Title
Life-cycle Environmental Inventory of Passenger Transportation in the United States

Permalink
https://escholarship.org/uc/item/7n29n303

Author
Chester, Mikhail V

Publication Date
2008-08-01

Institute of Transportation Studies
Dissertations
(University of California, Berkeley)

Year 2008 *Paper UCB-ITS-DS-2008-1*

Life-cycle Environmental Inventory of Passenger Transportation in the United States

Mikhail V. Chester
Institute of Transportation Studies, Berkeley

Life-cycle Environmental Inventory of Passenger Transportation in the United States

Abstract

Energy use and emission factors for passenger transportation modes typically ignore the total environmental inventory which includes vehicle non-operational components (e.g., vehicle manufacturing and maintenance), infrastructure components, and fuel production components from design through end-of-life processes. A life-cycle inventory for each mode is necessary to appropriately address and attribute the transportation sector's energy and emissions impacts to reduction goals instead of allowing tailpipe emissions to act as indicators of total system performance.

The contributions of U.S. passenger transportation modes to national energy and emissions inventories account for roughly 20% of U.S. totals, mostly attributed to gasoline consumption. Furthermore, world consumption of primary energy amounted to 490 EJ in 2005 with the U.S. responsible for 110 EJ, or 21% of the total. This means that passenger transportation in the U.S. accounts for roughly 5% of global primary energy consumption annually. With a predominant fossil fuel energy base, the impacts of U.S. passenger transportation have strong implications for global energy consumption, U.S. energy security, and climate change. Furthermore, criteria air pollutant emissions from transportation (passenger and freight) are also significant, accounting for 78% of national CO, 58% of NOX, 36% of VOCs, 9% of PM2.5, 2.6% of PM10, and 4.5% of SO2 emissions. These emissions often occur near population centers and can cause adverse direct human health effects as well as other impacts such as ground-level ozone formation and acid deposition.

To appropriately mitigate environmental impacts from transportation, it is necessary for decision makers to consider the life-cycle energy consumption and emissions associated with each mode. A life-cycle energy, greenhouse gas, and criteria air pollutant emissions inventory is created for the passenger transportation modes of automobiles, urban buses, heavy rail transit, light rail transit, and aircraft in the U.S. Each mode's inventory includes an assessment of vehicles, infrastructure, and fuel components. For each component, analysis is performed for material extraction through use and maintenance in both direct and indirect (supply chain) processes.

For each mode's life-cycle components, energy inputs and emission outputs are determined. Energy inputs include electricity and petroleum-based fuels. Emission outputs include greenhouse gases (CO2, CH4, and N2O) and criteria pollutants (CO, SO2, NOX, VOCs, and PM). The inputs and outputs are normalized by vehicle lifetime, vehicle mile traveled, and passenger mile traveled. A consistent system boundary is applied to all modal inventories which captures the entire life-cycle, except for end-of-life. For each modal life-cycle component, both direct and indirect processes are included if possible. A hybrid life-cycle assessment approach is used to estimate the components in the inventories. We find that life-cycle energy inputs and emission outputs increase significantly compared to the vehicle operational phase. Life-cycle energy consumption is 39-56% larger than vehicle operation for autos, 38% for buses, 93-160% for rail, and 19-24% for air systems per passenger mile traveled. Life-cycle greenhouse gas emissions are 47-65% larger than vehicle operation for autos, 43% for buses, 39-150% for rail, and 24-31% for air systems per passenger mile traveled. The energy and greenhouse gas increases are primarily due to vehicle manufacturing and maintenance, infrastructure construction, and fuel production. For criteria air pollutants, life-cycle components often dominate total emissions and can be a magnitude larger than operational counterparts. Per passenger mile traveled, total SO2 emissions (between 350 and 460 mg) are 19-27 times larger than operational emissions as a result of electricity generation in vehicle manufacturing, infrastructure construction, and fuel production. NOX emissions increase 50-73% for automobiles, 24% for buses, 13-1300% for rail, and 19-24% for aircraft. Non-tailpipe VOCs are 27-40% of total automobile, 71-95% of rail, and 51-81% of air total emissions. Infrastructure and parking construction are major components of total PM10 emissions resulting in total emissions over three times larger than operational emissions for autos and even larger for many rail systems and aircraft (the major contributor being emissions from hot-mix asphalt plants and concrete production). Infrastructure construction and operation as well as vehicle manufacturing increase total CO emissions by 5-17 times from tailpipe performance for rail and 3-9 times for air.

A case study comparing the environmental performance of metropolitan regions is presented as an application of the inventory results. The San Francisco Bay Area, Chicago, and New York City are evaluated capturing passenger transportation life-cycle energy inputs and greenhouse gas and criteria air pollutant emissions. The regions are compared between off-peak and peak travel as well as personal and public transit. Additionally, healthcare externalities are computed from vehicle emissions. It is estimated that life-cycle energy varies from 6.3 MJ/PMT in the Bay Area to 5.7 MJ/PMT in Chicago and 5.3 MJ/PMT in New York for an average trip. Life-cycle GHG emissions range from 480 g C02e/PMT in the Bay Area to 440 g C02e/PMT for Chicago and 410 g C02e/PMT in New York. CAP emissions vary depending on the pollutant with differences as large as 25% between regions. Life-cycle CAP emissions are between 11% and 380% larger than their operational counterparts. Peak travel, with typical higher riderships, does not necessarily environmentally outperform off-peak travel due to the large share of auto PMT and less than ideal operating conditions during congestion. The social costs of travel range from 51 cent (in 2007 cents) per auto passenger per trip during peak in New York to 6 cents per public transit passenger per trip during peak hours in the Bay Area and New York. Average personal transit costs are around 30 cents while public transit ranges from 28 cents to 41 cents.

This dissertation was completed with Professor Arpad Horvath serving as the advisor. This document supercedes the University of California, Berkeley, Center for Future Urban Transport papers, vwp-2007-7 and vwp-2008-2. Additional project information can be found at http://www.sustainable-transportation.com.

Life-cycle Environmental Inventory of Passenger Transportation in the United States

Mikhail Vin Chester

DISSERTATION SERIES
UCB-ITS-DS-2008-1

Fall 2008
ISSN 0192 4109

Version note: This document was posted in August 2008. An update to Table 25 occurred in March 2009.

Life-cycle Environmental Inventory of Passenger Transportation Modes in the United States

by

Mikhail Vin Chester

B.S. (Carnegie Mellon University) 2002

M.S. (Carnegie Mellon University) 2003

M.S. (University of California, Berkeley) 2005

A dissertation submitted in partial satisfaction of the requirements for the degree of

Doctor of Philosophy

in

Engineering – Civil and Environmental Engineering

at the

University of California, Berkeley

Committee in Charge

Professor Arpad Horvath (Chair)

Professor Samer Madanat

Professor Catherine Koshland

Fall 2008

This dissertation of Mikhail Chester is approved:

7/31/08

Professor Arpad Horvath (Chair) Date

Samer Madanat 8/5/08

Professor Samer Madanat Date

Catherine P. Koshland 8/7/08

Professor Catherine Koshland Date

University of California, Berkeley

Fall 2008

Abstract

Life-cycle Environmental Inventory of Passenger Transportation in the United States

by

Mikhail Vin Chester

Doctor of Philosophy in Engineering – Civil and Environmental Engineering

University of California, Berkeley

Professor Arpad Horvath, Chair

Energy use and emission factors for passenger transportation modes typically ignore the total environmental inventory which includes vehicle non-operational components (e.g., vehicle manufacturing and maintenance), infrastructure components, and fuel production components from design through end-of-life processes. A life-cycle inventory for each mode is necessary to appropriately address and attribute the transportation sector's energy and emissions impacts to reduction goals instead of allowing tailpipe emissions to act as indicators of total system performance.

The contributions of U.S. passenger transportation modes to national energy and emissions inventories account for roughly 20% of U.S. totals, mostly attributed to gasoline consumption. Furthermore, world consumption of primary energy amounted to 490 EJ in 2005 with the U.S. responsible for 110 EJ, or 21% of the total. This means that passenger transportation in the U.S. accounts for roughly 5% of global primary energy consumption annually. With a predominant fossil fuel energy base, the impacts of U.S. passenger transportation have strong implications for

global energy consumption, U.S. energy security, and climate change. Furthermore, criteria air pollutant emissions from transportation (passenger and freight) are also significant, accounting for 78% of national CO, 58% of NO_X, 36% of VOCs, 9% of $PM_{2.5}$, 2.6% of PM_{10}, and 4.5% of SO_2 emissions. These emissions often occur near population centers and can cause adverse direct human health effects as well as other impacts such as ground-level ozone formation and acid deposition.

To appropriately mitigate environmental impacts from transportation, it is necessary for decision makers to consider the life-cycle energy consumption and emissions associated with each mode. A life-cycle energy, greenhouse gas, and criteria air pollutant emissions inventory is created for the passenger transportation modes of automobiles, urban buses, heavy rail transit, light rail transit, and aircraft in the U.S.. Each mode's inventory includes an assessment of vehicles, infrastructure, and fuel components. For each component, analysis is performed for material extraction through use and maintenance in both direct and indirect (supply chain) processes.

For each mode's life-cycle components, energy inputs and emission outputs are determined. Energy inputs include electricity and petroleum-based fuels. Emission outputs include greenhouse gases (CO_2, CH_4, and N_2O) and criteria pollutants (CO, SO_2, NO_X, VOCs, and PM). The inputs and outputs are normalized by vehicle lifetime, vehicle mile traveled, and passenger mile traveled. A consistent system boundary is applied to all modal inventories which captures the entire life-cycle, except for end-of-life. For each modal life-cycle component, both direct and indirect processes are included if possible. A hybrid life-cycle assessment approach is used to estimate the components in the inventories.

We find that life-cycle energy inputs and emission outputs increase significantly compared to the vehicle operational phase. Life-cycle energy consumption is 39-56% larger than vehicle operation for autos, 38% for buses, 93-160% for rail, and 19-24% for air systems per passenger mile traveled. Life-cycle greenhouse gas emissions are 47-65% larger than vehicle operation for autos, 43% for buses, 39-150% for rail, and 24-31% for air systems per passenger mile traveled. The energy and greenhouse gas increases are primarily due to vehicle manufacturing and maintenance, infrastructure construction, and fuel production. For criteria air pollutants, life-cycle components often dominate total emissions and can be a magnitude larger than operational counterparts. Per passenger mile traveled, total SO_2 emissions (between 350 and 460 mg) are 19-27 times larger than operational emissions as a result of electricity generation in vehicle manufacturing, infrastructure construction, and fuel production. NO_X emissions increase 50-73% for automobiles, 24% for buses, 13-1300% for rail, and 19-24% for aircraft. Non-tailpipe VOCs are 27-40% of total automobile, 71-95% of rail, and 51-81% of air total emissions. Infrastructure and parking construction are major components of total PM_{10} emissions resulting in total emissions over three times larger than operational emissions for autos and even larger for many rail systems and aircraft (the major contributor being emissions from hot-mix asphalt plants and concrete production). Infrastructure construction and operation as well as vehicle manufacturing increase total CO emissions by 5-17 times from tailpipe performance for rail and 3-9 times for air.

A case study comparing the environmental performance of metropolitan regions is presented as an application of the inventory results. The San Francisco Bay Area, Chicago, and New York City are evaluated capturing passenger transportation life-cycle energy inputs and greenhouse gas and criteria air pollutant emissions. The regions are compared between off-peak and peak travel as well as personal and public transit. Additionally, healthcare externalities are computed from

vehicle emissions. It is estimated that life-cycle energy varies from 6.3 MJ/PMT in the Bay Area to 5.7 MJ/PMT in Chicago and 5.3 MJ/PMT in New York for an average trip. Life-cycle GHG emissions range from 480 g CO_2e/PMT in the Bay Area to 440 g CO_2e/PMT for Chicago and 410 g CO_2e/PMT in New York. CAP emissions vary depending on the pollutant with differences as large as 25% between regions. Life-cycle CAP emissions are between 11% and 380% larger than their operational counterparts. Peak travel, with typical higher riderships, does not necessarily environmentally outperform off-peak travel due to the large share of auto PMT and less than ideal operating conditions during congestion. The social costs of travel range from ¢51 (in ¢2007) per auto passenger per trip during peak in New York to ¢6 per public transit passenger per trip during peak hours in the Bay Area and New York. Average personal transit costs are around ¢30 while public transit ranges from ¢28 to ¢41.

7/31/08

Professor Arpad Horvath (Chair)

Date

Table of Contents

Dedication and Acknowledgements

With each accomplishment, the more I realize the importance of surrounding myself with the right individuals to give me appropriate direction and constructive challenges to help me grow and succeed. As I reach the conclusion of my doctoral work, I realize that I have been fortunate enough to have had exposure to many of these individuals, each of which has made contributions pieces to my mental fabric. Through their collective efforts, I have been provided a strong personal foundation. The completion of this doctoral work lies significantly on the efforts of these individuals, some of which I would like to acknowledge.

The pursuit of my doctoral work was made possible by Professor Arpad Horvath, to which I am forever grateful. Professor Horvath has served as the finest of mentors continually encouraging me towards higher goals. His advising has been nothing short of exceptional giving me an appreciation for how much more difficult the work in this thesis could have been. His insight into how best to address problems encountered during my research and also which critical issues were most important to tackle, provide much of the backbone that makes this work as strong as it is. His unending thoughts on what other ways we can use this work, how else we should look at results, and his selfless giving of time provided me with much of the fuel that was needed to continually improve my approaches to the problems I faced. As my doctoral work comes to a close, I hope to approach my future work with the same determination and sharp problem solving that Professor Horvath has shown me.

I am very grateful to my dissertation committee members, Professor Samer Madanat and Professor Catherine Koshland. Professor Madanat helped me to define the scope of the project, address critical transportation components, and continually improve my approach. The efforts of Professor Koshland under challenging circumstances were extraordinary. Her efforts exemplify the ideals of cooperation that make the University an environment that promotes academic excellence. The involvement of Professor Alex Farrell also contributed to the defining of this thesis as he helped to illuminate several of the key issues that this work now addresses.

My graduate academic career began and took off with several professors at Carnegie Mellon University. These professors cultivated my interests and took an active role in helping to provide for me an environment where I could grow as an academic. Professor Chris Hendrickson and Professor Scott Matthews are two professors in particular to whom I am especially appreciative.

The efforts of my mother and father have provided me with the personal foundation and determination to which most of my success lies. My parents, both educators, provided for me an environment where intelligence is valued more than many other qualities. From an early age, I was exposed to many different types of people helping me to expand my appreciation for diversity of thought. I was also pushed to try many different activities, both in and out of academic environments, helping me to develop a strong base for problem solving. My mother, Teresa Vinagre, imparted on me the importance of accepting people and their beliefs, a lesson that became invaluable during my doctoral career as I worked with a lot of talented individuals. And my father, Dr. Mitchell Chester, who with a penchant for mathematics and sciences, helped me to excel in these fields. This included staying up with me to finish my mathematics' homework assignment that I had remembered the night before they were due, and speaking to my elementary school math teacher when I had not been selected to join the advanced math group. My success is a great deal the result of the love and support of my parents.

My family members have all served as positive forces for me. My grandmother, Zelda Chester, and grandfather, Dr. Herbert Chester, helped me to understand the importance of continually educating yourself throughout life. My sister, Sarah-Beth Chester, served as my partner-in-crime for all of our childhood experiments. My uncle, Philip Chester, exposed me to engineering starting the path I am on today. My stepmother, Angela Sangeorge, has always made me feel like I was on my way to doing great things. And my stepfather, John Kowalski, has always taken an interest in my activities, helping to encourage me, despite always being far away.

I am also grateful to have been a part of two of the finest academic institutions in the world, and with that, some of the smartest individuals. I am fortunate to consider many of these people my colleagues. As I have tackled the day-to-day setbacks of a dissertation, these individuals have served as a sounding board for my ideas. Despite their sometimes foreign relationship to my field of work, I have found that they have always welcomed the challenge of the problems I am posing and not accepted my answers as the best solution. These individuals include Sebastien Humbert, Kofi Inkabi, Elliot Martin, Megan Smirti, Dr. Jennifer Stokes-Draught, and Dr. Pedro Vieira.

Lastly, this work would not be possible without the funding of two organizations: the University of California Transportation Center and the University of California, Berkeley, Institute of Transportation Studies Volvo Center for Future Urban Transport.

List of Figures

List of Tables

List of Equations

Table of Acronyms and Symbols

\$	2005 U.S. dollars unless year stated otherwise
$I/O_{\gamma}^{\alpha,\beta}$	Input or Output for mode (α), system component (β), and functional unit (γ). Modes (α) are onroad (autos and buses), rail, and air. Functional units (γ) are per vehicle lifetime, VMT, and PMT.
¢	2005 U.S. cents unless year stated otherwise
§	Section in document
µ	Mean for quantity. Micro (10^{-6}) for unit.
B	Billion (10^{9})
BART	Bay Area Rapid Transit
CAHSR	California High Speed Rail
CAP	Criteria Air Pollutants
CO	Carbon Monoxide
E	Exa (10^{18})
EF	Emission Factor
EIO-LCA	Economic Input-Output Life-cycle Assessment
EPA	U.S. Environmental Protection Agency
FAA	U.S. Federal Aviation Administration
g	Gram
G	Giga (10^{9})
GGE	Greenhouse Gas Equivalence
GHG	Greenhouse Gases
Green Line	Massachusetts Bay Transportation Authority Green Line Light Rail
HC	Hydrocarbons
ISO	International Standards Organization
J	Joule
lb	Pound (equivalent to 453.6 grams)
LCA	Life-cycle Assessment

LCI	Life-cycle Inventory
LTO	Landing-Takeoff Cycle
M	Million (10^6)
mt	Metric Tonne
Muni	San Francisco Municipal Railway Light Rail
NO_X	Nitrogen Oxides
P	Peta (10^{15})
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
Pax	Passengers
Pb	Lead
PMT	Passenger Mile(s) Traveled
PM_X	Particulate Matter (subscript denotes particle diameter in microns, 10^{-6} meters)
SO_2	Sulfur Dioxide
T	Tera (10^{12})
Tonne	Metric Tonne (mt)
VMT	Vehicle Mile(s) Traveled
VOC	Volatile Organic Compound
Wh	Watt-Hour (where 1 watt = 1 joule × second^{-1} and 1 kWh = 3.6 megajoules)

Thesis Documentation

This dissertation supersedes the following papers:

- Chester, M.; Horvath, A.; Environmental Life-cycle Assessment of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas, and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air (v2); University of California, Berkeley, Institute of Transportation Studies, 2008, Working Paper, UCB-ITS-VWP-2008-2;
  http://repositories.cdlib.org/its/future_urban_transport/vwp-2008-2/

- Chester, M.; Horvath, A.; Environmental Life-cycle Assessment of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas, and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air; University of California, Berkeley, Institute of Transportation Studies, 2007, Working Paper, UCB-ITS-VWP-2007-7;
  http://repositories.cdlib.org/its/future_urban_transport/vwp-2007-7/

- Horvath, A.; Chester, M.; Environmental Life-cycle Assessment of Passenger Transportation: An Energy, Greenhouse Gas, and Criteria Pollutant Inventory of Rail and Air Transportation; University of California Transportation Center, 2007;
  http://www.uctc.net/papers/844.pdf

While the results in this dissertation may not have changed from the results in the working papers for some inventory components, this dissertation represents a final presentation of all results and documentation of the study.

This dissertation is complemented by a manuscript submitted for publication with the tentative title "Energy and Emissions Inventory for Automobiles, Buses, Trains, and Aircraft" by Mikhail Chester and Arpad Horvath. At the date of submittal of this dissertation, the manuscript was in the peer review process.

The inventory results presented in §1 of this thesis are based on the models 20080814/compiled, 20080724/onroad, 20080805/rail, and 20080714/air.

The case study results presented in §2 of this thesis are based on the model 20080811/analysis.

This dissertation was submitted on Friday, August 15, 2008.

1 Life-cycle Environmental Inventory of Automobiles, Buses, Rail, and Aircraft

1.1 Problem Statement

Passenger transportation modes encompass a variety of options for moving people from sources to destinations. Although the automobile is the most widely used transportation vehicle in the United States, passengers often have the alternatives of using buses, rail, air or other modes at economically reasonable prices for their trips. Within urban areas, infrastructure is typically in place for cars, buses, metro, and light rail [Levinson 1998b, Madison 1996, Small 1995, Verhoef 1994]. For traveling longer distances, between regions or states, cars, buses, heavy rail, and air infrastructure provide passengers with affordable modes of transport [Mayeres 1996].

A few studies have already been published on the life-cycle environmental effects of automobiles [MacLean 1998, Sullivan 1998, Delucchi 1997]. However, a comprehensive, systematic study of the life-cycle environmental effects of passenger modes in the United States has not yet been published. The environmental impacts of passenger transportation modes are typically understood at the operational level. In quantifying energy impacts and emissions, these modes have been analyzed at the vehicle level. To fully understand the system-wide, comprehensive environmental implications, analysis should be performed on the other life-cycle phases of these modes as well: design, raw materials extraction, manufacturing, construction, operation, maintenance, and end-of-life of the vehicles, infrastructure, and fuels.

As concern grows for the mounting energy and environmental costs associated with passenger transportation, a total inventory is needed to fully evaluate the impacts of transport habits in the U.S.. Currently, passenger and freight transport account for 30% of national energy consumption [Davis 2007]. Passenger transportation is roughly two-thirds of this, amounting to 20% of national energy consumption [Davis 2007]. Assuming that certain emissions, particularly GHGs, are directly correlated with energy consumption (given that nearly all transport fuels are fossil based carbon inputs) then transportation emissions are responsible for a large fraction of total U.S. emissions. Additionally, the U.S. is responsible for nearly 25% of world energy consumption [Davis 2007]. This means that U.S. passenger transportation consumes roughly 5% of the world's annual energy. The implications of such a habit should have profound effects in the development of any policy or regulatory framework.

While the externalities of energy inputs are important, so are the externalities of emission outputs. Outside of the potential global impacts from GHG emissions and climate change, CAP emissions pose direct human health effects and are often inequitably burdened on populations. Those who drive vehicles are not usually the individuals who inhale the emissions. And vehicles are often driven near populations which may inhale the emissions. In the U.S., 20% of land is within 500 m of a paved roadway [NGN 2002]. Several studies highlight the impacts of driving on the health of nearby populations [Matthews 2001, Marshall 2003, Marshall 2005, NYT 2006, English 1999]. These studies identify instances when people living near roadways experience adverse health effects from the emissions of vehicles.

Developing transportation policy at the "tail-pipe" may prove effective but could also lead to additional costs not considered by the decision makers. Policy decisions on transportation fuels are good examples of problems associated with "tail-pipe" approaches ignoring full cost accounting. While the removal of tetraethyllead (which started in 1973 after the compound was accepted as harmful to human brain development) and the reduction of sulfur from diesel fuels (which began in 2005) yielded overall human health benefits, the benefits of other policy decisions are questionable. The 1990 Clean Air Act amendment stipulated a 2% oxygen requirement for fuels (to reduce ground-level ozone and human health impacts through VOC releases) without rigorous assessment of which chemicals should be used. Methyl Tertiary Butyl Ether (MTBE), which was easily manufactured from refinery byproducts, was the preferred oxygenate additive given its low production costs and previous use during the phase out of tetraethyllead. Life-cycle environmental accounting was not performed on MTBE and the result of implementation was contaminated water supplies due the chemical's high vapor pressure, water solubility, and weak partition to soil. The short term exposure effects may be nose and throat irritation, headaches, nausea, and dizziness while the long term effects are still under study [CDC 1997]. The contamination of water supplies coupled with the chemical's potential health risks resulted in a phasing out of MTBE and a replacement by ethanol, an additive in abundant supply in a nation with large corn crops. Only recently have the full benefits and costs of ethanol begun to be studied [Farrell 2006]. Implementation of fuel policies considering only vehicle operation and ignoring anything outside of that scope is profoundly short-sighted. As new technologies mature (such as electric and hydrogen vehicles), this approach cannot continue to be used.

1.2 Literature Survey

There has not been a comprehensive life-cycle analysis comparing the passenger transportation modes of automobiles, buses, HRT, LRT, and air. Many studies have been performed relating to automobiles and their infrastructure but these tend to focus on the operations stage in the life-cycle. Automobiles have been evaluated through many different frameworks (technical, social, economic, environmental) and are continuously scrutinized as developing countries invest in automobile infrastructures [Economist 2005, Friedman 2007].

Table 1 lists several studies related to the environmental impacts of the transportation modes in this dissertation. The table is grouped by each of the modes and divided into infrastructure, vehicle, and fuel components for several major life-cycle stages. While the studies in Table 1 all touch on environmental aspects of the modes, some are geared towards other aspects of transport including economic and social issues. Also, some studies focus on freight aspects, which are not irrelevant to passenger mode life-cycle components since infrastructure components are not mutually exclusive to the two systems.

Most studies to date focus on automobiles as they dominate the passenger transport market. Particularly, vehicle life-cycle components have been studied in many different forms. Few studies however, have aggregated these components into a single inventory. An LCA of interest is MacLean 1998 who used EIO-LCA (see §1.3.1) to estimate a total environmental inventory for an automobile vehicle from design through end-of-life phases. This study did not include any of the infrastructure or fuel components. Marheineke 1998, Nocker 2000, and Facanha 2007 consider the environmental effects of freight operations including passenger relevant infrastructure components. Additionally, Sullivan 1998 creates an environmental life-cycle inventory of a sedan, evaluating vehicle components from procurement through end-of-life. Energy consumption of automobiles (predominantly gasoline) and buses (predominantly diesel) has also been evaluated from production through combustion for several fuels [Cohen 2003, MacLean 2003, Farrell 2006]. While all of these studies provide critical analysis of life-cycle environmental inventory of transportation, none provide a comprehensive inventory of passenger transportation including vehicle, infrastructure, and fuel components.

Table 1 – Scope of Work

		Design	*Production, Construction, or Manufacturing*	*Operation*	*End-of-Life*
Automobiles	Roadways & Other Infrastructure	N	M, N, AO	M, N, AO	N, AO
	Cars & Trucks	K, L, N, AJ, AK, AN	J, K, L, M, N, AH, AJ, AK, AM, AN	A, B, C, D, E, F, G, H, J, K, L, M, N, AJ, AM, AN	K, L, M, N, AJ, AL
	Fuel (Gasoline)		AS, AD, AO		
Buses	Roadways & Other Infrastructure	N	M, N, AO	M, N, AO	N, AO
	Vehicles			Q, R, AP	
	Fuel (Diesel)		AO		
Rail	Tracks & Stations	N	N, AB, AE, AF, AG, AO	N, AX, AO	N, AO
	Trains	N	J, N, AE, AO	F, H, J, N, P, X, Y, Z, AA, AB, AC, AE, AO	N, AO
	Fuel (Diesel, Electricity)		T, AO		
Aircraft	Airports & Runways		AO	O	AO
	Aircraft		AO	G, H, I, O, U, V, W, AI, AO	AO
	Fuel (Jet-A)		AO		

Sources: A. Delucchi 1997 (Economic); B. Madison 1996 (Economic); C. Mayeres 1996 (Economic); D. Verhoef 1994 (Economic); E. Small 1995 (Economic); F. Levinson 1996 (Economic); G. Levinson 1998b (Economic); H. INFRAS 1994 (Economic); I. Schipper 2003 (Economic); J. Stodolsky 1998 (Freight); K. Sullivan 1998; L. MacLean 1998; M. Marheineke 1998 (Freight); N. Nocker 2000 (Freight); O. FAA 2007; P. Fritz 1994; Q. Clark 2003; R. Cohen 2003; S. MacLean 2003; T. Deru 2007; U. Greene 1992; V. EEA 2006; W. EPA 1999b; X. Fels 1978; Y. EPA 1997; Z. Anderrson 2006; AA. Jorgensen 1997; AB. Pikarsky 1991; AC. Healy 1973; AD. Farrell 2006; AE. Lave 1977; AF. Bei 1978; AG. Carrington 1984; AH. Cobas-Flores 1998; AI. Lee 2001; AJ. Sullivan 1995; AK. Gediga 1998; AL. Cobas-Flores 1998b; AM. Di Carlo 1998; AN. Kaniut 1997; AO. Facanha 2007 (Freight); AP. McCormick 2000.

The dominance of freight rail transport in the U.S. over passenger transport from a total VMT perspective has led to many studies. The passenger rail transport market has been evaluated for several commuter systems but again focuses on vehicle operation. During the energy crisis in the late 1970s, Fels 1978 compared three commuter rail transit systems in the U.S. including vehicle operation and several infrastructure components in an energy analysis. Lave 1977 also considered the total energy requirements of a commuter rail system during this time. Diesel locomotive technology has not changed much in the past few decades and its energy requirements and emissions have also evaluated [Fritz 1994, EPA 1997].

Given the long travel distances and large fuel requirements, most environmental studies of aircraft are at the cruise phase during vehicle operation. The landing-takeoff cycle during vehicle operation is also a major consideration given that population exposure rates could be higher. Several energy and emission inventories have been evaluated for aircraft during the cruise phase [EEA 2006, EPA 1999b, Greene 1992, Olivier 1991]. These studies acknowledge the difficulties of estimating emissions from aircraft during cruise and identify several approaches to do so [Romano 1999]. Given the altitude at which human health impacting pollutants are released, the prioritization of this inventory drops. The landing-takeoff cycle can result in more serious health consequences. [NASA 2008, Kesgin 2006, Woodmansey 1994, FAA 2007]. Ground support equipment operation has also been evaluated [EPA 1999]. Similar to the other modes, no study to date has created a comprehensive environmental inventory of all of the vehicle, infrastructure, and fuel components associated with aircraft. Airports have not been reviewed at all from a life-cycle framework. The lack of analysis related to air transportation could stem from a lack of data available to researchers. The Bureau of Transportation Statistics (BTS) reports an abundance of data related to passenger travel habits and some data related to the U.S. aircraft fleet [BTS 2007]. Unfortunately, information related to aircraft construction remains with only a few major companies (including Boeing and Airbus). The structures of aircraft are well researched and documented but represent only part of the life-cycle material usage. From carpeting to seating to regularly scheduled replacement of landing gear, information on aircraft material requirements remain somewhat protected.

1.3 Methodology

The passenger transportation sectors play key roles in the economy by moving people between sources and destinations, and are some of the largest energy consumers and polluters in our society [Greene 1997, Mayeres 1996]. Some statistics have been compiled comparing the environmental impacts of these modes of transportation, but few consider anything beyond the operational impact of the vehicle. Environmental regulations, primarily at the government level, are made using these statistics to target energy and emission reductions for transportation modes. The aircraft emission standard is just one example of this practice. The EPA Office of Transportation and Air Quality (OTAQ) is responsible for regulating aircraft emissions, but considers only operation of the vehicle while ignoring the environmental impacts that result from the design, construction, and end-of-life of the infrastructure and vehicles. The United Nations International Civil Aviation Organization (ICAO) performs a similar role of suggesting standards for aircraft emissions for the global community.

A comprehensive environmental assessment comparing passenger transportation modes has not yet been published. To appropriately address the environmental impacts of these modes, it is necessary to accurately quantify the entire life-cycle of the vehicles, infrastructure, and fuels. Informed decisions should not be made on partial data acting as indicators for whole system performance. Some studies have been completed for rail transportation vehicles at specific stages in the life-cycle (Table 1). These studies tend to quantify social costs at each stage without considering the full environmental costs.

With increasing environmental regulation and pressures from consumers and the public, it is important that complete data be presented to target areas of opportunity for improvement. These data will be valuable to private and governmental organizations. Private entities (such as transportation companies) will have the information to proactively address the environmentally "weak points" of their transportation systems and improve the sustainability, and ultimately the competitiveness, of their networks. The manufacturing sector (e.g., aircraft companies) will have the information to improve their processes and technologies, avoiding the future impact of government regulations and policies. Government agencies will have the data to improve on their policies to reduce environmental impacts.

The environmental effects of transportation should not be measured by a single stage in the life cycle of the infrastructure or vehicle. A methodology for understanding the impacts of these modes should be created to accurately quantify the environmental impacts. Accurate quantification will provide an improved understanding of the resource inputs and emissions associated with each mode at each stage.

1.3.1 Life-cycle Assessment

The vehicles, infrastructure, and fuels that serve these modes are complex with many resource inputs and environmental outputs. Their analysis involves many processes. The most comprehensive tool for dealing with these complexities and for quantifying environmental effects is life-cycle assessment (LCA).

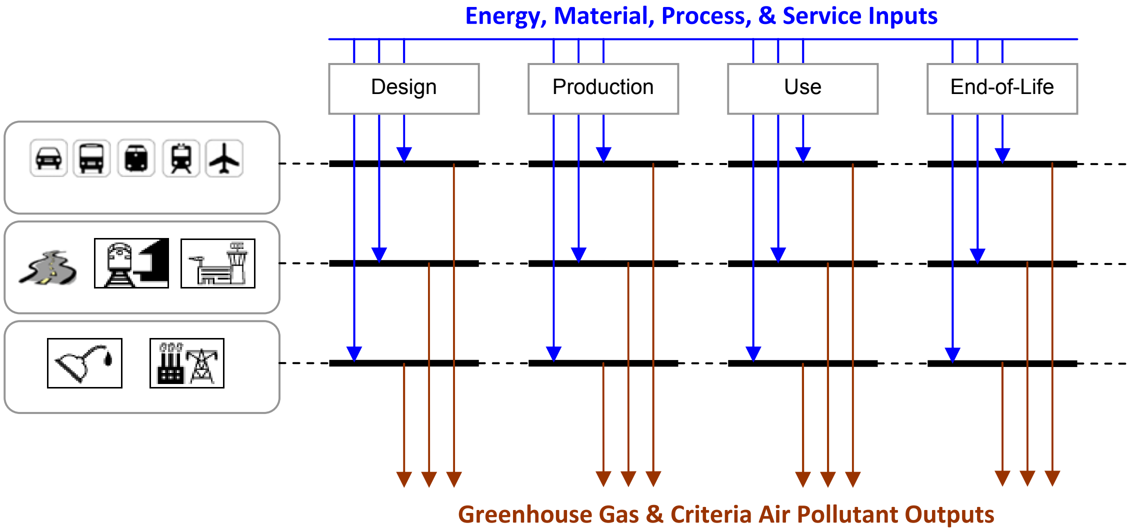
LCA has become the necessary systematic method in pollution prevention and life-cycle engineering to analyze the environmental implications associated with products, processes, and services through the different stages of the life cycle: design, materials and energy acquisition, transportation, manufacturing, construction, use and operation, maintenance, repair/renovation/retrofit, and end-of-life treatment (reuse, recycling, incineration, landfilling) [Curran 1996]. The Society for Environmental Toxicology and Chemistry, the U.S. Environmental Protection Agency, as well as the International Organization for Standardization (ISO) have helped develop and promote LCA over the last several decades [Fava 1991, Bare 2003, ISO 2005]. The LCA methodology consists of four stages (Figure 1): defining of the goal and scope of the study and determining the boundaries; inventory analysis involving data collection and calculation of the environmental burdens associated with the functional unit and each of the life-cycle stages; impact assessment of regional, global, and human health effects of emissions; and interpretation of the results in the face of uncertainty, subjected to sensitivity analysis, and prepared for communication to stakeholders.

In this research, we will use a combination of two LCA models:

- the process model approach that identifies and quantifies resource inputs and environmental outputs at each life-cycle stage based on unit process modeling and mass-balance calculations [Curran 1996, Keoleian 1993], and
- the Economic Input-Output Analysis-based LCA as a general equilibrium model of the U.S. economy that integrates economic input-output analysis and publicly available environmental databases for inventory analysis of the entire supply chain associated with a product or service [Hendrickson 1998].

The process-based LCA maps every process associated with a product within the system boundaries, and associates energy and material inputs and environmental outputs and wastes with each process. Although this model enables specific analyses, it is usually time- and cost-intensive due to heavy data requirements, especially when the first, second, third, etc. tiers of suppliers is attempted to be included. An alternative LCA model has been created to overcome some of the challenges posed by process-based LCA [Hendrickson 1998]. The economic input-output analysis-based LCA adds environmental data to economic input-output modeling. This well-established econometric model quantifies the interdependencies among the different sectors, effectively mapping the economic interactions along a supply chain of any product or service in an economy. A specific final demand (purchase) induces demand not just for that commodity, but also for a series of products and services in the entire supply chain that is accounted for in input-output analysis. EIO-LCA associates economic output from a sector (given in producer prices, e.g., $100,000 worth of steel manufactured) with environmental metrics (e.g., energy, air pollutants, hazardous waste generation, etc. associated with steel production) [EIO-LCA 2008]. Even though this model results in a comprehensive and industry-wide environmental assessment, it may not offer the level of detail included in a well-executed process-based LCA. This is especially critical when the studied commodity falls into a sector that is broadly defined (e.g., plastics manufacturing), or when the product's use phase is analyzed (e.g., burning diesel in a locomotive). A hybrid LCA model that combines the advantages of both process model-based LCA and economic input-output- based LCA is the appropriate approach for the most comprehensive studies, and it will be employed in this research [Suh 2004]. Figure 1 shows a conceptual model of this LCA.

Figure 1 – A Conceptual Model of Modal Life-cycle Components



The most recent EIO-LCA model at the time of the work is based on 1997 economic tables. For the component inventoried with EIO-LCA, this is typically not an issue because the technology and processes involved have not changed radically. The EIO-LCA model requires inputs in U.S. 1997 dollars of producer cost. For example, to estimate the emissions produced from manufacturing a 2005 sedan, overhead, profit, transport, and other non-producer portions of the price must first be removed. The remaining value must then be transformed from 2005 to 1997 dollars. Later discussion of transforming items to $1997 typically relates to the necessary step of putting the component input into a form which can then be inventoried in EIO-LCA.

1.3.2 Environmental Effects Included

We will quantify the energy inputs, greenhouse gas emissions (carbon dioxide, nitrous oxide, methane) and criteria air pollutant emissions (particulate matter, carbon monoxide, sulfur dioxide, nitrogen oxides, lead, volatile organic compounds) associated with the life cycles of vehicles, infrastructure, and fuels associated with each mode.

The emissions of concern are [Nazaroff 2001, EPA 2008b, EPA 2008c]:

- Greenhouse Gases – principally carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases that trap heat in the atmosphere resulting in a warming of the Earth.
- Sulfur Dioxide (SO_2) – a respiratory irritant and precursor to acid deposition. SO_2 negatively impacts breathing, contributes to the development of respiratory illnesses, inhibits defense mechanisms of the lungs, and can aggravate existing pulmonary and cardiovascular conditions. Emitted to air, SO_2 can deposit to the earth's surface as a gas molecule or dissolved in rain or fog droplets, typically in the form of sulfuric acid (H_2SO_4). Plants and aquatic wildlife are particularly affected.

- Carbon Monoxide (CO) – forms carboxyhemoglobin in blood reducing the oxygen carrying capacity of red blood cells. CO is a product of incomplete combustion of carbon-based fuels. Exposure to low concentrations could result in hypoxia, leading to angina, impaired vision, and reduced brain function. Exposures to high concentrations could result in asphyxiation.
- Nitrogen Oxides (NO_X) – react with VOCs in the presence of sunlight to create ground-level ozone (O_3). O_3 can damage lung tissues and exacerbate previous respiratory conditions. It can be transported long distances and cause health impacts far from the original source. NO_X can also contribute to acid deposition, increase the nitrogen loading in water bodies upsetting the chemical and nutrient balance in the ecosystem, and react with common organic chemicals in the atmosphere to produce toxic products.
- Volatile Organic Compounds (VOC) – gaseous emissions from certain liquids or solids as a variety of chemicals which have human health and environmental effects. VOCs can cause eye, nose, and throat irritation, headaches, loss of coordination, nausea, liver, kidney, central nervous system damage, and cancer. Some VOCs are highly toxic while others are not known to have any health effects. Reacting with NO_X in the presence of sunlight, VOCs contribute to ground-level ozone formation.
- Particulate Matter (PM) – typically classified as PM_{10} (with a diameter of 10 µm or less) and $PM_{2.5}$ (with a diameter of 2.5 µm or less) and is a mixture of small particles and liquid droplets. The different diameters result in varying transport characteristics and likelihood to make their way into the lungs and blood stream. PM exposure may result in difficulty breathing, aggravate respiratory conditions such as asthma, contribute to the development of bronchitis, cause irregular heartbeats, and contribute to premature mortality.

- Lead (Pb) – a potent neurotoxin, is known to impede brain development and once in the bloodstream can cause a variety of other adverse health effects including anemia, kidney damage, and elevated blood pressure. Tetraethyllead was phased out as a gasoline additive starting in 1973.

1.3.3 Availability of Lead Emissions Data

For many life-cycle components, lead airborne emission data are not reported but other CAP emissions are. This leads to a dilemma in reporting of total emissions. While lead data exist for some components in a mode, it has not been determined for all components. Further effort would be needed to find, if available, additional lead emission data for several products and processes. To not give the impression that total lead inventories have been computed in the LCI of a mode, reporting of final results excludes this pollutant. This is not to say, however, that lead has been excluded entirely in this analysis. Where lead data exist, it has been compiled and reported, particularly in the LCI sections for each mode. For any mode, the lead emissions reported represent only a fraction of total emissions.

1.4 Data Sources

Across the five modes and twelve vehicle types, many data sources were used to analyze the environmental inventory and normalize values to the functional units. These data sources are described in further sections in each mode's inventory. Table 2, Table 3, and Table 4 summarize these data sources. The tables are arranged by life-cycle component where for each stage, both the data source and LCA type (process, EIO-LCA, hybrid) is reported.

Table 2 – Onroad Data Sources

Component	**Data Sources**	**LCA Type**
Vehicle		
Manufacturing		
Manufacturing	AN 2005	EIOLCA
Operation		
Running	EPA 2006, EPA 2003	Process
Startup	EPA 2003	Process
Braking	EPA 2003	Process
Tire Wear	EPA 2003	Process
Evaporative Losses	EPA 2003	Process
Idling	CARB 2002, Clarke 2005, McCormick 2000	Process
Maintenance		
Vehicle	AAA 2006, FTA 2005b	EIOLCA
Tire Production	AAA 2006, FTA 2005b	EIOLCA
Automotive Repair	CARB 1997	Process
Insurance		
Fixed Costs / Insurance	AAA 2006, FTA 2005b, APTA 2006	EIOLCA
Infrastructure		
Construction & Maintenance		
Roadway Construction	FHWA 2000, AASHTO 2001, PaLATE 2004, EPA 2001	Hybrid
Roadway Maintenance	FTA 2006, PaLATE 2004, EPA 2001	Hybrid
Roadway & Parking Lighting	EERE 2002, Deru 2007	Process
Parking	IPI 2007, EPA 2005, TRB 1991, Census 2002, MR 2007, Guggemos 2005, PaLATE 2004, EPA 2001	Hybrid
Operation		
Herbicides & Salt Production	EPA 2004, TRB 1991	EIOLCA
Fuel		
Gasoline & Diesel Production	EIA 2007, EIA 2007b	EIOLCA

Table 3 – Rail Data Sources

Component	Data Sources	LCA Type
Vehicles		
Manufacturing		
Vehicle Manufacturing	SimaPro 2006, Breda 2007, Breda 2007b	Process
Operation		
Propulsion, Idling, Auxiliaries	Fels 1978, FTA 2005, Caltrain 2007c, Fritz 1994, Anderrson 2006, Deru 2007	Process
Maintenance		
Vehicle	SimaPro 2006	Process
Cleaning	SFC 2006, EERE 2007b, BuiLCA 2007	Process
Flooring Replacement	SFC 2006	EIOLCA
Insurance		
Operator Health & Benefits	BART 2006c, Muni 2007, FTA 2005	EIOLCA
Vehicle Incidentals	BART 2006c, FTA 2005, Muni 2007, CAHSR 2005, FRA 1997, Levinson 1996	EIOLCA
Infrastructure		
Construction & Maintenance		
Station Construction	BART 2006, BART 2007e, Bombardier 2007, Guggemos 2005	Hybrid
Track Construction	BART 2007, SVRTC 2006, Carrington 1984, Muni 2006, PB 1999, Bei 1978, WBZ 2007, Griest 1915, WSDOT 2007, WSDOT 2007b, USGS 1999	Hybrid
Track Maintenance	SimaPro 2006, MBTA 2007	Process
Station Maintenance	BART 2006, BART 2007e, Bombardier 2007, Guggemos 2005	Hybrid
Station Parking	SFC 2007, Caltrain 2004, MBTA 2007, PaLATE 2004, EPA 2001	Hybrid
Operation		
Station Lighting	Fels 1978, Deru 2007	Process
Station Escalators	EERE 2007, FTA 2005, Fels 1978, Deru 2007	Process
Train Control	Fels 1978, Deru 2007	Process
Station Parking Lighting	Deru 2007	Process
Station Miscellaneous	Fels 1978, MEOT 2005, EIA 2005	Process
Station Cleaning	Paulsen 2003, Deru 2007	Process
Insurance		
Non-Oper. Health & Benefits	BART 2006c, Muni 2007, FTA 2005	EIOLCA
Infrastructure Incidentals	BART 2006c, FTA 2005, Muni 2007, CAHSR 2005, FRA 1997, Levinson 1996	EIOLCA
Fuels		
Indirect Energy Production	Deru 2007	Process
Trans. and Distrib. Losses	Deru 2007	Process

Table 4 – Air Data Sources

Component	Data Sources	LCA Type
Vehicle		
Manufacturing		
Airframe	Janes 2004, AIA 2007, Boeing 2007	EIOLCA
Engine	Jenkinson 1999	EIOLCA
Operation		
Auxiliary Power Unit	FAA 2007	Process
Startup	FAA 2007	Process
Taxi Out	FAA 2007	Process
Take Off	FAA 2007	Process
Climb Out	FAA 2007	Process
Cruise	EEA 2006, Romano 1999	Process
Approach	FAA 2007	Process
Taxi In	FAA 2007	Process
Maintenance		
Aircraft Components	EPA 1998, BTS 2007	EIOLCA
Engine Components	EPA 1998, BTS 2007	EIOLCA
Insurance		
Vehicle Incidents	BTS 2007	EIOLCA
Flight Crew Health & Benefits	BTS 2007	EIOLCA
Infrastructure		
Construction & Maintenance		
Airport Construction	MWAA 2005, GE 2007, MWAA 2007, RSM 2002	EIOLCA
Runway, Taxiways, and Tarmacs	Sandel 2006, FAA 1996, GE 2007, PaLATE 2004, EPA 2001	Hybrid
Airport Parking	MWAA 2007, PaLATE 2004, EPA 2001	Hybrid
Operation		
Runway Lighting	EERE 2002, Deru 2007	Process
Deicing Fluid Production	EPA 2000	EIOLCA
Ground Support Equipment	FAA 2007, EPA 1999	Process
Insurance		
Airport Insurance	MWAA 2005	EIOLCA
Non-Flight Crew Health & Benefits	MWAA 2005	EIOLCA
Fuel		
Production	SimaPro 2006	Process

1.5 Vehicle and Fuel Analysis Year

This study evaluates several transportation modes, many of which have vehicles that were constructed and fuel inputs which were consumed during different years. With the onset of new vehicle performance requirements, environmental performance is not consistent from year to year. For example, new CAFE requirements would change the fuel economy of vehicles at a given year [TLOC 2007]. Additionally, changes to regulations of gasoline and diesel fuels would also affect the environmental performance of several modes [EPA 2007]. Given the myriad of factors which determine the environmental performance of any mode, it is unrealistic to define an average vehicle model or operational performance. Table 5 identifies the vehicle year and fuel year for the evaluated modes in this study.

Table 5 – Vehicle and Fuel Analysis Years

Vehicle	Vehicle Year	Fuel Year	Fuel Environmental Source
Sedan	2005	2007	EPA 2003
SUV	2005	2007	EPA 2003
Pickup	2005	2007	EPA 2003
Bus	2005	2008	EPA 2003, McCormick 2000, EPA 2007
BART	1969-1992	2007	Fels 1978, Deru 2007, PGE 2008
Caltrain	1994	2008	Fritz 1994, EPA 2007
Muni	1998	2008	Deru 2007, PGE 2008
Green Line	1995	2007	Deru 2007
CAHSR	2005	2007	CAHSR 2005, Deru 2007
Embraer 145	2005	2005	ATA 2003, Romano 1999, Pehrson 2005, IPCC 2006
Boeing 737	2005	2005	EEA 2006, Romano 1999, Pehrson 2005, IPCC 2006
Boeing 747	2005	2005	EEA 2006, Romano 1999, Pehrson 2005

The vehicle years range from several decades to 2005 and can capture reconstruction during major maintenance (BART). The fuel year identifies the time in which gasoline, diesel, or electricity energy inputs were consumed which determine environmental performance. Onroad vehicles are modeled to capture the EPA's Tier 2 standards which have significantly reduced emissions, particularly of SO_2 [EPA 2007]. The electric modes are determined from year 2007 and 2008 electricity mixes [Deru 2007, PGE 2008].

1.6 Life-cycle Environmental Inventory of Automobiles and Urban Buses

Automobiles and transit buses consumed 18M TJ of energy in 2005, approximately 60% of the 31M TJ consumed in the U.S. by the entire transportation sector [Davis 2007]. The impact of these vehicles is felt not just directly through fuel consumption and tail-pipe emissions but also in the infrastructure and life-cycle components required to support them.

Automobiles come in many different configurations but can be generalized into the three major categories: sedans, SUVs, and pickup trucks. Urban buses are represented by a typical diesel-powered 40-foot vehicle.

1.6.1 Vehicles

To select the most typical vehicles representing the three automobile categories, vehicle sales data are evaluated for 2005 [Wards 2006]. Table 6 shows the ranking of vehicle sales in 2005 for the three categories. Representative vehicles are assumed to be the top selling models for the year. The vehicle categories represent extremes in environmental impacts of conventional gasoline vehicles. The sedan is the most fuel efficient and lightest vehicle (representing the best vehicle on the road), the sport utility has poor fuel efficiency and is the heaviest, and the pickup also has poor fuel efficiency and a heavy weight (and is the highest selling vehicle). The sedan averages 1.58 passengers per car, the SUV 1.74, and the pickup 1.46 [Davis 2006].

Table 6 – 2005 Top 20 Automobile Sales by Vehicle Type [Wards 2006]

	Sedan		Sport Utility Vehicle		Pickup	
Rank	Make & Model	Number	Make & Model	Number	Make & Model	Number
1	Toyota Camry	431,703	Chevrolet TrailBlazer	244,150	Ford F-Series	854,878
2	Honda Accord	369,293	Ford Explorer	239,788	Chevrolet Silverado	705,980
3	Toyota Corolla/Matrix	341,290	Jeep Grand Cherokee	213,584	Dodge Ram Pickup	400,543
4	Honda Civic	308,415	Jeep Liberty	166,883	GMC Sierra	229,488
5	Nissan Altima	255,371	Chevrolet Tahoe	152,305	Toyota Tacoma	168,831
6	Chevrolet Impala	246,481	Dodge Durango	115,439	Chevrolet Colorado	128,359
7	Chevrolet Malibu	245,861	Ford Expedition	114,137	Toyota Tundra	126,529
8	Chevrolet Cobalt	212,667	GMC Envoy	107,862	Ford Ranger	120,958
9	Ford Taurus	196,919	Toyota 4Runner	103,830	Dodge Dakota	104,051
10	Ford Focus	184,825	Chevrolet Suburban	87,011	Nissan Titan	86,945
11	Ford Mustang	160,975	Jeep Wrangler	79,017	Nissan Frontier	72,838
12	Chrysler 300 Series	144,048	Nissan Pathfinder	76,156	Chevrolet Avalanche	63,186
13	Hyundai Sonata	130,365	GMC Yukon	73,458	Honda Ridgeline	42,593
14	Pontiac Pontiac G6	124,844	Nissan Xterra	72,447	GMC Canyon	34,845
15	Pontiac Grand Prix	122,398	GMC Yukon XL	53,652	Lincoln LT	10,274
16	Nissan Sentra	119,489	Kia Sorento	47,610	Chevrolet SSR	8,107
17	Hyundai Elandra	116,336	Toyota Sequoia	45,904	Cadillac Escalade EXT	7,766
18	Dodge Neon	113,332	Nissan Armada	39,508	Subaru Baja	6,239
19	Ford Five Hundred	107,932	Mercedes M-Class	34,959	Mazda Pickup	5,872
20	Toyota Prius	107,897	Lexus GX470	34,339	Mitsubishi Raider	1,145

The Toyota Camry, Chevrolet Trailblazer, and Ford F-Series are used to determine total life-cycle environmental impacts of automobiles. A 40-foot bus is chosen as the representative U.S. urban transit bus based on sales data [FTA 2006]. These buses represent about 75% of transit buses purchased each year. The average occupancy of the bus is 10.5 passengers [FHWA 2004]. It is assumed that an off-peak bus has 5 passengers and a peak bus 40 passengers.

Several vehicle parameters are identified for normalization of inventory results to the functional units: effect per vehicle lifetime, vehicle-mile-traveled, and passenger-mile-traveled. Sedans are assigned a 16.9 year lifetime, SUVs 15.5 years, and pickups 15.5 years, the median lifetime of each vehicle [Davis 2006]. The lifetime of a bus is specified as 12 years which is the industry standard retirement age [FTA 2006]. The average annual VMT for all automobiles was 11,100 and for buses 42,000 (which is the annual mileage given a mandatory 500,000 mile lifetime) [Davis 2006, FTA 2006]. Lastly, PMT is calculated from VMT. The vehicle-specific factors are summarized in Table 7.

Table 7 – Vehicle Parameters

	Sedan	SUV	Pickup	Bus
Vehicle Weight (lbs)	3,200	4,600	5,200	25,000
Vehicle Lifetime (yrs)	16.9	15.5	15.5	12
Yearly VMT (mi/yr)	11,000	11,000	11,000	42,000
Average Vehicle Occupancy (pax)	1.58	1.74	1.46	10.5
Yearly PMT (mi/yr)	17,000	19,000	16,000	440,000

1.6.1.1 Manufacturing

The production of an automobile is a complex process relying on many activities and materials. Several studies have estimated the impacts of automobile production sometimes including limited direct and indirect impacts [MacLean 1998, Sullivan 1998]. The production of an automobile matches the economic sector Automobile and Light Truck Manufacturing (#336110) in EIO-LCA which serves as a good estimate for the total direct and indirect impacts of the process. This sector in EIO-LCA is used to determine the total inventory for the three automobiles. To determine automobile production costs, the base invoice price, the price the manufacturer sells the vehicle at to the dealer, is used. 20% is removed from this price to exclude markups and marketing. The base invoice prices are $21,000 for the sedan, $29,000 for the SUV, and $20,000 for the pickup [AN 2005]. Reducing these prices by the markup and inputting in EIO-LCA produces the vehicle environmental inventory. The general mathematical framework is shown in Equation Set 1.

