*9*)

Mode	Emissions (E)	Vehicle miles (VM)		Revenue Vehicle Hours (RH)		Passenger miles (PM)	
		Total	E/VM	Total	E/RH	Total	E/PM
Bus	E_b	VM_b	E_b/VM_b	RH_b	E_b/RH_b	PM_b	E_b/PM_b
Light rail	E_{LR}	VM_{LR}	E_{LR}/VM_{LR}	RH_{LR}	E_{LR}/RH_{LR}	PM_{LR}	E_{LR}/PM_{LR}
[repeat for other NTD modes]							
Nonrevenue	E_{NR}						
Stationary sources	$E_{stationary}$						
Total[1]	E_{tot}	VM_{tot}	E_{tot}/VM_{tot}	RH_{tot}	E_{tot}/RH_{tot}	PM_{tot}	E_{tot}/P_{tot}

1. Including emissions from stationary sources.

The required performance metrics listed in Table 5 include emissions per vehicle mile (E/VM), emissions per revenue vehicle hour (E/RH), and emissions per passenger mile (E/PM). An emissions per passenger mile performance metric allows comparison of the GHG emissions performance not only between different public transit modes, but also between public transit and non-public transit modes. Although APTA does not endorse the use of any performance metrics for stationary sources, the calculator presented in this thesis employs an emissions per square foot (E/SF) performance metric. As mentioned previously in Chapter 3, this performance metric is necessary for calculating the cost-effectiveness of facility-based GHG emission reduction strategies.

The GHG emission calculations described in this chapter estimate a particular GHG (CO_2, CH_4, or N_2O). For each vehicle and facility inventory, the calculator aggregates these emissions into carbon dioxide equivalents (CO_2e) based on the global warming potentials (GWPs) published in the IPCC's 2007 4th Assessment Report: 1 for CO_2, 25 for CH_4, and 298 for N_2O.

3.3.2. Mobile Source Emissions

One of the major categories of GHG emissions from public transit agency activities is mobile source emissions. The calculation methodology for mobile source GHG emissions is generally divided between direct combustion emissions, fuel-cycle emissions, and vehicle-cycle emissions. The following sub-sections describe the calculation methodologies used to estimate mobile source GHG emissions.

3.3.2.1. Direct Combustion Emissions

The calculations for direct (Scope 1) GHG emissions from mobile source combustion of liquid or gaseous fuel are based on the methodologies prescribed by the GHG emission inventory protocol standards. The specific calculations for direct GHG emissions depend upon the available data inputs, which are structured on the data quality tiers of the GHG emissions registry protocols. The data quality tiers effectively sort preferable types of data inputs and help to categorize the tradeoff between data quality and data availability. Table 6 and Table 7 show the activity and emission factor data quality tiers for CO_2 emissions and CH_4/N_2O emissions respectively.

Table 6: Data Quality Tiers for Mobile Source CO_2 Emissions. Based on (*6, 9*).

Tier	Activity Data	Emission Factor Data
A1	Actual fuel use (user input)	Actual carbon content of fuel (user input) and either actual heat content of fuel (user input) or actual density of fuel (user input)
A2	Actual fuel use (user input)	Actual carbon content of fuel (user input) and default heat content of fuel (TCR value); or Default carbon content of fuel (TCR value) and actual heat content of fuel (user input)
B	Actual fuel use (user input)	Default emission factor of fuel (TCR value)
C	Fuel use estimated from vehicle miles traveled (user input) and vehicle fuel economy (user input)	Default emission factor of fuel (TCR value)

Table 7: Data Quality Tiers for Mobile Source CH_4 and N_2O Emissions. Based on (*6, 9*).

Tier	Activity Data	Emission Factor Data
A	Actual vehicle miles traveled (user input)	Default emission factor by vehicle type and emissions control technology (TCR value)
B	Actual vehicle miles traveled (user input)	Default emission factor by vehicle type and model year (TCR value)
C	Vehicle miles traveled estimated from actual fuel use (user input) and vehicle fuel economy (user input)	Default emission factor by vehicle type (TCR value)

The tables are based mainly on APTA's recommended practices (*9*) which are in turn based on The Climate Registry General Reporting Protocol (*6*). Table 6 contains one notable deviation from the source data in the protocols. For emission factor data tier A2, the option of using actual carbon content data with default fuel density data is not included. The reason for this omission is that the GHG emissions protocols do not include data on fuel densities, thus the option of "default" fuel density has no real meaning.

For the higher data tiers for mobile source CO_2 emission, the CO_2 emission factors are calculated from user input data, or a combination of user input data and default data. The following equation is used to calculate CO_2 emission factors from data on the fuel density and carbon content (Tier A1 CO_2 emission factor data) (*6*, *9*):

Equation 1

$$F_{(CO2)fuel} = \rho_{fuel} \times C_{(m)fuel} \times \theta \times K$$

where $F_{(CO2)fuel}$ = CO_2 emission factor [kg CO_2/gallon]

ρ_{fuel} = fuel density [kg/gallon]

$C_{(m)fuel}$ = carbon content [kg C/kg fuel]

θ = % oxidized (assumed to be 100%)

K = 44/12 [mol. wt. of CO_2/mol. wt. of C]

In accordance with GHG emissions registry protocols, actual carbon content and fuel density data are to be used (*6*).

To calculate CO_2 emission factors from data on the fuel heat content and carbon content, the following equation is used (Tier A1/A2 CO_2 emission factor data) (*6*, *9*):

Equation 2

$$F_{(CO2)fuel} = H_{(v)fuel} \times C_{(H)fuel} \times \theta \times K$$

where $F_{(CO2)fuel}$ = CO_2 emission factor [kg CO_2/gallon]

$H_{(v)fuel}$ = heat content [Btu/gallon]

$C_{(H)fuel}$ = carbon content [kg C/Btu]

θ = % oxidized (assumed to be 100%)

K = 44/12 [mol. wt. of CO_2/mol. wt. of C]

In accordance with GHG emission registry protocols, actual carbon content and actual heat content data are to be used (Tier A1 CO_2 emission factor data), otherwise actual carbon content and default heat content data are to be used (Tier A2 CO_2 emission factor data) (*6*). Although either Equation 1 or Equation 2 above may be used to produce a Tier A1 CO_2 emission factor calculation, Equation 2 generally provides a more accurate result than does Equation 1. According to the U.S. EPA, "carbon content factors based on energy units are less variable than carbon content factors per mass or volume units because the heat content or energy value of a fuel is more closely related to the amount of carbon in the fuel than to the total physical quantity of fuel" (*38*). In the calculator, the first CO_2 emission factor data entry input available to the user is the cell for actual heat content. If a value is entered into this cell, the data entry inputs for actual carbon content per unit mass of fuel and actual fuel density are locked. By this mechanism, fuel heat content data is given priority over fuel density data for tier A1 CO_2 emission factor calculations. Similarly, for tier A2 CO_2 emission factor calculations, priority is given to the input of fuel heat content data. For whichever variable is not provided an input (heat content or carbon content) the default value is queried based on the type of fuel selected by the user. Table 25 in the appendix shows the default transport fuel CO_2 data used by the calculator.

In the calculator, user supplied heat content data and carbon content data must be provided in terms of “gross” energy content, which is sometimes referred to as the “higher heating value” (HHV). The HHV accounts for the combustion energy absorbed in the vaporization of exhaust water vapor. Alternative values that do not report the vaporization energy are referred to as “lower heating values” (LLV), or “net” energy content. GHG emissions may be estimated from either HHV or LHV data, but the calculator is designed for HHV data, which is the most common form of fuel energy data in the U.S.

Once the emission factors are calculated (or specified as defaults in the case of tier B/C CO_2 emission factor data), the emission factors may be applied to a calculation of GHG emissions. The following equation is used to calculate CO_2 emissions from actual fuel use data (Tier A/B CO_2 emissions activity data) and either an emission factor calculated from one of the aforementioned formulae (Tier A1/A2 CO_2 emission factor data) or a default emission factor (Tier B/C CO_2 emission factor data) (*6*, *9*):

Equation 3

$$E_{(CO2)fuel} = Q_{(v)fuel} \times F_{(CO2)fuel}$$

where $E_{(CO2)fuel}$ = CO_2 emissions [kg CO_2]

$Q_{(v)fuel}$ = fuel combusted [gal]

$F_{(CO2)fuel}$ = CO_2 emission factor [kg CO_2/gallon]

The fuel units and the corresponding fuel emission factor units will vary according to the type of fuel used. For example, since CNG is a compressible/compressed gas, CNG fuel use is not reported in gallons, but is instead reported in diesel gallon equivalents (DGE), standard cubic feet (SCF), or therms. A diesel gallon equivalent represents the equivalent volume of diesel fuel in terms of fuel energy, and it is the unit of energy used by transit agencies for reporting energy consumption to the National Transit Database (NTD) (*54*). On average, a gallon of diesel fuel contains 138,691 British Thermal Units (BTUs) of combustion energy, and one SCF of natural gas contains on average 1,027 BTUs of combustion energy, so one DGE of CNG is equal to (1 gal) x (138,691 BTU/gal) / (1,027 BTU/SCF) = 135 SCF. The calculator provides unit conversion from DGE to native liquid and gaseous fuel units (gallons and SCF respectively) and bases the conversion on GHG emission inventory protocol defaults.

If data on the actual quantity of fuel use is unavailable (Tier A/B activity data), then the fuel use may be estimated by the following formula (Tier C CO_2 emission activity data) (*6*):

Equation 4

$$Q_{(v)fuel} = \frac{D_{veh}}{mpg_{veh}}$$

where $Q_{(v)fuel}$ = fuel combusted [gal]

D_{veh} = vehicle driving distance [miles]

mpg_{veh} = vehicle fuel economy [miles/gallon]

This equation is then used in conjunction with Equation 3 above to calculate mobile direct CO_2 emissions. In the calculator, the miles per gallon fuel economy of each record is included both as an input (for Equation 4) and as an output, based on user entered fuel consumption and vehicle miles of travel (VMT).

Unlike CO_2 emissions, which are simply the result of the degree of combustion and the carbon content of fuels, CH_4 and N_2O emissions are a complex function of combustion dynamics that vary between vehicle and fuel-types. CH_4 and N_2O emissions may be estimated by multiplying VMT by vehicle/fuel technology-specific, distance-based emission factors. The following equations are used to calculate CH_4 and N_2O emissions from driving distance vehicle activity data (Tier A/B CH_4 and N_2O emissions activity data) and default emission factors (Tier A/B/C CH_4 and N_2O emission factor data) (*6*, *9*):

Equation 5

$$E_{(CH4)veh} = D_{veh} \times F_{(CH4)veh}$$

where $E_{(CH4)veh}$ = CH_4 emissions [g CH_4]

D_{veh} = vehicle driving distance [miles]

$F_{(CH4)veh}$ = CH_4 emission factor [g CH_4/mile]

Equation 6

$$E_{(N2O)veh} = D_{veh} \times F_{(N2O)veh}$$

where $E_{(N2O)veh}$ = N_2O emissions [g N_2O]

D_{veh} = vehicle driving distance [miles]

$F_{(N2O)veh}$ = N_2O emission factor [g N_2O/mile]

The tier of the CH_4 and N_2O emission factors depends upon the precision of the emission factor data. Tier A data is based on a U.S. EPA vehicle technology category (see Table 26 in the Appendix), Tier B data is based on vehicle type and model year (see Table 27 in the Appendix), and Tier C data is based on vehicle type (see Table 28 in the Appendix) (*6*).

If VMT data is unavailable, then the VMT may be estimated by the equation below (Tier C CH_4 and N_2O emissions activity data) (*6*):

Equation 7

$$D_{veh} = Q_{(v)fuel} \times mpg_{veh}$$

where D_{veh} = vehicle driving distance [miles]

$Q_{(v)fuel}$ = fuel combusted [gal]

mpg_{veh} = vehicle fuel economy [miles/gallon]

The vehicle driving distance estimated from Equation 7 above is then coupled with Equations 5 and 6 to calculate the CH_4 and N_2O emissions. It is important to note that vehicle driving distance is not always the best activity variable for estimating CH_4 and N_2O emissions, particularly for non-highway vehicles such as locomotives or construction equipment. For non-highway vehicles, the CH_4 and N_2O emissions are estimated from fuel consumption, following the method used in Equation 3. For non-highway vehicles, this is considered to be a Tier A CH_4 and N_2O calculation (*6*). The default CH_4 and N_2O emission factor data is shown in Table 29 in the Appendix.

3.3.2.2. Fuel-Cycle Emissions

The upstream well-to-pump (WTP) or well-to-tank (WTT) GHG emissions in the fuel-cycle of mobile combustion vehicle fuels are calculated from default results from Argonne National Laboratory's GREET fuel-cycle model (*46*). The GREET model is a process-based spreadsheet calculator of energy, GHG emissions, and CAP emissions in the transportation fuel supply-chain. The spreadsheet is designed to support a graphical user interface (GUI) and Microsoft Visual Basic macros that handle user inputs and calculation outputs. Unlike the GUI, the spreadsheet provides direct access to the data and calculation formulae of the model. After running the model with default inputs and assumptions, WTP emission factors were extracted from the spreadsheet for the fuels used in the calculator presented in this thesis. Table 8 shows the WTP CO_2, CH_4, and N_2O emission factors extracted from the GREET model. These emission factors are the product of a multitude of process calculations and assumptions which are far too complex to adequately describe here. Generally speaking, the GHG emission factors are calculated and accounted in terms of the amount of fuel combustion energy. The combustion energy is dependent upon the assumed heat content of the fuel. For the purpose of checking consistency between the GHG inventory protocol data and the GREET data, Table 8 includes a comparison of the fuel heat content data (both reported as HHV). Some variation exists between the datasets, but no major discrepancy is evident. What is perhaps more notable is that upstream emission factors are not available for all of the fuels included in the GHG inventory protocols. Consequently, upstream fuel-cycle GHG emission calculations are not feasible for all of the fuel types included in the developed calculator.

Table 8: GREET Fuel-Cycle Model 1.8c.0 Well-to-Pump Upstream GHG Emissions. Based on (*6, 46*).

Fuel	Heat Content (1)	Heat Content (2)	CO2 (3)	CH4 (3)	N2O (3)
	Btu / gal	Btu / gal	g / MMBtu	g / MMBtu	g / MMBtu
gasoline	124,238	124,340	16,812	108.74	1.14
diesel	138,690	137,380	15,488	104.53	0.25
biodiesel	138,690	137,380	1,272	93.06	2.22
kerosene	135,000	N/A	N/A	N/A	N/A
CNG	1,027 Btu/SCF	1,089 Btu/SCF	11,468	246.60	0.17
LNG	N/A	84,820	12,693	199.10	0.26
propane	91,048	91,420	N/A	N/A	N/A
LPG	91,643	91,410	9,195	115.28	0.16
ethane	69,429	N/A	N/A	N/A	N/A
isobutane	99,095	98,560	N/A	N/A	N/A
n-butane	103,048	103,220	N/A	N/A	N/A
ethanol (E100)	84,262	84,530	-10,464	108.73	30.64
methanol	N/A	65,200	24,549	168.53	0.58
hydrogen	N/A	36,020	196,244	477.35	1.63

Source:
(1) Table 25 of this thesis
(2) GREET Fuel-Cycle Model 1.8c.0, "Fuel_Specs" Worksheet , Table 1, HHV
(3) GREET Fuel-Cycle Model 1.8c.0, "Results" Worksheet , Table 1 "Well-to-Pump Energy Consumption and Emissions: Btu or Grams per mmBtu of Fuel Available at Fuel Station Pumps"

The GREET model is not the only public resource for calculating fuel-cycle GHG emissions, but it is one of the most widely used (if not *the* most widely used) life cycle transportation emissions models that is free to the public and not constrained by user licensing. One alternative life cycle transportation emissions model is Natural Resources Canada's GHGenius model (*49*). GHGenius is similarly a publicly funded process-based spreadsheet calculator of upstream fuel-cycle GHG emissions, but its use is considerably more limited. The GHGenius Sub-License Agreement states that "Canada provides limited personal permission for the Licensee to use the Material. The use of the Material is limited in that you may not: Modify, incorporate, translate, adapt, improve, further develop, manufacture in whole or in part the Material" (*49*). Emission factors from the GHGenius model were incorporated into the developed calculator, but this work stopped due to the Sub-License Agreement.

For the purpose of academic comparison, Table 9 below provides upstream fuel-cycle GHG emissions factors from both GREET and GHGenius. Large differences are noticeable in the data, particularly for alternative fuels. For instance, in GREET the upstream processes for ethanol act as a carbon sink (negative CO_2 emission factor), whereas in GHGenius ethanol upstream processes result in net emissions of CO_2. Discrepancies such as these cast serious doubt on the accuracy of emission factors from life cycle emissions models. At the very least, differences in inputs and assumptions can result in significant variations in results. To address this reality, the calculator presented in this thesis allows the user to update upstream emission factors by running the GREET model according to his/her preferred assumptions and inputs, and then copying and pasting the results table into the developed calculator.

Table 9: Comparison of Upstream Well-to-Tank GHG Emissions Results from GREET and GHGenius (*46, 49*)

Fuel	CO2 (1) g / MMBtu	CO2 (2) g / MMBtu	CH4 (1) g / MMBtu	CH4 (2) g / MMBtu	N2O (1) g / MMBtu	N2O (2) g / MMBtu
gasoline	16,812	18,216	108.74	131.88	1.14	0.97
diesel	15,488	15,940	104.53	127.25	0.25	0.78
biodiesel	1,272	17,298	93.06	123.88	2.22	10.75
kerosene	N/A	N/A	N/A	N/A	N/A	N/A
CNG	11,468	8,974	246.60	314.94	0.17	0.26
LNG	12,693	N/A	199.10	N/A	0.26	N/A
propane	N/A	N/A	N/A	N/A	N/A	N/A
LPG	9,195	12,971	115.28	120.32	0.16	0.53
ethane	N/A	N/A	N/A	N/A	N/A	N/A
isobutane	N/A	N/A	N/A	N/A	N/A	N/A
n-butane	N/A	N/A	N/A	N/A	N/A	N/A
ethanol (E100)	-10,464	55,092	108.73	69.79	30.64	48.13
methanol	24,549	17,239	168.53	144.87	0.58	1.34
hydrogen	196,244	118,020	477.35	527.53	1.63	1.61

Source:
(1) GREET Fuel-Cycle Model 1.8c.0, "Results" Worksheet , Table 1 "Well-to-Pump Energy Consumption and Emissions: Btu or Grams per mmBtu of Fuel Available at Fuel Station Pumps"
(2) GHGenius 3.15, "Upstream Results HHV" Worksheet, Tables 55a, 55b, and 55c

To calculate the upstream fuel-cycle GHG emissions, the emission factors from GREET are multiplied by the heat content and the quantity of fuel combusted:

Equation 8

$$E_{fuel} = Q_{(v)fuel} \times H_{(v)fuel} \times F_{(H)fuel} \times \frac{\text{MMBtu}}{10^6\text{Btu}}$$

where E_{fuel} = CO_2 (or CH_4, or N_2O) emissions [g CO_2 (or g CH_4, or g N_2O)]

$Q_{(v)fuel}$ = fuel combusted [gal (or SCF)]

$H_{(v)fuel}$ = heat content [Btu/gallon]

$F_{(H)fuel}$ = emission factor [g CO_2/MMBtu (or CH_4, or N_2O)]

This calculation procedure is used for all three of the primary GHGs: CO_2, CH_4, and N_2O.

3.3.2.3. Vehicle-Cycle Emissions

The vehicle-cycle processes accounted for in the calculator include all of the upstream extraction, harvesting, refining, manufacture, assembly, transportation, storage, and downstream disposal associated with the manufacture of new vehicles and for vehicle maintenance parts. Due to a lack of available emission factor data for these vehicle-cycle processes, an EIO-LCA calculation approach is used (*30*). The calculator makes use of the EIO-LCA model from The Green Design Institute at Carnegie Mellon University (*52*) to model the GHG emissions from vehicle manufacturing sectors. This helps to simplify the calculations done within the calculator by making use of emission factors representing the amount of GHG emissions per dollar spent on a particular vehicle product sector. Thus, the calculation of vehicle-cycle emissions is as follows:

Equation 9

$$E_{veh} = (Cap\_Cost_{veh} \times Mfg\_EF_{sector}) + (Maint\_Cost_{veh} \times Maint\_EF_{sector})$$

where E_{veh} = vehicle-cycle GHG emissions [kg]

Cap_Cost_{veh} = capital cost of manufacturing (vehicle purchase cost) [$]

Mfg_EF_{sector} = manufacturing sector GHG emissions factor [kg GHG / $]

$Maint\_Cost_{veh}$= maintenance costs (parts purchase cost) [$]

$Maint\_EF_{sector}$= parts sector GHG emissions factor [kg GHG / $]

Only parts costs are included in the maintenance cost input, because most transit agency maintenance activities occur in-house. If facility costs were included, the result would be a double-counting of GHG emissions that are already accounted for in transit facility energy consumption calculations (stationary combustion and purchased electricity).

The emission factors from the EIO-LCA model are reported in metric tonnes / $1M, but the emission factors used in the calculator are converted to kg / $. Table 10 below shows the emission factors used for the vehicle-cycle GHG emissions calculations. The data are produced from the U.S. National Producer Price 2002 tables. The CO_2(e) emission factors represent a GWP-weighted combination of "CO_2 Fossil," "CO_2 Process," and "HFC/PFCs" emission factors from the EIO-LCA model.

Table 10: Vehicle-Cycle GHG Emission Factors. Based on (*52*)

Vehicles		**Detailed Sector**	**CO2(e) (kg/$)**	**CH4 (kg/$)**	**N2O (kg/$)**
Mfg.	Bus and heavy duty veh.	Heavy duty truck manufacturing	0.6277	0.0455	0.00909
	Heavy rail and light rail	Railroad rolling stock manufacturing	0.46885	0.0307	0.0049
	Light duty veh.	Light truck and utility vehicle manufacturing	0.5487	0.0424	0.0121
	Automobile	Automobile manufacturing	0.5079	0.0419	0.013
Maint.	Bus, heavy duty, light duty, and auto	Motor vehicle parts manufacturing	0.6916	0.0514	0.0133
	Heavy rail and light rail	All other transportation equipment manufacturing	0.5914	0.0401	0.0083
Source: Carnegie Mellon University Green Design Institute. (2010) Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428) model [Internet], Available from: <http://www.eiolca.net/> [Accessed 17 Jun, 2010] Broad Sector Group: Vehicles and Other Transportation Equipment					

Vehicle-cycle GHG emissions are unique among other inventory emissions in that the vehicle manufacturing emissions occur once at the beginning of the life cycle, whereas most all other emissions will occur during the inventory year. A method is needed to reasonably allocate the upfront GHG emissions over the vehicle lifecycle so that the emissions are captured in subsequent annual inventories. The method used by the calculator is to divide the total upfront GHG emissions by the estimated service life (in years) of the vehicle. An alternative method used in studies of life cycle GHG emissions from transportation is to divide the total upfront GHG emissions by the estimated total lifetime VMT and then multiply by the VMT for the inventory period (*24*). There are notable advantages and disadvantages of each method. The VMT-based method has the advantage of producing consistent per-mile vehicle emissions for each inventory year. This means the proportion of vehicle GHG emissions attributed to the vehicle cycle does not change from year to year. However, one odd result of this accounting method is that the total vehicle-cycle manufacturing emissions will vary between years with different VMT, even though increases or decreases in VMT do not cause differences in vehicle-cycle manufacturing emissions. Furthermore, vehicles assigned to short distance duty cycles with more stops, starts, and congested traffic conditions may reach the end of useful life at a lower total accumulated mileage than may be estimated for other similar vehicles. From the perspective of managing GHG emissions from vehicle fleets, the time-based method may offer a better measurement of vehicle-cycle emissions from underutilized vehicle; vehicles with low mileage will report undiminished vehicle-cycle emissions, thereby highlighting within an annual inventory the relatively high vehicle-cycle GHG emissions cost of underutilization. The calculator utilizes the time-based method of estimating annual vehicle-cycle GHG emissions, and calculator users may enter and adjust the estimated vehicle service lives. Default bus and van service lives are based on minimum requirements of FTA grant programs (e.g. 12 years for a 40' heavy duty bus) (*55*).

In the EIO-LCA method of estimating vehicle-cycle GHG emissions, cost is the single independent variable for estimating emissions. The calculator provides a robust accounting framework for estimating and aggregating the capital and maintenance costs impacting vehicle-cycle GHG emissions. Included in the calculator is a worksheet for entering "cost profiles" for particular vehicles or types of vehicles. The cost profiles contain a multitude of cost data fields, most of which are used for calculating cost-effectiveness (see Section 3.3.5 for details on the cost-effectiveness calculations and the use of cost profiles). For the purpose of calculating vehicle-cycle GHG emissions, the cost profiles account for the following cost data: vehicle purchase cost, estimated vehicle service life (years), amortized vehicle purchase cost ($/year), and vehicle parts cost ($/year and $/mile). Each cost profile is assigned a unique "Vehicle Cost ID" (or name) by the user. For each vehicle record on the vehicle GHG emissions inventory worksheets, the "Vehicle Cost ID" may be queried from a dropdown list. Once selected, the cost profile data is coupled with the vehicle inventory data to calculate manufacturing and maintenance costs. The manufacturing costs are the product of the amortized vehicle purchase cost and the vehicle quantity field (user input on each vehicle inventory row). The maintenance costs are the sum of the annual parts cost times the quantity of vehicles, and the per mile parts cost times the inventory mileage. These costs are then applied to the EIO-LCA emission factors, as described earlier in this section, to calculate vehicle-cycle GHG emissions.

3.3.3. Stationary Source Emissions

This section describes the calculation methodology for agency stationary source emissions, which are the GHG emissions produced from on-site stationary combustion and from the associated upstream fuel supply-chain. GHG emissions produced from purchased electricity are described in a later section (Section 3.3.4).

3.3.3.1. Direct Combustion Emissions

Similar to the mobile source emissions, the stationary source direct combustion GHG emissions are calculated in accordance with the methodology prescribed by the GHG emission inventory protocols. Table 11 and Table 12 show the data tiers for stationary source CO_2 and stationary source CH_4 and N_2O emissions respectively.

Table 11: Data Quality Tiers for Stationary Source CO_2 Emissions. Based on (*6*).

Tier	Activity Data	Emission Factor Data
A1	Continuous emissions monitoring (user input)	Continuous emissions monitoring (user input)
A2	Actual fuel use (user input)	Actual carbon content of fuel (user input) and actual heat content of fuel (user input)
B	Actual fuel use (user input)	Actual carbon content of fuel (user input) and default heat content of fuel (TCR value); or Default carbon content of fuel (TCR value) and actual heat content of fuel (user input)
C	Actual fuel use (user input)	Default emission factor of fuel (TCR value)

Table 12: Data Quality Tiers for Stationary Source CH_4 and N_2O Emissions. Based on (*6*).

Tier	Activity Data	Emission Factor Data
A	Continuous emissions monitoring (user input)	Continuous emissions monitoring (user input)
B	Actual fuel use (user input)	Default emission factor by sector and technology type (TCR value)
C	Actual fuel use (user input)	Default emission factor by sector and fuel type (TCR value)

The calculator is designed for data tiers A2 and lower (Tier A1 and A correspond with direct emissions monitoring, an emissions measurement process that requires no emissions estimation calculations). The stationary combustion GHG emissions estimation procedure follows approximately the same procedure used for estimating mobile combustion GHG emissions. First, a CO_2 emission factor is calculated from the available Tier A2 or Tier B heat content and carbon content data (see Equation 2). Then, using either this calculated CO_2 emission factor or a default CO_2 emission factor (Tier B or Tier C CO_2 emission factor), the CO_2 emissions are calculated from the amount of fuel consumed (see Equation 3).

Once the CO_2 emissions are calculated, the next step is to calculate the CH_4 and N_2O emissions. Much like the procedure used for mobile combustion, the CH_4 and N_2O emissions from stationary combustion utilize technology specific default emission factors. These default emission factors are given on per unit of energy basis (g/MMBtu). Thus, fuel consumption data (mass or volume) must be converted to energy consumption (MMBtu). The following equation is used to calculate CH_4 and N_2O emissions (Tier B/C CH_4 and N_2O emission factor data):

Equation 10

$$E_{fuel} = Q_{(h)fuel} \times F_{fuel}$$

where E_{fuel} = CH_4 (or N_2O) emissions [g CH_4 (or g N_2O)]

$Q_{(h)fuel}$= fuel combusted [MMBtu]

F_{fuel} = CH_4 (or N_2O) emission factor [g CH_4/MMBtu (or g N_2O /MMBtu)]

The developed calculator accommodates fuel consumption data in the following units: gallons, barrels, SCF, therms, and short tons. The calculator performs the necessary unit conversions to calculate GHG emissions using Equation 3 and Equation 10. Table 30 and Table 31 in the Appendix show the default factors for stationary combustion CO_2 emissions.

3.3.3.2. Fuel-Cycle Emissions

The methodology employed for calculating fuel-cycle GHG emissions from stationary source combustion fuels is primarily the same as that employed for mobile source combustion fuels. The amount of fuel consumed is multiplied by the heat content and energy-based emission factor (see Equation 8). The main difference for calculating upstream emissions for stationary combustion is the source of the emission factors. The emission factors are derived from the GREET fuel-cycle model (*46*), but from different process values within the model. Table 33 and Table 34 in the Appendix show the GREET emission factors used for each of the stationary combustion fuel types used (see Table 30). Unfortunately, appropriate upstream GHG emission factors are not currently available for all of the stationary combustion fuel types included in the calculator.

3.3.4. Purchased Electricity Emissions

The GHG emissions from purchased electricity are classified as “indirect” (Scope 2) emissions by the GHG inventory protocols. The term “indirect” refers to the fact that organizations purchasing electricity do not have direct control over the power production (and GHG emissions production) process. This section describes the calculation methodology used for estimating GHG emissions from purchased electricity, both for the propulsion of electric transit vehicles and for the operation of transit facilities.

3.3.4.1. Indirect Combustion Emissions

The electric power grid supplies electrical energy generated from a variety of production facilities and feedstocks. At the national scale, much of the electric power is produced from the combustion of fossil fuels. The proportion of various types of fossil fuels used to supply electric power to electric power consumers affects the GHG emissions intensity of the electric grid, thus, the GHG emissions intensity of the electric grid varies regionally across the U.S. To estimate the GHG emissions associated with the consumption of purchased electricity, the calculator follows the methodology of the GHG emissions inventory protocols, which use generator-specific or regionally-based power generation emission factors to estimate the GHGs produced per unit of electrical energy consumed. Table 13 below shows the emission factor and activity data tiers for estimating CO_2, CH_4, and N_2O emissions from purchased electricity.

Table 13: Data Quality Tiers for Scope 2 CO_2, CH_4, and N_2O Emissions. Based on (*6*).

Tier	Activity Data	Emission Factor Data
A	Actual electricity use (user input)	Generator-specific emission factor (user input)
B	Actual electricity use (user input)	Default emission factor of eGRID power pool (TCR value)
C	Proportional electricity use estimated from building area (user input), building actual electricity use (user input) and building sub-area (user input)	Generator-specific emission factor (user input) or Default emission factor of eGRID power pool (TCR value)

The indirect combustion GHG emissions from purchased electricity are calculated with Equation 11 and Equation 12 below.

Equation 11

$$E_{(CO2)fac} = q_{fac} \times F_{(CO2)grid}$$

where $E_{(CO2)fac}$ = CO_2 emissions [lbs CO_2]

q_{fac} = electricity consumed [MWh]

$F_{(CO2)grid}$ = CO_2 emission factor [lbs CO_2/MWh]

Equation 12

$$E_{fac} = q_{fac} \times F_{grid}$$

where E_{fac} = CH_4 (or N_2O) emissions [lbs CH_4 (or N_2O)]

q_{fac} = electricity consumed [GWh]

F_{grid} = CH_4 (or N_2O) emission factor [lbs CO_2/GWh]

The emission factors for CH_4 and N_2O used in Equation 12 are expressed in larger units of energy (GWh vs. MWh) than are the emission factors for CO_2 used in Equation 11 since electrical power generation generally produces much less CH_4 and N_2O per unit of energy generated. Users of the calculator must have data on the total quantity of electricity consumed, and the calculator can be used to estimate the electricity consumed within a part of a metered facility, based on proportional floor area (Tier C activity data).

Table 13 shows that according to the protocols, generator-specific emission factors are considered to be more accurate than power pool defaults. The power pool defaults are sourced from the U.S. EPA's eGRID database of electric power production and emissions (*44*). The eGRID defaults are available at multiple levels of aggregation (ordered from lower to higher aggregation): state-level, eGRID subregion-level, and eGRID NERC region-level. For each level of aggregation, both annual and non-baseload GHG emission factors are available. The annual emission factors represent the annual average GHG emission rates and are used for annual inventories of GHG emission from purchased electricity (*44*). The non-baseload emission rates represent the output of GHG emissions during peak periods of electric power consumption from the grid and are used for determining GHG emission savings from energy consumption reductions (*44*). The developed calculator allows the user to select either annual or non-baseload GHG emission rates. The eGRID emission rates used are shown in Table 35 through Table 38 in the Appendix.