Equation Set 1 – Onroad Vehicle Manufacturing

$$I/O_{vehicle-lifetime}^{onroad,manufacturing} = Manufacturing\ I/O\ Determined\ in\ EIOLCA$$

$$I/O_{VMT}^{onroad,manufacturing} = I/O_{vehicle-lifetime}^{onroad,manufacturing} \times \frac{lifetime_{vehicle}}{VMT}$$

$$I/O_{VMT}^{onroad,manufacturing} = I/O_{vehicle-lifetime}^{onroad,manufacturing} \times \frac{lifetime_{vehicle}}{VMT} \times \frac{VMT}{PMT}$$

The bus manufacturing inventory is computed similarly. An invoice price of $310,000 is used with a similar markup [FTA 2006]. Life-cycle assessments of bus manufacturing have not been performed. The economic sector Heavy Duty Truck Manufacturing (#336120) was assumed to reasonably estimate the inventory for bus production.

1.6.1.2 Operation

Emissions from vehicle operation are computed using the EPA Mobile 6.2 model [EPA 2003]. This software requires specification of multiple inputs for vehicle, fuel, and environmental variables to estimate environmental inventory. Instead of reporting inventory results for vehicle operation in an aggregated manner (e.g., total CO emissions from driving a certain distance), components are kept at the highest level of detail generated by the software. The emissions inventory generated in Mobile 6.2 disaggregates driving, startup, tires, brakes, evaporative, and idling components.

It is important to consider the specific disaggregated components for different reasons. Cold start emissions are the time when the catalytic converter is not operating at peak efficiency. The catalytic converter's purpose is to simultaneously oxidize hydrocarbons and carbon monoxide and reduce nitrogen oxides through the chemistry in Equation Set 2. During the time when the catalytic converter is not running optimally, NO_X, VOC, and CO emissions will be larger (in grams per VMT) than when the converter is warm.

Equation Set 2 – Catalytic Converter Chemistry

$$\mathit{Oxidation\ \ Reactions}:$$
$$2 \cdot \mathrm{H_N C_M} \ + \ ½ \cdot (\mathrm{N} + 4 \cdot \mathrm{M}) \cdot \mathrm{O_2} \ \rightarrow \ \mathrm{N} \cdot \mathrm{H_2O} \ + \ \mathrm{M} \cdot \mathrm{CO_2}$$
$$2 \cdot \mathrm{CO} \ + \ \mathrm{O_2} \ \rightarrow \ 2 \cdot \mathrm{CO_2}$$
$$\mathit{Reduction\ Reactions}:$$
$$2 \cdot \mathrm{NO_X} \ \rightarrow \ \mathrm{N_2} \ + \ \mathrm{X} \cdot \mathrm{O_2}$$

PM emissions do not typically distinguish among combustion, tire wear, and brake pad wear. With fluctuations in daily temperature, some gasoline in the fuel tank volatilizes and escapes in the form of VOCs. This can also happen just after engine shut-off when fuel not in the tank volatilizes (hot-soak, resting, running, and crankcase losses are disaggregated). Additionally, VOCs are emitted during refueling. These evaporative emissions are computed separately from operational VOC emissions. Lastly, the time a bus spends idling can be as large as 20% depending on the drive cycle [CARB 2002]. While engine loads are lower than during driving, fuel is still consumed and emissions result.

The Mobile software requires several inputs to calculate the inventory. The combined fuel economy for each vehicle type is specified as 28 for the sedan, 17 for the SUV, 16 for the pickup, and 4.3 for the bus [EPA 2006, EPA 2003]. Two scenarios are run: one for the summer months where the average temperature is between 72 and 92°F, and one for the winter months with average temperatures between 20 and 40°F. In both scenarios, the Reid Vapor Pressure is specified as 8.7 lbs/in^2 and a diesel sulfur fuel content of 15 ppm (corresponding to EPA Tier 2 low sulfur fuel standards starting in 2006) [EPA 2007]. The average emission values are used from the summer and winter scenarios. Table 8 and Table 9 summarizes these emission values. Energy consumption in the fuel is computed from fuel economy estimates and the fuel’s energy content.

Table 8 – Automobile Vehicle Emissions (in g/VMT) from EPA Mobile 6.2 [EPA 2003]

	Sedan			SUV			Pickup		
	S	W	AVG	S	W	AVG	S	W	AVG
Operational Emissions									
CO_2	365	368	367	479	476	478	618	617	618
SO_2	0.021	0.021	0.021	0.027	0.027	0.027	0.035	0.035	0.035
CO	9.5	12	11	9.6	14.0	11.8	12.4	19.3	15.9
NO_X	0.80	0.89	0.85	0.94	1.15	1.04	1.2	1.5	1.4
VOC	0.28	0.35	0.31	0.34	0.45	0.40	0.54	0.74	0.64
Lead									
PM_{10}	0.11	0.11	0.11	0.11	0.11	0.11	0.10	0.10	0.10
Non-Operational Emissions									
Startup CO	2.4	12	7.3	4.2	15	9.4	6.4	17	11.7
Startup NO_X	0.15	0.19	0.17	0.19	0.25	0.22	0.24	0.31	0.28
Brake Wear PM_{10}	0.22	0.48	0.35	0.29	0.65	0.47	0.49	1.15	0.82
Tire Wear PM_{10}	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
Evaporative VOC Losses	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008

S = Summer, W = Winter, AVG = Average of summer and winter

Table 9 – Bus Vehicle Emissions (in g/VMT) from EPA Mobile 6.2 [EPA 2003]

	Urban Bus		
	S	W	AVG
Operational Emission			
CO_2	2,373	2,374	2,373
SO_2	0.022	0.022	0.022
CO	4.4	4.5	4.5
NO_X	18	18	18
VOC	0.55	0.56	0.55
Lead			
PM_{10}	0.61	0.63	0.62
Non-Operational Emissions			
Startup CO			
Startup NO_X			
Brake Wear PM_{10}	0.013	0.013	0.013
Tire Wear PM_{10}	0.012	0.012	0.012
Evaporative VOC Losses			

S = Summer, W = Winter,
AVG = Average of summer and winter

Multiplying the average emission factors in Table 8 and Table 9 for each vehicle by the VMT in the vehicle's lifetime yields the effect per vehicle lifetime. Similarly, dividing by the average occupancy yields the effect per PMT. There exists some debate as to the accuracy of the CO emission factors generated in Mobile 6.2. A data source which disaggregates CO emissions for sedans, SUVs, and pickups was not readily identified so the EPA's factors were kept. Verification of the Mobile 6.2's CO factors is discussed in §3.2.

For the bus, vehicle idling fuel consumption and emissions are computed differently. Average bus idling fuel and emission factors of 0.47 gallons of diesel per hour, 4,600 g CO_2/hr, 80 g CO/hr, 120 g NO_X/hr, 8 g VOC/hr, and 3 g PM_{10}/hr are used [Clarke 2005, McCormick 2000]. Idling hours are based on the Orange County Drive Cycle with an average speed of 12 mi/hr [CARB 2002].

1.6.1.3 Maintenance

Vehicle maintenance is separated into maintenance of the vehicle and tire replacement. Maintenance and tire costs for sedans and SUVs are estimated by the American Automobile Association (AAA). Maintenance costs are \$0.05/VMT for the sedan and \$0.056/VMT for the SUV. Tire costs are \$0.008/VMT for the sedan and SUV [AAA 2006]. Pickup costs are extrapolated from vehicle weights. For buses, the total yearly operating cost is \$7.8/VMT of which 20% is attributed to maintenance [FTA 2005b]. Multiplying lifetime VMT by these factors yields lifetime costs for the two components. To estimate energy inputs and emission outputs from automobile maintenance, EIO-LCA is used because of the commensurate economic sectors and processes. The Automotive Repair and Maintenance (#8111A0) and Tire Manufacturing (#326210) sectors are used for the two components. The general framework for normalizing these maintenance inventories to the functional units is shown in Equation Set 3.

Equation Set 3 – Onroad Vehicle Maintenance

$$I/O_{vehicle-lifetime}^{onroad,maintenance} = Maintenance\ I/O\ Determined\ in\ EIOLCA$$
$$I/O_{VMT}^{onroad,maintenance} = I/O_{vehicle-lifetime}^{onroad,maintenance} \times \frac{lifetime_{vehicle}}{VMT}$$
$$I/O_{PMT}^{onroad,maintenance} = I/O_{vehicle-lifetime}^{onroad,maintenance} \times \frac{lifetime_{vehicle}}{VMT} \times \frac{VMT}{PMT}$$

1.6.1.4 Automotive Repair

The use of brake cleaners, carburetor cleaners, choke cleaners, and engine degreasers releases emissions which should be attributed to the automobile and bus infrastructure. The California Air Resources Board Consumer Products Program has quantified the emissions of VOCs and CO_2 from production of 100 product categories [CARB 1997]. The emissions of automotive brake cleaners, carburetor and choke cleaners, and engine degreasers are reported as 5.61, 6.48, and 2.21 tons per day for VOCs and 0.43, 0.15, and 0.04 tons per day for CO_2 in 1997 in California. Energy inputs and other CAP emissions are not reported. The use of the cleaners and degreasers encompasses not only automobiles but the entire spectrum of onroad vehicles. To determine emissions per vehicle in the U.S., it is necessary to know the California vehicle mix in 1997 as well as the number of VMT. Fleet characteristics are determined from California and national fleet statistics [Wards 1998, BTS 2005]. The California fleet mix is not significantly different than the national average so extrapolation of total California emissions to national emissions is done based on the number of vehicles. Implementing the U.S. fleet mix in 2005 allows for the determination of total national VOC and CO_2 emissions from repair facilities. These stock emissions are then attributed to the sedan, SUV, pickup, and urban bus as shown in Equation Set 4.

Equation Set 4 – Onroad Vehicle Repair Facilities

$$I/O^{onroad,auto\ repair}_{VOC,CO2} = \frac{emissions_{CA}}{yr} \times \frac{vehicles_{US}}{vehicles_{CA}} = \frac{emissions_{US}}{yr}$$

$$I/O^{onroad,auto\ repair}_{vehicle-lifetime} = I/O^{onroad,auto\ repair}_{VOC,CO2} \times share_{vehicle} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{lifetime_{vehicle}}$$

$$I/O^{onroad,auto\ repair}_{VMT} = I/O^{onroad,auto\ repair}_{VOC,CO2} \times share_{vehicle} \times \frac{yr}{VMT_{vehicle}}$$

$$I/O^{onroad,auto\ repair}_{PMT} = I/O^{onroad,auto\ repair}_{VOC,CO2} \times share_{vehicle} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

1.6.1.5 Insurance

Vehicle insurance provides the critical service of liability coverage. This service requires facilities and operations which consume energy and emit pollutants. The average cost of insuring a sedan is $900 per year and an SUV $920 per year in the U.S. [AAA 2006]. Based on vehicle weights, it is estimated that a pickup truck costs $930 per year to insure. For buses, the average yearly insurance costs are calculated from yearly operating costs per mile ($7.8/VMT) and percentage of operating costs attributed to insurance (2.6%) [FTA 2005b, APTA 2006]. This results in an $8,500 per bus per year insurance cost.

The EIO-LCA sector Insurance Carriers is used to estimate the inventory from this service for each vehicle type. The lifetime insurance costs are computed and input into this sector for the environmental inventory as shown in Equation Set 5.

Equation Set 5 – Onroad Vehicle Insurance

$$I/O^{onroad,insurance}_{vehicle-lifetime} = Insurance\ I/O\ determined\ in\ EIOLCA$$

$$I/O^{onroad,insurance}_{VMT} = I/O^{onroad,insurance}_{vehicle-lifetime} \times \frac{lifetime_{vehicle}}{VMT_{vehicle}}$$

$$I/O^{onroad,insurance}_{VMT} = I/O^{onroad,insurance}_{vehicle-lifetime} \times \frac{lifetime_{vehicle}}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

1.6.1.6 Vehicle Results

The environmental inventories for the life-cycle components associated with the vehicles are presented in Table 10 to Table 15 with all functional units.

Table 10 – Onroad Vehicle Results for Sedans

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
V, Manufacture	Energy	100 GJ	550 kJ	350 kJ
	GHG	8.5 mt GGE	45 g GGE	29 g GGE
	SO_2	20 kg	110 mg	67 mg
	CO	110 kg	560 mg	350 mg
	NO_X	20 kg	110 mg	66 mg
	VOC	21 kg	110 mg	70 mg
	PM_{10}	5.7 kg	30 mg	19 mg
	Pb	0.027 kg	0.14 mg	0.092 mg
V, Operation (Running)	Energy	890 GJ	4,800 kJ	3,000 kJ
	GHG	69 mt GGE	370 g GGE	230 g GGE
	SO_2	3.9 kg	21 mg	13 mg
	CO	2,100 kg	11,000 mg	6,900 mg
	NO_X	160 kg	850 mg	530 mg
	VOC	59 kg	310 mg	200 mg
	PM_{10}	20 kg	110 mg	68 mg
	Pb	-	-	-
V, Operation (Start)	CO	1,400 kg	7,300 mg	4,600 mg
	NO_X	32 kg	170 mg	110 mg
	VOC	66 kg	350 mg	220 mg
V, Operation (Tire)	PM_{10}	1.5 kg	8.0 mg	5.1 mg
V, Operation (Brake)	PM_{10}	2.3 kg	13 mg	7.9 mg
V, Automotive Repair	GHG	0.00015 mt GGE	0.00078 g GGE	0.00049 g GGE
V, Automotive Repair	VOC	3.4 kg	18 mg	11 mg
V, Evaporative Losses	VOC	94 kg	500 mg	320 mg
V, Tire Production	Energy	19 GJ	99 kJ	63 kJ
	GHG	1.3 mt GGE	7.2 g GGE	4.5 g GGE
	SO_2	2.4 kg	13 mg	8.2 mg
	CO	19 kg	100 mg	63 mg
	NO_X	2.5 kg	13 mg	8.4 mg
	VOC	3.2 kg	17 mg	11 mg
	PM_{10}	-	-	-
	Pb	1.4 kg	7.5 mg	4.7 mg
V, Maintenance	Energy	40 GJ	210 kJ	140 kJ
	GHG	3.3 mt GGE	17 g GGE	11 g GGE
	SO_2	8.4 kg	45 mg	28 mg
	CO	33 kg	180 mg	110 mg
	NO_X	7.7 kg	41 mg	26 mg
	VOC	9.7 kg	52 mg	33 mg
	PM_{10}	-	-	-
	Pb	1.6 kg	8.8 mg	5.6 mg
V, Fixed Costs / Insurance	Energy	13 GJ	69 kJ	44 kJ
	GHG	1.1 mt GGE	5.6 g GGE	3.6 g GGE
	SO_2	2.6 kg	14 mg	8.7 mg
	CO	12 kg	62 mg	39 mg
	NO_X	2.9 kg	16 mg	9.8 mg
	VOC	2.2 kg	12 mg	7.3 mg
	PM_{10}	0.55 kg	2.9 mg	1.9 mg
	Pb	-	-	-

Table 11 – Onroad Vehicle Results for SUVs

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
V, Manufacture	Energy	150 GJ	850 kJ	490 kJ
	GHG	12 mt GGE	71 g GGE	41 g GGE
	SO_2	28 kg	160 mg	94 mg
	CO	150 kg	870 mg	500 mg
	NO_X	28 kg	160 mg	94 mg
	VOC	29 kg	170 mg	98 mg
	PM_{10}	8.1 kg	47 mg	27 mg
	Pb	0.039 kg	0.22 mg	0.13 mg
V, Operation (Running)	Energy	1,300 GJ	7,800 kJ	4,500 kJ
	GHG	82 mt GGE	480 g GGE	270 g GGE
	SO_2	4.6 kg	27 mg	15 mg
	CO	2,000 kg	12,000 mg	6,800 mg
	NO_X	180 kg	1,000 mg	600 mg
	VOC	69 kg	400 mg	230 mg
	PM_{10}	18 kg	110 mg	61 mg
	Pb	-	-	-
V, Operation (Start)	CO	1,600 kg	9,400 mg	5,400 mg
	NO_X	38 kg	220 mg	130 mg
	VOC	82 kg	470 mg	270 mg
V, Operation (Tire)	PM_{10}	1.4 kg	8.0 mg	4.6 mg
V, Operation (Brake)	PM_{10}	2.2 kg	13 mg	7.2 mg
V, Automotive Repair	GHG	0.00011 mt GGE	0.00064 g GGE	0.00037 g GGE
V, Automotive Repair	VOC	2.5 kg	15 mg	8.5 mg
V, Evaporative Losses	VOC	86 kg	500 mg	290 mg
V, Tire Production	Energy	17 GJ	99 kJ	57 kJ
	GHG	1.2 mt GGE	7.2 g GGE	4.1 g GGE
	SO_2	2.2 kg	13 mg	7.4 mg
	CO	17 kg	100 mg	57 mg
	NO_X	2.3 kg	13 mg	7.7 mg
	VOC	2.9 kg	17 mg	9.8 mg
	PM_{10}	-	-	-
	Pb	1.3 kg	7.5 mg	4.3 mg
V, Maintenance	Energy	41 GJ	240 kJ	140 kJ
	GHG	3.3 mt GGE	19 g GGE	11 g GGE
	SO_2	8.6 kg	50 mg	29 mg
	CO	34 kg	200 mg	110 mg
	NO_X	7.9 kg	46 mg	26 mg
	VOC	10.0 kg	58 mg	33 mg
	PM_{10}	-	-	-
	Pb	1.7 kg	9.8 mg	5.7 mg
V, Fixed Costs / Insurance	Energy	12 GJ	70 kJ	40 kJ
	GHG	0.99 mt GGE	5.7 g GGE	3.3 g GGE
	SO_2	2.4 kg	14 mg	8.1 mg
	CO	11 kg	63 mg	36 mg
	NO_X	2.7 kg	16 mg	9.1 mg
	VOC	2.0 kg	12 mg	6.8 mg
	PM_{10}	0.51 kg	3.0 mg	1.7 mg
	Pb	-	-	-

Table 12 – Onroad Vehicle Results for Pickups

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
V, Manufacture	Energy	100 GJ	580 kJ	400 kJ
	GHG	8.3 mt GGE	48 g GGE	33 g GGE
	SO_2	19 kg	110 mg	77 mg
	CO	100 kg	590 mg	410 mg
	NO_X	19 kg	110 mg	76 mg
	VOC	20 kg	120 mg	80 mg
	PM_{10}	5.5 kg	32 mg	22 mg
	Pb	0.026 kg	0.15 mg	0.11 mg
V, Operation (Running)	Energy	1,400 GJ	8,300 kJ	5,700 kJ
	GHG	110 mt GGE	620 g GGE	420 g GGE
	SO_2	6.0 kg	35 mg	24 mg
	CO	2,700 kg	16,000 mg	11,000 mg
	NO_X	240 kg	1,400 mg	950 mg
	VOC	110 kg	640 mg	440 mg
	PM_{10}	18 kg	100 mg	72 mg
	Pb	-	-	-
V, Operation (Start)	CO	2,000 kg	12,000 mg	8,000 mg
	NO_X	48 kg	280 mg	190 mg
	VOC	140 kg	820 mg	560 mg
V, Operation (Tire)	PM_{10}	1.4 kg	8.0 mg	5.5 mg
V, Operation (Brake)	PM_{10}	2.2 kg	13 mg	8.6 mg
V, Automotive Repair	GHG	0.00011 mt GGE	0.00065 g GGE	0.00044 g GGE
V, Automotive Repair	VOC	2.6 kg	15 mg	10 mg
V, Evaporative Losses	VOC	140 kg	800 mg	550 mg
V, Tire Production	Energy	17 GJ	99 kJ	68 kJ
	GHG	1.2 mt GGE	7.2 g GGE	4.9 g GGE
	SO_2	2.2 kg	13 mg	8.8 mg
	CO	17 kg	100 mg	68 mg
	NO_X	2.3 kg	13 mg	9.1 mg
	VOC	2.9 kg	17 mg	12 mg
	PM_{10}	-	-	-
	Pb	1.3 kg	7.5 mg	5.1 mg
V, Maintenance	Energy	41 GJ	240 kJ	160 kJ
	GHG	3.3 mt GGE	19 g GGE	13 g GGE
	SO_2	8.6 kg	50 mg	34 mg
	CO	34 kg	200 mg	140 mg
	NO_X	7.9 kg	46 mg	31 mg
	VOC	10.0 kg	58 mg	40 mg
	PM_{10}	-	-	-
	Pb	1.7 kg	9.8 mg	6.7 mg
V, Fixed Costs / Insurance	Energy	12 GJ	71 kJ	48 kJ
	GHG	0.99 mt GGE	5.8 g GGE	4.0 g GGE
	SO_2	2.4 kg	14 mg	9.7 mg
	CO	11 kg	64 mg	44 mg
	NO_X	2.7 kg	16 mg	11 mg
	VOC	2.0 kg	12 mg	8.1 mg
	PM_{10}	0.52 kg	3.0 mg	2.1 mg
	Pb	-	-	-

Table 13 – Onroad Vehicle Results for an Average Bus

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
V, Manufacture	Energy	2,000 GJ	4,100 kJ	390 kJ
	GHG	160 mt GGE	320 g GGE	31 g GGE
	SO_2	330 kg	670 mg	64 mg
	CO	1,600 kg	3,100 mg	300 mg
	NO_X	300 kg	600 mg	58 mg
	VOC	390 kg	780 mg	75 mg
	PM_{10}	87 kg	170 mg	17 mg
	Pb	0.32 kg	0.65 mg	0.062 mg
V, Operation (Running)	Energy	16,000 GJ	32,000 kJ	3,100 kJ
	GHG	1,200 mt GGE	2,400 g GGE	230 g GGE
	SO_2	11 kg	22 mg	2.1 mg
	CO	2,200 kg	4,500 mg	420 mg
	NO_X	8,900 kg	18,000 mg	1,700 mg
	VOC	280 kg	550 mg	52 mg
	PM_{10}	340 kg	690 mg	66 mg
	Pb	-	-	-
V, Operation (Tire)	PM_{10}	6.0 kg	12 mg	1.1 mg
V, Operation (Brake)	PM_{10}	6.3 kg	13 mg	1.2 mg
V, Automotive Repair	GHG	0.00014 mt GGE	0.00029 g GGE	0.000027 g GGE
	VOC	3.3 kg	6.7 mg	0.63 mg
V, Evaporative Losses	VOC	-	-	-
V, Idling	Energy	560 GJ	1,100 kJ	110 kJ
	GHG	40 mt GGE	80 g GGE	7.6 g GGE
	SO_2	-	-	-
	CO	690 kg	1,400 mg	130 mg
	NO_X	1,000 kg	2,100 mg	200 mg
	VOC	71 kg	140 mg	14 mg
	PM_{10}	25 kg	50 mg	4.7 mg
	Pb	-	-	-
V, Tire Production	Energy	18 GJ	35 kJ	3.4 kJ
	GHG	1.3 mt GGE	2.5 g GGE	0.24 g GGE
	SO_2	2.3 kg	4.6 mg	0.44 mg
	CO	18 kg	36 mg	3.4 mg
	NO_X	2.4 kg	4.7 mg	0.45 mg
	VOC	3.0 kg	6.1 mg	0.58 mg
	PM_{10}	-	-	-
	Pb	1.3 kg	2.7 mg	0.25 mg
V, Maintenance	Energy	270 GJ	550 kJ	52 kJ
	GHG	22 mt GGE	45 g GGE	4.2 g GGE
	SO_2	57 kg	110 mg	11 mg
	CO	230 kg	460 mg	43 mg
	NO_X	52 kg	100 mg	10.0 mg
	VOC	66 kg	130 mg	13 mg
	PM_{10}	-	-	-
	Pb	11 kg	23 mg	2.1 mg
V, Fixed Costs / Insurance	Energy	86 GJ	170 kJ	16 kJ
	GHG	7.0 mt GGE	14 g GGE	1.3 g GGE
	SO_2	17 kg	34 mg	3.3 mg
	CO	78 kg	160 mg	15 mg
	NO_X	19 kg	39 mg	3.7 mg
	VOC	14 kg	29 mg	2.7 mg
	PM_{10}	3.7 kg	7.3 mg	0.70 mg
	Pb	-	-	-

Table 14 – Onroad Vehicle Results for an Off-Peak Bus

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
V, Manufacture	Energy	2,000 GJ	4,100 kJ	820 kJ
	GHG	160 mt GGE	320 g GGE	65 g GGE
	SO_2	330 kg	670 mg	130 mg
	CO	1,600 kg	3,100 mg	620 mg
	NO_X	300 kg	600 mg	120 mg
	VOC	390 kg	780 mg	160 mg
	PM_{10}	87 kg	170 mg	35 mg
	Pb	0.32 kg	0.65 mg	0.13 mg
V, Operation (Running)	Energy	16,000 GJ	32,000 kJ	6,400 kJ
	GHG	1,200 mt GGE	2,400 g GGE	470 g GGE
	SO_2	11 kg	22 mg	4.4 mg
	CO	2,200 kg	4,500 mg	890 mg
	NO_X	8,900 kg	18,000 mg	3,600 mg
	VOC	280 kg	550 mg	110 mg
	PM_{10}	340 kg	690 mg	140 mg
	Pb	-	-	-
V, Operation (Tire)	PM_{10}	6.0 kg	12 mg	2.4 mg
V, Operation (Brake)	PM_{10}	6.3 kg	13 mg	2.5 mg
V, Automotive Repair	GHG	0.00014 mt GGE	0.00029 g GGE	0.000058 g GGE
	VOC	3.3 kg	6.7 mg	1.3 mg
V, Evaporative Losses	VOC	-	-	-
V, Idling	Energy	560 GJ	1,100 kJ	220 kJ
	GHG	40 mt GGE	80 g GGE	16 g GGE
	SO_2	-	-	-
	CO	690 kg	1,400 mg	270 mg
	NO_X	1,000 kg	2,100 mg	420 mg
	VOC	71 kg	140 mg	28 mg
	PM_{10}	25 kg	50 mg	10.0 mg
	Pb	-	-	-
V, Tire Production	Energy	18 GJ	35 kJ	7.1 kJ
	GHG	1.3 mt GGE	2.5 g GGE	0.51 g GGE
	SO_2	2.3 kg	4.6 mg	0.92 mg
	CO	18 kg	36 mg	7.1 mg
	NO_X	2.4 kg	4.7 mg	0.95 mg
	VOC	3.0 kg	6.1 mg	1.2 mg
	PM_{10}	-	-	-
	Pb	1.3 kg	2.7 mg	0.53 mg
V, Maintenance	Energy	270 GJ	550 kJ	110 kJ
	GHG	22 mt GGE	45 g GGE	8.9 g GGE
	SO_2	57 kg	110 mg	23 mg
	CO	230 kg	460 mg	91 mg
	NO_X	52 kg	100 mg	21 mg
	VOC	66 kg	130 mg	27 mg
	PM_{10}	-	-	-
	Pb	11 kg	23 mg	4.5 mg
V, Fixed Costs / Insurance	Energy	86 GJ	170 kJ	34 kJ
	GHG	7.0 mt GGE	14 g GGE	2.8 g GGE
	SO_2	17 kg	34 mg	6.9 mg
	CO	78 kg	160 mg	31 mg
	NO_X	19 kg	39 mg	7.8 mg
	VOC	14 kg	29 mg	5.8 mg
	PM_{10}	3.7 kg	7.3 mg	1.5 mg
	Pb	-	-	-

Table 15 – Onroad Vehicle Results for a Peak Bus

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
V, Manufacture	Energy	2,000 GJ	4,100 kJ	100 kJ
	GHG	160 mt GGE	320 g GGE	8.1 g GGE
	SO_2	330 kg	670 mg	17 mg
	CO	1,600 kg	3,100 mg	78 mg
	NO_X	300 kg	600 mg	15 mg
	VOC	390 kg	780 mg	20 mg
	PM_{10}	87 kg	170 mg	4.4 mg
	Pb	0.32 kg	0.65 mg	0.016 mg
V, Operation (Running)	Energy	16,000 GJ	32,000 kJ	800 kJ
	GHG	1,200 mt GGE	2,400 g GGE	59 g GGE
	SO_2	11 kg	22 mg	0.55 mg
	CO	2,200 kg	4,500 mg	110 mg
	NO_X	8,900 kg	18,000 mg	450 mg
	VOC	280 kg	550 mg	14 mg
	PM_{10}	340 kg	690 mg	17 mg
	Pb	-	-	-
V, Operation (Tire)	PM_{10}	6.0 kg	12 mg	0.30 mg
V, Operation (Brake)	PM_{10}	6.3 kg	13 mg	0.31 mg
V, Automotive Repair	GHG	0.00014 mt GGE	0.00029 g GGE	0.0000072 g GGE
	VOC	3.3 kg	6.7 mg	0.17 mg
V, Evaporative Losses	VOC	-	-	-
V, Idling	Energy	560 GJ	1,100 kJ	28 kJ
	GHG	40 mt GGE	80 g GGE	2.0 g GGE
	SO_2	-	-	-
	CO	690 kg	1,400 mg	34 mg
	NO_X	1,000 kg	2,100 mg	52 mg
	VOC	71 kg	140 mg	3.6 mg
	PM_{10}	25 kg	50 mg	1.2 mg
	Pb	-	-	-
V, Tire Production	Energy	18 GJ	35 kJ	0.88 kJ
	GHG	1.3 mt GGE	2.5 g GGE	0.064 g GGE
	SO_2	2.3 kg	4.6 mg	0.11 mg
	CO	18 kg	36 mg	0.89 mg
	NO_X	2.4 kg	4.7 mg	0.12 mg
	VOC	3.0 kg	6.1 mg	0.15 mg
	PM_{10}	-	-	-
	Pb	1.3 kg	2.7 mg	0.067 mg
V, Maintenance	Energy	270 GJ	550 kJ	14 kJ
	GHG	22 mt GGE	45 g GGE	1.1 g GGE
	SO_2	57 kg	110 mg	2.9 mg
	CO	230 kg	460 mg	11 mg
	NO_X	52 kg	100 mg	2.6 mg
	VOC	66 kg	130 mg	3.3 mg
	PM_{10}	-	-	-
	Pb	11 kg	23 mg	0.56 mg
V, Fixed Costs / Insurance	Energy	86 GJ	170 kJ	4.3 kJ
	GHG	7.0 mt GGE	14 g GGE	0.35 g GGE
	SO_2	17 kg	34 mg	0.86 mg
	CO	78 kg	160 mg	3.9 mg
	NO_X	19 kg	39 mg	0.97 mg
	VOC	14 kg	29 mg	0.72 mg
	PM_{10}	3.7 kg	7.3 mg	0.18 mg
	Pb	-	-	-

1.6.2 Infrastructure (Roadways, Parking, and Others)

Automobiles and buses cannot functionally exist without the infrastructure that supports them. Roads, parking lots, lighting, and other components are necessary to allow vehicles to perform their functions under a wide array of conditions. The infrastructure components included in this analysis are:

- Roadway construction
- Roadway maintenance
- Parking construction and maintenance
- Roadway lighting
- Herbicides
- Salting
- Repair facilities

The methodologies used to calculate the environmental inventory and normalize results to the functional units are described in the following sub-sections.

1.6.2.1 Roadway Construction

Roadways are constructed to achieve vehicle throughput. The following scheme is used to identify the functionality of roadways in the U.S. [FHWA 2000]:

- Interstate – Provide the highest mobility levels and highest speeds over long uninterrupted distances (typical speeds range from 55 to 75 mi/hr)
- Arterial – Complement the interstate system but are not classified as interstate (may be classified as freeway). Connect major urban areas or industrial centers (typical speeds range from 50 to 70 mi/hr).

- Collector – Connect local roads to interstates and arterials (typical speeds range from 35 to 55 mi/hr).
- Local – Provide the lowest mobility levels but are the primary access to residential, business and other local areas (typical speeds range from 20 to 45 mi/hr).

The impacts from roadway construction are estimated using PaLATE, a pavement life-cycle assessment tool which estimates the environmental effects of roadway construction [PaLATE 2004]. PaLATE allows specification of parameters for the design, initial construction, maintenance, and equipment used in roadway construction. Ten roadway types are evaluated for this analysis: interstate, major arterials, minor arterials, collectors, and local roadways in both the urban and rural context. Roadways are designed with two major components, the subbase and wearing layers. The subbase includes soil compaction layers and aggregate bases which serve as the foundation for the wearing layers. The wearing layers are the layers of asphalt laid over the subbase. These layers are what are replaced during roadway resurfacing. Specifications for each roadway type were taken from the American Association of State Highway and Transportation Officials specifications for roadway design [AASHTO 2001]. These are shown in Table 16.

Table 16 – AASHTO Roadway Geometry by Functional Class [AASHTO 2001]

Functional Class	Traveled Way Width (ft)	Both Shoulders Width (ft)	Parking Width (ft)	Total Width (ft)	Note
Rural Interstate	48	28	0	76	Two lanes in each direction
Urban Interstate	48	28	0	76	Two lanes in each direction
Rural Major Arterial	23	12	0	35	One lane in each direction
Urban Major Arterial	23	12	0	35	One lane in each direction
Rural Minor Arterial	23	12	0	35	One lane in each direction
Urban Minor Arterial	23	12	11	46	One lane in each direction, parking on one side
Rural Collectors	22	10	0	32	One lane in each direction
Urban Collectors	22	10	10	42	One lane in each direction, parking
Rural Local	21	10	0	31	One lane in each direction
Urban Local	22	4	11	37	One lane in each direction, parking

Using this roadway geometry, specifications are input into PaLATE for environmental factors on a per-roadway-mile basis (see Appendix B – LCI PaLATE Roadway Construction Factors). The roadway miles by functional class are shown in Table 17 and are extrapolated out ten years based on historical mileage [BTS 2005]. The expected lifetime of the road is specified at ten years so all infrastructure analyses evaluate roadways over this horizon.

Table 17 – Roadway Mileage by Functional Class at 10-year Horizon

Type of Paved Road Miles (2005-2014)	Mileage
Interstate Urban	29,000
Interstate Rural	31,000
Major Arterial Urban	63,000
Major Arterial Rural	100,000
Minor Arterial Urban	110,000
Minor Arterial Rural	130,000
Collector Urban	110,000
Collector Rural	560,000
Local Urban	750,000
Local Rural	820,000

Multiplying these mileages by their environmental per-mile factors yields total emissions for roadway construction. PaLATE computes all environmental factors except for VOCs, which are computed separately. The asphalt market share is made up of 90% cement type, 3% cutback, and 7% emulsified [EPA 2001]. VOC emissions result from the diluent used in the asphalt mix. Some of the material volatilizes and escapes in the form of VOCs during asphalt placement, estimated at 554 and 58 lbs VOC/mt asphalt for the cutback and emulsified types. Only the cutback and emulsified asphalts have diluent. It is estimated that during placement, the diluent is 28% by volume of the cutback and 7% by volume of the emulsified type [EPA 2001]. 75% and 95% of the diluent in cutback and emulsified types escapes during placement. Using these factors, a weighted average VOC emission factor of 3.8 lbs VOC/mt asphalt is determined for all asphalt placement in the U.S. (this includes all three types assuming that the market share type weightings are used in roadways).

With total roadway construction impacts of all environmental inventory computed, functional units are normalized. This is done using VMT data by vehicle type extrapolated to 2014 [BTS 2005]. The extrapolation is necessary because the analysis calculates the inventory for a roadway constructed in 2005 with a lifetime of 10 years. VMT data are extrapolated from 2005 through 2014 to capture the change in driving during this period. Equation Set 6 details the inventory calculations to the functional units for roadway construction.

Equation Set 6 – Onroad Infrastructure Roadway Construction

$$I/O^{onroad,road\ construction} = \sum_{road\ types} I/O_{road\ type} \left[in\ \frac{effect_{road\ lifetime}}{distance} \right] \times mi$$

$$I/O^{onroad,road\ construction}_{vehicle-lifetime} = I/O^{onroad,road\ construction} \times \frac{lifetime_{road}}{VMT_{road}} \times \frac{VMT_{vehicle}}{lifetime_{vehicle}}$$

$$I/O^{onroad,road\ construction}_{VMT} = I/O^{onroad,road\ construction} \times \frac{lifetime_{road}}{VMT_{road}}$$

$$I/O^{onroad,road\ construction}_{PMT} = I/O^{onroad,road\ construction} \times \frac{lifetime_{road}}{VMT_{road}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

Many roadways are constructed with additional space for on-street parking. This analysis disaggregates the environmental inventory fractions of roadways used for movement and parking (see §1.6.2.3). The parking lanes of urban roadways as specified by AASHTO 2001 has been excluded from the roadway construction inventory and attributed to parking.

1.6.2.2 Roadway Maintenance

Unlike construction, roadway maintenance is not determined by the number of vehicles but by their respective weights and resulting damage to the pavement. The damage to a roadway follows a fourth-power function of axle-loads (weight per axle) [Huang 2004]. Generally, damage to roadways results from heavy vehicles such as trucks and buses. Equation Set 7 shows generalized damage factors computed for various vehicle types (a vehicle weight of 25,000 lbs is assumed for the bus and 62,000 lbs for a freight truck) [FTA 2006, Facanha 2006].

Equation Set 7 – Onroad Infrastructure Roadway Maintenance Damage Factors

$$DF = Damage\ Factor = \left(\frac{weight_{vehicle}}{number_{axles}}\right)^4$$

$$DF_{sedan} = \left(\frac{3{,}200\ lbs}{2}\right)^4 = 6.9 \cdot 10^{12}$$

$$DF_{SUV} = \left(\frac{4{,}600\ lbs}{2}\right)^4 = 2.9 \cdot 10^{13}$$

$$DF_{pickup} = \left(\frac{5{,}200\ lbs}{2}\right)^4 = 4.7 \cdot 10^{13}$$

$$DF_{bus} = \left(\frac{25{,}000\ lbs}{2}\right)^4 = 2.4 \cdot 10^{16}$$

$$DF_{freight\ truck} = \left(\frac{62{,}000\ lbs}{5}\right)^4 = 2.3 \cdot 10^{16}$$

While the SUV and pickup do 4 and 7 times more damage to the roadway than the sedan, the bus and truck do 3,600 and 3,300 times more damage. The effects from the bus and truck dwarf the effects from any other vehicles as shown in Table 18. As a result, only the maintenance on roadways attributed to bus traffic is considered.

Table 18 – Roadway Damage Fraction Calculations by Vehicle and Functional Class

	Sedan	Pickup	SUV	Van	Mot.cycle	Other Bus	Transit Bus	Freight
Interstate (Urban)	0.16%	0.39%	0.26%	0.06%	0%	1.60%	0%	97.54%
Interstate (Rural)	0.06%	0.15%	0.10%	0.02%	0%	1.28%	0%	98.39%
Arterial (Urban)	0.33%	0.83%	0.54%	0.12%	0%	1.98%	0%	96.20%
Arterial (Rural)	0.14%	0.34%	0.22%	0.05%	0%	1.35%	0%	97.91%
Collector (Urban)	0.33%	0.82%	0.53%	0.12%	0%	1.92%	2.99%	93.30%
Collector (Rural)	0.17%	0.42%	0.27%	0.06%	0%	3.04%	5.57%	90.48%
Local (Urban)	0.32%	0.79%	0.52%	0.11%	0%	1.90%	4.05%	92.31%
Local (Rural)	0.18%	0.44%	0.29%	0.06%	0%	3.04%	5.46%	90.53%

Roadway maintenance is considered to be the replacement of the wearing layers after 10 years on all roadway types. PaLATE is again used to determine the life-cycle emissions from reconstruction of the wearing layers (VOCs are again calculated separately). Total emissions for the U.S. roadway system are then determined using the same methodology described in §1.6.2.1.

To determine what portion of the total maintenance inventory is attributable to bus operations requires use of the damage factors. VMT by vehicle type are multiplied by the vehicle's damage factor to compute total damage. The ratio of bus damage to total damage is taken and multiplied by the total energy input or emission output. This yields the portion of inventory attributable to buses (Equation Set 8).

Equation Set 8 – Onroad Infrastructure Roadway Maintenance

$$D_{bus} = VMT_{bus} \times DF_{bus} \qquad D_{all} = \sum_{vehicle\ types} \left(VMT_{type} \times DF_{type}\right)$$

$$I/O^{onroad,road\ maintenance} = \sum_{road\ types} \left(I/O_{road\ type} \times \frac{D_{bus,road\ type}}{D_{all,road\ type}}\right)$$

$$I/O^{onroad,road\ maintenance}_{vehicle-lifetime} = I/O^{road\ maintenance} \times \frac{lifetime_{road}}{VMT_{road}} \times \frac{VMT_{vehicle}}{lifetime_{vehicle}}$$

$$I/O^{onroad,road\ maintenance}_{VMT} = I/O^{road\ maintenance} \times \frac{lifetime_{road}}{VMT_{road}}$$

$$I/O^{onroad,road\ maintenance}_{PMT} = I/O^{road\ maintenance} \times \frac{lifetime_{road}}{VMT_{road}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

1.6.2.3 Parking

The effects of parking area construction and maintenance are similar to the effects of roadway construction and maintenance. Energy is required and emissions result from the production and placement of asphalt. Additionally, parking garages, often constructed of steel, have additional material and construction requirements. There are an estimated 105M parking spaces in the U.S. of which ⅓ are on-street with the remaining ⅔ in parking garages and surface lots [IPI 2007, EPA 2005]. The typical parking space has an area of 300 ft^2 plus access ways [TRB 1991]. Roadside and surface lot parking spaces are assumed to have lifetimes of 10 and 15 years while parking garages have lifetimes of 30 years [TRB 1991].

Parking is disaggregated into roadside, surface lots, and parking garages. The 35M roadside spaces cover an area of 12B ft^2, assumed to be constructed primarily from asphalt. There are over 16,000 surface lots in the U.S. making up 36M spaces [Census 2002]. This represents an area of 18B ft^2 assuming an additional 50% area for access ways. Lastly, there are 35,000 parking garages in the U.S. with an average area of 150,000 ft^2 per floor [MR 2007, TRB 1991]. Parking garages constitute 10B ft^2 of paved area plus the impact from the structures. PaLATE is used to determine total impact from the parking paved area under the assumption that asphalt is the primary construction materials [PaLATE 2004]. All parking surfaces are assumed to have two wearing layers (each with a 3 inch depth). Roadside parking and surface lots also have a subbase layer with a 12 inch depth. The portion of roads in urban areas that are used for roadside parking and not movement are included. VOC emissions are calculated separately using the same methodology described in §1.6.2.1. The life-cycle impacts of the parking garages are computed as a steel-framed structure based on square-foot estimates [Guggemos 2005].

With total impacts computed for all three parking space types, the estimated lifetimes are used to annualize the inventory values. Parking lots are is assumed to increase proportionally with the number of registered vehicles in the U.S.. With a total annual impact determined, Equation Set 9 is used to normalize results.

Equation Set 9 – Onroad Infrastructure Parking Construction and Maintenance

$$I/O^{onroad,parking} = Annual\ I/O\ from\ Parking\ Construction\ \&\ Maintenance$$

$$I/O^{onroad,parking}_{vehicle-lifetime} = I/O^{onroad,parking} \times share_{VMT,vehicle} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{lifetime_{vehicle}}$$

$$I/O^{onroad,parking}_{VMT} = I/O^{onroad,parking} \times share_{VMT,vehicle} \times \frac{yr}{VMT_{vehicle}}$$

$$I/O^{onroad,parking}_{PMT} = I/O^{onroad,parking} \times share_{VMT,vehicle} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

1.6.2.4 Roadway and Parking Lighting

A 2002 U.S. lighting inventory study estimates annual electricity consumption by lighting sectors including roadways and parking lots [EERE 2002]. The study estimates electricity consumption for traffic signals, roadway overhead lights, and parking lot lights. In 2001, these components consumed 3.6, 31 and 22 TWh [EERE 2002]. Assuming that roadway and parking lot lighting increases linearly with road miles, an extrapolation is performed over the lifetime of the roadway. Multiplying this electricity consumption by national electricity production factors yields the environmental inventory [Deru 2007]. With the 2005 roadway and parking lighting inventory computed, the methodology shown in Equation Set 10 is used to normalize to the functional units.

Equation Set 10 – Onroad Infrastructure Roadway and Parking Lighting

$$EF_{I/O} = Electricity\ Generation\ Emissions\ (per\ kWh)$$

$$E = Annual\ Electricity\ Consumption$$

$$I/O^{onroad,parking\ lighting}_{vehicle-lifetime} = E_{lighting} \times EF_{I/O} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{lifetime_{vehicle}}$$

$$I/O^{onroad,parking\ lighting}_{VMT} = E_{lighting} \times EF_{I/O} \times \frac{yr}{VMT_{vehicle}}$$

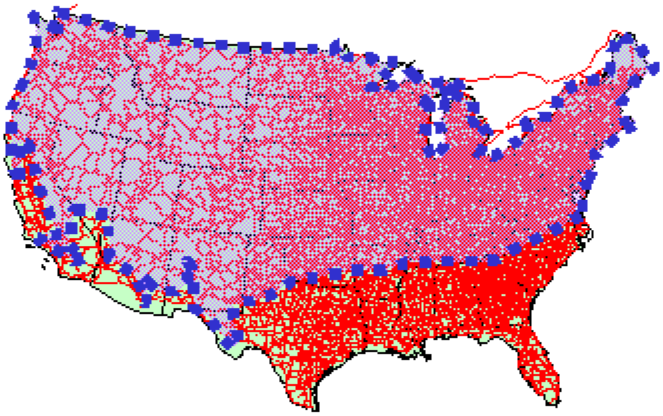
$$I/O^{onroad,parking\ lighting}_{PMT} = E_{lighting} \times EF_{I/O} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

1.6.2.5 Herbicides and Salting

Herbicides are routinely used for vegetation management along roadways. The U.S. is the world's largest producer and consumer of pesticides primarily due to the dominating share of world agriculture production [EPA 2004]. In 2001, the commercial, industrial, and government sectors in the U.S. consumed 49M lbs of herbicides, roughly 12% of U.S. herbicide consumption. This amounted to $792M (in $2001) in pesticide expenditures. Agriculture is by far the largest herbicide-consuming sector at 78% of U.S. use while home and garden applications accounted for 10%. Assuming that herbicide use was split evenly among the commercial, industrial, and government subsectors and that all government use went to roadways, then roadways are responsible for ⅓ of this sector's usage (or 16M lbs and $264M in 2001, roughly 4% of total U.S. herbicide consumption).

Over 70% of U.S. roadways are in potential snow and ice regions (Figure 2) requiring the application of over 10M tons of salt annually [FHWA 2007, TRB 1991]. The cost of this salt is $30 per ton (in $1991) [TRB 1991].

Figure 2 – Roadways in Potential Snow and Ice Regions [FHWA 2007]



The production of herbicides and salt for application along and on roadways is evaluated. The energy and emissions from vehicles applying these compounds is not included. It is assumed that application of these materials increases linearly with road miles. The sectors Other Basic Inorganic Chemical Manufacturing (#325180) and Other Basic Organic Chemical Manufacturing (#325190) in EIO-LCA are used to determine the production inventories. Extrapolating usage of these compounds to 2005 based on road miles, calculating their costs, and inputting into the respective EIO-LCA sectors yields the environmental inventories. Equation Set 11 shows the general framework for normalization to the functional units.

Equation Set 11 – Onroad Infrastructure Herbicides and Salting

$$I/O^{onroad,herbicide/salting} = Annual\ Herbicide\ or\ Salt\ Production\ I/O$$

$$I/O^{onroad,herbicide/salting}_{vehicle-lifetime} = I/O^{onroad,herbicide/salting} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{lifetime_{vehicle}}$$

$$I/O^{onroad,herbicide/salting}_{VMT} = I/O^{onroad,herbicide/salting} \times \frac{yr}{VMT_{vehicle}}$$

$$I/O^{onroad,herbicide/salting}_{PMT} = I/O^{onroad,herbicide/salting} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

1.6.2.6 *Infrastructure Results*

Table 19 – Onroad Infrastructure Results for Sedans

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
I, Roadway Construction	Energy	160 GJ	870 kJ	550 kJ
	GHG	14 mt GGE	73 g GGE	46 g GGE
	SO_2	26 kg	140 mg	86 mg
	CO	50 kg	270 mg	170 mg
	NO_X	65 kg	350 mg	220 mg
	VOC	85 kg	450 mg	290 mg
	PM_{10}	32 kg	170 mg	110 mg
	Pb	0.0079 kg	0.042 mg	0.027 mg
I, Herbicides / Salting	Energy	0.94 GJ	5.0 kJ	3.2 kJ
	GHG	0.070 mt GGE	0.37 g GGE	0.24 g GGE
	SO_2	0.00014 kg	0.00074 mg	0.00047 mg
	CO	0.00026 kg	0.0014 mg	0.00086 mg
	NO_X	0.000093 kg	0.00050 mg	0.00031 mg
	VOC	0.000100 kg	0.00053 mg	0.00034 mg
	PM_{10}	0.000019 kg	0.00010 mg	0.000065 mg
	Pb	-	-	-
I, Roadway Lighting	Energy	12 GJ	64 kJ	40 kJ
	GHG	2.5 mt GGE	13 g GGE	8.5 g GGE
	SO_2	13 kg	67 mg	43 mg
	CO	1.2 kg	6.5 mg	4.1 mg
	NO_X	4.2 kg	22 mg	14 mg
	VOC	0.11 kg	0.58 mg	0.36 mg
	PM_{10}	0.14 kg	0.74 mg	0.47 mg
	Pb	0.00020 kg	0.0011 mg	0.00067 mg
I, Parking	Energy	22 GJ	120 kJ	74 kJ
	GHG	2.9 mt GGE	16 g GGE	9.9 g GGE
	SO_2	8.1 kg	43 mg	27 mg
	CO	15 kg	78 mg	49 mg
	NO_X	19 kg	100 mg	64 mg
	VOC	8.8 kg	47 mg	30 mg
	PM_{10}	6.0 kg	32 mg	20 mg
	Pb	0.0010 kg	0.0055 mg	0.0035 mg

Table 20 – Onroad Infrastructure Results for SUVs

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
I, Roadway Construction	Energy	150 GJ	870 kJ	500 kJ
	GHG	13 mt GGE	73 g GGE	42 g GGE
	SO_2	24 kg	140 mg	79 mg
	CO	46 kg	270 mg	150 mg
	NO_X	60 kg	350 mg	200 mg
	VOC	78 kg	450 mg	260 mg
	PM_{10}	29 kg	170 mg	97 mg
	Pb	0.0073 kg	0.042 mg	0.024 mg
I, Herbicides / Salting	Energy	0.94 GJ	5.5 kJ	3.2 kJ
	GHG	0.070 mt GGE	0.41 g GGE	0.23 g GGE
	SO_2	0.00014 kg	0.00082 mg	0.00047 mg
	CO	0.00026 kg	0.0015 mg	0.00086 mg
	NO_X	0.000094 kg	0.00054 mg	0.00031 mg
	VOC	0.00010 kg	0.00058 mg	0.00033 mg
	PM_{10}	0.000019 kg	0.00011 mg	0.000065 mg
	Pb	-	-	-
I, Roadway Lighting	Energy	11 GJ	64 kJ	37 kJ
	GHG	2.3 mt GGE	14 g GGE	7.8 g GGE
	SO_2	12 kg	68 mg	39 mg
	CO	1.1 kg	6.5 mg	3.7 mg
	NO_X	3.8 kg	22 mg	13 mg
	VOC	0.099 kg	0.58 mg	0.33 mg
	PM_{10}	0.13 kg	0.74 mg	0.43 mg
	Pb	0.00018 kg	0.0011 mg	0.00061 mg
I, Parking	Energy	20 GJ	120 kJ	67 kJ
	GHG	2.7 mt GGE	16 g GGE	9.0 g GGE
	SO_2	7.5 kg	43 mg	25 mg
	CO	13 kg	78 mg	45 mg
	NO_X	17 kg	100 mg	58 mg
	VOC	8.1 kg	47 mg	27 mg
	PM_{10}	5.5 kg	32 mg	18 mg
	Pb	0.00094 kg	0.0055 mg	0.0031 mg

Table 21 – Onroad Infrastructure Results for Pickups

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
I, Roadway Construction	Energy	150 GJ	870 kJ	600 kJ
	GHG	13 mt GGE	73 g GGE	50 g GGE
	SO$_2$	24 kg	140 mg	94 mg
	CO	46 kg	270 mg	180 mg
	NO$_X$	60 kg	350 mg	240 mg
	VOC	78 kg	450 mg	310 mg
	PM$_{10}$	29 kg	170 mg	120 mg
	Pb	0.0073 kg	0.042 mg	0.029 mg
I, Herbicides / Salting	Energy	0.94 GJ	5.5 kJ	3.8 kJ
	GHG	0.070 mt GGE	0.41 g GGE	0.28 g GGE
	SO$_2$	0.00014 kg	0.00082 mg	0.00056 mg
	CO	0.00026 kg	0.0015 mg	0.0010 mg
	NO$_X$	0.000094 kg	0.00054 mg	0.00037 mg
	VOC	0.00010 kg	0.00058 mg	0.00040 mg
	PM$_{10}$	0.000019 kg	0.00011 mg	0.000077 mg
	Pb	-	-	-
I, Roadway Lighting	Energy	11 GJ	64 kJ	44 kJ
	GHG	2.3 mt GGE	14 g GGE	9.3 g GGE
	SO$_2$	12 kg	68 mg	46 mg
	CO	1.1 kg	6.5 mg	4.5 mg
	NO$_X$	3.8 kg	22 mg	15 mg
	VOC	0.099 kg	0.58 mg	0.40 mg
	PM$_{10}$	0.13 kg	0.74 mg	0.51 mg
	Pb	0.00018 kg	0.0011 mg	0.00072 mg
I, Parking	Energy	20 GJ	120 kJ	80 kJ
	GHG	2.7 mt GGE	16 g GGE	11 g GGE
	SO$_2$	7.5 kg	43 mg	30 mg
	CO	13 kg	78 mg	53 mg
	NO$_X$	17 kg	100 mg	69 mg
	VOC	8.1 kg	47 mg	32 mg
	PM$_{10}$	5.5 kg	32 mg	22 mg
	Pb	0.00094 kg	0.0055 mg	0.0037 mg

Table 22 – Onroad Infrastructure Results for an Average Bus

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
I, Roadway Construction	Energy	400 GJ	800 kJ	76 kJ
	GHG	34 mt GGE	67 g GGE	6.4 g GGE
	SO_2	63 kg	130 mg	12 mg
	CO	120 kg	240 mg	23 mg
	NO_X	160 kg	320 mg	30 mg
	VOC	210 kg	410 mg	39 mg
	PM_{10}	77 kg	150 mg	15 mg
	Pb	0.019 kg	0.039 mg	0.0037 mg
I, Roadway Maintenance	Energy	590 GJ	1,200 kJ	110 kJ
	GHG	50 mt GGE	100 g GGE	9.5 g GGE
	SO_2	92 kg	180 mg	18 mg
	CO	180 kg	360 mg	35 mg
	NO_X	230 kg	450 mg	43 mg
	VOC	320 kg	630 mg	60 mg
	PM_{10}	120 kg	230 mg	22 mg
	Pb	0.029 kg	0.058 mg	0.0056 mg
I, Herbicides / Salting	Energy	2.5 GJ	5.0 kJ	0.48 kJ
	GHG	0.19 mt GGE	0.37 g GGE	0.036 g GGE
	SO_2	0.00037 kg	0.00075 mg	0.000071 mg
	CO	0.00068 kg	0.0014 mg	0.00013 mg
	NO_X	0.00025 kg	0.00050 mg	0.000048 mg
	VOC	0.00027 kg	0.00053 mg	0.000051 mg
	PM_{10}	0.000052 kg	0.00010 mg	0.0000098 mg
	Pb	-	-	-
I, Roadway Lighting	Energy	12 GJ	23 kJ	2.2 kJ
	GHG	2.4 mt GGE	4.9 g GGE	0.47 g GGE
	SO_2	12 kg	24 mg	2.3 mg
	CO	1.2 kg	2.4 mg	0.22 mg
	NO_X	4.0 kg	8.1 mg	0.77 mg
	VOC	0.10 kg	0.21 mg	0.020 mg
	PM_{10}	0.13 kg	0.27 mg	0.026 mg
	Pb	0.00019 kg	0.00038 mg	0.000036 mg

Table 23 – Onroad Infrastructure Results for an Off-Peak Bus

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
I, Roadway Construction	Energy	400 GJ	800 kJ	160 kJ
	GHG	34 mt GGE	67 g GGE	13 g GGE
	SO_2	63 kg	130 mg	25 mg
	CO	120 kg	240 mg	49 mg
	NO_X	160 kg	320 mg	64 mg
	VOC	210 kg	410 mg	82 mg
	PM_{10}	77 kg	150 mg	31 mg
	Pb	0.019 kg	0.039 mg	0.0077 mg
I, Roadway Maintenance	Energy	590 GJ	1,200 kJ	240 kJ
	GHG	50 mt GGE	100 g GGE	20 g GGE
	SO_2	92 kg	180 mg	37 mg
	CO	180 kg	360 mg	73 mg
	NO_X	230 kg	450 mg	91 mg
	VOC	320 kg	630 mg	130 mg
	PM_{10}	120 kg	230 mg	46 mg
	Pb	0.029 kg	0.058 mg	0.012 mg
I, Herbicides / Salting	Energy	2.5 GJ	5.0 kJ	1.0 kJ
	GHG	0.19 mt GGE	0.37 g GGE	0.075 g GGE
	SO_2	0.00037 kg	0.00075 mg	0.00015 mg
	CO	0.00068 kg	0.0014 mg	0.00027 mg
	NO_X	0.00025 kg	0.00050 mg	0.000100 mg
	VOC	0.00027 kg	0.00053 mg	0.00011 mg
	PM_{10}	0.000052 kg	0.00010 mg	0.000021 mg
	Pb	-	-	-
I, Roadway Lighting	Energy	12 GJ	23 kJ	4.6 kJ
	GHG	2.4 mt GGE	4.9 g GGE	0.98 g GGE
	SO_2	12 kg	24 mg	4.9 mg
	CO	1.2 kg	2.4 mg	0.47 mg
	NO_X	4.0 kg	8.1 mg	1.6 mg
	VOC	0.10 kg	0.21 mg	0.042 mg
	PM_{10}	0.13 kg	0.27 mg	0.054 mg
	Pb	0.00019 kg	0.00038 mg	0.000076 mg

Table 24 – Onroad Infrastructure Results for a Peak Bus

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
I, Roadway Construction	Energy	400 GJ	800 kJ	20 kJ
	GHG	34 mt GGE	67 g GGE	1.7 g GGE
	SO_2	63 kg	130 mg	3.1 mg
	CO	120 kg	240 mg	6.1 mg
	NO_X	160 kg	320 mg	8.0 mg
	VOC	210 kg	410 mg	10 mg
	PM_{10}	77 kg	150 mg	3.9 mg
	Pb	0.019 kg	0.039 mg	0.00097 mg
I, Roadway Maintenance	Energy	590 GJ	1,200 kJ	30 kJ
	GHG	50 mt GGE	100 g GGE	2.5 g GGE
	SO_2	92 kg	180 mg	4.6 mg
	CO	180 kg	360 mg	9.1 mg
	NO_X	230 kg	450 mg	11 mg
	VOC	320 kg	630 mg	16 mg
	PM_{10}	120 kg	230 mg	5.8 mg
	Pb	0.029 kg	0.058 mg	0.0015 mg
I, Herbicides / Salting	Energy	2.5 GJ	5.0 kJ	0.13 kJ
	GHG	0.19 mt GGE	0.37 g GGE	0.0094 g GGE
	SO_2	0.00037 kg	0.00075 mg	0.000019 mg
	CO	0.00068 kg	0.0014 mg	0.000034 mg
	NO_X	0.00025 kg	0.00050 mg	0.000012 mg
	VOC	0.00027 kg	0.00053 mg	0.000013 mg
	PM_{10}	0.000052 kg	0.00010 mg	0.0000026 mg
	Pb	-	-	-
I, Roadway Lighting	Energy	12 GJ	23 kJ	0.58 kJ
	GHG	2.4 mt GGE	4.9 g GGE	0.12 g GGE
	SO_2	12 kg	24 mg	0.61 mg
	CO	1.2 kg	2.4 mg	0.059 mg
	NO_X	4.0 kg	8.1 mg	0.20 mg
	VOC	0.10 kg	0.21 mg	0.0052 mg
	PM_{10}	0.13 kg	0.27 mg	0.0067 mg
	Pb	0.00019 kg	0.00038 mg	0.0000095 mg

1.6.3 Fuel Production (Gasoline and Diesel)

1.6.3.1 Fuel Production

The life-cycle inventory for gasoline and diesel fuel production is calculated using EIO-LCA. The Petroleum Refineries (#324110) economic sector is an accurate representation of the petroleum refining process. Table 25 summarizes the parameters used to determine fuel production impacts. The cost of fuel (in $1997) represents the price of fuel reduced by various federal and state taxes as well as distribution, marketing and profits [MacLean 1998, EIA 2007, EIA 2007b].

Table 25 – Fuel Production Parameters by Vehicle

	Sedan	SUV	Truck	Bus
Vehicle Fuel	Gasoline	Gasoline	Gasoline	Diesel
Cost of Fuel ($1997/gal)	0.76	0.76	0.76	0.72
Vehicle Fuel Economy (mi/gal)	28	17	16	4.3
Vehicle Lifetime Miles (mi/vehicle-life)	190,000	170,000	170,000	500,000
Lifetime Fuel Consumed (gal/life)	6,700	10,000	11,000	120,000

Using the cost of fuel and the lifetime gallons consumed, a total lifetime cost is determined. This is then input into EIO-LCA for the environmental inventory. The EIO-LCA model estimates that for every 100 MJ of energy of gasoline or diesel produced, and additional 16 were required to produce it. This is 9 units of direct energy, during the production and transport process, and 7 units of indirect energy in the supply chain. Equation Set 12 summarizes the normalization of output from EIO-LCA.

Equation Set 12 – Onroad Fuel Production

$$I/O_{vehicle-lifetime}^{onroad,fuel\,production} = Vehicle\ Lifetime\ Fuel\ Production\ I/O\ (from\ EIOLCA)$$

$$I/O_{VMT}^{onroad,fuel\,production} = I/O_{vehicle-lifetime}^{onroad,fuel\,production} \times \frac{lifetime_{vehicle}}{VMT_{vehicle}}$$

$$I/O_{PMT}^{onroad,fuel\,production} = I/O_{vehicle-lifetime}^{onroad,fuel\,production} \times \frac{lifetime_{vehicle}}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

1.6.3.2 Fuel Distribution

The fuel production environmental performance determines the energy and emissions associated with the creation of the fuel. This estimate stops at the refinery and does not include transport of that fuel to refueling stations; this was estimated separately.

It was assumed that all gasoline (for automobiles) and diesel fuel (for buses) was transported 100 miles by tanker truck during distribution. Truck emission factors from Facanha 2007 were assumed reasonable for fuel transport environmental performance. It was also assumed that the tanker trucks operate on diesel fuel themselves and achieve 110 ton-miles per gallon [BTS 2008]. The resulting energy consumption and emissions from distribution are included in the fuel refining and distribution results shown in §1.6.3.3.

1.6.3.3 Fuel Results

Table 26 – Onroad Fuel Production Results for Sedans

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
F, Refining & Distribution	Energy	130 GJ	680 kJ	430 kJ
	GHG	12 mt GGE	61 g GGE	39 g GGE
	SO_2	22 kg	120 mg	73 mg
	CO	32 kg	170 mg	110 mg
	NO_X	18 kg	95 mg	60 mg
	VOC	14 kg	74 mg	47 mg
	PM_{10}	2.9 kg	16 mg	9.9 mg
	Pb	-	-	-

Table 27 – Onroad Fuel Production Results for SUVs

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
F, Refining & Distribution	Energy	190 GJ	1,100 kJ	640 kJ
	GHG	17 mt GGE	100 g GGE	58 g GGE
	SO_2	33 kg	190 mg	110 mg
	CO	48 kg	280 mg	160 mg
	NO_X	27 kg	160 mg	90 mg
	VOC	21 kg	120 mg	70 mg
	PM_{10}	4.4 kg	26 mg	15 mg
	Pb	-	-	-

Table 28 – Onroad Fuel Production Results for Pickups

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
F, Refining & Distribution	Energy	200 GJ	1,200 kJ	810 kJ
	GHG	19 mt GGE	110 g GGE	74 g GGE
	SO_2	35 kg	200 mg	140 mg
	CO	51 kg	300 mg	200 mg
	NO_X	29 kg	170 mg	110 mg
	VOC	22 kg	130 mg	88 mg
	PM_{10}	4.7 kg	27 mg	19 mg
	Pb	-	-	-

Table 29 – Onroad Fuel Production Results for an Average Bus

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
F, Refining & Distribution	Energy	2,100 GJ	4,200 kJ	400 kJ
	GHG	190 mt GGE	380 g GGE	36 g GGE
	SO_2	360 kg	720 mg	68 mg
	CO	530 kg	1,100 mg	100 mg
	NO_X	310 kg	620 mg	59 mg
	VOC	230 kg	460 mg	43 mg
	PM_{10}	51 kg	100 mg	9.7 mg
	Pb	-	-	-

Table 30 – Onroad Fuel Production Results for an Off-Peak Bus

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
F, Refining & Distribution	Energy	2,100 GJ	4,200 kJ	840 kJ
	GHG	190 mt GGE	380 g GGE	77 g GGE
	SO_2	360 kg	720 mg	140 mg
	CO	530 kg	1,100 mg	210 mg
	NO_X	310 kg	620 mg	120 mg
	VOC	230 kg	460 mg	91 mg
	PM_{10}	51 kg	100 mg	20 mg
	Pb	-	-	-

Table 31 – Onroad Fuel Production Results for a Peak Bus

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
F, Refining & Distribution	Energy	2,100 GJ	4,200 kJ	110 kJ
	GHG	190 mt GGE	380 g GGE	9.6 g GGE
	SO_2	360 kg	720 mg	18 mg
	CO	530 kg	1,100 mg	26 mg
	NO_X	310 kg	620 mg	16 mg
	VOC	230 kg	460 mg	11 mg
	PM_{10}	51 kg	100 mg	2.5 mg
	Pb	-	-	-

1.6.4 Fundamental Environmental Factors for Onroad

The fundamental environmental factors for the onroad modes are shown in Table 32. These factors are the basis for each component's environmental inventory calculations.

Table 32 – Fundamental Environmental Factors for Onroad Modes (Sources, Energy, & GHG)

Grouping	Component	Sources	Energy		GHG (CO$_2$e)	
Vehicles						
Manufacturing	Sedan	EIO-LCA 2008 (#336110), AN 2005	121	GJ/veh.	10	mt/veh.
	SUV	EIO-LCA 2008 (#336110), AN 2005	103	GJ/veh.	9	mt/veh.
	Pickup	EIO-LCA 2008 (#336110), AN 2005	146	GJ/veh.	12	mt/veh.
	Bus	EIO-LCA 2008 (#336120), FTA 2006	114	GJ/veh.	129	mt/veh.
Sedan Operation	Running	MacLean 1998, EPA 2006, EPA 2003	4.8	MJ/VMT	367	g/VMT
	Startup	EPA 2003				
	Brake Wear	EPA 2003				
	Tire Wear	EPA 2003				
	Evaporative	EPA 2003				
SUV Operation	Running	MacLean 1998, EPA 2006, EPA 2003	7.8	MJ/VMT	478	g/VMT
	Startup	EPA 2003				
	Brake Wear	EPA 2003				
	Tire Wear	EPA 2003				
	Evaporative	EPA 2003				
Pickup Operation	Running	MacLean 1998, EPA 2006, EPA 2003	8.3	MJ/VMT	618	g/VMT
	Startup	EPA 2003				
	Brake Wear	EPA 2003				
	Tire Wear	EPA 2003				
	Evaporative	EPA 2003				
Bus Operation	Running	EPA 2003	32	MJ/VMT	2,373	g/VMT
	Brake Wear	EPA 2003				
	Tire Wear	EPA 2003				
	Evaporative	EPA 2003				
	Idling	Clarke 2005, CARB 2002, EPA 2003	65	MJ/hr	4,614	g/hr
Maintenance	Vehicle	EIO-LCA 2008 (#8111A0)	5.2	TJ/$M	423	mt/$M
	Tire	EIO-LCA 2008 (#326210)	15.1	TJ/$M	1090	mt/$M
	Repair Stations	CARB 1997			205	mt/yr
Insurance	Vehicle Insurance	EIO-LCA 2008 (#524100)	1.0	TJ/$M	84	mt/$M
Infrastructure						
Construction	Roads & Highways	PaLATE 2004, EPA 2001, MA 2005, BTS 2005	76	MJ/ft^2	6	kg/ft^2
Maintenance	Roads & Highways	PaLATE 2004, EPA 2001, MA 2005, BTS 2005	7.3	MJ/ft^2	614	g/ft^2
Vegetation Control	Herbicide Production	EIO-LCA 2008 (#325180), EPA 2004	529	MJ/lb	31	kg/lb
Deicing	Salt Production	EIO-LCA 2008 (#325190), TRB 1991	883	MJ/ton	77	kg/ton
Lighting	Electricity Production	EERE 2002, Deru 2007	205	PJ/yr	758	g/kWh
Parking	Road/Surface Parking	PaLATE 2004, EPA 2001	86	MJ/ft^2	7.1	kg/ft^2
	Garage Parking	PaLATE 2004, EPA 2001	8	MJ/ft^2	53	kg/ft^2
Fuels						
Gasoline Production	Refining & Distribution	EIO-LCA 2008 (#324110)	19	MJ/gal	1.7	kg/gal
Diesel Production	Refining & Distribution	EIO-LCA 2008 (#324110)	18	MJ/gal	1.6	kg/gal

Table 32 – Fundamental Environmental Factors for Onroad Modes (cont'd) (CAP)

Grouping	Component	SO_2		CO		NO_X		VOC		Pb		PM_{10}	
Vehicles													
Manufacturing	Sedan	23	kg/veh	124	kg/veh	23	kg/veh	24	kg/veh	32	g/veh	7	kg/veh
	SUV	20	kg/veh	105	kg/veh	20	kg/veh	21	kg/veh	27	g/veh	6	kg/veh
	Pickup	28	kg/veh	149	kg/veh	28	kg/veh	29	kg/veh	39	g/veh	8	kg/veh
	Bus	1600	kg/veh	302	kg/veh	392	kg/veh	0.3	kg/veh	87	kg/veh	162	mt/veh
Sedan Operation	Running	0.02	g/VMT	11	g/VMT	0.8	g/VMT	0.3	g/VMT			0.11	g/VMT
	Startup			7	g/VMT	0.2	g/VMT	0.4	g/VMT				
	Brake Wear											.013	g/VMT
	Tire Wear											.008	g/VMT
	Evaporative							0.5	g/VMT				
SUV Operation	Running	0.03	g/VMT	12	g/VMT	1.0	g/VMT	0.4	g/VMT			0.11	g/VMT
	Startup			9	g/VMT	0.2	g/VMT	0.5	g/VMT				
	Brake Wear											.013	g/VMT
	Tire Wear											.008	g/VMT
	Evaporative							0.5	g/VMT				
Pickup Operation	Running	0.03	g/VMT	16	g/VMT	1.4	g/VMT	0.6	g/VMT			0.10	g/VMT
	Startup			12	g/VMT	0.3	g/VMT	0.8	g/VMT				
	Brake Wear											.013	g/VMT
	Tire Wear											.008	g/VMT
	Evaporative							0.8	g/VMT				
Bus Operation	Running	0.02	g/VMT	4	g/VMT	17.8	g/VMT	0.6	g/VMT			0.03	g/VMT
	Brake Wear											.013	g/VMT
	Tire Wear											.012	g/VMT
	Idling			80	g/hr	121	g/hr	8.2	g/hr			2.9	g/hr
Maintenance	Vehicle	1090	kg/$M	4340	kg/$M	994	kg/$M	1260	kg/$M			214	kg/$M
	Tire	1960	kg/$M	15.2	mt/$M	2030	kg/$M	2600	kg/$M			1140	kg/$M
	Repair Stations							4735	mt/yr				
Insurance	Vehicle	207	kg/$M	934	kg/$M	233	kg/$M	173	kg/$M			44	kg/$M
Infrastructure													
Construction	Roads & Hwys	12	g/ft^2	23	g/ft^2	30	g/ft^2	85	g/ft^2	3.7	g/ft^2	15	g/ft^2
Maintenance	Roads & Hiwys	1	g/ft^2	2236	mg/ft^2	2.8	g/ft^2			359	mg/ft^2	1419	mg/ft^2
Vegetation Control	Herbicide Prod.	86	g/lb	81	g/lb	37	g/lb	18	g/lb			8	g/lb
Deicing	Salt Production	122	g/ton	322	g/ton	108	g/ton	144	g/ton			21	g/ton
Lighting	Electricity Prod.	4	g/kWh	365	mg/kWh	1.3	g/kWh	32	mg/kWh	42	mg/kWh	59	µg/kWh
Parking	Road/Surface	14	g/ft^2	26	g/ft^2	39	g/ft^2	36	g/ft^2	16	g/ft^2	3.9	mg/ft^2
	Garage	222	g/ft^2	380	g/ft^2	465	g/ft^2	36	g/ft^2	84	g/ft^2		
Fuels													
Gasoline	Refining	3.2	g/gal	4.6	g/gal	1.9	g/gal	2.1	g/gal			0.33	g/gal
Diesel	Refining	3.0	g/gal	4.3	g/gal	1.8	g/gal	2.0	g/gal			0.31	g/gal

1.6.5 Onroad Summary

Non-operational components show non-negligible effects in the inventory for the onroad modes. These components capture many direct and indirect processes. In this section, energy, GHG, and CAP inventory results are discussed and the significant contributors for non-negligible components are identified.

1.6.5.1 Energy and GHG Emissions

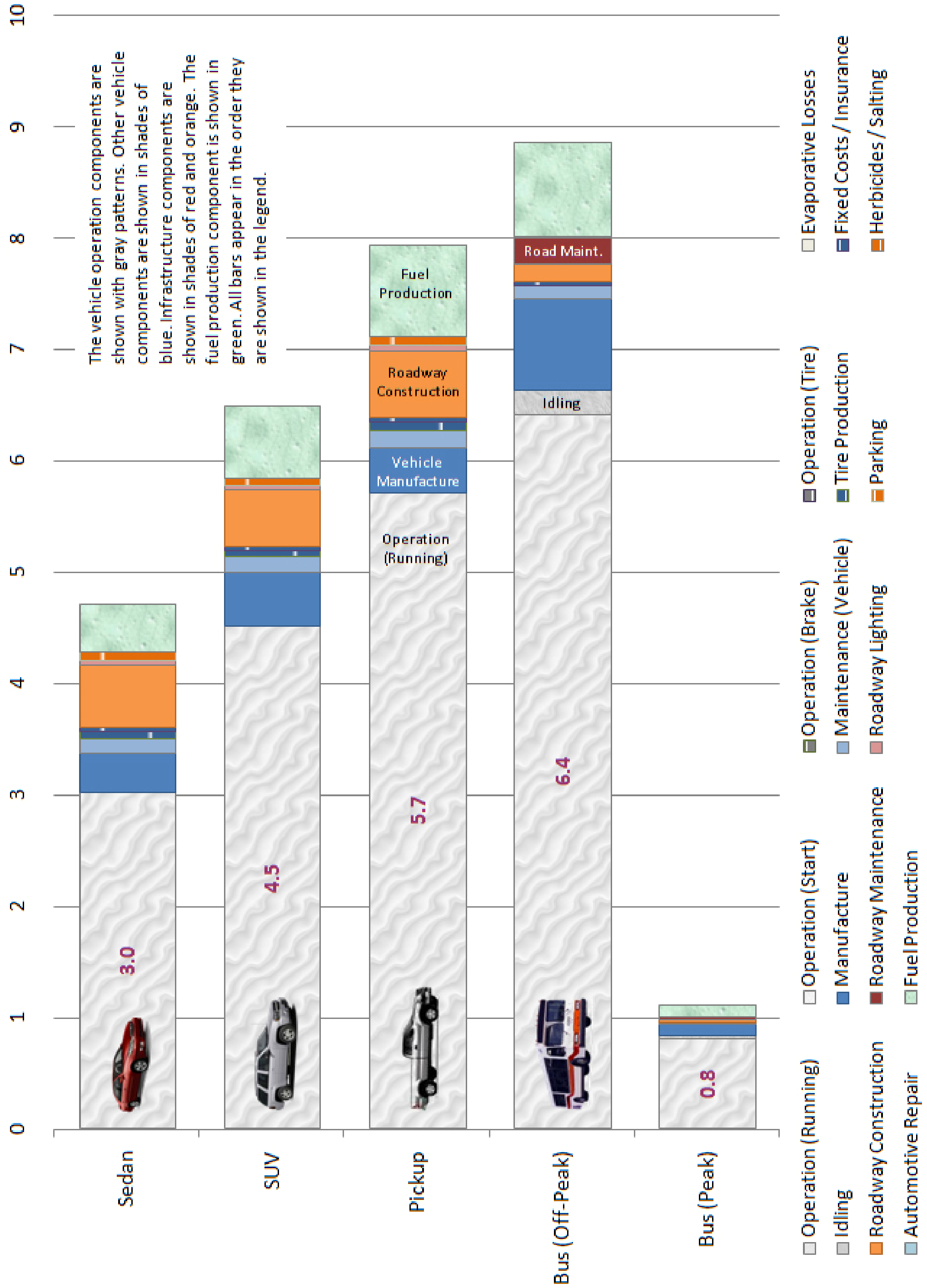
The onroad life-cycle assessment is composed of 17 components, not all of which have significant contributions to energy and GHG emissions. The primary life-cycle contributors to these two inventory categories are vehicle manufacturing, vehicle maintenance, roadway construction and maintenance, roadway lighting, parking construction and maintenance, and petroleum production. The inclusion of these components increases energy consumption and GHG emission per PMT by 38% to 65%.

<u>Vehicle Manufacturing</u>

The large energy requirements to manufacture the onroad modes have significant effects when normalized over the lifetime of the vehicle. The energy, and resulting GHG emissions, are the result not only of direct manufacturing, but also the production and transport of motor vehicle parts, and the materials that go in them. Automobile manufacturing energy is between 0.35 and 0.49 MJ/PMT depending on the mode and GHG emissions are 29 to 41 g CO_2e/PMT. The off-peak bus consumes 6.4 MJ/PMT in direct operational diesel fuel combustion and an additional 0.8 MJ/PMT is the result of vehicle manufacturing. For peak buses, energy consumption is significantly smaller per PMT at 0.8 MJ during operation and 0.1 MJ from manufacturing. For GHG emissions, vehicle manufacturing accounts for 65 g CO_2e/PMT out of the total 680 g

CO$_2$e/PMT for off-peak buses and 8.1 g CO$_2$e /PMT out of the total 85 g CO$_2$e /PMT for peak buses.

Figure 3 – Onroad Travel Energy Inventory (in MJ/PMT)



The vehicle operation components are shown with gray patterns. Other vehicle components are shown in shades of blue. Infrastructure components are shown in shades of red and orange. The fuel production component is shown in green. All bars appear in the order they are shown in the legend.

Vehicle Maintenance

The effects of vehicle maintenance are shown in the GHG inventory mainly as the result of power generation for the automotive repair industry. Emissions from power generation account for over 35% of total GHG emissions in the automotive repair sector [EIO-LCA 2008]. While vehicle maintenance does not show as largely for the buses (around 1.3% of total emissions), it accounts for around 2-3% (11 to 13 g CO_2e /PMT) of automobile emissions.

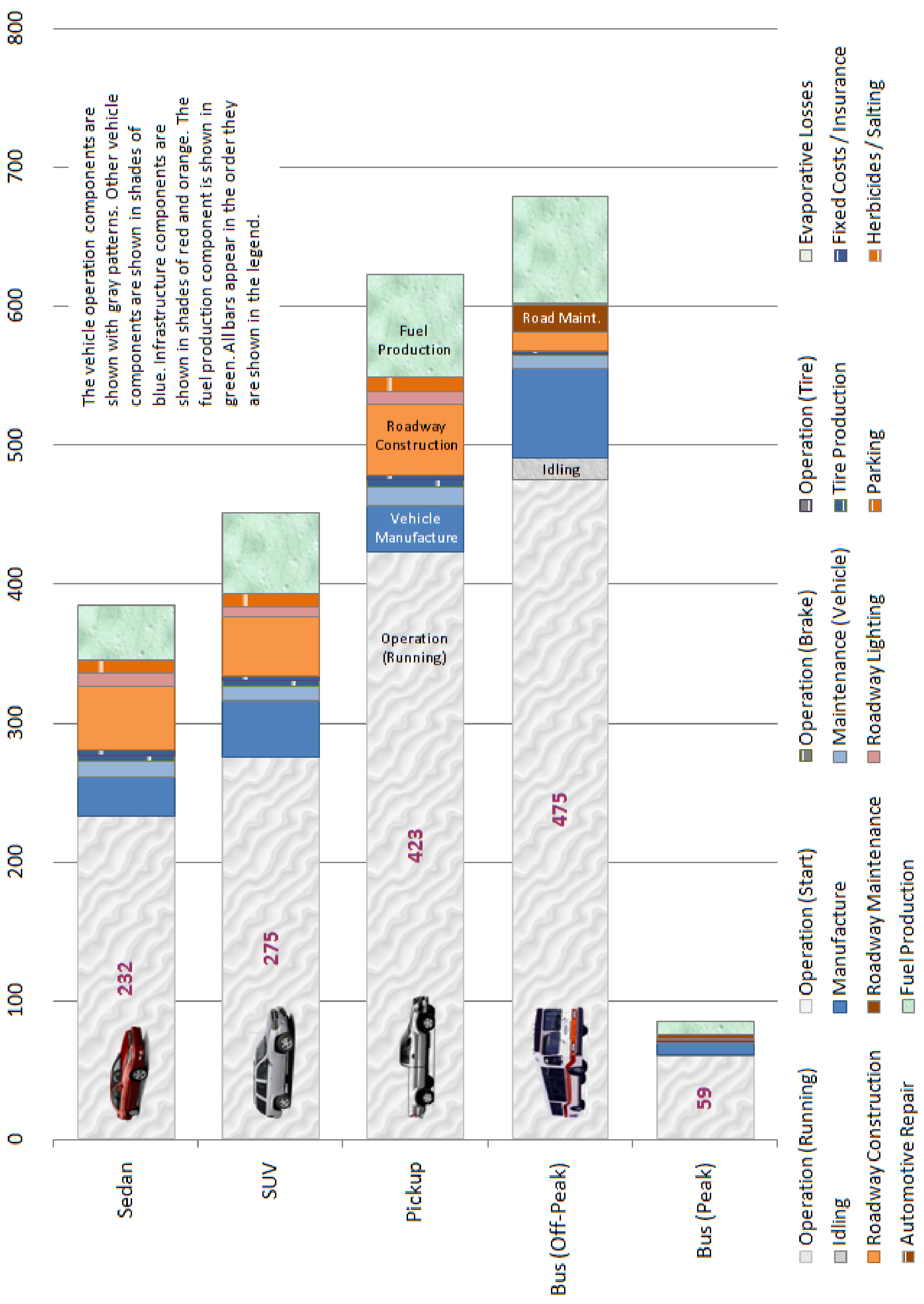
Roadway Construction and Maintenance

Construction and operation of roadways are the most significant contributors to the life-cycle energy and GHG inventory. The impact of roadways affects all four modes but most significantly the automobiles to which a larger share of construction is attributed based on VMT. The energy and GHG emissions in this component are primarily due to material production and transport. The actual process of building the roadways is not as significant [PaLATE 2004].

Roadway Lighting

The consumption of over 200,000 TJ of electricity to light roadways and parking lots in 2001 and the GHG emissions to produce this energy affect the automobile modes inventory [EERE 2002]. Due to a small share of urban bus VMT on the national road network, lighting does not show as significantly for the bus modes.

Figure 4 – Onroad Travel GHG Inventory (in g CO_2e/PMT)



The vehicle operation components are shown with gray patterns. Other vehicle components are shown in shades of blue. Infrastructure components are shown in shades of red and orange. The fuel production component is shown in green. All bars appear in the order they are shown in the legend.

Parking Construction and Maintenance

Similar to roadway construction, parking construction and maintenance has non-negligible effects on the total inventory, particularly for GHG emissions. Again, buses are attributed a very small share of total parking requirements so burdens attributed to automobiles are much larger. Again, the GHG emissions are the result of material production and transport. For automobiles, the energy and GHG impacts of lighting are about as large as vehicle maintenance.

Petroleum Production

As discussed in §1.6.3, the energy required to extract, transport, and refine petroleum-based fuels is over 10% of the energy in the fuel itself. The production of gasoline and diesel requires an additional 9% direct energy and 7% indirect energy based on the energy content of the fuel. This production energy is primarily electricity and other fossil fuels which have large GHG emissions.

Summary

Table 33 summarizes the total and operational inventory for automobiles and the bus.

Table 33 – Onroad Energy and GHG Total and Operational Inventory

(operational emissions in parenthesis)

	Sedan	**SUV**	**Pickup**	**Bus (Off-Peak)**	**Bus (Peak)**
Energy (MJ/PMT)	4.7 (3.0)	6.5 (4.5)	7.9 (5.7)	8.8 (6.4)	1.1 (0.8)
GHG (g CO_2e/PMT)	380 (230)	450 (270)	620 (420)	680 (470)	85 (59)

1.6.5.2 Criteria Air Pollutant Emissions

The CAP emissions per vehicle type are shown in Figure 5. The life-cycle effects of certain components constitute the majority of total emissions, contrary to approaches where tailpipe factors dominate. The primary contributing components are cold starts, operational evaporative losses, vehicle manufacturing, roadway construction, roadway lighting, parking construction and maintenance, roadway maintenance, and petroleum production.

Cold Starts

As described in §1.6.1.2, the catalytic converter does not reach full efficiency until after some warm-up time. During these cold starts, higher concentrations of NO_X, CO, and VOCs are released; hence, these three pollutants are a large fraction of total emissions. It is most strongly felt with CO where cold start emissions are 66% to 80% as large as running emissions.

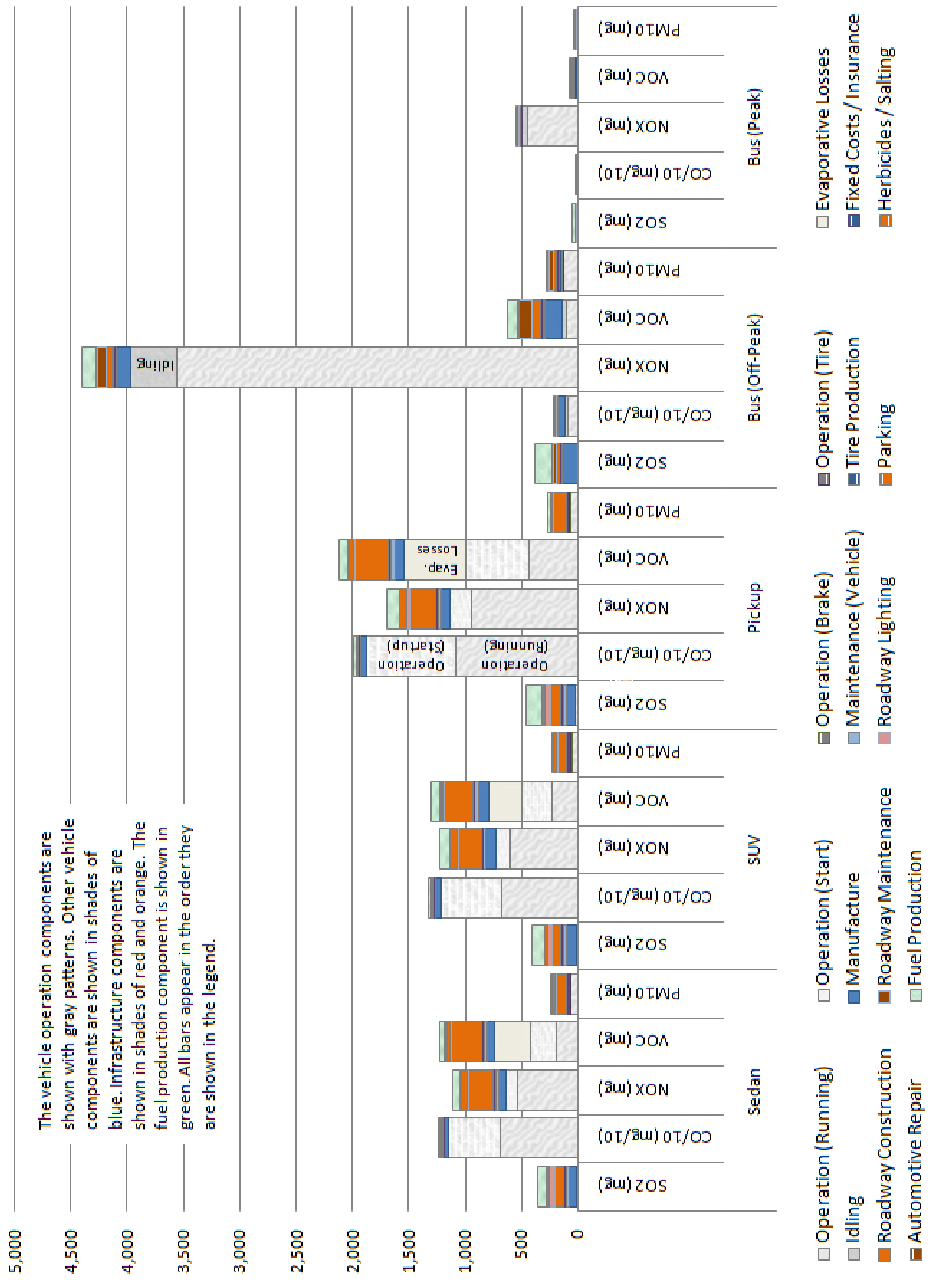
Evaporative Losses

Evaporative losses, primarily from running, resting, and hot soak, contribute heavily to total VOC emissions from automobiles. These emissions constitute 35% to 43% of total operational VOC emissions; the largest percentage is from the sedan. The inclusion of VOC emissions from evaporative losses increases total operational emissions (from fuel combustion) by up to 80%.

Vehicle Manufacturing

The large energy and material requirements for bus manufacturing result in significant CAP pollutants. The SO_2 and NO_X are the result of fossil fuel derived electricity used at the plant. CO results from the reliance on truck transportation to move parts and materials upstream of assembly. VOCs are released directly in the assembly of the vehicle and PM_{10} comes from the manufacturing of steel for the components of the vehicle [EIO-LCA 2008].

Figure 5 – Onroad Travel CAP Inventory (in mg/PMT)



The vehicle operation components are shown with gray patterns. Other vehicle components are shown in shades of blue. Infrastructure components are shown in shades of red and orange. The fuel production component is shown in green. All bars appear in the order they are shown in the legend.

Roadway Construction

The construction of roadways has major effects on SO_2, NO_X, VOC, and PM_{10} emissions. For automobiles, SO_2 from roadway construction is 6.6 times larger (for the sedan) or and 4.5 times larger (for the SUV and pickup) than tail-pipe emissions. NO_X emissions in this component are responsible for 200 to 240 mg/PMT of the 1,000 to 1,700 mg/PMT total emissions for the automobiles. The SO_2 and NO_X emissions result in the transport of asphalt bitumen used in the wearing layers of the roadways. VOC emissions, as described in §1.6.2.1, are emitted when the diluent in the asphalt mix volatilizes during placement. These emissions are about 19% of total automobile VOC emissions and about 13% of bus emissions. The fugitive dust emissions during asphalt placement overwhelm tailpipe PM_{10} emissions for the automobile modes. Roadway construction emissions are 1.6 times larger than tail-pipe emissions for the automobile.

Roadway Lighting

SO_2, from the production of fossil fuel derived electricity, shows up as a non-negligible contributor in the automobile inventories. Lighting SO_2 is around twice as large as tail-pipe SO_2 emissions per PMT for the SUV and pickups.

Roadway Maintenance

The SO_2 emissions from the resurfacing of roadways attributed to the damage from urban bus travel overwhelms operational emissions. The origin of the SO_2 emissions is the electricity requirements in the production of hot-mix asphalt at the plant. Roadway maintenance SO_2 emissions for buses are 37 and 5 mg/PMT for the off-peak and peak buses as compared to the 4.4 and 0.6 g/PMT released in diesel fuel combustion.

Parking Construction and Maintenance

Similar to roadway construction, parking construction and maintenance strongly affects SO_2, NO_X, VOC, and PM_{10} emissions. The same causes that are described for roadway construction apply to parking lot construction but effects are smaller.

Petroleum Production

The production of gasoline and diesel fuels is responsible for large portions of total SO_2, NO_X, and VOC emissions. Again, SO_2 is the result of the electricity used in the refineries as well as refinery off-gasing. Petroleum production SO2 emissions are 5.6 to 7.1 times larger than tail-pipe emissions for automobiles per PMT. NO_X is also the result of electricity generation. VOCs result from both direct refinery emissions as well as oil and gas extraction processes [EIO-LCA 2008].

Summary

Table 34 summarizes the onroad CAP total and operational inventory.

Table 34 – Onroad CAP Total and Operational Inventory (operational emissions in parenthesis)

	Sedan	**SUV**	**Pickup**	**Bus (Off-Peak)**	**Bus (Peak)**
CO (g/PMT)	12 (12)	13 (12)	20 (19)	2.2 (0.89)	0.28 (0.11)
SO_2 (mg/PMT)	350 (13)	410 (15)	460 (24)	380 (4.4)	47 (0.55)
NO_X (mg/PMT)	1,100 (640)	1,200 (730)	1,700 (1,100)	4,400 (3,600)	550 (450)
VOC (mg/PMT)	1,200 (740)	1,300 (790)	2,100 (1,500)	630 (110)	79 (14)
PM_{10} (mg/PMT)	240 (81)	230 (73)	270 (86)	290 (140)	36 (18)

1.7 Life-cycle Environmental Inventory of Rail

Passenger rail systems do not fit into a single engineering design but range across many to accommodate differing ridership and performance goals. Five rail transit systems are considered: the San Francisco's Bay Area Rapid Transit System (BART), Municipal Railway (Muni), Caltrain, Boston's Green Line, and the proposed California High Speed Rail (CAHSR). The BART and Caltrain systems are considered Heavy Rail Transit (HRT) while the Muni and Green Line are considered Light Rail Transit (LRT). The CAHSR is a high speed heavy rail system which is expected to compete with air and auto modes in the Sacramento to San Diego corridor. Of these five systems, only Caltrain trains are powered directly by diesel fuel while the others are powered by electricity. These four systems encompass the short and long range distance heavy and light rail systems.

1.7.1 Vehicles (Trains)

BART

The first set of BART cars were constructed in 1969 by Rohr Industries [BART 2007]. The 63,000 lb cars are composed of 14,000 lbs of aluminum (due to corrosion concerns in the Bay Area), an energy intensive material to mine and manufacture [Keyser 1991]. At peak, BART operates 60 trains and 502 cars (8.4 cars per train) [BART 2006]. The average train (across peak and non-peak times) is assumed to have 8 cars.

Muni

The San Francisco Municipal Railway, an organization in existence for over a century, purchased a new fleet of electric-powered trains in 1998 [SFW 1998]. 127 light rail vehicle cars are operated by the organization with an effective lifetime of 27 years [Muni 2006].

Caltrain

Caltrain is a diesel-powered heavy rail Amtrak-style commuter train operating on a single line from Gilroy to San Francisco. Caltrain has 34 locomotives and 110 passenger cars each with average useful lives of 30 years [Caltrain 2007, Caltrain 2004]. Passenger cars have between 82 and 148 seats depending on the model [Caltrain 2007]. On average, Caltrain operates 3 passenger cars per train.

Boston Green Line

As part of the Massachusetts Bay Transportation Authority, the light rail Green Line is one of many public transit modes serving the Boston area. All four lines start in Cambridge, travel through downtown Boston, and end as far away as Newton. The electric trains are powered from overhead catenary wire. There are currently 144 cars in the fleet [FTA 2005].

CAHSR

The high speed rail project seeks to implement approximately 700 miles of track connecting San Diego, Los Angeles, San Francisco, and Sacramento. The project hopes to provide an alternative transit mode across the state reducing the need to expand the auto and air infrastructure expected to grow heavily in the next few decades. 42 electric-powered trains will provide service with speeds averaging 220 mph [Levinson 1996].

1.7.1.1 Manufacturing

To estimate manufacturing energy and emissions, process-based LCA software SimaPro is used [SimaPro 2006]. SimaPro provides data on 3 distinctly different passenger rail vehicles: a light rail system, a heavy rail long distance system, and a high speed train. The data in SimaPro is gathered from systems operating in Switzerland and Germany.

For each of the 5 rail systems analyzed, a representative train was used in SimaPro and the life-cycle inventory was determined after substituting the appropriate electricity mix (California, Massachusetts). For BART and Caltrain, the long distance train is used, for Muni and the Green Line, the light rail train, and for the California High Speed system, the high speed train. Two light rail train life-cycle inventories were computed by inputting the California and Massachusetts electricity mixes. For the other two SimaPro train inventories, the California mix is used. The inventories output by SimaPro are shown in Table 35 for manufacturing of a train.

Table 35 – LCI of Rail Vehicle Manufacturing in SimaPro (per Train)

SimaPro System ⇨		Light Rail Transit (CA Mix)	Light Rail Transit (MA Mix)	High Speed Rail (CA Mix)	Long Distance Rail (CA Mix)
Impact	Unit	**Muni**	**Green Line**	**CAHSR**	**BART, Caltrain**
Energy	TJ	6.7	7.1	44	30
Global Warming Potential (GWP)	mt GGE	340	370	2,100	1,800
Sulfur Dioxide (SO_2)	kg	1,700	1,900	10,000	6,900
Carbon Monoxide (CO)	kg	2,800	2,800	8,400	2,100
Nitrogen Oxides (NO_X)	kg	980	1,100	5,600	3,800
Volatile Organic Compounds (VOC)	kg	250	250	1,700	960
Lead (Pb)	kg	6.8	6.7	25	8.0
Particulate Matter >10μ ($PM_{>10}$)	kg	610	650	2,400	1,700
Particulate Matter 2.5-10μ ($PM_{2.5\leq d\leq 10}$)	kg	440	440	1,900	1,200
Particulate Matter <2.5μ ($PM_{<2.5}$)	kg	240	250	1,200	800
Particulate Matter ≤10μ ($PM_{\leq 10}$)	kg	680	690	3,100	1,900

To compute manufacturing impacts for the five modes from the SimaPro inventories, results were prorated based on train weights. SimaPro's light rail, long distance, and high speed trains weigh 170, 360, and 730 tonnes. BART trains weigh 220 tonnes, Caltrain 360 tonnes (190 tonnes for the locomotive and 32 tonnes for each passenger car), Muni 36 tonnes, and the Green Line 39 tonnes [Caltrain 2006, Breda 2007, Breda 2007b]. The California High Speed rail trains haven’t yet been designed so their weight is assumed to be equal to that of the SimaPro high speed train (modeled on the German ICE).

Equation Set 13 shows the general framework for calculating impacts from train manufacturing. VMT for each mode is based on historical data and forecasted over the life of the system [MTC 2006, FTA 2005, CAHSR 2005]. Passengers on each train at any given time are computed as 146 for BART, 22 for Muni, 155 for Caltrain, 54 for the Green Line, and 761 for High Speed Rail [FTA 2005, CAHSR 2005].

Equation Set 13 – Rail Vehicle Manufacturing

$$I/O_{from\ SimaPro}^{rail,vehicle\ manufacturing} = Vehicle\ Manufacturing\ I/O$$

$$I/O_{train-lifetime}^{rail,vehicle\ manufacturing} = I/O_{SimaPro\ vehicle}^{rail,vehicle\ manufacturing} \times \frac{weight_{train}}{weight_{SimaPro\ train}}$$

$$I/O_{VMT}^{rail,vehicle\ manufacturing} = I/O_{train-lifetime}^{rail,vehicle\ manufacturing} \times \frac{lifetime_{train}}{VMT_{train}}$$

$$I/O_{PMT}^{rail,vehicle\ manufacturing} = I/O_{train-lifetime}^{rail,vehicle\ manufacturing} \times \frac{lifetime_{train}}{VMT_{train}} \times \frac{VMT_{train}}{PMT_{train}}$$

1.7.1.2 Operation

The operational energy and emissions for mass transit systems are not typically disaggregated based on vehicle operating components. With electric-powered modes, this is partially the result of low-resolution monitoring where total electricity is measured at power stations while detailed consumption characteristics of the vehicles remain poorly understood. For each mode, operational energy consumption is disaggregated into propulsion (moving the trains), idling (when trains are stopped both at stations and at the end of their lines or shifts), and auxiliaries (lighting and HVAC).

Given the low resolution of operational energy consumption data for the modes, several interpolations were made to distinguish propulsion, idling, and auxiliary energy consumption. BART's electricity consumption is one of the better understood systems given several assessments performed in the late 1970s during the U.S. energy crisis [Fels 1978, Lave 1977]. Introduced during the early 1970's, BART's propulsion energy performance quickly improved to the 4 kWh/car-VMT it is today [Fels 1978, SVRTC 2006]. There are several idling components to consider in the activity of a BART train: stopping at stations, stopping at the end of routes, and keeping train systems "hot" before they will be used. The total energy consumption for these activities amounts to about 2 kWh/car-VMT [Fels 1978]. Lastly, auxiliary systems for lighting and ventilation consume an additional 0.5 kWh/car-VMT bringing the total consumption to about 7 kWh/car-VMT [Fels 1978].

Operational consumption for the Muni and Green Line trains is determined from total electricity consumption of 50M kWh and 44M kWh in 2005 [FTA 2005]. This total consumption is the sum of propulsion, idling, and auxiliaries. Auxiliaries are estimated from manufacturer specifications of the onboard equipment installed [Breda 2007, Breda 2007b]. It is assumed that this onboard equipment is utilized at 75% of its 10 kW rating during all hours of train operation. It is also assumed that there are 240 and 180 heating days for Muni and the Green Line and 90 and 90 cooling days per year. Lighting is assumed to draw 2 kW/train for both systems and is on at 100% utilization, 10 hours per day. This results in a 1.2 kWh/train-VMT for Muni and 1.0 kWh/train-VMT for the Green Line. The remaining total electricity consumption (now that auxiliaries are removed) is split into propulsion and idling energy. This is done based on BART's propulsion and idling energy fractions. For every 3.6 kWh BART consumes in propulsion, an additional 1.8 kWh are consumed in idling. The result is 4.9 and 8.1 kWh/train-VMT propulsion for Muni and the Green Line and 2.5 and 4.1 kWh/train-VMT idling.

Caltrain must be addressed differently than the other modes because it is the only one powered directly by diesel fuel. To start, electricity and lighting energy consumption were computed based on similar installed equipment to Muni. To determine propulsion and idling energy consumption, drive cycles were created based on schedules for the system [Caltrain 2007c]. Using the schedule and distance between stations, engine fuel consumption and emission data was applied to calculate the inventory [Fritz 1994]. It was assumed that each train is hot-started 1 hour before its first start is scheduled, 30 minutes when its last stop of the day is complete, and 1 hour between routes. Idling time is assumed to be the time the train is stopped at the stations. Table 36 summarizes the Caltrain operational factors computed from the drive cycles and emission data.

Table 36 – Caltrain Operational Environmental Factors

Average Inventory Parameter	Active	Idling	Hot Start
Energy Consumption (MJ/PMT)	150	9	10
CO_2 Emissions (kg/VMT)	10	0.6	0.7
SO_2 Emissions * (mg/VMT)	45	2.6	3.1
CO Emissions (g/VMT)	9.8	1.4	1.5
NO_X Emissions (g/VMT)	190	12	18
HC Emissions (g/VMT)	6	2	2
PM_{10} Emissions (g/VMT)	2.1	0.5	0.4

* Diesel fuel sulfur content reflects the Tier 2 standards (15 ppm).

The electricity consumption of the proposed California High Speed Rail system is based on several estimates. Using data from the CAHSR final environmental impact report, operational components are broken out [CAHSR 2005]. The train in the report is based on the German ICE. The CAHSR trains are estimated to consume 271 kWh/VMT in total of which 6 kWh/VMT is consumed during idling [CAHSR 2005]. This estimate appears to represent the high end of HSR trains operational energy consumption and weight. The Swedish X2000, a lightweight vehicle which carries around ⅓ the passengers and is much smaller consumes 92 kWh/VMT [Anderrson 2006]. Using similar methodology to Muni, auxiliary electricity consumption is estimated at 14 kWh/VMT.

Having computed the kWh/train-VMT operational factors for the electricity-powered systems, emissions factors for electricity production are applied to determine emissions. California and Massachusetts have two distinctly different mixes. California produces 55% of its electricity from fossil fuels and a large portion from nuclear and hydro (33%). Massachusetts produces 82% of its electricity from fossil fuels [Deru 2007]. Although the California mix is significantly cleaner than the Massachusetts mix, BART, Muni, and Caltrain operate in the Bay Area within the Pacific Gas and Electric (PGE) utility's region, which is slightly cleaner than the state's. PGE's electricity mix is 49% fossil (47% natural gas, 1.6% coal), 23% nuclear, and 13% hydro [PGE 2008]. Using the electricity generation factors from Deru 2007, a Bay Area emission profile is estimated. For almost all pollutants, the Bay Area factors are less than California's. This affects direct vehicle electricity consumption of BART and Muni and also every electricity-consuming life-cycle component of BART, Muni, and Caltrain. The direct electricity generation emission factors are reported in Table 37 [Deru 2007].

Table 37 – Direct Electricity Generation Emission Factors (per kWh Delivered)

	California (State)	California (Bay Area)	Massachusetts
g CO_2e	260	200	510
g SO_2	1.4	1.1	3.0
mg CO	140	110	570
mg NO_X	100	65	670
mg VOC	30	30	39
µg Pb	1.8	0.7	25
mg PM_{10}	15	12	30

Equation Set 14 shows the general framework for calculating operational inventory components.

Equation Set 14 – Rail Vehicle Operation

$$EF_{I/O} = Electricity\ Generation\ Emissions\ Factor\ (per\ kWh)$$

$$I/O_{train-lifetime}^{rail,vehicle\ operation} = \frac{kWh}{VMT_{train}} \times \frac{VMT_{train}}{lifetime_{train}} \times \frac{EF_{I/O}}{kWh}$$

$$I/O_{VMT}^{rail,vehicle\ operation} = \frac{kWh}{VMT_{train}} \times \frac{EF_{I/O}}{kWh}$$

$$I/O_{PMT}^{rail,vehicle\ operation} = \frac{kWh}{VMT_{train}} \times \frac{VMT_{train}}{PMT_{train}} \times \frac{EF_{I/O}}{kWh}$$

1.7.1.3 Maintenance

The maintenance of trains is separated into three categories: routine maintenance (standard upkeep and inspection), cleaning, and flooring replacement. Routine maintenance includes material replacement, wheel grinding, lubrication, brake parts replacement, and inspection [Van Eck 1974]. Due to a lack of primary data on the many components and processes that go into standard maintenance of the trains in each system, SimaPro train maintenance data is used with the same methodology as train manufacturing. Maintenance impacts in SimaPro are reported for three train types (LRT, long distance, and high speed) over their lifetime and are then prorated based on vehicle weights. California and Massachusetts electricity mixes are applied. Table 38 shows the impacts for the three train types and the different mixes.