The eGRID database offers a concise record of electric power GHG emission rates, but there are several limitations of the data. Firstly, the emission rates are derived from annual averages and thus do not allow users to account for seasonal variations in the electric power generation mix. Secondly, the spatial aggregation of GHG emission rates may not be representative of the actual supply of electric power to a given location at a given hour. In other words, the spatial and temporal aggregation of the GHG emission rates do not enable estimation of GHG emission reductions by shifting consumption to different hours of the day. The "annual" and "non-baseload" emission rates provide some capability on this front, but do not support hour-by-hour consumption management decisions. Thirdly, the eGRID emission rates are compiled only once every few years and possibly do not represent the actual GHG emission rates for each/every inventory year. The latest version of the eGRID database, eGRID2007, is composed of emission rates from the year 2005. Alternatively, the U.S. Energy Information Administration (EIA) provides more up to date CO_2 emission factors (year 2008 currently available) in its state electricity profiles (*56*). The calculator accommodates user entry of higher tiers of data, such as power plant-specific emission factors. Plant-specific emission factors are considered by the GHG emissions inventory protocols to be more precise than power pool-specific emission factors, but users of plant-specific data should verify the source of power from the electric grid since the difference in emission factors can be substantial. For example, in a recent unpublished study of emissions from the Metropolitan Atlanta Rapid Transit Authority's (MARTA) heavy rail operations, emission factors for each of the nine local power plants supplying electricity to MARTA heavy rail operations were weighted in proportion to the amount of power produced from each. The emission factor data was collected from the Georgia Environmental Facilities Authority and the U.S. EPA. The averaged CO_2 emissions factor from the local power plants was 2,040 lbs CO_2/MWh, whereas the eGRID annaual subregion emission factor for SERC South, which includes Atlanta, GA, is 1,490 lbs CO2/MWH – a relative difference of over 30 percent.

Finally, the eGRID emission rates do not account for the energy and emissions associated with electric power transmission and distribution (T&D) losses (*44*). The developed calculator is designed to account for not only T&D losses, but also the many significant upstream GHG emissions in the electric power generation supply-chain.

3.3.4.2. Fuel-Cycle Emissions

The fuel-cycle of purchased electricity consists of processes that are both upstream and downstream from a power generation facility. The upstream processes consist of the extraction/harvesting, refining, and transportation of the fuels, and the downstream processes consist of the transmission and distribution (T&D) of the electric power.

To calculate the GHG emissions from processes upstream of the generation of electric power, emission factor data is needed for each of the fuel types included in the eGRID database: coal, fuel oil, natural gas, nuclear, biomass, hydro, wind, other carbon, and other (*44*). Table 14 shows the emission factors derived from the GREET fuel-cycle model, using default model inputs and assumptions.

Table 14: Purchased Electricity Upstream Fuel-Cycle Emission Factors. Based on (*46*)

Fuel	CO2 Em. Fact. (g / MMBtu of Fuel)	CH4 Em. Fact. (g / MMBtu of Fuel)	N2O Em. Fact. (g / MMBtu of Fuel)	Source
Coal	1,620.18	119.203	0.03125	Worksheet Coal, Table 3, Coal to Power Plants
Oil	1,0616.2	99.1796	0.17588	Worksheet Petroleum, Table 5.1, Crude for Use in U.S. Refineries, and Residual Oil
NG	5,162.64	175.272	0.08395	Worksheet NG, Table 4.1, Natural Gas for Electricity Generation
Nuclear	0.00412	6.8E-06	5.9E-08	Worksheet Electric, Table 1, and Worksheet Uranium, Table 4, Total: LWR electricity generation
Biomass	-0.0043	2.8E-06	9.9E-07	Worksheet EtOH, Table 3, Farmed Trees to Ethanol, and Worksheet Fuel_Specs, Table 1, Farmed Trees
Hydro	0	0	0	
Wind	0	0	0	
Other	0	0	0	
Other Carbon	3479.81	78.731	0.05822	Average of above

Each of the emission factors are given in terms of the fuel energy supplied to the power generation facility. Emission factors were unavailable for “hydro,” “wind,” “other,” and “other carbon” fuel-types. Considering that the calculator presented in this thesis does not estimate GHG emissions from the construction and maintenance of fuel/energy supply-chain infrastructure, it is reasonable to assume that the GHG emissions from “hydro,” “wind,” and “other” (non-combustion energy sources) are negligible. The GHG emission factors for “other carbon” are assumed to be the average of the non-zero emission factors derived from the GREET model.

Since the upstream emission factors are provided in terms of the fuel energy supplied to the power generation facility, a calculation step is needed to determine the amount of fuel energy required to supply the amount of electrical energy that is purchased. To do so, the energy losses associated with the inefficiency of the generation facility and T&D must be accounted for. The calculator uses Equation 13 to determine how much more fuel energy is needed to supply the amount of delivered electrical energy.

Equation 13

$$\frac{Energy\ Input_{fuel}}{Energy\ Output_{fuel}} = \left(\frac{1}{Eff_{fuel}}\right) \times \left(\frac{1}{1 - TD_{fuel}}\right)$$

where $Energy\ Input_{fuel}$ = fuel energy supplied to generation facility [KWh]

$Energy\ Output_{fuel}$ = energy delivered for consumption [KWh delivered]

Eff_{fuel} = power plant efficiency [%]

TD_{fuel} = transmission & distribution (T&D) losses [%]

The power plant efficiency is specific to the type of fuel and power plant technology. The calculator uses default values found in the GHGenius model (*49*), but the user may override these defaults with alternative efficiency values. Similarly, the T&D losses are assumed to be 8%, but the user may adjust this value as he or she sees fit. The fuel input vs. energy output scaling factors calculated from the power plant efficiencies and T&D losses are applied to the fuel emission factors from GREET:

Equation 14

$$UpstreamEF_{fuel} = \frac{Energy\ Input_{fuel}}{Energy\ Output_{fuel}} \times\ GREET\_EF_{fuel} \times \left(\frac{1\ MMBtu}{293.071\ KWh}\right)$$

where $UpstreamEF_{fuel}$ = upstream fuel emission factor [g GHG / KWh delivered]

$\frac{Energy\ Input_{fuel}}{Energy\ Output_{fuel}}$ = fuel consumption ratio [KWh fuel / KWh delivered]

$GREET\_EF_{fuel}$ = GREET fuel emission factor [g / MMBtu of fuel]

The resulting emission factors for each fuel type are expressed in terms of the amount of delivered (purchased) energy. The final calculation step for estimating Scope 3 fuel-cycle GHG emissions from purchased electricity contains two parts: 1) the upstream fuel emissions for each of the fuel/plant types; and 2) the scaling up of plant combustion emissions to account for T&D losses. Equation 15 below shows each of these calculation steps summed together:

Equation 15

$$Scope3\_E = \left([UpstreamEF_{fuel\,1} \quad \cdots \quad UpstreamEF_{fuel\,n}] \cdot \begin{bmatrix} PowerMix_{fuel\,1} \\ \vdots \\ PowerMix_{fuel\,n} \end{bmatrix} \times q_{fac} \right) + \left(Scope2\_E \times \left(\frac{1}{1 - TD} - 1 \right) \right)$$

where $Scope3\_E$ = fuel-cycle emissions [g GHG]

$PowerMix_{fuel}$ = eGRID fuel power mix [%]

q_{fac} = electricity consumed [KWh]

$Scope2\_E$ = combustion emissions [g GHG]

The power mix percentages are referenced from the eGRID database and are shown in Tables 39 to 42 in the Appendix. Unfortunately, the eGRID database provides power mix percentages for only annual emission rates. Thus, calculations of fuel-cycle GHG emissions for non-baseload power will not reflect the non-baseload power mix.

It is important to note why the second half of Equation 15 is included in the calculator. This calculation does not result in a double-counting of the T&D losses – the Scope 2 emissions calculated from the eGRID emission factors account for power generation efficiencies, but do not include T&D losses. Therefore, to fully account for the fuel-cycle emissions associated with purchased electricity, the additional Scope 2 combustion emissions associated with T&D losses must be accounted for.

3.3.5. Cost Calculations

The calculator includes the capability for estimating the cost-effectiveness of vehicle-based or facility-based GHG emission reductions. Emission reductions are modeled by comparing the normalized emissions (GHGs/mile or GHGs/SF) between inventory records in the calculator worksheets. To calculate the normalized cost differences between alternatives, the user must enter the costs associated with an alternative and a baseline. Figure 13 shows the cost profile worksheet for transit facility costs. The "Facility Cost ID" names at the top are entered by the user to save unique cost profiles. The available cost categories include both capital and operation/maintenance costs. For operation and maintenance costs, the user may select the units that correspond with the data available for input (e.g. per gal, per year, per SF, per kWh, etc.) and annual growth factors may be applied as either a total increment (arithmetic gradient) or a percentage increment (geometric gradient). In the existing literature for transit LCCA calculators, the effect of inflation on the time value of money is sometimes considered, but the effect of capital interest rates is not (*35, 51*). The growth factors in the cost profile calculator may be used to model inflationary costs, and the salvage discount rate may be used to discount the future return from any future salvage values. It is important to note that for the purposes of calculating incremental cost-effectiveness, not all costs need to be entered – only the estimated differences in costs between an alternative and its baseline need to be entered. For example, if two facility inventory records have different amounts of fuel consumption, but have the same facility construction cost, only the fuel cost needs to be entered to calculate the cost-effectiveness of a relative reduction in GHG emissions.

Facility Cost ID	Base Facility		LED Lights	
Facility Strategy Lifetime	50	years	50	years
Beginning Year	2008		2008	
Salvage discount rate	10	% per year	10	% per year
Capital Costs				
Facility construction/renovation	$300,000.00		$330,000.00	
Facility credit/grant	20	%	20	%
credit/grant	60000		66000	
Total facility const./renov.	$240,000.00		$264,000.00	
Facility salvage value	$25,000.00		$25,000.00	
Equipment purchase				
Equipment credit/grant		*select*		*select*
credit/grant	0		0	
Total equipment purchase	$0.00		$0.00	
Equipment salvage value				
Total Capital Costs	$232,034.23		$256,034.23	
Annualized Capital Costs	$19,336.19		$21,336.19	
Operating and Maintenace Costs (annual)				
Facility Energy	$2.000	per gal	$2.000	per gal
Fuel cost growth factor		*select*		*select*
Facility operation		*select*		*select*
Operation cost growth factor		*select*		*select*
Facility maintenance		*select*		*select*
Maintenance cost growth factor		*select*		*select*
Equipment maintenance (labor)	$500.00	per year	$500.00	per year
Labor cost growth factor		*select*		*select*
Equipment maintenance (parts)		*select*		*select*
Parts cost growth factor		*select*		*select*
Equipment Fuel/energy	$0.12	per kWh	$0.12	per kWh
Fuel/energy cost growth factor		*select*		*select*

Figure 13: Calculator facility cost profile worksheet.

A similar cost profile form is available for vehicle costs, which include more inputs related to vehicle operation and maintenance costs. It is recognized that transit agencies have available to them fleet management software for managing operations, maintenance, and procurement costs. This calculator is not designed as a standalone operation, maintenance, and procurement cost management tool. Rather, it is designed as a tool that utilizes existing fleet management data to assist with the management of cost-effective GHG emissions.

The cost-effectiveness of a strategy that reduces GHG emissions may be calculated by dividing the incremental cost increase of a strategy by the incremental decrease in GHG emissions (*49*). Cost-effectiveness may thus be defined by Equation 16:

Equation 16

$$CE = \frac{Cost_A - Cost_B}{GHG_B - GHG_A}$$

where CE = cost-effectiveness [$/kg]

$Cost_A$ = cost of alternative [$/mile or $/SF]

$Cost_B$ = cost of baseline [$/mile or $/SF]

GHG_A = GHGs of alternative [kg/mile or kg/SF]

GHG_B = GHGs of baseline [kg/mile or kg/SF]

The above formula may be used for evaluating either vehicle-based or facility-based strategies, and the units may be converted to $/tonne for the purpose of comparing the cost-effectiveness against carbon credits trading on the carbon market. Historically, carbon credits on the European Climate Exchange have been trading around $20 to $30 per tonne (*57*). Therefore, for a transit GHG emission reduction strategy to be competitive on the global carbon marketplace, the cost per tonne should be comparable to historical averages.

Calculation of the cost-effectiveness of GHG emission reduction alternatives requires both cost profile and activity profile data (quantity of vehicles, VMT, fuel consumption, and GHGs). At the right hand side of the calculator's inventory worksheets (see Appendix B), the user selects a "Cost ID" from a dropdown list of cost profiles saved by the user. For each vehicle record with a selected "Cost ID", the volume of fuel consumed is multiplied by the cost profile's fuel cost per unit volume, the quantity of vehicles is multiplied by the cost profile's annual operation & maintenance costs and annualized capital costs. This result, divided by the VMT plus any given per mile costs in the cost profile, is the record's cost per mile, which is used in Equation 16 to calculate the record's cost-effectiveness.

Figure 14 shows sample cost-effectiveness calculations for transit bus alternatives. Each row corresponds with a bus inventory record from the bus inventory worksheet. The cost-effectiveness is relative to a cost baseline selected by the user (see 2nd column in Figure 14). A negative cost-effectiveness indicates that the alternative reduces both GHG emissions and costs on a per mile basis. No cost-effectiveness value is calculated for the baseline or for any alternative with per mile GHG emissions that are higher than the baseline.

			Scope	
			1	

Cost ID	Cost-Eff. Baseline?	Cost ($/mile)	CO2e Emiss. Rate (g/mile)	Cost-Eff. ($/tonne)
Diesel Bus Base	yes	$1.62	3,404	
Biodiesel Bus		$1.60	0	-$5.53
CNG Bus		$1.92	2,546	$348.00
Diesel Bus Base		$1.91	4,055	GHG Increase

Figure 14: Sample Cost-Effectiveness Calculations for Transit Bus Alternatives

For alternatives that are estimated to have relatively higher capital costs and lower annual costs, a payback period may be calculated. The payback period of a strategy that reduces GHG emissions may be calculated by dividing the incremental increase in capital cost by the incremental annual cost savings. The payback period may thus be defined by Equation 17 below:

Equation 17

$$PP = \frac{CC_A - CC_B}{AC_B - AC_A}$$

where PP = payback period [yr]

CC_A = capital cost of alternative [$]

CC_B = capital cost of baseline [$]

AC_A = annual cost of alternative [$/yr]

AC_B = annual cost of baseline [$/yr]

Figure 15 shows a sample payback period calculation for a transit bus alternative. A cost profile ("Cost ID") and activity profile ("Inventory ID") are based on user inputs and are used for both the baseline and the alternative. The "Cost ID" is a dropdown list query of the cost profile, and the "Inventory ID" is a dropdown list query of GHG emission inventory records. The activity data of the emission inventory records (quantity of vehicles, VMT, and fuel consumption) are multiplied by the respective per year, per mile, and per unit of fuel costs entered for the "Cost ID" cost profile. The result is the average annual costs shown in the figure.

	Baseline	Alternative	Difference
Option	Option #1	Option #2	
Cost ID	Diesel Bus Base	Biodiesel Bus	
Inventory ID	3003 - 3024	3003 - 3024	
# of Vehicles	22	22	
Service Life (years)	12	12	
Capital Cost (w/ salvage)	$5,104,753.05	$5,280,753.05	$176,000.00
Average Annual Cost	$1,340,391.60	$1,303,876.20	$36,515.40
Life Cycle Cost	$21,189,452.25	$20,927,267.45	
B/C Ratio			0.207
Payback (years)			4.82

Figure 15: Sample payback period calculation for a transit bus alternative.

The life cycle cost is the average annual cost multiplied by the service life, plus the capital cost. The capital cost reflects the discounted salvage value calculated in the cost profile. The benefit/cost ("B/C") ratio is calculated by dividing the annual cost savings (the benefit) by the extra capital cost of the alternative. The payback is calculated in accordance with Equation 17 and is the inverse of the B/C ratio for the annual cost savings. The sample hypothetical calculation in Figure 15 indicates that the biodiesel bus investment(s) would be recouped through operation & maintenance savings in 4.82 years.

CHAPTER 4

APPLICATION AND ASSESSMENT

To synthesize and assess its capabilities, the developed calculator has been utilized for a GHG inventory (carbon footprint) of a typical mid- to large-sized transit agency, and for an evaluation of the cost-effectiveness of transit GHG emission reduction strategies. The GHG inventory was based on the Metropolitan Atlanta Rapid Transit Authority (MARTA) for the year 2008. The cost-effectiveness evaluations are based on two case studies: 1) King County Metro Transit articulated diesel hybrid bus evaluation; and 2) New York Metropolitan Transit Authority (MTA) Grand Central Terminal lighting replacement evaluation.

4.1. GHG Inventory of MARTA (2008)

One of the main functions for which the calculator is designed is the creation of an annual GHG emissions inventory for a public transit agency. As a partner in the development of the forthcoming *Transit Greenhouse Gas Emissions Management Compendium*, MARTA and MARTA's consultant S.L. King Technologies Inc. have provided data for a 2008 GHG emissions inventory. These data, along with supplemental data from the NTD and APTA, were used by the authors of the compendium to calculate MARTA's 2008 carbon footprint. The calculator presented in this thesis uses the same accounting framework as in the compendium footprint, but several calculation differences exist. Unlike the compendium footprint calculations, the calculator is designed to accommodate a GHG emissions inventory for agencies of any size, type, or level of calculation expertise. As such, some of the calculation formulae and methodologies in the developed calculator differ from those used in the compendium carbon footprint. Furthermore, the GHG inventory presented here makes more use of agency supplied activity data (fuel consumption, VMT, etc.) than does the compendium carbon footprint, which relied more on NTD activity data. The results of the application of the calculator to a MARTA GHG emissions inventory are discussed in terms of the opportunities and limitations for managing GHG emission reductions.

A variety of data types and sources are required to conduct an agency GHG emissions inventory. Table 15 and Table 16 show the aggregated data input values and sources used for the 2008 MARTA GHG emissions inventory. The capital costs shown are per vehicle costs, whereas all other values are aggregated for a particular mode. For heavy rail, the manufacturing cost (purchase cost) was derived from a national average, rather than the MARTA purchase costs reported to the APTA Vehicle Database (*58*). The MARTA purchase costs underreport the vehicle costs by listing prices from 25 years ago, which do not reflect inflationary effects. Added to these purchase costs are the costs for the recent heavy rail vehicle rebuild program, which is estimated to extend vehicle service lives by 15 years. Due to a lack of disaggregate vehicle maintenance cost data, the mode-specific maintenance costs extracted from the NTD are assumed to be distributed evenly within the quantity of vehicles.

Table 15: 2008 MARTA GHG Inventory Aggregated Data Input Values and Sources.

Mode	Data	Value	Source
Bus	Qty	189 diesel 441 CNG	MARTA / S.L. King
	Est. Service Life	Varies by model, generally 12 years	http://www.fta.dot.gov/grants_financing.html.
	Cap. Cost	Varies by model	APTA 2009 Public Transportation Vehicle Database
	Maint. Cost	$13,085,012.00	2008 NTD: Table Operating_Expense: Tire_Tube_Amt and Other_Mat_Sup_Amt
	Fuel	2,416,653 gal diesel 6,798,270 DGE CNG	MARTA / S.L. King
	VMT	30,551,811	MARTA / S.L. King
	Rev. Veh. Hrs	2,191,400	2008 NTD: Table 19 Transit Operating Statistics: Service Supplied and Consumed
	PMT	213,459,600	2008 NTD: Table 19 Transit Operating Statistics: Service Supplied and Consumed
Para-transit	Qty	225	MARTA / S.L. King
	Est. Service Life	4 years	http://www.fta.dot.gov/grants_financing.html.
	Cap. Cost	$80,000.00	APTA 2009 Public Transportation Vehicle Database
	Maint. Cost	$840,698.00	2008 NTD Table: Operating_Expense: Tire_Tube_Amt and Other_Mat_Sup_Amt
	Fuel	773,593 gal diesel	MARTA / S.L. King
	VMT	6,665,571	MARTA / S.L. King
	Rev. Veh. Hrs	283,800	2008 NTD: Table 19 Transit Operating Statistics: Service Supplied and Consumed
	PMT	5,423,300	2008 NTD: Table 19 Transit Operating Statistics: Service Supplied and Consumed

Table 16: 2008 MARTA GHG Inventory Aggregated Data Input Values and Sources (cont.).

Mode	Data	Value	Source
Heavy Rail	Qty	338	2008 NTD Table: Revenue_Vehicle_Inventory: Total_Fleet
	Est. Service Life	25 years (mfg) 15 years (rebld)	2008 NTD Table: Revenue_Vehicle_Inventory: Total_Fleet http://www.itsmarta.com/railcar-rehabilitation.aspx
	Cap. Cost	$1,500,000 (mfg): 120 veh. $1,128,440 (rbld): 218 veh.	APTA 2009 Public Transportation Vehicle Database: Table 22 http://www.itsmarta.com/railcar-rehabilitation.aspx
	Maint. Cost	$7,674,749.00	2008 NTD Table: Operating_Expense: Tire_Tube_Amt and Other_Mat_Sup_Amt
	Energy	97,411,500 KWh	MARTA / S.L. King
	VMT	24,063,100	2008 NTD: Table 19 Transit Operating Statistics: Service Supplied and Consumed
	Rev. Veh. Hrs	873,400	2008 NTD: Table 19 Transit Operating Statistics: Service Supplied and Consumed
	PMT	593,419,400	2008 NTD: Table 19 Transit Operating Statistics: Service Supplied and Consumed
Non-Rev. Veh.	Qty	389 gasoline 16 CNG 41 diesel (road) 9 diesel (non-road)	MARTA / S.L. King
	Est. Service Life	12 years	N/A
	Cap. Cost	Varies by model	N/A
	Maint. Cost	N/A	N/A
	Fuel	405,728 gal diesel 57,033 gal gasoline 633,368 SCF (est. 13 mpDGE)	MARTA / S.L. King
	VMT	5,926,994	MARTA / S.L. King
Stationary (combustion)	Fuel	510,604.86 therms	MARTA / S.L. King
Stationary (electricity)	Energy	11,139,2734.06 KWh	MARTA / S.L. King

The input and output worksheets for the MARTA 2008 GHG Emissions Inventory are shown in Appendix D. The inventory records (rows) preserve the resolution of vehicle and facility activity data provided by MARTA. For both the bus and paratransit inventory worksheets, each record represents a unique vehicle model type. Heavy rail vehicle activity data was only available for the heavy rail vehicle fleet as a whole. Stationary combustion activity data (natural gas consumption) is combined into a single record, but purchased electricity activity data for facilities is disaggregated by each metered facility. No specific fuel emission factor data was available from MARTA, so all GHG emissions calculations are performed using calculator defaults (bottom tier emission factor data).

The calculator produces bar graphs of the major categories of agency GHG emissions. These graphs are intended to help agencies identify the major sources of GHG emissions from agency activities. Figure 16 shows a graph of MARTA’s Scope 1 GHG emissions for 2008. Far and away the largest source of GHG emissions is the bus fleet, with CNG buses producing the greatest proportion of bus fleet emissions. This result is to be expected, since the CNG fleet outnumbers the diesel bus and paratransit fleets. As should be expected, the non-revenue vehicle GHG emissions are the lowest among all other vehicle fleet GHGs. Figure 16 helps to highlight that stationary combustion GHGs from agency facilities comprise the smallest source of Scope 1 GHG emissions. This is not to say that agency facilities contribute very little to the agency carbon footprint. To understand the degree of facility emissions, the Scope 2 emissions from purchased electricity must be considered.

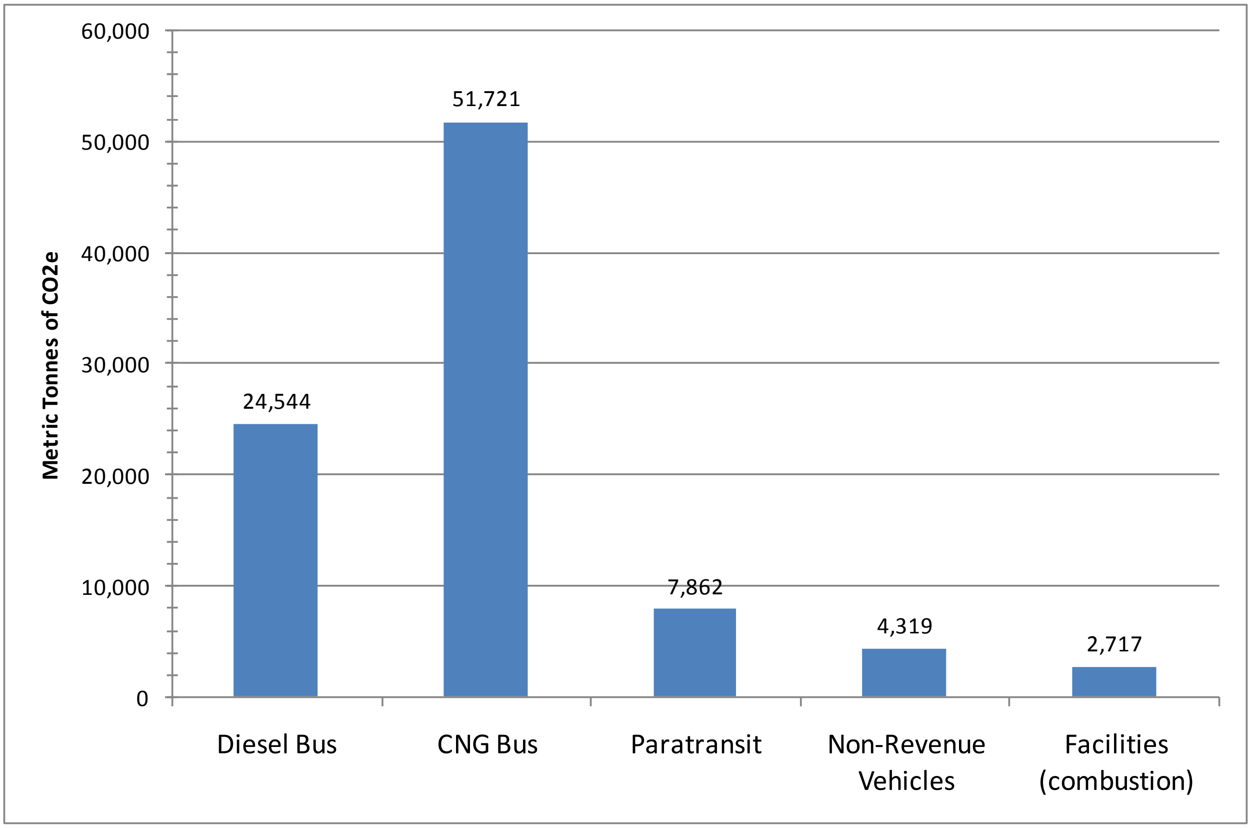

Figure 16: MARTA Scope 1 GHG emissions for 2008.

Figure 17 shows the Scope 2 MARTA GHG emissions from 2008. Figure 17 indicates that facility related GHGs are a major portion of the agency carbon footprint. Most facility GHGs arise from the production of electricity for rail stations and yards, and the combined emissions from rail stations and yards, main offices, and other facilities are equal to 70,867 MT of CO_2e, which is more than the emissions generated for heavy rail vehicle propulsion. It is apparent that agency facilities present significant opportunities for reducing agency GHG emissions. It should be noted that the electrical energy for heavy rail propulsion and rail station and yard power are delivered through the same connections to the grid and are not metered separately. Thus the proportions of electrical energy consumption for propulsion and facility power are estimated by agency engineers. Considering the total magnitude of emissions from purchased electricity, MARTA efforts to target GHG emission reduction opportunities would likely benefit from direct metering of either facility or heavy rail propulsion energy consumption.

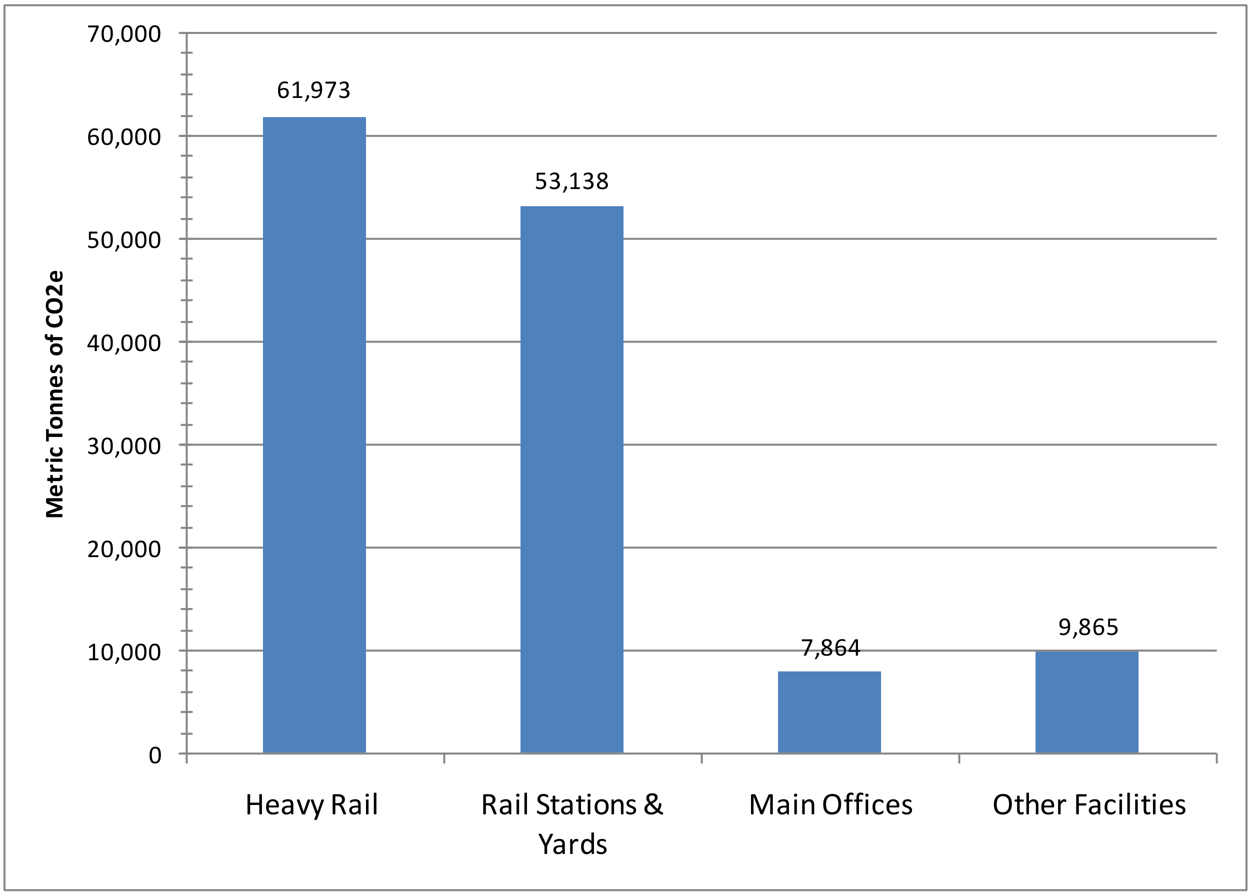

Figure 17: MARTA Scope 2 GHG emissions for 2008.

The Scope 2 emission presented in Figure 17 are estimated from default emission factors from the eGRID2007 database, which contains state-level (in this case Georgia) emission factors from 2005. The results in Figure 17 are likely lower than the actual 2008 GHG emissions from purchased electricity, since the 2008 Georgia CO_2 emission factor data from the U.S. EIA is higher than the 2005 Georgia CO_2 emission factor data from eGRID (1,449 lbs/MWh vs. 1,403 lbs/MWh) (*44*, *56*). The older eGRID data was used since 2008 CH_4 and N_2O emission factor data is currently unavailable from the U.S. EIA. The lack of 2008 emission factor data likely impacts the accuracy of the inventory, but does not thwart the assessment of the calculator, which is in part an effort to test the use of the built-in default data. It is anticipated that 2007 emission factor data will be available from eGRID toward the end of the year 2010 (*44*).

The total Scope 1 and Scope 2 emissions, along with the agency performance metrics, are reported below in Table 17. The performance metrics indicate that even though heavy rail transit is the most carbon-intensive vehicle (highest emissions per vehicle-mile) it is MARTA's most carbon efficient mode of public transportation (lowest emissions per passenger-mile). This comparison neglects the GHG emissions produced from rail yards and stations; emissions that could conceivably be tacked onto the heavy rail mode. APTA does not recommend that such infrastructure emissions be added to transit modes since it creates an unfair comparison with highway modes, which are said to typically neglect infrastructure emissions (*9*). Had data been available, the performance metrics results would have benefited from an analysis of the facility GHG emissions per square foot. A calculation of GHG emissions per square foot would enable comparison of facility GHG emissions to the GHG emissions of other commercial buildings in the Atlanta metropolitan region.

Table 17: MARTA GHG Performance Metrics, Annual CO_2e Scope 1 and Scope 2 Emissions for 2008

Mode	Emissions (E)	Vehicle Miles (VM)		Revenue Vehicle Hours (RH)		Passenger Miles (PM)	
	Metric Tons	Total (000s)	E/VM (kg/mi)	Total (000s)	E/RH (kg/hr)	Total (000s)	E/PM (kg/pax-mi)
Bus (MB)	76,265	30,552	2.50	2,191	34.80	213,460	0.36
Paratransit (DR)	7,862	6,666	1.18	284	27.70	5,423	1.45
Heavy Rail (HR)	61,973	24,063	2.58	873	70.96	593,419	0.10
Non-Revenue Vehicles	4,319	5,927	0.73	--	--	--	--
Stationary (combustion)	2,717	--	--	--	--	--	--
Stationary (electricity)	70,868	--	--	--	--	--	--
Total	224,004	67,207	3.33	3,349	66.89	812,302	0.28

In addition to direct and indirect fuel combustion emissions, the calculator estimates the indirect Scope 3 emissions. Figure 18 below shows the 2008 MARTA Scope 3 fuel-cycle and vehicle-cycle GHG emissions.