Table 38 – LCI of Rail Vehicle Maintenance in SimaPro (per Train Lifetime)

SimaPro System ⇨		Light Rail Transit (CA Mix)	Light Rail Transit (MA Mix)	High Speed Rail (CA Mix)	Long Distance Rail (CA Mix)
Impact	Unit	**Muni**	**Green Line**	**CAHSR**	**BART, Caltrain**
Energy	TJ	1.3	1.4	28	25
Global Warming Potential (GWP)	mt GGE	64	68	1,300	1,100
Sulfur Dioxide (SO_2)	kg	170	190	1,200	3,100
Carbon Monoxide (CO)	kg	240	240	2,600	2,800
Nitrogen Oxides (NO_X)	kg	200	210	2,500	2,600
Volatile Organic Compounds (VOC)	kg	130	130	4,000	4,100
Lead (Pb)	kg	1.4	1.4	1.8	11
Particulate Matter >10µ ($PM_{>10}$)	kg	46	50	320	720
Particulate Matter 2.5-10µ ($PM_{2.5\leq d\leq 10}$)	kg	27	27	170	470
Particulate Matter <2.5µ ($PM_{<2.5}$)	kg	29	30	220	310
Particulate Matter ≤10µ ($PM_{\leq 10}$)	kg	56	57	390	780

Equation Set 15 shows the general framework for calculating routine maintenance inventory components.

Equation Set 15 – Rail Vehicle Maintenance (Parts and Service)

$$I/O_{from\ SimaPro}^{rail,vehicle\ maintenance} = Vehicle\ Maintenance\ I/O$$

$$I/O_{train-lifetime}^{rail,vehicle\ maintenance} = I/O_{SimaPro\ vehicle}^{rail,vehicle\ maintenance} \times \frac{weight_{train}}{weight_{SimaPro\ train}}$$

$$I/O_{VMT}^{rail,vehicle\ maintenance} = I/O_{train-lifetime}^{rail,vehicle\ maintenance} \times \frac{lifetime_{train}}{VMT_{train}}$$

$$I/O_{PMT}^{rail,vehicle\ maintenance} = I/O_{train-lifetime}^{rail,vehicle\ maintenance} \times \frac{lifetime_{train}}{VMT_{train}} \times \frac{VMT_{train}}{PMT_{train}}$$

Cleaning of cars is a major operation for each system. Regardless of floor type (carpet or composite), it is assumed that vacuuming takes place every other night for all train systems [SFC 2006]. An electricity consumption factor of 1.44 kW and a speed of 30 sec/m^2 are used for cleaning operations [EERE 2007b, BuiLCA 2007]. The dimensions of the trains are gathered from several sources and California High Speed Rail train dimensions are assumed to be equal to the German ICE high speed rail trains. [Keyser 1991, Breda 2007, Caltrain 2007d, Breda 2007b, Bombardier 2007]. Electricity consumption for cleaning is multiplied by state emission factors to determine total impact.

Equation Set 16 – Rail Vehicle Maintenance (Cleaning)

$$EF_{I/O} = Electricity\ Production\ I/O\ Factor\ (per\ kWh)$$

$$I/O_{train\ lifetime}^{rail,cleaning} = \frac{kWh}{ft^2 - cleaning} \times \frac{ft^2}{train} \times \frac{cleanings}{yr} \times \frac{yrs}{lifetime_{train}} \times EF_{I/O}$$

$$I/O_{VMT}^{rail,cleaning} = \frac{kWh}{ft^2 - cleaning} \times \frac{ft^2}{train} \times \frac{cleanings}{yr} \times \frac{yr}{VMT_{train}} \times EF_{I/O}$$

$$I/O_{PMT}^{rail,cleaning} = \frac{kWh}{ft^2 - cleaning} \times \frac{ft^2}{train} \times \frac{cleanings}{yr} \times \frac{yr}{VMT_{train}} \times \frac{VMT_{train}}{PMT_{train}} \times EF_{I/O}$$

Two floor types are considered for the systems: carpet and plastic composite. The replacement of carpet (BART, Caltrain, CAHSR) costs $6,500 and lasts 4 years while resilient plastic composite (Muni, Green Line) costs $3,400 and lasts 10 years [SFC 2006]. The production of carpets has a much larger environmental impact than plastic composite flooring [EIO-LCA 2008]. Using the flooring replacement costs and vehicle dimensions, yearly replacement costs are determined. Using the EIO-LCA sector Carpet and Rug Mills (#314110) and Resilient Floor Covering Manufacturing (#326192), total impacts are computed.

Equation Set 17 – Rail Vehicle Maintenance (Flooring Replacement)

$$EF_{EIOLCA} = Flooring\ Material\ Production\ I/O\ (per\ unit\ cost)$$

$$I/O_{train\ lifetime}^{rail,flooring} = \frac{cost_{replacement}}{yr} \times \frac{yrs}{lifetime_{train}} \times EF_{EIOLCA}$$

$$I/O_{VMT}^{rail,flooring} = \frac{cost_{replacement}}{yr} \times \frac{yr}{VMT_{train}} \times EF_{EIOLCA}$$

$$I/O_{VMT}^{rail,flooring} = \frac{cost_{replacement}}{yr} \times \frac{yr}{VMT_{train}} \times \frac{VMT_{train}}{PMT_{train}} \times EF_{EIOLCA}$$

1.7.1.4 Insurance

Insurance costs covering operator health and casualty/liability with regards to the vehicles remains a significant portion of system operation. To provide this insurance, buildings are constructed, office operations are performed, energy is consumed, and emissions are produced. The EIO-LCA sector Insurance Carriers (#524100) is used to quantify these effects. Yearly operator insurance costs are gathered from financial statements and the National Transit Database [BART 2006c, Muni 2007, FTA 2005]. For the case of the CAHSR, vehicle insurance costs per train crew member were assumed equal to that of Caltrain. Operating insurance for personnel includes both train operators and non-operators (maintenance, general administration, etc.). Total yearly insurance costs were prorated by the fraction of train operators to determine direct operational personnel insurance. These costs are summarized in Table 39.

Table 39 – Rail Vehicle Insurance Costs ($\$_{2005}$/train-yr)

	BART	Caltrain	Muni	Green Line	CAHSR
Operator Health	22,000	17,000	31,000	100,000	310,000
Vehicle Casualty and Liability	48,000	37,000	39,000	60,000	450,000

Casualty and liability insurance on vehicles is also included. Using similar methodology to operator health insurance, casualty and liability insurance was determined for just vehicles by removing insurance associated with infrastructure (discussed in §1.7.2.7). This was done by taking the total casualty and liability yearly amount and prorating based on the capital value of vehicles and infrastructure [BART 2006c, FTA 2005, Muni 2007, CAHSR 2005, FRA 1997, Levinson 1996]. The costs per train per year are shown in Table 39. Again, using the EIO-LCA sector Insurance Carriers (#524100), total impacts are computed.

The general framework for computing insurance costs for the vehicles is shown in Equation Set 18.

Equation Set 18 – Rail Vehicle Insurance

$$EF_{EIOLCA} = I/O\ for\ Insurance\ Services\ (per\ unit\ cost)$$

$$\alpha = Fraction\ of\ Mode's\ Total\ Insurance\ Cost\ to\ Vehicles$$

$$I/O_{train\ lifetime}^{rail,vehicle\ insurance} = \frac{cost_{system\ insurance}}{yr} \times \alpha \times \frac{yr}{lifetime_{train}} \times EF_{EIOLCA}$$

$$I/O_{VMT}^{rail,vehicle\ insurance} = \frac{cost_{system\ insurance}}{yr} \times \alpha \times \frac{yr}{VMT_{system}} \times EF_{EIOLCA}$$

$$I/O_{PMT}^{rail,vehicle\ insurance} = \frac{cost_{system\ insurance}}{yr} \times \alpha \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}} \times EF_{EIOLCA}$$

1.7.1.5 Rail Vehicle Results

Calculations are first normalized by vehicle lifetimes and are then presented on a per vehicle-mile or passenger-mile basis. For each system, vehicle lifetimes are determined from replacement data, specified effective lifetimes, and historical performance [BART 2006, Caltrain 2004, Muni 2006]. For the Green Line, the effective lifetime was assumed equal to Muni trains considering the similarity of vehicles. For CAHSR, a 30 year effective lifetime was assumed. VMT and PMT data is determined from the National Transit Database for the four existing modes and based on estimations for CAHSR [FTA 2005, CAHSR 2005, Levinson 1996]. Table 40 summarizes these factors for each system.

Table 40 – Rail Vehicle Performance Data

	BART	Caltrain	Muni	Green Line	CAHSR
Vehicle Lifetime (years)	26	30	27	27	30
2005 VMT in Millions	8.6	1.3	5.5	3.3	22
2005 PMT in Millions	1,300	200	120	180	17,000

Table 41 – BART Vehicle Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Manufacture	Energy	19 TJ	5.4 MJ	0.037 MJ
	GHG	1,100 mt GGE	330 g GGE	2.3 g GGE
	SO_2	4,300 kg	1,200 mg	8.6 mg
	CO	1,300 kg	380 mg	2.6 mg
	NO_X	2,300 kg	680 mg	4.7 mg
	VOC	590 kg	170 mg	1.2 mg
	Pb	4.9 kg	1.4 mg	9.8 µg
	PM_{10}	1,200 kg	350 mg	2,400 µg
V, Operation (Active)	Energy	350 TJ	100 MJ	0.69 MJ
	GHG	19,000 mt GGE	5,600 g GGE	39 g GGE
	SO_2	110,000 kg	32,000 mg	220 mg
	CO	11,000 kg	3,200 mg	22 mg
	NO_X	6,300 kg	1,800 mg	13 mg
	VOC	2,900 kg	840 mg	5.8 mg
	Pb	0.070 kg	0.021 mg	0.14 µg
	PM_{10}	1,200 kg	340 mg	2,400 µg
V, Operation (Idling)	Energy	180 TJ	51 MJ	0.35 MJ
	GHG	9,800 mt GGE	2,900 g GGE	20 g GGE
	SO_2	55,000 kg	16,000 mg	110 mg
	CO	5,600 kg	1,600 mg	11 mg
	NO_X	3,200 kg	930 mg	6.4 mg
	VOC	1,500 kg	430 mg	2.9 mg
	Pb	0.036 kg	0.010 mg	0.072 µg
	PM_{10}	600 kg	170 mg	1,200 µg
V, Operation (HVAC)	Energy	48 TJ	14 MJ	0.096 MJ
	GHG	2,700 mt GGE	780 g GGE	5.4 g GGE
	SO_2	15,000 kg	4,400 mg	30 mg
	CO	1,500 kg	440 mg	3.0 mg
	NO_X	870 kg	250 mg	1.7 mg
	VOC	400 kg	120 mg	0.80 mg
	Pb	0.0098 kg	0.0028 mg	0.020 µg
	PM_{10}	160 kg	48 mg	330 µg

Table 41 – BART Vehicle Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Maintenance	Energy	15 TJ	4.4 MJ	0.030 MJ
	GHG	690 mt GGE	200 g GGE	1.4 g GGE
	SO_2	1,900 kg	560 mg	3.8 mg
	CO	1,700 kg	500 mg	3.5 mg
	NO_X	1,600 kg	470 mg	3.2 mg
	VOC	2,500 kg	730 mg	5.0 mg
	Pb	6.8 kg	2.0 mg	14 µg
	PM_{10}	480 kg	140 mg	960 µg
V, Maintenance (Cleaning)	Energy	0.096 TJ	0.028 MJ	0.00019 MJ
	GHG	7.1 mt GGE	2.1 g GGE	0.014 g GGE
	SO_2	38 kg	11 mg	0.076 mg
	CO	3.6 kg	1.1 mg	0.0073 mg
	NO_X	2.7 kg	0.79 mg	0.0055 mg
	VOC	0.81 kg	0.24 mg	0.0016 mg
	Pb	0.000049 kg	0.000014 mg	0.000098 µg
	PM_{10}	0.41 kg	0.12 mg	0.82 µg
V, Maintenance (Flooring)	Energy	3.8 TJ	1.1 MJ	0.0076 MJ
	GHG	300 mt GGE	88 g GGE	0.60 g GGE
	SO_2	550 kg	160 mg	1.1 mg
	CO	2,800 kg	830 mg	5.7 mg
	NO_X	550 kg	160 mg	1.1 mg
	VOC	490 kg	140 mg	0.98 mg
	Pb	0.26 kg	0.077 mg	0.53 µg
	PM_{10}	190 kg	55 mg	380 µg
V, Insurance (Employees)	Energy	0.47 TJ	0.14 MJ	0.00095 MJ
	GHG	39 mt GGE	11 g GGE	0.077 g GGE
	SO_2	95 kg	28 mg	0.19 mg
	CO	430 kg	120 mg	0.86 mg
	NO_X	110 kg	31 mg	0.21 mg
	VOC	79 kg	23 mg	0.16 mg
	Pb	-	-	-
	PM_{10}	20 kg	5.9 mg	40 µg
V, Insurance (Vehicles)	Energy	1.0 TJ	0.31 MJ	0.0021 MJ
	GHG	86 mt GGE	25 g GGE	0.17 g GGE
	SO_2	210 kg	61 mg	0.42 mg
	CO	950 kg	280 mg	1.9 mg
	NO_X	240 kg	69 mg	0.47 mg
	VOC	180 kg	51 mg	0.35 mg
	Pb	-	-	-
	PM_{10}	45 kg	13 mg	90 µg

Table 42 – Caltrain Vehicle Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Manufacture	Energy	30 TJ	24 MJ	0.16 MJ
	GHG	1,800 mt GGE	1,500 g GGE	9.6 g GGE
	SO_2	6,900 kg	5,600 mg	36 mg
	CO	2,100 kg	1,700 mg	11 mg
	NO_X	3,800 kg	3,100 mg	20 mg
	VOC	950 kg	770 mg	5.0 mg
	Pb	7.9 kg	6.4 mg	42 µg
	PM_{10}	1,900 kg	1,600 mg	10,000 µg
V, Operation (Active)	Energy	170 TJ	140 MJ	0.90 MJ
	GHG	12,000 mt GGE	9,600 g GGE	62 g GGE
	SO_2	52 kg	42 mg	0.27 mg
	CO	12,000 kg	9,300 mg	60 mg
	NO_X	220,000 kg	180,000 mg	1,200 mg
	VOC	7,000 kg	5,600 mg	36 mg
	Pb	-	-	-
	PM_{10}	6,000 kg	4,800 mg	31,000 µg
V, Operation (Idling)	Energy	23 TJ	19 MJ	0.12 MJ
	GHG	1,600 mt GGE	1,300 g GGE	8.4 g GGE
	SO_2	7.0 kg	5.7 mg	0.037 mg
	CO	3,700 kg	3,000 mg	19 mg
	NO_X	37,000 kg	30,000 mg	200 mg
	VOC	4,000 kg	3,200 mg	21 mg
	Pb	-	-	-
	PM_{10}	1,100 kg	850 mg	5,500 µg
V, Operation (HVAC)	Energy	9.2 TJ	7.4 MJ	0.048 MJ
	GHG	630 mt GGE	510 g GGE	3.3 g GGE
	SO_2	2.8 kg	2.3 mg	0.015 mg
	CO	610 kg	500 mg	3.2 mg
	NO_X	12,000 kg	9,600 mg	62 mg
	VOC	370 kg	300 mg	1.9 mg
	Pb	-	-	-
	PM_{10}	320 kg	260 mg	1,700 µg
V, Maintenance	Energy	25 TJ	20 MJ	0.13 MJ
	GHG	1,100 mt GGE	910 g GGE	5.9 g GGE
	SO_2	3,100 kg	2,500 mg	16 mg
	CO	2,800 kg	2,300 mg	15 mg
	NO_X	2,600 kg	2,100 mg	14 mg
	VOC	4,100 kg	3,300 mg	21 mg
	Pb	11 kg	8.9 mg	57 µg
	PM_{10}	780 kg	630 mg	4,100 µg
V, Maintenance (Cleaning)	Energy	0.060 TJ	0.049 MJ	0.00032 MJ
	GHG	4.4 mt GGE	3.6 g GGE	0.023 g GGE
	SO_2	24 kg	19 mg	0.12 mg
	CO	2.3 kg	1.8 mg	0.012 mg
	NO_X	1.7 kg	1.4 mg	0.0089 mg
	VOC	0.51 kg	0.41 mg	0.0027 mg
	Pb	0.000031 kg	0.000025 mg	0.00016 µg
	PM_{10}	0.26 kg	0.21 mg	1.3 µg

Table 42 – Caltrain Vehicle Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Maintenance (Flooring)	Energy	0.95 TJ	0.77 MJ	0.0050 MJ
	GHG	75 mt GGE	61 g GGE	0.39 g GGE
	SO_2	140 kg	110 mg	0.71 mg
	CO	710 kg	580 mg	3.7 mg
	NO_X	140 kg	110 mg	0.71 mg
	VOC	120 kg	99 mg	0.64 mg
	Pb	0.066 kg	0.053 mg	0.34 µg
	PM_{10}	47 kg	38 mg	250 µg
V, Insurance (Employees)	Energy	0.43 TJ	0.35 MJ	0.0023 MJ
	GHG	36 mt GGE	29 g GGE	0.19 g GGE
	SO_2	87 kg	71 mg	0.46 mg
	CO	390 kg	320 mg	2.1 mg
	NO_X	98 kg	80 mg	0.51 mg
	VOC	73 kg	59 mg	0.38 mg
	Pb	-	-	-
	PM_{10}	19 kg	15 mg	97 µg
V, Insurance (Vehicles)	Energy	0.95 TJ	0.77 MJ	0.0050 MJ
	GHG	78 mt GGE	63 g GGE	0.41 g GGE
	SO_2	190 kg	150 mg	1.00 mg
	CO	860 kg	700 mg	4.5 mg
	NO_X	210 kg	170 mg	1.1 mg
	VOC	160 kg	130 mg	0.83 mg
	Pb	-	-	-
	PM_{10}	41 kg	33 mg	210 µg

Table 43 – Muni Vehicle Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Manufacture	Energy	1.4 TJ	0.83 MJ	0.038 MJ
	GHG	71 mt GGE	42 g GGE	1.9 g GGE
	SO_2	360 kg	210 mg	9.6 mg
	CO	580 kg	340 mg	15 mg
	NO_X	210 kg	120 mg	5.5 mg
	VOC	53 kg	31 mg	1.4 mg
	Pb	1.4 kg	0.83 mg	38 µg
	PM_{10}	140 kg	83 mg	3,800 µg
V, Operation (Active)	Energy	28 TJ	16 MJ	0.73 MJ
	GHG	1,500 mt GGE	890 g GGE	41 g GGE
	SO_2	8,600 kg	5,000 mg	230 mg
	CO	870 kg	510 mg	23 mg
	NO_X	500 kg	290 mg	13 mg
	VOC	230 kg	130 mg	6.1 mg
	Pb	0.0056 kg	0.0033 mg	0.15 µg
	PM_{10}	94 kg	54 mg	2,500 µg

Table 43 – Muni Vehicle Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Operation (Idling)	Energy	14 TJ	8.2 MJ	0.37 MJ
	GHG	780 mt GGE	460 g GGE	21 g GGE
	SO$_2$	4,400 kg	2,500 mg	120 mg
	CO	440 kg	260 mg	12 mg
	NO$_X$	250 kg	150 mg	6.8 mg
	VOC	120 kg	68 mg	3.1 mg
	Pb	0.0029 kg	0.0017 mg	0.076 µg
	PM$_{10}$	48 kg	28 mg	1,300 µg
V, Operation (HVAC)	Energy	4.8 TJ	2.8 MJ	0.13 MJ
	GHG	270 mt GGE	160 g GGE	7.1 g GGE
	SO$_2$	1,500 kg	870 mg	40 mg
	CO	150 kg	88 mg	4.0 mg
	NO$_X$	87 kg	51 mg	2.3 mg
	VOC	40 kg	23 mg	1.1 mg
	Pb	0.00098 kg	0.00057 mg	0.026 µg
	PM$_{10}$	16 kg	9.5 mg	430 µg
V, Maintenance	Energy	0.28 TJ	0.16 MJ	0.0075 MJ
	GHG	14 mt GGE	7.9 g GGE	0.36 g GGE
	SO$_2$	36 kg	21 mg	0.97 mg
	CO	50 kg	29 mg	1.3 mg
	NO$_X$	43 kg	25 mg	1.1 mg
	VOC	28 kg	16 mg	0.74 mg
	Pb	0.29 kg	0.17 mg	7.6 µg
	PM$_{10}$	12 kg	6.9 mg	310 µg
V, Maintenance (Cleaning)	Energy	0.027 TJ	0.015 MJ	0.00070 MJ
	GHG	0.81 mt GGE	0.47 g GGE	0.022 g GGE
	SO$_2$	4.3 kg	2.5 mg	0.12 mg
	CO	0.42 kg	0.24 mg	0.011 mg
	NO$_X$	0.31 kg	0.18 mg	0.0083 mg
	VOC	0.093 kg	0.054 mg	0.0025 mg
	Pb	0.0000056 kg	0.0000033 mg	0.00015 µg
	PM$_{10}$	0.047 kg	0.027 mg	1.2 µg
V, Maintenance (Flooring)	Energy	0.044 TJ	0.026 MJ	0.0012 MJ
	GHG	3.3 mt GGE	1.9 g GGE	0.089 g GGE
	SO$_2$	6.8 kg	4.0 mg	0.18 mg
	CO	24 kg	14 mg	0.65 mg
	NO$_X$	6.2 kg	3.6 mg	0.16 mg
	VOC	5.6 kg	3.3 mg	0.15 mg
	Pb	-	-	-
	PM$_{10}$	1.1 kg	0.65 mg	30 µg
V, Insurance (Employees)	Energy	0.71 TJ	0.41 MJ	0.019 MJ
	GHG	58 mt GGE	34 g GGE	1.6 g GGE
	SO$_2$	140 kg	83 mg	3.8 mg
	CO	650 kg	380 mg	17 mg
	NO$_X$	160 kg	94 mg	4.3 mg
	VOC	120 kg	70 mg	3.2 mg
	Pb	-	-	-
	PM$_{10}$	31 kg	18 mg	810 µg

Table 43 – Muni Vehicle Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Insurance (Vehicles)	Energy	0.88 TJ	0.51 MJ	0.023 MJ
	GHG	72 mt GGE	42 g GGE	1.9 g GGE
	SO_2	180 kg	100 mg	4.7 mg
	CO	800 kg	470 mg	21 mg
	NO_X	200 kg	120 mg	5.3 mg
	VOC	150 kg	86 mg	3.9 mg
	Pb	-	-	-
	PM_{10}	38 kg	22 mg	1,000 µg

Table 44 – Green Line Vehicle Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Manufacture	Energy	1.6 TJ	1.2 MJ	0.021 MJ
	GHG	85 mt GGE	61 g GGE	1.1 g GGE
	SO_2	430 kg	310 mg	5.7 mg
	CO	630 kg	450 mg	8.3 mg
	NO_X	240 kg	170 mg	3.2 mg
	VOC	58 kg	41 mg	0.76 mg
	Pb	1.5 kg	1.1 mg	20 µg
	PM_{10}	160 kg	110 mg	2,100 µg
V, Operation (Active)	Energy	40 TJ	29 MJ	0.53 MJ
	GHG	5,600 mt GGE	4,000 g GGE	74 g GGE
	SO_2	33,000 kg	24,000 mg	440 mg
	CO	6,300 kg	4,500 mg	83 mg
	NO_X	7,400 kg	5,300 mg	98 mg
	VOC	430 kg	300 mg	5.6 mg
	Pb	0.28 kg	0.20 mg	3.7 µg
	PM_{10}	340 kg	240 mg	4,400 µg
V, Operation (Idling)	Energy	20 TJ	15 MJ	0.27 MJ
	GHG	2,900 mt GGE	2,100 g GGE	38 g GGE
	SO_2	17,000 kg	12,000 mg	220 mg
	CO	3,200 kg	2,300 mg	42 mg
	NO_X	3,800 kg	2,700 mg	50 mg
	VOC	220 kg	160 mg	2.9 mg
	Pb	0.14 kg	0.10 mg	1.9 µg
	PM_{10}	170 kg	120 mg	2,300 µg
V, Operation (HVAC)	Energy	6.0 TJ	4.3 MJ	0.079 MJ
	GHG	850 mt GGE	610 g GGE	11 g GGE
	SO_2	5,000 kg	3,600 mg	66 mg
	CO	950 kg	680 mg	13 mg
	NO_X	1,100 kg	800 mg	15 mg
	VOC	64 kg	46 mg	0.85 mg
	Pb	0.042 kg	0.030 mg	0.55 µg
	PM_{10}	51 kg	36 mg	670 µg

Table 44 – Green Line Vehicle Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Maintenance	Energy	0.31 TJ	0.22 MJ	0.0041 MJ
	GHG	16 mt GGE	11 g GGE	0.20 g GGE
	SO_2	44 kg	32 mg	0.58 mg
	CO	54 kg	39 mg	0.72 mg
	NO_X	49 kg	35 mg	0.64 mg
	VOC	30 kg	22 mg	0.40 mg
	Pb	0.31 kg	0.22 mg	4.1 µg
	PM_{10}	13 kg	9.3 mg	170 µg
V, Maintenance (Cleaning)	Energy	0.025 TJ	0.018 MJ	0.00033 MJ
	GHG	1.5 mt GGE	1.1 g GGE	0.020 g GGE
	SO_2	8.8 kg	6.3 mg	0.12 mg
	CO	1.7 kg	1.2 mg	0.022 mg
	NO_X	1.9 kg	1.4 mg	0.026 mg
	VOC	0.11 kg	0.080 mg	0.0015 mg
	Pb	0.000073 kg	0.000052 mg	0.00096 µg
	PM_{10}	0.088 kg	0.063 mg	1.2 µg
V, Maintenance (Flooring)	Energy	0.042 TJ	0.030 MJ	0.00055 MJ
	GHG	3.2 mt GGE	2.3 g GGE	0.042 g GGE
	SO_2	6.5 kg	4.6 mg	0.085 mg
	CO	23 kg	16 mg	0.30 mg
	NO_X	5.8 kg	4.2 mg	0.077 mg
	VOC	5.3 kg	3.8 mg	0.070 mg
	Pb	-	-	-
	PM_{10}	1.1 kg	0.75 mg	14 µg
V, Insurance (Employees)	Energy	2.3 TJ	1.7 MJ	0.031 MJ
	GHG	190 mt GGE	140 g GGE	2.5 g GGE
	SO_2	470 kg	330 mg	6.1 mg
	CO	2,100 kg	1,500 mg	28 mg
	NO_X	520 kg	370 mg	6.9 mg
	VOC	390 kg	280 mg	5.1 mg
	Pb	-	-	-
	PM_{10}	99 kg	71 mg	1,300 µg
V, Insurance (Vehicles)	Energy	1.4 TJ	0.97 MJ	0.018 MJ
	GHG	110 mt GGE	80 g GGE	1.5 g GGE
	SO_2	270 kg	200 mg	3.6 mg
	CO	1,200 kg	880 mg	16 mg
	NO_X	310 kg	220 mg	4.1 mg
	VOC	230 kg	160 mg	3.0 mg
	Pb	-	-	-
	PM_{10}	58 kg	42 mg	770 µg

Table 45 – CAHSR Vehicle Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Manufacture	Energy	44 TJ	2.8 MJ	0.0037 MJ
	GHG	2,100 mt GGE	140 g GGE	0.18 g GGE
	SO_2	10,000 kg	640 mg	0.85 mg
	CO	8,400 kg	540 mg	0.71 mg
	NO_X	5,600 kg	360 mg	0.47 mg
	VOC	1,700 kg	110 mg	0.14 mg
	Pb	25 kg	1.6 mg	2.1 µg
	PM_{10}	3,100 kg	200 mg	260 µg
V, Operation (Active)	Energy	14,000 TJ	900 MJ	1.2 MJ
	GHG	1,000,000 mt GGE	66,000 g GGE	87 g GGE
	SO_2	5,500,000 kg	350,000 mg	470 mg
	CO	530,000 kg	34,000 mg	45 mg
	NO_X	400,000 kg	26,000 mg	34 mg
	VOC	120,000 kg	7,600 mg	10 mg
	Pb	7.2 kg	0.46 mg	0.60 µg
	PM_{10}	60,000 kg	3,800 mg	5,100 µg
V, Operation (Idling)	Energy	350 TJ	23 MJ	0.030 MJ
	GHG	26,000 mt GGE	1,700 g GGE	2.2 g GGE
	SO_2	140,000 kg	8,900 mg	12 mg
	CO	13,000 kg	850 mg	1.1 mg
	NO_X	10,000 kg	640 mg	0.84 mg
	VOC	3,000 kg	190 mg	0.25 mg
	Pb	0.18 kg	0.012 mg	0.015 µg
	PM_{10}	1,500 kg	96 mg	130 µg
V, Operation (HVAC)	Energy	760 TJ	49 MJ	0.064 MJ
	GHG	56,000 mt GGE	3,600 g GGE	4.7 g GGE
	SO_2	300,000 kg	19,000 mg	25 mg
	CO	29,000 kg	1,800 mg	2.4 mg
	NO_X	22,000 kg	1,400 mg	1.8 mg
	VOC	6,400 kg	410 mg	0.54 mg
	Pb	0.39 kg	0.025 mg	0.033 µg
	PM_{10}	3,200 kg	210 mg	270 µg
V, Maintenance	Energy	28 TJ	1.8 MJ	0.0024 MJ
	GHG	1,300 mt GGE	85 g GGE	0.11 g GGE
	SO_2	1,200 kg	77 mg	0.10 mg
	CO	2,600 kg	170 mg	0.22 mg
	NO_X	2,500 kg	160 mg	0.21 mg
	VOC	4,000 kg	260 mg	0.34 mg
	Pb	1.8 kg	0.12 mg	0.16 µg
	PM_{10}	390 kg	25 mg	33 µg
V, Maintenance (Cleaning)	Energy	0.12 TJ	0.0074 MJ	0.0000098 MJ
	GHG	8.5 mt GGE	0.55 g GGE	0.00072 g GGE
	SO_2	46 kg	2.9 mg	0.0038 mg
	CO	4.4 kg	0.28 mg	0.00037 mg
	NO_X	3.3 kg	0.21 mg	0.00028 mg
	VOC	0.98 kg	0.063 mg	0.000082 mg
	Pb	0.000059 kg	0.0000038 mg	0.0000050 µg
	PM_{10}	0.49 kg	0.032 mg	0.042 µg

Table 45 – CAHSR Vehicle Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Maintenance (Flooring)	Energy	1.8 TJ	0.12 MJ	0.00015 MJ
	GHG	140 mt GGE	9.3 g GGE	0.012 g GGE
	SO_2	260 kg	17 mg	0.022 mg
	CO	1,400 kg	88 mg	0.12 mg
	NO_X	260 kg	17 mg	0.022 mg
	VOC	240 kg	15 mg	0.020 mg
	Pb	0.13 kg	0.0081 mg	0.011 µg
	PM_{10}	91 kg	5.8 mg	7.7 µg
V, Insurance (Employees)	Energy	7.9 TJ	0.50 MJ	0.00066 MJ
	GHG	640 mt GGE	41 g GGE	0.054 g GGE
	SO_2	1,600 kg	100 mg	0.13 mg
	CO	7,100 kg	460 mg	0.60 mg
	NO_X	1,800 kg	110 mg	0.15 mg
	VOC	1,300 kg	85 mg	0.11 mg
	Pb	-	-	-
	PM_{10}	340 kg	22 mg	28 µg
V, Insurance (Vehicles)	Energy	11 TJ	0.73 MJ	0.00096 MJ
	GHG	930 mt GGE	60 g GGE	0.078 g GGE
	SO_2	2,300 kg	150 mg	0.19 mg
	CO	10,000 kg	660 mg	0.87 mg
	NO_X	2,600 kg	160 mg	0.22 mg
	VOC	1,900 kg	120 mg	0.16 mg
	Pb	-	-	-
	PM_{10}	490 kg	31 mg	41 µg

1.7.2 Infrastructure (Stations, Tracks, and Others)

Rail infrastructure is estimated from stations, tracks, and insurance. For stations and tracks, construction, operation, and maintenance are included. The five systems exhibit vastly different infrastructure configurations depending on vehicle types, passengers served, and geography. The breadth of configurations is discussed as well as the environmental impact in the following sections.

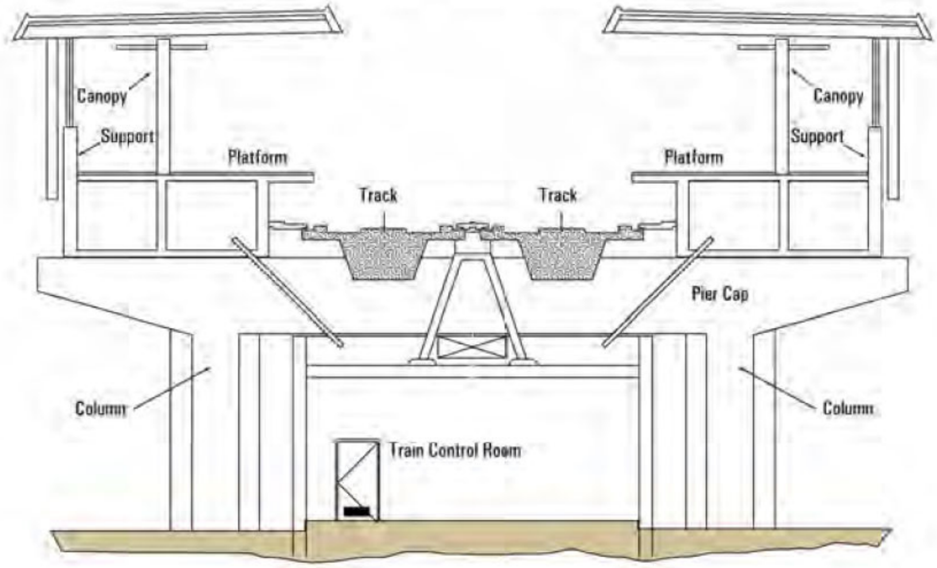
1.7.2.1 Station Construction

The range of station and infrastructure design across the five systems leads to many system-specific station designs which must be considered individually. The estimation goal for each of the five systems is to calculate the material requirements in station construction and then estimate environmental impacts from material production and construction.

BART

There are 43 stations in the BART system including 14 aerial platforms, 13 surface, and 16 underground [BART 2006]. Of the 16 underground stations, 11 service just BART trains while the remaining 5 service a combination of BART and Muni vehicles on separate floors. A typical aerial structure is shown in Figure 6. The primary material requirement of this station type is concrete. A material take-off is performed assuming a station length of 750 ft, a pier cap cross-sectional area of 275 ft^2, a platform cross-sectional area of 100 ft^2, 152 columns each with a volume of 750 ft^3 and 152 support footings each with a volume of 1,000 ft^3. The total concrete requirement of the aerial station is 520,000 ft^3 (or 7.3M ft^3 for all aerial stations). For the 13 surface stations, the same factors were used as for the aerial station except columns are excluded. This leads to 440,000 ft^3 of concrete per station (or 5.7M ft^3 for all surface stations). Lastly, for underground stations, similar parameters are used as with aerial and surface stations except for each floor, there is a pier cap (cross-sectional area of 275 ft^2), the entire station has a roof cap (cross-sectional area of 275 ft^2), and walls are included (12 ft height with a cross-sectional area of 60 ft^2). For non-shared stations, there is one floor with a pier and roof cap where ticketing and facilities are found at ground level. For shared stations, there are three floors where BART is at the lowest, Muni is in the middle, and at the first underground floor, ticketing and facilities are located. For shared stations, the total requirements (and impact) are split equally between BART and Muni. Non-shared stations require 770,000 ft^3 of concrete and shared 2.2M ft^3. The total volume of concrete required for BART stations (after removing Muni's share) is 27M ft^3.

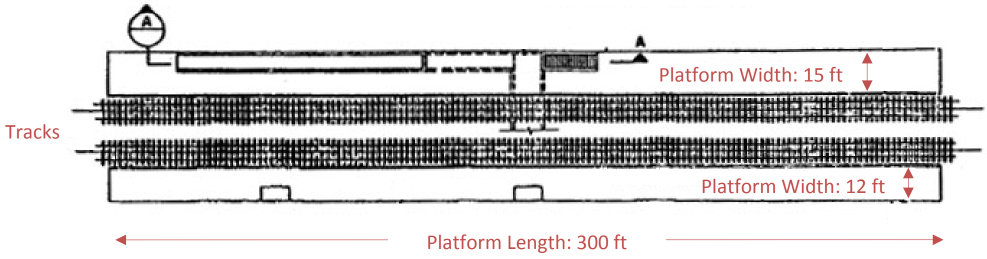
Figure 6 – Typical BART Aerial Structure [BART 2007e]



Caltrain

Caltrain exhibits small station requirements as two platforms are constructed at grade on the side of the tracks (Figure 7). The platforms are constructed 300 ft long and 12 or 15 ft wide at the 34 stations. For each station, it is assumed that the 2 platforms sit on 1 ft of subbase aggregate. The platforms are 2 ft in height constructed of concrete. This results in 18,000 ft^3 of concrete per station and 9,000 ft^3 of subbase (610,000 ft^3 of concrete and 310,000 ft^3 of subbase in the system).

Figure 7 – Typical Caltrain Station Platform [Caltrans 1988]



Muni

There are 47 Muni stations at-grade and 9 underground. Of the underground stations, 4 are not shared and 5 are shared with BART. For the at-grade stations, minimal materials are required as passengers typically load and unload from a platform slightly above street level. The typical design is assumed to be a concrete slab running under both tracks and the platform with a cross-sectional area of 72 ft^2 and the platform sitting on top with a cross-sectional area of 18 ft^2. The station length is estimated at 100 ft, slightly longer than the length of a train. This results in 9,000 ft^3 of concrete per station or 420,000 ft^3 for all at-grade stations. Underground stations follow the methodology described for BART underground station construction although adjusted for platform length (assumed 300 ft for dedicated Muni stations). The shared stations account for the other half of the BART/Muni requirements. For dedicated stations, 310,000 ft^3 of concrete are used and for shared, 1.1M ft^3.

Green Line

The Boston Green Line station profile is similar to that of Muni with many street-level at-grade stations and some underground stations. In addition, there are 2 elevated stations constructed on a large steel support structure (attributed to track construction and discussed in §1.7.2.5). For at-grade stations, unlike Muni, there is assumed to be no subgrade slab under the entire station as tracks run on wooden ties in the soil. An average station platform width of 17 ft is assumed with a depth of 1 ft. All at-grade stations are assumed to have a 300 ft length bringing total concrete requirements per station to 5,100 ft^3. The Green Line also has 4 dedicated underground stations and 5 shared. These stations are assumed to have the same material requirements as the Muni equivalents.

CAHSR

Most of the 25 expected CAHSR stations will be constructed as platforms next to tracks. Using similar methodology to Caltrain but using a platform length of 720 ft (since trains may be as long as 660 ft), concrete and subbase material requirements are determined as 43,000 ft^3 and 22,000 ft^3 per station [Bombardier 2007].

Station Construction Inventory

With the volume of concrete and subbase required for station construction for each system, the environmental inventory is determined through a hybrid LCA approach. The inventory includes concrete production, steel rebar production, concrete placement, and aggregate production. Table 46 summarizes the material requirements and their associated costs for each system.

Table 46 – Rail Infrastructure Station Material Requirements

	BART	Caltrain	Muni	Green Line	CAHSR
Volume of Concrete (10^6 ft^3)	26	0.6	6.8	5.9	1.1
Cost of Concrete (M_{1997}$)	870	20	230	200	35
Volume of Ballast (ft^3)		310,000			540,000
Cost of Ballast ($$_{1997}$)		20,000			36,000
Weight of Steel (10^3 lbs)	810	18	210	180	32
Cost of Steel ($$_{1997}$)	160,000	3,600	42,000	36,000	6,400

Using the EIO-LCA sectors Ready-Mix Concrete Manufacturing (#327320), Iron and Steel Mills (#331111), and Sand, Gravel, Clay, and Refractory Mining (#212320), energy consumption and environmental outputs are computed for the production of concrete, steel, and subbase materials used in station construction. EIO-LCA is suitable for estimating the production life-cycle impacts because the material matches the economic sector. The impacts of placing the concrete are determined from construction environmental factors [Guggemos 2005].

With total construction impacts determined, the results are normalized to the functional units as shown in Equation Set 19.

Equation Set 19 – Rail Infrastructure Station Construction

$$I/O^{rail,stations} = Construction\ I/O\ for\ Stations$$

$$I/O^{rail,stations}_{train\ lifetime} = I/O^{rail,stations} \times \frac{VMT_{train}}{lifetime_{train}} \times \frac{lifetime_{station}}{VMT_{station}}$$

$$I/O^{rail,stations}_{VMT} = I/O^{rail,stations} \times \frac{lifetime_{station}}{VMT_{station}}$$

$$I/O^{rail,stations}_{PMT} = I/O^{rail,stations} \times \frac{lifetime_{station}}{VMT_{station}} \times \frac{VMT_{train}}{PMT_{train}}$$

1.7.2.2 Station Operation

Electricity consumption at stations is distributed between lighting, escalators, train control, parking lighting, and several small miscellaneous items. Each of these systems is described in the following subsections as well as the environmental inventory from station operation.

Station Lighting

The amount of electricity consumed for lighting a train station can vary significantly based on many factors. The systems discussed in this analysis have vastly different infrastructures and resulting station designs. The extremes are large underground stations (with no natural lighting) which have the largest lighting requirements to bus-stop-like stations as with the Green Line, with only a few lamps on at night. To address the varying lighting requirements of the five systems, both existing data and estimates were used. The station lighting electricity consumption for BART stations has been measured at 2.3M kWh/station-yr for underground and 0.9M kWh/station-yr for aerial and at-grade stations [Fels 1978]. Based on observations of at-grade stations for the Green Line, an estimate of 2,600 kWh/station-yr is made. This assumes 4 lamps per station, 150 W per lamp, on 12 hours per night, 365 days per year. Aside from CAHSR, all systems have several underground stations which tend to be a large contributor to system-wide station lighting. BART lighting is estimated from past research and the number and type of each station after taking out Muni's portion for shared stations [Fels 1978]. Muni's 47 at-grade station's lighting consumption are assumed equal to the Green Line however underground stations dominate total lighting consumption (as estimated from BART underground stations). Caltrain and CAHSR stations are assumed equal in consumption to BART aerial and at-grade stations. This is not unreasonable given the similarity in designs between the station types. In addition to the Green Line's 61 at-grade stations, there are 9 underground stations. Using BART underground station consumption and adjusting for the lines which share these stations and the number of escalators, Green Line total lighting electricity is computed.

Equation Set 20 – Rail Infrastructure Station Operation (Station Lighting)

$$E_{station} = Station\ Electricity\ Consumption\ (in\ kWh \cdot station^{-1} \cdot yr^{-1})$$

$$E_{train\ lifetime}^{rail,station\ lighting} = E_{aerial+at-grade+underground} \times \frac{VMT_{train}}{lifetime_{train}} \times \frac{yr}{VMT_{system}}$$

$$E_{VMT}^{rail,station\ lighting} = E_{aerial+at-grade+underground} \times \frac{yr}{VMT_{system}}$$

$$E_{PMT}^{rail,station\ lighting} = E_{aerial+at-grade+underground} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}}$$

$$E_{aerial+at-grade+underground} = E_{aerial} + E_{at-grade} + E_{underground}$$

$$E_{aerial} = E_{BART\ aerial\ station}$$

$$E_{Caltrain\ at-grade} = E_{CAHSR\ at-grade} = E_{BART\ at-grade}$$

$$E_{Muni\ at-grade} = E_{Green\ Line\ at-grade} = \frac{4\ lamps}{station} \times \frac{150\ W}{lamp} \times \frac{12\ hrs}{day} \times \frac{365\ days}{yr}$$

$$E_{underground} = E_{BART\ underground} \times \alpha\ where\ \alpha = \%\ station\ for\ system$$

Escalators

The effect of escalators in a train system is not insignificant, accounting for up to 24% of station electricity consumption [Fels 1978]. There are currently 176 escalators in the BART system, 3 for Caltrain, 28 for Muni, and 16 for the Green Line [FTA 2005]. With Muni and the Green Line, the escalators are typically found at the underground stations. For CAHSR, it is assumed that there will be 2 escalators per station (or 50 total). For the systems studied, stations remain open during operation which is typically more than 16 hours per day. It is estimated that escalators remain operational 15 hours per day, 365 days per year. The electricity consumption rate of escalators is 4.7 kW [EERE 2007].

Equation Set 21 – Rail Infrastructure Station Operation (Escalators)

$$E = Escalator\ Electricity\ Consumption\ Rate$$

$$E_{train\ lifetime}^{rail,station\ escalators} = E \times \frac{hrs}{day} \times \frac{days}{yr} \times \frac{VMT_{train}}{lifetime_{train}} \times \frac{yr}{VMT_{train}}$$

$$E_{VMT}^{rail,station\ escalators} = E \times \frac{hrs}{day} \times \frac{days}{yr} \times \frac{yr}{VMT_{train}}$$

$$E_{PMT}^{rail,station\ escalators} = E \times \frac{hrs}{day} \times \frac{days}{yr} \times \frac{yr}{VMT_{train}} \times \frac{VMT_{train}}{PMT_{train}}$$

Train Control

Systems required for train operation and safety can consume up to 17% of total station electricity consumption [Fels 1978]. Per year, BART consumes 47,000 kWh per mile of track for train control systems [Fels 1978]. Data on the other systems was not obtainable so estimates were derived based on the BART factor as shown in Equation Set 22.

Equation Set 22 – Rail Infrastructure Station Operation (Train Control)

$$E = Electricity_{train\ control}\ \left[in\ kWh \cdot mi_{track}^{-1} \cdot yr^{-1}\right]$$

$$E_{train\ lifetime}^{rail,train\ control} = E \times track\ mileage_{system} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{lifetime_{train}}$$

$$E_{VMT}^{rail,train\ control} = E \times track\ mileage_{system} \times \frac{yr}{VMT_{system}}$$

$$E_{PMT}^{rail,train\ control} = E \times track\ mileage_{system} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}}$$

Parking Lot Lighting

Lamps at parking lots are assumed to be spaced every 40 feet, consume 400W of electricity and operate 10 hours per day, 365 days per year resulting in a 0.9 kWh/ft^2-yr parking lot lighting electricity consumption factor. For each system, the parking area is determined based on the number of spaces as described in §1.7.2.4. Given the electricity consumption factor and parking lot area, the appropriate state electricity generation emission factor is applied to determine total impacts.

Equation Set 23 – Rail Infrastructure Station Operation (Parking Lot Lighting)

$$E = Electricity_{parking\ lighting}\ [in\ kWh \cdot ft^{-2} \cdot yr^{-1}]$$

$$E_{train\ lifetime}^{rail,train\ control} = E \times ft_{system\ parking\ lots}^{2} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{lifetime_{train}}$$

$$E_{VMT}^{rail,train\ control} = E \times ft_{system\ parking\ lots}^{2} \times \frac{yr}{VMT_{system}}$$

$$E_{PMT}^{rail,train\ control} = E \times ft_{system\ parking\ lots}^{2} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}}$$

Miscellaneous

The remaining electricity consumption at stations (which accounts for only a small portion of the total electricity consumption, 3-4% for BART), is computed based on each system's station type's annual total consumption. Similar to other station operational components, BART station type electricity has been computed and Caltrain and CAHSR are assumed equivalent to BART's surface station [Fels 1978]. For Muni and the Green Line, underground stations are computed as equivalent to BART's underground stations and surface stations are computed from total operating cost for a Green Line station. The MBTA estimates total surface station yearly operational cost at $74,000 per year [MEOT 2005]. It is assumed that 40% of this cost is for station power and the cost of electricity to Massachusetts transportation was $0.048 per kWh [EIA 2005] leading to 160,000 kWh per year per station. Equation Set 24 presents the general mathematical framework.

Equation Set 24 – Rail Infrastructure Station Operation (Miscellaneous)

$$E = Electricity_{station\ miscellaneous}\ [in\ kWh \cdot station^{-1} \cdot yr^{-1}]$$

$$E^{rail,station\ miscellaneous}_{stations} = \sum_{stations} (E \times \#_{stations} \times \%_{shared})$$

$$E^{rail,station\ miscellaneous}_{train\ lifetime} = E^{rail,station\ miscellaneous}_{stations} \times \frac{yr}{VMT_{stations}} \times \frac{VMT_{train}}{lifetime_{train}}$$

$$E^{rail,station\ miscellaneous}_{VMT} = E^{rail,station\ miscellaneous}_{stations} \times \frac{yr}{VMT_{stations}}$$

$$E^{rail,station\ miscellaneous}_{PMT} = E^{rail,station\ miscellaneous}_{stations} \times \frac{yr}{VMT_{stations}} \times \frac{VMT_{train}}{PMT_{train}}$$

Station Operation Inventory

Having computed electricity consumption for each of the operational components, state and Bay Area electricity generation emission factors are used to determine GHG and CAP pollutants [Deru 2007]. Equation Set 25 describes the inventory calculations used to calculate emissions for a system in a particular state from the electricity consumption.

Equation Set 25 – Rail Infrastructure Station Operation (Inventory)

$$EF_{I/O} = Electricity\ Generation\ I/O\ Factor$$

$$I/O^{rail,station\ operation}_{train\ lifetime} = \sum_{components} \left(EF_{I/O} \times E^{rail,station\ operation\ component}_{train\ lifetime}\right)$$

$$I/O^{rail,station\ operation}_{VMT} = \sum_{components} \left(EF_{I/O} \times E^{rail,station\ operation\ component}_{VMT}\right)$$

$$I/O^{rail,station\ operation}_{PMT} = \sum_{components} \left(EF_{I/O} \times E^{rail,station\ operation\ component}_{PMT}\right)$$

1.7.2.3 Station Maintenance and Cleaning

Maintenance of railway stations includes routine rehabilitation as well as reconstruction. With a lack of accurate data on the materials and processes required to keep railway stations in acceptable performance, it was assumed that maintenance takes the form of 5% of initial construction impacts. This means that 5% of construction materials and processes are redone during the life of the facility. The reconstruction aspect dominates total maintenance impacts. Because construction was quantified based on materials and not one-time construction activities, it is reasonable to assume that construction impacts will be reassessed at the end of the facility's life.

Equation Set 26 – Rail Infrastructure Station Maintenance and Reconstruction

$$lifetime_{reconstruction} = lifetime_{system} - lifetime_{station}$$

$$I/O_{VMT}^{rail,reconstruction} = \frac{lifetime_{reconstruction}}{VMT_{reconstruction\ lifetime}} \times \frac{I/O^{rail,station\ construction}}{lifetime_{station}}$$

$$I/O_{train\ lifetime}^{rail,maintenance} = I/O_{train-lifetime}^{rail,station\ construction} \times 5\% + I/O_{VMT}^{rail,reconstruction} \times \frac{VMT\_train}{lifetime_{train}}$$

$$I/O_{VMT}^{rail,maintenance} = I/O_{VMT}^{rail,station\ construction} \times 5\% + I/O_{VMT}^{rail,reconstruction}$$

$$I/O_{PMT}^{rail,maintenance} = \left(I/O_{VMT}^{rail,station\ construction} \times 5\% + I/O_{VMT}^{rail,reconstruction}\right) \times \frac{VMT_{train}}{PMT_{train}}$$

Station cleaning is evaluated for the subsurface stations of BART, Muni, and the Green Line. Because Caltrain and CAHSR stations are outdoor platform-type stations, it is assumed that they will be swept manually and not polished like the indoor platform types. Cleaning is assumed to be PVC wet mopping with wax and that all of the energy required to perform operations (440,000 MJ per m^2 per year) is electrical [Paulsen 2003]. Equation Set 27 details the methodology where energy consumed per system is multiplied by the electricity emission factors and then normalized to the functional units.

Equation Set 27 – Rail Infrastructure Station Cleaning

$$EF_{I/O} = Electricity\ Production\ Emission\ I/O\ (per\ MJ)$$

$$E = Electrical\ Energy\ Consumed\ for\ Mopping\ Cleaning\ (MJ \cdot m^{-2} \cdot yr^{-1})$$

$$I/O_{train\ lifetime}^{rail,cleaning} = E \times EF_{I/O} \times \frac{m^2}{station} \times \frac{number_{stations}}{system} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{lifetime_{train}}$$

$$I/O_{VMT}^{rail,cleaning} = E \times EF_{I/O} \times \frac{m^2}{station} \times \frac{number_{stations}}{system} \times \frac{yr}{VMT_{system}}$$

$$I/O_{VMT}^{rail,cleaning} = E \times EF_{I/O} \times \frac{m^2}{station} \times \frac{number_{stations}}{system} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}}$$

1.7.2.4 Station Parking

Parking at rail stations is typically available for lines where drivers are encouraged to park at the station and then continue their commute to another destination. BART, Caltrain, and CAHSR all encourage this transit habit. For Muni and the Green Line, this is less so the case. This is exhibited in the number of parking spaces for each system as shown in Table 47 [SFC 2007, Caltrain 2004, MBTA 2007]. For CAHSR, it was assumed that 1,000 parking spaces would be constructed at each of the 25 stations.

Table 47 – Rail Station Parking

	BART	**Caltrain**	**Muni**	**Green Line**	**CAHSR**
Number of Spaces	45,890	7,814	0	2,000	25,000
Parking System Area (ft^2)	15,000,000	2,600,000	-	660,000	8,300,000

With the number of parking spaces for each system, it was assumed that each parking spot has an area of 300 ft^2 plus 10% for access ways (or 330 ft^2 per spot). Total system parking areas are then determined as shown in Table 47. It is assumed that parking area increases linearly with increases in system VMT. For all parking spaces, a lifetime of 10 years is assumed. This means that after 10 years, the wearing layers are removed (leaving the subbase as is) and new layers are applied. All parking area is assigned two 3 inch wearing layers and a 6 inch subbase. Using PaLATE, parking space characteristics are input to compute life-cycle environmental impacts in construction and maintenance [PaLATE 2004]. Because PaLATE does not capture VOC emissions, these were estimated separately assuming an asphalt mix of 90% cement, 3% cut-back, and 7% emulsion [EPA 2001].

The emissions from parking lot construction and maintenance are computed as lump-sum releases. They must be normalized to the functional units. To do this, Equation Set 28 is used.

Equation Set 28 – Rail Infrastructure Parking

$$EF_{I/O} = Parking\ Construction\ and\ Maintenance\ I/O\ (per\ parking\ area)$$

$$I/O_{train\ lifetime}^{rail,parking} = EF_{I/O} \times \frac{VMT}{lifetime_{train}} \times \frac{lifetime_{parking\ system}}{VMT_{system}}$$

$$I/O_{VMT}^{rail,parking} = EF_{I/O} \times \frac{lifetime_{parking\ system}}{VMT_{system}}$$

$$I/O_{PMT}^{rail,parking} = EF_{I/O} \times \frac{lifetime_{parking\ system}}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}}$$

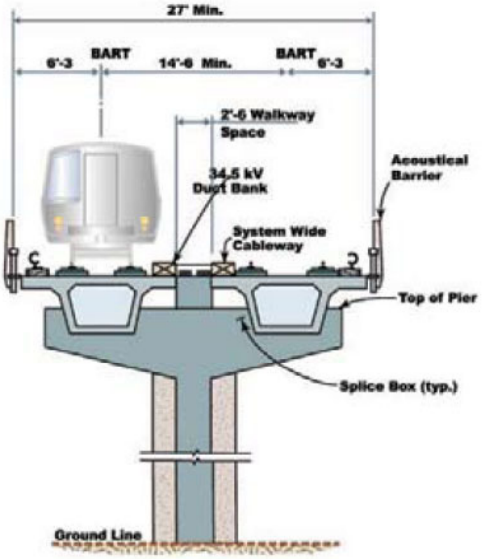
1.7.2.5 Track Construction

At-grade, retained fill, underground, and elevated or aerial are the major descriptors for track construction. For each of the systems, miles of each type of track are identified in order to estimate material requirements. A hybrid LCA is performed for track construction after the quantities of aggregate, concrete, steel, and wood are estimated. Additionally, power structures and substations are included. While BART stands alone in the large diversity of track types, other systems (Caltrain and CAHSR, Muni and Green Line) are similar. For all systems, tunnel and bridge construction is not included. While construction of these track segments is likely more environmentally intensive than other tracks, accurate estimation procedures were not easily identified and therefore excluded for all systems.

BART

There are 44 miles of surface track, 23 miles of aerial track, and 21 miles of underground track (including the 14 mile Transbay tube) in the BART system [BART 2007]. It is assumed that 75% of the surface track is at-grade with the remaining 25% retained fill. All track is assumed 100 lbs per 3 feet. For all surface track, ballast and ties are used. A ballast cross-sectional area of 71 ft^2 is used and it is estimated that concrete ties are placed every 24 inches [SVRTC 2006]. Ties are estimated to have a volume of 6 ft^3 (9 ft × ¾ ft × 1 ft). The retained fill tracks have a wall on each side of the track (each with a height of 12 ft and a width of 1 ft) and ballast as their top layer with a cross-sectional area of 54 ft^2. For the aerial tracks, there are 1,918 supports (Figure 8) in the system [SVRTC 2006]. Each support is assumed to have a footing with a 1,000 ft^3 volume. The supports themselves have a volume of 1,400 ft^3 including the pier cap [BART 2007e]. On top of the pier cap, the track structure sits with a cross-sectional area of 40 ft^2. The power (cabling and other power components) and substation (electricity transmission system for train propulsion) structure is estimated from Muni's late 1980s power structure upgrade and their 2004 replacement of 5 substations [Carrington 1984, Muni 2006]. During the early 1980s upgrade, \$58M (in \$1980) was spent to replace the rail and bus power structure. This is assumed to be composed of 50% labor, overhead, and markup costs and 10% is attributable to rail (with the remainder attributed to Muni's electric buses) and includes substations. This results in a power structure material cost of \$4.7M for the 64 track miles, or \$74,000 per mile. Total substations cost for the Muni system is estimated at \$22M for materials or \$34,000 per mile. These per mile factors are applied to the BART system to estimate material costs for the power delivery and substation components.

Figure 8 – BART Aerial Support [SVRTC 2006]



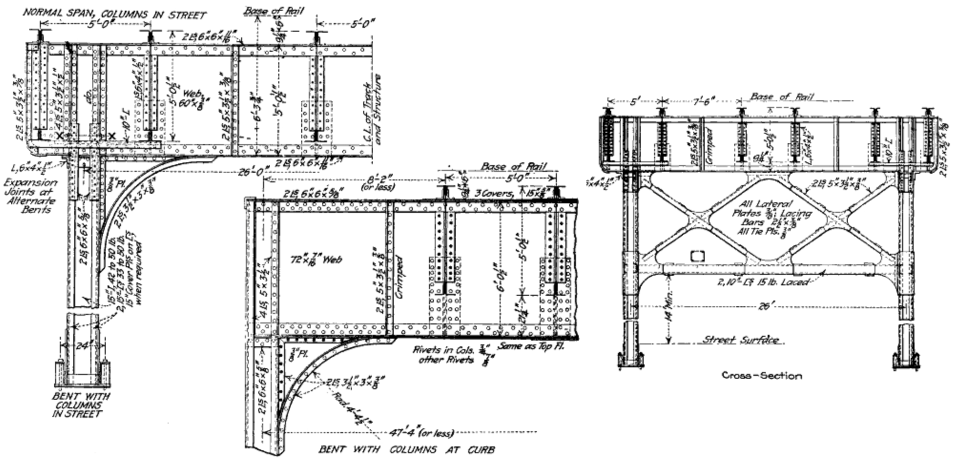
Caltrain and CAHSR

Caltrain and CAHSR are composed of essentially all surface level tracks (although CAHSR has a few segments of proposed elevated track, these have been excluded because they are so few compared to the entire system). While all of Caltrain's surface level track is considered at-grade, 570 miles of CAHSR are considered such with the remaining evaluated as retained-fill. The methodology for evaluating at-grade and retained-fill track segments is the same as for BART. A track subbase cross-sectional area of 71 ft^2 and 54 ft^2 are assigned for all segments [SVRTC 2006, PB 1999]. For CAHSR retained-fill segments, concrete retaining walls have a cross-sectional area of 214 ft^2 [PB 1999]. For both systems, concrete ties are used and are assumed to be placed every 24 in. Ties have dimensions of 9 ft by 8 in by 12 in. For both systems, the power structure required for train control, signaling, and safety is determined from Muni costs. Because Caltrain is diesel powered, substations for train propulsion are not included. CAHSR substation construction was estimated from Muni data. All track is treated as 100 lbs per 3 feet.

Muni and the Green Line

The 64 Muni track miles and 39 Boston Green Line track miles are treated as at-grade except for 2 miles of elevated track on the Green Line. While Muni and the Green Line have underground segments, these were not considered due to the complexities and lack of representative data for tunnel construction. Again, track is treated as 100 lbs per 3 feet. Tracks for both systems are considered to have a ballast subbase (assumed 50 ft^2 cross-sectional area) on 50% of segments since many track miles are directly on streets. Ties for these systems are timber and there are 57,000 in the Muni network and 100,000 in the Green Line network [Bei 1978, WBZ 2007]. The power structure and substations construction costs have been quantified as described in the BART track construction section. For the Green Line, similar to other systems, costs are calculated based on Muni costs per mile of track. Additionally, the 2 mile aerial component of the Green Line is included. This steel structure, similar to the one shown in Figure 9, is assigned a weight of 2,250 lbs of steel per linear foot of structure [Griest 1915].

Figure 9 – Typical Green Line Elevated Rail Structure [Adapted from Griest 1915]



Track Construction Inventory

The total track material requirements are shown in Table 48. Steel is computed from the tracks and structures (as with the Green Line) as well as the rebar in concrete (steel is assumed to be 3% of concrete by volume). These materials are evaluated in the EIO-LCA sectors Sand, Gravel, Clay, and Refractory Mining (#212320), Mix Concrete Manufacturing (#327320), Iron and Steel Mills (#331111), Sawmills (#321113), Other Communication and Energy Wire Manufacturing (#335929), and Electric Power and Specialty Transformer Manufacturing (#335311). In order to compute impacts in EIO-LCA, costs must be assigned to each material. Ballast is \$10 per ton, concrete costs \$300 per yd^3, and steel is \$0.20 per lb (all in \$1997) [WSDOT 2007, WSDOT 2007b, USGS 1999]. Total track construction costs by material type are shown in Table 48.

Table 48 – Rail Infrastructure Track Construction Material Requirements

	BART	Caltrain	Muni	Green Line	CAHSR
Volume of Ballast (10^6 ft^3)	16	29			200
Cost of Ballast ($\$M_{1997}$)	1.0	1.9			14
Volume of Concrete (10^6 ft^3)	16	2.4			340
Cost of Concrete ($\$M_{1997}$)	530	79			11,000
Weight of Steel (10^6 lbs)	16	27	22	37	260
Cost of Steel ($\$M_{1997}$)	3.2	5.4	4.4	7.4	52
Cost of Wood ($\$M_{1997}$)			0.9	1.7	
Cost of Power Structures ($\$M_{1997}$)	2.0		3.9	2.4	34
Cost of Substations ($\$M_{1997}$)	19		1.8	1.1	7

Ballast is assumed to have a lifetime of 25 years, concrete 50 years, track 25 years, power structures 35 years, and substations 20 years. Inputting the material costs into EIO-LCA for each system, total construction impacts are computed per year. These impacts are then normalized to the functional units as shown in Equation Set 29.

Equation Set 29 – Rail Infrastructure Track Construction

$$I/O_{EIOLCA}^{rail,track\ construction} = Lifetime\ Track\ Material\ Production\ IO$$

$$I/O_{train\ lifetime}^{rail,track\ construction} = \frac{I/O_{EIOLCA}^{rail,track\ construction}}{lifetime_{track}} \times \frac{yr_{system}}{VMT_{system}} \times \frac{VMT_{train}}{lifetime_{train}}$$

$$I/O_{train\ lifetime}^{rail,track\ construction} = \frac{I/O_{EIOLCA}^{rail,track\ construction}}{lifetime_{track}} \times \frac{yr_{system}}{VMT_{system}}$$

$$I/O_{train\ lifetime}^{rail,track\ construction} = \frac{I/O_{EIOLCA}^{rail,track\ construction}}{lifetime_{track}} \times \frac{yr_{system}}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}}$$

1.7.2.6 Track Maintenance

Material replacement, grinding (or smoothing), and inspection are the main activities involved in railroad track maintenance. Little data exists on the five systems with respect to routine maintenance. Using two estimation methods, impacts are calculated.

For BART, Caltrain, and CAHSR, SimaPro’s long distance and high speed rail maintenance factors are used (Table 49) [SimaPro 2006]. The SimaPro factors (adjusted for the California electricity mix in the supply chain) are for a combined long distance and high speed rail network in Germany and Switzerland. Both systems share the same track and are computer controlled giving the high speed train priority. The factors are applied to BART, Caltrain, and CAHSR systems to determine total maintenance costs.

Table 49 – Rail Infrastructure Track Maintenance SimaPro Factors (per Meter per Year)

SimaPro System ⇨		High Speed Rail (CA Mix)
Impact	Unit	**CAHSR**
Energy	MJ	57
Global Warming Potential (GWP)	kg GGE	2.4
Sulfur Dioxide (SO_2)	g	2.2
Carbon Monoxide (CO)	g	1.1
Nitrogen Oxides (NO_X)	g	3.9
Volatile Organic Compounds (VOC)	g	0.8
Lead (Pb)	mg	2.6
Particulate Matter >10µ ($PM_{>10}$)	g	0.3
Particulate Matter 2.5-10µ ($PM_{2.5 \le d \le 10}$)	g	0.1
Particulate Matter <2.5µ ($PM_{<2.5}$)	g	0.6
Particulate Matter ≤10µ ($PM_{\le 10}$)	g	0.7

Equation Set 30 describes the mathematical framework for calculating impacts from track maintenance for the three systems.

Equation Set 30 – Rail Infrastructure Maintenance for BART, Caltrain, and CAHSR

$$I/O_{SimaPro}^{rail,track\ maintenance} = Yearly\ Maintenance\ I/O\ for\ Tracks\ (in\ m^{-1} \cdot yr^{-1})$$

$$I/O_{track\ lifetime}^{rail,track\ maintenance} = I/O_{SimaPro}^{rail,track\ maintenance} \times meters_{system\ track} \times \frac{yrs}{lifetime_{track}}$$

$$I/O_{train\ lifetime}^{rail,track\ maintenance} = I/O_{track\ lifetime}^{rail,track\ maintenance} \times \frac{system}{VMT_{system}} \times \frac{VMT_{train}}{lifetime_{train}}$$

$$I/O_{VMT}^{rail,track\ maintenance} = I/O_{track\ lifetime}^{rail,track\ maintenance} \times \frac{system}{VMT_{system}}$$

$$I/O_{PMT}^{rail,track\ maintenance} = I/O_{track\ lifetime}^{rail,track\ maintenance} \times \frac{system}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}}$$

Although SimaPro does have an evaluation of light rail track maintenance, the European track system it represents is different than that of the Muni or Green Line. An alternative methodology, estimating directly the inventory, was employed from the other three systems. Communications with operations personnel at the Green Line provided data on the equipment used and productivities during track maintenance [MBTA 2007]. The frequency of material replacement was also provided. Given fuel consumption of equipment and rated horsepower, emission factors for similar horsepower engines are applied to determine the environmental inventory [FAA 2007]. The emissions per year are then normalized to the functional units as show in Equation Set 31.

Equation Set 31 – Rail Infrastructure Maintenance for Muni and the Green Line

$$EF_{I/O} = Equipment\ Use\ I/O\ (per\ gallon\ of\ fuel)$$

$$I/O_{train\ lifetime}^{rail,track\ maintenance} = EF_{I/O} \times \frac{gallons}{yr} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{lifetime_{train}}$$

$$I/O_{VMT}^{rail,track\ maintenance} = EF_{I/O} \times \frac{gallons}{yr} \times \frac{yr}{VMT_{system}}$$

$$I/O_{PMT}^{rail,track\ maintenance} = EF_{I/O} \times \frac{gallons}{yr} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}}$$

1.7.2.7 Insurance

Complementing vehicle insurance, infrastructure insurance consists of health and fringe benefits received by non-vehicle personnel as well as casualty and liability on non-vehicle assets. Using the same methodology as described for vehicle insurances (§1.7.1.4), non-vehicle insurances are calculated. These are summarized in Table 50. Equation Set 18 summarizes the framework used for calculating environmental impacts from the insurance infrastructure.

Table 50 – Rail Infrastructure Insurance Costs ($\$_{2005}$/train-yr)

	BART	Caltrain	Muni	Green Line	CAHSR
Operator Health	61,000	120,000	75,000	370,000	1,500,000
Vehicle Casualty and Liability	370,000	70,000	140,000	230,000	1,300,000

1.7.2.8 Rail Infrastructure Results

Similar to the rail vehicle results (§1.7.1.5), inventory results are shown per vehicle lifetime, per vehicle-mile traveled, and per passenger-mile traveled for each infrastructure components. Vehicle and passenger-miles traveled are shown in Table 40.

Table 51 – BART Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Construction	Energy	110 TJ	31 MJ	0.21 MJ
	GHG	11,000 mt GGE	3,100 g GGE	21 g GGE
	SO$_2$	33,000 kg	9,500 mg	65 mg
	CO	88,000 kg	26,000 mg	180 mg
	NO$_X$	44,000 kg	13,000 mg	89 mg
	VOC	28,000 kg	8,200 mg	56 mg
	Pb	5.0 kg	1.4 mg	9.9 µg
	PM$_{10}$	5,700 kg	1,700 mg	11,000 µg
I, Station Lighting	Energy	3.7 TJ	1.1 MJ	0.0075 MJ
	GHG	210 mt GGE	61 g GGE	0.42 g GGE
	SO$_2$	1,200 kg	340 mg	2.3 mg
	CO	120 kg	34 mg	0.24 mg
	NO$_X$	68 kg	20 mg	0.14 mg
	VOC	31 kg	9.1 mg	0.062 mg
	Pb	0.00076 kg	0.00022 mg	0.0015 µg
	PM$_{10}$	13 kg	3.7 mg	26 µg

Table 51 – BART Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Escalators	Energy	0.93 TJ	0.27 MJ	0.0019 MJ
	GHG	52 mt GGE	15 g GGE	0.10 g GGE
	SO_2	290 kg	85 mg	0.58 mg
	CO	29 kg	8.6 mg	0.059 mg
	NO_X	17 kg	4.9 mg	0.034 mg
	VOC	7.7 kg	2.3 mg	0.016 mg
	Pb	0.00019 kg	0.000055 mg	0.00038 μg
	PM_{10}	3.2 kg	0.93 mg	6.4 μg
I, Station Train Control	Energy	1.6 TJ	0.47 MJ	0.0032 MJ
	GHG	89 mt GGE	26 g GGE	0.18 g GGE
	SO_2	500 kg	150 mg	1.0 mg
	CO	51 kg	15 mg	0.10 mg
	NO_X	29 kg	8.5 mg	0.058 mg
	VOC	13 kg	3.9 mg	0.027 mg
	Pb	0.00033 kg	0.000095 mg	0.00065 μg
	PM_{10}	5.4 kg	1.6 mg	11 μg
I, Station Parking Lighting	Energy	22 TJ	6.4 MJ	0.044 MJ
	GHG	1,200 mt GGE	360 g GGE	2.5 g GGE
	SO_2	6,900 kg	2,000 mg	14 mg
	CO	700 kg	200 mg	1.4 mg
	NO_X	400 kg	120 mg	0.80 mg
	VOC	180 kg	54 mg	0.37 mg
	Pb	0.0045 kg	0.0013 mg	0.0090 μg
	PM_{10}	75 kg	22 mg	150 μg
I, Station Miscellaneous	Energy	0.40 TJ	0.12 MJ	0.00079 MJ
	GHG	22 mt GGE	6.4 g GGE	0.044 g GGE
	SO_2	120 kg	36 mg	0.25 mg
	CO	12 kg	3.6 mg	0.025 mg
	NO_X	7.2 kg	2.1 mg	0.014 mg
	VOC	3.3 kg	0.96 mg	0.0066 mg
	Pb	0.000080 kg	0.000023 mg	0.00016 μg
	PM_{10}	1.3 kg	0.39 mg	2.7 μg
I, Station Maintenance	Energy	71 TJ	21 MJ	0.14 MJ
	GHG	7,100 mt GGE	2,100 g GGE	14 g GGE
	SO_2	22,000 kg	6,300 mg	43 mg
	CO	58,000 kg	17,000 mg	120 mg
	NO_X	30,000 kg	8,600 mg	59 mg
	VOC	19,000 kg	5,500 mg	38 mg
	Pb	3.3 kg	0.97 mg	6.6 μg
	PM_{10}	3,800 kg	1,100 mg	7,600 μg
I, Station Cleaning	Energy	0.096 TJ	0.028 MJ	0.00019 MJ
	GHG	7.1 mt GGE	2.1 g GGE	0.014 g GGE
	SO_2	38 kg	11 mg	0.076 mg
	CO	3.6 kg	1.1 mg	0.0073 mg
	NO_X	2.7 kg	0.79 mg	0.0055 mg
	VOC	0.81 kg	0.24 mg	0.0016 mg
	Pb	0.000049 kg	0.000014 mg	0.000098 μg
	PM_{10}	0.41 kg	0.12 mg	0.82 μg

Table 51 – BART Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Parking	Energy	48 TJ	14 MJ	0.095 MJ
	GHG	4,000 mt GGE	1,200 g GGE	8.0 g GGE
	SO_2	7,500 kg	2,200 mg	15 mg
	CO	14,000 kg	4,200 mg	29 mg
	NO_X	20,000 kg	5,800 mg	40 mg
	VOC	24,000 kg	6,900 mg	47 mg
	Pb	2.3 kg	0.66 mg	4.5 µg
	PM_{10}	9,200 kg	2,700 mg	18,000 µg
I, Track/Power Construction	Energy	83 TJ	24 MJ	0.17 MJ
	GHG	7,800 mt GGE	2,300 g GGE	16 g GGE
	SO_2	23,000 kg	6,700 mg	46 mg
	CO	65,000 kg	19,000 mg	130 mg
	NO_X	28,000 kg	8,300 mg	57 mg
	VOC	20,000 kg	5,900 mg	40 mg
	Pb	7.3 kg	2.1 mg	15 µg
	PM_{10}	4,200 kg	1,200 mg	8,500 µg
I, Track Maintenance	Energy	4.4 TJ	1.3 MJ	0.0088 MJ
	GHG	180 mt GGE	53 g GGE	0.37 g GGE
	SO_2	170 kg	50 mg	0.34 mg
	CO	88 kg	26 mg	0.18 mg
	NO_X	300 kg	88 mg	0.60 mg
	VOC	59 kg	17 mg	0.12 mg
	Pb	0.20 kg	0.059 mg	0.40 µg
	PM_{10}	51 kg	15 mg	100 µg
I, Insurance (Employees)	Energy	1.3 TJ	0.38 MJ	0.0026 MJ
	GHG	110 mt GGE	31 g GGE	0.21 g GGE
	SO_2	260 kg	77 mg	0.53 mg
	CO	1,200 kg	350 mg	2.4 mg
	NO_X	300 kg	86 mg	0.59 mg
	VOC	220 kg	64 mg	0.44 mg
	Pb	-	-	-
	PM_{10}	56 kg	16 mg	110 µg
I, Insurance (Facilities)	Energy	7.9 TJ	2.3 MJ	0.016 MJ
	GHG	640 mt GGE	190 g GGE	1.3 g GGE
	SO_2	1,600 kg	460 mg	3.2 mg
	CO	7,100 kg	2,100 mg	14 mg
	NO_X	1,800 kg	520 mg	3.6 mg
	VOC	1,300 kg	390 mg	2.6 mg
	Pb	-	-	-
	PM_{10}	340 kg	98 mg	670 µg

Table 52 – Caltrain Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Construction	Energy	5.2 TJ	4.2 MJ	0.027 MJ
	GHG	510 mt GGE	410 g GGE	2.7 g GGE
	SO_2	1,600 kg	1,300 mg	8.2 mg
	CO	4,200 kg	3,400 mg	22 mg
	NO_X	2,100 kg	1,700 mg	11 mg
	VOC	1,400 kg	1,100 mg	7.1 mg
	Pb	0.24 kg	0.19 mg	1.3 µg
	PM_{10}	270 kg	220 mg	1,400 µg
I, Station Lighting	Energy	14 TJ	11 MJ	0.071 MJ
	GHG	760 mt GGE	620 g GGE	4.0 g GGE
	SO_2	4,300 kg	3,400 mg	22 mg
	CO	430 kg	350 mg	2.3 mg
	NO_X	250 kg	200 mg	1.3 mg
	VOC	110 kg	92 mg	0.59 mg
	Pb	0.0028 kg	0.0022 mg	0.014 µg
	PM_{10}	46 kg	38 mg	240 µg
I, Station Escalators	Energy	0.26 TJ	0.21 MJ	0.0014 MJ
	GHG	15 mt GGE	12 g GGE	0.077 g GGE
	SO_2	82 kg	66 mg	0.43 mg
	CO	8.3 kg	6.7 mg	0.043 mg
	NO_X	4.8 kg	3.9 mg	0.025 mg
	VOC	2.2 kg	1.8 mg	0.011 mg
	Pb	0.000053 kg	0.000043 mg	0.00028 µg
	PM_{10}	0.89 kg	0.72 mg	4.7 µg
I, Station Train Control	Energy	25 TJ	20 MJ	0.13 MJ
	GHG	1,400 mt GGE	1,100 g GGE	7.3 g GGE
	SO_2	7,800 kg	6,300 mg	41 mg
	CO	790 kg	640 mg	4.1 mg
	NO_X	450 kg	370 mg	2.4 mg
	VOC	210 kg	170 mg	1.1 mg
	Pb	0.0051 kg	0.0041 mg	0.027 µg
	PM_{10}	85 kg	69 mg	450 µg
I, Station Parking Lighting	Energy	8.4 TJ	6.8 MJ	0.044 MJ
	GHG	470 mt GGE	380 g GGE	2.5 g GGE
	SO_2	2,600 kg	2,100 mg	14 mg
	CO	270 kg	210 mg	1.4 mg
	NO_X	150 kg	120 mg	0.80 mg
	VOC	70 kg	57 mg	0.37 mg
	Pb	0.0017 kg	0.0014 mg	0.0089 µg
	PM_{10}	29 kg	23 mg	150 µg
I, Station Miscellaneous	Energy	3.1 TJ	2.5 MJ	0.016 MJ
	GHG	180 mt GGE	140 g GGE	0.92 g GGE
	SO_2	980 kg	800 mg	5.1 mg
	CO	99 kg	80 mg	0.52 mg
	NO_X	57 kg	46 mg	0.30 mg
	VOC	26 kg	21 mg	0.14 mg
	Pb	0.00064 kg	0.00052 mg	0.0033 µg
	PM_{10}	11 kg	8.7 mg	56 µg

Table 52 – Caltrain Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Maintenance	Energy	1.5 TJ	1.3 MJ	0.0081 MJ
	GHG	150 mt GGE	120 g GGE	0.80 g GGE
	SO_2	470 kg	380 mg	2.5 mg
	CO	1,300 kg	1,000 mg	6.6 mg
	NO_X	640 kg	520 mg	3.3 mg
	VOC	410 kg	330 mg	2.1 mg
	Pb	0.072 kg	0.058 mg	0.38 µg
	PM_{10}	82 kg	67 mg	430 µg
I, Station Cleaning	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-
I, Station Parking	Energy	18 TJ	15 MJ	0.094 MJ
	GHG	1,500 mt GGE	1,200 g GGE	7.8 g GGE
	SO_2	2,800 kg	2,300 mg	15 mg
	CO	5,400 kg	4,400 mg	28 mg
	NO_X	7,500 kg	6,000 mg	39 mg
	VOC	8,900 kg	7,200 mg	47 mg
	Pb	0.85 kg	0.69 mg	4.4 µg
	PM_{10}	3,500 kg	2,800 mg	18,000 µg
I, Track/Power Construction	Energy	47 TJ	38 MJ	0.24 MJ
	GHG	4,300 mt GGE	3,500 g GGE	22 g GGE
	SO_2	11,000 kg	8,500 mg	55 mg
	CO	37,000 kg	30,000 mg	190 mg
	NO_X	12,000 kg	9,500 mg	62 mg
	VOC	8,000 kg	6,400 mg	42 mg
	Pb	12 kg	9.5 mg	61 µg
	PM_{10}	3,000 kg	2,400 mg	16,000 µg
I, Track Maintenance	Energy	9.8 TJ	7.9 MJ	0.051 MJ
	GHG	410 mt GGE	330 g GGE	2.1 g GGE
	SO_2	380 kg	310 mg	2.0 mg
	CO	200 kg	160 mg	1.0 mg
	NO_X	670 kg	540 mg	3.5 mg
	VOC	130 kg	110 mg	0.69 mg
	Pb	0.45 kg	0.36 mg	2.3 µg
	PM_{10}	110 kg	93 mg	600 µg
I, Insurance (Employees)	Energy	3.1 TJ	2.5 MJ	0.016 MJ
	GHG	250 mt GGE	200 g GGE	1.3 g GGE
	SO_2	620 kg	500 mg	3.2 mg
	CO	2,800 kg	2,300 mg	15 mg
	NO_X	690 kg	560 mg	3.6 mg
	VOC	520 kg	420 mg	2.7 mg
	Pb	-	-	-
	PM_{10}	130 kg	110 mg	690 µg

Table 52 – Caltrain Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Insurance (Facilities)	Energy	1.7 TJ	1.4 MJ	0.0090 MJ
	GHG	140 mt GGE	110 g GGE	0.74 g GGE
	SO_2	350 kg	280 mg	1.8 mg
	CO	1,600 kg	1,300 mg	8.2 mg
	NO_X	390 kg	320 mg	2.0 mg
	VOC	290 kg	230 mg	1.5 mg
	Pb	-	-	-
	PM_{10}	73 kg	59 mg	380 µg

Table 53 – Muni Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Construction	Energy	12 TJ	6.7 MJ	0.31 MJ
	GHG	1,200 mt GGE	670 g GGE	31 g GGE
	SO_2	3,500 kg	2,000 mg	93 mg
	CO	9,500 kg	5,500 mg	250 mg
	NO_X	4,800 kg	2,800 mg	130 mg
	VOC	3,000 kg	1,800 mg	81 mg
	Pb	0.54 kg	0.31 mg	14 µg
	PM_{10}	620 kg	360 mg	16,000 µg
I, Station Lighting	Energy	8.0 TJ	4.6 MJ	0.21 MJ
	GHG	450 mt GGE	260 g GGE	12 g GGE
	SO_2	2,500 kg	1,500 mg	66 mg
	CO	250 kg	150 mg	6.7 mg
	NO_X	140 kg	84 mg	3.8 mg
	VOC	66 kg	39 mg	1.8 mg
	Pb	0.0016 kg	0.00094 mg	0.043 µg
	PM_{10}	27 kg	16 mg	720 µg
I, Station Escalators	Energy	0.82 TJ	0.47 MJ	0.022 MJ
	GHG	46 mt GGE	26 g GGE	1.2 g GGE
	SO_2	260 kg	150 mg	6.8 mg
	CO	26 kg	15 mg	0.68 mg
	NO_X	15 kg	8.6 mg	0.39 mg
	VOC	6.8 kg	3.9 mg	0.18 mg
	Pb	0.00017 kg	0.000096 mg	0.0044 µg
	PM_{10}	2.8 kg	1.6 mg	74 µg
I, Station Train Control	Energy	4.9 TJ	2.9 MJ	0.13 MJ
	GHG	280 mt GGE	160 g GGE	7.3 g GGE
	SO_2	1,500 kg	900 mg	41 mg
	CO	160 kg	90 mg	4.1 mg
	NO_X	90 kg	52 mg	2.4 mg
	VOC	41 kg	24 mg	1.1 mg
	Pb	0.0010 kg	0.00058 mg	0.027 µg
	PM_{10}	17 kg	9.8 mg	450 µg

Table 53 – Muni Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Parking Lighting	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-
I, Station Miscellaneous	Energy	6.7 TJ	3.9 MJ	0.18 MJ
	GHG	380 mt GGE	220 g GGE	10.0 g GGE
	SO_2	2,100 kg	1,200 mg	56 mg
	CO	210 kg	120 mg	5.6 mg
	NO_X	120 kg	71 mg	3.2 mg
	VOC	56 kg	33 mg	1.5 mg
	Pb	0.0014 kg	0.00080 mg	0.036 µg
	PM_{10}	23 kg	13 mg	610 µg
I, Station Maintenance	Energy	0.69 TJ	0.40 MJ	0.018 MJ
	GHG	68 mt GGE	40 g GGE	1.8 g GGE
	SO_2	210 kg	120 mg	5.5 mg
	CO	560 kg	330 mg	15 mg
	NO_X	280 kg	170 mg	7.5 mg
	VOC	180 kg	100 mg	4.8 mg
	Pb	0.032 kg	0.019 mg	0.85 µg
	PM_{10}	37 kg	21 mg	970 µg
I, Station Cleaning	Energy	0.027 TJ	0.015 MJ	0.00070 MJ
	GHG	0.81 mt GGE	0.47 g GGE	0.022 g GGE
	SO_2	4.3 kg	2.5 mg	0.12 mg
	CO	0.42 kg	0.24 mg	0.011 mg
	NO_X	0.31 kg	0.18 mg	0.0083 mg
	VOC	0.093 kg	0.054 mg	0.0025 mg
	Pb	0.0000056 kg	0.0000033 mg	0.00015 µg
	PM_{10}	0.047 kg	0.027 mg	1.2 µg
I, Station Parking	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-
I, Track/Power Construction	Energy	6.3 TJ	3.7 MJ	0.17 MJ
	GHG	570 mt GGE	330 g GGE	15 g GGE
	SO_2	1,000 kg	610 mg	28 mg
	CO	5,500 kg	3,200 mg	150 mg
	NO_X	930 kg	540 mg	25 mg
	VOC	580 kg	340 mg	15 mg
	Pb	2.9 kg	1.7 mg	76 µg
	PM_{10}	550 kg	320 mg	14,000 µg

Table 53 – Muni Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Track Maintenance	Energy	2.4 TJ	1.4 MJ	0.063 MJ
	GHG	170 mt GGE	100 g GGE	4.6 g GGE
	SO_2	120 kg	67 mg	3.1 mg
	CO	390 kg	230 mg	10 mg
	NO_X	810 kg	470 mg	21 mg
	VOC	84 kg	49 mg	2.2 mg
	Pb	-	-	-
	PM_{10}	84 kg	49 mg	2,200 μg
I, Insurance (Employees)	Energy	1.7 TJ	0.99 MJ	0.045 MJ
	GHG	140 mt GGE	81 g GGE	3.7 g GGE
	SO_2	340 kg	200 mg	9.1 mg
	CO	1,600 kg	900 mg	41 mg
	NO_X	390 kg	230 mg	10 mg
	VOC	290 kg	170 mg	7.6 mg
	Pb	-	-	-
	PM_{10}	73 kg	42 mg	1,900 μg
I, Insurance (Facilities)	Energy	3.2 TJ	1.8 MJ	0.084 MJ
	GHG	260 mt GGE	150 g GGE	6.9 g GGE
	SO_2	640 kg	370 mg	17 mg
	CO	2,900 kg	1,700 mg	76 mg
	NO_X	720 kg	420 mg	19 mg
	VOC	530 kg	310 mg	14 mg
	Pb	-	-	-
	PM_{10}	140 kg	79 mg	3,600 μg

Table 54 – Green Line Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Construction	Energy	11 TJ	7.9 MJ	0.15 MJ
	GHG	1,100 mt GGE	780 g GGE	14 g GGE
	SO_2	3,400 kg	2,400 mg	44 mg
	CO	9,000 kg	6,500 mg	120 mg
	NO_X	4,600 kg	3,300 mg	60 mg
	VOC	2,900 kg	2,100 mg	38 mg
	Pb	0.51 kg	0.37 mg	6.8 μg
	PM_{10}	590 kg	420 mg	7,700 μg
I, Station Lighting	Energy	4.8 TJ	3.4 MJ	0.064 MJ
	GHG	680 mt GGE	490 g GGE	9.0 g GGE
	SO_2	4,000 kg	2,900 mg	53 mg
	CO	760 kg	550 mg	10 mg
	NO_X	900 kg	640 mg	12 mg
	VOC	52 kg	37 mg	0.68 mg
	Pb	0.034 kg	0.024 mg	0.44 μg
	PM_{10}	41 kg	29 mg	540 μg

Table 54 – Green Line Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Escalators	Energy	0.62 TJ	0.44 MJ	0.0082 MJ
	GHG	88 mt GGE	63 g GGE	1.2 g GGE
	SO_2	520 kg	370 mg	6.9 mg
	CO	99 kg	70 mg	1.3 mg
	NO_X	120 kg	83 mg	1.5 mg
	VOC	6.7 kg	4.8 mg	0.088 mg
	Pb	0.0043 kg	0.0031 mg	0.057 µg
	PM_{10}	5.3 kg	3.8 mg	69 µg
I, Station Train Control	Energy	3.1 TJ	2.2 MJ	0.041 MJ
	GHG	440 mt GGE	320 g GGE	5.8 g GGE
	SO_2	2,600 kg	1,900 mg	35 mg
	CO	500 kg	350 mg	6.6 mg
	NO_X	580 kg	420 mg	7.7 mg
	VOC	34 kg	24 mg	0.44 mg
	Pb	0.022 kg	0.016 mg	0.29 µg
	PM_{10}	26 kg	19 mg	350 µg
I, Station Parking Lighting	Energy	0.87 TJ	0.62 MJ	0.012 MJ
	GHG	120 mt GGE	88 g GGE	1.6 g GGE
	SO_2	730 kg	520 mg	9.6 mg
	CO	140 kg	99 mg	1.8 mg
	NO_X	160 kg	120 mg	2.1 mg
	VOC	9.3 kg	6.7 mg	0.12 mg
	Pb	0.0061 kg	0.0044 mg	0.080 µg
	PM_{10}	7.4 kg	5.3 mg	97 µg
I, Station Miscellaneous	Energy	11 TJ	7.6 MJ	0.14 MJ
	GHG	1,500 mt GGE	1,100 g GGE	20 g GGE
	SO_2	8,900 kg	6,400 mg	120 mg
	CO	1,700 kg	1,200 mg	22 mg
	NO_X	2,000 kg	1,400 mg	26 mg
	VOC	110 kg	81 mg	1.5 mg
	Pb	0.074 kg	0.053 mg	0.98 µg
	PM_{10}	90 kg	64 mg	1,200 µg
I, Station Maintenance	Energy	3.3 TJ	2.4 MJ	0.044 MJ
	GHG	330 mt GGE	230 g GGE	4.3 g GGE
	SO_2	1,000 kg	720 mg	13 mg
	CO	2,700 kg	1,900 mg	36 mg
	NO_X	1,400 kg	980 mg	18 mg
	VOC	870 kg	620 mg	11 mg
	Pb	0.15 kg	0.11 mg	2.0 µg
	PM_{10}	180 kg	130 mg	2,300 µg
I, Station Cleaning	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-

Table 54 – Green Line Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Parking	Energy	1.4 TJ	1.0 MJ	0.019 MJ
	GHG	120 mt GGE	85 g GGE	1.6 g GGE
	SO_2	220 kg	160 mg	2.9 mg
	CO	430 kg	310 mg	5.7 mg
	NO_X	590 kg	420 mg	7.8 mg
	VOC	710 kg	500 mg	9.3 mg
	Pb	0.067 kg	0.048 mg	0.89 µg
	PM_{10}	270 kg	200 mg	3,600 µg
I, Track/Power Construction	Energy	11 TJ	8.0 MJ	0.15 MJ
	GHG	1,000 mt GGE	730 g GGE	13 g GGE
	SO_2	1,800 kg	1,300 mg	24 mg
	CO	9,800 kg	7,000 mg	130 mg
	NO_X	1,600 kg	1,200 mg	22 mg
	VOC	1,000 kg	720 mg	13 mg
	Pb	5.1 kg	3.7 mg	68 µg
	PM_{10}	990 kg	700 mg	13,000 µg
I, Track Maintenance	Energy	1.5 TJ	1.1 MJ	0.020 MJ
	GHG	110 mt GGE	80 g GGE	1.5 g GGE
	SO_2	74 kg	53 mg	0.98 mg
	CO	250 kg	180 mg	3.3 mg
	NO_X	520 kg	370 mg	6.8 mg
	VOC	54 kg	38 mg	0.71 mg
	Pb	-	-	-
	PM_{10}	54 kg	38 mg	710 µg
I, Insurance (Employees)	Energy	8.5 TJ	6.1 MJ	0.11 MJ
	GHG	700 mt GGE	500 g GGE	9.2 g GGE
	SO_2	1,700 kg	1,200 mg	23 mg
	CO	7,700 kg	5,500 mg	100 mg
	NO_X	1,900 kg	1,400 mg	25 mg
	VOC	1,400 kg	1,000 mg	19 mg
	Pb	-	-	-
	PM_{10}	360 kg	260 mg	4,800 µg
I, Insurance (Facilities)	Energy	5.4 TJ	3.8 MJ	0.071 MJ
	GHG	440 mt GGE	310 g GGE	5.8 g GGE
	SO_2	1,100 kg	770 mg	14 mg
	CO	4,900 kg	3,500 mg	64 mg
	NO_X	1,200 kg	870 mg	16 mg
	VOC	900 kg	640 mg	12 mg
	Pb	-	-	-
	PM_{10}	230 kg	160 mg	3,000 µg

Table 55 – CAHSR Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Construction	Energy	11 TJ	0.69 MJ	0.00090 MJ
	GHG	1,100 mt GGE	68 g GGE	0.090 g GGE
	SO_2	3,300 kg	210 mg	0.27 mg
	CO	8,800 kg	560 mg	0.74 mg
	NO_X	4,400 kg	280 mg	0.37 mg
	VOC	2,800 kg	180 mg	0.24 mg
	Pb	0.50 kg	0.032 mg	0.042 µg
	PM_{10}	570 kg	37 mg	48 µg
I, Station Lighting	Energy	0.15 TJ	0.0094 MJ	0.000012 MJ
	GHG	11 mt GGE	0.69 g GGE	0.00091 g GGE
	SO_2	58 kg	3.7 mg	0.0049 mg
	CO	5.6 kg	0.36 mg	0.00047 mg
	NO_X	4.2 kg	0.27 mg	0.00035 mg
	VOC	1.2 kg	0.080 mg	0.00010 mg
	Pb	0.000075 kg	0.0000048 mg	0.0000063 µg
	PM_{10}	0.63 kg	0.040 mg	0.053 µg
I, Station Escalators	Energy	0.066 TJ	0.0042 MJ	0.0000055 MJ
	GHG	4.8 mt GGE	0.31 g GGE	0.00041 g GGE
	SO_2	26 kg	1.6 mg	0.0022 mg
	CO	2.5 kg	0.16 mg	0.00021 mg
	NO_X	1.9 kg	0.12 mg	0.00016 mg
	VOC	0.56 kg	0.035 mg	0.000047 mg
	Pb	0.000034 kg	0.0000021 mg	0.0000028 µg
	PM_{10}	0.28 kg	0.018 mg	0.024 µg
I, Station Train Control	Energy	180 TJ	11 MJ	0.015 MJ
	GHG	13,000 mt GGE	830 g GGE	1.1 g GGE
	SO_2	69,000 kg	4,400 mg	5.8 mg
	CO	6,700 kg	430 mg	0.56 mg
	NO_X	5,000 kg	320 mg	0.42 mg
	VOC	1,500 kg	95 mg	0.13 mg
	Pb	0.090 kg	0.0057 mg	0.0076 µg
	PM_{10}	750 kg	48 mg	63 µg
I, Station Parking Lighting	Energy	19 TJ	1.2 MJ	0.0016 MJ
	GHG	1,400 mt GGE	90 g GGE	0.12 g GGE
	SO_2	7,500 kg	480 mg	0.63 mg
	CO	730 kg	46 mg	0.061 mg
	NO_X	540 kg	35 mg	0.046 mg
	VOC	160 kg	10 mg	0.014 mg
	Pb	0.0098 kg	0.00063 mg	0.00082 µg
	PM_{10}	82 kg	5.2 mg	6.9 µg
I, Station Miscellaneous	Energy	0.034 TJ	0.0022 MJ	0.0000029 MJ
	GHG	2.5 mt GGE	0.16 g GGE	0.00021 g GGE
	SO_2	13 kg	0.85 mg	0.0011 mg
	CO	1.3 kg	0.082 mg	0.00011 mg
	NO_X	0.96 kg	0.062 mg	0.000081 mg
	VOC	0.29 kg	0.018 mg	0.000024 mg
	Pb	0.000017 kg	0.0000011 mg	0.0000015 µg
	PM_{10}	0.14 kg	0.0093 mg	0.012 µg

Table 55 – CAHSR Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Maintenance	Energy	11 TJ	0.72 MJ	0.00095 MJ
	GHG	1,100 mt GGE	72 g GGE	0.094 g GGE
	SO_2	3,400 kg	220 mg	0.29 mg
	CO	9,300 kg	590 mg	0.78 mg
	NO_X	4,700 kg	300 mg	0.39 mg
	VOC	3,000 kg	190 mg	0.25 mg
	Pb	0.52 kg	0.034 mg	0.044 µg
	PM_{10}	600 kg	38 mg	50 µg
I, Station Cleaning	Energy	0.12 TJ	0.0074 MJ	0.0000098 MJ
	GHG	8.5 mt GGE	0.55 g GGE	0.00072 g GGE
	SO_2	46 kg	2.9 mg	0.0038 mg
	CO	4.4 kg	0.28 mg	0.00037 mg
	NO_X	3.3 kg	0.21 mg	0.00028 mg
	VOC	0.98 kg	0.063 mg	0.000082 mg
	Pb	0.000059 kg	0.0000038 mg	0.0000050 µg
	PM_{10}	0.49 kg	0.032 mg	0.042 µg
I, Station Parking	Energy	47 TJ	3.0 MJ	0.0040 MJ
	GHG	3,900 mt GGE	250 g GGE	0.33 g GGE
	SO_2	7,400 kg	470 mg	0.62 mg
	CO	14,000 kg	910 mg	1.2 mg
	NO_X	20,000 kg	1,300 mg	1.6 mg
	VOC	23,000 kg	1,500 mg	2.0 mg
	Pb	2.2 kg	0.14 mg	0.19 µg
	PM_{10}	9,100 kg	580 mg	760 µg
I, Track/Power Construction	Energy	3,800 TJ	240 MJ	0.32 MJ
	GHG	360,000 mt GGE	23,000 g GGE	30 g GGE
	SO_2	1,100,000 kg	69,000 mg	91 mg
	CO	3,000,000 kg	190,000 mg	250 mg
	NO_X	1,300,000 kg	86,000 mg	110 mg
	VOC	950,000 kg	61,000 mg	80 mg
	Pb	280 kg	18 mg	23 µg
	PM_{10}	190,000 kg	12,000 mg	16,000 µg
I, Track Maintenance	Energy	96 TJ	6.1 MJ	0.0081 MJ
	GHG	4,000 mt GGE	260 g GGE	0.34 g GGE
	SO_2	3,700 kg	240 mg	0.31 mg
	CO	1,900 kg	120 mg	0.16 mg
	NO_X	6,600 kg	420 mg	0.55 mg
	VOC	1,300 kg	83 mg	0.11 mg
	Pb	4.4 kg	0.28 mg	0.37 µg
	PM_{10}	1,100 kg	72 mg	94 µg
I, Insurance (Employees)	Energy	37 TJ	2.4 MJ	0.0031 MJ
	GHG	3,000 mt GGE	190 g GGE	0.26 g GGE
	SO_2	7,500 kg	480 mg	0.63 mg
	CO	34,000 kg	2,200 mg	2.8 mg
	NO_X	8,400 kg	540 mg	0.71 mg
	VOC	6,300 kg	400 mg	0.53 mg
	Pb	-	-	-
	PM_{10}	1,600 kg	100 mg	130 µg

Table 55 – CAHSR Infrastructure Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Insurance (Facilities)	Energy	33 TJ	2.1 MJ	0.0027 MJ
	GHG	2,700 mt GGE	170 g GGE	0.22 g GGE
	SO_2	6,600 kg	420 mg	0.55 mg
	CO	30,000 kg	1,900 mg	2.5 mg
	NO_X	7,400 kg	470 mg	0.62 mg
	VOC	5,500 kg	350 mg	0.46 mg
	Pb	-	-	-
	PM_{10}	1,400 kg	89 mg	120 µg

1.7.3 Fuels (Electricity and Diesel)

BART, Muni, Green Line, and CAHSR vehicles are powered by electricity while Caltrain uses diesel fuel. Infrastructure for all systems requires electricity as an input, in addition to vehicle propulsion energy. For each fuel type (electricity in California, the San Francisco Bay Area, and Massachusetts and diesel fuel), electricity and fuel production energy is evaluated. For electricity, transmission and distribution loses are included.

1.7.3.1 Electricity in California and Massachusetts

The energy required to produce a unit of electricity in each region has been evaluated [Deru 2007]. The authors define precombustion energy and emissions as resulting from extraction, processing, and delivering a fuel to the point of use in a power plant. These factors are shown in Table 56 per kilowatt-hour of delivered electricity. While Deru 2007 reports state factors, the PGE Bay Area specific electricity generation factors were determined from the fuel mix [PGE 2008]. Additionally, there is an 8.4% transmission and distribution loss in California (the Bay Area is assumed equivalent) and 9.6% in Massachusetts.

Table 56 – Electricity Generation Direct and Indirect Factors

	California		California (Bay Area)		Massachusetts	
Input/Output	**Precomb.**	**Comb.**	**Precomb.**	**Comb.**	**Precomb.**	**Comb.**
$kWh_{primary}$ / kWh	0.14	3.0	0.14	3.00	0.32	3.0
g CO_2e / kWh	63	290	48	220	69	560
mg SO_2 / kWh	1400	1500	1100	1200	840	3300
mg CO / kWh	95	150	81	130	240	630
mg NO_X / kWh	160	110	100	72	240	740
mg VOC / kWh	7.2	33	7.2	33	9.0	43
µg Pb / kWh	1.2	2.0	0.47	0.8	1.9	28
mg PM_{10} / kWh	4.7	17	3.8	14	6.7	34

Precomb. = Precombustion, Comb. = Combustion

The emissions from use of the delivered electricity are counted in the vehicle operational factors. Based on the precombustion factors and transmission and distribution losses, the electricity production supply chain inventory is determined. This is separated based on vehicle and infrastructure electricity consumption.

Table 57 – Rail Vehicle and Infrastructure Electricity Consumption (GWh/train-life)

	BART	Caltrain	Muni	Green Line	CAHSR
Vehicle Consumption	160	0.017	13	18	4,200
Infrastructure Consumption	8.0	14	5.7	5.6	54

Using the precombustion factors in Table 56, the transmission and distribution losses percentages, and the vehicle and infrastructure electricity consumption factors in Table 58, the electricity inventory is computed as shown in Equation Set 32.

Equation Set 32 – Rail Electricity Precombustion and Transmission and Distribution Losses

$$E^{system,component} = Annual\ Electricity\ Consumption\ for\ Component$$

$$E^{precombustion} = of\ Precombustion\ Energy\ Consumed\ of\ Delivered\ Electricity$$

$$EF^{s}_{I/O} = Electricity\ Production\ I/O\ for\ component\ s\ (per\ kWh)$$

$$where\ s \in \{precombustion, combustion\}$$

$$EM^{precombustion}_{I/O,total} = E^{system,component} \times E^{precombustion} \times EF^{precombustion}_{I/O}$$

$$I/O^{rail,electricity\ precombusion,component}_{train\ lifetime} = EM^{precombustion}_{I/O,total} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{lifetime_{train}}$$

$$I/O^{rail,electricity\ precombusion,component}_{VMT} = EM^{precombustion}_{I/O,total} \times \frac{yr}{VMT_{system}}$$

$$I/O^{rail,electricity\ precombusion,component}_{PMT} = EM^{precombustion}_{I/O,total} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}}$$

$$EM^{T\&D}_{I/O,total} = \left[\frac{E^{system,component} \times \left(1 - \%^{T\&D\ loss}\right)}{\%^{T\&D\ loss}}\right] \times EF^{combustion}_{I/O}$$

$$I/O^{rail,T\&D\ loss,component}_{train\ lifetime} = EM^{T\&D}_{I/O,total} \times \frac{yr_{system}}{VMT_{system}} \times \frac{VMT_{train}}{lifetime_{train}}$$

$$I/O^{rail,T\&D\ loss,component}_{VMT} = EM^{T\&D}_{I/O,total} \times \frac{yr_{system}}{VMT_{system}}$$

$$I/O^{rail,T\&D\ loss,component}_{PMT} = EM^{T\&D}_{I/O,total} \times \frac{yr_{system}}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}}$$

1.7.3.2 Diesel

The production of diesel fuel for Caltrain operations is handled with EIO-LCA using the sector Petroleum Refineries (#324110). This sector quantifies the direct requirements of producing the diesel fuel as well as the indirect requirements in the supply chain. Assuming a diesel fuel cost of \$0.72/gal (in \$1997 which excludes markups, marketing, and taxes), the total diesel fuel cost is input into EIO-LCA [EIA 2007, EIA 2007b, EIO-LCA 2008]. Normalization of inventory output from EIO-LCA to the functional units is the same as other methods which rely on EIO-LCA output.

Similar to onroad modes, the EIO-LCA fuel production sectors estimates energy inputs and emission outputs through the creation of the product. The distribution of diesel fuel from the refineries to the Caltrain fueling facilities is estimated separately. Following the methodology described in §1.6.3.2, it was assumed that the fuel is transported by tanker truck a distance of 100 miles. The tanker truck environmental performance is the same as that described for onroad modes.

1.7.3.3 Rail Fuels Results

Rail fuel results are summarized in the following tables.