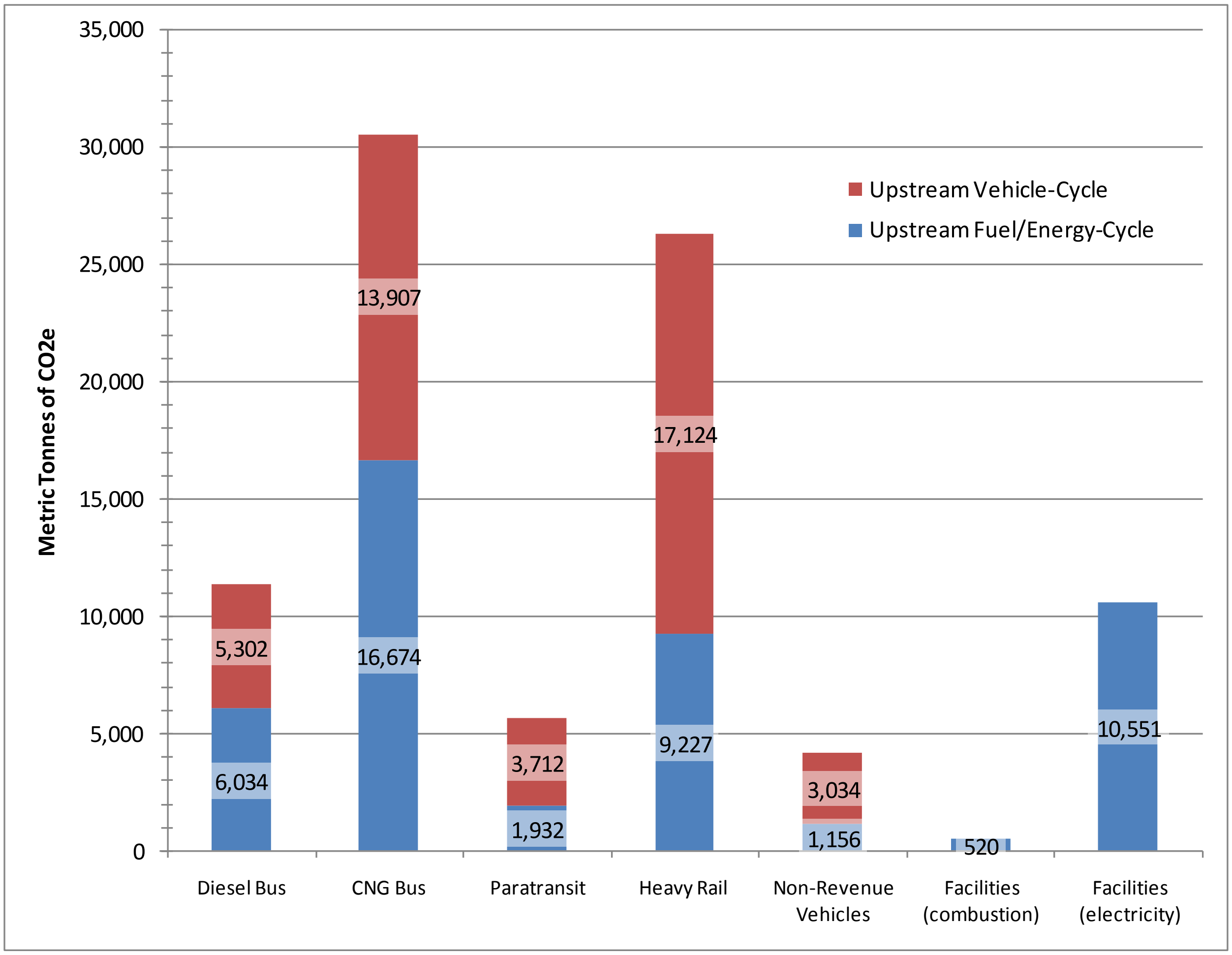

Figure 18: MARTA Scope 3 GHG emissions for 2008.

It should be noted that the fuel-cycle GHG emissions in Figure 17 are proportional to the VMT and/or the amount of fuel combusted for each of the modes/fuels, whereas the vehicle-cycle GHG emissions are based on annualized costs and are thus not directly proportional to VMT. It was mentioned previously that mode-specific annual maintenance costs are assumed to be distributed evenly between the vehicles of a particular mode. At the level of individual vehicle records, this assumption results in higher than average per mile maintenance costs for vehicles with lower than average VMT. Thus, the EIO-LCA-estimated vehicle-cycle GHG emissions for each of the vehicle inventory records are expected to be either too high or too low (depending upon VMT data for the vehicle class), but for each mode the total sum of vehicle-cycle GHG emissions will be consistent with the mode's average maintenance GHGs/mile. The calculator accommodates the input of maintenance cost data on a per mile basis, and such data for each of the vehicle classes would have provided a more precise estimate of vehicle-cycle maintenance emissions. This is especially true for the MARTA diesel and CNG buses, for which only a combined annual total of maintenance costs was available. The calculator's approach to estimating vehicle-cycle GHG emissions attempts to effectively leverage data for both vehicle manufacture and vehicle maintenance. In consideration of the fact that the industrial sectors in the EIO-LCA do not capture material differences in products within a sector (see Section 3.3.2.3), and considering that separate sector emissions for tires and other vehicle accessories should be applied separately from the selected vehicle maintenance sectors, it is questionable whether the calculation results are worth the level of sophistication used in the calculator. In terms of minimizing data requirements for the generation of meaningful calculation outputs, users of the calculator may benefit from a simplification of the vehicle-cycle GHG emissions estimation.

During the development of the calculator, it was discovered that the EIO-LCA model and model results are restricted to non-commercial use (otherwise a commercial-use license must be obtained, for a substantial fee). Considering that the calculator is intended to be available for free use by transit agencies, an alternative (free and unrestricted) calculation method is desired. One promising option is the use of average upstream emission factors, expressed as a percentage of vehicle operation emissions. Such factors are available in Appendix B of the U.S. EPA's report of transportation GHGs from 1990-2003 (*21*). Due to the age and the lack of supporting detail on these emission factors, it is unclear whether these emission factors in particular are appropriate for incorporation into the calculator. Further research is needed to derive emission factors that are consistent with current research literature findings of life cycle transportation GHG emissions.

The direct, fuel-cycle, and vehicle-cycle GHG emissions of MARTA are summarized in Figure 19. The upstream GHG emissions comprise a considerable proportion of agency emissions, but most of the emissions arise from the combustion of fossil fuels for vehicle propulsion and facility energy demands.

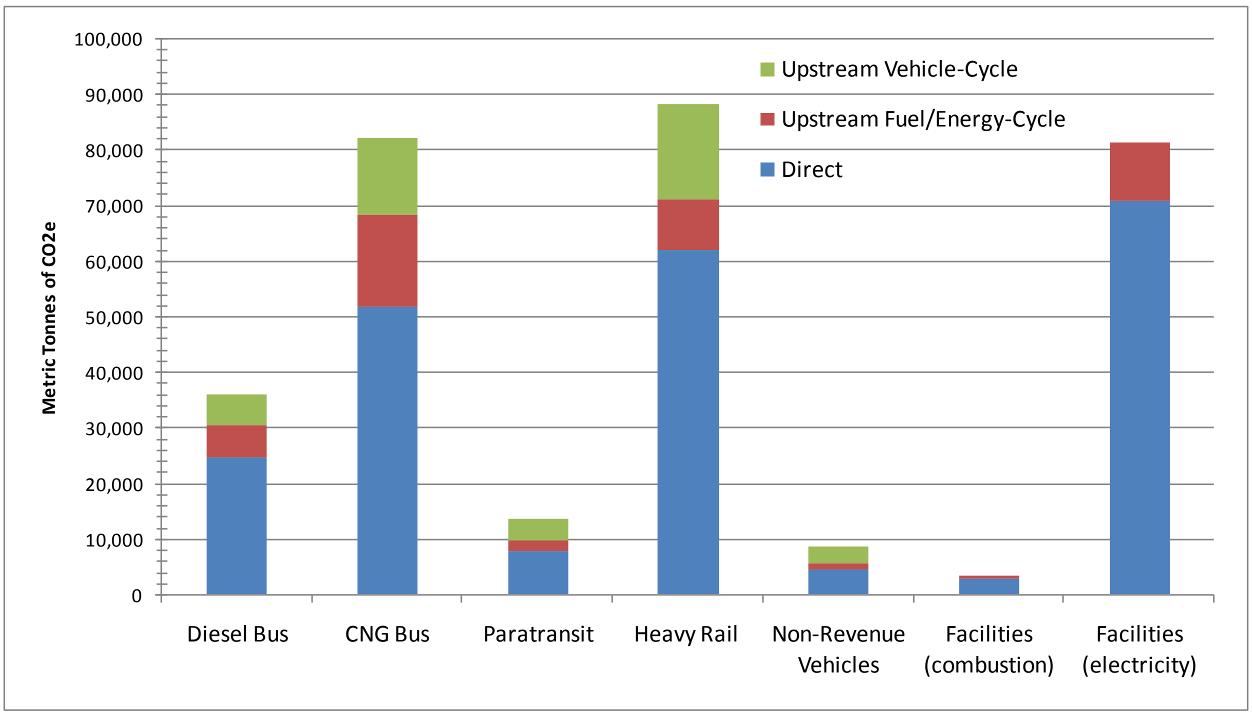

Figure 19: MARTA direct and life cycle GHG emissions for 2008.

The life cycle GHG emissions performance of MARTA is evinced by the total Scope 1, 2, and 3 emissions and performance metrics in Table 18. The relative GHG emissions performance of MARTA's transit modes are approximately the same when considering or ignoring life cycle emissions (see Table 17 and Figure 19). The main message to be gleaned from the results of the life cycle calculations is that agency activities produce significant, quantifiable impacts on GHG emissions in the vehicle and fuel supply chains.

Table 18: MARTA GHG Performance Metrics, Annual CO_2e Scope 1, 2, and 3 Emissions for 2008

Mode	Emissions (E)	Vehicle Miles (VM)		Revenue Vehicle Hours (RH)		Passenger Miles (PM)	
	Metric Tons	Total (000s)	E/VM (kg/mi)	Total (000s)	E/RH (kg/hr)	Total (000s)	E/PM (kg/pax-mi)
Bus (MB)	118,181	30,552	3.87	2,191	53.93	213,460	0.55
Paratransit (DR)	13,506	6,666	2.03	284	47.59	5,423	2.49
Heavy Rail (HR)	88,324	24,063	3.67	873	101.13	593,419	0.15
Non-Revenue Vehicles	8,509	5,927	1.44	--	--	--	--
Stationary (combustion)	3,238	--	--	--	--	--	--
Stationary (electricity)	81,419	--	--	--	--	--	--
Total	313,177	67,207	4.66	3,349	93.52	812,302	0.39

4.2. Cost-Effectiveness of GHG Emission Reduction Strategies

The following cost-effectiveness evaluations test the application of the developed calculator to the evaluation of the effectiveness of vehicle-based and facility-based strategies for reducing transit agency GHG emissions.

4.2.1. King County Metro Transit Articulated Diesel Hybrid Bus Evaluation

Diesel hybrid-electric propulsion has become a popular vehicle propulsion technology among transit agencies. Diesel hybrid buses typically achieve higher fuel efficiencies than conventional diesel buses, thereby reducing operational GHG emissions. According to a recent study from the National Academy of Sciences, hybridization is one of the most effective fuel consumption reduction technologies for heavy duty vehicles (*59*). King County Metro Transit in Seattle, WA has 235 hybrid buses (nearly one-quarter of its bus fleet), 213 of which are 60 ft articulated hybrid buses (*60*). The articulated hybrid buses serve as replacements for the retired/rebuilt Breda dual-mode (diesel and overhead catenary electric) buses that operated in the Seattle downtown transit tunnel. The National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy (DOE) has helped Metro Transit evaluate and compare the cost and emissions of the articulated hybrid buses relative to conventional diesel articulated buses (*61*).

For the evaluation, 10 model year 2004 New Flyer DE60LF diesel hybrid buses were compared against 10 model year 2004 New Flyer D60LF diesel buses. The hybrid and conventional diesel buses operated from different maintenance garages and each bus was randomly dispatched for service on the transit routes. During the 12 month evaluation period (between April 1, 2005 and March 31, 2006) the hybrid and diesel buses logged similar average monthly miles of service. Table 19 summarizes the specifications, costs, and performance data relevant to an evaluation of the bus GHG emissions.

Table 19: King County Metro Hybrid Bus Cost and Emissions Evaluation Data (*61*)

	Diesel	**Hybrid**
Number of Buses	10	10
Manufacturer and Model	New Flyer D60LF	New Flyer DE60LF
Model Year	2004	2004
Seats	58	58
Purchase Cost (per bus)	**$445,000**	**$645,000**
Maintenance Cost ($/mile)	**0.462**	**0.444**
Total Mileage (maint. cost est.)	353,785	371,458
Total Mileage (fuel est.)	**350,567**	**362,049**
Fuel Cost ($/mile)	**0.791**	**0.624**
Fuel Consumption (gallons)	**139,996**	**114,054**
Fuel Type	B5	ULSD
Fuel Economy (avg.)	2.5	3.17

The diesel and hybrid buses are based on the same vehicle platform and provide the same service capacity. The maintenance costs accounts for all maintenance activities during the evaluation period. It is important to note that the maintenance costs do not account for major repair and overhaul activities that are known to occur during the bus life cycles, such as engine rebuilds, transmission rebuilds, and battery replacement (hybrid). It should also be noted that different mileage totals were used to estimate the maintenance costs per mile and the fuel cost per mile. Different types of fuels were used at the respective garages; however, from a GHG emissions perspective, the difference is negligible. The bus evaluation did not include a calculation of the GHG emissions produced during the evaluation period. However, using the fuel consumption and mileage data in Table 19 the calculator was used to estimate GHG emissions.

The calculator inputs and outputs of the bus GHG emissions are shown in Appendix E. The calculation results indicate that on a per mile basis, the hybrid buses achieved a 21.1 percent reduction in Scope 1 GHG emissions relative to the diesel buses. The bus worksheet figures in

Appendix E show the diesel bus and hybrid bus calculations twice (four inventory rows). The GHG inventory rows are repeated to accommodate two variations of the cost-effectiveness calculations (see Figure 64). The first two rows present a cost-effectiveness based directly on the costs given in Table 19, whereas the last two rows present a cost-effectiveness based on an 80 percent vehicle purchase subsidy, which is typical of FTA support (*59*). The costs shown in columns DC and DE are used for Scope 3 vehicle-cycle GHG emissions estimation, not the cost-effectiveness calculations. The cost profiles of the subsidized and unsubsidized buses are shown in Figure 65 in the Appendix. The inventory data and cost profile data are combined in the following calculations of the cost effectiveness:

<u>Without subsidy</u>:

$$\frac{\left(\frac{\frac{\$645{,}000 \times 10\ veh.}{12\ yrs.}}{362{,}049\ mi.} - \frac{\frac{\$445{,}000 \times 10\ veh.}{12\ yrs.}}{350{,}567\ mi.}\right) + \left(\frac{\$1.068}{mi.} - \frac{\$1.253}{mi.}\right)}{\left(\frac{\frac{1{,}421.51\ tonnes\ CO2e}{yr.}}{350{,}567\ mi.}\right) - \left(\frac{\frac{1{,}158.21\ tonnes\ CO2e}{yr.}}{362{,}049\ mi.}\right)} = \frac{\$282.53}{tonne\ CO2e}$$

With subsidy:

$$\frac{\left(\frac{\frac{\$645{,}000 \times (1-0.8) \times 10\ veh.}{12\ yrs.}}{362{,}049\ mi.} - \frac{\frac{\$445{,}000 \times (1-0.8) \times 10\ veh.}{12\ yrs.}}{350{,}567\ mi.}\right) + \left(\frac{\$1.068}{mi.} - \frac{\$1.253}{mi.}\right)}{\left(\frac{\frac{1{,}421.51\ tonnes\ CO2e}{yr.}}{350{,}567\ mi.}\right) - \left(\frac{\frac{1{,}158.21\ tonnes\ CO2e}{yr.}}{362{,}049\ mi.}\right)}$$

$$= \frac{-\$116.43}{tonne\ CO2e}$$

Without a vehicle purchase subsidy, the cost-effectiveness of the GHG emissions reduction from the hybrid buses is \$282.53 per tonne of CO_2e. This value is considerably higher than the cost of carbon credits trading in international markets, but this is not to say that the GHG emission reductions are not worth the investment. When interpreting the cost-effectiveness results, it is important to keep in mind that hybrid buses offer several co-benefits beyond GHG emissions reductions, such as reduced CAP idling emissions, reduced fuel consumption, reduced noise, etc. *With* a vehicle purchase subsidy, the cost-effectiveness of the GHG emissions reduction from the hybrid buses (from the perspective of the transit agency) is -\$116.43 per tonne of CO_2e (see calculation results shown in Figure 20 below).

Scope
1

Cost ID	Cost-Eff. Baseline?	Cost (\$/mile)	CO2e Emiss. Rate (g/mile)	Cost-Eff. (\$/tonne)
KCM diesel sub	yes	\$1.46	4,055	
KCM hybrid sub		\$1.36	3,199	-\$116.43

Figure 20: Cost-effectiveness results for KC Metro hybrid bus evaluation.

This negative cost-effectiveness value indicates that relative to diesel buses, the hybrid buses reduce both agency GHG emissions and agency costs. It should be noted that the cost-effectiveness of the hybrid buses could be improved further if the agency were to partially finance the hybrid buses with carbon reduction credits sold on the carbon market.

The cost data from the one year bus evaluation enables an approximate calculation of the payback period for offsetting the higher vehicle purchase cost with the fuel cost savings. First the following assumptions must be made: 12 year lifetime for both bus types; bus mileage and fuel consumption remain constant each year; per mile maintenance costs remain constant (or major repair costs in future years are similar between bus types); fuel costs remain constant, and no interest is charged/earned on bus procurement, operation, and maintenance cash flows. With these assumptions the fuel cost savings of the hybrid bus would not offset the higher purchase cost until after the bus lifetime (payback period of 38 years). The payback period calculation follows Equation 17:

$$\frac{(\$645{,}000 \times 10\ veh.) - (\$445{,}000 \times 10\ veh.)}{\left(\frac{\$1.253}{mi.} \times \frac{350{,}567\ mi.}{yr.}\right) - \left(\frac{\$1.068}{mi.} \times \frac{362{,}049\ mi.}{yr.}\right)} = 38.03\ yrs.$$

Figure 21 shows the calculator’s payback period calculation for the unsubsidized KC Metro hybrid buses.

	Baseline	Alternative	Difference
Option	Option #1	Option #2	
Cost ID	KCM diesel	KCM hybrid	
Inventory ID	2880-2889	2780-2789	
# of Vehicles	10	10	
Service Life (years)	12	12	
Capital Cost (w/ salvage)	$4,450,000.00	$6,450,000.00	$2,000,000.00
Average Annual Cost	$439,260.45	$386,668.33	$52,592.12
Life Cycle Cost	$9,721,125.41	$11,090,019.98	
B/C Ratio			0.026
Payback (years)			38.03

Figure 21: Payback period calculation for KC Metro hybrid buses (unsubsidized).

The calculations in Figure 21 indicate a higher life cycle agency cost for hybrid buses relative to diesel buses when no purchase subsidy is applied. This result is consistent with the TCRB's study of hybrid bus lifecycle cost (*35*). If an 80 percent subsidy is applied to the purchase of both hybrid and diesel buses, the hybrid bus fuel cost savings would recover the higher purchase cost in 7.6 years (see Figure 22).

	Baseline	Alternative	Difference
Option	Option #1	Option #2	
Cost ID	KCM diesel sub	KCM hybrid sub	
Inventory ID	2880-2889	2780-2789	
# of Vehicles	10	10	
Service Life (years)	12	12	
Capital Cost (w/ salvage)	$890,000.00	$1,290,000.00	$400,000.00
Average Annual Cost	$439,260.45	$386,668.33	$52,592.12
Life Cycle Cost	$6,161,125.41	$5,930,019.98	
B/C Ratio			0.131
Payback (years)			7.61

Figure 22: Payback period calculation for KC Metro hybrid buses (subsidized).

The 7.6 year payback period is well within the estimated 12 year service life of the buses. Therefore, from the perspective of the transit agency, hybrid buses can not only deliver cost-effective reductions in agency GHG emissions, but can also lower vehicle life cycle costs.

4.2.2. New York Metropolitan Transit Authority Grand Central Terminal Lighting Replacement Evaluation

Transit agencies often manage extensive infrastructures that consume energy and produce GHG emissions. Therefore, facility-based strategies for reducing GHG emissions should not go overlooked. To reduce energy consumption, GHG emissions, and costs, the New York

Metropolitan Transit Authority (NY MTA) has pursued a lighting replacement project for one of the nation's most well-known infrastructures – Grand Central Terminal. The NY MTA replaced 1,700 incandescent light bulbs with compact fluorescent lamps (CFLs). Table 20 shows the hardware, cost, and energy consumption data for the lighting replacement.

Table 20: NY MTA Grand Central Terminal Lighting Replacement Data (*62*)

	Incandescent	CFL
Number of Lamps	1,700	1,700
Wattage	60 W (700), 100W (1,000)	15 W (700), 20W (1,000)
Replacement cost ($/yr)	$10,200/yr	$11,050/yr
Electricity Cost Savings ($/yr)	--	$147,000/yr
Electricity Savings (kWh)	--	980,000

Although total energy consumption and cost data were unavailable for this case study, the GHG emissions reduced, the cost-effectiveness, and the payback period may be calculated from the differences in costs and energy consumption. Local emission factor data was unavailable, so default emission factors in the calculator were used to estimate the GHG emissions saved. For estimating the GHG emissions saved from reductions in electrical energy consumption, the eGRID database documentation recommends use of non-baseload emission rates (*44*). Based on eGRID non-baseload emission rates for the NYCW subregion (1,525.05 lbs CO_2/MWh, 56.80 lbs CH_4/GWh, and 9.08 lbs N_2O/GWh) (*44*), the yearly savings in annual energy consumption equates to annual Scope 2 GHG emissions savings of approximately 677.9 tonnes of CO_2e. If annual emission rates are used, the Scope 2 GHG emission savings are approximately 362.5 tonnes of CO_2e. With a percent difference of 60.6 percent, these estimates of GHG emission savings underscore the need for more precise time-of-day emission factor data and activity data. The calculator worksheet inputs and outputs for this case study are shown in Appendix E.

The lighting replacement data in Table 20 indicate that both costs and energy consumption (and by extension GHG emissions) were reduced. Thus, the \$/tonne cost-effectiveness of the lighting replacement for Grand Central Terminal is a negative figure. Specifically, the calculator estimates a cost-effectiveness of -\$215.58 per tonne of CO_2e. This result invites a calculation of the payback period for the lighting replacement. Using Equation 17, the yearly lamp replacement costs may be taken as the capital costs and the electricity cost savings may be taken as the annual costs (see cost profiles in Figure 68 in Appendix E). The annual lamp replacement costs are treated as capital costs since these are the only initial project costs and because the data on cost savings indicate that all initial costs are recovered before the end of the year (a one year capital project that is repeated annually). The calculated payback period is shown in Figure 23.

	Baseline	Alternative	Difference
Option	Option #1	Option #2	
Cost ID	Base Facility	CFL Lights	
Inventory ID	Grand Central Terminal	Grand Central Terminal (CFL)	
Use i?			
Service Life (years)	1	1	
Capital Cost (w/ salvage)	$10,200.00	$11,050.00	$850.00
Average Annual Cost	$147,000.00	$0.00	$147,000.00
Life Cycle Cost	$157,200.00	$11,050.00	
B/C Ratio			172.94
Payback (years)			0.006

Figure 23: Payback period calculation for NY MTA Grand Central Terminal lighting replacement.

The payback for the lighting replacement occurs in approximately 0.006 years (or about two days). The calculated life cycle costs in Figure 23 do not include all associated costs (energy costs for the baseline and alternative were not available), but the estimated life cycle costs summarize the relative savings of the CFL lighting replacement.

The hardware used in this lighting replacement case study are typical of those used for many transit agency facilities. Thus, this case study highlights the significant cost and GHG emissions savings that are possible through lighting replacements. Transit agencies that manage extensive, lighted passenger facilities would do well to pursue lighting efficiency strategies to cost-effectively reduce their carbon footprint.

CHAPTER 5

CONCLUSION

The calculation tool presented in this thesis effectively integrates life cycle GHG emissions estimation and cost accounting for the management of strategies aimed at reducing GHG emissions from public transit agency operations. The tool enables quantification of an agency's GHG emission inventory, and identification of the most cost-effective GHG emission reduction strategies, for both vehicle-based and facility-based strategies.

With respect to estimation of life cycle costs, cost-effectiveness, and payback periods, further research is needed to account for finance costs and uncertainty in future energy costs. In its current form, the calculator incorporates the time value of money only for discounting the salvage value of assets. The calculation tool currently allows the user to model both arithmetic and geometric increases in annual costs; however, the cost-effectiveness and payback period calculations currently treat annual costs as average values over the lifecycle.

The calculation tool considers only one cost (cost to agency) and one benefit (GHG emission reductions). In light of this fact, the tool does not provide an automatic determination of the best strategy for investment. Such a determination should account for co-benefits of the investment. For example, the $/tonne cost-effectiveness of an HVAC retrofit at a maintenance facility may be superior to the $/tonne cost-effectiveness of a hybrid bus procurement, but the hybrid bus may offer superior co-benefits such as reduced criteria air pollutant emissions in urban areas, reduced roadway noise, improved passenger comfort, etc. In such a case, the best GHG emission reduction strategy (for investment of transit agency resources) may not be the alternative with the lowest $/tonne cost-effectiveness. Ultimately, the "best" investment alternative for an agency is the one that most cost-effectively serves an agency's mission and/or goals. Although the developed calculation tool does not determine the "best" investment alternative for an agency, it can help to quantify the GHG emissions performance of transit agency investment alternatives.

Despite its limitations, the developed calculator provides an improved framework and evaluation capability for managing strategies for reducing public transit agency GHG emissions. At the very least, the developed calculator compiles GHG emission estimation protocol methods and data into a single spreadsheet model. This compilation includes the distillation and incorporation of life cycle GHG emission estimation methods, which are generally undefined by GHG emission estimation protocols. The fuel-cycle and vehicle-cycle methodologies included in the calculator leverage established methods and data sources, but given the many assumptions behind the methods and data sources (particularly for process-based life cycle GHG emission calculations) the overall accuracy of these estimation methods are questionable. In the field of life cycle analysis of GHG emissions from transportation, further research is needed to reconcile variations in assumptions and results from different life cycle calculation methods. Some progress had been made for developing baseline data and methods of fuel-cycle GHG emissions from petroleum-based fuels (*63*), but considering the diversity of fuels, modes, and facilities used by public transportation agencies, the task of establishing consistency in life cycle calculation methods is a formidable one. Although the uncertainties of life cycle emissions estimation warrant future research, such uncertainties do not negate the value of the developed calculator. Considering the basic motivations for quantifying GHG emissions from public transit agency operations (voluntary reporting, federal funding applications, and carbon trading) users of the developed calculator are likely most interested in quantifying GHG emissions arising directly from agency operations (Scope 1 and Scope 2 emissions).

This thesis has achieved its primary research objective: to develop an integrative calculation tool for the estimation and management of public transit agency-level life cycle GHG emissions. The application and assessment presented in this thesis (see Chapter 4) demonstrates the capabilities and limitations of the calculator, but the intended application of the developed calculator is its direct use by transit agency personnel. The architecture and user interface of the calculator is designed to facilitate ease of use by persons who are not experts in GHG emissions estimation. To determine how well the calculator meets user needs, and to reap practical benefits from the academic work presented in this thesis, the calculator will be provided for public use by transit agency personnel. Based on feedback from users of the calculator, and based on advancements in the literature on life cycle GHG emissions estimation methods and data, the calculator will continue to evolve as a GHG emissions estimation and management tool.

APPENDIX A: EXISTING GHG EMISSION CALCULATORS

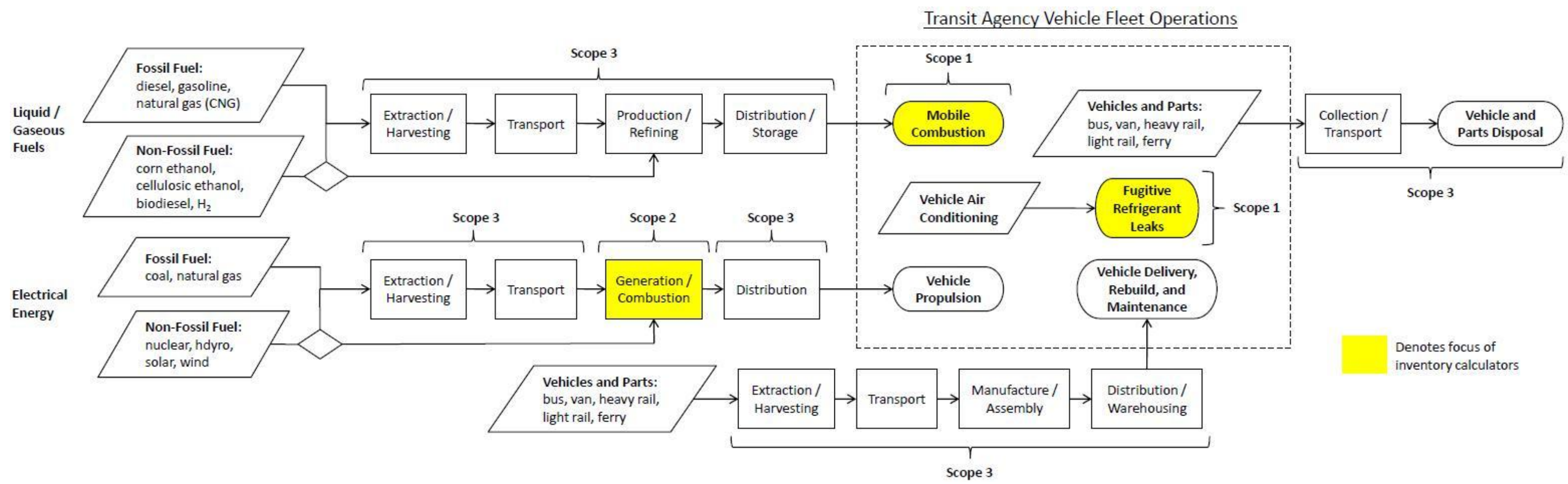

Figure 24: Simplified Diagram of Life Cycle GHG Emissions Producing Activities Related to Transit Agency Vehicle Fleet Operations (*1*).

Table 21: Inventory GHG Emissions Calculators for Transit Vehicles and Fuels (*1*)

Calculator	Format	Output
World Resources Institute (WRI): The Greenhouse Gas Protocol (*40*), Calculating CO2 Emissions from Mobile Sources GHG Protocol Tool for Mobile Combustion, V2.0 Indirect CO2 Emissions from Purchased Electricity GHG Protocol Tool for Purchased Electricity, V4.0	guidance report and spreadsheets	Total metric tonnes of CO2e. For each mode: metric tonnes of CO2, kg of CH4, kg of N2O, metric tonnes of biofuel CO2e.
The Climate Registry (TCR): General Reporting Protocol V1.1 (*6*) The Climate Registry Information System (CRIS) (*39*), Mobile Combustion Emissions from Electricity Use Fugitive Emissions from the Use of Refrigeration and Air Conditioning Equipment	guidance report and online forms	Total metric tonnes of CO2, CH4, N2O, CO2e, and biomass CO2e. For each refrigerant, total metric tonnes of CO2e.
California Climate Action Registry (CCAR): General Reporting Protocol V3.1 (*41*), Direct Emissions from Mobile Combustion Indirect Emissions from Electricity Use Direct Fugitive Emissions from Refrigeration Systems	guidance report	Total metric tonnes of CO2, CH4, N2O, CO2e, and biomass CO2e. For each refrigerant, total metric tonnes of CO2e.
International Council for Local Environmental Initiatives (ICLEI): Local Government Operation (LGO) Protocol (*42*), Vehicle Fleet (Mobile Combustion) Vehicle Fleet (Fugitive Emissions from Motor Vehicle Air Conditioning) Electricity Use	guidance report	Total metric tonnes of CO2, CH4, N2O, CO2e, and biomass CO2e. For each refrigerant, total lbs or kg of CO2e.
Environmental Defense Fund (EDF) / NAFA Fleet Management Association Fleet Greenhouse Gas Emissions Calculator (*64*)	guidance report and online forms	Total metric tonnes of CO2, CH4, N2O, and HFCs.
U.S. EPA Climate Leaders: Cross Sector Guidance (*38*) Simplified GHG Emissions Calculator: Direct Emissions from Mobile Combustion Sources Indirect Emissions from Purchase of Electricity Direct Emissions from Refrigeration and Air Conditioning Equipment	guidance reports and spreadsheets	For each fuel, total kg of CO2. For each fuel and vehicle, g of CH4, g of N2O. Total metric tonnes of CO2e, biomass CO2e. For electricity, total lb of CO2, lb of CH4, lb of N2O, total metric tonnes of CO2e. For each refrigerant, total lbs or kg of CO2e.

Table 22: Life Cycle GHG Emissions Calculators for Transit Vehicles and Fuels (cont.) (*1*)

Calculator	Format	Output
Transport Canada (TC) Urban Transportation Emissions Calculator (*65*)*	online forms	For each vehicle type: Kg CO2e (upstream, operation, and total), Kg CAC's, veh-km of annual travel (road vehicles) pass-km of annual travel (non-road vehicles).
Travel Matters , Center for Neighborhood Technology (CNT): Transit Planning Calculator (*66*)*	online forms and spreadsheets	Total annual lbs CO2 by mode, lbs CO2/mile by vehicle type,
Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Fleet Footprint Calculator 1.0 (*48*)*	spreadsheet with user guide	Total short tons of CO2e and barrels of petroleum used
Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Fuel-Cycle Model 1.8c.0 (*46*)*	software and reference spreadsheets	For each fuel type: well-to-pump Btu/mmBtu of energy consumption, g/mmBtu of CO2e, CO2, CH4, and N2O, well-to-wheel Btu/mile of energy consumption, and g/mile of CO2e, CO2, CH4, and N2O.
Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Vehicle-Cycle Model 2.7 (*47*)	spreadsheets	For each vehicle type: well-to-pump, vehicle cycle, vehicle operation, and total Btu/mile of energy consumption, and g/mile of CO2e, CO2, CH4, and N2O
Lifecycle Emissions Model (LEM) (*50*)	software	For each combination of vehicle type and fuel type process: well-to-pump g/GJ of CO2e, CO2, CH4, N2O, and HFC-134a, lifecycle g/mi of CO2e, CO2, CH4, and N2O, and HFC-134a
GHGenius 3.15 (*49*)	spreadsheets	For each combination of vehicle type and fuel type process: well-to-pump g/GJ of CO2e, CO2, CH4, N2O, HFC-134a, lifecycle g/km of CO2e, CO2, CH4, N2O, and HFC-134a
Economic Input-Output Life Cycle Analysis (EIO-LCA) (*52*)	online forms	Per $1M of economic activity and for each sector: total metric tonnes of CO2e and total CO2e of CO2, CH4, N20, and CFCs
U.S. EPA: Motor Vehicle Emission Simulator (MOVES) (*67*)*,**	software	CO2e and total energy consumption

* Partial life cycle: upstream fuel emissions

** MOVES is currently available in a draft version, but a complete version is scheduled to officially replace MOBILE 6.2 as the U.S. EPA's on-road, mobile source, emission factor software.