Table 58 – BART Fuel Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
F, Supply Chain (Vehicles)	Energy	82 TJ	24 MJ	0.16 MJ
	GHG	1,100 mt GGE	320 g GGE	2.2 g GGE
	SO_2	25,000 kg	7,400 mg	51 mg
	CO	1,800 kg	540 mg	3.7 mg
	NO_X	2,300 kg	670 mg	4.6 mg
	VOC	160 kg	48 mg	0.33 mg
	Pb	0.011 kg	0.0031 mg	0.021 µg
	PM_{10}	87 kg	25 mg	170 µg
F, T&D Losses (Vehicles)	Energy	52 TJ	15 MJ	0.10 MJ
	GHG	310 mt GGE	90 g GGE	0.62 g GGE
	SO_2	1,700 kg	510 mg	3.5 mg
	CO	180 kg	51 mg	0.35 mg
	NO_X	100 kg	29 mg	0.20 mg
	VOC	46 kg	13 mg	0.092 mg
	Pb	0.0011 kg	0.00033 mg	0.0023 µg
	PM_{10}	19 kg	5.5 mg	38 µg
F, Supply Chain (Infrastructure)	Energy	4.1 TJ	1.2 MJ	0.0083 MJ
	GHG	55 mt GGE	16 g GGE	0.11 g GGE
	SO_2	1,300 kg	370 mg	2.6 mg
	CO	93 kg	27 mg	0.19 mg
	NO_X	120 kg	34 mg	0.23 mg
	VOC	8.2 kg	2.4 mg	0.016 mg
	Pb	0.00054 kg	0.00016 mg	0.0011 µg
	PM_{10}	4.4 kg	1.3 mg	8.7 µg
F, T&D Losses (Infrastructure)	Energy	2.6 TJ	0.77 MJ	0.0053 MJ
	GHG	16 mt GGE	4.6 g GGE	0.031 g GGE
	SO_2	88 kg	26 mg	0.18 mg
	CO	8.8 kg	2.6 mg	0.018 mg
	NO_X	5.1 kg	1.5 mg	0.010 mg
	VOC	2.3 kg	0.68 mg	0.0047 mg
	Pb	0.000057 kg	0.000017 mg	0.00011 µg
	PM_{10}	0.95 kg	0.28 mg	1.9 µg

Table 59 – Caltrain Fuel Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
F, Supply Chain (Vehicles)	Energy	27 TJ	22 MJ	0.14 MJ
	GHG	2,400 mt GGE	2,000 g GGE	13 g GGE
	SO_2	4,600 kg	3,700 mg	24 mg
	CO	6,700 kg	5,400 mg	35 mg
	NO_X	4,000 kg	3,200 mg	21 mg
	VOC	2,900 kg	2,400 mg	15 mg
	Pb	-	-	-
	PM_{10}	650 kg	520 mg	3,400 µg
F, T&D Losses (Vehicles)	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-
F, Supply Chain (Infrastructure)	Energy	7.3 TJ	5.9 MJ	0.038 MJ
	GHG	97 mt GGE	79 g GGE	0.51 g GGE
	SO_2	2,200 kg	1,800 mg	12 mg
	CO	160 kg	130 mg	0.85 mg
	NO_X	200 kg	170 mg	1.1 mg
	VOC	14 kg	12 mg	0.076 mg
	Pb	0.00094 kg	0.00076 mg	0.0049 µg
	PM_{10}	7.7 kg	6.2 mg	40 µg
F, T&D Losses (Infrastructure)	Energy	4.6 TJ	3.7 MJ	0.024 MJ
	GHG	27 mt GGE	22 g GGE	0.14 g GGE
	SO_2	150 kg	120 mg	0.80 mg
	CO	16 kg	13 mg	0.081 mg
	NO_X	8.9 kg	7.2 mg	0.047 mg
	VOC	4.1 kg	3.3 mg	0.021 mg
	Pb	0.000100 kg	0.000081 mg	0.00052 µg
	PM_{10}	1.7 kg	1.4 mg	8.8 µg

Table 60 – Muni Fuel Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
F, Supply Chain (Vehicles)	Energy	6.7 TJ	3.9 MJ	0.18 MJ
	GHG	89 mt GGE	52 g GGE	2.4 g GGE
	SO_2	2,100 kg	1,200 mg	54 mg
	CO	150 kg	87 mg	4.0 mg
	NO_X	190 kg	110 mg	5.0 mg
	VOC	13 kg	7.7 mg	0.35 mg
	Pb	0.00086 kg	0.00050 mg	0.023 µg
	PM_{10}	7.0 kg	4.1 mg	190 µg
F, T&D Losses (Vehicles)	Energy	4.3 TJ	2.5 MJ	0.11 MJ
	GHG	25 mt GGE	15 g GGE	0.67 g GGE
	SO_2	140 kg	82 mg	3.7 mg
	CO	14 kg	8.3 mg	0.38 mg
	NO_X	8.2 kg	4.8 mg	0.22 mg
	VOC	3.8 kg	2.2 mg	0.100 mg
	Pb	0.000092 kg	0.000053 mg	0.0024 µg
	PM_{10}	1.5 kg	0.89 mg	41 µg
F, Supply Chain (Infrastructure)	Energy	2.9 TJ	1.7 MJ	0.078 MJ
	GHG	39 mt GGE	23 g GGE	1.0 g GGE
	SO_2	910 kg	530 mg	24 mg
	CO	66 kg	38 mg	1.7 mg
	NO_X	83 kg	48 mg	2.2 mg
	VOC	5.9 kg	3.4 mg	0.16 mg
	Pb	0.00038 kg	0.00022 mg	0.010 µg
	PM_{10}	3.1 kg	1.8 mg	82 µg
F, T&D Losses (Infrastructure)	Energy	1.9 TJ	1.1 MJ	0.050 MJ
	GHG	11 mt GGE	6.5 g GGE	0.30 g GGE
	SO_2	62 kg	36 mg	1.7 mg
	CO	6.3 kg	3.7 mg	0.17 mg
	NO_X	3.6 kg	2.1 mg	0.096 mg
	VOC	1.7 kg	0.96 mg	0.044 mg
	Pb	0.000041 kg	0.000024 mg	0.0011 µg
	PM_{10}	0.68 kg	0.39 mg	18 µg

Table 61 – Green Line Fuel Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
F, Supply Chain (Vehicles)	Energy	21 TJ	15 MJ	0.28 MJ
	GHG	410 mt GGE	290 g GGE	5.4 g GGE
	SO_2	5,000 kg	3,600 mg	66 mg
	CO	1,400 kg	1,000 mg	19 mg
	NO_X	1,400 kg	1,000 mg	19 mg
	VOC	54 kg	38 mg	0.71 mg
	Pb	0.011 kg	0.0081 mg	0.15 µg
	PM_{10}	40 kg	28 mg	520 µg
F, T&D Losses (Vehicles)	Energy	7.0 TJ	5.0 MJ	0.093 MJ
	GHG	110 mt GGE	75 g GGE	1.4 g GGE
	SO_2	630 kg	450 mg	8.2 mg
	CO	120 kg	85 mg	1.6 mg
	NO_X	140 kg	99 mg	1.8 mg
	VOC	8.0 kg	5.7 mg	0.11 mg
	Pb	0.0052 kg	0.0037 mg	0.069 µg
	PM_{10}	6.3 kg	4.5 mg	83 µg
F, Supply Chain (Infrastructure)	Energy	6.5 TJ	4.6 MJ	0.086 MJ
	GHG	120 mt GGE	89 g GGE	1.6 g GGE
	SO_2	1,500 kg	1,100 mg	20 mg
	CO	430 kg	300 mg	5.6 mg
	NO_X	430 kg	310 mg	5.7 mg
	VOC	16 kg	12 mg	0.21 mg
	Pb	0.0034 kg	0.0025 mg	0.045 µg
	PM_{10}	12 kg	8.6 mg	160 µg
F, T&D Losses (Infrastructure)	Energy	2.1 TJ	1.5 MJ	0.028 MJ
	GHG	32 mt GGE	23 g GGE	0.42 g GGE
	SO_2	190 kg	140 mg	2.5 mg
	CO	36 kg	26 mg	0.47 mg
	NO_X	42 kg	30 mg	0.56 mg
	VOC	2.4 kg	1.7 mg	0.032 mg
	Pb	0.0016 kg	0.0011 mg	0.021 µg
	PM_{10}	1.9 kg	1.4 mg	25 µg

Table 62 – CAHSR Fuel Inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
F, Supply Chain (Vehicles)	Energy	2,200 TJ	140 MJ	0.18 MJ
	GHG	38,000 mt GGE	2,400 g GGE	3.2 g GGE
	SO_2	840,000 kg	53,000 mg	70 mg
	CO	58,000 kg	3,700 mg	4.9 mg
	NO_X	95,000 kg	6,100 mg	8.0 mg
	VOC	4,400 kg	280 mg	0.37 mg
	Pb	0.70 kg	0.045 mg	0.059 µg
	PM_{10}	2,900 kg	180 mg	240 µg
F, T&D Losses (Vehicles)	Energy	1,400 TJ	89 MJ	0.12 MJ
	GHG	9,400 mt GGE	600 g GGE	0.79 g GGE
	SO_2	50,000 kg	3,200 mg	4.2 mg
	CO	4,800 kg	310 mg	0.41 mg
	NO_X	3,600 kg	230 mg	0.30 mg
	VOC	1,100 kg	69 mg	0.091 mg
	Pb	0.065 kg	0.0042 mg	0.0055 µg
	PM_{10}	550 kg	35 mg	46 µg
F, Supply Chain (Infrastructure)	Energy	28 TJ	1.8 MJ	0.0024 MJ
	GHG	490 mt GGE	31 g GGE	0.041 g GGE
	SO_2	11,000 kg	690 mg	0.90 mg
	CO	740 kg	48 mg	0.063 mg
	NO_X	1,200 kg	78 mg	0.10 mg
	VOC	56 kg	3.6 mg	0.0047 mg
	Pb	0.0090 kg	0.00058 mg	0.00076 µg
	PM_{10}	37 kg	2.3 mg	3.1 µg
F, T&D Losses (Infrastructure)	Energy	18 TJ	1.2 MJ	0.0015 MJ
	GHG	120 mt GGE	7.7 g GGE	0.010 g GGE
	SO_2	650 kg	41 mg	0.054 mg
	CO	62 kg	4.0 mg	0.0052 mg
	NO_X	47 kg	3.0 mg	0.0039 mg
	VOC	14 kg	0.89 mg	0.0012 mg
	Pb	0.00084 kg	0.000054 mg	0.000071 µg
	PM_{10}	7.0 kg	0.45 mg	0.59 µg

1.7.4 Fundamental Environmental Factors for Rail

The fundamental environmental factors for the rail modes are shown in Table 63. These factors are the bases for the component’s environmental inventory calculations.

Table 63 – Fundamental Environmental Factors for Rail Modes **(Sources, Energy, and GHG)**
Vehicle and Fuel Components

Grouping	Component	Source	Energy		GHG (CO$_2$e)	
Vehicles						
Manufacturing	BART/Caltrain	SimaPro 2006 (Long Distance Train)	30	TJ/train	1841	mt/train
	Muni	SimaPro 2006 (LRT w/CA Mix)	7	TJ/train	338	mt/train
	Green Line	SimaPro 2006 (LRT w/MA Mix)	7	TJ/train	373	mt/train
	CAHSR	SimaPro 2006 (High Speed Train)	44	TJ/train	2127	mt/train
BART Operation	Propulsion	Fels 1978, Healy 1973, Deru 2007	28	kWh/VMT	10	kg/VMT
	Idling	Fels 1978, Healy 1973, Deru 2007	14	kWh/VMT	5	kg/VMT
	Auxiliaries	Fels 1978, Healy 1973, Deru 2007	3.9	kWh/VMT	1	kg/VMT
Caltrain Operation	Propulsion	Fritz 1994, Caltrain 2007c, Fels 1978, Healy 1973	41	kWh/VMT	10	kg/VMT
	Idling	Fritz 1994, Caltrain 2007c, Fels 1978, Healy 1973	2.4	kWh/VMT	0.6	kg/VMT
	Auxiliaries	Fritz 1994, Caltrain 2007c, Fels 1978, Healy 1973	2.1	kWh/VMT	0.5	kg/VMT
Muni Operation	Propulsion	FTA 2005, Fels 1978, Healy 1973, Deru 2007	4.4	kWh/VMT	1.6	kg/VMT
	Idling	FTA 2005, Fels 1978, Healy 1973, Deru 2007	1.1	kWh/VMT	0.4	kg/VMT
	Auxiliaries	FTA 2005, Fels 1978, Healy 1973, Deru 2007	2.3	kWh/VMT	0.8	kg/VMT
Green Line Operation	Propulsion	FTA 2005, Fels 1978, Healy 1973, Deru 2007	7.9	kWh/VMT	5.0	kg/VMT
	Idling	FTA 2005, Fels 1978, Healy 1973, Deru 2007	4.0	kWh/VMT	2.5	kg/VMT
	Auxiliaries	FTA 2005, Fels 1978, Healy 1973, Deru 2007	1.2	kWh/VMT	0.8	kg/VMT
CAHSR Operation	Propulsion	Anderrson 2006, Fels 1978, Healy 1973, Deru 2007	251	kWh/VMT	88	kg/VMT
	Idling	Anderrson 2006, Fels 1978, Healy 1973, Deru 2007	6.3	kWh/VMT	2.2	kg/VMT
	Auxiliaries	Anderrson 2006, Fels 1978, Healy 1973, Deru 2007	14	kWh/VMT	4.8	kg/VMT
Maintenance	BART/Caltrain	SimaPro 2006 (Long Distance Train)	25	TJ/life	1128	mt/life
	Muni	SimaPro 2006 (LRT w/CA Mix)	1.3	TJ/life	64	mt/life
	Green Line	SimaPro 2006 (LRT w/MA Mix)	1.4	TJ/life	68	mt/life
	CAHSR	SimaPro 2006 (High Speed Train)	28	TJ/life	1329	mt/life
Cleaning	Vacuuming (BA)	EERE 2007b, BuiLCA 2007, PGE 2008, Deru 2007	1.1	Wh/ft^2	271	g/kWh
	Vacuuming (CA)	EERE 2007b, BuiLCA 2007, Deru 2007	1.1	Wh/ft^2	351	g/kWh
	Vacuuming (MA)	EERE 2007b, BuiLCA 2007, Deru 2007	1.1	Wh/ft^2	632	g/kWh
Flooring Replacement	Carpet Production	EIO-LCA 2008 (#314110)	15	TJ/$M	1140	mt/$M
Insurances	Benefits & Liability	EIO-LCA 2008 (#524100)	1.0	TJ/$M	84	mt/$M
Fuels						
Electricity Production	Bay Area Mix	PGE 2008, Deru 2007			271	g/kWh
	California Mix	Deru 2007			351	g/kWh
	Massachusetts Mix	Deru 2007			632	g/kWh
Diesel Production	Fuel Refining	EIO-LCA 2008 (#324110)	18	MJ/gal	1.6	kg/gal

Table 63 – Fundamental Environmental Factors for Rail Modes (Sources, Energy, and GHG)

Infrastructure Components (cont’d)

Grouping	Component	Source	Energy		GHG (CO_2e)	
Infrastructure						
Station Construction	Concrete Production	EIO-LCA 2008 (#327320), WSDOT 2007b	6.5	GJ/yd^3	609	kg/yd^3
	Concrete Placement	Guggemos 2005	5.7	MJ/yd^3	35	kg/yd^3
	Steel Production	EIO-LCA 2008 (#331111), USGS 2007	5.9	MJ/yd^3	543	g/yd^3
Station Lighting	BART	Fels 1978, BART 2006	450,000	kWh/yr	351	g/kWh
(per station)	Caltrain	Fels 1978	120,000	kWh/yr	351	g/kWh
	Muni	Fels 1978, FTA 2005	2,600	kWh/yr	351	g/kWh
	Green Line	Observation, EERE 2002	2,600	kWh/yr	632	g/kWh
	CAHSR	Fels 1978	120,000	kWh/yr	351	g/kWh
Station Escalators	BART	Fels 1978, BART 2006	280,000	kWh/yr	351	g/kWh
(per station)	Caltrain	EERE 2007, FTA 2005	4.7	kW	351	g/kWh
	Muni	EERE 2007, FTA 2005	4.7	kW	351	g/kWh
	Green Line	EERE 2007, FTA 2005	4.7	kW	632	g/kWh
	CAHSR	EERE 2007, FTA 2005	4.7	kW	351	g/kWh
Train Control	BART	Fels 1978, BART 2006	190,000	kWh/yr	351	g/kWh
(per station)	Caltrain	Fels 1978	210,000	kWh/yr	351	g/kWh
	Muni	Fels 1978, FTA 2005	130,000	kWh/yr	351	g/kWh
	Green Line	Fels 1978, FTA 2005	52,000	kWh/yr	632	g/kWh
	CAHSR	Fels 1978	2,800,000	kWh/yr	351	g/kWh
Parking Lighting	BART	Estimation	0.9	kWh/ft^2-yr	351	g/kWh
(per station)	Caltrain	Estimation	0.9	kWh/ft^2-yr	351	g/kWh
	Green Line	Estimation	0.9	kWh/ft^2-yr	632	g/kWh
	CAHSR	Estimation	0.9	kWh/ft^2-yr	351	g/kWh
Station	BART	Fels 1978, BART 2006	47,000	kWh/yr	351	g/kWh
Miscellaneous	Caltrain	Fels 1978	27,000	kWh/yr	351	g/kWh
(per station)	Muni	Fels 1978, FTA 2005	160,000	kWh/yr	351	g/kWh
	Green Line	Fels 1978, FTA 2005	160,000	kWh/yr	632	g/kWh
	CAHSR	Fels 1978	27,000	kWh/yr	351	g/kWh
Station Maintenance	For all systems, assumed 5% of station construction.					
Station Cleaning	Mopping, BA Mix	Paulsen 2003, PGE 2008, Deru 2007	0.6	kWh/ft^2-yr	0.2	kg/ft^2-yr
	Mopping, CA Mix	Paulsen 2003, Deru 2007	0.6	kWh/ft^2-yr	0.2	kg/ft^2-yr
	Mopping, MA Mix	Paulsen 2003, Deru 2007	0.6	kWh/ft^2-yr	0.4	kg/ft^2-yr
Parking	BART	PaLATE 2004, EPA 2001	80	MJ/ft^2	6.7	kg/ft^2
	Caltrain	PaLATE 2004, EPA 2001	80	MJ/ft^2	6.7	kg/ft^2
	Green Line	PaLATE 2004, EPA 2001	80	MJ/ft^2	6.7	kg/ft^2
	CAHSR	PaLATE 2004, EPA 2001	80	MJ/ft^2	6.7	kg/ft^2
Track &	Aggregate Production	EIO-LCA 2008 (#212320), USGS 2007	193	MJ/ton	14	kg/ton
Power	Concrete Production	EIO-LCA 2008 (#327320), WSDOT 2007b	6,500	MJ/yd^3	609	kg/yd^3
Delivery	Concrete Placement	Guggemos 2005	5.7	MJ/yd^3	35	kg/yd^3
	Steel Production	EIO-LCA 2008 (#331111), USGS 2007	5.9	MJ/yd^3	543	g/yd^3
	Wood Production	EIO-LCA 2008 (#321113), Gauntt 2000	138	MJ/tie	12	kg/tie
	Power Structure Production	EIO-LCA 2008 (#335929)	9	TJ/$M	728	mt/$M
	Substation Production	EIO-LCA 2008 (#335311)	10	TJ/$M	807	mt/$M
Track Maintenance	For all systems, assumed 5% of track construction.					
Insurances	Benefits & Liability	EIO-LCA 2008 (#524100)	1.0	TJ/$M	84	mt/$M

Table 63 – Fundamental Environmental Factors for Rail Modes (cont'd)

Vehicle and Fuel Components

(CAP)

Grouping	Component	SO_2		CO		NO_X		VOC		Pb		PM_{10}	
Vehicles													
Manufacturing	BART/Caltrain	6.9	mt/train	2.1	mt/train	3.8	mt/train	1.0	mt/train	8.0	mt/train	1.9	mt/train
	Muni	1.7	mt/train	2.8	mt/train	1.0	mt/train	0.2	mt/train	6.8	mt/train	0.7	mt/train
	Green Line	1.9	mt/train	2.8	mt/train	1.1	mt/train	0.3	mt/train	6.7	mt/train	0.7	mt/train
	CAHSR	10	mt/train	8.4	mt/train	5.6	mt/train	1.7	mt/train	25	mt/train	3.1	mt/train
BART Operation	Propulsion	81	g/VMT	6.8	g/VMT	7.5	g/VMT	1.1	g/VMT			0.60	g/VMT
	Idling	41	g/VMT	3.5	g/VMT	3.8	g/VMT	0.6	g/VMT			0.31	g/VMT
	Auxiliaries	11	g/VMT	0.9	g/VMT	1.0	g/VMT	0.2	g/VMT			0.08	g/VMT
Caltrain Operation	Propulsion	0.0	g/VMT	10	g/VMT	190	g/VMT	5.9	g/VMT			5.1	g/VMT
	Idling	0.0	g/VMT	1	g/VMT	12	g/VMT	1.6	g/VMT			0.5	g/VMT
	Auxiliaries	0.0	g/VMT	0.5	g/VMT	10	g/VMT	0.3	g/VMT			0.3	g/VMT
Muni Operation	Propulsion	13	g/VMT	1.1	g/VMT	1.2	g/VMT	0.2	g/VMT			0.10	g/VMT
	Idling	3.3	g/VMT	0.3	g/VMT	0.3	g/VMT	0.0	g/VMT			0.02	g/VMT
	Auxiliaries	6.6	g/VMT	0.6	g/VMT	0.6	g/VMT	0.1	g/VMT			0.05	g/VMT
Green Line Operation	Propulsion	33	g/VMT	6.9	g/VMT	7.8	g/VMT	0.4	g/VMT			0.32	g/VMT
	Idling	17	g/VMT	3.5	g/VMT	3.9	g/VMT	0.2	g/VMT			0.16	g/VMT
	Auxiliaries	5	g/VMT	1.0	g/VMT	1.2	g/VMT	0.1	g/VMT			0.05	g/VMT
CAHSR Operation	Propulsion	731	g/VMT	61	g/VMT	67	g/VMT	10	g/VMT			5.37	g/VMT
	Idling	18	g/VMT	1.5	g/VMT	1.7	g/VMT	0.3	g/VMT			0.13	g/VMT
	Auxiliaries	39	g/VMT	3.3	g/VMT	3.6	g/VMT	0.5	g/VMT			0.29	g/VMT
Maintenance	BART/Caltrain	3.1	mt/life	2.8	mt/life	2.6	mt/life	4.1	mt/life	11	mt/life	0.8	mt/life
	Muni	0.2	mt/life	0.2	mt/life	0.2	mt/life	0.1	mt/life	1.4	mt/life	0.1	mt/life
	Green Line	0.2	mt/life	0.2	mt/life	0.2	mt/life	0.1	mt/life	1.4	mt/life	0.1	mt/life
	CAHSR	1	mt/life	2.6	mt/life	2.5	mt/life	4.0	mt/life	2	mt/life	0.4	mt/life
Cleaning	Vacuuming (BA)	2353	mg/kWh	206	mg/kWh	174	mg/kWh	40	mg/kWh			17	mg/kWh
	Vacuuming (CA)	2910	mg/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh			21	mg/kWh
	Vacuuming (MA)	4170	mg/kWh	867	mg/kWh	979	mg/kWh	52	mg/kWh			40	mg/kWh
Flooring	Carpet Production	2.1	mt/$M	11	mt/$M	2.1	mt/$M	1.9	mt/$M	1.0	kg/$M	0.7	mt/$M
Insurances	Benefits & Liability	207	kg/$M	934	kg/$M	233	kg/$M	173	kg/$M	0	kg/$M	44	kg/$M
Fuels													
Electricity	Bay Area	2353	mg/kWh	206	mg/kWh	174	mg/kWh	40	mg/kWh			17	mg/kWh
	CA	2910	mg/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh			21	mg/kWh
	MA	4170	mg/kWh	867	mg/kWh	979	mg/kWh	52	mg/kWh			40	mg/kWh
Diesel	Fuel Refining	3.0	g/gal	4.3	g/gal	1.8	g/gal	2.0	g/gal			0.3	g/gal

Table 63 – Fundamental Environmental Factors for Rail Modes (cont'd)

Infrastructure Components

(CAP)

Grouping	Component	SO_2		CO		NO_X		VOC		Pb		PM_{10}	
Infrastructure													
Station	Concrete Production	1.9	kg/yd^3	5.1	kg/yd^3	2.4	kg/yd^3	1.7	kg/yd^3			309	g/yd^3
Construction	Concrete Placement	82	g/yd^3	241	g/yd^3	312	g/yd^3	12	g/yd^3			35	g/yd^3
	Steel Production	0.9	g/yd^3	5.0	g/yd^3	0.9	g/yd^3	0.5	g/yd^3			0.5	g/yd^3
Station	BART	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
Lighting	Caltrain	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
(per station)	Muni	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
	Green Line	4.2	g/kWh	867	mg/kWh	979	mg/kWh	52	mg/kWh	30	µg/kWh	40	mg/kWh
	CAHSR	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
Station	BART	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
Escalators	Caltrain	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
(per station)	Muni	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
	Green Line	4.2	g/kWh	867	mg/kWh	979	mg/kWh	52	mg/kWh	30	µg/kWh	40	mg/kWh
	CAHSR	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
Train	BART	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
Control	Caltrain	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
(per station)	Muni	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
	Green Line	4.2	g/kWh	867	mg/kWh	979	mg/kWh	52	mg/kWh	30	µg/kWh	40	mg/kWh
	CAHSR	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
Parking	BART	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
Lighting	Caltrain	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
(per station)	Green Line	4.2	g/kWh	867	mg/kWh	979	mg/kWh	52	mg/kWh	30	µg/kWh	40	mg/kWh
	CAHSR	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
Station	BART	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
Miscellaneous	Caltrain	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
(per station)	Muni	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
	Green Line	4.2	g/kWh	867	mg/kWh	979	mg/kWh	52	mg/kWh	30	µg/kWh	40	mg/kWh
	CAHSR	2.9	g/kWh	243	mg/kWh	267	mg/kWh	40	mg/kWh	3.2	µg/kWh	21	mg/kWh
Station Maintenance	For all systems, assumed 5% of station construction.												
Station	Mopping (BA)	1.3	g/ft^2-yr	0.1	g/ft^2-yr	0.1	g/ft^2-yr	0.02	g/ft^2-yr			0.01	g/ft^2-yr
Cleaning	Mopping (CA)	1.7	g/ft^2-yr	0.1	g/ft^2-yr	0.2	g/ft^2-yr	0.02	g/ft^2-yr			0.01	g/ft^2-yr
	Mopping (MA)	2	g/ft^2-yr	0.5	g/ft^2-yr	0.6	g/ft^2-yr	0.03	g/ft^2-yr			0.02	g/ft^2-yr
Parking	BART	13	g/ft^2	24	g/ft^2	33	g/ft^2	40	g/ft^2	3.8	mg/ft^2	15	g/ft^2
	Caltrain	13	g/ft^2	24	g/ft^2	33	g/ft^2	40	g/ft^2	3.8	mg/ft^2	15	g/ft^2
	Green Line	13	g/ft^2	24	g/ft^2	33	g/ft^2	40	g/ft^2	3.8	mg/ft^2	15	g/ft^2
	CAHSR	13	g/ft^2	24	g/ft^2	33	g/ft^2	40	g/ft^2	3.8	mg/ft^2	15	g/ft^2
Track &	Aggregate Production	30	g/ton	38	g/ton	20	g/ton	8	g/ton			3	g/ton
Power	Concrete Production	1900	g/yd^3	5100	g/yd^3	2400	g/yd^3	1700	g/yd^3			310	g/yd^3
Delivery	Concrete Placement	82	g/yd^3	241	g/yd^3	312	g/yd^3	12	g/yd^3			35	g/yd^3
	Steel Production	0.9	g/yd^3	5.0	g/yd^3	0.9	g/yd^3	0.5	g/yd^3			0.5	g/yd^3
	Wood Production	22	g/tie	626	g/tie	39	g/tie	87	g/tie			83	g/tie
	Power Structure Production	3.3	mt/$M	8.3	mt/$M	1.8	mt/$M	1.7	mt/$M	5	kg/$M	0.7	mt/$M
	Substation Production	1.8	mt/$M	7.8	mt/$M	1.6	mt/$M	1.3	mt/$M	3	kg/$M	0.6	mt/$M
Track Maintenance	For all systems, assumed 5% of track construction												
Insurances	Benefits & Liability	207	kg/$M	934	kg/$M	233	kg/$M	173	kg/$M			44	kg/$M

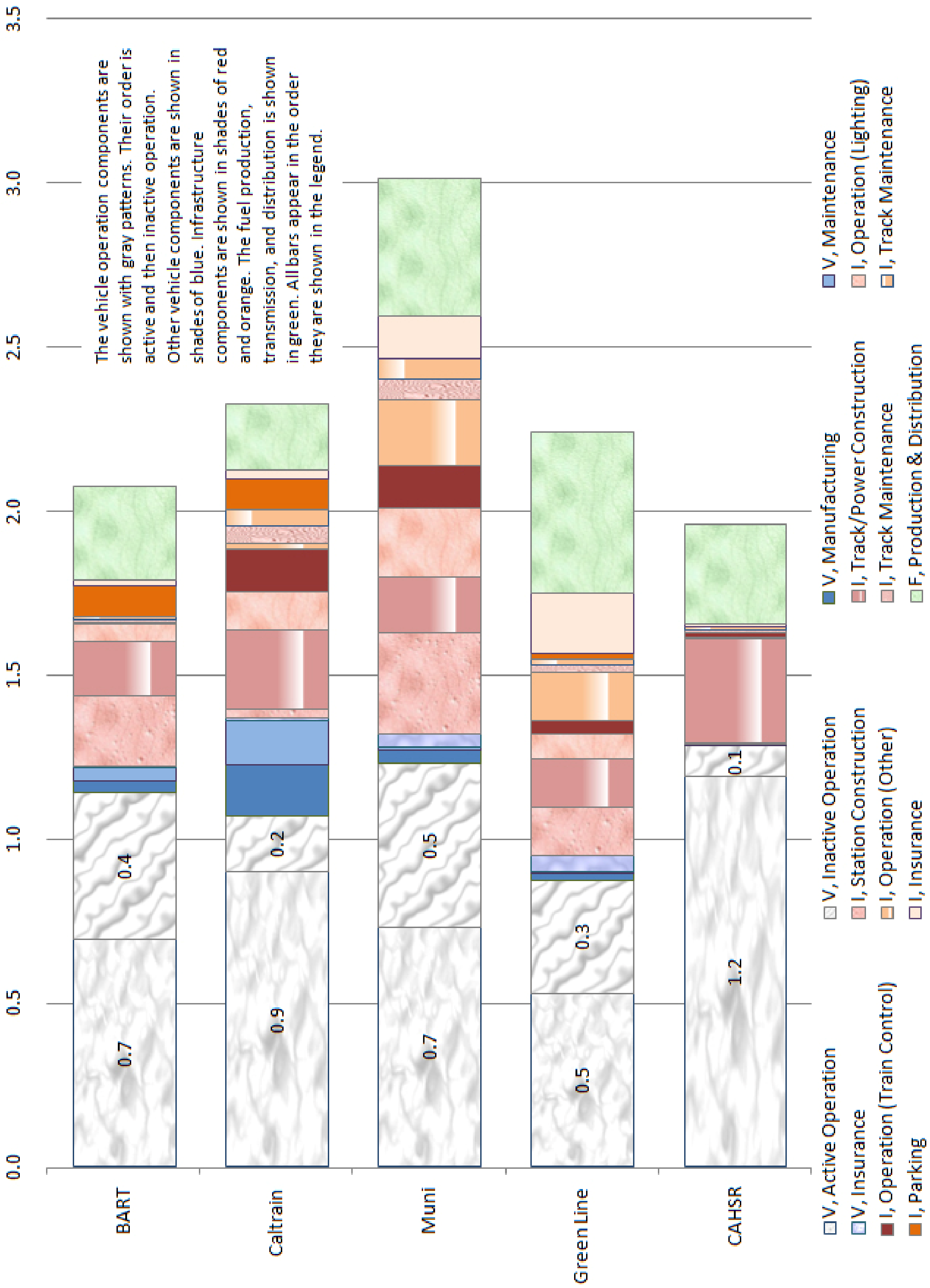
1.7.5 Rail Summary

All rail systems experience significant energy and emission contributions from non-operational phases. For energy inputs and GHG emissions, the non-operational life-cycle components account for around 50% of total effects (except for CAHSR) meaning that there was a doubling of effects when life-cycle impacts are accounted for. The inclusion of infrastructure components significantly increases the emissions of CAP. The following subsections identify the major life-cycle component contributors to energy consumption, GHG emissions, and CAP emissions for each system.

1.7.5.1 Energy and GHG Emissions

While 26 life-cycle components are included in the rail inventory, only a few have major contributions to total energy consumption and GHG emissions for the systems. These are vehicle manufacturing, station construction, track and power delivery construction, station lighting, station maintenance, miscellaneous station electricity consumption, fuel production, transmission and distribution losses, and insurance. Figure 10 shows the rail energy inventory for each of the five modes normalized to MJ per passenger-mile. Figure 11 shows the same for the GHG emissions inventory.

Figure 10 – Rail Travel Energy Inventory (MJ/PMT)



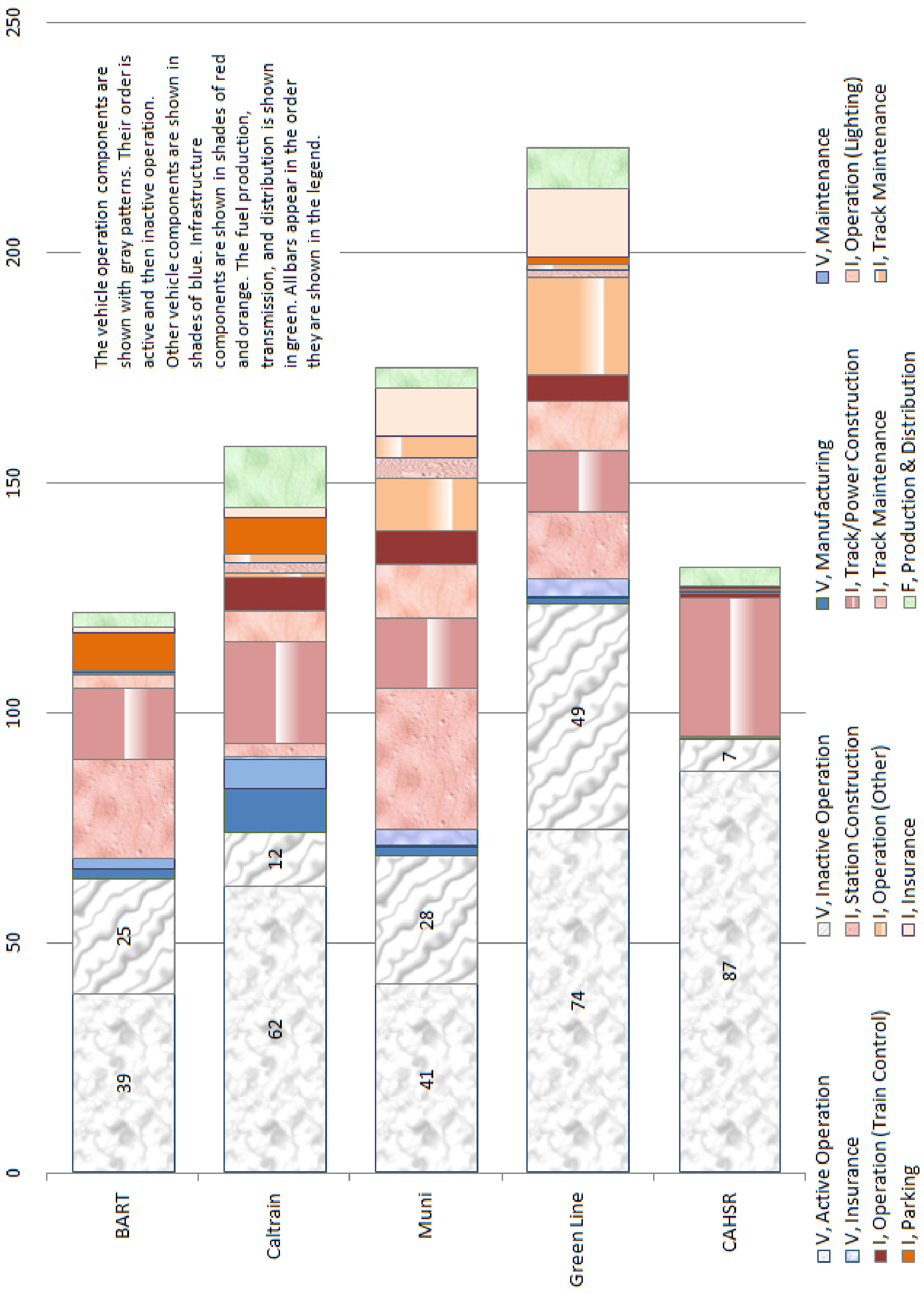
The vehicle operation components are shown with gray patterns. Their order is active and then inactive operation. Other vehicle components are shown in shades of blue. Infrastructure components are shown in shades of red and orange. The fuel production, transmission, and distribution is shown in green. All bars appear in the order they are shown in the legend.

Vehicle Operation

Before discussing the life-cycle components, it is interesting to consider the disaggregation of operational components. Total operational energy consumption for BART, Muni, Caltrain, and the Green Line average 1.1 MJ/PMT with CAHSR at 1.3 MJ/PMT. Disaggregating the three components of this total operational energy (propulsion, idling, and auxiliaries) shows how that energy is used. For the four commuter modes, propulsion energy accounts for between 59% and 84%, idling is between 11% and 31%, and auxiliaries are between 4% and 10%. While CAHSR stands by itself as a long distance atypical rail system, the other four exhibit more similar operational characteristics. These percentages are essentially the same for BART, Muni, and the Green Line while Caltrain consumes most of its operational energy in propulsion. This is due to the use of diesel as its primary fuel instead of electricity and the efficiencies and weight of the train.

Similar characteristics hold with GHG emissions; however, the more fossil fuel intense electricity mix in Massachusetts increases the effects of the Green Line in comparison to the California Muni system.

Figure 11 – Rail Travel GHG Emission Inventory



The vehicle operation components are shown with gray patterns. Their order is active and then inactive operation. Other vehicle components are shown in shades of blue. Infrastructure components are shown in shades of red and orange. The fuel production, transmission, and distribution is shown in green. All bars appear in the order they are shown in the legend.

Vehicle Manufacturing

Train production shows in each of the 4 commuter modes and most significantly with Caltrain since it is one of the most materials intensive vehicles. The construction of the Caltrain train (including locomotive and passenger cars) requires 30 TJ while BART requires 19 TJ, Muni 1.4, the Green Line 1.6, and CAHSR 15 TJ. The energy required to produce the trains is largely the result of the electricity at the manufacturing facility and the energy required to produce the primary metals in the cars [SimaPro 2006]. Per PMT, emissions from production of the trains (1,800 mt CO_2e for Caltrain, 1,100 mt CO_2e for BART, 71 mt CO_2e for Muni, 85 mt CO_2e for the Green Line, and 700 mt CO_2e for CAHSR) is largest for Caltrain on a per passenger-mile bases but also non-negligible for Muni and the Green Line.

Station Construction

For BART, Muni, and the Green Line, station construction shows as a large contributor to total energy consumption due to large energy requirements in concrete production. BART's extensive station infrastructure requires 26M ft^3 of concrete, approximately 5 times as much as Muni and the Green Line, 50 times as much as Caltrain, and 25 times as much as CAHSR. Muni and the Green Line have similar concrete requirements (essentially due to the underground stations) resulting in 0.3 and 0.1 MJ/PMT. The release of CO_2 in cement production is the main reason for GHG emissions in track production. For every tonne of cement produced, approximately ½ tonne of CO_2 is emitted directly.

Track and Power Delivery Construction

The extensive use of concrete in BART and Caltrain track infrastructure and steel manufacturing for tracks in Muni and the Green Line contribute to life-cycle energy consumption. CASHR, however, shows the largest component contributor to total effects per PMT. For BART, aerial tracks and retaining walls made of concrete are the largest contributors. For Caltrain, the use of concrete ties has the largest effect. For Muni and the Green Line, the steel production alone for tracks has significant life-cycle energy contribution. Similar to station construction, the production of concrete is the main reason for such high GHG emissions in the BART and Caltrain systems. For Muni and the Green Line, emissions are driven by the production of steel for the tracks. CAHSR requires 0.3 MJ and emits 30 g CO_2e per PMT which is about 16% of total effects.

Station Lighting and Miscellaneous Station Electricity

Electricity for station lighting is a major contributor to overall energy consumption for Muni, the Green Line, and Caltrain. For Muni and the Green Line, station lighting results primarily from the few underground stations which must be lit all day. Surface stations have a small contribution to the overall lighting requirement.

Miscellaneous station electricity appears with Muni and the Green Line due to the electricity consumption of traffic lights and cross signals at street-level stations. These two systems, since constructed on roadways, require these traffic and pedestrian measures where roads intersect tracks and cars and people must cross in rail traffic. The street lamps consume 3.6 kW and the pedestrian cross signals 1 kW [EERE 2002]. They are assumed to operate 24 hours per day.

Station Maintenance

The reconstruction of stations affects the BART, Muni, and Green Line systems. Again, BART's extensive use of concrete in stations which is replaced after an estimated 80 years has strong energy and GHG implications. For Muni and the Green Line, the effects of station reconstruction are due primarily to the handful of underground stations which are much more material intensive than surface level stations.

Fuel Production and Transmission and Distribution Losses

The precombustion electricity factors shown in Table 56 result in an instantaneous 10% increase in California and 32% increase in Massachusetts [Deru 2007]. This increases the energy consumption for all systems since they all use electricity somewhere in their infrastructure. Additionally, the 8.4% and 9.6% transmission and distribution losses in California and Massachusetts also result in an increase for electricity consuming components [Deru 2007]. Similarly, the petroleum refining sector in EIO-LCA used to calculate diesel fuel production shows that for every 100 MJ of energy in the diesel fuel produced, an additional 16 MJ were required to produce it. These 16 MJ are composed of 9 MJ direct energy (extraction, transport) and 7 MJ indirect energy (energy in the supply chain supporting production activities). The corresponding precombustion emission factors for electricity generation in each state are likely the result of diesel fuel combustion and electricity consumption necessary to extract, process, and transport the primary fuels.

Insurance

Muni and the Green Line show non-negligible insurance impacts. The health benefits given to system employees and the insurance on infrastructure assets results in insurance carrier operations that require electricity. Approximately 40% of the energy required by insurance carriers is in the form of electricity used for facilities and operations. The production of electricity from mostly fossil fuels (EIO-LCA assumes a national average mix) for insurance carriers is the reason for large GHG emissions.

Summary

Table 64 summarizes the total and operational energy inputs and GHG emissions for the rail systems.

Table 64 – Rail Energy and GHG Emissions Inventory (operational emissions in parenthesis)

	BART	Caltrain	Muni	Green Line	CAHSR
Energy (MJ/PMT)	2.2 (1.1)	2.3 (1.1)	3.0 (1.2)	2.3 (0.87)	2.0 (1.3)
GHG (g CO_2e/PMT)	140 (64)	160 (74)	170 (69)	230 (120)	130 (94)

1.7.5.2 CAP Emissions

Sulfur Dioxide (SO_2)

The operational emissions of SO_2 are much larger for electric-powered systems than Caltrain. During electricity production, low concentrations of sulfur in coal lead to large emissions when normalized per PMT. While operational emissions account for between 49% and 74% of total SO_2 emissions for electric-powered systems, they are negligible for Caltrain. Total emissions amount to between 250 mg/PMT (Caltrain) and 1,200 mg/PMT (Green Line). Caltrain's relatively low SO_2 emission factor results from the mode's use of diesel and not electricity, however, life-cycle non-operational components account for over 99% of total SO_2 emissions for the system. For the other systems, life-cycle components can double the total SO_2 emissions. Station construction, track construction, station lighting, train control, miscellaneous station electricity, and fuel production all have associated SO_2 emissions. For station and track construction, the large energy requirement in concrete production (from direct use of fossil fuels as well as electricity use which is mostly coal-derived) results in significant emissions. For station lighting, train control, and miscellaneous station electricity, again, the burning of fossil fuels to produce this energy results in release of sulfur mostly in the form of SO_2. Lastly, the production of the electricity and diesel fuel used to power vehicles and support infrastructure faces similar issues.

Carbon Monoxide (CO), Nitrogen Oxides (NO_X), and Volatile Organic Compounds (VOCs)

Unlike SO_2, the operational emissions of CO account for a much smaller portion of total life-cycle CO emissions, between 6% and 19% (excluding CAHSR). The remainder is found mostly in the station construction, track construction, station maintenance, and insurance components. Station and track construction experience high CO contributions due to concrete production and the energy required to produce the material. Track construction dominates CAHSR total emissions (79%). Similarly, station maintenance is large because of station reconstruction. The reliability of insurance components on truck transportation affects CO emissions. CO emissions of 320 mg/PMT for CAHSR are influenced by the large concrete requirements for track construction. For the commuter systems, emissions range from 440 (Caltrain) to 710 (Green Line) mg/PMT.

The primary contributors of NO_X and VOC emissions are the life-cycle components described in CO emissions plus station parking lot construction and maintenance. The release of NO_X, from diesel equipment use, and VOCs, from the asphalt diluent evaporation, result in significant contributions to total emissions for BART and Caltrain. NO_X and VOC emissions from concrete produced for track construction (NO_X results from electricity requirements and truck transport while VOCs result from organics found in materials during cement production) result in major contributions to CAHSR emissions (110 of 160 mg/PMT for NO_X and 80 of 100 mg/PMT for VOCs). With a small parking infrastructure, Muni and the Green Line do not experience this effect. Total NO_X emissions for the commuter systems are between 260 (Muni) and 1,600 (Caltrain) mg/PMT while VOCs amount to between 130 (Green Line) and 200 (BART) mg/PMT.

While 88% of life-cycle Caltrain NO_X emissions are in vehicle operation, only 5% to 29% of total emissions for the other commuter systems are in this component. The majority of emissions are found in the life-cycle. The same holds true for VOCs where operational emissions range from 5% to 29% of total emissions for the commuter systems.

Particulate Matter (PM_{10})

Station parking, track maintenance, and track construction are the two largest contributors to PM emissions. Fugitive dust emissions from asphalt paving have a large impact for CAHSR, BART, and Caltrain. The diesel equipment used to repair tracks results in large PM contributions from track maintenance. Operational PM composes between 7% and 41% of total PM emissions for all rail modes. CAHSR has life-cycle PM emissions of 23 mg/PMT (68% of total) while the commuter modes range from 52 mg/PMT (Muni) to 90 mg/PMT (Caltrain).

Summary

For the commuter systems, no single network outperforms the other for all CAP categories. Depending on the factors already detailed, certain systems perform better or worse than others with respect to specific pollutants. Table 65 details the CAP emissions for each system with both their life-cycle and operational effects.

Table 65 – Rail Travel CAP Inventory (operational emissions in parenthesis)

	BART	**Caltrain**	**Muni**	**Green Line**	**CAHSR**
CO (g/PMT)	530 (36)	440 (83)	660 (39)	720 (140)	320 (48)
SO_2 (mg/PMT)	619 (360)	260 (0.32)	810 (380)	1,200 (730)	680 (500)
NO_X (mg/PMT)	290 (21)	1,600 (1,400)	270 (22)	410 (160)	160 (36)
VOC (mg/PMT)	200 (9.5)	210 (59)	150 (10)	130 (9.3)	96 (11)
PM_{10} (mg/PMT)	55 (3.9)	95 (38)	52 (4.2)	50 (7.4)	23 (5.5)

1.8 Life-cycle Environmental Inventory of Aircraft

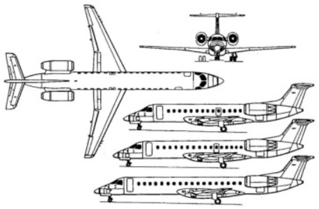
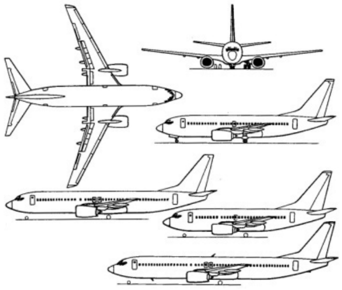
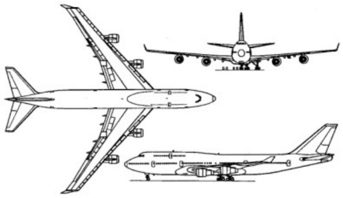
Air travel in the U.S. was responsible for 2.5M TJ of energy consumption in 2005 [Davis 2007], 9% of total transportation energy consumption in that year. The life-cycle inventory for aircraft includes manufacturing, operation, maintenance, and insurance for the vehicles. The major infrastructure components are airport construction, runway, taxiway, and tarmac construction, operation (electricity consumption), maintenance, parking, and insurance. The production of Jet-A fuel (the primary fuel used by commercial aircraft) is also included.

Air travel in the U.S. can be split into three categories: commercial passenger, general passenger, and freight. This analysis only includes commercial passenger which dominates aircraft VMT in the U.S. [BTS 2007].

1.8.1 Vehicles

Three representative aircraft are chosen to model the entire commercial passenger fleet: the Embraer 145 (short-haul, $\mu=33$ passengers per flight), Boeing 737 (medium-haul, $\mu=101$ passengers per flight), and Boeing 747 (long-haul, $\mu=3.5$ passengers per flight) [BTS 2007]. These aircraft represent the small, medium, and large aircrafts each designed for specific travel distances and passenger loads. The three aircraft makeup 30% of VMT and 26% of PMT among all commercial aircraft [BTS 2007]. Assuming the Boeing 737 is representative of the Airbus A300s, Boeing 717, 727, 757, 777, and the McDonnell Douglas DC9 and the Boeing 747 is representative of the Boeing 767 then they make up 80% of VMT and 92% of PMT. Figure 12 shows schematics of each aircraft and specifications.

Figure 12 – Aircraft Parameters [Janes 2004]

Embraer 145	Boeing 737	Boeing 747
		
Dimensions for all models: Wingspan: 11.14 m Fuselage Length: 10.53 m Height: 3.90 m Empty operating weight: 5,335 lbs	Dimensions for 600 series: Wingspan: 34.31 m Fuselage Length: 31.24 m Height: 12.57 m Empty operating weight: 81,800 lbs	Dimensions for 400 series: Wingspan: 64.44 m Fuselage Length: 68.63 m Height: 19.51 m Empty operating weight: 397,900 lbs

The Embraer 145 has one commercial passenger model while the Boeing 737 and 747 have several. The Boeing 737 has been produced since 1967 and is in its ninth series (the 900 series). Considering a 737 constructed in 2005, the only models that are currently manufactured are the 600 series and above. Weighted average production costs are used from the 600 to 900 series. The Boeing 747 has two models of which the 400 series is currently produced. Operational characteristics for the U.S. fleet do not distinguish between series for the 737 and 747. Average number of passengers and distances per trip are computed for all 737 and 747 models [BTS 2007]. The average age assumed for the aircraft is 30 years and for the engine 20 years.

While different aircraft models have different engine models, typically a particular engine model accounts for a majority of the share on that aircraft. The Embraer's typical engine is a Rolls Royce AE3007A model, the Boeing 737 a CFM-56-3, and the 747 a Pratt and Whitney 4056 [Janes 2004, Jenkinson 1999].

Based on analysis of aircraft trips in 2005, the annual VMT and number of passengers per aircraft are determined [BTS 2007]. The average Embraer 145 travels 500 miles with 33 passengers per flight, the Boeing 737 travels 950 miles with 101 passengers per flight, and the Boeing 747 travels 4,500 miles with 305 passengers per flight. The average number of flights per year is also computed based on fleet sizes and total flights by aircraft type [AIA 2007, BTS 2007].

1.8.1.1 Manufacturing

The aircraft and its engines are considered separately when computing the environmental inventory for aircraft manufacturing. The EIO-LCA sectors Aircraft Manufacturing (#336411) and Aircraft and Engine Parts Manufacturing (#336411) well represent the manufacturing processes for these two components. All aircraft are produced in the U.S. including the Brazilian Embraer 145 which manufactures its U.S.-destined aircraft in Oklahoma.

Aircraft and engine costs must be determined before EIO-LCA can be used to determine impacts of manufacturing. The price of the Embraer 145 is $19M, the Boeing 737 $58M, and the Boeing 747 $213M. These prices must be reduced to production costs and must exclude the engine costs [Janes 2004, AIA 2007, Boeing 2007]. A 10% markup is assumed for all aircraft and engines which includes overhead, profit, distribution, and marketing. Engine costs (per engine) are $1.9M for the Embraer 145's RR AE3007, $3.8M for the Boeing 737's CFM-56-3, and $7.2M for the Boeing 747's PW 4056 [Jenkinson 1999]. Both the Embraer 145 and Boeing 737 have 2 engines while the Boeing 747 has 4 engines. Inputting the cost parameters into the EIO-LCA sectors and normalizing to the functional units (as shown in Equation Set 33) produces the aircraft manufacturing inventory.

Equation Set 33 – Aircraft Manufacturing

$$\frac{I/O_{EIOLCA}^{air,c,manufacturing}}{lifetime_{component}} = Annual\ I/O\ from\ Aircraft\ Component\ Manufacturing$$

$$where\ c\ is\ component \in \{aircraft, engine\}$$

$$I/O_{aircraft\ lifetime}^{air,c,manufacturing} = \frac{I/O_{EIOLCA}^{air,c,manufacturing}}{lifetime_{component}} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{aircraft}}{lifetime_{aircraft}}$$

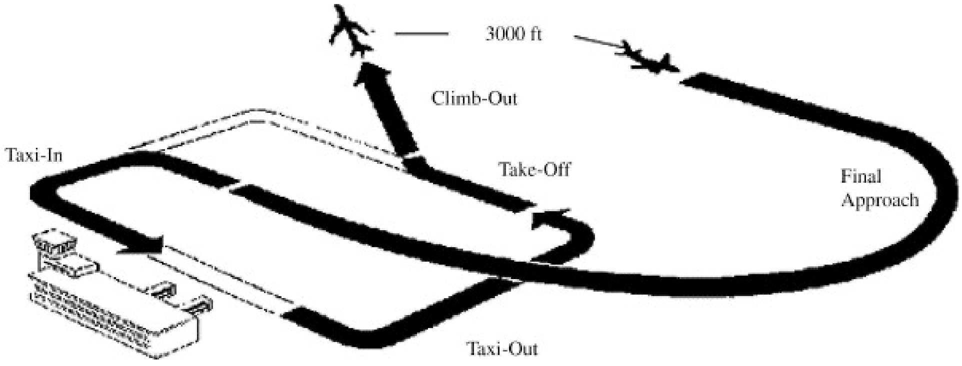
$$I/O_{VMT}^{air,c,manufacturing} = \frac{I/O_{EIOLCA}^{air,c,manufacturing}}{lifetime_{component}} \times \frac{yr}{VMT_{system}}$$

$$I/O_{PMT}^{air,c,manufacturing} = \frac{I/O_{EIOLCA}^{air,c,manufacturing}}{lifetime_{component}} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}$$

1.8.1.2 Operation

Evaluation of aircraft fuel-burn emissions in aggregate per VMT or PMT does not illustrate the critical geographic or engine load characteristics which are important during impact assessment. Emissions at or near airports should be evaluated separately from cruise emissions to allow for more detailed assessment of engine performance during the landing-takeoff (LTO) cycle or for population exposure. For every flight, several stages should be evaluated separately: aircraft startup, taxi out, takeoff, climb out, cruise, approach, and taxi in (illustrated in Figure 13). Additionally, as an aircraft remains stationary at the gate, an on-aircraft auxiliary power unit (APU) is used to provide electricity and hydraulic pressure to aircraft components (lighting, ventilation, etc…).

Figure 13 – Aircraft Landing-Takeoff Cycle [IPCC 1999]



Two approaches are used to estimate the multiple stages. Non-cruise emissions, which occur at or near airports, are modeled with the Federal Aviation Administration's (FAA) Emission Data Modeling Software (EDMS) [FAA 2007]. EDMS is a model for calculating emission sources at airports including not only aircraft but ground support equipment (GSE) and stationary sources. Emissions during the cruise cycle are calculated from emission factors for various aircraft and engine types [EEA 2006, Romano 1999].

At or Near-Airport Operations

Aircraft emissions from startup, taxi out, take off, climb out, approach, and taxi in are determined from the EDMS model. The model requires specification of aircraft and engines as well as the number of landings and takeoffs in a year. The aircraft and engine types described in §1.8.1 are input into the EDMS software. This analysis uses Dulles International Airport (IAD) near Washington, D.C. to evaluate the effects of aircraft and airport operational emissions (the purpose of modeling Dulles airport is discussed in §1.8.2). The number of LTOs by aircraft are determined for Dulles airport in 2005 [BTS 2007]. The default engine loading and amount of time spent in each stage in EDMS are used (19 min. to taxi out, 0.7 min. for takeoff, 2.2 min. for climb, 4 min. for approach, and 7 min. for taxi in). EDMS emission factors are shown in Table 66. The fuel sulfur content is specified as 0.068% with a SO_X emission factor of 1.36 g/kg.

Table 66 – EDMS Emission Factors by LTO Stage (per kg of fuel burned) [FAA 2007]

	Fuel Flow (kg/s)	CO (g/kg)	THC (g/kg)	NMHC (g/kg)	VOC (g/kg)	NO_X (g/kg)	PM (g/kg)
Embraer 145							
Taxi Out	0.056	17	2.4	2.4	2.3	3.9	0.15
Takeoff	0.40	0.81	0.26	0.26	0.25	21	0.27
Climb	0.33	0.81	0.26	0.26	0.25	18	0.24
Approach	0.12	3.2	0.62	0.62	0.58	8.0	0.22
Taxi In	0.056	17	2.4	2.4	2.3	3.9	0.15
Boeing 737							
Taxi Out	0.13	33	2.2	2.2	2.1	4.0	0.24
Takeoff	1.00	0.89	0.043	0.043	0.041	18	0.22
Climb	0.84	0.89	0.043	0.043	0.041	16	0.19
Approach	0.31	3.7	0.077	0.077	0.073	8.5	0.20
Taxi In	0.13	33	2.2	2.2	2.1	4.0	0.24
Boeing 747							
Taxi Out	0.22	11	0.64	0.64	0.60	5.1	0.32
Takeoff	2.6	0.11	0.14	0.14	0.13	33	0.54
Climb	2.1	0.11	0.14	0.14	0.13	25	0.55
Approach	0.69	0.87	0.24	0.24	0.23	12	0.30
Taxi In	0.22	11	0.64	0.64	0.60	5.1	0.32

For aircraft startup, only VOC emissions are tallied in EDMS which are associated with the APU [FAA 2007]. During startup, the APU consumes jet fuel to provide bleed air for the main engine start.

With these inputs, the EDMS model is used to calculate total emissions by aircraft type at Dulles in 2005. Dividing each emission by the number of LTOs for that aircraft yields the at-airport emissions per flight. Equation Set 34 is then used to normalize to the functional units.

Equation Set 34 – Aircraft At or Near Airport Operations

$$I/O_{stage}^{air,aircraft\ LTO\ operations} = \frac{I/O_{EDMS}}{number_{LTO\ in\ EDMS\ inventory}}$$

$$= Aircraft\ LTO\ I/O\ Determined\ in\ FAA\ EDMS\ Software$$

$$I/O_{stage,aircraft\ lifetime}^{air,aircraft\ LTO\ operations}$$

$$= I/O_{stage}^{air,aircraft\ LTO\ operations} \times \frac{flight}{VMT_{flight}} \times \frac{VMT_{aircraft}}{lifetime_{aircraft}}$$

$$I/O_{stage,VMT}^{air,aircraft\ LTO\ operations} = I/O_{stage}^{air,aircraft\ LTO\ operations} \times \frac{flight}{VMT_{flight}}$$

$$I/O_{stage,PMT}^{air,aircraft\ LTO\ operations} = I/O_{stage}^{air,aircraft\ LTO\ operations} \times \frac{flight}{VMT_{flight}} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}$$

Cruise Operations

Cruise emission factors for the three aircraft are gathered from a variety of sources and are normalized per VMT. Fuel consumption is gathered from the European Environment Agency for the Boeing 737 and 747 [EEA 2006]. For the Embraer 145, an estimated 3,000 kg of fuel is consumed during a 1,300 mile trip. Based on a 3.15 kg CO_2 and 1 g SO_2 per kg fuel emission factor, GHG and SO_2 emissions are computed for each aircraft [Romano 1999]. CO, NO_X, and VOCs emissions are determined from the European Environment Agency for the Boeing 737 and 747. Embraer 145 specific CO, NO_X and VOC factors could not be determined so average emissions per kg of fuel were used from the 737 and 747. Trace lead emissions are excluded due to a general lack of data and the inability to disaggregate by aircraft type. Lastly, PM emissions were assumed to be 0.04 g per kg of fuel [Pehrson 2005]. These factors are summarized in Table 67.

Table 67 – Aircraft Cruise Environmental Factors (per VMT)

	Embraer 145	Boeing 737	Boeing 747
Fuel Consumption (kg)	2.4	4.8	17
Energy Consumption (MJ)	80	220	780
GHG Emissions (kg)	5.3	15	53
SO_2 Emissions (g)	1.7	4.8	17
CO Emissions (g)	2.3	8.3	16
NO_X Emissions (g)	13	52	207
VOC Emissions (g)	0.3	0.5	4.1
PM_{10} Emissions (g)	0.07	0.19	0.67

Once fuel and emission factors are normalized, they are multiplied by average aircraft flight characteristics as shown in Equation Set 35.

Equation Set 35 – Aircraft Cruise Operations

$$EF_{IO} = Energy\,/\,Emission\,Factor\;per\,VMT$$

$$I^{air,aircraft-airport-operation}_{IO-aircraft-life} = EF_{IO} \times \frac{VMT_{aircraft}}{aircraft-life}$$

$$I^{air,aircraft-airport-cruise}_{IO-VMT} = EF_{IO}$$

$$I^{air,aircraft-airport-operation}_{IO-PMT} = EF_{IO} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}$$

1.8.1.3 Maintenance

There are many maintenance components for aircraft which are included in inspections, preventative maintenance, repairs, and refurbishing [EPA 1998]. From daily maintenance to repairs, there are many components of aircraft maintenance which can be considered. The environmental impacts of many of these components are not well understood. Also, there exists no sector in EIO-LCA which reasonably estimates effects of aircraft maintenance. As a result, maintenance items were disaggregated and assigned best-fit EIO-LCA sectors as shown in Table 68.

Table 68 – Aircraft Maintenance Components and Corresponding EIO-LCA Sectors

	% of Total Maintenance Costs	EIOLCA Sector Number	EIOLCA Sector Name
Airframe Maintenance			
Lubrication & Fuel Changes	10%	324191	Petrol. lubricating oil and grease manufacturing
Battery Repair & Replacement	10%	335912	Primary battery manufacturing
Chemical Milling, Maskant, & Application	10%	324110	Petroleum refineries
Parts Cleaning	10%	325190	Other basic organic chemical manufacturing
Metal Finishing	10%	325180	Other basic inorganic chemical manufacturing
Coating Application	10%	325510	Paint and coating manufacturing
Depainting	10%	325180	Other basic inorganic chemical manufacturing
Painting	30%	325510	Paint and coating manufacturing
Engine Maintenance			
Engine Maintenance		336412	Aircraft engine and engine parts manufacturing

The costs of these components are based on total airframe and engine material costs [BTS 2007]. The average airframe and engine material costs were determined from the fleet reports which are disaggregated by aircraft type. These costs are shown in Table 69.

Table 69 – Aircraft Maintenance Component Costs ($/hour of flight)

	Embraer 145	Boeing 737	Boeing 747
Airframe Material Costs	28	110	220
Engine Material Costs	10	61	640

The airframe material costs are multiplied by their respective percentages in Table 68 and then input into their corresponding EIO-LCA sector. Engine maintenance inventory is computed with the EIO-LCA sector Aircraft Engine and Engine Parts Manufacturing (#336412). With the inventory calculated from each component, total maintenance costs are normalized to the functional unit based on the methodology in Equation Set 36.

Equation Set 36 – Aircraft Maintenance

$$I/O_{EIOLCA}^{air,aircraft\ maintenance} = \sum_{components} \frac{I/O_{EIOLCA}^{component}}{lifetime_{component}}$$

$$I/O_{aircraft\ lifetime}^{air,aircraft\ maintenance} = I/O_{EIOLCA}^{air,aircraft\ maintenance} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{aircraft}}{lifetime_{aircraft}}$$

$$I/O_{VMT}^{air,aircraft\ maintenance} = I/O_{EIOLCA}^{air,aircraft\ maintenance} \times \frac{yr}{VMT_{system}}$$

$$I/O_{PMT}^{air,aircraft\ maintenance} = I/O_{EIOLCA}^{air,aircraft\ maintenance} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}$$

1.8.1.4 Insurance

Similar to other modes' inventory calculations, insurance on aircraft is computed from liability and benefits through EIO-LCA. Insurance costs are determined from air carrier financial data reported to the U.S. Department of Transportation for each quarter, airline, and aircraft type [BTS 2007]. The costs are computed per hour of air travel and then multiplied by the total air hours in the aircraft's life. This yields a total insurance cost per aircraft life which is input in EIOCLA's Insurance Carriers (#524100) sector (costs are shown in Table 70).

Table 70 – Aircraft Insurance Costs ($M/aircraft lifetime)

	Embraer 145	Boeing 737	Boeing 747
Pilot and Flight Crew Benefits	0.8	17	12
Vehicle Casualty and Liability	0.4	3.7	1.1

1.8.1.5 *Usage Attribution (Passengers, Freight, and Mail)*

While the primary purpose of any commercial passenger flight is to transport people, freight and mail are often transported. This is the case for all aircraft sizes although the larger the aircraft, the more freight and mail is typically transported (as a percentage of total weight). The exact attribution of passengers, freight, and mail, by weight, is shown in Table 71 [BTS 2007]. The small, medium, and larger aircraft sizes correspond to the Embraer 145, Boeing 737, and Boeing 747. It is assumed that the average person weighs 150 lbs and travels with 40 lbs of luggage.

Table 71 – Weight of Passengers, Freight, and Mail on an Average Flight

Aircraft Size	Pax	Weight of Pax & Luggage (lbs)	Weight of Freight (lbs)	Weight of Mail (lbs)	% Weight to Pax
Small	33	6,300	50	7	99%
Medium	101	19,000	360	150	97%
Large	305	58,000	10,000	1,600	83%

While small aircraft are almost entirely dedicated to passenger travel, the large aircraft are 17% dedicated (by weight) to transporting freight and mail. The percentage attribution for each aircraft size is applied to the vehicle inventory to account for the passenger's effect.

1.8.1.6 Air Vehicle Results

Table 72 – Air Vehicle Inventory for an Embraer 145

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Aircraft Manufacture	Energy	63,000 GJ	4,600 kJ	140 kJ
	GHG	5,100 mt GGE	370 g GGE	11 g GGE
	SO_2	13,000 kg	970 mg	29 mg
	CO	50,000 kg	3,700 mg	110 mg
	NO_X	11,000 kg	810 mg	24 mg
	VOC	8,300 kg	610 mg	18 mg
	Pb	11 kg	0.80 mg	0.024 mg
	PM_{10}	3,100 kg	230 mg	6.8 mg
V, Engine Manufacture	Energy	22,000 GJ	1,600 kJ	48 kJ
	GHG	1,800 mt GGE	130 g GGE	3.9 g GGE
	SO_2	5,000 kg	360 mg	11 mg
	CO	15,000 kg	1,100 mg	33 mg
	NO_X	3,900 kg	290 mg	8.6 mg
	VOC	2,300 kg	170 mg	5.0 mg
	Pb	4.3 kg	0.31 mg	0.0094 mg
	PM_{10}	1,100 kg	81 mg	2.4 mg
V, Operation, APU	Energy	14,000 GJ	1,000 kJ	31 kJ
	GHG	950 mt GGE	69 g GGE	2.1 g GGE
	SO_2	880 kg	64 mg	1.9 mg
	CO	5,700 kg	420 mg	12 mg
	NO_X	4,000 kg	300 mg	8.9 mg
	VOC	540 kg	39 mg	1.2 mg
	Pb	-	-	-
	PM_{10}	-	-	-
V, Operation, Startup	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	14,000 kg	1,000 mg	31 mg
	Pb	-	-	-
	PM_{10}	-	-	-
V, Operation, Taxi	Energy	180,000 GJ	13,000 kJ	400 kJ
	GHG	12,000 mt GGE	880 g GGE	26 g GGE
	SO_2	5,200 kg	380 mg	12 mg
	CO	64,000 kg	4,700 mg	140 mg
	NO_X	15,000 kg	1,100 mg	33 mg
	VOC	8,800 kg	650 mg	19 mg
	Pb	-	-	-
	PM_{10}	590 kg	43 mg	1.3 mg
V, Operation, Take Off	Energy	47,000 GJ	3,400 kJ	100 kJ
	GHG	3,100 mt GGE	230 g GGE	6.9 g GGE
	SO_2	1,400 kg	100 mg	3.0 mg
	CO	810 kg	59 mg	1.8 mg
	NO_X	21,000 kg	1,500 mg	46 mg
	VOC	250 kg	18 mg	0.54 mg
	Pb	-	-	-
	PM_{10}	270 kg	20 mg	0.59 mg

Table 72 – Air Vehicle Inventory for an Embraer 145

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Operation, Climb Out	Energy	120,000 GJ	9,100 kJ	270 kJ
	GHG	8,200 mt GGE	600 g GGE	18 g GGE
	SO_2	3,600 kg	260 mg	7.9 mg
	CO	2,100 kg	160 mg	4.7 mg
	NO_X	47,000 kg	3,500 mg	100 mg
	VOC	650 kg	48 mg	1.4 mg
	Pb	-	-	-
	PM_{10}	630 kg	46 mg	1.4 mg
V, Operation, Cruise	Energy	1,100,000 GJ	78,000 kJ	2,300 kJ
	GHG	71,000 mt GGE	5,200 g GGE	160 g GGE
	SO_2	23,000 kg	1,700 mg	50 mg
	CO	31,000 kg	2,300 mg	68 mg
	NO_X	180,000 kg	13,000 mg	390 mg
	VOC	3,900 kg	280 mg	8.6 mg
	Pb	-	-	-
	PM_{10}	910 kg	66 mg	2.0 mg
V, Operation, Approach	Energy	84,000 GJ	6,100 kJ	180 kJ
	GHG	5,600 mt GGE	410 g GGE	12 g GGE
	SO_2	2,400 kg	180 mg	5.4 mg
	CO	5,700 kg	410 mg	12 mg
	NO_X	14,000 kg	1,000 mg	31 mg
	VOC	1,000 kg	77 mg	2.3 mg
	Pb	-	-	-
	PM_{10}	390 kg	29 mg	0.87 mg
V, Operation, Taxi In	Energy	66,000 GJ	4,900 kJ	150 kJ
	GHG	4,400 mt GGE	320 g GGE	9.7 g GGE
	SO_2	1,900 kg	140 mg	4.2 mg
	CO	24,000 kg	1,700 mg	52 mg
	NO_X	5,600 kg	410 mg	12 mg
	VOC	3,200 kg	240 mg	7.1 mg
	Pb	-	-	-
	PM_{10}	220 kg	16 mg	0.48 mg
V, Maintenance, Lubrication & Fuel	Energy	5,300 GJ	390 kJ	12 kJ
	GHG	350 mt GGE	25 g GGE	0.76 g GGE
	SO_2	190 kg	14 mg	0.41 mg
	CO	620 kg	45 mg	1.4 mg
	NO_X	170 kg	12 mg	0.37 mg
	VOC	160 kg	11 mg	0.34 mg
	Pb	-	-	-
	PM_{10}	32 kg	2.4 mg	0.071 mg
V, Maintenance, Battery	Energy	660 GJ	48 kJ	1.4 kJ
	GHG	50 mt GGE	3.7 g GGE	0.11 g GGE
	SO_2	120 kg	9.1 mg	0.27 mg
	CO	650 kg	47 mg	1.4 mg
	NO_X	110 kg	7.8 mg	0.24 mg
	VOC	84 kg	6.1 mg	0.18 mg
	Pb	0.35 kg	0.025 mg	0.00076 mg
	PM_{10}	34 kg	2.5 mg	0.074 mg

Table 72 – Air Vehicle Inventory for an Embraer 145

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Maintenance, Chemical Application	Energy	2,100 GJ	160 kJ	4.7 kJ
	GHG	190 mt GGE	14 g GGE	0.42 g GGE
	SO_2	360 kg	27 mg	0.80 mg
	CO	520 kg	38 mg	1.1 mg
	NO_X	210 kg	16 mg	0.47 mg
	VOC	240 kg	17 mg	0.52 mg
	Pb	-	-	-
	PM_{10}	38 kg	2.8 mg	0.083 mg
V, Maintenance, Parts Cleaning	Energy	1,900 GJ	140 kJ	4.1 kJ
	GHG	160 mt GGE	12 g GGE	0.36 g GGE
	SO_2	260 kg	19 mg	0.57 mg
	CO	680 kg	50 mg	1.5 mg
	NO_X	230 kg	17 mg	0.51 mg
	VOC	300 kg	22 mg	0.67 mg
	Pb	-	-	-
	PM_{10}	46 kg	3.3 mg	0.10 mg
V, Maintenance, Metal Finishing	Energy	3,100 GJ	230 kJ	6.9 kJ
	GHG	180 mt GGE	13 g GGE	0.40 g GGE
	SO_2	500 kg	37 mg	1.1 mg
	CO	480 kg	35 mg	1.0 mg
	NO_X	220 kg	16 mg	0.48 mg
	VOC	110 kg	7.7 mg	0.23 mg
	Pb	-	-	-
	PM_{10}	49 kg	3.6 mg	0.11 mg
V, Maintenance, Coating Application	Energy	1,400 GJ	100 kJ	3.1 kJ
	GHG	100 mt GGE	7.5 g GGE	0.22 g GGE
	SO_2	190 kg	14 mg	0.43 mg
	CO	860 kg	63 mg	1.9 mg
	NO_X	170 kg	13 mg	0.38 mg
	VOC	250 kg	19 mg	0.56 mg
	Pb	0.35 kg	0.025 mg	0.00076 mg
	PM_{10}	64 kg	4.7 mg	0.14 mg
V, Maintenance, Depainting	Energy	3,100 GJ	230 kJ	6.9 kJ
	GHG	180 mt GGE	13 g GGE	0.40 g GGE
	SO_2	500 kg	37 mg	1.1 mg
	CO	480 kg	35 mg	1.0 mg
	NO_X	220 kg	16 mg	0.48 mg
	VOC	110 kg	7.7 mg	0.23 mg
	Pb	-	-	-
	PM_{10}	49 kg	3.6 mg	0.11 mg
V, Maintenance, Painting	Energy	4,200 GJ	310 kJ	9.2 kJ
	GHG	310 mt GGE	22 g GGE	0.67 g GGE
	SO_2	580 kg	42 mg	1.3 mg
	CO	2,600 kg	190 mg	5.7 mg
	NO_X	520 kg	38 mg	1.2 mg
	VOC	760 kg	56 mg	1.7 mg
	Pb	1.0 kg	0.076 mg	0.0023 mg
	PM_{10}	190 kg	14 mg	0.42 mg

Table 72 – Air Vehicle Inventory for an Embraer 145

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Maintenance, Engine	Energy	1,600 GJ	110 kJ	3.4 kJ
	GHG	120 mt GGE	9.1 g GGE	0.27 g GGE
	SO$_2$	350 kg	26 mg	0.77 mg
	CO	1,100 kg	78 mg	2.3 mg
	NO$_X$	280 kg	20 mg	0.61 mg
	VOC	160 kg	12 mg	0.35 mg
	Pb	0.30 kg	0.022 mg	0.00067 mg
	PM$_{10}$	78 kg	5.7 mg	0.17 mg
V, Insurance, Incidents	Energy	300 GJ	22 kJ	0.65 kJ
	GHG	24 mt GGE	1.8 g GGE	0.053 g GGE
	SO$_2$	60 kg	4.4 mg	0.13 mg
	CO	270 kg	20 mg	0.59 mg
	NO$_X$	67 kg	4.9 mg	0.15 mg
	VOC	50 kg	3.6 mg	0.11 mg
	Pb	-	-	-
	PM$_{10}$	13 kg	0.93 mg	0.028 mg
V, Insurance, Health	Energy	670 GJ	49 kJ	1.5 kJ
	GHG	54 mt GGE	4.0 g GGE	0.12 g GGE
	SO$_2$	130 kg	9.8 mg	0.29 mg
	CO	600 kg	44 mg	1.3 mg
	NO$_X$	150 kg	11 mg	0.33 mg
	VOC	110 kg	8.2 mg	0.25 mg
	Pb	-	-	-
	PM$_{10}$	28 kg	2.1 mg	0.062 mg

Table 73 – Air Vehicle Inventory for a Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Aircraft Manufacture	Energy	210,000 GJ	4,200 kJ	41 kJ
	GHG	17,000 mt GGE	340 g GGE	3.3 g GGE
	SO$_2$	44,000 kg	880 mg	8.7 mg
	CO	170,000 kg	3,300 mg	33 mg
	NO$_X$	37,000 kg	730 mg	7.2 mg
	VOC	27,000 kg	550 mg	5.4 mg
	Pb	36 kg	0.73 mg	0.0072 mg
	PM$_{10}$	10,000 kg	200 mg	2.0 mg
V, Engine Manufacture	Energy	42,000 GJ	830 kJ	8.2 kJ
	GHG	3,300 mt GGE	67 g GGE	0.66 g GGE
	SO$_2$	9,400 kg	190 mg	1.9 mg
	CO	28,000 kg	570 mg	5.6 mg
	NO$_X$	7,400 kg	150 mg	1.5 mg
	VOC	4,300 kg	86 mg	0.84 mg
	Pb	8.1 kg	0.16 mg	0.0016 mg
	PM$_{10}$	2,100 kg	42 mg	0.41 mg

Table 73 – Air Vehicle Inventory for a Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Operation, APU	Energy	99,000 GJ	2,000 kJ	20 kJ
	GHG	6,600 mt GGE	130 g GGE	1.3 g GGE
	SO_2	2,400 kg	47 mg	0.47 mg
	CO	43,000 kg	850 mg	8.4 mg
	NO_X	11,000 kg	220 mg	2.2 mg
	VOC	2,400 kg	49 mg	0.48 mg
	Pb	-	-	-
	PM_{10}	-	-	-
V, Operation, Startup	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	45,000 kg	890 mg	8.8 mg
	Pb	-	-	-
	PM_{10}	-	-	-
V, Operation, Taxi	Energy	710,000 GJ	14,000 kJ	140 kJ
	GHG	47,000 mt GGE	950 g GGE	9.4 g GGE
	SO_2	21,000 kg	410 mg	4.1 mg
	CO	500,000 kg	10,000 mg	100 mg
	NO_X	61,000 kg	1,200 mg	12 mg
	VOC	32,000 kg	630 mg	6.3 mg
	Pb	-	-	-
	PM_{10}	3,700 kg	74 mg	0.73 mg
V, Operation, Take Off	Energy	200,000 GJ	4,000 kJ	40 kJ
	GHG	13,000 mt GGE	270 g GGE	2.6 g GGE
	SO_2	5,800 kg	120 mg	1.1 mg
	CO	3,800 kg	76 mg	0.75 mg
	NO_X	78,000 kg	1,600 mg	15 mg
	VOC	180 kg	3.5 mg	0.035 mg
	Pb	-	-	-
	PM_{10}	920 kg	18 mg	0.18 mg
V, Operation, Climb Out	Energy	530,000 GJ	11,000 kJ	100 kJ
	GHG	35,000 mt GGE	700 g GGE	6.9 g GGE
	SO_2	15,000 kg	310 mg	3.0 mg
	CO	10,000 kg	200 mg	2.0 mg
	NO_X	180,000 kg	3,600 mg	35 mg
	VOC	460 kg	9.3 mg	0.091 mg
	Pb	-	-	-
	PM_{10}	2,100 kg	42 mg	0.41 mg
V, Operation, Cruise	Energy	11,000,000 GJ	220,000 kJ	2,100 kJ
	GHG	730,000 mt GGE	15,000 g GGE	140 g GGE
	SO_2	230,000 kg	4,600 mg	46 mg
	CO	410,000 kg	8,100 mg	80 mg
	NO_X	2,600,000 kg	51,000 mg	500 mg
	VOC	22,000 kg	450 mg	4.4 mg
	Pb	-	-	-
	PM_{10}	9,300 kg	190 mg	1.8 mg

Table 73 – Air Vehicle Inventory for a Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Operation, Approach	Energy	350,000 GJ	7,100 kJ	70 kJ
	GHG	24,000 mt GGE	470 g GGE	4.7 g GGE
	SO_2	10,000 kg	210 mg	2.0 mg
	CO	28,000 kg	560 mg	5.5 mg
	NO_X	64,000 kg	1,300 mg	13 mg
	VOC	550 kg	11 mg	0.11 mg
	Pb	-	-	-
	PM_{10}	1,500 kg	31 mg	0.30 mg
V, Operation, Taxi In	Energy	260,000 GJ	5,300 kJ	52 kJ
	GHG	18,000 mt GGE	350 g GGE	3.5 g GGE
	SO_2	7,600 kg	150 mg	1.5 mg
	CO	190,000 kg	3,700 mg	37 mg
	NO_X	22,000 kg	450 mg	4.4 mg
	VOC	12,000 kg	230 mg	2.3 mg
	Pb	-	-	-
	PM_{10}	1,400 kg	27 mg	0.27 mg
V, Maintenance, Lubrication & Fuel	Energy	61,000 GJ	1,200 kJ	12 kJ
	GHG	4,000 mt GGE	80 g GGE	0.79 g GGE
	SO_2	2,100 kg	43 mg	0.42 mg
	CO	7,200 kg	140 mg	1.4 mg
	NO_X	2,000 kg	39 mg	0.39 mg
	VOC	1,800 kg	36 mg	0.36 mg
	Pb	-	-	-
	PM_{10}	370 kg	7.5 mg	0.073 mg
V, Maintenance, Battery	Energy	7,600 GJ	150 kJ	1.5 kJ
	GHG	580 mt GGE	12 g GGE	0.11 g GGE
	SO_2	1,400 kg	29 mg	0.28 mg
	CO	7,400 kg	150 mg	1.5 mg
	NO_X	1,200 kg	25 mg	0.24 mg
	VOC	970 kg	19 mg	0.19 mg
	Pb	4.0 kg	0.080 mg	0.00079 mg
	PM_{10}	390 kg	7.8 mg	0.077 mg
V, Maintenance, Chemical Application	Energy	24,000 GJ	490 kJ	4.8 kJ
	GHG	2,200 mt GGE	44 g GGE	0.43 g GGE
	SO_2	4,200 kg	84 mg	0.83 mg
	CO	6,000 kg	120 mg	1.2 mg
	NO_X	2,400 kg	49 mg	0.48 mg
	VOC	2,700 kg	54 mg	0.54 mg
	Pb	-	-	-
	PM_{10}	430 kg	8.7 mg	0.086 mg
V, Maintenance, Parts Cleaning	Energy	22,000 GJ	430 kJ	4.3 kJ
	GHG	1,900 mt GGE	37 g GGE	0.37 g GGE
	SO_2	3,000 kg	60 mg	0.59 mg
	CO	7,900 kg	160 mg	1.6 mg
	NO_X	2,600 kg	53 mg	0.52 mg
	VOC	3,500 kg	70 mg	0.69 mg
	Pb	-	-	-
	PM_{10}	520 kg	11 mg	0.10 mg

Table 73 – Air Vehicle Inventory for a Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Maintenance, Metal Finishing	Energy	36,000 GJ	720 kJ	7.1 kJ
	GHG	2,100 mt GGE	42 g GGE	0.42 g GGE
	SO_2	5,800 kg	120 mg	1.1 mg
	CO	5,500 kg	110 mg	1.1 mg
	NO_X	2,500 kg	50 mg	0.49 mg
	VOC	1,200 kg	24 mg	0.24 mg
	Pb	-	-	-
	PM_{10}	560 kg	11 mg	0.11 mg
V, Maintenance, Coating Application	Energy	16,000 GJ	320 kJ	3.2 kJ
	GHG	1,200 mt GGE	24 g GGE	0.23 g GGE
	SO_2	2,200 kg	45 mg	0.44 mg
	CO	9,900 kg	200 mg	1.9 mg
	NO_X	2,000 kg	40 mg	0.40 mg
	VOC	2,900 kg	58 mg	0.58 mg
	Pb	4.0 kg	0.080 mg	0.00079 mg
	PM_{10}	740 kg	15 mg	0.15 mg
V, Maintenance, Depainting	Energy	36,000 GJ	720 kJ	7.1 kJ
	GHG	2,100 mt GGE	42 g GGE	0.42 g GGE
	SO_2	5,800 kg	120 mg	1.1 mg
	CO	5,500 kg	110 mg	1.1 mg
	NO_X	2,500 kg	50 mg	0.49 mg
	VOC	1,200 kg	24 mg	0.24 mg
	Pb	-	-	-
	PM_{10}	560 kg	11 mg	0.11 mg
V, Maintenance, Painting	Energy	48,000 GJ	970 kJ	9.5 kJ
	GHG	3,500 mt GGE	71 g GGE	0.70 g GGE
	SO_2	6,700 kg	130 mg	1.3 mg
	CO	30,000 kg	590 mg	5.8 mg
	NO_X	6,000 kg	120 mg	1.2 mg
	VOC	8,800 kg	180 mg	1.7 mg
	Pb	12 kg	0.24 mg	0.0024 mg
	PM_{10}	2,200 kg	44 mg	0.44 mg
V, Maintenance, Engine	Energy	29,000 GJ	570 kJ	5.6 kJ
	GHG	2,300 mt GGE	46 g GGE	0.45 g GGE
	SO_2	6,500 kg	130 mg	1.3 mg
	CO	20,000 kg	390 mg	3.8 mg
	NO_X	5,100 kg	100 mg	1.0 mg
	VOC	2,900 kg	59 mg	0.58 mg
	Pb	5.6 kg	0.11 mg	0.0011 mg
	PM_{10}	1,400 kg	29 mg	0.28 mg
V, Insurance, Incidents	Energy	3,100 GJ	62 kJ	0.61 kJ
	GHG	250 mt GGE	5.0 g GGE	0.050 g GGE
	SO_2	620 kg	12 mg	0.12 mg
	CO	2,800 kg	56 mg	0.55 mg
	NO_X	700 kg	14 mg	0.14 mg
	VOC	520 kg	10 mg	0.10 mg
	Pb	-	-	-
	PM_{10}	130 kg	2.6 mg	0.026 mg

Table 73 – Air Vehicle Inventory for a Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Insurance, Health	Energy	14,000 GJ	280 kJ	2.8 kJ
	GHG	1,200 mt GGE	23 g GGE	0.23 g GGE
	SO_2	2,800 kg	57 mg	0.56 mg
	CO	13,000 kg	260 mg	2.5 mg
	NO_X	3,200 kg	64 mg	0.63 mg
	VOC	2,400 kg	47 mg	0.47 mg
	Pb	-	-	-
	PM_{10}	600 kg	12 mg	0.12 mg

Table 74 – Air Vehicle Inventory for a Boeing 747

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Aircraft Manufacture	Energy	650,000 GJ	43,000 kJ	140 kJ
	GHG	52,000 mt GGE	3,500 g GGE	11 g GGE
	SO_2	140,000 kg	9,100 mg	30 mg
	CO	520,000 kg	35,000 mg	110 mg
	NO_X	110,000 kg	7,600 mg	25 mg
	VOC	85,000 kg	5,700 mg	19 mg
	Pb	110 kg	7.6 mg	0.025 mg
	PM_{10}	32,000 kg	2,100 mg	7.0 mg
V, Engine Manufacture	Energy	140,000 GJ	9,100 kJ	30 kJ
	GHG	11,000 mt GGE	730 g GGE	2.4 g GGE
	SO_2	31,000 kg	2,100 mg	6.8 mg
	CO	93,000 kg	6,200 mg	20 mg
	NO_X	24,000 kg	1,600 mg	5.3 mg
	VOC	14,000 kg	940 mg	3.1 mg
	Pb	27 kg	1.8 mg	0.0058 mg
	PM_{10}	6,900 kg	460 mg	1.5 mg
V, Operation, APU	Energy	93,000 GJ	6,200 kJ	20 kJ
	GHG	6,200 mt GGE	410 g GGE	1.3 g GGE
	SO_2	470 kg	31 mg	0.10 mg
	CO	7,800 kg	520 mg	1.7 mg
	NO_X	1,500 kg	98 mg	0.32 mg
	VOC	700 kg	47 mg	0.15 mg
	Pb	-	-	-
	PM_{10}	-	-	-
V, Operation, Startup	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	3,200 kg	210 mg	0.70 mg
	Pb	-	-	-
	PM_{10}	-	-	-

Table 74 – Air Vehicle Inventory for a Boeing 747

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Operation, Taxi	Energy	130,000 GJ	8,500 kJ	28 kJ
	GHG	8,400 mt GGE	560 g GGE	1.8 g GGE
	SO_2	3,700 kg	250 mg	0.81 mg
	CO	30,000 kg	2,000 mg	6.6 mg
	NO_X	14,000 kg	930 mg	3.0 mg
	VOC	1,600 kg	110 mg	0.36 mg
	Pb	-	-	-
	PM_{10}	850 kg	57 mg	0.19 mg
V, Operation, Take Off	Energy	56,000 GJ	3,700 kJ	12 kJ
	GHG	3,700 mt GGE	250 g GGE	0.81 g GGE
	SO_2	1,600 kg	110 mg	0.36 mg
	CO	130 kg	8.5 mg	0.028 mg
	NO_X	40,000 kg	2,700 mg	8.7 mg
	VOC	150 kg	10 mg	0.033 mg
	Pb	-	-	-
	PM_{10}	640 kg	43 mg	0.14 mg
V, Operation, Climb Out	Energy	140,000 GJ	9,500 kJ	31 kJ
	GHG	9,500 mt GGE	630 g GGE	2.1 g GGE
	SO_2	4,100 kg	280 mg	0.91 mg
	CO	320 kg	22 mg	0.071 mg
	NO_X	77,000 kg	5,100 mg	17 mg
	VOC	390 kg	26 mg	0.085 mg
	Pb	-	-	-
	PM_{10}	1,700 kg	110 mg	0.36 mg
V, Operation, Cruise	Energy	9,800,000 GJ	650,000 kJ	2,100 kJ
	GHG	660,000 mt GGE	44,000 g GGE	140 g GGE
	SO_2	210,000 kg	14,000 mg	46 mg
	CO	200,000 kg	13,000 mg	44 mg
	NO_X	2,600,000 kg	170,000 mg	570 mg
	VOC	51,000 kg	3,400 mg	11 mg
	Pb	-	-	-
	PM_{10}	8,300 kg	560 mg	1.8 mg
V, Operation, Approach	Energy	85,000 GJ	5,700 kJ	19 kJ
	GHG	5,700 mt GGE	380 g GGE	1.2 g GGE
	SO_2	2,500 kg	170 mg	0.54 mg
	CO	1,600 kg	110 mg	0.35 mg
	NO_X	22,000 kg	1,400 mg	4.7 mg
	VOC	410 kg	28 mg	0.091 mg
	Pb	-	-	-
	PM_{10}	550 kg	37 mg	0.12 mg
V, Operation, Taxi In	Energy	47,000 GJ	3,100 kJ	10 kJ
	GHG	3,100 mt GGE	210 g GGE	0.68 g GGE
	SO_2	1,400 kg	91 mg	0.30 mg
	CO	11,000 kg	740 mg	2.4 mg
	NO_X	5,100 kg	340 mg	1.1 mg
	VOC	600 kg	40 mg	0.13 mg
	Pb	-	-	-
	PM_{10}	310 kg	21 mg	0.069 mg

Table 74 – Air Vehicle Inventory for a Boeing 747

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Maintenance, Lubrication & Fuel	Energy	26,000 GJ	1,800 kJ	5.7 kJ
	GHG	1,700 mt GGE	110 g GGE	0.38 g GGE
	SO_2	920 kg	62 mg	0.20 mg
	CO	3,100 kg	210 mg	0.67 mg
	NO_X	840 kg	56 mg	0.18 mg
	VOC	780 kg	52 mg	0.17 mg
	Pb	-	-	-
	PM_{10}	160 kg	11 mg	0.035 mg
V, Maintenance, Battery	Energy	3,300 GJ	220 kJ	0.71 kJ
	GHG	250 mt GGE	17 g GGE	0.055 g GGE
	SO_2	620 kg	41 mg	0.14 mg
	CO	3,200 kg	210 mg	0.70 mg
	NO_X	530 kg	35 mg	0.12 mg
	VOC	420 kg	28 mg	0.091 mg
	Pb	1.7 kg	0.11 mg	0.00038 mg
	PM_{10}	170 kg	11 mg	0.037 mg
V, Maintenance, Chemical Application	Energy	11,000 GJ	700 kJ	2.3 kJ
	GHG	940 mt GGE	63 g GGE	0.21 g GGE
	SO_2	1,800 kg	120 mg	0.40 mg
	CO	2,600 kg	170 mg	0.56 mg
	NO_X	1,100 kg	70 mg	0.23 mg
	VOC	1,200 kg	78 mg	0.26 mg
	Pb	-	-	-
	PM_{10}	190 kg	12 mg	0.041 mg
V, Maintenance, Parts Cleaning	Energy	9,300 GJ	620 kJ	2.0 kJ
	GHG	810 mt GGE	54 g GGE	0.18 g GGE
	SO_2	1,300 kg	86 mg	0.28 mg
	CO	3,400 kg	230 mg	0.74 mg
	NO_X	1,100 kg	76 mg	0.25 mg
	VOC	1,500 kg	100 mg	0.33 mg
	Pb	-	-	-
	PM_{10}	230 kg	15 mg	0.049 mg
V, Maintenance, Metal Finishing	Energy	15,000 GJ	1,000 kJ	3.4 kJ
	GHG	910 mt GGE	61 g GGE	0.20 g GGE
	SO_2	2,500 kg	170 mg	0.55 mg
	CO	2,400 kg	160 mg	0.52 mg
	NO_X	1,100 kg	72 mg	0.24 mg
	VOC	520 kg	35 mg	0.11 mg
	Pb	-	-	-
	PM_{10}	240 kg	16 mg	0.053 mg
V, Maintenance, Coating Application	Energy	6,900 GJ	460 kJ	1.5 kJ
	GHG	510 mt GGE	34 g GGE	0.11 g GGE
	SO_2	960 kg	64 mg	0.21 mg
	CO	4,200 kg	280 mg	0.93 mg
	NO_X	870 kg	58 mg	0.19 mg
	VOC	1,300 kg	84 mg	0.27 mg
	Pb	1.7 kg	0.11 mg	0.00038 mg
	PM_{10}	320 kg	21 mg	0.069 mg

Table 74 – Air Vehicle Inventory for a Boeing 747

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Maintenance, Depainting	Energy	15,000 GJ	1,000 kJ	3.4 kJ
	GHG	910 mt GGE	61 g GGE	0.20 g GGE
	SO_2	2,500 kg	170 mg	0.55 mg
	CO	2,400 kg	160 mg	0.52 mg
	NO_X	1,100 kg	72 mg	0.24 mg
	VOC	520 kg	35 mg	0.11 mg
	Pb	-	-	-
	PM_{10}	240 kg	16 mg	0.053 mg
V, Maintenance, Painting	Energy	21,000 GJ	1,400 kJ	4.6 kJ
	GHG	1,500 mt GGE	100 g GGE	0.33 g GGE
	SO_2	2,900 kg	190 mg	0.63 mg
	CO	13,000 kg	850 mg	2.8 mg
	NO_X	2,600 kg	170 mg	0.57 mg
	VOC	3,800 kg	250 mg	0.82 mg
	Pb	5.1 kg	0.34 mg	0.0011 mg
	PM_{10}	950 kg	64 mg	0.21 mg
V, Maintenance, Engine	Energy	63,000 GJ	4,200 kJ	14 kJ
	GHG	5,000 mt GGE	340 g GGE	1.1 g GGE
	SO_2	14,000 kg	950 mg	3.1 mg
	CO	43,000 kg	2,900 mg	9.4 mg
	NO_X	11,000 kg	750 mg	2.4 mg
	VOC	6,400 kg	430 mg	1.4 mg
	Pb	12 kg	0.82 mg	0.0027 mg
	PM_{10}	3,200 kg	210 mg	0.69 mg
V, Insurance, Incidents	Energy	770 GJ	51 kJ	0.17 kJ
	GHG	63 mt GGE	4.2 g GGE	0.014 g GGE
	SO_2	150 kg	10 mg	0.034 mg
	CO	700 kg	47 mg	0.15 mg
	NO_X	170 kg	12 mg	0.038 mg
	VOC	130 kg	8.6 mg	0.028 mg
	Pb	-	-	-
	PM_{10}	33 kg	2.2 mg	0.0072 mg
V, Insurance, Health	Energy	8,500 GJ	570 kJ	1.9 kJ
	GHG	690 mt GGE	46 g GGE	0.15 g GGE
	SO_2	1,700 kg	110 mg	0.37 mg
	CO	7,700 kg	510 mg	1.7 mg
	NO_X	1,900 kg	130 mg	0.42 mg
	VOC	1,400 kg	95 mg	0.31 mg
	Pb	-	-	-
	PM_{10}	360 kg	24 mg	0.079 mg

1.8.2 Infrastructure (Airports and Other Components)

Airport construction, operation, and maintenance are included in the air inventory. To evaluate airport impacts, an average airport is considered. To select the average airport, airport passenger throughput is evaluated [BTS 2006]. The top 50 airports are responsible for 610M of the 730M passenger enplanements. Evaluating the top 50 airports reveals that an average airport is around 12M passenger enplanements per year (where Atlanta's Hartsfield-Jackson airport accommodates 42M enplanements annually, the most in the U.S.). Dulles airport is chosen as the average airport because it lies close to the mean and accommodates several Boeing 747 LTOs each day.

Dulles airport consists of 1.2M ft^2 of concourse and 0.5M ft^2 of other buildings [MWAA 2007]. There are three runways, two 11,500 feet, and one 10,500 feet [MWAA 2007]. There are 6.1M ft^2 of taxiways and 14M ft^2 of tarmac [GE 2007]. The airport hosts 25,000 total parking spaces [MWAA 2007].

To account for the entire U.S. fleet, categorizations have been made grouping aircraft by size. All small jet aircraft are considered Embraer 145s, all medium-sized jet aircraft are considered Boeing 737s, and all large aircraft are considered Boeing 747s. These categorizations are shown in Appendix C.

1.8.2.1 Airport Construction

Airport construction is a heavy construction activity which has not been rigorously studied from an environmental standpoint. The materials and process required to construct the airport facilities have not been evaluated in any life-cycle framework. To estimate these impacts, airports have been likened to office buildings. Using the R.S. Means Square Foot Costs construction estimation data (\$80/ft^2 in \$2002) and the facility square footage, total costs for the airport are estimated [RSM 2002]. Extrapolating by the number of passenger enplanements in the U.S. yields a total facility costs for all U.S. airports. All airports are assumed to have a lifetime of 50 years. The impact from construction is determined using the EIO-LCA sector Commercial and Institutional Buildings (#230220) and output is normalized to the functional units as shown in Equation Set 37 [EIO-LCA 2008].

Equation Set 37 – Airport Buildings Inventory

$$\begin{aligned}
I/O^{air,airport\ construction} &= \frac{I/O^{air,airport\ construction}_{EIOLCA}}{lifetime_{airport}} \times \frac{PMT_{aircraft\ size,yr}}{PMT_{all\ U.S.aircraft,yr}} \\
I/O^{air,airport\ construction}_{aircraft\ lifetime} &= I/O^{air,airport\ construction} \times \frac{yr}{PMT_{system}} \times \frac{PMT_{aircraft}}{lifetime_{aircraft}} \\
I/O^{air,airport\ construction}_{VMT} &= I/O^{air,airport\ construction} \times \frac{yr}{VMT_{system}} \\
I/O^{air,airport\ construction}_{PMT} &= I/O^{air,airport\ construction} \times \frac{yr}{VMT_{system}} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}
\end{aligned}$$

1.8.2.2 Runway, Taxiway, and Tarmac Construction and Maintenance

The production and placement of concrete for runways, taxiways, and tarmac construction and maintenance have large environmental impacts. Runway construction and maintenance for U.S. airports is quantified based on runway length data and wearing and subbase layer specifications. Taxiway and tarmac construction and maintenance is based on the Dulles layout and extrapolated for all U.S. airports.

Runways are constructed for a number of quality and reliability characteristics which influence the materials chosen and design specifications. Runways are designed for the most demanding aircraft which will land at the airport [FAA 1998], typically the heaviest aircraft which requires longer runways for landings and takeoffs and does more damage to the material (requiring increased design strength and durability). The top 50 airports average between 3 and 4 runways and most can accommodate large aircraft [Sandel 2006]. Runway construction is estimated with PaLATE and EPA VOC data [PaLATE 2004, EPA 2001]. The top 50 U.S. airports have a combined 1.6M ft of runway [Sandel 2006]. All runways are assigned a wearing layer thickness of 17 in and a subbase thickness of 18 in [FAA 1996]. All runway widths are specified as 163 ft [FAA 1996].

A comprehensive dataset of taxiway and tarmac construction was not located so a takeoff was performed on Dulles airport and extrapolated to all U.S. airports. Taxiways are considered all non-runway paths used by aircraft, and tarmacs are considered the parking and staging areas near terminals, end of runways, and support facilities. Google Earth was used to estimate the area of these concrete components at Dulles Airport [GE 2007]. Taxiways amount to 6.1M ft^2 of area and tarmacs 14M ft^2. A wearing layer of 12 in and subbase of 12 in are assigned to all areas. Extrapolating by the total U.S. runways length and Dulles' total runway length (34,000 ft), a total taxiway and tarmac area was determined. Again, PaLATE was used to estimate the environmental inventory [PaLATE 2004].

The use of PaLATE to estimate runway construction and maintenance likely provides a conservative estimate of total impacts for these components. PaLATE is intended to estimate impacts from roadway construction which is fairly different from runway, taxiway, and tarmac construction. Higher grade materials and additional processes are employed in airport construction that are not used in roadway construction. This includes higher quality aggregate, additional considerations for water runoff, and different concrete mixtures.

The output from PaLATE for these components which reports gross emissions for the entire U.S., must be normalized to the functional units. All components are given a lifetime of 10 years which is a typical expectancy for concrete and asphalt layers with heavy impact.

Equation Set 38 – Airport Infrastructure Runways, Taxiways, and Tarmac Construction and Maintenance

$$rttcm = Runway, Taxiway, or\ Tarmac\ Construction\ and\ Maintenance$$

$$I/O_{PaLATE}^{air,rttcm} = rttcm\ IO\ Determined\ from\ PaLATE$$

$$I/O_{aircraft\ lifetime}^{air,rttcm} = \frac{I/O_{PaLATE}^{air,rttcm}}{lifetime_{rttcm}} \times \frac{yr}{PMT_{aircraft\ size}} \times \frac{PMT_{aircraft}}{lifetime_{aircraft}}$$

$$I/O_{VMT}^{air,rttcm} = \frac{I/O_{PaLATE}^{air,rttcm}}{lifetime_{rttcm}} \times \frac{yr}{VMT_{aircraft\ size}}$$

$$I/O_{PMT}^{air,rttcm} = \frac{I/O_{PaLATE}^{air,rttcm}}{lifetime_{rttcm}} \times \frac{yr}{VMT_{aircraft\ size}} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}$$

1.8.2.3 Operation

The components included in airport operations are lighting electricity, deicing fluid production, and ground support equipment. These components are evaluated with different methodologies which are discussed individually.

Lighting

Airport lighting is split into approach systems, touchdown lights, centerline lights, and edge lights. The electricity consumption of airport lighting systems has been inventoried [EERE 2002]. It is estimated that these systems consume 57, 120, 160, and 140 GWh annually across all U.S. airports. With this annual electricity consumption, emissions are computed assuming a national average electricity mix [Deru 2007].

Deicing Fluid Production

35M gallons of deicing fluid are used each year during low temperatures [EPA 2000]. Most airports use an ethylene or propylene glycol-based fluid which is of particular concern if it enters surface waters where it can significantly impact water quality by reducing dissolved oxygen levels. The production of this fluid contributes to GHG and CAP emissions. The EIO-LCA sector Other Miscellaneous Chemical Product Manufacturing (#325998) captures production of these fluids [EIO-LCA 2008]. The cost of these fluids is between $4.70 and $5 per gallon (in $2000) [EPA 2000]. Using total yearly gallons consumed and the price per gallon, impacts from production were determined in EIO-LCA.

Ground Support Equipment

The multitude of aircraft and airport services which keep vehicles and infrastructure operational are responsible for significant fuel consumption and emissions [EPA 1999]. Support equipment consumes an array of fuels from electricity to fossil-based energy (gasoline, diesel, LNG, CNG) [FAA 2007].

Typical GSEs are [EPA 1999]:

- Aircraft Pushback Tractor
- Conditioned Air Unit
- Air Start Unit
- Baggage Tug
- Belt Loader
- Bobtail
- Cargo Loader
- Cart
- Deicer
- Forklift
- Fuel Truck
- Ground Power Unit
- Lavatory Cart
- Lavatory Truck
- Lift
- Maintenance Truck
- Service Truck
- Bus
- Car
- Pickup Truck
- Van
- Water Truck

There are over 45,000 GSE vehicles in the U.S. airport fleet [EPA 1999]. For every vehicle type, multiple fuel configurations are found. Typical horsepower ratings and equipment load factors are specified for each GSE vehicle and fuel configuration [EPA 1999].

Dulles airport services close to 2% of total U.S. enplanements [BTS 2006]. GSE emissions are determined using the EDMS model. The model requires specific airport GSE populations. The number and configuration of each vehicle type at Dulles is determined by multiplying the U.S. GSE fleet by 2% assuming a linear distribution of vehicles across all airports based on enplanements. Each vehicle was input into the EDMS model including its horsepower rating and load factor. EDMS has default yearly operating hours for each vehicle which are used.

The EDMS model computes CAP emissions (excluding lead) but not fuel consumption and GHG emissions. This analysis is done based on the output of the EDMS model. Fuel consumption is determined from fuel consumption factors by vehicle type per brake-horsepower hour (bhp-hr), which is a measure of the amount of work the engine performs [EPA 1999]. The total work is determined from the EDMS output which allows calculation of total fuel consumption. Given the horsepower rating and fuel configuration of each vehicle, GHG emission factors are also known [EPA 1999]. These factors, combined with the total fuel consumed, determine annual GHG emissions. EDMS does not compute emissions from electricity-powered vehicles because the software is intended to evaluate emissions at airports so these vehicles have been excluded from this analysis. The emissions inventory is scaled up based on Dulles' share of enplanements to capture the U.S. inventory.

Airport Operations Inventory

The airport operation inventory components are computed annually as gross energy consumption or emissions for the U.S.. Each component is normalized as shown in Equation Set 39.

Equation Set 39 – Airport Infrastructure Operations

$$I/O^{air,operation,i} = Annual\ I/O\ of\ Infrastructure\ Operation\ for\ Component\ i$$

$$I/O^{air,operation,i}_{aircraft\ lifetime} = I/O^{air,operation,i} \times \frac{yr}{PMT_{U.S.}} \times \frac{PMT_{aircraft}}{lifetime_{aircraft}}$$

$$I/O^{air,operation,i}_{VMT} = I/O^{air,operation,i} \times \frac{yr}{VMT_{U.S.,aircraft\ size}}$$

$$I/O^{air,operation,i}_{PMT} = I/O^{air,operation,i} \times \frac{yr}{VMT_{U.S.,aircraft\ size}} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}$$

1.8.2.4 Maintenance

Airport maintenance is estimated as 5% of airport construction impacts. This approach is used due to a lack of airport maintenance data and quantifies the environmental effects of yearly material replacement and its associated processes.

1.8.2.5 Parking

Airport parking lot construction and maintenance is treated the same way as parking in other mode inventories. Total parking area is first determined and then the PaLATE tool and pavement VOC data is used to quantify impacts [PaLATE 2004, EPA 2001]. Dulles' 25,000 parking spaces correspond to 1.4M parking spaces at all U.S. airports when extrapolated by the 730M U.S. enplanements and Dulles' 13M [BTS 2006]. Assuming a parking space area of 300 ft^2 plus 10% for access ways, this corresponds to an area of 470M ft^2 of parking area at all U.S. airports. Assuming two 3 in wearing layers and a 6 in subbase, total emissions from airport parking lot construction and maintenance are determined (Equation Set 40). All parking area is assumed to have a 10 year lifetime.

Equation Set 40 – Airport Infrastructure Parking Construction and Maintenance

$$I/O_{PaLATE}^{air,parking} = Airport\ Parking\ Construction\ and\ Maintenance\ I/O$$

$$I/O_{aircraft\ lifetime}^{air,parking} = \frac{I/O_{PaLATE}^{air,parking}}{lifetime_{parking\ area}} \times \frac{yr}{PMT_{U.S.}} \times \frac{PMT_{aircraft}}{lifetime_{aircraft}}$$

$$I/O_{VMT}^{air,parking} = \frac{I/O_{PaLATE}^{air,parking}}{lifetime_{parking\ area}} \times \frac{yr}{VMT_{U.S.}}$$

$$I/O_{PMT}^{air,parking} = \frac{I/O_{PaLATE}^{air,parking}}{lifetime_{parking\ area}} \times \frac{yr}{PMT_{U.S.}}$$

1.8.2.6 Insurance

Non-flight crew benefits and airport insurances are gathered on Dulles airport and extrapolated across the U.S.. Dulles airport reports that $66M was spent on employee salaries and benefits in 2005 [MWAA 2005]. Assuming that salaries and benefits are half of this amount, the remaining half is employee insurances. Extrapolating based on U.S. PMT and Dulles PMT yields a national annual $1.5B expenditure by airports on non-flight crew benefits [BTS 2006]. In 2005, Dulles spent $3.7M on airport insurance [MWAA 2005]. To calculate total U.S. airport expenditures, this was also extrapolated based on PMT. The resulting costs were input into the Insurance Carriers (#524100) sector of EIO-LCA to compute impact.