Table 23: Vehicle and Fuel Types Covered by GHG Emissions Calculators (*1*)

Calculator	Vehicle Types	Fuel Types
WRI: The Greenhouse Gas Protocol (*40*) Calculating CO2 Emissions from Mobile Sources	local bus, coach, freight truck, light rail, tram, subway (gasoline, diesel, CNG, ethanol) bus. (gasoline, diesel) passenger car, light goods vehicle. (diesel) locomotive. (gasoline, diesel, CNG, LNG, LPG, ethanol) heavy duty vehicle.	gasoline, diesel, residual fuel oil, LPG, CNG, LNG, ethanol, B100, jet fuel, aviation gasoline, E85 (both with biofuel or fossil fuel), B20 (both with biofuel or fossil fuel).
TCR: General Reporting Protocol Version 1.1, CRIS, (*6, 39*) Mobile Combustion *	(gasoline, diesel) passenger cars, light trucks, heavy-duty vehicles, ships, boats. (diesel) locomotives. (methanol, CNG, ethanol) buses, light duty vehicles, heavy duty vehicles. (LPG) light duty vehicles heavy duty vehicles. (LNG) heavy duty vehicles.	motor gasoline, diesel fuel No. 1 and 2, aviation gasoline, jet fuel (Jet A or A-1), kerosene, residual fuel oil (#5 and 6), crude oil, B100, E100, methanol, LNG, LPG, propane, ethane, isobutane, n-butane, CNG.
CCAR: General Reporting Protocol V3.1 (*41*), Direct Emissions from Mobile Combustion*	(gasoline, diesel) passenger cars, light trucks, ships, boats. (diesel) locomotives, heavy-duty vehicles. (biodiesel) heavy duty vehicles. (methanol, CNG, ethanol) buses, light duty vehicles, heavy duty vehicles. (LPG) light duty vehicles, heavy duty vehicles. (LNG) heavy duty vehicles.	motor gasoline, diesel fuel No. 1 and 2, aviation gasoline, jet fuel (Jet A or A-1), kerosene, residual fuel oil (#5 and 6), crude oil, B100, E100, methanol, LNG, LPG, propane, ethane, isobutane, n-butane, CNG.
ICLEI LGO Protocol (*42*): Vehicle Fleet (Mobile Combustion)*	(gasoline, diesel) passenger cars, light trucks, heavy-duty vehicles, ships, boats. (diesel) locomotives. (methanol, CNG, ethanol) buses, light duty vehicles, heavy duty vehicles. (LPG) light duty vehicles, heavy duty vehicles. (LNG) heavy duty vehicles.	motor gasoline, diesel fuel No. 1 and 2, aviation gasoline, jet fuel (Jet A or A-1), kerosene, residual fuel oil (#5 and 6), crude oil, B100, E100, methanol, LNG, LPG, propane, ethane, isobutane, n-butane, CNG.
EDF Fleet Greenhouse Gas Emissions Calculator (*64*)**	(gasoline, diesel, LPG, ethanol, biodiesel, LNG, CNG, electricity) passenger cars, light duty trucks, vans, SUVs, medium and heavy duty vehicles, (gasoline, diesel) ships, boats, other. (diesel) locomotives.	gasoline, diesel, LPG, ethanol, biodiesel, LNG, CNG, electricity.
EPA Climate Leaders: Simplified GHG Emissions Calculator (*38*): Direct Emissions from Mobile Combustion Sources*,***	(gasoline, diesel) passenger cars, light trucks, heavy-duty vehicles, ships, boats. (diesel) locomotives. (*methanol*, CNG, ethanol) buses, light duty vehicles, heavy duty vehicles. (LPG) light duty vehicles, heavy duty vehicles. (LNG) heavy duty vehicles. (residual fuel oil) ships, boats.	motor gasoline, diesel fuel No. 1 and 2, aviation gasoline, jet fuel, residual fuel oil (#5 and 6), crude oil, *B100*, ethanol, *E100*, *methanol*, LNG, LPG, *propane*, *ethane*, *isobutane*, *n-butane*, CNG.

*CH4 and N2O calculations are limited to combinations of vehicles and fuels shown in vehicle type field, where fuels are shown in parentheses, followed by the vehicles available for the fuel type. CO2 calculations are performed for any vehicle shown

** Calculations are limited to combinations of vehicles and fuels shown in vehicle type field, where fuels are shown in parentheses, followed by the vehicles available for the fuel type.

***Fuels shown in italics are not available in the spreadsheet calculator, but are available in calculation guide.

Table 24: Vehicle and Fuel Types Covered by GHG Emissions Calculators (continued) (*1*)

Calculator	Vehicle Types	Fuel Types
TC Urban Transportation Emissions Calculator (*65*)	light-duty passenger vehicles, light-duty commercial vehicles, medium-duty commercial vehicles, heavy-duty commercial vehicles, public transit buses, public transit trolley buses, light rail, subway/metro, heavy rail (diesel-fuelled) commuter rail.	gasoline, diesel, propane, CNG, LNG, E10, E85, M85, ED10, B100, hybrid, plug-in hybrid, electric vehicle, fuel cell.
LEM (*50*)	light-duty passenger cars, battery-powered electric vehicles, fuel-cell vehicles, full-size buses, mini-buses, mini-cars, heavy-rail transit, light-rail transit, medium and heavy-duty trucks, diesel trains.	gasoline, methanol, ethanol, diesel, biodiesels, CNG, LNG. Electricity: coal, petroleum, NG, nuclear, solar, biomass, hydro.
GHGenius 3.15 (*49*)	light duty vehicles, passenger cars, light trucks, heavy duty vehicles, buses, trucks.	gasoline, methanol, ethanol, butanol, petrol diesel, FT diesel, biodiesels, H2, CNG, LNG. Electricity: coal, fuel oil, NG, nuclear, wind, biomass, hydro, other.
EIO-LCA (*52*)	automobile, light truck, heavy duty truck, railroad rolling stock, ships, boats.	petroleum (oil and gas), electricity.
GREET Fuel-Cycle Model 1.8c.0 (*46*)	passenger cars, light duty vehicles 1, light duty vehicles 2.	gasoline, diesel, CARFG, LPG, Crude Naptha, CNG, LNG, Methanol, DME, FTD, Naptha, E5-10, E50-90, E100, gaseous hydrogen, liquid hydrogen, biodiesel. Electricity: residual oil, natural gas, coal, nuclear power, biomass, other. Ethanol: corn, woody biomass, herbaceous biomass, corn stover, forest residue, sugar cane.
GREET Fleet Footprint Calculator 1.0 (*48*)	school bus, transit bus, shuttle/paratransit bus, transport/freight truck, medium/heavy duty pickup truck, other.	gasoline, diesel, biodiesel (B100), corn ethanol (E100), cellulosic ethanol (E100), CNG, LNG, LPG, liquid hydrogen, gaseous hydrogen. Electricity: residual oil, natural gas, coal, nuclear power, biomass, wind/solar/hydro.
GREET Vehicle-Cycle Model 2.7 (*47*)	For both passenger car and SUV (conventional or lightweight materials): internal combustion engine vehicle, hybrid electric vehicle, fuel-cell vehicle.	Process fuels: residual oil, diesel, natural gas, coal, electricity.
Travel Matters, Center for Neighborhood Technology: Transit Planning Calculator (*66*)	Online form: Vehicles reported by transit agency on Form 408 (Revenue Vehicle Inventory Form) for NTD 2002 data report. Spreadsheet: Bus, commuter rail, heavy rail, light rail/trolleybus.	Online form: (bus and van): diesel, B20, biodiesel, CNG, Electro-diesel, ethanol, fuel-cell/natural gas, fuel-cell/electrolysis. (rail electricity): biomass, coal, gas, geothermal, hydro, nuclear, oil, solar, wind, other. Spreadsheet: (bus) diesel, B20, CNG/LNG, Electricity, fuel-cell/electrolysis. (rail) electricity.
U.S. EPA: MOVES (*67*)	intercity bus, light commercial truck, motor home, passenger car, passenger truck, school bus, transit bus. Alternative Vehicle and Fuel Technologies: conventional internal combustion (IC), advanced IC, moderate hybrid - conventional IC, full hybrid - conventional IC, hybrid - advanced IC, moderate hybrid - advanced IC, full hybrid - advanced IC, electric, fuel cell, hybrid - fuel cell.	CNG, diesel fuel, electricity, E85, gasoline, LPG.

APPENDIX B: CALCULATOR WORKSHEETS

	A	B	C	D	E	F	G	H	I	J	K
1						Data Tiers					
2					CO2		N2O, CH4			User	
3	Bus Number(s)	Model	Qty. of Buses	Fuel Type	Activity	Em. Fact.	Activity	Em. Fact.	Biofuel (%)	Fuel Combustion (actual)	Units
4											
5											
6											
7											
8											
9											
10											
11											
12											
13				gasoline	A1/A2/B	A1	A/B	A			gal
14				diesel	C	A2	C	B			barrel
15				biodiesel		B/C		C			DGE
16				kerosene							SCF
17				natural gas							therms
18				CNG							
19				LNG							
20				propane							
21				LPG							
22				ethane							
23				isobutane							
24				n-butane							
25				ethanol (E100)							
26				methanol							
27				butanol							

Figure 25: Calculator worksheet: Bus

	L	M	N	O	P
1		C (CO2)			
2	Std1	Calc		Std2	User
3	fuel quantity	Fuel Combustion (estimated)	Units	fuel quantity	Vehicle Miles (actual)
4	=IF(K4=$K$15,J4*VLOOKUP(D4,DGE_Conv,4,FALSE),IF(K4=$K$14,J4/42,IF(K4=$K$17,IF(NOT(ISBLANK(AA4)),J4*100000/AA4,IF(NOT(ISBLANK(AD4)),J4*100000/AD4,J4*100000/1027)),J4)))	=IF(OR(R4="",R4=0),"",IF(D4=$D$18,P4/(R4/VLOOKUP(D4,DGE_Conv,4,FALSE)),P4/R4))	=IF(M4="","",IF(D4=$D$18,$N$14,$N$13))	=IF(E4=$E$14,M4,L4)	
5	=IF(K5=$K$15,J5*VLOOKUP(D5,DGE_Conv,4,FALSE),IF(K5=$K$14,J5/42,IF(K5=$K$17,IF(NOT(ISBLANK(AA5)),J5*100000/AA5,IF(NOT(ISBLANK(AD5)),J5*100000/AD5,J5*100000/1027)),J5)))	=IF(OR(R5="",R5=0),"",IF(D5=$D$18,P5/(R5/VLOOKUP(D5,DGE_Conv,4,FALSE)),P5/R5))	=IF(M5="","",IF(D5=$D$18,$N$14,$N$13))	=IF(E5=$E$14,M5,L5)	
6	=IF(K6=$K$15,J6*VLOOKUP(D6,DGE_Conv,4,FALSE),IF(K6=$K$14,J6/42,IF(K6=$K$17,IF(NOT(ISBLANK(AA6)),J6*100000/AA6,IF(NOT(ISBLANK(AD6)),J6*100000/AD6,J6*100000/1027)),J6)))	=IF(OR(R6="",R6=0),"",IF(D6=$D$18,P6/(R6/VLOOKUP(D6,DGE_Conv,4,FALSE)),P6/R6))	=IF(M6="","",IF(D6=$D$18,$N$14,$N$13))	=IF(E6=$E$14,M6,L6)	

	Q	R	S	T	U	V
1	C (CH4, N2O)					
2	Calc	User	Calc			
3	Vehicle Miles (estimated)	Fuel Econ. (mpg)	Fuel Econ. (mpg)	Rev. Veh-Hr	Avg. Occ.	PMT
4	=IF(D4=$D$18,(L4/VLOOKUP($D$18,DGE_Conv,4,FALSE))*R4,L4*R4)		=IFERROR(IF(D4=$D$18,P4/(L4/VLOOKUP($D$18,DGE_Conv,4,FALSE)),P4/L4),"")			=U4*MAX(P4,Q4)
5	=IF(D5=$D$18,(L5/VLOOKUP($D$18,DGE_Conv,4,FALSE))*R5,L5*R5)		=IFERROR(IF(D5=$D$18,P5/(L5/VLOOKUP($D$18,DGE_Conv,4,FALSE)),P5/L5),"")			=U5*MAX(P5,Q5)
6	=IF(D6=$D$18,(L6/VLOOKUP($D$18,DGE_Conv,4,FALSE))*R6,L6*R6)		=IFERROR(IF(D6=$D$18,P6/(L6/VLOOKUP($D$18,DGE_Conv,4,FALSE)),P6/L6),"")			=U6*MAX(P6,Q6)
7	=SUM(P4:Q6)	VM		=SUM(T4:T6)	RH	=SUM(V4:V6)
8						
9						
10						=IF(W10=W7,V7,IF(W10=W8,V8,""))

Figure 26: Calculator worksheet: Bus (cont.).

	W	X	Y	Z	AA	AB
1					A1, A2	
2					User	
3	Vehicle Category	Control Technology	Model Year	Vehicle Type	Heat Content (actual)	Units
4						
5						
6						
7	Passenger-Miles (sum)					
8	Passenger-Miles (alternate total)					
9						
10						
11						
12						
13	Gasoline Passenger Cars	EPA Tier 2	Model Years 1984-1993	gasoline		MMBtu/gal
14	Gasoline Light Trucks (Vans, Pickup Trucks, SUVs)	Low Emission Vehicles	Model Year 1994	diesel		MMBtu/barrel
15	Gasoline Heavy-Duty Vehicles	EPA Tier 1	Model Year 1995	methanol		Btu/SCF
16	Diesel Passenger Cars	EPA Tier 0	Model Year 1996	CNG		
17	Diesel Light Trucks	Oxidation Catalyst	Model Year 1997	LPG		
18	Diesel Heavy-Duty Vehicles	Non-Catalyst Control	Model Year 1998	ethanol		
19		Uncontrolled	Model Year 1999			
20			Model Year 2000	gasoline		
21	Light Duty Vehicles	Advanced	Model Year 2001	diesel		
22	Heavy Duty Vehicles	Moderate	Model Year 2002	methanol		
23	Buses	Uncontrolled	Model Year 2003	CNG		
24			Model Year 2004	LNG		
25			Model Year 2005	LPG		
26				ethanol		
27			Model Years 1987-1993			
28			Model Year 1994	gasoline		
29			Model Year 1995	diesel		
30			Model Year 1996	methanol		
31			Model Year 1997	CNG		
32			Model Year 1998	ethanol		
33			Model Year 1999			
34			Model Year 2000			
35			Model Year 2001			
36			Model Year 2002			
37			Model Year 2003			
38			Model Year 2004			
39			Model Year 2005			
40						
41			Model Years 1985-1986			
42			Model Year 1987			
43			Model Years 1988-1989			
44			Model Years 1990-1995			
45			Model Year 1996			
46			Model Year 1997			
47			Model Year 1998			
48			Model Year 1999			
49			Model Year 2000			
50			Model Year 2001			
51			Model Year 2002			
52			Model Year 2003			
53			Model Year 2004			
54			Model Year 2005			
55						
56			Model Years 1960-1982			
57			Model Years 1983-2004			
58						
59			Model Years 1960-1982			
60			Model Years 1983-1995			
61			Model Years 1996-2004			
62						
63			All Model Years			

Figure 27: Calculator worksheet: Bus (cont.).

	AC	AD	AE	AF	AG	AH
1		A2		A1, A2		
2	Std	Default		User		Std
3		Heat Content (default)	Units	Carbon Content (actual)	Units	
4	=IF(AB4=$AB$14,AA4/42,IF(D4=$D$18,AA4/1000000,AA4))	=IF(AND(F4=$F$14,ISBLANK(AA4)),VLOOKUP(D4,CO2_A2_Bus,5,FALSE),"")	=IF(AD4="","",IF(D4=$D$18,$AE$14,$AE$13))			=IF(AG4=$AG$14,AF4*0.4536,AF4)
5	=IF(AB5=$AB$14,AA5/42,IF(D5=$D$18,AA5/1000000,AA5))	=IF(AND(F5=$F$14,ISBLANK(AA5)),VLOOKUP(D5,CO2_A2_Bus,5,FALSE),"")	=IF(AD5="","",IF(D5=$D$18,$AE$14,$AE$13))			=IF(AG5=$AG$14,AF5*0.4536,AF5)
6	=IF(AB6=$AB$14,AA6/42,IF(D6=$D$18,AA6/1000000,AA6))	=IF(AND(F6=$F$14,ISBLANK(AA6)),VLOOKUP(D6,CO2_A2_Bus,5,FALSE),"")	=IF(AD6="","",IF(D6=$D$18,$AE$14,$AE$13))			=IF(AG6=$AG$14,AF6*0.4536,AF6)
7						
8						
9						
10						
11						
12						
13			MMBtu/barrel		kg C/MMBtu	
14			Btu/SCF		lb C/MMBtu	

	AI	AJ	AK	AL	AM	AN	AO
1	A2		A1			A1	
2	Default		User		Std	User	
3	Carbon Content (default)	Units	Carbon Content (actual)	Units		Density (actual)	Units
4	=IF(AND(F4=$F$14,ISBLANK(AF4)),VLOOKUP(D4,CO2_A2_Bus,4,FALSE),"")	=IF(AI4="","",$AJ$13)			=IF(AL4=$AL$14,AK4*0.45359237,AK4)		
5	=IF(AND(F5=$F$14,ISBLANK(AF5)),VLOOKUP(D5,CO2_A2_Bus,4,FALSE),"")	=IF(AI5="","",$AJ$13)			=IF(AL5=$AL$14,AK5*0.45359237,AK5)		
6	=IF(AND(F6=$F$14,ISBLANK(AF6)),VLOOKUP(D6,CO2_A2_Bus,4,FALSE),"")	=IF(AI6="","",$AJ$13)			=IF(AL6=$AL$14,AK6*0.45359237,AK6)		
7							
8							
9							
10							
11							
12							
13		kg C/MMBtu		kg C/kg fuel			kg/gal
14				lb C/lb fuel			lb/gal
15							kg/barrel
16							lb/barrel
17							kg/SCF
18							lb/SCF

Figure 28: Calculator worksheet: Bus (cont.).

	AP	AQ	AR	AS	AT
1		A1		A2	
2	Std	CO2		CO2	
3		CO2 Emission Factor	Units	CO2 Emission Factor	Units
4	AO$14,AN4*0.4536,IF(AO4=$AO$16,AN4*0.4536/42,IF(AO4=$AO$18,AN4*0.4536,AN4))))	=IF(ISBLANK(AA4),AM4*AP4,AC4*AH4)*1*(44/12)	=IF(D4=$D$18,$AR$14,$AR$13)	=$AE$13,AD4/42*AH4,AD4*AH4),AC4*AI4)*1*(44/12)	=IF(D4=$D$18,$AT$14,$AT$13)
5	AO$14,AN5*0.4536,IF(AO5=$AO$16,AN5*0.4536/42,IF(AO5=$AO$18,AN5*0.4536,AN5))))	=IF(ISBLANK(AA5),AM5*AP5,AC5*AH5)*1*(44/12)	=IF(D5=$D$18,$AR$14,$AR$13)	=$AE$13,AD5/42*AH5,AD5*AH5),AC5*AI5)*1*(44/12)	=IF(D5=$D$18,$AT$14,$AT$13)
6	AO$14,AN6*0.4536,IF(AO6=$AO$16,AN6*0.4536/42,IF(AO6=$AO$18,AN6*0.4536,AN6))))	=IF(ISBLANK(AA6),AM6*AP6,AC6*AH6)*1*(44/12)	=IF(D6=$D$18,$AR$14,$AR$13)	=$AE$13,AD6/42*AH6,AD6*AH6),AC6*AI6)*1*(44/12)	=IF(D6=$D$18,$AT$14,$AT$13)
7					
8					
9					
10					
11					
12					
13			kg/gal		kg/gal
14			kg/SCF		kg/SCF

	AU	AV	AW	AX
1	B/C		Direct	
2	CO2		CO2	
3	CO2 Emission Factor	Units	Emission Factor	Units
4	=VLOOKUP(D4,CO2_B_C_Bus,4,FALSE)	=IF(D4=$D$18,$AV$14,$AV$13)	=IF(F4=$F$13,AQ4,IF(F4=$F$14,AS4,AU4))	=IF(F4=$F$13,AR4,IF(F4=$F$14,AT4,AV4))
5	=VLOOKUP(D5,CO2_B_C_Bus,4,FALSE)	=IF(D5=$D$18,$AV$14,$AV$13)	=IF(F5=$F$13,AQ5,IF(F5=$F$14,AS5,AU5))	=IF(F5=$F$13,AR5,IF(F5=$F$14,AT5,AV5))
6	=VLOOKUP(D6,CO2_B_C_Bus,4,FALSE)	=IF(D6=$D$18,$AV$14,$AV$13)	=IF(F6=$F$13,AQ6,IF(F6=$F$14,AS6,AU6))	=IF(F6=$F$13,AR6,IF(F6=$F$14,AT6,AV6))
7				
8				
9				
10				
11				
12				
13		kg/gal		
14		kg/SCF		

Figure 29: Calculator worksheet: Bus (cont.).

	AY
1	A
2	N2O
3	Emission Factor (g/mi.)
4	=IF(W4=$W$13,VLOOKUP(X4,N2O_CH4_A_gas_pax_car,2,FALSE),IF(W4=$W$14,VLOOKUP(X4,N2O_CH4_A_gas_light_truck,2,FALSE),IF(W4=$W$15,VLOOKUP(X4,N2O_CH4_A_gas_heavy_duty,2,FALSE),IF(W4=$W$16,VLOOKUP(X4,N2O_CH4_A_diesel_pax_car,2,FALSE),IF(W4=$W$17,VLOOKUP(X4,N2O_CH4_A_diesel_light_truck,2,FALSE),IF(W4=$W$18,VLOOKUP(X4,N2O_CH4_A_diesel_heavy_duty,2,FALSE),""))))))
5	=IF(W5=$W$13,VLOOKUP(X5,N2O_CH4_A_gas_pax_car,2,FALSE),IF(W5=$W$14,VLOOKUP(X5,N2O_CH4_A_gas_light_truck,2,FALSE),IF(W5=$W$15,VLOOKUP(X5,N2O_CH4_A_gas_heavy_duty,2,FALSE),IF(W5=$W$16,VLOOKUP(X5,N2O_CH4_A_diesel_pax_car,2,FALSE),IF(W5=$W$17,VLOOKUP(X5,N2O_CH4_A_diesel_light_truck,2,FALSE),IF(W5=$W$18,VLOOKUP(X5,N2O_CH4_A_diesel_heavy_duty,2,FALSE),""))))))
6	=IF(W6=$W$13,VLOOKUP(X6,N2O_CH4_A_gas_pax_car,2,FALSE),IF(W6=$W$14,VLOOKUP(X6,N2O_CH4_A_gas_light_truck,2,FALSE),IF(W6=$W$15,VLOOKUP(X6,N2O_CH4_A_gas_heavy_duty,2,FALSE),IF(W6=$W$16,VLOOKUP(X6,N2O_CH4_A_diesel_pax_car,2,FALSE),IF(W6=$W$17,VLOOKUP(X6,N2O_CH4_A_diesel_light_truck,2,FALSE),IF(W6=$W$18,VLOOKUP(X6,N2O_CH4_A_diesel_heavy_duty,2,FALSE),""))))))

	AZ
1	A
2	CH4
3	Emission Factor (g/mi.)
4	=IF(W4=$W$13,VLOOKUP(X4,N2O_CH4_A_gas_pax_car,3,FALSE),IF(W4=$W$14,VLOOKUP(X4,N2O_CH4_A_gas_light_truck,3,FALSE),IF(W4=$W$15,VLOOKUP(X4,N2O_CH4_A_gas_heavy_duty,3,FALSE),IF(W4=$W$16,VLOOKUP(X4,N2O_CH4_A_diesel_pax_car,3,FALSE),IF(W4=$W$17,VLOOKUP(X4,N2O_CH4_A_diesel_light_truck,3,FALSE),IF(W4=$W$18,VLOOKUP(X4,N2O_CH4_A_diesel_heavy_duty,3,FALSE),""))))))
5	=IF(W5=$W$13,VLOOKUP(X5,N2O_CH4_A_gas_pax_car,3,FALSE),IF(W5=$W$14,VLOOKUP(X5,N2O_CH4_A_gas_light_truck,3,FALSE),IF(W5=$W$15,VLOOKUP(X5,N2O_CH4_A_gas_heavy_duty,3,FALSE),IF(W5=$W$16,VLOOKUP(X5,N2O_CH4_A_diesel_pax_car,3,FALSE),IF(W5=$W$17,VLOOKUP(X5,N2O_CH4_A_diesel_light_truck,3,FALSE),IF(W5=$W$18,VLOOKUP(X5,N2O_CH4_A_diesel_heavy_duty,3,FALSE),""))))))
6	=IF(W6=$W$13,VLOOKUP(X6,N2O_CH4_A_gas_pax_car,3,FALSE),IF(W6=$W$14,VLOOKUP(X6,N2O_CH4_A_gas_light_truck,3,FALSE),IF(W6=$W$15,VLOOKUP(X6,N2O_CH4_A_gas_heavy_duty,3,FALSE),IF(W6=$W$16,VLOOKUP(X6,N2O_CH4_A_diesel_pax_car,3,FALSE),IF(W6=$W$17,VLOOKUP(X6,N2O_CH4_A_diesel_light_truck,3,FALSE),IF(W6=$W$18,VLOOKUP(X6,N2O_CH4_A_diesel_heavy_duty,3,FALSE),""))))))

	BA
1	B
2	N2O
3	Emission Factor (g/mi.)
4	=IF(W4=$W$13,VLOOKUP(Y4,N2O_CH4_B_gas_pax_car,2,FALSE),IF(W4=$W$14,VLOOKUP(Y4,N2O_CH4_B_gas_light_truck,2,FALSE),IF(W4=$W$15,VLOOKUP(Y4,N2O_CH4_B_gas_heavy_duty,2,FALSE),IF(W4=$W$16,VLOOKUP(Y4,N2O_CH4_B_diesel_pax_car,2,FALSE),IF(W4=$W$17,VLOOKUP(Y4,N2O_CH4_B_diesel_light_truck,2,FALSE),IF(W4=$W$18,VLOOKUP(Y4,N2O_CH4_B_diesel_heavy_duty,2,FALSE),""))))))
5	=IF(W5=$W$13,VLOOKUP(Y5,N2O_CH4_B_gas_pax_car,2,FALSE),IF(W5=$W$14,VLOOKUP(Y5,N2O_CH4_B_gas_light_truck,2,FALSE),IF(W5=$W$15,VLOOKUP(Y5,N2O_CH4_B_gas_heavy_duty,2,FALSE),IF(W5=$W$16,VLOOKUP(Y5,N2O_CH4_B_diesel_pax_car,2,FALSE),IF(W5=$W$17,VLOOKUP(Y5,N2O_CH4_B_diesel_light_truck,2,FALSE),IF(W5=$W$18,VLOOKUP(Y5,N2O_CH4_B_diesel_heavy_duty,2,FALSE),""))))))
6	=IF(W6=$W$13,VLOOKUP(Y6,N2O_CH4_B_gas_pax_car,2,FALSE),IF(W6=$W$14,VLOOKUP(Y6,N2O_CH4_B_gas_light_truck,2,FALSE),IF(W6=$W$15,VLOOKUP(Y6,N2O_CH4_B_gas_heavy_duty,2,FALSE),IF(W6=$W$16,VLOOKUP(Y6,N2O_CH4_B_diesel_pax_car,2,FALSE),IF(W6=$W$17,VLOOKUP(Y6,N2O_CH4_B_diesel_light_truck,2,FALSE),IF(W6=$W$18,VLOOKUP(Y6,N2O_CH4_B_diesel_heavy_duty,2,FALSE),""))))))

Figure 30: Calculator worksheet: Bus (cont.).

	BB
1	B
2	CH4
3	Emission Factor (g/mi.)
4	=IF(W4=$W$13,VLOOKUP(Y4,N2O_CH4_B_gas_pax_car,3,FALSE),IF(W4=$W$14,VLOOKUP(Y4,N2O_CH4_B_gas_light_truck,3,FALSE),IF(W4=$W$15,VLOOKUP(Y4,N2O_CH4_B_gas_heavy_duty,3,FALSE),IF(W4=$W$16,VLOOKUP(Y4,N2O_CH4_B_diesel_pax_car,3,FALSE),IF(W4=$W$17,VLOOKUP(Y4,N2O_CH4_B_diesel_light_truck,3,FALSE),IF(W4=$W$18,VLOOKUP(Y4,N2O_CH4_B_diesel_heavy_duty,3,FALSE),""))))))
5	=IF(W5=$W$13,VLOOKUP(Y5,N2O_CH4_B_gas_pax_car,3,FALSE),IF(W5=$W$14,VLOOKUP(Y5,N2O_CH4_B_gas_light_truck,3,FALSE),IF(W5=$W$15,VLOOKUP(Y5,N2O_CH4_B_gas_heavy_duty,3,FALSE),IF(W5=$W$16,VLOOKUP(Y5,N2O_CH4_B_diesel_pax_car,3,FALSE),IF(W5=$W$17,VLOOKUP(Y5,N2O_CH4_B_diesel_light_truck,3,FALSE),IF(W5=$W$18,VLOOKUP(Y5,N2O_CH4_B_diesel_heavy_duty,3,FALSE),""))))))
6	=IF(W6=$W$13,VLOOKUP(Y6,N2O_CH4_B_gas_pax_car,3,FALSE),IF(W6=$W$14,VLOOKUP(Y6,N2O_CH4_B_gas_light_truck,3,FALSE),IF(W6=$W$15,VLOOKUP(Y6,N2O_CH4_B_gas_heavy_duty,3,FALSE),IF(W6=$W$16,VLOOKUP(Y6,N2O_CH4_B_diesel_pax_car,3,FALSE),IF(W6=$W$17,VLOOKUP(Y6,N2O_CH4_B_diesel_light_truck,3,FALSE),IF(W6=$W$18,VLOOKUP(Y6,N2O_CH4_B_diesel_heavy_duty,3,FALSE),""))))))

	BC	BD
1	C	C
2	N2O	CH4
3	Emission Factor (g/mi.)	Emission Factor (g/mi.)
4	=IF(W4=$W$21,VLOOKUP(Z4,N2O_CH4_C_light_duty_veh,2,FALSE),IF(W4=$W$22,VLOOKUP(Z4,N2O_CH4_C_heavy_duty_veh,2,FALSE),IF(W4=$W$23,VLOOKUP(Z4,N2O_CH4_C_bus,2,FALSE),"")))	=IF(W4=$W$21,VLOOKUP(Z4,N2O_CH4_C_light_duty_veh,3,FALSE),IF(W4=$W$22,VLOOKUP(Z4,N2O_CH4_C_heavy_duty_veh,3,FALSE),IF(W4=$W$23,VLOOKUP(Z4,N2O_CH4_C_bus,3,FALSE),"")))
5	=IF(W5=$W$21,VLOOKUP(Z5,N2O_CH4_C_light_duty_veh,2,FALSE),IF(W5=$W$22,VLOOKUP(Z5,N2O_CH4_C_heavy_duty_veh,2,FALSE),IF(W5=$W$23,VLOOKUP(Z5,N2O_CH4_C_bus,2,FALSE),"")))	=IF(W5=$W$21,VLOOKUP(Z5,N2O_CH4_C_light_duty_veh,3,FALSE),IF(W5=$W$22,VLOOKUP(Z5,N2O_CH4_C_heavy_duty_veh,3,FALSE),IF(W5=$W$23,VLOOKUP(Z5,N2O_CH4_C_bus,3,FALSE),"")))
6	=IF(W6=$W$21,VLOOKUP(Z6,N2O_CH4_C_light_duty_veh,2,FALSE),IF(W6=$W$22,VLOOKUP(Z6,N2O_CH4_C_heavy_duty_veh,2,FALSE),IF(W6=$W$23,VLOOKUP(Z6,N2O_CH4_C_bus,2,FALSE),"")))	=IF(W6=$W$21,VLOOKUP(Z6,N2O_CH4_C_light_duty_veh,3,FALSE),IF(W6=$W$22,VLOOKUP(Z6,N2O_CH4_C_heavy_duty_veh,3,FALSE),IF(W6=$W$23,VLOOKUP(Z6,N2O_CH4_C_bus,3,FALSE),"")))

	BE	BF	BG	BH	BI	BJ	BK	BL
1			A1, A2, B Activity	C Activity	A, B Activity	C Activity	A, B Activity	C Activity
2	N2O	CH4	Direct	Direct	Direct	Direct	Direct	Direct
3	Emission Factor (g/mi.)	Emission Factor (g/mi.)	CO2 (kg)	CO2 (kg)	N2O (g)	N2O (g)	CH4 (g)	CH4 (g)
4	=IF(H4=$H$13,AY4,IF(H4=$H$14,BA4,BC4))	=IF(H4=$H$13,AZ4,IF(H4=$H$14,BB4,BD4))	=L4*AW4	=M4*AW4	=P4*BE4	=Q4*BE4	=P4*BF4	=Q4*BF4
5	=IF(H5=$H$13,AY5,IF(H5=$H$14,BA5,BC5))	=IF(H5=$H$13,AZ5,IF(H5=$H$14,BB5,BD5))	=L5*AW5	=M5*AW5	=P5*BE5	=Q5*BE5	=P5*BF5	=Q5*BF5
6	=IF(H6=$H$13,AY6,IF(H6=$H$14,BA6,BC6))	=IF(H6=$H$13,AZ6,IF(H6=$H$14,BB6,BD6))	=L6*AW6	=M6*AW6	=P6*BE6	=Q6*BE6	=P6*BF6	=Q6*BF6

Figure 31: Calculator worksheet: Bus (cont.).

	BM	BN	BO	BP	BQ	BR	BS	BT
1								
2	Scope 1 Emissions						Total	
3	CO2		N2O		CH4		CO2e	
4	**=IFERROR(IF(E4=$E$14,BH4,BG4),"0")*(1-I4)**	kg	**=IFERROR(IF(G4=$G$14,BJ4,BI4),"0")*(1-I4)**	g	**=IFERROR(IF(G4=$G$14,BL4,BK4),"0")*(1-I4)**	g	**=(BM4/1000)+(BO4*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000000)+(BQ4*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000000)**	tonnes
5	**=IFERROR(IF(E5=$E$14,BH5,BG5),"0")*(1-I5)**	kg	**=IFERROR(IF(G5=$G$14,BJ5,BI5),"0")*(1-I5)**	g	**=IFERROR(IF(G5=$G$14,BL5,BK5),"0")*(1-I5)**	g	**=(BM5/1000)+(BO5*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000000)+(BQ5*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000000)**	tonnes
6	**=IFERROR(IF(E6=$E$14,BH6,BG6),"0")*(1-I6)**	kg	**=IFERROR(IF(G6=$G$14,BJ6,BI6),"0")*(1-I6)**	g	**=IFERROR(IF(G6=$G$14,BL6,BK6),"0")*(1-I6)**	g	**=(BM6/1000)+(BO6*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000000)+(BQ6*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000000)**	tonnes
7	**=SUM(BM4:BM6)**	kg	**=SUM(BO4:BO6)**	g	**=SUM(BQ4:BQ6)**	g	**=(BM7/1000)+(BO7*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000000)+(BQ7*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000000)**	tonnes

	BU	BV	BW
1	Fuel-Cycle	GREET V1.8c	
2	CO2	N2O	CH4
3	Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)
4	=VLOOKUP(D4,IF($BV$1=$BV$13,fuel_upstream_em_fact_GREET,fuel_upstream_em_fact_GHGenius),4,FALSE)	=VLOOKUP(D4,IF($BV$1=$BV$13,fuel_upstream_em_fact_GREET,fuel_upstream_em_fact_GHGenius),6,FALSE)	=VLOOKUP(D4,IF($BV$1=$BV$13,fuel_upstream_em_fact_GREET,fuel_upstream_em_fact_GHGenius),5,FALSE)
5	=VLOOKUP(D5,IF($BV$1=$BV$13,fuel_upstream_em_fact_GREET,fuel_upstream_em_fact_GHGenius),4,FALSE)	=VLOOKUP(D5,IF($BV$1=$BV$13,fuel_upstream_em_fact_GREET,fuel_upstream_em_fact_GHGenius),6,FALSE)	=VLOOKUP(D5,IF($BV$1=$BV$13,fuel_upstream_em_fact_GREET,fuel_upstream_em_fact_GHGenius),5,FALSE)
6	=VLOOKUP(D6,IF($BV$1=$BV$13,fuel_upstream_em_fact_GREET,fuel_upstream_em_fact_GHGenius),4,FALSE)	=VLOOKUP(D6,IF($BV$1=$BV$13,fuel_upstream_em_fact_GREET,fuel_upstream_em_fact_GHGenius),6,FALSE)	=VLOOKUP(D6,IF($BV$1=$BV$13,fuel_upstream_em_fact_GREET,fuel_upstream_em_fact_GHGenius),5,FALSE)

	BX	BY
1	Include Fuel-Cycle?	
2	Scope 3 Emissions: Fuel-Cycle	
3	CO2	
4	**=IF($BZ$1=$BZ$13,IFERROR(IF(D4=$D$18,IF(ISBLANK(AA4)=FALSE,O4*AC4,O4*1027/1000000)*BU4,O4*(VLOOKUP(D4,fuel_upstream_em_fact_GREET,3,FALSE)/1000000)*BU4)/1000,"0"),0)**	kg
5	**=IF($BZ$1=$BZ$13,IFERROR(IF(D5=$D$18,IF(ISBLANK(AA5)=FALSE,O5*AC5,O5*1027/1000000)*BU5,O5*(VLOOKUP(D5,fuel_upstream_em_fact_GREET,3,FALSE)/1000000)*BU5)/1000,"0"),0)**	kg
6	**=IF($BZ$1=$BZ$13,IFERROR(IF(D6=$D$18,IF(ISBLANK(AA6)=FALSE,O6*AC6,O6*1027/1000000)*BU6,O6*(VLOOKUP(D6,fuel_upstream_em_fact_GREET,3,FALSE)/1000000)*BU6)/1000,"0"),0)**	kg
7	**=SUM(BX4:BX6)**	kg

Figure 32: Calculator worksheet: Bus (cont.).

	BZ	CA
1	YES	
2		
3	N2O	
4	=IF($BZ$1=$BZ$13,IFERROR(IF(D4=$D$18,IF(ISBLANK(AA4)=FALSE,O4*AC4,O4*1027/1000000)*BV4,O4*(VLOOKUP(D4,fuel_upstream_em_fact_GREET,3,FALSE)/1000000)*BV4)/1000,"0"),0)	kg
5	=IF($BZ$1=$BZ$13,IFERROR(IF(D5=$D$18,IF(ISBLANK(AA5)=FALSE,O5*AC5,O5*1027/1000000)*BV5,O5*(VLOOKUP(D5,fuel_upstream_em_fact_GREET,3,FALSE)/1000000)*BV5)/1000,"0"),0)	kg
6	=IF($BZ$1=$BZ$13,IFERROR(IF(D6=$D$18,IF(ISBLANK(AA6)=FALSE,O6*AC6,O6*1027/1000000)*BV6,O6*(VLOOKUP(D6,fuel_upstream_em_fact_GREET,3,FALSE)/1000000)*BV6)/1000,"0"),0)	kg
7	=SUM(BZ4:BZ6)	kg
8		
9		
10		
11		
12		
13	YES	
14	NO	

	CB
1	
2	
3	CH4
4	=IF($BZ$1=$BZ$13,IFERROR(IF(D4=$D$18,IF(ISBLANK(AA4)=FALSE,O4*AC4,O4*1027/1000000)*BW4,O4*(VLOOKUP(D4,fuel_upstream_em_fact_GREET,3,FALSE)/1000000)*BW4)/1000,"0"),0)
5	=IF($BZ$1=$BZ$13,IFERROR(IF(D5=$D$18,IF(ISBLANK(AA5)=FALSE,O5*AC5,O5*1027/1000000)*BW5,O5*(VLOOKUP(D5,fuel_upstream_em_fact_GREET,3,FALSE)/1000000)*BW5)/1000,"0"),0)
6	=IF($BZ$1=$BZ$13,IFERROR(IF(D6=$D$18,IF(ISBLANK(AA6)=FALSE,O6*AC6,O6*1027/1000000)*BW6,O6*(VLOOKUP(D6,fuel_upstream_em_fact_GREET,3,FALSE)/1000000)*BW6)/1000,"0"),0)
7	=SUM(CB4:CB6)

Figure 33: Calculator worksheet: Bus (cont.).

	CD	CE	CF
1			
2			
3	CO2e		EIO-LCA Sector / Vehicle Type
4	**=(BX4/1000)+(BZ4*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CB4* VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes	
5	**=(BX5/1000)+(BZ5*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CB5* VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes	
6	**=(BX6/1000)+(BZ6*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CB6* VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes	
7	**=(BX7/1000)+(BZ7*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CB7* VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes	
8			
9			
10			
11			
12			
13			Heavy duty
14			Light truck/utility

	CG	CH	CI	CJ
1	Manufacturing			Maintenance
2	CO2	N2O	CH4	CO2
3	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)
4	=IF(CF4=$CF$13,'EIO-LCA_factors'!$D$5,IF(CF4=$CF$14,'EIO-LCA_factors'!$V$5,0))	=IF(CF4=$CF$13,'EIO-LCA_factors'!$G$5,IF(CF4=$CF$14,'EIO-LCA_factors'!$Y$5,0))/VLOOKUP(background!$I$12,GWP,4,FALSE)	=IF(CF4=$CF$13,'EIO-LCA_factors'!$F$5,IF(CF4=$CF$14,'EIO-LCA_factors'!$X$5,0))/VLOOKUP(background!$I$12,GWP,3,FALSE)	=IF(ISBLANK(CF4),0,'EIO-LCA_factors'!$AN$5)
5	=IF(CF5=$CF$13,'EIO-LCA_factors'!$D$5,IF(CF5=$CF$14,'EIO-LCA_factors'!$V$5,0))	=IF(CF5=$CF$13,'EIO-LCA_factors'!$G$5,IF(CF5=$CF$14,'EIO-LCA_factors'!$Y$5,0))/VLOOKUP(background!$I$12,GWP,4,FALSE)	=IF(CF5=$CF$13,'EIO-LCA_factors'!$F$5,IF(CF5=$CF$14,'EIO-LCA_factors'!$X$5,0))/VLOOKUP(background!$I$12,GWP,3,FALSE)	=IF(ISBLANK(CF5),0,'EIO-LCA_factors'!$AN$5)
6	=IF(CF6=$CF$13,'EIO-LCA_factors'!$D$5,IF(CF6=$CF$14,'EIO-LCA_factors'!$V$5,0))	=IF(CF6=$CF$13,'EIO-LCA_factors'!$G$5,IF(CF6=$CF$14,'EIO-LCA_factors'!$Y$5,0))/VLOOKUP(background!$I$12,GWP,4,FALSE)	=IF(CF6=$CF$13,'EIO-LCA_factors'!$F$5,IF(CF6=$CF$14,'EIO-LCA_factors'!$X$5,0))/VLOOKUP(background!$I$12,GWP,3,FALSE)	=IF(ISBLANK(CF6),0,'EIO-LCA_factors'!$AN$5)

Figure 34: Calculator worksheet: Bus (cont.).

	CK	CL	CM	CN
1			Include Veh.-Cycle?	
2	N2O	CH4	Scope 3 Emissions: Vehicle-Cycle	
3	Em. Fact. (kg/$)	Em. Fact. (kg/$)	CO2	
4	=IF(ISBLANK(CF4),0,'EIO-LCA_factors'!$AQ$5)/VLOOKUP(background!$I$12,GWP,4,FALSE)	=IF(ISBLANK(CF4),0,'EIO-LCA_factors'!$AP$5)/VLOOKUP(background!$I$12,GWP,3,FALSE)	**=IFERROR(IF($CO$1=$BZ$13,DC4*CG4+CJ4*DD4,0),"0")** kg	
5	=IF(ISBLANK(CF5),0,'EIO-LCA_factors'!$AQ$5)/VLOOKUP(background!$I$12,GWP,4,FALSE)	=IF(ISBLANK(CF5),0,'EIO-LCA_factors'!$AP$5)/VLOOKUP(background!$I$12,GWP,3,FALSE)	**=IFERROR(IF($CO$1=$BZ$13,DC5*CG5+CJ5*DD5,0),"0")** kg	
6	=IF(ISBLANK(CF6),0,'EIO-LCA_factors'!$AQ$5)/VLOOKUP(background!$I$12,GWP,4,FALSE)	=IF(ISBLANK(CF6),0,'EIO-LCA_factors'!$AP$5)/VLOOKUP(background!$I$12,GWP,3,FALSE)	**=IFERROR(IF($CO$1=$BZ$13,DC6*CG6+CJ6*DD6,0),"0")** kg	
7			**=SUM(CM4:CM6)** kg	

	CO	CP	CQ	CR	CS	CT
1	YES					
2						
3	N2O		CH4		CO2e	
4	**=IFERROR(IF($CO$1=$BZ$13,(DC4*CH4+CK4*DD4),0),"0")**	kg	**=IFERROR(IF($CO$1=$BZ$13,(DC4*CI4+CL4*DD4),0),"0")**	kg	**=(CM4/1000)+(CO4*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CQ4*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes
5	**=IFERROR(IF($CO$1=$BZ$13,(DC5*CH5+CK5*DD5),0),"0")**	kg	**=IFERROR(IF($CO$1=$BZ$13,(DC5*CI5+CL5*DD5),0),"0")**	kg	**=(CM5/1000)+(CO5*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CQ5*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes
6	**=IFERROR(IF($CO$1=$BZ$13,(DC6*CH6+CK6*DD6),0),"0")**	kg	**=IFERROR(IF($CO$1=$BZ$13,(DC6*CI6+CL6*DD6),0),"0")**	kg	**=(CM6/1000)+(CO6*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CQ6*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes
7	**=SUM(CO4:CO6)**	kg	**=SUM(CQ4:CQ6)**	kg	**=(CM7/1000)+(CO7*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CQ7*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes

	CU	CV	CW	CX	CY	CZ
1						
2	Scope 3 Emissions: Total					
3	CO2		N2O		CH4	
4	**=BX4+CM4**	kg	**=BZ4+CO4**	kg	**=CB4+CQ4**	kg
5	**=BX5+CM5**	kg	**=BZ5+CO5**	kg	**=CB5+CQ5**	kg
6	**=BX6+CM6**	kg	**=BZ6+CO6**	kg	**=CB6+CQ6**	kg
7	**=SUM(CU4:CU6)**	kg	**=SUM(CW4:CW6)**	kg	**=SUM(CY4:CY6)**	kg

Figure 35: Calculator worksheet: Bus (cont.).

	DA	DB	DC	DD
1				
2				
3	CO2e		Vehicle Capital Cost ($)	Vehicle Maint. Cost ($)
4	**=(CU4/1000)+(CW4*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CY4*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes	=IFERROR(HLOOKUP(DE4,Cost_vehicle,73,FALSE)*C4,0)	=IFERROR(HLOOKUP(DE4,Cost_vehicle,71,FALSE)*C4+HLOOKUP(DE4,Cost_vehicle,72,FALSE)*MAX(P4,Q4),0)
5	**=(CU5/1000)+(CW5*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CY5*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes	=IFERROR(HLOOKUP(DE5,Cost_vehicle,73,FALSE)*C5,0)	=IFERROR(HLOOKUP(DE5,Cost_vehicle,71,FALSE)*C5+HLOOKUP(DE5,Cost_vehicle,72,FALSE)*MAX(P5,Q5),0)
6	**=(CU6/1000)+(CW6*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CY6*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes	=IFERROR(HLOOKUP(DE6,Cost_vehicle,73,FALSE)*C6,0)	=IFERROR(HLOOKUP(DE6,Cost_vehicle,71,FALSE)*C6+HLOOKUP(DE6,Cost_vehicle,72,FALSE)*MAX(P6,Q6),0)
7	**=(CU7/1000)+(CW7*VLOOKUP(background!$I$12,GWP,4,FALSE)/1000)+(CY7*VLOOKUP(background!$I$12,GWP,3,FALSE)/1000)**	tonnes		

	DE	DF	DG
1			
2			
3	Cost ID	Cost-Eff. Baseline?	Cost ($/mile)
4			=IFERROR(HLOOKUP(DE4,Cost_vehicle,66,FALSE)+((HLOOKUP(DE4,Cost_vehicle,65,FALSE)+HLOOKUP(DE4,Cost_vehicle,69,FALSE))*C4+(O4*HLOOKUP(DE4,Cost_vehicle,67,FALSE)))/MAX(P4,Q4),"")
5			=IFERROR(HLOOKUP(DE5,Cost_vehicle,66,FALSE)+((HLOOKUP(DE5,Cost_vehicle,65,FALSE)+HLOOKUP(DE5,Cost_vehicle,69,FALSE))*C5+(O5*HLOOKUP(DE5,Cost_vehicle,67,FALSE)))/MAX(P5,Q5),"")
6			=IFERROR(HLOOKUP(DE6,Cost_vehicle,66,FALSE)+((HLOOKUP(DE6,Cost_vehicle,65,FALSE)+HLOOKUP(DE6,Cost_vehicle,69,FALSE))*C6+(O6*HLOOKUP(DE6,Cost_vehicle,67,FALSE)))/MAX(P6,Q6),"")

Figure 36: Calculator worksheet: Bus (cont.).

	DH	DI
1	Scope	
2	1	
3	CO2e Emiss. Rate (g/mile)	Cost-Eff. ($/tonne)
4	=IFERROR(IF($DH$2=$DH$13,BS4,IF($DH$2=$DH$14,BS4+DA4,0))/MAX(P4,Q4)*1000000,"")	=IFERROR(IF((DH4-VLOOKUP($DF$13,Cost_Baseline,3,FALSE))>0,"GHG Increase",((DG4-VLOOKUP($DF$13,Cost_Baseline,2,FALSE))/(VLOOKUP($DF$13,Cost_Baseline,3,FALSE)-DH4))*1000000),"")
5	=IFERROR(IF($DH$2=$DH$13,BS5,IF($DH$2=$DH$14,BS5+DA5,0))/MAX(P5,Q5)*1000000,"")	=IFERROR(IF((DH5-VLOOKUP($DF$13,Cost_Baseline,3,FALSE))>0,"GHG Increase",((DG5-VLOOKUP($DF$13,Cost_Baseline,2,FALSE))/(VLOOKUP($DF$13,Cost_Baseline,3,FALSE)-DH5))*1000000),"")
6	=IFERROR(IF($DH$2=$DH$13,BS6,IF($DH$2=$DH$14,BS6+DA6,0))/MAX(P6,Q6)*1000000,"")	=IFERROR(IF((DH6-VLOOKUP($DF$13,Cost_Baseline,3,FALSE))>0,"GHG Increase",((DG6-VLOOKUP($DF$13,Cost_Baseline,2,FALSE))/(VLOOKUP($DF$13,Cost_Baseline,3,FALSE)-DH6))*1000000),"")

Figure 37: Calculator worksheet: Bus (cont.).

APPENDIX C: CALCULATOR DATA TABLES

Table 25: U.S. Default CO_2 Emission Factors for Transport Fuels. Based on (*6*)

	Tier A2				**Tier B/C**		
Fuel	**Carbon Content**		**Heat Content**		**Emission Factor**		**Source**
biodiesel (B100)	NA		NA		9.46	kg CO2 / gal	(1)
CNG	14.47	kg C / MMBtu	1027	MMBtu/SCF	0.054	kg CO2 / SCF	(1)
diesel	19.95	kg C / MMBtu	5.825	MMBtu/barrel	10.15	kg CO2 / gal	(2)
ethane	16.25	kg C / MMBtu	2.916	MMBtu/barrel	4.14	kg CO2 / gal	(3)
ethanol (E100)	17.99	kg C / MMBtu	3.539	MMBtu/barrel	5.56	kg CO2 / gal	(1)
gasoline	19.33	kg C / MMBtu	5.218	MMBtu/barrel	8.81	kg CO2 / gal	(3)
isobutane	17.75	kg C / MMBtu	4.162	MMBtu/barrel	6.45	kg CO2 / gal	(3)
kerosene	19.72	kg C / MMBtu	5.67	MMBtu/barrel	9.76	kg CO2 / gal	(2)
LNG	NA	kg C / MMBtu	NA		4.46	kg CO2 / gal	(1)
LPG	17.23	kg C / MMBtu	3.849	MMBtu/barrel	5.79	kg CO2 / gal	(1)
methanol	NA	kg C / MMBtu	NA		4.1	kg CO2 / gal	(4)
n-butane	17.72	kg C / MMBtu	4.328	MMBtu/barrel	6.7	kg CO2 / gal	(3)
propane	17.2	kg C / MMBtu	3.824	MMBtu/barrel	5.74	kg CO2 / gal	(3)
Source:	(1) TCR GRP Table 13.1: EPA Climate Leaders, Mobile Combustion Guidance, 2007 (2) TCR GRP Table 13.1: U.S. EPA, Inventory of Greenhouse Gas Emissions and Sinks: 1990-005 (2007), Annex 2.1, Tables A-31, A-34, A-36, A-40 (3) TCR GRP Table 13.1: U.S. EPA, Inventory of Greenhouse Gas Emissions and Sinks: 1990-005 (2007), Annex 2.1, Tables A-31, A-34, A-36, A-39 (4) TCR GRP Table 13.1: California Climate Action Registry General Reporting Protocol Version 2.2, 2007, Table C.3						

Table 26: Tier A Default CH_4 and N_2O Emission Factors for Highway Vehicles by Vehicle Type and Control Technology. Based on (*6*)

Gasoline Passenger Cars	**N2O (g/mi)**	**CH4 (g/mi)**	**Gasoline Heavy-Duty Vehicles**	**N2O (g/mi)**	**CH4 (g/mi)**
EPA Tier 2	0.0036	0.0173	EPA Tier 2	0.0134	0.0333
Low Emission Vehicles	0.015	0.0105	Low Emission Vehicles	0.032	0.0303
EPA Tier 1	0.0429	0.0271	EPA Tier 1	0.175	0.0655
EPA Tier 0	0.0647	0.0704	EPA Tier 0	0.2135	0.263
Oxidation Catalyst	0.0504	0.1355	Oxidation Catalyst	0.1317	0.2356
Non-Catalyst Control	0.0197	0.1696	Non-Catalyst Control	0.0473	0.4181
Uncontrolled	0.0197	0.178	Uncontrolled	0.0497	0.4604
Gasoline Light Trucks (Vans, Pickup Trucks, SUVs)	**N2O (g/mi)**	**CH4 (g/mi)**	**Diesel Heavy-Duty Vehicles**	N2O (g/mi)	CH4 (g/mi)
EPA Tier 2	0.0066	0.0163	Advanced	0.0048	0.0051
Low Emission Vehicles	0.0157	0.0148	Moderate	0.0048	0.0051
EPA Tier 1	0.0871	0.0452	Uncontrolled	0.0048	0.0051
EPA Tier 0	0.1056	0.0776	**Diesel Light Trucks**	**N2O (g/mi)**	**CH4 (g/mi)**
Oxidation Catalyst	0.0639	0.1516	Advanced	0.0015	0.001
Non-Catalyst Control	0.0218	0.1908	Moderate	0.0014	0.0009
Uncontrolled	0.022	0.2024	Uncontrolled	0.0017	0.0011
Diesel Passenger Cars	**N2O (g/mi)**	**CH4 (g/mi)**	Source: TCR GRP Table 13.3: U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005 (2007), Annex 3.2, Table A-99.		
Advanced	0.001	0.0005			
Moderate	0.001	0.0005			
Uncontrolled	0.0012	0.0006			

Table 27: Tier B Default CH_4 and N_2O Emission Factors for Highway Vehicles by Vehicle Type and Model Year. Based on (*6*)

Gasoline Passenger Cars	**N2O (g/mi)**	**CH4 (g/mi)**	**Gasoline Light Trucks (Vans, Pickup Trucks, SUVs)**	**N2O (g/mi)**	**CH4 (g/mi)**
Model Years 1984-1993	0.0647	0.0704	Model Years 1987-1993	0.1035	0.0813
Model Year 1994	0.056	0.0531	Model Year 1994	0.0982	0.0646
Model Year 1995	0.0473	0.0358	Model Year 1995	0.0908	0.0517
Model Year 1996	0.0426	0.0272	Model Year 1996	0.0871	0.0452
Model Year 1997	0.0422	0.0268	Model Year 1997	0.0871	0.0452
Model Year 1998	0.0393	0.0249	Model Year 1998	0.0728	0.0391
Model Year 1999	0.0337	0.0216	Model Year 1999	0.0564	0.0321
Model Year 2000	0.0273	0.0178	Model Year 2000	0.0621	0.0346
Model Year 2001	0.0158	0.011	Model Year 2001	0.0164	0.0151
Model Year 2002	0.0153	0.0107	Model Year 2002	0.0228	0.0178
Model Year 2003	0.0135	0.0114	Model Year 2003	0.0114	0.0155
Model Year 2004	0.0083	0.0145	Model Year 2004	0.0132	0.0152
Model Year 2005	0.0079	0.0147	Model Year 2005	0.0101	0.0157
Gasoline Heavy-Duty Vehicles	**N2O (g/mi)**	**CH4 (g/mi)**	**Diesel Passenger Cars**	**N2O (g/mi)**	**CH4 (g/mi)**
Model Years 1985-1986	0.0515	0.409	Model Years 1960-1982	0.0012	0.0006
Model Year 1987	0.0849	0.3675	Model Years 1983-2004	0.001	0.0005
Model Years 1988-1989	0.0933	0.3492	**Diesel Light Trucks**	**N2O (g/mi)**	**CH4 (g/mi)**
Model Years 1990-1995	0.1142	0.3246	Model Years 1960-1982	0.0017	0.0011
Model Year 1996	0.168	0.1278	Model Years 1983-1995	0.0014	0.0009
Model Year 1997	0.1726	0.0924	Model Years 1996-2004	0.0015	0.001
Model Year 1998	0.1693	0.0641	**Diesel Heavy-Duty Vehicles**	**N2O (g/mi)**	**CH4 (g/mi)**
Model Year 1999	0.1435	0.0578	All Model Years	0.0048	0.0051
Model Year 2000	0.1092	0.0493	Source: TCR GRP Table 13.4: U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005 (2007), Annex 3.2, Table A-98.		
Model Year 2001	0.1235	0.0528			
Model Year 2002	0.1307	0.0546			
Model Year 2003	0.124	0.0533			
Model Year 2004	0.0285	0.0341			
Model Year 2005	0.0177	0.0326			

Table 28: Tier C U.S. Default CH_4 and N_2O Emission Factors for Highway Vehicles by Vehicle Type. Based on (*6*)

Light Duty Vehicles	**N2O (g/mi)**	**CH4 (g/mi)**	Source
gasoline	0.0639	0.1516	(1)
diesel	0.0014	0.0009	(2)
methanol	0.067	0.018	(3)
CNG	0.05	0.737	(3)
LPG	0.067	0.037	(3)
ethanol	0.067	0.055	(3)
Heavy Duty Vehicles	**N2O (g/mi)**	**CH4 (g/mi)**	Source
gasoline	0.1317	0.2356	(4)
diesel	0.0048	0.0051	(5)
methanol	0.175	0.066	(3)
CNG	0.175	1.966	(3)
LNG	0.175	1.966	(3)
LPG	0.175	0.066	(3)
ethanol	0.175	0.197	(3)
Buses	**N2O (g/mi)**	**CH4 (g/mi)**	Source
gasoline	0.1317	0.2356	(4)
diesel	0.0048	0.0051	(5)
methanol	0.175	0.066	(3)
CNG	0.175	1.966	(3)
ethanol	0.175	0.197	(3)

Source:
(1) TCR GRP Table 13.3, Gasoline Light Trucks, Oxidation Catalyst: U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005 (2007), Annex 3.2, Table A-99.
(2) TCR GRP Table 13.3, Diesel Light Trucks, Moderate: U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005 (2007), Annex 3.2, Table A-99.
(3) TCR GRP Table 13.5: U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005 (2007), Annex 3.2, Table A-100.
(4) TCR GRP Table 13.3, Gasoline Heavy-Duty Vehicles, Oxidation Catalyst: U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005 (2007), Annex 3.2, Table A-99.
(5) TCR GRP Table 13.3, Diesel Heavy-Duty Vehicles: U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005 (2007), Annex 3.2, Table A-99.

Table 29: Default CH_4 and N_2O Emission Factors for Non-Highway Vehicles by Vehicle Type and Fuel Type. Based on (*6*)

Ships and Boats	**N2O (g/gal)**	**CH4 (g/gal)**
Residual Fuel Oil	0.3	0.86
Diesel Fuel	0.26	0.74
Gasoline	0.22	0.64
Locomotives	**N2O (g/gal)**	**CH4 (g/gal)**
Diesel Fuel	0.26	0.8
Agricultural Equipment	**N2O (g/gal)**	**CH4 (g/gal)**
Gasoline	0.22	1.26
Diesel Fuel	0.26	1.44
Construction	**N2O (g/gal)**	**CH4 (g/gal)**
Gasoline	0.22	0.5
Diesel Fuel	0.26	0.58
Other Non-Highway	**N2O (g/gal)**	**CH4 (g/gal)**
Snowmobiles (Gasoline)	0.22	0.5
Other Recreational (Gasoline)	0.22	0.5
Other Small Utility (Gasoline)	0.22	0.5
Other Large Utility (Gasoline)	0.22	0.5
Other Large Utility (Diesel)	0.26	0.58
Aircraft	**N2O (g/gal)**	**CH4 (g/gal)**
Jet Fuel	0.31	0.27
Aviation Gasoline	0.11	7.04
Source: TCR GRP Table 13.6, U.S. EPA Climate Leaders, Mobile Combustion Guidance (2007) based on U.S. EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005 (2007), Annex 3.2, Table A-101.		

Table 30: U.S. Default Factors for Stationary Combustion CO_2 Emissions. Based on (*6*)

Fuel	Tier B Heat Content	Tier B Carbon Content	Tier C CO2 Em. Fact.	Tier C CO2 Em. Fact.	Source
Coal and Coke	**MMBtu / short ton**	**kg C / MMBtu**	**kg CO2 / MMBtu**	**kg CO2 / short ton**	**Source**
Anthracite Coal	25.09	28.26	103.62	2,599.83	(1)
Bituminous Coal	24.93	25.49	93.46	2,330.04	(1)
Sub-bituminous Coal	17.25	26.48	97.09	1,674.86	(1)
Lignite	14.21	26.3	96.43	1,370.32	(1)
Unspecified (Residential/ Commercial)	22.05	26	95.33	2,102.29	(1)
Unspecified (Industrial Coking)	26.27	25.56	93.72	2,462.12	(1)
Unspecified (Other Industrial)	22.05	25.63	93.98	2,072.19	(1)
Unspecified (Electric Utility)	19.95	25.76	94.45	1,884.53	(1)
Coke	24.8	31	113.67	2,818.93	(1)
Natural Gas (By Heat Content)	**Btu / SCF**	**kg C / MMBtu**	**kg CO2 / MMBtu**	**kg CO2 / SCF**	
975 to 1,000 Btu / Std cubic foot	988	14.73	54.01	0.0534	(1)
1,000 to 1,025 Btu / Std cubic foot	1013	14.43	52.91	0.0536	(1)
1,025 to 1,050 Btu / Std cubic foot	1038	14.47	53.06	0.0551	(1)
1,050 to 1,075 Btu / Std cubic foot	1063	14.58	53.46	0.0568	(1)
1,075 to 1,100 Btu / Std cubic foot	1088	14.65	53.72	0.0584	(1)
Greater than 1,100 Btu / Std cubic foot	1115	14.92	54.71	0.0610	(1)
Unspecified (Weighted U.S. Average)	1,029	14.47	53.06	0.0546	(1)
Non-Fossil Fuels (solid)	**MMBtu / short ton**	**kg C / MMBtu**	**kg CO2 / MMBtu**	**kg CO2 / short ton**	
Waste Tires	28	30.77	112.84	3,159.49	(2)
Wood and Wood Waste (12% moisture)	15.38	25.6	93.87	1,443.67	(2)
Kraft Black Liquor (North American hardwood)	11.98	25.75	94.41	1,130.76	(2)
Kraft Black Liquor (North American softwood)	12.24	25.95	95.13	1,164.02	(2)
Non-Fossil Fuels (gas)	**Btu / SCF**	**kg C / MMBtu**	**kg CO2 / MMBtu**	**kg CO2 / SCF**	
Landfill Gas (50% CH4 / 50% CO2)	502.5	14.2	52.07	0.0262	(2)
Wastewater Treatment Biogas	502.5	14.2	52.07	0.0262	(2)

Source:
(1) TCR GRP Table 12.1 U.S. Default Factors for Calculating CO2 Emissions from Fossil Fuel Combustion
(2) TCR GRP Table 12.2 U.S. Default Factors for Calculating CO2 Emissions from Non-Fossil Fuel Combustion

Table 31: U.S. Default Factors for Stationary Combustion CO_2 Emissions (cont.). Based on (*6*)

	Tier B		Tier C	
Fuel	**Heat Content**	**Carbon Content**	**CO2 Em. Fact.**	**CO2 Em. Fact.**
Petroleum Products	**MMBtu / barrel**	**kg C / MMBtu**	**kg CO2 / MMBtu**	**kg CO2 / gal**
Asphalt & Road Oil	6.636	20.62	75.61	11.95
Aviation Gasoline	5.048	18.87	69.19	8.32
Distillate Fuel Oil (#1, 2 & 4)	5.825	19.95	73.15	10.15
Jet Fuel	5.67	19.33	70.88	9.57
Kerosene	5.67	19.72	72.31	9.76
LPG (average for fuel use)	3.849	17.23	63.16	5.79
Propane	3.824	17.2	63.07	5.74
Ethane	2.916	16.25	59.58	4.14
Isobutene	4.162	17.75	65.08	6.45
n-Butane	4.328	17.72	64.97	6.7
Lubricants	6.065	20.24	74.21	10.72
Motor Gasoline	5.218	19.33	70.88	8.81
Residual Fuel Oil (#5 & 6)	6.287	21.49	78.8	11.8
Crude Oil	5.8	20.33	74.54	10.29
Naphtha (<401 deg. F)	5.248	18.14	66.51	8.31
Natural Gasoline	4.62	18.24	66.88	7.36
Other Oil (>401 deg. F)	5.825	19.95	73.15	10.15
Pentanes Plus	4.62	18.24	66.88	7.36
Petrochemical Feedstocks	5.428	19.37	71.02	9.18
Petroleum Coke	6.024	27.85	102.12	14.65
Still Gas	6	17.51	64.2	9.17
Special Naphtha	5.248	19.86	72.82	9.1
Unfinished Oils	5.825	20.33	74.54	10.34
Waxes	5.537	19.81	72.64	9.58
Source: TCR GRP Table 12.1 U.S. Default Factors for Calculating CO2 Emissions from Fossil Fuel Combustion				

Table 32: Default CH_4 and N_2O Emission Factors by Technology Type (Tier B) and Fuel Type (Tier C) for the Commercial Sector. Based on (*6*)

Tier B: Fuel Type and Basic Technology, Source (1)	Configuration	CH4 (g/MMBtu)	N2O (g/MMBtu)
Liquid Fuels	--		
Residual Fuel Oil Boilers	--	1.4	0.3
Gas/Diesel Oil Boilers	--	0.7	0.4
Liquefied Petroleum Gases Boilers	--	0.9	4
Solid Fuels			
Other Bituminous/Sub-bit. Overfeed Stoker Boilers	--	1	0.7
Other Bituminous/Sub-bit. Underfeed Stoker Boilers	--	14	0.7
Other Bituminous/Sub-bit. Hand-fed Units	--	87.2	0.7
Other Bituminous/Sub-bituminous Pulverized Boilers	Dry Bottom, wall fired	0.7	0.5
Other Bituminous/Sub-bituminous Pulverized Boilers	Dry Bottom, tangentially fired	0.7	1.4
Other Bituminous/Sub-bituminous Pulverized Boilers	Wet Bottom	0.9	1.4
Other Bituminous Spreader Stokers	--	1	0.7
Other Bituminous/Sub-bit. Fluidized Bed Combustor	Circulating Bed	1	61.1
Other Bituminous/Sub-bit. Fluidized Bed Combustor	Bubbling Bed	1	61.1
Natural Gas			
Natural Gas Boilers	--	0.9	0.9
Gas-Fired Gas Turbines >3MWa	--	3.8	1.3
Biomass			
Wood/Wood Waste Boilers	--	9.3	5.9
Tier C: Fuel Type, Source (2)		**CH4 (g/MMBtu)**	**N2O (g/MMBtu)**
Coal	--	11	1.6
Petroleum Products	--	11	0.6
Natural Gas	--	5	0.1
Wood	--	316	4.2

Source:

(1) TCR GRP Table 12.8 Default CH4 and N2O Emission Factors by Technology Type for the Commercial Sector (Tier B)
(2) TCR GRP Table 12.9 COMMERCIAL SECTOR Default CH4 and N2O Emission Factors By Fuel Type and Sector (Tier C)

Table 33: Stationary Combustion Upstream Fuel-Cycle Emission Factors. Based on (*46*)

Fuel (TCR)	Fuel (GREET)	CO2 (g / MMBtu of Fuel)	CH4 (g / MMBtu of Fuel)	N2O (g / MMBtu of Fuel)	Source
Anthracite Coal	Coal	1,620.18	119.20	0.0313	(1)
Bituminous Coal	Coal	1,620.18	119.20	0.0313	(1)
Sub-bituminous Coal	Coal	1,620.18	119.20	0.0313	(1)
Lignite	Coal	1,620.18	119.20	0.0313	(1)
Unspecified (Residential/ Commercial)	Coal	1,620.18	119.20	0.0313	(1)
Unspecified (Industrial Coking)	Coal	1,620.18	119.20	0.0313	(1)
Unspecified (Other Industrial)	Coal	1,620.18	119.20	0.0313	(1)
Unspecified (Electric Utility)	Coal	1,620.18	119.20	0.0313	(1)
Coke	Coke	1,349.52	118.87	0.0244	(1)
coal and coke	Coal and Coke	1,620.18	119.20	0.0313	(1)
975 to 1,000 Btu / Std cubic foot	Nat. Gas	5,257.73	196.36	0.0867	(2)
1,000 to 1,025 Btu / Std cubic foot	Nat. Gas	5,257.73	196.36	0.0867	(2)
1,025 to 1,050 Btu / Std cubic foot	Nat. Gas	5,257.73	196.36	0.0867	(2)
1,050 to 1,075 Btu / Std cubic foot	Nat. Gas	5,257.73	196.36	0.0867	(2)
1,075 to 1,100 Btu / Std cubic foot	Nat. Gas	5,257.73	196.36	0.0867	(2)
Greater than 1,100 Btu / Std cubic foot	Nat. Gas	5,257.73	196.36	0.0867	(2)
Unspecified (Weighted U.S. Average)	Nat. Gas	5,257.73	196.36	0.0867	(2)
natural gas	Nat. Gas	5,257.73	196.36	0.0867	(2)
Source					
(1) Worksheet "Coal", Table 3, Coal to Power Plants					
(2) Worksheet "NG", Table 4.1, Natural Gas as Stationary Fuels					

Table 34: Stationary Combustion Upstream Fuel-Cycle Emission Factors (cont.). Based on (*46*)

Fuel (TCR)	Fuel (GREET)	CO2 (g / MMBtu of Fuel)	CH4 (g / MMBtu of Fuel)	N2O (g / MMBtu of Fuel)	Source
Residual Fuel Oil (#5 & 6)	Petrol. (resid.)	10,616.24	99.18	0.1759	(1)
Asphalt & Road Oil	Petrol. (resid.)	10,616.24	99.18	0.1759	(1)
Distillate Fuel Oil (#1, 2 & 4)	Petrol. (diesel)	14,415.49	103.39	0.2328	(1)
Crude Oil	Petrol.	4,970.04	92.92	0.0870	(2)
Other Oil (>401 deg. F)	Petrol.	4,970.04	92.92	0.0870	(2)
Motor Gasoline	Petrol. (gasoline)	17,112.13	106.37	0.2736	(3)
Aviation Gasoline	Petrol. (gasoline)	17,112.13	106.37	0.2736	(3)
Natural Gasoline	Petrol. (gasoline)	17,112.13	106.37	0.2736	(3)
LPG (average for fuel use)	Petrol. (LPG)	10,715.11	99.30	0.1787	(4)
Propane	Petrol. (LPG)	10,715.11	99.30	0.1787	(4)
Naphtha (<401 deg. F)	Petrol. (Naptha)	10,519.34	99.10	0.1739	(5)
Special Naphtha	Petrol. (Naptha)	10,519.34	99.10	0.1739	(5)
petroleum products	Petrol. (resid.)	10,616.24	99.18	0.1759	(6)
Source					
(1) Worksheet "Petroleum", Table 5.1, Crude for Use in U.S. Refineries, and Residual Oil					
(2) Worksheet "Petroleum", Table 5.1, Crude for Use in U.S. Refineries					
(3) Worksheet "Petroleum", Table 5.1, Crude for Use in U.S. Refineries, and Conv. Gasoline					
(4) Worksheet "Petroleum", Table 5.1, Crude for Use in U.S. Refineries, and LPG					
(5) Worksheet "Petroleum", Table 5.1, Crude for Use in U.S. Refineries, and Crude Naptha					
(6) Worksheet "Petroleum", Table 5.1, Crude for Use in U.S. Refineries, and Residual Oil					

Table 35: eGRID2007 State GHG Annual Emission Rates. Based on (*44*)

State	lbs CO2 / MWh	lbs CH4 / GWh	lbs N2O / GWh	State	lbs CO2 / MWh	lbs CH4 / GWh	lbs N2O / GWh
AK	1,089.79	24.66	6.04	MT	1,592.05	19.73	27.20
AL	1,340.53	25.10	23.08	NC	1,224.97	19.82	21.32
AR	1,229.23	31.98	22.30	ND	2,325.16	25.10	37.35
AZ	1,158.58	15.53	15.93	NE	1,605.90	18.58	26.69
CA	540.06	30.60	4.50	NH	788.28	61.00	15.01
CO	1,910.88	23.48	29.26	NJ	718.57	30.22	10.79
CT	803.92	67.79	13.63	NM	1,935.90	23.28	30.53
DC	2,432.30	104.97	21.00	NV	1,440.79	20.02	17.85
DE	2,018.04	36.49	26.52	NY	828.33	36.96	10.41
FL	1,340.54	45.73	17.68	OH	1,771.84	20.99	29.90
GA	1,402.54	22.02	23.93	OK	1,562.76	21.67	20.44
HI	1,731.01	165.40	29.96	OR	401.45	16.97	4.80
IA	1,907.24	22.38	31.62	PA	1,244.50	25.42	20.94
ID	133.73	19.16	3.44	RI	964.72	19.21	1.98
IL	1,126.00	13.15	18.50	SC	893.86	14.92	15.17
IN	2,087.75	24.54	34.76	SD	1,181.45	13.96	19.03
KS	1,894.92	23.25	31.31	TN	1,259.07	16.41	21.69
KY	2,057.45	24.13	34.91	TX	1,355.41	19.75	15.35
LA	1,175.49	25.45	13.42	UT	2,102.97	24.14	35.19
MA	1,262.91	68.41	17.23	VA	1,196.05	40.99	21.27
MD	1,352.27	34.58	22.73	VT	4.65	88.61	11.83
ME	739.65	229.01	32.49	WA	331.11	16.40	6.04
MI	1,347.55	29.65	23.65	WI	1,720.13	25.52	28.28
MN	1,594.67	38.72	28.49	WV	1,928.12	21.89	32.72
MO	1,846.93	21.31	30.71	WY	2,251.46	25.68	37.24
MS	1,225.77	26.49	17.42				

Table 36: eGRID2007 State GHG Non-Baseload Emission Rates. Based on (*44*)

State	lbs CO2 / MWh	lbs CH4 / GWh	lbs N2O / GWh	State	lbs CO2 / MWh	lbs CH4 / GWh	lbs N2O / GWh
AK	1,470.56	40.63	8.87	MT	2,760.93	75.25	50.35
AL	1,723.00	41.29	28.23	NC	1,952.11	29.80	31.41
AR	1,572.16	45.70	24.18	ND	2,508.90	41.00	41.71
AZ	1,175.38	20.04	9.39	NE	2,172.49	29.03	29.49
CA	1,061.13	39.98	4.90	NH	1,362.59	63.24	15.84
CO	1,606.13	22.10	20.35	NJ	1,464.80	35.42	17.03
CT	1,478.77	77.68	17.37	NM	1,480.82	24.85	10.41
DC	2,432.30	104.97	21.00	NV	1,254.35	22.07	7.26
DE	1,947.85	39.23	23.37	NY	1,517.76	51.98	13.83
FL	1,382.92	47.46	14.04	OH	1,988.51	24.17	32.48
GA	1,654.63	33.18	24.93	OK	1,293.63	21.57	10.08
HI	1,800.75	185.69	29.99	OR	999.75	42.47	11.10
IA	2,240.01	27.16	36.15	PA	1,845.16	34.63	25.71
ID	653.57	72.11	13.81	RI	1,053.31	21.14	2.20
IL	2,097.08	25.51	32.78	SC	1,760.87	28.36	25.34
IN	2,120.76	25.55	33.93	SD	2,224.28	29.49	29.90
KS	2,351.42	37.22	34.58	TN	2,050.63	26.41	34.99
KY	2,113.67	25.68	35.31	TX	1,138.47	20.71	5.83
LA	1,294.94	27.53	10.02	UT	1,838.57	24.47	24.85
MA	1,295.66	44.94	12.48	VA	1,612.42	55.13	24.39
MD	1,964.52	50.19	31.08	VT	173.96	1,016.50	136.04
ME	1,261.17	264.00	37.23	WA	1,240.81	71.56	21.36
MI	1,698.29	29.59	26.93	WI	1,789.46	36.34	25.23
MN	2,102.88	72.75	36.74	WV	1,965.62	22.52	33.10
MO	2,031.97	25.04	31.25	WY	2,141.24	25.98	33.46
MS	1,473.67	29.27	16.86				

Table 37: eGRID2007 Subregion GHG Emission Rates. Based on (*44*)

Subregion	Subregion Name	Annual			Non-baseload		
		lbs CO2 / MWh	lbs CH4 / GWh	lbs N2O / GWh	lbs CO2 / MWh	lbs CH4 / GWh	lbs N2O / GWh
AKGD	ASCC Alaska Grid	1,232.36	25.60	6.51	1,473.43	36.41	8.24
AKMS	ASCC Miscellaneous	498.86	20.75	4.08	1,457.11	60.47	11.87
ERCT	ERCOT All	1,324.35	18.65	15.11	1,118.86	20.15	5.68
FRCC	FRCC All	1,318.57	45.92	16.94	1,353.72	48.16	12.95
HIMS	HICC Miscellaneous	1,514.92	314.68	46.88	1,674.15	338.44	51.42
HIOA	HICC Oahu	1,811.98	109.47	23.62	1,855.10	120.11	20.79
MROE	MRO East	1,834.72	27.59	30.36	1,828.63	28.82	25.20
MROW	MRO West	1,821.84	28.00	30.71	2,158.79	45.57	35.22
NYLI	NPCC Long Island	1,536.80	115.41	18.09	1,509.85	60.32	10.78
NEWE	NPCC New England	927.68	86.49	17.01	1,314.53	77.47	16.02
NYCW	NPCC NYC/Westchester	815.45	36.02	5.46	1,525.05	56.80	9.08
NYUP	NPCC Upstate NY	720.80	24.82	11.19	1,514.11	45.30	18.41
RFCE	RFC East	1,139.07	30.27	18.71	1,790.50	41.61	24.36
RFCM	RFC Michigan	1,563.28	33.93	27.17	1,663.15	29.40	26.24
RFCW	RFC West	1,537.82	18.23	25.71	1,992.86	24.49	31.72
SRMW	SERC Midwest	1,830.51	21.15	30.50	2,101.16	25.66	32.92
SRMV	SERC Mississippi Valley	1,019.74	24.31	11.71	1,257.10	29.50	9.82
SRSO	SERC South	1,489.54	26.27	25.47	1,697.22	35.20	26.41
SRTV	SERC Tennessee Valley	1,510.44	20.05	25.64	1,998.36	28.25	32.86
SRVC	SERC Virginia/Carolina	1,134.88	23.77	19.79	1,781.28	40.09	27.46
SPNO	SPP North	1,960.94	23.82	32.09	2,169.74	31.18	31.99
SPSO	SPP South	1,658.14	24.98	22.61	1,379.05	24.40	12.04
CAMX	WECC California	724.12	30.24	8.08	1,083.02	39.24	5.55
NWPP	WECC Northwest	902.24	19.13	14.90	1,333.64	49.28	18.73
RMPA	WECC Rockies	1,883.08	22.88	28.75	1,617.71	22.42	20.14
AZNM	WECC Southwest	1,311.05	17.45	17.94	1,201.44	20.80	8.50

Table 38: eGRID2007 NERC Region GHG Emission Rates. Based on (*44*)

NERC	NERC Name	Annual			Non-baseload		
		lbs CO_2 / MWh	lbs CH_4 / GWh	lbs N_2O / GWh	lbs CO_2 / MWh	lbs CH_4 / GWh	lbs N_2O / GWh
ASCC	Alaska Systems Coordinating Council	1,089.79	24.66	6.04	1,470.56	40.63	8.87
FRCC	Florida Reliability Coordinating Council	1,318.57	45.92	16.94	1,353.72	48.16	12.95
HICC	Hawaiian Islands Coordinating Council	1,731.01	165.40	29.96	1,800.75	185.69	29.99
MRO	Midwest Reliability Organization	1,823.69	27.94	30.66	2,092.64	42.21	33.22
NPCC	Northeast Power Coordinating Council	875.74	60.56	13.55	1,413.51	65.00	14.94
RFC	Reliability First Corporation	1,427.21	23.19	23.87	1,882.91	30.33	28.70
SERC	SERC Reliability Corporation	1,368.85	23.32	22.54	1,726.81	32.36	25.07
SPP	Southwest Power Pool	1,751.37	24.62	25.52	1,560.25	25.95	16.62
TRE	Texas Regional Entity	1,324.35	18.65	15.11	1,118.86	20.15	5.68
WECC	Western Electricity Coordinating Council	1,033.12	22.62	14.77	1,218.34	33.26	10.23

Table 39: eGRID2007 State Power Mixes. Based on (*44*)

State	Coal	Fuel oil	NG	Nuclear	Biomass	Hydro	Wind	Other	Other Carbon
AK	9.47%	11.56%	56.62%	0.00%	0.08%	22.26%	0.01%	0.00%	0.00%
AL	56.85%	0.15%	10.10%	23.08%	2.35%	7.39%	0.00%	0.01%	0.09%
AR	48.20%	0.43%	12.57%	28.64%	3.63%	6.49%	0.00%	0.00%	0.03%
AZ	39.56%	0.04%	28.48%	25.43%	0.06%	6.41%	0.00%	0.01%	0.00%
CA	0.98%	1.29%	46.71%	18.08%	2.91%	19.88%	2.13%	6.89%	1.13%
CO	71.67%	0.03%	24.06%	0.00%	0.07%	2.61%	1.56%	0.00%	0.00%
CT	11.91%	9.41%	26.42%	46.39%	2.12%	1.42%	0.00%	0.03%	2.30%
DC	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
DE	59.40%	14.95%	19.55%	0.00%	0.00%	0.00%	0.00%	0.00%	6.10%
FL	28.43%	16.93%	38.05%	13.08%	1.97%	0.12%	0.00%	0.79%	0.62%
GA	63.85%	0.74%	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%
HI	14.16%	78.77%	0.00%	0.00%	2.61%	0.83%	0.06%	1.92%	1.65%
IA	77.49%	0.34%	5.64%	10.32%	0.26%	2.18%	3.74%	0.00%	0.03%
ID	0.88%	0.00%	14.32%	0.00%	5.33%	78.91%	0.00%	0.56%	0.00%
IL	47.52%	0.17%	3.66%	48.03%	0.35%	0.07%	0.07%	0.00%	0.12%
IN	94.25%	0.20%	2.76%	0.00%	0.05%	0.34%	0.00%	0.33%	2.07%
KS	75.18%	2.15%	2.48%	19.23%	0.00%	0.02%	0.93%	0.00%	0.00%
KY	91.07%	3.76%	1.70%	0.00%	0.43%	3.03%	0.00%	0.00%	0.02%
LA	24.89%	3.76%	47.29%	16.91%	2.89%	0.88%	0.00%	0.34%	3.04%
MA	25.34%	14.98%	42.69%	11.53%	2.53%	1.18%	0.00%	0.00%	1.75%
MD	55.69%	7.25%	3.59%	27.93%	1.04%	3.24%	0.00%	0.00%	1.25%
ME	1.83%	8.62%	42.60%	0.00%	21.93%	23.28%	0.00%	0.00%	1.74%
MI	57.83%	0.74%	11.21%	27.02%	2.09%	0.29%	0.00%	0.00%	0.83%
MN	62.12%	1.48%	5.14%	24.26%	1.89%	1.46%	2.99%	0.09%	0.56%
MO	85.23%	0.19%	4.29%	8.84%	0.01%	1.37%	0.00%	0.00%	0.08%
MS	36.91%	3.19%	34.02%	22.36%	3.48%	0.00%	0.00%	0.00%	0.04%

Table 40: eGRID2007 State Power Mixes. Based on (*44*)

State	Coal	Fuel oil	NG	Nuclear	Biomass	Hydro	Wind	Other	Other Carbon
MT	63.79%	1.48%	0.13%	0.00%	0.23%	34.32%	0.00%	0.00%	0.05%
NC	60.47%	0.37%	2.41%	30.82%	1.42%	4.27%	0.00%	0.18%	0.06%
ND	94.76%	0.11%	0.03%	0.00%	0.03%	4.20%	0.69%	0.00%	0.18%
NE	66.16%	0.10%	2.55%	27.97%	0.14%	2.77%	0.31%	0.00%	0.00%
NH	16.68%	5.56%	27.79%	38.73%	3.84%	7.14%	0.00%	0.00%	0.26%
NJ	19.10%	1.80%	25.09%	51.58%	1.38%	0.00%	0.00%	0.10%	0.95%
NM	85.23%	0.11%	11.92%	0.00%	0.01%	0.47%	2.26%	0.00%	0.00%
NV	44.93%	0.11%	47.44%	0.00%	0.00%	4.16%	0.00%	3.09%	0.27%
NY	13.75%	16.23%	22.46%	28.66%	1.24%	16.89%	0.07%	0.00%	0.70%
OH	87.19%	0.89%	1.72%	9.43%	0.25%	0.33%	0.01%	0.00%	0.19%
OK	51.72%	0.10%	43.00%	0.00%	0.41%	3.52%	1.21%	0.01%	0.03%
OR	7.00%	0.12%	27.04%	0.00%	1.77%	62.50%	1.48%	0.00%	0.09%
PA	55.44%	2.27%	4.96%	34.99%	0.91%	0.69%	0.13%	0.01%	0.58%
RI	0.00%	0.92%	98.97%	0.00%	0.00%	0.11%	0.00%	0.00%	0.00%
SC	38.70%	0.66%	5.28%	51.83%	1.74%	1.70%	0.00%	0.00%	0.09%
SD	45.95%	0.32%	4.16%	0.00%	0.00%	47.15%	2.42%	0.00%	0.00%
TN	61.00%	0.24%	0.55%	28.66%	0.57%	8.98%	0.00%	0.00%	0.00%
TX	37.35%	0.57%	49.26%	9.62%	0.28%	0.34%	1.07%	0.21%	1.30%
UT	94.27%	0.11%	3.09%	0.00%	0.00%	2.06%	0.00%	0.48%	0.00%
VA	44.91%	5.38%	10.43%	35.42%	3.12%	0.08%	0.00%	0.00%	0.65%
VT	0.00%	0.18%	0.04%	71.22%	7.18%	21.18%	0.20%	0.00%	0.00%
WA	10.30%	0.10%	8.42%	8.08%	1.56%	70.68%	0.49%	0.00%	0.37%
WI	67.35%	1.14%	10.48%	16.04%	1.89%	2.75%	0.15%	0.07%	0.12%
WV	97.66%	0.24%	0.29%	0.00%	0.00%	1.55%	0.16%	0.00%	0.10%
WY	95.12%	0.09%	0.71%	0.00%	0.00%	1.77%	1.57%	0.14%	0.58%

Table 41: eGRID2007 Subregion Power Mixes. Based on (*44*)

Subregion	Coal	Fuel oil	NG/boiler	Nuclear	Biomass	Hydro	Wind	Other	Other Carbon
AKGD	11.76%	7.13%	69.38%	0.00%	0.01%	11.72%	0.00%	0.00%	0.00%
AKMS	0.00%	29.91%	3.71%	0.00%	0.38%	65.95%	0.05%	0.00%	0.00%
ERCT	37.06%	0.48%	47.52%	11.91%	0.07%	0.31%	1.24%	0.17%	1.24%
FRCC	26.24%	17.87%	39.03%	13.83%	1.54%	0.01%	0.00%	0.84%	0.64%
HIMS	1.47%	83.49%	0.00%	0.00%	4.70%	3.06%	0.21%	7.06%	0.00%
HIOA	18.91%	77.00%	0.00%	0.00%	1.83%	0.00%	0.00%	0.00%	2.26%
MROE	67.95%	2.19%	11.99%	10.18%	3.68%	3.59%	0.12%	0.15%	0.15%
MROW	73.52%	0.60%	4.04%	14.62%	0.76%	4.15%	2.07%	0.03%	0.22%
NYLI	0.00%	59.06%	34.74%	0.00%	3.33%	0.00%	0.00%	0.00%	2.87%
NEWE	15.15%	9.80%	36.65%	25.64%	5.28%	6.01%	0.01%	0.01%	1.46%
NYCW	0.00%	20.21%	34.93%	43.82%	0.54%	0.02%	0.00%	0.00%	0.48%
NYUP	21.55%	7.76%	15.48%	27.04%	1.19%	26.43%	0.11%	0.00%	0.44%
RFCE	45.09%	3.97%	9.64%	38.31%	1.07%	0.91%	0.09%	0.03%	0.89%
RFCM	66.89%	0.85%	13.75%	15.60%	1.89%	0.00%	0.00%	0.00%	1.02%
RFCW	72.83%	0.35%	2.73%	22.34%	0.34%	0.67%	0.07%	0.07%	0.61%
SRMW	83.15%	0.26%	3.52%	11.95%	0.08%	0.99%	0.00%	0.00%	0.04%
SRMV	21.20%	3.34%	45.16%	24.47%	2.07%	1.27%	0.00%	0.22%	2.28%
SRSO	64.73%	0.47%	10.96%	17.34%	3.09%	3.32%	0.00%	0.01%	0.08%
SRTV	66.74%	1.69%	3.58%	19.48%	0.81%	7.70%	0.00%	0.00%	0.01%
SRVC	50.46%	1.69%	4.95%	38.73%	1.93%	1.93%	0.00%	0.07%	0.22%
SPNO	78.26%	1.60%	5.94%	13.36%	0.00%	0.12%	0.65%	0.00%	0.08%
SPSO	55.67%	0.36%	37.41%	0.00%	1.52%	3.67%	0.94%	0.17%	0.25%
CAMX	11.90%	1.17%	42.27%	16.46%	2.61%	17.65%	1.94%	4.96%	1.03%
NWPP	34.36%	0.27%	10.84%	3.28%	1.27%	48.61%	0.71%	0.38%	0.28%
RMPA	71.69%	0.04%	19.46%	0.00%	0.05%	7.37%	1.39%	0.00%	0.00%
AZNM	45.75%	0.06%	31.61%	16.38%	0.04%	3.54%	0.33%	2.22%	0.07%

Table 42: eGRID2007 NERC Region Power Mixes. Based on (*44*)

NERC Region	Coal	Fuel oil	NG/boiler	Nuclear	Biomass	Hydro	Wind	Other	Other Carbon
ASCC	9.47%	11.56%	56.62%	0.00%	0.08%	22.26%	0.01%	0.00%	0.00%
FRCC	26.24%	17.87%	39.03%	13.83%	1.54%	0.01%	0.00%	0.84%	0.64%
HICC	14.16%	78.77%	0.00%	0.00%	2.61%	0.83%	0.06%	1.92%	1.65%
MRO	72.72%	0.82%	5.18%	13.98%	1.18%	4.07%	1.79%	0.04%	0.21%
NPCC	14.42%	13.16%	29.24%	27.22%	3.16%	11.70%	0.04%	0.00%	1.06%
RFC	64.42%	1.43%	5.78%	26.22%	0.70%	0.61%	0.07%	0.05%	0.73%
SERC	57.14%	1.46%	11.73%	24.17%	1.75%	3.27%	0.00%	0.05%	0.42%
SPP	62.63%	0.74%	27.72%	4.11%	1.05%	2.58%	0.85%	0.12%	0.20%
TRE	37.06%	0.48%	47.52%	11.91%	0.07%	0.31%	1.24%	0.17%	1.24%
WECC	33.45%	0.48%	26.29%	10.09%	1.30%	24.66%	1.08%	2.21%	0.44%

APPENDIX D: MARTA GHG EMISSIONS INVENTORY

	A	B	C	D	E	F	G	H	J	K	P	Q	R	S	T	U
1						Data Tiers						C (CH4, N2O)				
2					CO2		N2O, CH4		User Fuel		User	Calc	User Fuel	Calc Fuel		
3	Bus Number(s)	Model	Qty. of Buses	Fuel Type	Activity	Em. Fact.	Activity	Em. Fact.	Combustion (actual)	Units	Vehicle Miles (actual)	Vehicle Miles (estimated)	Econ. (mpg)	Econ. (mpg)	Rev. Veh-Hr	Avg. Occ.
4	2231 - 2240	OR-D40-02-2200	10	diesel	A1/A2/B	B/C	A/B	C	93,684	gal	353,789	0		3.78		
5	2191 - 2230	OR-D40-04-2200	40	diesel	A1/A2/B	B/C	A/B	C	493,050	gal	1,752,365	0		3.55		
6	2301 - 2360	OR-D35-04-2300	60	diesel	A1/A2/B	B/C	A/B	C	910,876	gal	3,433,290	0		3.77		
7	2361 - 2410	NF-D40-05-2300	49	diesel	A1/A2/B	B/C	A/B	C	846,638	gal	3,175,913	0		3.75		
8	3667 - 3681	SM.BUS E450 RETIRED	15	diesel	A1/A2/B	B/C	A/B	C	43,774	gal	471,626	0		10.77		
9	3947 - 3975	SM.BUS GOSHEN	15	diesel	A1/A2/B	B/C	A/B	C	28,631	gal	186,271	0		6.51		
10									2,416,653			9,373,254 VM			0 RH	

	V	W	Z	AW	AX	BE	BF	BM	BN	BO	BP	BQ	BR	BS	BT
1				Direct											
2				CO2		N2O Emission	CH4 Emission	Scope 1 Emissions						Total	
3	PMT	Vehicle Category	Vehicle Type	Emission Factor	Units	Factor (g/mi.)	Factor (g/mi.)	CO2		N2O		CH4		CO2e	
4	0	Buses	diesel	10.15	kg/gal	0.0048	0.0051	**950,893**	kg	**1,698**	g	**1,804**	g	**951.44**	tonnes
5	0	Buses	diesel	10.15	kg/gal	0.0048	0.0051	**5,004,458**	kg	**8,411**	g	**8,937**	g	**5,007.19**	tonnes
6	0	Buses	diesel	10.15	kg/gal	0.0048	0.0051	**9,245,391**	kg	**16,480**	g	**17,510**	g	**9,250.74**	tonnes
7	0	Buses	diesel	10.15	kg/gal	0.0048	0.0051	**8,593,376**	kg	**15,244**	g	**16,197**	g	**8,598.32**	tonnes
8	0	Buses	diesel	10.15	kg/gal	0.0048	0.0051	**444,306**	kg	**2,264**	g	**2,405**	g	**445.04**	tonnes
9	0	Buses	diesel	10.15	kg/gal	0.0048	0.0051	**290,605**	kg	**894**	g	**950**	g	**290.89**	tonnes
10	0	Passenger-Miles (sum)						**24,529,028**	kg	**44,992**	g	**47,804**	g	**24,543.63**	tonnes
11		[illegible]													
12															
13															

Figure 38: MARTA GHG Emissions Inventory. Worksheet: bus_diesel.

	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ
1	Fuel-Cycle	GREET V1.8c		Include Fuel-Cycle?		YES							Manufacturing			Maintenan
2	CO2	N2O	CH4	Scope 3 Emissions: Fuel-Cycle									CO2	N2O	CH4	CO2
3	Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)	CO2		N2O		CH4		CO2e		EIO-LCA Sector / Vehicle Type	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)
4	15,487.71	0.25	104.53	**199,332**	kg	**3**	kg	**1,345**	kg	**233.92**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
5	15,487.71	0.25	104.53	**1,049,063**	kg	**17**	kg	**7,080**	kg	**1,231.08**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
6	15,487.71	0.25	104.53	**1,938,072**	kg	**31**	kg	**13,080**	kg	**2,274.34**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
7	15,487.71	0.25	104.53	**1,801,393**	kg	**29**	kg	**12,158**	kg	**2,113.94**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
8	15,487.71	0.25	104.53	**93,138**	kg	**1**	kg	**629**	kg	**109.30**	tonnes	Light truck/utility	0.5487	4.0604E-05	0.001696	0.6916
9	15,487.71	0.25	104.53	**60,918**	kg	**1**	kg	**411**	kg	**71.49**	tonnes	Light truck/utility	0.5487	4.0604E-05	0.001696	0.6916
10				**5,141,916**	kg	**82**	kg	**34,703**	kg	**6,034.06**	tonnes					

	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW	CX	CY	CZ	DA	DB
1	ce		Include Veh.-Cycle?		YES													
2	N2O	CH4	Scope 3 Emissions: Vehicle-Cycle								Scope 3 Emissions: Total							
3	Em. Fact. (kg/$)	Em. Fact. (kg/$)	CO2		N2O		CH4		CO2e		CO2		N2O		CH4		CO2e	
4	4.46309E-05	0.002056	**269,132**	kg	**15**	kg	**791**	kg	**293.48**	tonnes	**468,464**	kg	**19**	kg	**2,136**	kg	**527.40**	tonnes
5	4.46309E-05	0.002056	**1,117,852**	kg	**63**	kg	**3,283**	kg	**1,218.85**	tonnes	**2,166,915**	kg	**80**	kg	**10,364**	kg	**2,449.93**	tonnes
6	4.46309E-05	0.002056	**1,676,778**	kg	**95**	kg	**4,925**	kg	**1,828.28**	tonnes	**3,614,850**	kg	**126**	kg	**18,005**	kg	**4,102.61**	tonnes
7	4.46309E-05	0.002056	**1,398,652**	kg	**79**	kg	**4,107**	kg	**1,524.92**	tonnes	**3,200,045**	kg	**108**	kg	**16,265**	kg	**3,638.87**	tonnes
8	4.46309E-05	0.002056	**198,812**	kg	**14**	kg	**610**	kg	**218.36**	tonnes	**291,950**	kg	**16**	kg	**1,239**	kg	**327.66**	tonnes
9	4.46309E-05	0.002056	**198,812**	kg	**14**	kg	**610**	kg	**218.36**	tonnes	**259,730**	kg	**15**	kg	**1,022**	kg	**289.85**	tonnes
10			**4,860,037**	kg	**282**	kg	**14,327**	kg	**5,302.26**	tonnes	**10,001,952**	kg	**364**	kg	**49,030**	kg	**11,336.32**	tonnes

Figure 39: MARTA GHG Emissions Inventory. Worksheet: bus_diesel (cont.).

	DC	DD	DE	DF	DG	DH	DI
1						Scope	
2						1	
3	Vehicle Capital Cost ($)	Vehicle Maint. Cost ($)	Cost ID	Cost-Eff. Baseline?	Cost ($/mile)	CO2e Emiss. Rate (g/mile)	Cost-Eff. ($/tonne)
4	$199,917	$207,699	diesel Orion 10		$1.15	2,689	
5	$865,500	$830,794	diesel Orion 40		$0.97	2,857	
6	$1,298,250	$1,246,192	diesel Orion 40		$0.74	2,694	
7	$1,106,890	$1,017,723	diesel NF 54		$0.67	2,707	
8	$300,000	$49,453	Paratransit		$0.74	944	
9	$300,000	$49,453	Paratransit		$1.88	1,562	

Figure 40: MARTA GHG Emissions Inventory. Worksheet: bus_diesel (cont.).

	A	B	C	D	E	F	G	H	J	K	P	Q	R	S	T	U
1					Data Tiers							C (CH4, N2O)				
2					CO2		N2O, CH4		User Fuel		User	Calc	User Fuel	Calc Fuel		
3	Bus Number(s)	Model	Qty. of Buses	Fuel Type	Activity	Em. Fact.	Activity	Em. Fact.	Combustion (actual)	Units	Vehicle Miles (actual)	Vehicle Miles (estimated)	Econ. (mpg)	Econ. (mpg)	Rev. Veh-Hr	Avg. Occ.
4	3003 - 3024	NF-G30-00-3000	22	CNG	A1/A2/B	B/C	A/B	C	365,154	DGE	1,089,435	0		2.98		
5	2819 - 2900	NF-G40-00-2800	81	CNG	A1/A2/B	B/C	A/B	C	1,205,811	DGE	3,753,658	0		3.11		
6	2901 - 3002	NF-G40-01-2900	100	CNG	A1/A2/B	B/C	A/B	C	1,525,434	DGE	4,789,934	0		3.14		
7	2701 - 2818	NF-G40-96-2700	91	CNG	A1/A2/B	B/C	A/B	C	1,386,159	DGE	4,332,380	0		3.13		
8	2411 - 2465	NF-G40-06-2400	55	CNG	A1/A2/B	B/C	A/B	C	850,332	DGE	2,802,978	0		3.30		
9	2101 - 2160	OR-G40-02-2100	60	CNG	A1/A2/B	B/C	A/B	C	958,779	DGE	2,868,174	0		2.99		
10	2161 - 2190	OR-G40-04-2100	30	CNG	A1/A2/B	B/C	A/B	C	480,155	DGE	1,461,361	0		3.04		
11	2800 - 2801	NF-G40-96-REPWR	2	CNG	A1/A2/B	B/C	A/B	C	26,446	DGE	80,637	0		3.05		
12									6,798,270			21,178,557 VM			0 RH	

	V	W	Z	AW	AX	BE	BF	BM	BN	BO	BP	BQ	BR	BS	BT
1				Direct											
2				CO2		N2O Emission	CH4 Emission	Scope 1 Emissions						Total	
3	PMT	Vehicle Category	Vehicle Type	Emission Factor	Units	Factor (g/mi.)	Factor (g/mi.)	CO2		N2O		CH4		CO2e	
4	0	Buses	CNG	0.05	kg/SCF	0.175	1.966	**2,662,846** kg		**190,651** g		**2,141,829** g		**2,773.21** tonnes	
5	0	Buses	CNG	0.05	kg/SCF	0.175	1.966	**8,793,245** kg		**656,890** g		**7,379,692** g		**9,173.49** tonnes	
6	0	Buses	CNG	0.05	kg/SCF	0.175	1.966	**11,124,061** kg		**838,238** g		**9,417,010** g		**11,609.28** tonnes	
7	0	Buses	CNG	0.05	kg/SCF	0.175	1.966	**10,108,414** kg		**758,167** g		**8,517,459** g		**10,547.28** tonnes	
8	0	Buses	CNG	0.05	kg/SCF	0.175	1.966	**6,200,954** kg		**490,521** g		**5,510,655** g		**6,484.90** tonnes	
9	0	Buses	CNG	0.05	kg/SCF	0.175	1.966	**6,991,791** kg		**501,930** g		**5,638,830** g		**7,282.34** tonnes	
10	0	Buses	CNG	0.05	kg/SCF	0.175	1.966	**3,501,478** kg		**255,738** g		**2,873,036** g		**3,649.51** tonnes	
11	0	Buses	CNG	0.05	kg/SCF	0.175	1.966	**192,855** kg		**14,111** g		**158,532** g		**201.02** tonnes	
12	0	Passenger-Miles (sum)						**49,575,644** kg		**3,706,247** g		**41,637,043** g		**51,721.03** tonnes	
13		Passenger-Miles (alternate total)													
14															
15															

Figure 41: MARTA GHG Emissions Inventory. Worksheet: bus_CNG.

	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ
1	Fuel-Cycle	GREET V1.8c		Include Fuel-Cycle?		YES							Manufacturing			Maintenan
2	CO2	N2O	CH4	Scope 3 Emissions: Fuel-Cycle									CO2	N2O	CH4	CO2
3	Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)	CO2		N2O		CH4		CO2e		EIO-LCA Sector / Vehicle Type	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)
4	11,468.36	0.17	246.60	**580,796**	kg	**9**	kg	**12,488**	kg	**895.59**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
5	11,468.36	0.17	246.60	**1,917,905**	kg	**29**	kg	**41,239**	kg	**2,957.41**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
6	11,468.36	0.17	246.60	**2,426,282**	kg	**36**	kg	**52,171**	kg	**3,741.33**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
7	11,468.36	0.17	246.60	**2,204,758**	kg	**33**	kg	**47,407**	kg	**3,399.74**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
8	11,468.36	0.17	246.60	**1,352,497**	kg	**20**	kg	**29,082**	kg	**2,085.55**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
9	11,468.36	0.17	246.60	**1,524,988**	kg	**23**	kg	**32,791**	kg	**2,351.53**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
10	11,468.36	0.17	246.60	**763,711**	kg	**11**	kg	**16,422**	kg	**1,177.64**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
11	11,468.36	0.17	246.60	**42,064**	kg	**1**	kg	**904**	kg	**64.86**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182	0.6916
12				**10,813,000**	kg	**161**	kg	**232,504**	kg	**16,673.67**	tonnes					

	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW	CX	CY	CZ	DA	DB
1	ce		Include Veh.-Cycle?		YES													
2	N2O	CH4	Scope 3 Emissions: Vehicle-Cycle								Scope 3 Emissions: Total							
3	Em. Fact. (kg/$)	Em. Fact. (kg/$)	CO2		N2O		CH4		CO2e		CO2		N2O		CH4		CO2e	
4	4.46309E-05	0.002056	**641,059**	kg	**36**	kg	**1,882**	kg	**698.89**	tonnes	**1,221,855**	kg	**45**	kg	**14,370**	kg	**1,594.48**	tonnes
5	4.46309E-05	0.002056	**2,422,422**	kg	**136**	kg	**7,109**	kg	**2,640.76**	tonnes	**4,340,327**	kg	**165**	kg	**48,348**	kg	**5,598.17**	tonnes
6	4.46309E-05	0.002056	**2,990,644**	kg	**168**	kg	**8,777**	kg	**3,260.19**	tonnes	**5,416,926**	kg	**204**	kg	**60,947**	kg	**7,001.52**	tonnes
7	4.46309E-05	0.002056	**2,596,625**	kg	**147**	kg	**7,625**	kg	**2,831.05**	tonnes	**4,801,383**	kg	**180**	kg	**55,032**	kg	**6,230.80**	tonnes
8	4.46309E-05	0.002056	**1,405,713**	kg	**81**	kg	**4,134**	kg	**1,533.17**	tonnes	**2,758,210**	kg	**101**	kg	**33,216**	kg	**3,618.72**	tonnes
9	4.46309E-05	0.002056	**1,759,163**	kg	**99**	kg	**5,164**	kg	**1,917.83**	tonnes	**3,284,151**	kg	**122**	kg	**37,955**	kg	**4,269.36**	tonnes
10	4.46309E-05	0.002056	**882,934**	kg	**50**	kg	**2,592**	kg	**962.56**	tonnes	**1,646,645**	kg	**61**	kg	**19,013**	kg	**2,140.20**	tonnes
11	4.46309E-05	0.002056	**57,069**	kg	**3**	kg	**168**	kg	**62.22**	tonnes	**99,132**	kg	**4**	kg	**1,072**	kg	**127.08**	tonnes
12			**12,755,629**	kg	**721**	kg	**37,449**	kg	**13,906.67**	tonnes	**23,568,630**	kg	**882**	kg	**269,954**	kg	**30,580.34**	tonnes

Figure 42: MARTA GHG Emissions Inventory. Worksheet: bus_CNG (cont.).

	DC	DD	DE	DF	DG	DH	DI
1						Scope	
2						1	
3	Vehicle Capital Cost ($)	Vehicle Maint. Cost ($)	Cost ID	Cost-Eff. Baseline?	Cost ($/mile)	CO2e Emiss. Rate (g/mile)	Cost-Eff. ($/tonne)
4	$517,829	$456,937	CNG NF 22		$0.89	2,546	
5	$2,005,580	$1,682,359	CNG NF 81		$0.98	2,444	
6	$2,476,025	$2,076,986	CNG NF 101		$0.95	2,424	
7	$2,054,264	$1,890,057	CNG NF 94		$0.91	2,435	
8	$980,833	$1,142,342	CNG NF 55		$0.76	2,314	
9	$1,429,500	$1,246,192	CNG Orion 60		$0.93	2,539	
10	$720,090	$623,096	CNG Orion 30		$0.92	2,497	
11	$45,149	$41,540	CNG NF 94		$1.08	2,493	

Figure 43: MARTA GHG Emissions Inventory. Worksheet: bus_CNG (cont.).

	A	B	C	D	E	F	G	H	J	K	P
1					Data Tiers						
2					CO_2		N_2O, CH_4		User Fuel		User
3	Veh. Number(s)	Model	Qty. of Veh.	Fuel Type	Activity	Em. Fact.	Activity	Em. Fact.	Combustion (actual)	Units	Vehicle Miles (actual)
4	3529-3666	L/VAN FORD RETIRED	81	diesel	A1/A2/B	B/C	A/B	C	114,022	gal	985,012
5	3701-3731	L/VAN GM/GLAVAL	30	diesel	A1/A2/B	B/C	A/B	C	159,117	gal	1,452,864
6	3801-3945	L/VAN GM/GOSHEN	144	diesel	A1/A2/B	B/C	A/B	C	500,454	gal	4,227,695
7									773,593		
8											
9											
10											

	Q	R	S	T	U	V	W	Z	AW
1	C (CH_4, N_2O)								Direct
2	Calc	User Fuel	Calc Fuel						CO_2
3	Vehicle Miles (estimated)	Econ. (mpg)	Econ. (mpg)	Rev. Veh-Hr	Avg. Occ.	PMT	Vehicle Category	Vehicle Type	Emission Factor
4	0		8.64			0	Heavy Duty Vehicles	diesel	10.15
5	0		9.13			0	Heavy Duty Vehicles	diesel	10.15
6	0		8.45			0	Heavy Duty Vehicles	diesel	10.15
7	6,665,571 VM			0 RH		0	Passenger-Miles (sum)		
8						5,423,300	Passenger-Miles (alternate total)		
9									
10						5,423,300	Passenger-Miles (alternate total)		

	AX	BE	BF	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW
1												Fuel-Cycle	GREET V1.8c	
2		N_2O Emission	CH_4 Emission	Scope 1 Emissions						Total		CO_2	N_2O	CH_4
3	Units	Factor (g/mi.)	Factor (g/mi.)	CO_2		N_2O		CH_4		CO_2e		Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)
4	kg/gal	0.0048	0.0051	**1,157,323**	kg	**4,728**	g	**5,024**	g	**1,158.86**	tonnes	15,487.71	0.25	104.53
5	kg/gal	0.0048	0.0051	**1,615,038**	kg	**6,974**	g	**7,410**	g	**1,617.30**	tonnes	15,487.71	0.25	104.53
6	kg/gal	0.0048	0.0051	**5,079,608**	kg	**20,293**	g	**21,561**	g	**5,086.19**	tonnes	15,487.71	0.25	104.53
7				**7,851,969**	kg	**31,995**	g	**33,994**	g	**7,862.35**	tonnes			
8														
9														
10														

	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ
1	Include Fuel-Cycle?		YES							Manufacturing			Maintenan
2	Scope 3 Emissions: Fuel-Cycle									CO_2	N_2O	CH_4	CO_2
3	CO_2		N_2O		CH_4		CO_2e		EIO-LCA Sector / Vehicle Type	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)
4	**242,605**	kg	**4**	kg	**1,637**	kg	**284.70**	tonnes	Light truck/utility	0.5487	4.0604E-05	0.001696	0.6916
5	**338,553**	kg	**5**	kg	**2,285**	kg	**397.29**	tonnes	Light truck/utility	0.5487	4.0604E-05	0.001696	0.6916
6	**1,064,817**	kg	**17**	kg	**7,187**	kg	**1,249.57**	tonnes	Light truck/utility	0.5487	4.0604E-05	0.001696	0.6916
7	**1,645,975**	kg	**26**	kg	**11,109**	kg	**1,931.56**	tonnes					
8													
9													
10													

Figure 44: MARTA GHG Emissions Inventory. Worksheet: Paratransit.

	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW	CX	CY	CZ
1	ce		Include Veh.-Cycle?		YES											
2	N2O	CH4	Scope 3 Emissions: Vehicle-Cycle								Scope 3 Emissions: Total					
3	Em. Fact. (kg/$)	Em. Fact. (kg/$)	CO2		N2O		CH4		CO2e		CO2		N2O		CH4	
4	4.46E-05	0.002056	**1,073,582**	kg	**78**	kg	**3,297**	kg	**1,179.15**	tonnes	**1,316,187**	kg	**82**	kg	**4,934**	kg
5	4.46E-05	0.002056	**397,623**	kg	**29**	kg	**1,221**	kg	**436.72**	tonnes	**736,177**	kg	**34**	kg	**3,506**	kg
6	4.46E-05	0.002056	**1,908,591**	kg	**138**	kg	**5,861**	kg	**2,096.27**	tonnes	**2,973,408**	kg	**155**	kg	**13,047**	kg
7			**3,379,797**	kg	**245**	kg	**10,378**	kg	**3,712.14**	tonnes	**5,025,772**	kg	**271**	kg	**21,487**	kg
8																
9																
10																

	DA	DB	DC	DD	DE	DF	DG	DH	DI
1								Scope	
2								1	
3	CO2e		Vehicle Capital Cost ($)	Vehicle Maint. Cost ($)	Cost ID	Cost-Eff. Baseline?	Cost ($/mile)	CO2e Emiss. Rate (g/mile)	Cost-Eff. ($/tonne)
4	**1,463.85**	tonnes	$1,620,000	$267,045	Paratransit		$1.92	1,176	
5	**834.02**	tonnes	$600,000	$98,906	Paratransit		$0.48	1,113	
6	**3,345.83**	tonnes	$2,880,000	$474,747	Paratransit		$0.79	1,203	
7	**5,643.70**	tonnes							
8									
9									
10									

Figure 45: MARTA GHG Emissions Inventory. Worksheet: Paratransit (cont.).

	A	B	C	D	E	F	G	H
1					Data Tier			
2					CO_2, CH_4, N_2O	CO_2, CH_4, N_2O		
3	**Veh. Number(s)**	**Model**	**Qty. of Veh.**	**Line**	**Activity**	**Em. Factor**	**Energy Consumption (kWh)**	**Vehicle Miles**
4	All	NA	338	NA	A/B	B	97,411,500.00	24,063,100.00
5	Old	NA	120	NA				
6	Rebuilds	NA	218	NA				
7								24,063,100
8								
9								
10								24,063,100

	I	J	K	O	P	R	S	T	U
1							Direct		
2							CO_2	CH_4	N_2O
3	**Avg. Occ.**	**Rev. Veh-Hr**	**PMT**	**Electricity Grid Region**		**Emission Rate**	**Emission Factor (lbs/MWh) (default)**	**Emission Factor (lbs/GWh) (default)**	**Emission Factor (lbs/GWh) (default)**
4			0	state	GA	Annual	1402.5397	22.0169	23.9289
5			0						
6			0						
7	VM (sum)	0	0						
8			593,419,400						
9									
10	VM (sum)		593,419,400						

	V	W	X	Y	AI	AJ	AK	AL	AM	AN	AO	AP
1												
2	Scope 2 Emissions				Scope 3 Emissions (power mix)							
3	**CO_2 (kg)**	**CH_4 (g)**	**N_2O (g)**	**CO_2e (tonnes)**	**Coal (default)**	**Oil (default)**	**NG (default)**	**Nuclear (default)**	**Biomass (default)**	**Hydro (default)**	**Wind (default)**	**Other (default)**
4	61,972,417.8	972.8	1,057.3	**61,972.8**	63.85%	0.74%	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%
5	0.0	0.0	0.0	**0.0**								
6	0.0	0.0	0.0	**0.0**								
7	61,972,417.8	972.8	1,057.3	**61,972.8**								
8												
9												
10												

Figure 46: MARTA GHG Emissions Inventory. Worksheet: HR.

	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	CM	CN	CO
1												Fuel-Cycle?	YES	
2		Scope 3 Emissions (plant efficiency)										Scope 3 Emissions: Fuel-Cycle		
3	**Other Carbon (default)**	**Coal**	**Oil**	**NG**	**Nuclear**	**Biomass**	**Hydro**	**Wind**	**Other**	**Other Carbon**	**T&D Losses**	**CO2 (kg)**	**CH4 (kg)**	**N2O (g)**
4	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%	100.0%	34.0%	34.0%	8.0%	6,900,307.2	92,730.5	28,014.7
5		34.1%	34.8%	40.1%	100.0%	32.1%	100.0%	100.0%	34.0%	34.0%	8.0%	0.0	0.0	0.0
6		34.1%	34.8%	40.1%	100.0%	32.1%	100.0%	100.0%	34.0%	34.0%	8.0%	0.0	0.0	0.0
7												6,900,307.2	92,730.5	28,014.7
8														
9														
10														

	CP	CQ	CR	CS	CT	CU	CV	CW	CX	CY	CZ
1		Manufacturing			Maintenance			Veh.-Cycle?	YES		
2		CO2	CH4	N2O	CO2	CH4	N2O	Scope 3 Emissions: Vehicle Cycle			
3	**CO2e (tonnes)**	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (g/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (g/$)	**CO2 (kg)**	**CH4 (kg)**	**N2O (g)**	**CO2e (tonnes)**
4	**9,226.9**	0.46885	0.001228	0.01644295	0.5914	0.001604	0.027852349	0.0	0.0	0.0	**0.0**
5	**0.0**	0.46885	0.001228	0.01644295	0.5914	0.001604	0.027852349	5,088,492.3	13,487.0	199,053.3	**5,485.0**
6	**0.0**	0.46885	0.001228	0.01644295	0.5914	0.001604	0.027852349	10,800,676.3	28,578.3	416,204.2	**11,639.2**
7	**9,226.9**							15,889,168.6	42,065.3	615,257.5	**17,124.1**
8											
9											
10											

	DA	DB	DC	DD	DE	DF	DG	DH	DI	DJ	DK
1										Scope	
2	Scope 3 Emissions									2	
3	**CO2 (kg)**	**CH4 (kg)**	**N2O (g)**	**CO2e (tonnes)**	Vehicle Capital Cost ($)	Vehicle Maint. Cost ($)	**Cost ID**	**Cost-Eff. Baseline?**	**Cost ($/mi.)**	**CO2e Emiss. Rate (g/mi.)**	**Cost-Eff. ($/tonne)**
4	6,900,307.2	92,730.5	28,014.7	**9,226.9**	$0	$0				2,575	
5	5,088,492.3	13,487.0	199,053.3	**5,485.0**	$7,200,000	$2,896,132	HR Veh. Old				
6	10,800,676.3	28,578.3	416,204.2	**11,639.2**	$16,400,000	$5,261,306	HR Veh. Rebld				
7	22,789,475.8	134,795.9	643,272.2	**26,351.1**							
8											
9											
10											

Figure 47: MARTA GHG Emissions Inventory. Worksheet: HR (cont.).

	A	B	C	D	E	F	G	H	I	K	L
1						Data Tiers					
2					CO2		N2O, CH4			User	
3	Veh. Number(s)	Model	Qty. of Veh.	Fuel Type	Activity	Em. Fact.	Activity	Em. Fact.	Non-High way	Fuel Combustion (actual)	Units
4	NA	Light Duty	389	gasoline	A1/A2/B	B/C	A/B	C	NO	405,728	gal
5	NA	Heavy Duty	41	diesel	A1/A2/B	B/C	A/B	C	NO	55,811	gal
6	NA	Automobile	16	CNG	C	B/C	A/B	C	NO		
7	NA	Non-road, loco.	5	diesel	A1/A2/B	B/C	A/B	A	YES	1,130	gal
8	NA	Non-road, const.	4	diesel	A1/A2/B	B/C	A/B	A	YES	92	gal
9											

	N	O	Q	R	S	T	U	V
1	C (CO2)			C (CH4, N2O)				
2	Calc		User	Calc	User	Calc		
3	Fuel Combustion (estimated)	Units	Vehicle Miles (actual)	Vehicle Miles (estimated)	Fuel Econ. (mpg)	Fuel Econ. (mpg)	Vehicle Category	Control Technology
4			5,661,474	0		13.95	Light Duty Vehicles	
5			204,549	0		3.67	Heavy Duty Vehicles	
6	633,368	SCF	60,971	0	13.00		Light Duty Vehicles	
7				0		0.00	Locomotives	Diesel Fuel
8				0		0.00	Construction	Diesel Fuel
9				5,926,994	VM			

	X	AU	AV	BC	BD	BK	BL	BM	BN	BO	BP	BQ	BR	BS
1		Direct												Fuel-Cycle
2		CO2		N2O	CH4	Scope 1 Emissions						Total		CO2
3	Vehicle Type	Emission Factor	Units	N2O Emission Factor (g/mi.)	CH4 Emission Factor (g/mi.)	CO2		N2O		CH4		CO2e		Em. Fact. (g/MMBtu)
4	gasoline	8.81	kg/gal	0.0639	0.1516	**3,574,464**	kg	**361,768**	g	**858,279**	g	**3,703.73**	tonnes	16,812.32
5	diesel	10.15	kg/gal	0.0048	0.0051	**566,482**	kg	**982**	g	**1,043**	g	**566.80**	tonnes	15,487.71
6	CNG	0.05	kg/SCF	0.05	0.737	**34,202**	kg	**3,049**	g	**44,936**	g	**36.23**	tonnes	11,468.36
7		10.15	kg/gal	0.26	0.8	**11,470**	kg	**294**	g	**904**	g	**11.58**	tonnes	15,487.71
8		10.15	kg/gal	0.26	0.58	**934**	kg	**24**	g	**53**	g	**0.94**	tonnes	15,487.71
9						**4,187,551**	kg	**366,116**	g	**905,216**	g	**4,319.28**	tonnes	

	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE
1	GREET V1.8c		Fuel-Cycle?	YES								Manufactu
2	N2O	CH4	Scope 3 Emissions: Fuel-Cycle									CO2
3	Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)	CO2		N2O		CH4		CO2e		EIO-LCA Sector / Vehicle Type	Em. Fact. (kg/$)
4	1.14	108.74	**848,151**	kg	**58**	kg	**5,486**	kg	**1,002.44**	tonnes	Automobile	0.5079
5	0.25	104.53	**118,749**	kg	**2**	kg	**801**	kg	**139.35**	tonnes	Light truck/utility	0.5487
6	0.17	246.60	**7,460**	kg	**0**	kg	**160**	kg	**11.50**	tonnes	Automobile	0.5079
7	0.25	104.53	**2,404**	kg	**0**	kg	**16**	kg	**2.82**	tonnes	Heavy duty	0.6277
8	0.25	104.53	**196**	kg	**0**	kg	**1**	kg	**0.23**	tonnes	Light truck/utility	0.5487
9			**976,960**	kg	**60**	kg	**6,465**	kg	**1,156.34**	tonnes		

Figure 48: MARTA GHG Emissions Inventory. Worksheet: Non-Rev_Veh.

	CF	CG	CH	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR
1	ring		Maintenance			Veh.-Cycle?	YES						
2	N2O	CH4	CO2	N2O	CH4	Scope 3 Emissions: Vehicle-Cycle							
3	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)	CO2		N2O		CH4		CO2e	
4	4.36242E-05	0.001676	0.6916	4.46E-05	0.002056	**576,255**	kg	**49**	kg	**1,902**	kg	**638.54**	tonnes
5	0.0121	0.0424	0.6916	4.46E-05	0.002056	**187,473**	kg	**4,134**	kg	**14,487**	kg	**1,781.62**	tonnes
6	0.013	0.0419	0.6916	4.46E-05	0.002056	**23,702**	kg	**607**	kg	**1,955**	kg	**253.37**	tonnes
7	0.00909	0.0455	0.6916	4.46E-05	0.002056	**26,154**	kg	**379**	kg	**1,896**	kg	**186.42**	tonnes
8	0.0121	0.0424	0.6916	4.46E-05	0.002056	**18,290**	kg	**403**	kg	**1,413**	kg	**173.82**	tonnes
9						**831,874**	kg	**5,572**	kg	**21,653**	kg	**3,033.77**	tonnes

	CS	CT	CU	CV	CW	CX	CY	CZ	DA	DB	DC	DD
1												
2	Scope 3 Emissions: Total											
3	CO2		N2O		CH4		CO2e		Vehicle Capital Cost ($)	Vehicle Maint. Cost ($)	Cost ID	Cost-Eff. Baseline?
4	**1,424,406**	kg	**107**	kg	**7,387**	kg	**1,640.98**	tonnes	$1,134,583	$0	Non-Rev gasoline	
5	**306,222**	kg	**4,136**	kg	**15,288**	kg	**1,920.97**	tonnes	$341,667	$0	Non-Rev diesel	
6	**31,162**	kg	**607**	kg	**2,116**	kg	**264.88**	tonnes	$46,667	$0	Non-Rev CNG	
7	**28,558**	kg	**379**	kg	**1,912**	kg	**189.24**	tonnes	$41,667	$0	Non-Rev diesel	
8	**18,486**	kg	**403**	kg	**1,415**	kg	**174.05**	tonnes	$33,333	$0	Non-Rev diesel	
9	**1,808,834**	kg	**5,632**	kg	**28,118**	kg	**4,190.11**	tonnes				

	DE	DF	DG
1		Scope	
2		1	
3	Cost ($/mile)	CO2e Emiss. Rate (g/mile)	Cost-Eff. ($/tonne)
4	$0.20	654	
5	$1.67	2,771	
6	$0.77	594	
7			
8			
9			

Figure 49: MARTA GHG Emissions Inventory. Worksheet: Non-Rev_Veh (cont.).

	A	B	C	D	E	F	G	H	I	J	K
1				Data Tiers							
2				CO2	N2O, CH4	For Cost-Eff.		CO2 (B, C)		User	
3	Facility	Type	Qty.	Em. Fact.	Em. Fact.	**Facility Area (SF)**	Fuel Type	Fuel Type	Biofuel (%)	Fuel Combustion (actual)	Units
4	All	NA	1	C	C		natural gas	Unspecified (Weighted U.S. Average)		510,605	therms
5											
6											
7											

	P	Q	R	S	U	V	X	Y	AA	AB
1			A2, B		B		A2, B		B, C	
2	CH4, N2O (B, C)	CH4, N2O (B, C)	User		Default		User		Default	
3	Fuel Type and Basic Technology (Commercial Sector)	Configuration	Heat Content (actual)	Units	Heat Content (default)	Units	Carbon Content (actual)	Units	Carbon Content (default)	Units
4	Natural Gas				1,029	Btu / SCF			0.0545987	kg CO2 / SCF
5									FALSE	FALSE
6									FALSE	FALSE
7										

	AC	AD	AK	AL	AQ	AR	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD
1	A2		Direct												Upstream	GREET V1.8c	
2	User		CO2		N2O Emission	CH4 Emission	Scope 1 Emissions						Total		CO2	N2O	CH4
3	Carbon Content (actual)	Units	Emission Factor	Units	Factor (g/MMBt	Factor (g/MMBt	CO2		N2O		CH4		CO2e		Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)
4			0.05	kg CO2 / SCF	0.1	5	**2,709,269**	kg	**5,106**	g	**255,302**	g	**2,717.17**	tonnes	5,257.73	0.09	196.36
5							**0**	kg	**0**	g	**0**	g	**0.00**	tonnes	#N/A	#N/A	#N/A
6							**0**	kg	**0**	g	**0**	g	**0.00**	tonnes	#N/A	#N/A	#N/A
7							**2,709,269**	kg	**5,106**	g	**255,302**	g	**2,717.17**	tonnes			

	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ
1	Fuel-Cycle?	YES										Scope	
2	Scope 3 Emissions						Total					1	
3	CO2		N2O		CH4		CO2e		**Cost ID**	**Cost-Eff. Baseline?**	**Cost ($/SF)**	**CO2e Emiss. Rate (kg/SF)**	**Cost-Eff. ($/tonne)**
4	**268,462**	kg	**4**	kg	**10,026**	kg	**520.43**	tonnes					
5	**0**	kg	**0**	kg	**0**	kg	**0.00**	tonnes					
6	**0**	kg	**0**	kg	**0**	kg	**0.00**	tonnes					
7	**268,462**	kg	**4**	kg	**10,026**	kg	**520.43**	tonnes					

Figure 50: MARTA GHG Emissions Inventory. Worksheet: Stat_Comb.

	A	B	C	D	H	N	O
1		Data Tier					
2		CO2, CH4, N2O	CO2, CH4, N2O		For Cost-Eff.		
3	**Facility**	**Activity**	**Em. Factor**	**Facility Energy Consumption (kWh)**	**Facility Area (SF)**	Electricity Grid Region	
4	Staions & Yards	A/B	B	83,525,011.06		state	GA
5	MARTA Headquarters	A/B	B	6,267,791.00		state	GA
6	Wachovia Building	A/B	B	6,093,039.00		state	GA
7	2622 PIEDMONT RD NE	A/B	B	10,200.00		state	GA
8	1600 PERRY BLVD NW	A/B	B	434,220.00		state	GA
9	5772 NEW PEACHTREE RD	A/B	B	45,330.00		state	GA
10	1600 PERRY BLVD NW	A/B	B	1,380,000.00		state	GA
11	0 FLAT SHOALS RD	A/B	B	56,645.00		state	GA
12	3056 CALDWELL RD NE	A/B	B	52,400.00		state	GA
13	277 LAREDO DR	A/B	B	851,120.00		state	GA
14	5936 NEW PEACHTREE RD	A/B	B	609,400.00		state	GA
15	1040 BRADY AVE NW	A/B	B	870,960.00		state	GA
16	1111 HAMMOND DR	A/B	B	272,440.00		state	GA
17	11405 N FULTON INDUSTRIAL	A/B	B	51,287.00		state	GA
18	12585 DRYDEN RD	A/B	B	89,943.00		state	GA
19	1378 MAYSON ST NE	A/B	B	32,454.00		state	GA
20	1424 MAYSON ST NE	A/B	B	35,880.00		state	GA
21	1600 PERRY BLVD NW	A/B	B	960,840.00		state	GA
22	240 STARLIGHT DR NE	A/B	B	22,980.00		state	GA
23	3385 HAMILTON BLVD	A/B	B	2,437.00		state	GA
24	3401 BROWNS MILL RD	A/B	B	2,643,200.00		state	GA
25	4000 OAKLEY ROAD EXT TOWER	A/B	B	51,320.00		state	GA
26	4115 STATEWOOD RD NE	A/B	B	31.00		state	GA
27	448 PLASAMOUR DR NE	A/B	B	318,960.00		state	GA
28	460 PLASAMOUR DR NE	A/B	B	78,320.00		state	GA

Figure 51: MARTA GHG Emissions Inventory. Worksheet: Purch_Elect.

	A	B	C	D	H	N	O
1		Data Tier					
2		CO2, CH4, N2O	CO2, CH4, N2O		For Cost-Eff.		
3	**Facility**	**Activity**	**Em. Factor**	**Facility Energy Consumption (kWh)**	**Facility Area (SF)**	Electricity Grid Region	
29	4747 GRANITE DR UNIT B	A/B	B	21,556.00		state	GA
30	500 PLASTER AVE NE	A/B	B	324,520.00		state	GA
31	3385 HAMILTON BLVD SW	A/B	B	1,910,160.00		state	GA
32	4200 MEMORIAL DR	A/B	B	37,014.00		state	GA
33	572 MOROSGO DR NE	A/B	B	30,720.00		state	GA
34	6110 NEW PEACHTREE RD	A/B	B	43,320.00		state	GA
35	6444 WATSON ST	A/B	B	1,125.00		state	GA
36	650 CANTERBURY RD NE	A/B	B	28,814.00		state	GA
37	3509 MAIN ST	A/B	B	34,588.00		state	GA
38	996 FIFTH ST	A/B	B	18,894.00		state	GA
39	227 LAREDO DR UNIT BOOTH	A/B	B	4,391.00		state	GA
40	227 LAREDO DR	A/B	B	2,534,560.00		state	GA
41	3385 HAMILTON BLVD	A/B	B	245,120.00		state	GA
42	1484 DEKALB AVE NE	A/B	B	1,171,760.00		state	GA
43	6190 NEW PEACHTREE RD	A/B	B	39,947.00		state	GA
44	0 DEKALB AVE NE UNIT GAPBK	A/B	B	5,680.00		state	GA
45	686 WINDSOR TER	A/B	B	46,200.00		state	GA
46	3401 BROWNS MILL RD SE	A/B	B	8,789.00		state	GA
47	0 MANSELL RD PARK	A/B	B	41,236.00		state	GA
48	7010 PEACHTREE DUNWOODY RD	A/B	B	85,861.00		state	GA
49	3401 BROWNS MILL RD	A/B	B	2,271.00		state	GA
50							
51				111,392,734.06			

Figure 52: MARTA GHG Emissions Inventory. Worksheet: Purch_Elect (cont.).

	Q	R	S	T	U	V	W	X	AH	AI
1		Direct								
2		CO2	CH4	N2O	Scope 2 Emissions				Scope 3 Emissions (powe	
3	**Emission Rate**	**Emission Factor (lbs/MWh) (default)**	**Emission Factor (lbs/GWh) (default)**	**Emission Factor (lbs/GWh) (default)**	**CO2 (kg)**	**CH4 (g)**	**N2O (g)**	**CO2e (tonnes)**	**Coal (default)**	**Oil (default)**
4		1402.5397	22.0169	23.9289	53,137,944.5	834.2	906.6	**53,138.2**	63.85%	0.74%
5		1402.5397	22.0169	23.9289	3,987,518.5	62.6	68.0	**3,987.5**	63.85%	0.74%
6		1402.5397	22.0169	23.9289	3,876,342.7	60.9	66.1	**3,876.4**	63.85%	0.74%
7		1402.5397	22.0169	23.9289	6,489.2	0.1	0.1	**6.5**	63.85%	0.74%
8		1402.5397	22.0169	23.9289	276,247.3	4.3	4.7	**276.2**	63.85%	0.74%
9		1402.5397	22.0169	23.9289	28,838.6	0.5	0.5	**28.8**	63.85%	0.74%
10		1402.5397	22.0169	23.9289	877,945.0	13.8	15.0	**877.9**	63.85%	0.74%
11		1402.5397	22.0169	23.9289	36,037.1	0.6	0.6	**36.0**	63.85%	0.74%
12		1402.5397	22.0169	23.9289	33,336.5	0.5	0.6	**33.3**	63.85%	0.74%
13		1402.5397	22.0169	23.9289	541,475.7	8.5	9.2	**541.5**	63.85%	0.74%
14		1402.5397	22.0169	23.9289	387,695.4	6.1	6.6	**387.7**	63.85%	0.74%
15		1402.5397	22.0169	23.9289	554,097.8	8.7	9.5	**554.1**	63.85%	0.74%
16		1402.5397	22.0169	23.9289	173,324.2	2.7	3.0	**173.3**	63.85%	0.74%
17		1402.5397	22.0169	23.9289	32,628.4	0.5	0.6	**32.6**	63.85%	0.74%
18		1402.5397	22.0169	23.9289	57,221.0	0.9	1.0	**57.2**	63.85%	0.74%
19		1402.5397	22.0169	23.9289	20,647.0	0.3	0.4	**20.6**	63.85%	0.74%
20		1402.5397	22.0169	23.9289	22,826.6	0.4	0.4	**22.8**	63.85%	0.74%
21		1402.5397	22.0169	23.9289	611,278.7	9.6	10.4	**611.3**	63.85%	0.74%
22		1402.5397	22.0169	23.9289	14,619.7	0.2	0.2	**14.6**	63.85%	0.74%
23		1402.5397	22.0169	23.9289	1,550.4	0.0	0.0	**1.6**	63.85%	0.74%
24		1402.5397	22.0169	23.9289	1,681,582.7	26.4	28.7	**1,681.6**	63.85%	0.74%
25		1402.5397	22.0169	23.9289	32,649.4	0.5	0.6	**32.6**	63.85%	0.74%
26		1402.5397	22.0169	23.9289	19.7	0.0	0.0	**0.0**	63.85%	0.74%
27		1402.5397	22.0169	23.9289	202,919.8	3.2	3.5	**202.9**	63.85%	0.74%
28		1402.5397	22.0169	23.9289	49,826.6	0.8	0.9	**49.8**	63.85%	0.74%

Figure 53: MARTA GHG Emissions Inventory. Worksheet: Purch_Elect (cont.).

	Q	R	S	T	U	V	W	X	AH	AI
1		Direct								
2		CO2	CH4	N2O	Scope 2 Emissions				Scope 3 Emissions (powe	
3	**Emission Rate**	**Emission Factor (lbs/MWh) (default)**	**Emission Factor (lbs/GWh) (default)**	**Emission Factor (lbs/GWh) (default)**	**CO2 (kg)**	**CH4 (g)**	**N2O (g)**	**CO2e (tonnes)**	**Coal (default)**	**Oil (default)**
29		1402.5397	22.0169	23.9289	13,713.8	0.2	0.2	**13.7**	63.85%	0.74%
30		1402.5397	22.0169	23.9289	206,457.0	3.2	3.5	**206.5**	63.85%	0.74%
31		1402.5397	22.0169	23.9289	1,215,228.5	19.1	20.7	**1,215.2**	63.85%	0.74%
32		1402.5397	22.0169	23.9289	23,548.0	0.4	0.4	**23.5**	63.85%	0.74%
33		1402.5397	22.0169	23.9289	19,543.8	0.3	0.3	**19.5**	63.85%	0.74%
34		1402.5397	22.0169	23.9289	27,559.8	0.4	0.5	**27.6**	63.85%	0.74%
35		1402.5397	22.0169	23.9289	715.7	0.0	0.0	**0.7**	63.85%	0.74%
36		1402.5397	22.0169	23.9289	18,331.2	0.3	0.3	**18.3**	63.85%	0.74%
37		1402.5397	22.0169	23.9289	22,004.6	0.3	0.4	**22.0**	63.85%	0.74%
38		1402.5397	22.0169	23.9289	12,020.2	0.2	0.2	**12.0**	63.85%	0.74%
39		1402.5397	22.0169	23.9289	2,793.5	0.0	0.0	**2.8**	63.85%	0.74%
40		1402.5397	22.0169	23.9289	1,612,466.8	25.3	27.5	**1,612.5**	63.85%	0.74%
41		1402.5397	22.0169	23.9289	155,943.4	2.4	2.7	**155.9**	63.85%	0.74%
42		1402.5397	22.0169	23.9289	745,464.3	11.7	12.7	**745.5**	63.85%	0.74%
43		1402.5397	22.0169	23.9289	25,414.0	0.4	0.4	**25.4**	63.85%	0.74%
44		1402.5397	22.0169	23.9289	3,613.6	0.1	0.1	**3.6**	63.85%	0.74%
45		1402.5397	22.0169	23.9289	29,392.1	0.5	0.5	**29.4**	63.85%	0.74%
46		1402.5397	22.0169	23.9289	5,591.5	0.1	0.1	**5.6**	63.85%	0.74%
47		1402.5397	22.0169	23.9289	26,234.0	0.4	0.4	**26.2**	63.85%	0.74%
48		1402.5397	22.0169	23.9289	54,624.1	0.9	0.9	**54.6**	63.85%	0.74%
49		1402.5397	22.0169	23.9289	1,444.8	0.0	0.0	**1.4**	63.85%	0.74%
50					0.0	0.0	0.0	**0.0**		
51					70,867,167.1	1,112.5	1,209.1	**70,867.6**		

Figure 54: MARTA GHG Emissions Inventory. Worksheet: Purch_Elect (cont.).

	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV
1													
2	r mix)							Scope 3 Emissions (plant efficiency)					
3	NG (default)	Nuclear (default)	Biomass (default)	Hydro (default)	Wind (default)	Other (default)	Other Carbon (default)	Coal	Oil	NG	Nuclear	Biomass	Hydro
4	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
5	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
6	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
7	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
8	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
9	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
10	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
11	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
12	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
13	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
14	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
15	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
16	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
17	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
18	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
19	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
20	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
21	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
22	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
23	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
24	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
25	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
26	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
27	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
28	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%

Figure 55: MARTA GHG Emissions Inventory. Worksheet: Purch_Elect (cont.).

	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV
1													
2	er mix)							Scope 3 Emissions (plant efficiency)					
3	NG (default)	Nuclear (default)	Biomass (default)	Hydro (default)	Wind (default)	Other (default)	Other Carbon (default)	Coal	Oil	NG	Nuclear	Biomass	Hydro
29	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
30	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
31	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
32	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
33	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
34	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
35	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
36	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
37	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
38	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
39	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
40	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
41	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
42	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
43	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
44	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
45	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
46	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
47	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
48	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
49	7.15%	23.08%	2.34%	2.80%	0.00%	0.00%	0.04%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
50								34.1%	34.8%	40.1%	100.0%	32.1%	100.0%
51													

Figure 56: MARTA GHG Emissions Inventory. Worksheet: Purch_Elect (cont.).

	AW	AX	AY	AZ	CL	CM	CN	CO	CP	CQ	CR	CS	CT
1					Fuel-Cycle?	YES						Scope	
2					Scope 3 Emissions							2	
3	**Wind**	**Other**	**Other Carbon**	**T&D Losses**	**CO2 (kg)**	**CH4 (kg)**	**N2O (g)**	**CO2e (tonnes)**	**Cost ID**	**Cost-Eff. Baseline?**	**Cost ($/SF)**	**CO2e Emiss. Rate (kg/SF)**	**Cost-Eff. ($/tonne)**
4	100.0%	34.0%	34.0%	8.0%	5,916,634.5	79,511.3	24,021.1	**7,911.6**					
5	100.0%	34.0%	34.0%	8.0%	443,989.5	5,966.6	1,802.6	**593.7**					
6	100.0%	34.0%	34.0%	8.0%	431,610.7	5,800.2	1,752.3	**577.1**					
7	100.0%	34.0%	34.0%	8.0%	722.5	9.7	2.9	**1.0**					
8	100.0%	34.0%	34.0%	8.0%	30,758.7	413.4	124.9	**41.1**					
9	100.0%	34.0%	34.0%	8.0%	3,211.0	43.2	13.0	**4.3**					
10	100.0%	34.0%	34.0%	8.0%	97,754.6	1,313.7	396.9	**130.7**					
11	100.0%	34.0%	34.0%	8.0%	4,012.5	53.9	16.3	**5.4**					
12	100.0%	34.0%	34.0%	8.0%	3,711.8	49.9	15.1	**5.0**					
13	100.0%	34.0%	34.0%	8.0%	60,290.5	810.2	244.8	**80.6**					
14	100.0%	34.0%	34.0%	8.0%	43,167.9	580.1	175.3	**57.7**					
15	100.0%	34.0%	34.0%	8.0%	61,695.9	829.1	250.5	**82.5**					
16	100.0%	34.0%	34.0%	8.0%	19,298.7	259.3	78.4	**25.8**					
17	100.0%	34.0%	34.0%	8.0%	3,633.0	48.8	14.7	**4.9**					
18	100.0%	34.0%	34.0%	8.0%	6,371.3	85.6	25.9	**8.5**					
19	100.0%	34.0%	34.0%	8.0%	2,298.9	30.9	9.3	**3.1**					
20	100.0%	34.0%	34.0%	8.0%	2,541.6	34.2	10.3	**3.4**					
21	100.0%	34.0%	34.0%	8.0%	68,062.7	914.7	276.3	**91.0**					
22	100.0%	34.0%	34.0%	8.0%	1,627.8	21.9	6.6	**2.2**					
23	100.0%	34.0%	34.0%	8.0%	172.6	2.3	0.7	**0.2**					
24	100.0%	34.0%	34.0%	8.0%	187,235.5	2,516.2	760.2	**250.4**					
25	100.0%	34.0%	34.0%	8.0%	3,635.3	48.9	14.8	**4.9**					
26	100.0%	34.0%	34.0%	8.0%	2.2	0.0	0.0	**0.0**					
27	100.0%	34.0%	34.0%	8.0%	22,594.1	303.6	91.7	**30.2**					
28	100.0%	34.0%	34.0%	8.0%	5,547.9	74.6	22.5	**7.4**					

Figure 57: MARTA GHG Emissions Inventory. Worksheet: Purch_Elect (cont.).

	AW	AX	AY	AZ	CL	CM	CN	CO	CP	CQ	CR	CS	CT
1					Fuel-Cycle?	YES						Scope	
2					Scope 3 Emissions							2	
3	**Wind**	**Other**	**Other Carbon**	**T&D Losses**	**CO2 (kg)**	**CH4 (kg)**	**N2O (g)**	**CO2e (tonnes)**	**Cost ID**	**Cost-Eff. Baseline?**	**Cost ($/SF)**	**CO2e Emiss. Rate (kg/SF)**	**Cost-Eff. ($/tonne)**
29	100.0%	34.0%	34.0%	8.0%	1,527.0	20.5	6.2	**2.0**					
30	100.0%	34.0%	34.0%	8.0%	22,987.9	308.9	93.3	**30.7**					
31	100.0%	34.0%	34.0%	8.0%	135,309.4	1,818.4	549.3	**180.9**					
32	100.0%	34.0%	34.0%	8.0%	2,621.9	35.2	10.6	**3.5**					
33	100.0%	34.0%	34.0%	8.0%	2,176.1	29.2	8.8	**2.9**					
34	100.0%	34.0%	34.0%	8.0%	3,068.6	41.2	12.5	**4.1**					
35	100.0%	34.0%	34.0%	8.0%	79.7	1.1	0.3	**0.1**					
36	100.0%	34.0%	34.0%	8.0%	2,041.1	27.4	8.3	**2.7**					
37	100.0%	34.0%	34.0%	8.0%	2,450.1	32.9	9.9	**3.3**					
38	100.0%	34.0%	34.0%	8.0%	1,338.4	18.0	5.4	**1.8**					
39	100.0%	34.0%	34.0%	8.0%	311.0	4.2	1.3	**0.4**					
40	100.0%	34.0%	34.0%	8.0%	179,539.8	2,412.8	728.9	**240.1**					
41	100.0%	34.0%	34.0%	8.0%	17,363.5	233.3	70.5	**23.2**					
42	100.0%	34.0%	34.0%	8.0%	83,003.6	1,115.5	337.0	**111.0**					
43	100.0%	34.0%	34.0%	8.0%	2,829.7	38.0	11.5	**3.8**					
44	100.0%	34.0%	34.0%	8.0%	402.4	5.4	1.6	**0.5**					
45	100.0%	34.0%	34.0%	8.0%	3,272.7	44.0	13.3	**4.4**					
46	100.0%	34.0%	34.0%	8.0%	622.6	8.4	2.5	**0.8**					
47	100.0%	34.0%	34.0%	8.0%	2,921.0	39.3	11.9	**3.9**					
48	100.0%	34.0%	34.0%	8.0%	6,082.1	81.7	24.7	**8.1**					
49	100.0%	34.0%	34.0%	8.0%	160.9	2.2	0.7	**0.2**					
50	100.0%	34.0%	34.0%	8.0%	0.0	0.0	0.0	**0.0**					
51					7,890,691.4	106,039.9	32,035.6	**10,551.2**					

Figure 58: MARTA GHG Emissions Inventory. Worksheet: Purch_Elect (cont.).

	A	B	C	D	E	F	G	H
1	**Vehicle Cost ID**		HR Veh.		HR Veh. Old		HR Veh. Rebld	
2		Fuel/energy type						
3		Vehicle/Equipment Lifetime	40	years	25	years	15	years
5		Beginning Year						
6		Salvage discount rate	10	% per year	10	% per year	10	% per year
7								
8	**Capital Costs**							
9		Vehicle purchase	$2,628,440.37		$1,500,000.00		$1,128,440.37	
10		Vehicle credit/grant		%		%		%
11		credit/grant	0		0		0	
12		Total vehicle purchase	$2,628,440.37		$1,500,000.00		$1,128,440.37	
27		**Total Capital Costs**	$2,628,440.37		$1,500,000.00		$1,128,440.37	
28		**Annualized Capital Costs**	$65,711.01		$60,000.00		$75,229.36	
29								
30	**Operating and Maintenace Costs (annual)**							
31								
36		Vehicle maintenance (parts)	$24,134.43	per year	$24,134.43	per year	$24,134.43	per year
37		Parts cost growth factor		*select*		*select*		*select*

	A	B	I	J	K	L	M	N
1	**Vehicle Cost ID**		Paratransit		CNG Orion 60		diesel Orion 10	
2		Fuel/energy type						
3		Vehicle/Equipment Lifetime	4	years	12	years	12	years
5		Beginning Year						
6		Salvage discount rate	10	% per year	10	% per year	10	% per year
7								
8	**Capital Costs**							
9		Vehicle purchase	$80,000.00		$285,900.00		$239,900.00	
10		Vehicle credit/grant		%		%		%
11		credit/grant	0		0		0	
12		Total vehicle purchase	$80,000.00		$285,900.00		$239,900.00	
27		**Total Capital Costs**	$80,000.00		$285,900.00		$239,900.00	
28		**Annualized Capital Costs**	$20,000.00		$23,825.00		$19,991.67	
29								
30	**Operating and Maintenace Costs (annual)**							
31								
36		Vehicle maintenance (parts)	$3,296.85	per year	$20,769.86	per year	$20,769.86	per year
37		Parts cost growth factor		*select*		*select*		*select*

Figure 59: MARTA GHG Emissions Inventory. Worksheet: Cost_Vehicle.

	A	B	O	P	Q	R	S	T
1	**Vehicle Cost ID**		CNG NF 94		CNG NF 55		diesel Orion 40	
2		Fuel/energy type						
3		Vehicle/Equipment Lifetime	12	years	12	years	12	years
5		Beginning Year						
6		Salvage discount rate	10	% per year	10	% per year	10	% per year
7								
8	**Capital Costs**							
9		Vehicle purchase	$270,892.00		$214,000.00		$259,650.00	
10		Vehicle credit/grant		%		%		%
11		credit/grant	0		0		0	
12		Total vehicle purchase	$270,892.00		$214,000.00		$259,650.00	
27		**Total Capital Costs**	$270,892.00		$214,000.00		$259,650.00	
28		**Annualized Capital Costs**	$22,574.33		$17,833.33		$21,637.50	
29								
30	**Operating and Maintenace Costs (annual)**							
31								
36		Vehicle maintenance (parts)	$20,769.86	per year	$20,769.86	per year	$20,769.86	per year
37		Parts cost growth factor		*select*		*select*		*select*

	A	B	U	V	W	X	Y	Z
1	**Vehicle Cost ID**		CNG Orion 30		CNG NF 101		CNG NF 81	
2		Fuel/energy type						
3		Vehicle/Equipment Lifetime	12	years	12	years	12	years
5		Beginning Year						
6		Salvage discount rate	10	% per year	10	% per year	10	% per year
7								
8	**Capital Costs**							
9		Vehicle purchase	$288,036.00		$297,123.00		$297,123.00	
10		Vehicle credit/grant		%		%		%
11		credit/grant	0		0		0	
12		Total vehicle purchase	$288,036.00		$297,123.00		$297,123.00	
27		**Total Capital Costs**	$288,036.00		$297,123.00		$297,123.00	
28		**Annualized Capital Costs**	$24,003.00		$24,760.25		$24,760.25	
29								
30	**Operating and Maintenace Costs (annual)**							
31								
36		Vehicle maintenance (parts)	$20,769.86	per year	$20,769.86	per year	$20,769.86	per year
37		Parts cost growth factor		*select*		*select*		*select*

Figure 60: MARTA GHG Emissions Inventory. Worksheet: Cost_Vehicle.

	A	B	AA	AB	AC	AD	AE	AF
1	**Vehicle Cost ID**		diesel NF 54		diesel NF 55		CNG NF 22	
2		Fuel/energy type						
3		Vehicle/Equipment Lifetime	12	years	12	years	10	years
5		Beginning Year						
6		Salvage discount rate	10	% per year	10	% per year	10	% per year
7								
8	**Capital Costs**							
9		Vehicle purchase	$271,075.00		$267,181.00		$235,377.00	
10		Vehicle credit/grant		%		%		%
11		credit/grant	0		0		0	
12		Total vehicle purchase	$271,075.00		$267,181.00		$235,377.00	
27		**Total Capital Costs**	$271,075.00		$267,181.00		$235,377.00	
28		**Annualized Capital Costs**	$22,589.58		$22,265.08		$23,537.70	
29								
30	**Operating and Maintenace Costs (annual)**							
31								
36		Vehicle maintenance (parts)	$20,769.86	per year	$20,769.86	per year	$20,769.86	per year
37		Parts cost growth factor		*select*		*select*		*select*

	A	B	AG	AH	AI	AJ	AK	AL
1	**Vehicle Cost ID**		Non-Rev diesel		Non-Rev gasoline		Non-Rev CNG	
2		Fuel/energy type						
3		Vehicle/Equipment Lifetime	12	years	12	years	12	years
5		Beginning Year						
6		Salvage discount rate	10	% per year	10	% per year	10	% per year
7								
8	**Capital Costs**							
9		Vehicle purchase	$100,000.00		$35,000.00		$35,000.00	
10		Vehicle credit/grant		%		%		%
11		credit/grant	0		0		0	
12		Total vehicle purchase	$100,000.00		$35,000.00		$35,000.00	
27		**Total Capital Costs**	$100,000.00		$35,000.00		$35,000.00	
28		**Annualized Capital Costs**	$8,333.33		$2,916.67		$2,916.67	
29								
30	**Operating and Maintenace Costs (annual)**							
31								
36		Vehicle maintenance (parts)		per year		per year		per year
37		Parts cost growth factor		*select*		*select*		*select*

Figure 61: MARTA GHG Emissions Inventory. Worksheet: Cost_Vehicle.

APPENDIX E: COST-EFFECTIVENESS EVALUATIONS

	A	B	C	D	E	F	G	H	J	K	P	S
1						Data Tiers						
2					CO2		N2O, CH4		User		User	Calc
3	Bus Number(s)	Model	Qty. of Buses	Fuel Type	Activity	Em. Fact.	Activity	Em. Fact.	Fuel Combustion (actual)	Units	Vehicle Miles (actual)	Fuel Econ. (mpg)
4	2880-2889	NF D60LF	10	diesel	A1/A2/B	B/C	A/B	A	139,996	gal	350,567	2.50
5	2780-2789	NF DE60LF hybrid	10	diesel	A1/A2/B	B/C	A/B	A	114,054	gal	362,049	3.17
6	2880-2889	NF D60LF	10	diesel	A1/A2/B	B/C	A/B	A	139,996	gal	350,567	2.50
7	2780-2789	NF DE60LF hybrid	10	diesel	A1/A2/B	B/C	A/B	A	114,054	gal	362,049	3.17

	W	X	AW	AX	BE	BF	BM	BN	BO	BP	BQ	BR	BS	BT
1			Direct											
2			CO2		N2O Emission	CH4 Emission	Scope 1 Emissions						Total	
3	Vehicle Category	Control Technology	Emission Factor	Units	Factor (g/mi.)	Factor (g/mi.)	CO2		N2O		CH4		CO2e	
4	Diesel Heavy-Duty Vehicles	Moderate	10.15	kg/gal	0.0048	0.0051	**1,420,959**	kg	**1,683**	g	**1,788**	g	**1,421.51**	tonnes
5	Diesel Heavy-Duty Vehicles	Moderate	10.15	kg/gal	0.0048	0.0051	**1,157,648**	kg	**1,738**	g	**1,846**	g	**1,158.21**	tonnes
6	Diesel Heavy-Duty Vehicles	Moderate	10.15	kg/gal	0.0048	0.0051	**1,420,959**	kg	**1,683**	g	**1,788**	g	**1,421.51**	tonnes
7	Diesel Heavy-Duty Vehicles	Moderate	10.15	kg/gal	0.0048	0.0051	**1,157,648**	kg	**1,738**	g	**1,846**	g	**1,158.21**	tonnes
8	Passenger-Miles (sum)						**5,157,215**	kg	**6,841**	g	**7,269**	g	**5,159.44**	tonnes

	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH	CI
1	Fuel-Cycle	GREET V1.8c		Include Fuel-Cycle?		YES							Manufacturing		
2	CO2	N2O	CH4	Scope 3 Emissions: Fuel-Cycle									CO2	N2O	CH4
3	Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)	Em. Fact. (g/MMBtu)	CO2		N2O		CH4		CO2e		EIO-LCA Sector / Vehicle Type	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)
4	15,487.71	0.25	104.53	**297,870**	kg	**5**	kg	**2,010**	kg	**349.55**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182
5	15,487.71	0.25	104.53	**242,673**	kg	**4**	kg	**1,638**	kg	**284.78**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182
6	15,487.71	0.25	104.53	**297,870**	kg	**5**	kg	**2,010**	kg	**349.55**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182
7	15,487.71	0.25	104.53	**242,673**	kg	**4**	kg	**1,638**	kg	**284.78**	tonnes	Heavy duty	0.6277	3.05034E-05	0.00182
8				**1,081,085**	kg	**17**	kg	**7,296**	kg	**1,268.66**	tonnes				

Figure 62: King County Metro hybrid bus GHG inventory and cost-effectiveness.

	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW	CX	CY	CZ	DA	DB
1	Maintenance			Include Veh.-Cycle?		YES													
2	CO_2	N_2O	CH_4	Scope 3 Emissions: Vehicle-Cycle								Scope 3 Emissions: Total							
3	Em. Fact. (kg/$)	Em. Fact. (kg/$)	Em. Fact. (kg/$)	CO_2		N_2O		CH_4		CO_2e		CO_2		N_2O		CH_4		CO_2e	
4	0.6916	4.46309E-05	0.002056	**344,785**	kg	**19**	kg	**1,008**	kg	**375.51**	tonnes	**642,655**	kg	**23**	kg	**3,018**	kg	**725.06**	tonnes
5	0.6916	4.46309E-05	0.002056	**448,563**	kg	**24**	kg	**1,309**	kg	**488.31**	tonnes	**691,236**	kg	**27**	kg	**2,947**	kg	**773.08**	tonnes
6	0.6916	4.46309E-05	0.002056	**344,785**	kg	**19**	kg	**1,008**	kg	**375.51**	tonnes	**642,655**	kg	**23**	kg	**3,018**	kg	**725.06**	tonnes
7	0.6916	4.46309E-05	0.002056	**448,563**	kg	**24**	kg	**1,309**	kg	**488.31**	tonnes	**691,236**	kg	**27**	kg	**2,947**	kg	**773.08**	tonnes
8				**1,586,697**	kg	**84**	kg	**4,633**	kg	**1,727.63**	tonnes	**2,667,782**	kg	**102**	kg	**11,930**	kg	**2,996.28**	tonnes

Figure 63: King County Metro hybrid bus GHG inventory and cost-effectiveness (cont.).

	DC	DD	DE	DF	DG	DH	DI
1						Scope	
2						1	
3	Vehicle Capital Cost ($)	Vehicle Maint. Cost ($)	Cost ID	Cost-Eff. Baseline?	Cost ($/mile)	CO2e Emiss. Rate (g/mile)	Cost-Eff. ($/tonne)
4	$370,833	$161,962	KCM diesel	yes	$2.31	4,055	
5	$537,500	$160,750	KCM hybrid		$2.55	3,199	$282.53
6	$370,833	$161,962	KCM diesel sub		$1.46	4,055	
7	$537,500	$160,750	KCM hybrid sub		$1.36	3,199	-$1,105.23

	DC	DD	DE	DF	DG	DH	DI
1						Scope	
2						1	
3	Vehicle Capital Cost ($)	Vehicle Maint. Cost ($)	Cost ID	Cost-Eff. Baseline?	Cost ($/mile)	CO2e Emiss. Rate (g/mile)	Cost-Eff. ($/tonne)
4	$370,833	$161,962	KCM diesel		$2.31	4,055	
5	$537,500	$160,750	KCM hybrid		$2.55	3,199	$1,271.34
6	$370,833	$161,962	KCM diesel sub	yes	$1.46	4,055	
7	$537,500	$160,750	KCM hybrid sub		$1.36	3,199	-$116.43

Figure 64: King County Metro hybrid bus GHG inventory and cost-effectiveness (cont.).

	A	B	C	D	E	F
1	**Vehicle Cost ID**		KCM diesel		KCM hybrid	
2		Fuel/energy type				
3		Vehicle/Equipment Lifetime	12	years	12	years
4		Age	0	years	0	years
5		Beginning Year				
6		Salvage discount rate		% per year		% per year
7						
8	**Capital Costs**					
9		Vehicle purchase	$445,000.00		$645,000.00	
10		Vehicle credit/grant				
11		credit/grant	0		0	
12		Total vehicle purchase	$445,000.00		$645,000.00	
13		Vehicle salvage value				
27		**Total Capital Costs**	$445,000.00		$645,000.00	
28		**Annualized Capital Costs**	$37,083.33		$53,750.00	
29						
30	**Operating and Maintenace Costs (annual)**					
31						
32		Vehicle operator (labor)		per year		per year
33		Labor cost growth factor		$ per year		*select*
34		Vehicle maintenance (labor)		per mile		per mile
35		Labor cost growth factor		*select*		*select*
36		Vehicle maintenance (parts)	$0.462	per mile	$0.444	per mile
37		Parts cost growth factor		*select*		*select*
38		Vehicle Fuel	$0.791	per mile	$0.624	per mile
39		Fuel cost growth factor		*select*		*select*

	A	B	G	H	I	J
1	**Vehicle Cost ID**		KCM diesel sub		KCM hybrid sub	
2		Fuel/energy type				
3		Vehicle/Equipment Lifetime	12	years	12	years
4		Age	0	years	0	years
5		Beginning Year				
6		Salvage discount rate		% per year		% per year
7						
8	**Capital Costs**					
9		Vehicle purchase	$445,000.00		$645,000.00	
10		Vehicle credit/grant	80	%	80	%
11		credit/grant	356000		516000	
12		Total vehicle purchase	$89,000.00		$129,000.00	
13		Vehicle salvage value				
27		**Total Capital Costs**	$89,000.00		$129,000.00	
28		**Annualized Capital Costs**	$7,416.67		$10,750.00	
29						
30	**Operating and Maintenace Costs (annual)**					
31						
32		Vehicle operator (labor)		per year		per year
33		Labor cost growth factor		*select*		*select*
34		Vehicle maintenance (labor)		per mile		per mile
35		Labor cost growth factor		*select*		*select*
36		Vehicle maintenance (parts)	$0.462	per mile	$0.444	per mile
37		Parts cost growth factor		*select*		*select*
38		Vehicle Fuel	$0.791	per mile	$0.624	per mile
39		Fuel cost growth factor		*select*		*select*

Figure 65: King County Metro hybrid bus cost profiles.

	A	B	C	D	H	N	O	P
1		Data Tier						
2		CO2, CH4, N2O	CO2, CH4, N2O		For Cost-Eff.			
3	**Facility**	**Activity**	**Em. Factor**	**Facility Energy Consumption (kWh)**	**Facility Area (SF)**	Electricity Grid Region		
4	Grand Central Terminal	A/B	B	980,000.00	1,000,000	eGRID subregi	NYCW	NPCC NYC/Westchester
5	Grand Central Terminal (CFL)	A/B	B		1,000,000	eGRID subregi	NYCW	NPCC NYC/Westchester
6				980,000.00				

	Q	R	S	T	U	V	W	X	AH	AI	AJ	AK	AL	AM
1		Direct												
2		CO2	CH4	N2O	Scope 2 Emissions				Scope 3 Emissions (power mix)					
3	**Emission Rate**	**Emission Factor (lbs/MWh) (default)**	**Emission Factor (lbs/GWh) (default)**	**Emission Factor (lbs/GWh) (default)**	**CO2 (kg)**	**CH4 (g)**	**N2O (g)**	**CO2e (tonnes)**	**Coal (default)**	**Oil (default)**	**NG (default)**	**Nuclear (default)**	**Biomass (default)**	**Hydro (default)**
4	Non-Baseload	1525.0547	56.8005	9.0818	677,929.5	25.2	4.0	**677.9**	0.00%	20.21%	34.93%	43.82%	0.54%	0.02%
5	Non-Baseload	1525.0547	56.8005	9.0818	0.0	0.0	0.0	**0.0**	0.00%	20.21%	34.93%	43.82%	0.54%	0.02%
6					677,929.5	25.2	4.0	**677.9**						

	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	CL	CM	CN	CO
1														Fuel-Cycle?	YES		
2				Scope 3 Emissions (plant efficiency)										Scope 3 Emissions			
3	**Wind (default)**	**Other (default)**	**Other Carbon (default)**	**Coal**	**Oil**	**NG**	**Nuclear**	**Biomass**	**Hydro**	**Wind**	**Other**	**Other Carbon**	**T&D Losses**	**CO2 (kg)**	**CH4 (kg)**	**N2O (g)**	**CO2e (tonnes)**
4	0.00%	0.00%	0.48%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%	100.0%	34.0%	34.0%	8.0%	97,886.5	768.3	640.5	**117.3**
5	0.00%	0.00%	0.48%	34.1%	34.8%	40.1%	100.0%	32.1%	100.0%	100.0%	34.0%	34.0%	8.0%	0.0	0.0	0.0	**0.0**
6														97,886.5	768.3	640.5	**117.3**

Figure 66: NY MTA Grand Central Terminal lighting replacement GHG estimation and cost-effectiveness.

	CP	CQ	CR	CS	CT
1				Scope	
2				2	
3	**Cost ID**	**Cost-Eff. Baseline?**	**Cost ($/SF)**	**CO2e Emiss. Rate (kg/SF)**	**Cost-Eff. ($/tonne)**
4	Base Facility	yes	0.16	0.68	
5	CFL Lights		0.01	0.00	-$215.58

Figure 67: NY MTA Grand Central Terminal lighting replacement GHG estimation and cost-effectiveness (cont.).

Facility Cost ID	Base Facility		CFL Lights	
Fuel/energy type				
Facility Strategy Lifetime	1	years	1	years
Beginning Year	2008		2008	
Salvage discount rate		% per year	10	% per year
Capital Costs				
Facility construction/renovation	$10,200.00		$11,050.00	
Facility credit/grant				
credit/grant	0		0	
Total facility const./renov.	$10,200.00		$11,050.00	
Facility salvage value				
Equipment purchase				
Equipment credit/grant		*select*		*select*
credit/grant	0		0	
Total equipment purchase	$0.00		$0.00	
Equipment salvage value				
Total Capital Costs	$10,200.00		$11,050.00	
Annualized Capital Costs	$10,200.00		$11,050.00	
Operating and Maintenace Costs (annual)				
Facility Energy	$147,000.000	per year	$0.000	per year
Fuel cost growth factor		*select*		*select*

Figure 68: NY MTA Grand Central Terminal lighting replacement cost profiles.

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