Table 75 – Aircraft Insurance Costs ($M/aircraft lifetime)

	Embraer 145	Boeing 737	Boeing 747
Benefits for Non-Flight Crew Personnel	1.4	16	14
Non-Vehicle Casualty and Liability	0.2	1.8	1.6

Normalization calculations are shown in Equation Set 41.

Equation Set 41 – Airport Insurance

$$I/O_{EIOLCA}^{air,airport\ insurance} = Annual\ Airport\ Insurance\ I/O$$

$$I/O_{aircraft\ lifetime}^{air,airport\ insurance} = I/O_{EIOLCA}^{air,airport\ insurance} \times \frac{yr}{PMT_{U.S.}} \times \frac{PMT_{aircraft}}{lifetime_{aircraft}}$$

$$I/O_{VMT}^{air,airport\ insurance} = I/O_{EIOLCA}^{air,airport\ insurance} \times \frac{yr}{VMT_{U.S.}}$$

$$I/O_{PMT}^{air,airport\ insurance} = I/O_{EIOLCA}^{air,airport\ insurance} \times \frac{yr}{VMT_{U.S.}} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}$$

1.8.2.7 Usage Attribution (Passengers, Freight, and Mail)

Similar to the vehicle components of air travel, the infrastructure components must also be reduced taking out freight and mail's contribution to overall environmental effects. The percentage share by weight of passengers on aircraft is used (see Table 71) but this does not account for dedicated freight flights which use almost every major airport in the U.S.. 7% of all flights in the U.S. are dedicated freight flights [BTS 2007]. These flights carry high value commodities and emergency shipments. It is assumed that these flights are uniformly distributed at the top 50 airports (although in reality there are freight hubs which account for a large fraction of total tonnage moved).

Infrastructure components are addressed individually for their passenger attribution. Airport terminal and parking construction and maintenance are charged entirely to passengers.

Runway, taxiway, and tarmac construction, operational components, and airport insurance are reduced by the percentage of freight flights as well as by the fraction of freight and mail on each aircraft type.

1.8.2.8 Air Infrastructure Results

Table 76 – Air Infrastructure Inventory for an Embraer 145

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Construction, Airports	Energy	520 GJ	38 kJ	1.1 kJ
	GHG	41 mt GGE	3.0 g GGE	0.089 g GGE
	SO_2	71 kg	5.2 mg	0.16 mg
	CO	370 kg	27 mg	0.82 mg
	NO_X	140 kg	10.0 mg	0.30 mg
	VOC	68 kg	5.0 mg	0.15 mg
	Pb	-	-	-
	PM_{10}	28 kg	2.0 mg	0.061 mg
I, Construction, Runways	Energy	7,300 GJ	530 kJ	16 kJ
	GHG	670 mt GGE	49 g GGE	1.5 g GGE
	SO_2	3,400 kg	250 mg	7.4 mg
	CO	4,800 kg	350 mg	10 mg
	NO_X	2,900 kg	220 mg	6.5 mg
	VOC	-	-	-
	Pb	0.50 kg	0.037 mg	0.0011 mg
	PM_{10}	570 kg	42 mg	1.3 mg
I, Construction, Tarmacs	Energy	19,000 GJ	1,400 kJ	42 kJ
	GHG	1,800 mt GGE	130 g GGE	3.9 g GGE
	SO_2	8,800 kg	650 mg	19 mg
	CO	13,000 kg	920 mg	28 mg
	NO_X	7,700 kg	560 mg	17 mg
	VOC	-	-	-
	Pb	1.3 kg	0.096 mg	0.0029 mg
	PM_{10}	1,500 kg	110 mg	3.3 mg
I, Operation, Runway Lighting	Energy	1,200 GJ	89 kJ	2.7 kJ
	GHG	250 mt GGE	19 g GGE	0.56 g GGE
	SO_2	1,300 kg	93 mg	2.8 mg
	CO	120 kg	9.0 mg	0.27 mg
	NO_X	420 kg	31 mg	0.92 mg
	VOC	11 kg	0.80 mg	0.024 mg
	Pb	0.020 kg	0.0015 mg	0.000044 mg
	PM_{10}	14 kg	1.0 mg	0.031 mg
I, Operation, Deicing Fluid Production	Energy	1,900 GJ	140 kJ	4.2 kJ
	GHG	140 mt GGE	10 g GGE	0.31 g GGE
	SO_2	580 kg	43 mg	1.3 mg
	CO	900 kg	66 mg	2.0 mg
	NO_X	610 kg	45 mg	1.3 mg
	VOC	290 kg	21 mg	0.64 mg
	Pb	-	-	-
	PM_{10}	91 kg	6.6 mg	0.20 mg

Table 76 – Air Infrastructure Inventory for an Embraer 145

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Operation, Ground Support Equipment (GSE)	Energy	15,000 GJ	1,100 kJ	33 kJ
	GHG	1,200 mt GGE	85 g GGE	2.5 g GGE
	SO_2	860 kg	63 mg	1.9 mg
	CO	84,000 kg	6,100 mg	180 mg
	NO_X	12,000 kg	850 mg	25 mg
	VOC	3,100 kg	230 mg	6.8 mg
	Pb	-	-	-
	PM_{10}	500 kg	37 mg	1.1 mg
I, Maintenance, Airports	Energy	26 GJ	1.9 kJ	0.057 kJ
	GHG	2.0 mt GGE	0.15 g GGE	0.0045 g GGE
	SO_2	3.6 kg	0.26 mg	0.0078 mg
	CO	19 kg	1.4 mg	0.041 mg
	NO_X	6.8 kg	0.50 mg	0.015 mg
	VOC	3.4 kg	0.25 mg	0.0075 mg
	Pb	-	-	-
	PM_{10}	1.4 kg	0.10 mg	0.0031 mg
I, Maintenance, Runways	Energy	580 GJ	43 kJ	1.3 kJ
	GHG	83 mt GGE	6.1 g GGE	0.18 g GGE
	SO_2	210 kg	15 mg	0.45 mg
	CO	630 kg	46 mg	1.4 mg
	NO_X	290 kg	21 mg	0.64 mg
	VOC	-	-	-
	Pb	0.077 kg	0.0057 mg	0.00017 mg
	PM_{10}	68 kg	5.0 mg	0.15 mg
I, Maintenance, Tarmacs	Energy	1,500 GJ	110 kJ	3.4 kJ
	GHG	220 mt GGE	16 g GGE	0.48 g GGE
	SO_2	540 kg	39 mg	1.2 mg
	CO	1,700 kg	120 mg	3.7 mg
	NO_X	770 kg	56 mg	1.7 mg
	VOC	-	-	-
	Pb	0.20 kg	0.015 mg	0.00045 mg
	PM_{10}	180 kg	13 mg	0.40 mg
I, Parking	Energy	6,400 GJ	470 kJ	14 kJ
	GHG	610 mt GGE	45 g GGE	1.3 g GGE
	SO_2	3,300 kg	240 mg	7.2 mg
	CO	4,400 kg	320 mg	9.7 mg
	NO_X	2,600 kg	190 mg	5.7 mg
	VOC	-	-	-
	Pb	0.37 kg	0.027 mg	0.00082 mg
	PM_{10}	480 kg	35 mg	1.0 mg
I, Insurance, Non-Operator	Energy	1,100 GJ	82 kJ	2.5 kJ
	GHG	91 mt GGE	6.7 g GGE	0.20 g GGE
	SO_2	220 kg	16 mg	0.49 mg
	CO	1,000 kg	74 mg	2.2 mg
	NO_X	250 kg	19 mg	0.56 mg
	VOC	190 kg	14 mg	0.41 mg
	Pb	-	-	-
	PM_{10}	48 kg	3.5 mg	0.10 mg

Table 76 – Air Infrastructure Inventory for an Embraer 145

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Insurance, Liability	Energy	130 GJ	9.2 kJ	0.28 kJ
	GHG	10 mt GGE	0.75 g GGE	0.023 g GGE
	SO_2	25 kg	1.8 mg	0.055 mg
	CO	110 kg	8.3 mg	0.25 mg
	NO_X	28 kg	2.1 mg	0.062 mg
	VOC	21 kg	1.5 mg	0.046 mg
	Pb	-	-	-
	PM_{10}	5.4 kg	0.39 mg	0.012 mg

Table 77 – Air Infrastructure Inventory for a Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Construction, Airports	Energy	5,800 GJ	120 kJ	1.1 kJ
	GHG	450 mt GGE	9.0 g GGE	0.089 g GGE
	SO_2	790 kg	16 mg	0.16 mg
	CO	4,100 kg	83 mg	0.82 mg
	NO_X	1,500 kg	30 mg	0.30 mg
	VOC	760 kg	15 mg	0.15 mg
	Pb	-	-	-
	PM_{10}	310 kg	6.2 mg	0.061 mg
I, Construction, Runways	Energy	80,000 GJ	1,600 kJ	16 kJ
	GHG	7,400 mt GGE	150 g GGE	1.5 g GGE
	SO_2	37,000 kg	740 mg	7.3 mg
	CO	52,000 kg	1,000 mg	10 mg
	NO_X	32,000 kg	650 mg	6.4 mg
	VOC	-	-	-
	Pb	5.5 kg	0.11 mg	0.0011 mg
	PM_{10}	6,300 kg	130 mg	1.2 mg
I, Construction, Tarmacs	Energy	210,000 GJ	4,200 kJ	41 kJ
	GHG	19,000 mt GGE	390 g GGE	3.8 g GGE
	SO_2	97,000 kg	1,900 mg	19 mg
	CO	140,000 kg	2,700 mg	27 mg
	NO_X	84,000 kg	1,700 mg	17 mg
	VOC	-	-	-
	Pb	14 kg	0.29 mg	0.0028 mg
	PM_{10}	16,000 kg	330 mg	3.2 mg
I, Operation, Runway Lighting	Energy	13,000 GJ	270 kJ	2.6 kJ
	GHG	2,800 mt GGE	56 g GGE	0.55 g GGE
	SO_2	14,000 kg	280 mg	2.8 mg
	CO	1,300 kg	27 mg	0.27 mg
	NO_X	4,600 kg	92 mg	0.91 mg
	VOC	120 kg	2.4 mg	0.024 mg
	Pb	0.22 kg	0.0044 mg	0.000043 mg
	PM_{10}	150 kg	3.1 mg	0.030 mg

Table 77 – Air Infrastructure Inventory for a Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Operation, Deicing Fluid Production	Energy	21,000 GJ	420 kJ	4.1 kJ
	GHG	1,500 mt GGE	31 g GGE	0.31 g GGE
	SO_2	6,400 kg	130 mg	1.3 mg
	CO	9,900 kg	200 mg	2.0 mg
	NO_X	6,700 kg	130 mg	1.3 mg
	VOC	3,200 kg	64 mg	0.63 mg
	Pb	-	-	-
	PM_{10}	990 kg	20 mg	0.20 mg
I, Operation, Ground Support Equipment (GSE)	Energy	170,000 GJ	3,300 kJ	33 kJ
	GHG	13,000 mt GGE	250 g GGE	2.5 g GGE
	SO_2	9,400 kg	190 mg	1.9 mg
	CO	920,000 kg	18,000 mg	180 mg
	NO_X	130,000 kg	2,500 mg	25 mg
	VOC	34,000 kg	680 mg	6.7 mg
	Pb	-	-	-
	PM_{10}	5,500 kg	110 mg	1.1 mg
I, Maintenance, Airports	Energy	290 GJ	5.8 kJ	0.057 kJ
	GHG	23 mt GGE	0.45 g GGE	0.0045 g GGE
	SO_2	40 kg	0.79 mg	0.0078 mg
	CO	210 kg	4.1 mg	0.041 mg
	NO_X	76 kg	1.5 mg	0.015 mg
	VOC	38 kg	0.76 mg	0.0075 mg
	Pb	-	-	-
	PM_{10}	16 kg	0.31 mg	0.0031 mg
I, Maintenance, Runways	Energy	6,400 GJ	130 kJ	1.3 kJ
	GHG	910 mt GGE	18 g GGE	0.18 g GGE
	SO_2	2,200 kg	45 mg	0.44 mg
	CO	6,900 kg	140 mg	1.4 mg
	NO_X	3,200 kg	64 mg	0.63 mg
	VOC	-	-	-
	Pb	0.85 kg	0.017 mg	0.00017 mg
	PM_{10}	750 kg	15 mg	0.15 mg
I, Maintenance, Tarmacs	Energy	17,000 GJ	340 kJ	3.3 kJ
	GHG	2,400 mt GGE	48 g GGE	0.47 g GGE
	SO_2	5,900 kg	120 mg	1.2 mg
	CO	18,000 kg	370 mg	3.6 mg
	NO_X	8,500 kg	170 mg	1.7 mg
	VOC	-	-	-
	Pb	2.2 kg	0.045 mg	0.00044 mg
	PM_{10}	2,000 kg	39 mg	0.39 mg
I, Parking	Energy	71,000 GJ	1,400 kJ	14 kJ
	GHG	6,800 mt GGE	140 g GGE	1.3 g GGE
	SO_2	36,000 kg	730 mg	7.2 mg
	CO	49,000 kg	990 mg	9.7 mg
	NO_X	29,000 kg	570 mg	5.7 mg
	VOC	-	-	-
	Pb	4.1 kg	0.083 mg	0.00082 mg
	PM_{10}	5,300 kg	110 mg	1.0 mg

Table 77 – Air Infrastructure Inventory for a Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Insurance, Non-Operator	Energy	12,000 GJ	240 kJ	2.4 kJ
	GHG	1,000 mt GGE	20 g GGE	0.20 g GGE
	SO_2	2,500 kg	49 mg	0.49 mg
	CO	11,000 kg	220 mg	2.2 mg
	NO_X	2,800 kg	55 mg	0.55 mg
	VOC	2,100 kg	41 mg	0.41 mg
	Pb	-	-	-
	PM_{10}	520 kg	10 mg	0.10 mg
I, Insurance, Liability	Energy	1,400 GJ	28 kJ	0.27 kJ
	GHG	110 mt GGE	2.3 g GGE	0.022 g GGE
	SO_2	280 kg	5.5 mg	0.055 mg
	CO	1,200 kg	25 mg	0.25 mg
	NO_X	310 kg	6.2 mg	0.061 mg
	VOC	230 kg	4.6 mg	0.046 mg
	Pb	-	-	-
	PM_{10}	59 kg	1.2 mg	0.012 mg

Table 78 – Air Infrastructure Inventory for a Boeing 747

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Construction, Airports	Energy	5,200 GJ	350 kJ	1.1 kJ
	GHG	410 mt GGE	27 g GGE	0.089 g GGE
	SO_2	710 kg	48 mg	0.16 mg
	CO	3,700 kg	250 mg	0.82 mg
	NO_X	1,400 kg	91 mg	0.30 mg
	VOC	690 kg	46 mg	0.15 mg
	Pb	-	-	-
	PM_{10}	280 kg	19 mg	0.061 mg
I, Construction, Runways	Energy	61,000 GJ	4,100 kJ	13 kJ
	GHG	5,700 mt GGE	380 g GGE	1.2 g GGE
	SO_2	28,000 kg	1,900 mg	6.2 mg
	CO	40,000 kg	2,700 mg	8.8 mg
	NO_X	25,000 kg	1,700 mg	5.4 mg
	VOC	-	-	-
	Pb	4.2 kg	0.28 mg	0.00092 mg
	PM_{10}	4,800 kg	320 mg	1.1 mg
I, Construction, Tarmacs	Energy	160,000 GJ	11,000 kJ	35 kJ
	GHG	15,000 mt GGE	1,000 g GGE	3.3 g GGE
	SO_2	75,000 kg	5,000 mg	16 mg
	CO	110,000 kg	7,100 mg	23 mg
	NO_X	65,000 kg	4,300 mg	14 mg
	VOC	-	-	-
	Pb	11 kg	0.74 mg	0.0024 mg
	PM_{10}	13,000 kg	850 mg	2.8 mg

Table 78 – Air Infrastructure Inventory for a Boeing 747

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Operation, Runway Lighting	Energy	10,000 GJ	680 kJ	2.2 kJ
	GHG	2,100 mt GGE	140 g GGE	0.47 g GGE
	SO_2	11,000 kg	720 mg	2.4 mg
	CO	1,000 kg	69 mg	0.23 mg
	NO_X	3,500 kg	240 mg	0.78 mg
	VOC	92 kg	6.1 mg	0.020 mg
	Pb	0.17 kg	0.011 mg	0.000037 mg
	PM_{10}	120 kg	7.9 mg	0.026 mg
I, Operation, Deicing Fluid Production	Energy	16,000 GJ	1,100 kJ	3.5 kJ
	GHG	1,200 mt GGE	80 g GGE	0.26 g GGE
	SO_2	4,900 kg	330 mg	1.1 mg
	CO	7,600 kg	510 mg	1.7 mg
	NO_X	5,100 kg	340 mg	1.1 mg
	VOC	2,400 kg	160 mg	0.53 mg
	Pb	-	-	-
	PM_{10}	760 kg	51 mg	0.17 mg
I, Operation, Ground Support Equipment (GSE)	Energy	130,000 GJ	8,500 kJ	28 kJ
	GHG	9,700 mt GGE	650 g GGE	2.1 g GGE
	SO_2	7,200 kg	480 mg	1.6 mg
	CO	710,000 kg	47,000 mg	150 mg
	NO_X	98,000 kg	6,500 mg	21 mg
	VOC	26,000 kg	1,700 mg	5.7 mg
	Pb	-	-	-
	PM_{10}	4,300 kg	280 mg	0.93 mg
I, Maintenance, Airports	Energy	260 GJ	18 kJ	0.057 kJ
	GHG	20 mt GGE	1.4 g GGE	0.0045 g GGE
	SO_2	36 kg	2.4 mg	0.0078 mg
	CO	190 kg	12 mg	0.041 mg
	NO_X	68 kg	4.6 mg	0.015 mg
	VOC	34 kg	2.3 mg	0.0075 mg
	Pb	-	-	-
	PM_{10}	14 kg	0.94 mg	0.0031 mg
I, Maintenance, Runways	Energy	4,900 GJ	330 kJ	1.1 kJ
	GHG	700 mt GGE	47 g GGE	0.15 g GGE
	SO_2	1,700 kg	120 mg	0.38 mg
	CO	5,300 kg	360 mg	1.2 mg
	NO_X	2,500 kg	170 mg	0.54 mg
	VOC	-	-	-
	Pb	0.65 kg	0.044 mg	0.00014 mg
	PM_{10}	580 kg	39 mg	0.13 mg
I, Maintenance, Tarmacs	Energy	13,000 GJ	860 kJ	2.8 kJ
	GHG	1,800 mt GGE	120 g GGE	0.40 g GGE
	SO_2	4,500 kg	300 mg	1.00 mg
	CO	14,000 kg	940 mg	3.1 mg
	NO_X	6,500 kg	430 mg	1.4 mg
	VOC	-	-	-
	Pb	1.7 kg	0.11 mg	0.00038 mg
	PM_{10}	1,500 kg	100 mg	0.33 mg

Table 78 – Air Infrastructure Inventory for a Boeing 747

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Parking	Energy	64,000 GJ	4,300 kJ	14 kJ
	GHG	6,100 mt GGE	410 g GGE	1.3 g GGE
	SO_2	33,000 kg	2,200 mg	7.2 mg
	CO	44,000 kg	3,000 mg	9.7 mg
	NO_X	26,000 kg	1,700 mg	5.7 mg
	VOC	-	-	-
	Pb	3.7 kg	0.25 mg	0.00082 mg
	PM_{10}	4,800 kg	320 mg	1.0 mg
I, Insurance, Non-Operator	Energy	9,400 GJ	630 kJ	2.1 kJ
	GHG	770 mt GGE	52 g GGE	0.17 g GGE
	SO_2	1,900 kg	130 mg	0.41 mg
	CO	8,500 kg	570 mg	1.9 mg
	NO_X	2,100 kg	140 mg	0.47 mg
	VOC	1,600 kg	110 mg	0.35 mg
	Pb	-	-	-
	PM_{10}	400 kg	27 mg	0.088 mg
I, Insurance, Liability	Energy	1,100 GJ	71 kJ	0.23 kJ
	GHG	87 mt GGE	5.8 g GGE	0.019 g GGE
	SO_2	210 kg	14 mg	0.047 mg
	CO	960 kg	64 mg	0.21 mg
	NO_X	240 kg	16 mg	0.052 mg
	VOC	180 kg	12 mg	0.039 mg
	Pb	-	-	-
	PM_{10}	45 kg	3.0 mg	0.0099 mg

1.8.3 Fuel Production

1.8.3.1 Fuel Production Inventory

The production of jet fuel requires energy and produces emissions. EIO-LCA is used to determine these impacts [EIO-LCA 2008]. The EIO-LCA data models all petroleum refining but the energy and emissions from jet fuel are presumed to be not significantly different from gasoline or diesel. The U.S. average electricity mix from EIO-LCA is used to determine production factors.

Based on total fuel consumption (as described in §1.8.1.2), the production inventory is computed. Fuel production has also been reduced to the portion attributable only to passengers as described in §1.8.1.5. Similar to onroad and diesel rail, distribution of the jet fuel is included assuming a transport distance of 100 miles from refinery to the airports. The environmental performance of tanker trucks is determined with the same factors as described in §1.6.3.2.

1.8.3.2 Fuel Production Results

Table 79 – Aircraft Fuel Production Inventory for an Embraer 145

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
F, Refining & Distribution	Energy	160,000 GJ	11,000 kJ	340 kJ
	GHG	14,000 mt GGE	1,000 g GGE	31 g GGE
	SO_2	26,000 kg	1,900 mg	58 mg
	CO	39,000 kg	2,900 mg	86 mg
	NO_X	25,000 kg	1,800 mg	54 mg
	VOC	17,000 kg	1,200 mg	37 mg
	Pb	-	-	-
	PM_{10}	4,000 kg	290 mg	8.7 mg

Table 80 – Aircraft Fuel Production Inventory for a Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
F, Refining & Distribution	Energy	1,300,000 GJ	26,000 kJ	250 kJ
	GHG	120,000 mt GGE	2,300 g GGE	23 g GGE
	SO_2	220,000 kg	4,400 mg	43 mg
	CO	320,000 kg	6,400 mg	64 mg
	NO_X	200,000 kg	4,100 mg	40 mg
	VOC	140,000 kg	2,800 mg	27 mg
	Pb	-	-	-
	PM_{10}	33,000 kg	660 mg	6.5 mg

Table 81 – Aircraft Fuel Production Inventory for a Boeing 747

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
F, Refining & Distribution	Energy	1,000,000 GJ	68,000 kJ	220 kJ
	GHG	92,000 mt GGE	6,200 g GGE	20 g GGE
	SO_2	170,000 kg	12,000 mg	38 mg
	CO	250,000 kg	17,000 mg	56 mg
	NO_X	160,000 kg	11,000 mg	35 mg
	VOC	110,000 kg	7,300 mg	24 mg
	Pb	-	-	-
	PM_{10}	26,000 kg	1,700 mg	5.7 mg

1.8.4 Fundamental Environmental Factors for Air

The fundamental environmental factors for the air modes are shown in Table 82. These factors are the bases for the component's environmental inventory calculations.

Table 82 – Fundamental Environmental Factors for Air (Sources, Energy, & GHG)

Grouping	Component	Source	Energy		GHG (CO$_2$e)	
Vehicles						
Manufacturing	Small Aircraft	EIO-LCA 2008 (#336411), Janes 2004, Jenkinson 1999	63	TJ/plane	5.1	kg/plane
	Midsize Aircraft	EIO-LCA 2008 (#336411), Boeing 2007, Jenkinson 1999	213	TJ/plane	17	kg/plane
	Large Aircraft	EIO-LCA 2008 (#336411), Boeing 2007, Jenkinson 1999	776	TJ/plane	63	kg/plane
	Small Aircraft Engine	EIO-LCA 2008 (#336412), Jenkinson 1999	7	TJ/eng	592	mt/eng
	Midsize Aircraft Engine	EIO-LCA 2008 (#336412), Jenkinson 1999	14	TJ/eng	1140	mt/eng
	Large Aircraft Engine	EIO-LCA 2008 (#336412), Jenkinson 1999	27	TJ/eng	2192	mt/eng
Small Aircraft Operation	APU Operation	FAA 2007	70	TJ/LTO	4,645	mt/LTO
	Startup	FAA 2007				
	Taxi Out	FAA 2007	884	TJ/LTO	58,793	mt/LTO
	Take Off	FAA 2007	230	TJ/LTO	15,302	mt/LTO
	Climb Out	FAA 2007	606	TJ/LTO	40,302	mt/LTO
	Cruise	IPCC 2006, ATA 2003, Romano 1999, Pehrson 2005	79	MJ/VMT	5.3	kg/VMT
	Approach	FAA 2007	411	TJ/LTO	27,365	mt/LTO
	Taxi In	FAA 2007	325	TJ/LTO	21,629	mt/LTO
Medium Aircraft Operation	APU Operation	FAA 2007	105	TJ/LTO	6,977	mt/LTO
	Startup	FAA 2007				
	Taxi Out	FAA 2007	756	TJ/LTO	50,302	mt/LTO
	Take Off	FAA 2007	212	TJ/LTO	14,120	mt/LTO
	Climb Out	FAA 2007	560	TJ/LTO	37,264	mt/LTO
	Cruise	EEA 2006, Romano 1999, Pehrson 2005, IPCC 2006	223	MJ/VMT	15.0	kg/VMT
	Approach	FAA 2007	376	TJ/LTO	25,006	mt/LTO
	Taxi In	FAA 2007	279	TJ/LTO	18,552	mt/LTO
Large Aircraft Operation	APU Operation	FAA 2007	146	TJ/LTO	9,728	mt/LTO
	Startup	FAA 2007				
	Taxi Out	FAA 2007	200	TJ/LTO	13,336	mt/LTO
	Take Off	FAA 2007	88	TJ/LTO	5,877	mt/LTO
	Climb Out	FAA 2007	225	TJ/LTO	14,984	mt/LTO
	Cruise	EEA 2006, Romano 1999, Pehrson 2005	783	MJ/VMT	52.6	kg/VMT
	Approach	FAA 2007	135	TJ/LTO	8,953	mt/LTO
	Taxi In	FAA 2007	74	TJ/LTO	4,910	mt/LTO
Maintenance	Aircraft	EIO-LCA 2008 (Various Sectors)	25	TJ/$M	1762	mt/$M
	Engine	EIO-LCA 2008 (#336412)	5.1	TJ/$M	411	mt/$M
Insurance	Crew Health and Benefits	EIO-LCA 2008 (#524100)	1.0	TJ/$M	84	mt/$M
	Aircraft liability	EIO-LCA 2008 (#524100)	1.0	TJ/$M	84	mt/$M
Infrastructure						
Construction	Airports	EIO-LCA 2008 (#230220)	549	MJ/ft^2	43	kg/ft^2
	Runway	PaLATE 2004, EPA 2001	136	MJ/ft^2	10	kg/ft^2
	Taxiway/Tarmac	PaLATE 2004, EPA 2001	95	MJ/ft^2	6.8	kg/ft^2
Operation	Runway Lighting	EERE 2002, Deru 2007	471	GWH/yr	758	g/kWh
	Deicing Fluid Production	EIO-LCA 2008 (#325998)	76	MJ/gal	6	kg/gal
	GSE Operation	FAA 2007	47	MJ/LTO	4	kg/LTO
Maintenance	Airports		28	TJ/ft^2	2	mt/ft^2
Parking	Airports	PaLATE 2004, EPA 2001	35	MJ/ft^2	2.2	kg/ft^2
Insurance	Non-Crew Health and Benefits	EIO-LCA 2008 (#524100)	1.0	TJ/$M	84	mt/$M
	Infrastructure Liability	EIO-LCA 2008 (#524100)	1.0	TJ/$M	84	mt/$M
Fuels						
Production	Jet Fuel Refining	EIO-LCA 2008 (#324100)	25	TJ/$M	2200	mt/$M

Table 82 – Fundamental Environmental Factors for Air (cont'd) (CAP)

Grouping	Component	SO_2		CO		NO_X		VOC		Pb		PM_{10}	
Vehicles													
Aircraft Manufacturing	Small	13	mt/pla	51	mt/pla	11	mt/pla	8.4	mt/pla			3.1	mt/pla
	Midsize	45	mt/pla	171	mt/pla	38	mt/pla	28	mt/pla			11	mt/pla
	Large	164	mt/pla	625	mt/pla	137	mt/pla	103	mt/pla			38	mt/pla
Engine Manufacturing	Small	1.7	mt/eng	5	mt/eng	1.3	mt/eng	0.8	mt/eng	1.4	kg/eng	0.4	mt/eng
	Midsize	3.2	mt/eng	10	mt/eng	2.5	mt/eng	1.5	mt/eng	2.8	kg/eng	0.7	mt/eng
	Large	6.2	mt/eng	19	mt/eng	4.9	mt/eng	2.8	mt/eng	5.3	kg/eng	1.4	mt/eng
Small Aircraft Operation	APU Operation	4.3	mt/LTO	28	mt/LTO	20	mt/LTO	2.6	mt/LTO				
	Startup							69	mt/LTO				
	Taxi Out	26	mt/LTO	315	mt/LTO	74	mt/LTO	43	mt/LTO			2.9	mt/LTO
	Take Off	6.7	mt/LTO	4	mt/LTO	103	mt/LTO	1.2	mt/LTO			1.3	mt/LTO
	Climb Out	17.6	mt/LTO	10	mt/LTO	232	mt/LTO	3.2	mt/LTO			3.1	mt/LTO
	Cruise	1.7	g/VMT	2.3	g/VMT	13	g/VMT	0.3	g/VMT			0.1	g/VMT
	Approach	11.9	mt/LTO	28	mt/LTO	70	mt/LTO	5.1	mt/LTO			1.9	mt/LTO
	Taxi In	9.4	mt/LTO	116	mt/LTO	27	mt/LTO	15.9	mt/LTO			1.1	mt/LTO
Medium Aircraft Operation	APU Operation	2.5	mt/LTO	45	mt/LTO	12	mt/LTO	2.6	mt/LTO				
	Startup							47	mt/LTO				
	Taxi Out	21.9	mt/LTO	535	mt/LTO	65	mt/LTO	33.6	mt/LTO			3.9	mt/LTO
	Take Off	6.2	mt/LTO	4	mt/LTO	82	mt/LTO	0.2	mt/LTO			1.0	mt/LTO
	Climb Out	16.3	mt/LTO	11	mt/LTO	190	mt/LTO	0.5	mt/LTO			2.2	mt/LTO
	Cruise	4.8	g/VMT	8.3	g/VMT	52	g/VMT	0.5	g/VMT			0.2	g/VMT
	Approach	10.9	mt/LTO	29	mt/LTO	68	mt/LTO	0.6	mt/LTO			1.6	mt/LTO
	Taxi In	8.1	mt/LTO	197	mt/LTO	24	mt/LTO	12.4	mt/LTO			1.4	mt/LTO
Large Aircraft Operation	APU Operation	0.7	mt/LTO	12	mt/LTO	2	mt/LTO	1.1	mt/LTO				
	Startup							5	mt/LTO				
	Taxi Out	5.8	mt/LTO	48	mt/LTO	22	mt/LTO	2.6	mt/LTO			1.3	mt/LTO
	Take Off	2.6	mt/LTO	0	mt/LTO	63	mt/LTO	0.2	mt/LTO			1.0	mt/LTO
	Climb Out	6.5	mt/LTO	1	mt/LTO	121	mt/LTO	0.6	mt/LTO			2.6	mt/LTO
	Cruise	16.7	g/VMT	16.1	g/VMT	207	g/VMT	4.1	g/VMT			0.7	g/VMT
	Approach	3.9	mt/LTO	2	mt/LTO	34	mt/LTO	0.7	mt/LTO			0.9	mt/LTO
	Taxi In	2.1	mt/LTO	18	mt/LTO	8	mt/LTO	0.9	mt/LTO			0.5	mt/LTO
Maintenance	Aircraft	3.1	mt/\$M	7.9	mt/\$M	2.1	mt/\$M	2.3	mt/\$M	2.0	kg/\$M	0.6	mt/\$M
	Engine	1160	kg/\$M	3500	kg/\$M	912	kg/\$M	527	kg/\$M	1.0	kg/\$M	258	kg/\$M
Insurance	Crew Health and Benefits	207	kg/\$M	934	kg/\$M	233	kg/\$M	173	kg/\$M	0	kg/\$M	44	kg/\$M
	Aircraft liability	207	kg/\$M	934	kg/\$M	233	kg/\$M	173	kg/\$M	0	kg/\$M	44	kg/\$M
Infrastructure													
Construction	Airports	75	g/ft^2	390	g/ft^2	143	g/ft^2	72	g/ft^2	0	g/ft^2	29	g/ft^2
	Runway	72	g/ft^2	58	g/ft^2	131	g/ft^2	0	g/ft^2	8.1	mg/ft^2	207	g/ft^2
	Taxiway/Tarmac	50	g/ft^2	41	g/ft^2	92	g/ft^2	0	g/ft^2	5.7	mg/ft^2	36	g/ft^2
Operation	Runway Lighting	4	g/kWh	0.4	g/kWh	1.3	g/kWh	0.03	g/kWh	0	g/kWh	42	mg/kWh
	Deicing Fluid Production	23	g/gal	36	g/gal	24	g/gal	12	g/gal	0	g/gal	3.6	g/gal
	GSE Operation	2.6	g/LTO	255	g/LTO	35	g/LTO	9.4	g/LTO			1.5	g/LTO
Maintenance	Airports	4	mt/ft^2	19	mt/ft^2	7	mt/ft^2	4	mt/ft^2	0	mt/ft^2	1	mt/ft^2
Parking	Airports	46	g/ft^2	10	g/ft^2	26	g/ft^2	36	g/ft^2	0.4	mg/ft^2	59	g/ft^2
Insurance	Non-Crew Health and Benefits	207	kg/\$M	934	kg/\$M	233	kg/\$M	173	kg/\$M	0	kg/\$M	44	kg/\$M
	Infrastructure Liability	207	kg/\$M	934	kg/\$M	233	kg/\$M	173	kg/\$M	0	kg/\$M	44	kg/\$M
Fuels													
Production	Jet Fuel Refining	4220	kg/\$M	6020	kg/\$M	2460	kg/\$M	2730	kg/\$M	0	kg/\$M	436	kg/\$M

1.8.5 Air Summary

While aircraft are dominated by operational phases in the life-cycle inventory for energy consumption and GHG emissions, this is not necessarily the case for CAP emissions. The large PMT traveled per flight has strong effects on which life-cycle components dominate each phase as compared to other modes.

Aircraft operation is modeled with average U.S. data which is not necessarily representative of specific U.S. conditions or international conditions. Aircraft operation outside of U.S. average conditions should be carefully evaluated before use of inventory results (§1.8.1.6, §1.8.2.8, and §1.8.3.2). This is particularly true for the Boeing 747 (large aircraft) which may show the largest range of operating conditions and resulting environmental performance (especially when normalized per PMT).

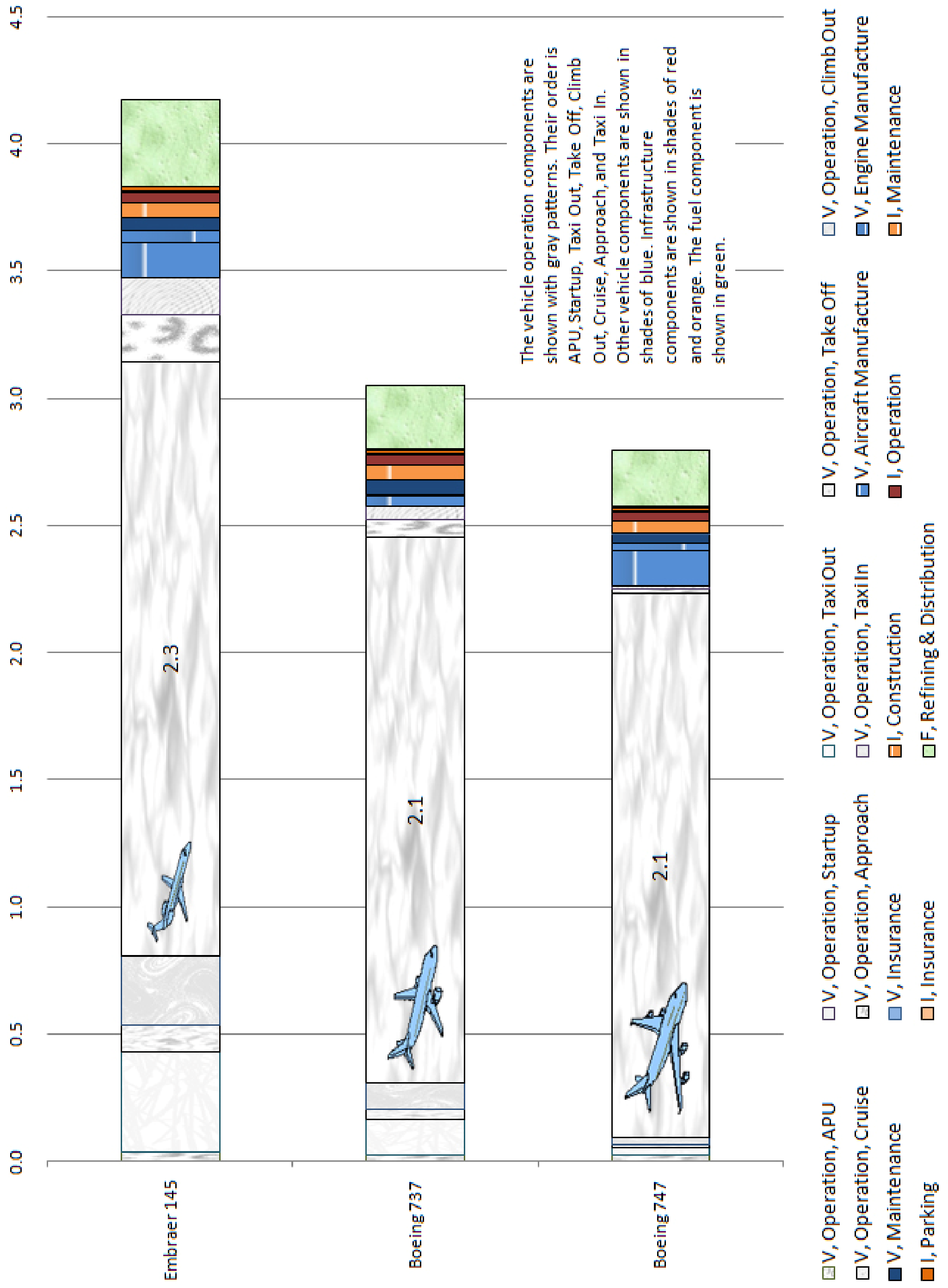
1.8.5.1 Energy and GHG Emissions

The significant components for energy and GHG emissions are the vehicle operational components, aircraft manufacturing, and jet fuel production.

Aircraft Operation

The cruise phase accounts for between 55% (Embraer 145) and 74% (Boeing 747) of total energy consumption and GHG emissions. The other operational components (APU, startup, taxi out, take off, climb out, approach, and taxi in) make up between 4% (Boeing 747) and 27% (Embraer 145) of total energy consumption and GHG emissions. The fuel and associated GHG emissions of an average 19 min taxi out show as a major component in final results. Additionally, the climb out and approach stages also show as major contributions. The importance of disaggregating operational emissions as discussed in §7.5.2 is less important with energy and GHG emissions because impacts occur at global scales.

Figure 14 – Air Travel Energy Inventory



The vehicle operation components are shown with gray patterns. Their order is APU, Startup, Taxi Out, Take Off, Climb Out, Cruise, Approach, and Taxi In. Other vehicle components are shown in shades of blue. Infrastructure components are shown in shades of red and orange. The fuel component is shown in green.

Aircraft Manufacturing

The impacts of aircraft manufacturing are significant for all aircraft but are most noticeable with the 747. For this aircraft, manufacturing energy consumption and emissions are about 43% larger than non-cruise operational emissions and 6% of total. The lowest manufacturing emissions (per PMT) are experienced with the 737. Given the medium-range nature of its flights coupled with manufacturing requirements, which are significantly less than the 747, leads to a comparatively low factor.

Fuel Production

For every 100 units of jet fuel produced, an additional 16 units are needed (in both direct and indirect supply chain support) [EIO-LCA 2008, SimaPro 2006]. Given that operational phases dominate aircraft energy and GHG emissions, the 16% fuel production component increase is a direct major contributor to energy and GHG inventories. Fuel production is about 8% of total energy consumption for all aircraft. With GHG emissions, approximately 10% is attributable to this component.

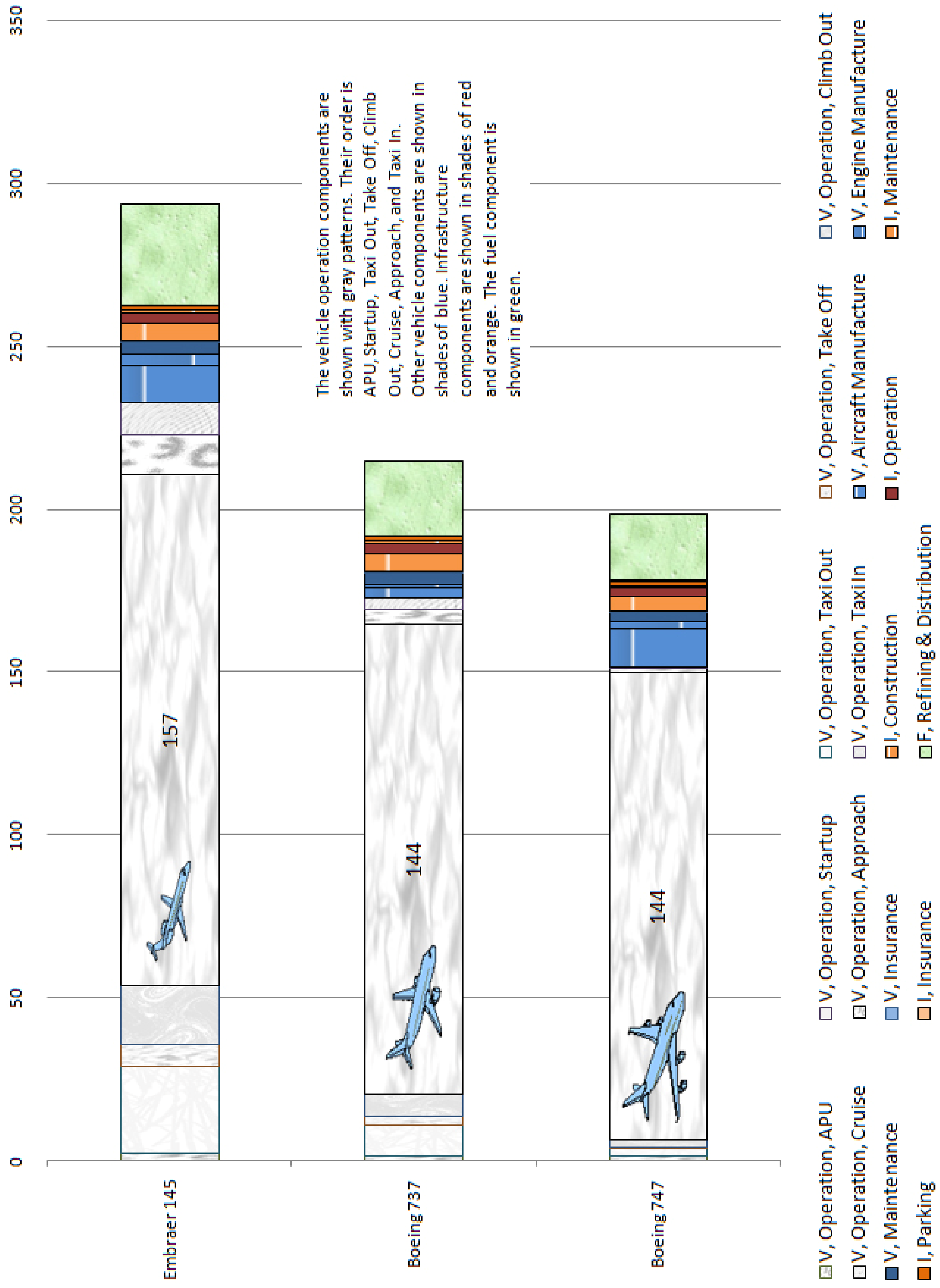
Summary

Table 83 details total and operational energy consumption and GHG emissions for the aircraft.

Table 83 – Air Energy and GHG Life-cycle Inventory (operational emissions in parenthesis)

	Embraer 145	Boeing 737	Boeing 747
Energy (MJ/PMT)	4.2 (3.5)	3.0 (2.6)	2.8 (2.3)
GHG (g/PMT)	290 (230)	210 (170)	200 (150)

Figure 15 – Air Travel GHG Inventory



The vehicle operation components are shown with gray patterns. Their order is APU, Startup, Taxi Out, Take Off, Climb Out, Cruise, Approach, and Taxi In. Other vehicle components are shown in shades of blue. Infrastructure components are shown in shades of red and orange. The fuel component is shown in green.

1.8.5.2 Criteria Air Pollutant Emissions

The CAP emission inventory is not always dominated by the operational phases of aircraft propulsion but sometimes by aircraft manufacturing, GSE operation, taxiway/tarmac construction, and fuel production.

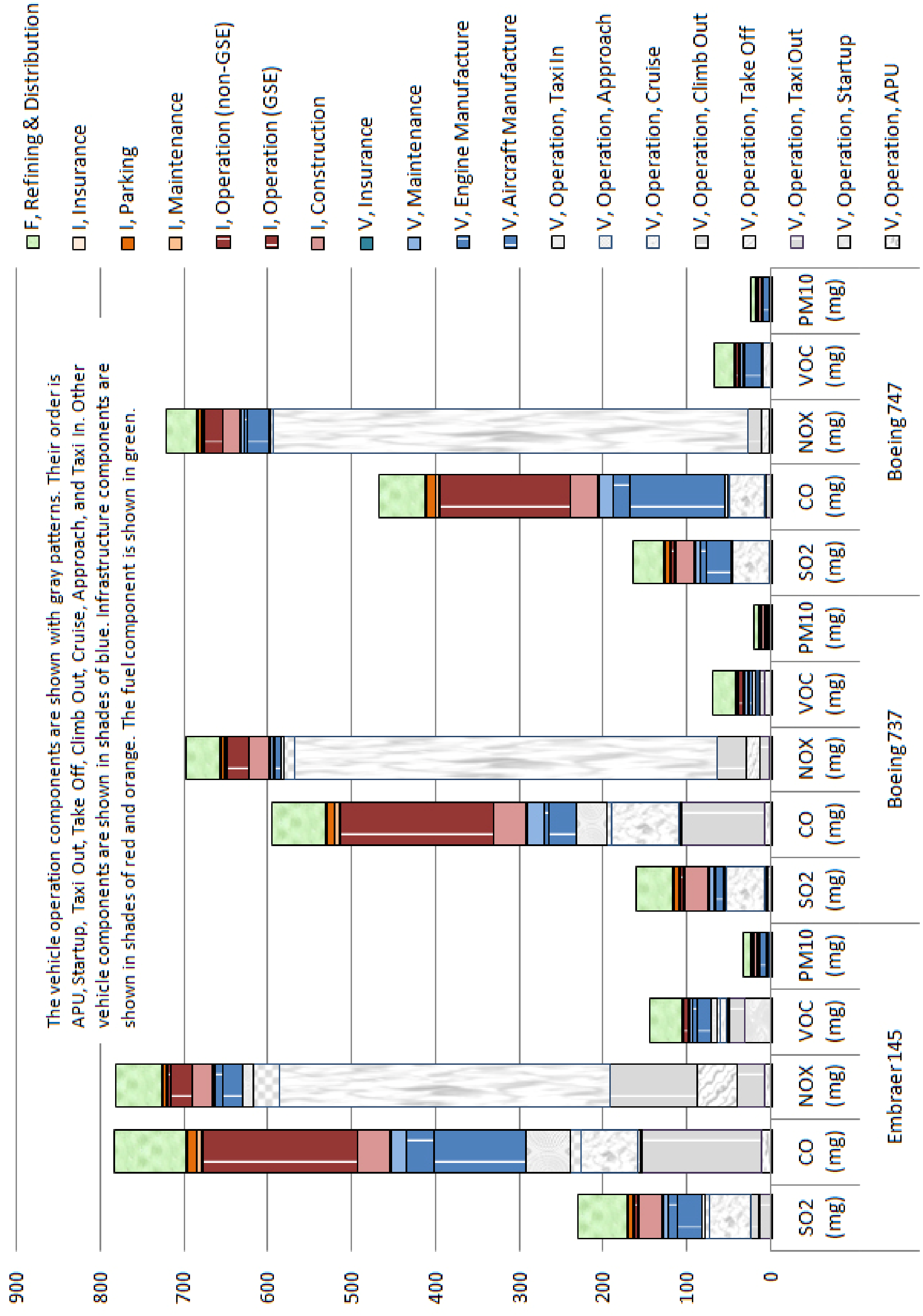
Aircraft Manufacturing

Total CO emissions are strongly affected by aircraft manufacturing. Half of these CO emissions result from truck transportation in the movement of parts for final assembly and sub assembly [EIO-LCA 2008]. Aircraft manufacturing contributes SO_2 emissions associated with electricity requirements (which are heavily produced from sulfur-laden coal). Additionally, the indirect electricity requirements to extract and refine copper and aluminum are major contributors. VOC emissions, from truck transport and directly from manufacturing processes, add 10-20 mg/PMT to total life-cycle emissions. PM in aircraft manufacturing (2-7 mg/PMT) results primarily from waste management and metal mining.

GSE Operation

The operation of fossil-fuel powered vehicles results in large CO emissions at airports. The primary culprit for these emissions is the gasoline baggage tractors which emit about one-half of all GSE CO emissions. The emissions from diesel, gasoline, and electric GSE at airports increase aircraft life-cycle NO_X emissions by 21-25 mg/PMT and CO emissions by 150-180 mg/PMT.

Figure 16 – Air Travel CAP Inventory



The vehicle operation components are shown with gray patterns. Their order is APU, Startup, Taxi Out, Take Off, Climb Out, Cruise, Approach, and Taxi In. Other vehicle components are shown in shades of blue. Infrastructure components are shown in shades of red and orange. The fuel component is shown in green.

Taxiway and Tarmac Construction

Fugitive dust emissions from the construction and maintenance of taxiways and tarmacs have a strong effect on total inventory PM_{10} emissions. The use of concrete with a 10 year replacement cycle produces repeated emissions at 3-4 mg/PMT.

Fuel Production

Emissions associated with fuel production are significant for all pollutants and aircraft. Similar to fuel production for other modes, the impacts are primarily the result of coal-derived electricity production, which releases CAPs during combustion, as well as SO_2 off gasing [EIO-LCA 2008]. Fuel production adds 24-37 mg/PMT of VOCs to total emissions resulting from direct refinery processes and diesel equipment use in oil extraction. The use of diesel trucks and equipment in oil extraction and transport contribute 56-86 mg/PMT to total CO.

Summary

The contribution of life-cycle components is very significant to total emissions from aircraft. The minimum increase is 1.2 times for NO_X comparing operation to total life-cycle impacts. PM_{10} emissions show large increases, 5.1 to 9.2 times for the different aircraft.

Table 84 – Air CAP Life-cycle Inventory (operational emissions in parenthesis)

	Embraer 145	Boeing 737	Boeing 747
CO (g/PMT)	780 (290)	600 (230)	470 (55)
SO_2 (mg/PMT)	230 (84)	160 (58)	170 (49)
NO_X (mg/PMT)	780 (630)	700 (590)	720 (600)
VOC (mg/PMT)	140 (71)	70 (22)	69 (13)
PM_{10} (mg/PMT)	34 (6.6)	22 (3.7)	25 (2.7)

It is important to distinguish the differences between life-cycle emissions when temporal and geographic factors are introduced. When and where emissions occur is critical to evaluating impact. Emissions reported here do not distinguish between temporal and geographic factors. The PM emissions from airport construction for example, occur once, but in this study, are represented over the life of the facility. Other PM emissions may occur continually throughout this time such as that from combustion in aircraft operation. Any impact assessment using these factors should attempt to address these issues.

1.9 Geographic and Temporal Considerations

The energy inputs and emission outputs in the life-cycle of the modes have been presented as geographically and temporally undifferentiated. For example, the CO emissions from manufacturing a train and moving a train have been normalized to CO per PMT. From a life-cycle emissions inventory perspective, this normalization is necessary to understand the magnitude of non-operational effects. This does not however, offer enough detail for impact assessment frameworks when the goal is to understand exposure and effects of the emissions. The CO emissions from manufacturing the train occurred during a short time frame where the facility was located. The CO emissions from train propulsion occur continuously over a larger region.

Table 85 – Onroad Life-cycle Component Temporal and Geographic Differentiation

Life-cycle Component	Input/Output Contributor		Temporal	Geographic
Vehicle				
Manufacturing	Manufacturing processes	◈	One-time	Manufacturing facilities, indirect support
Operation (Running)	Gasoline/Diesel fuel combustion		Continuous	Vehicle route
Operation (Start)	Gasoline/Diesel fuel combustion		Continuous	Vehicle route
Operation (Tire)	Tire wear		Continuous	Vehicle route
Operation (Brake)	Brake pad wear		Continuous	Vehicle route
Operation (Evaporative Losses)	Gasoline/Diesel fuel losses		Continuous	Vehicle route
Operation (Idling)	Gasoline/Diesel fuel combustion		Continuous	Vehicle route
Tire Production	Manufacturing processes	◈	One-time	Manufacturing facilities, indirect support
Vehicle Maintenance	Manufacturing processes for parts	◈	Continuous	Maintenance facilities, indirect support
Automotive Repair Stations	Cleaner & degreaser emissions		Continuous	Repair stations
Insurances	Insurance facilities requirements	◈	Continuous	Power plants, indirect support

Table 85 – Onroad Life-cycle Component Temporal and Geographic Differentiation

Life-cycle Component	Input/Output Contributor		Temporal	Geographic
Infrastructure				
Roadway Construciton	Direct processes, material production	◈	One-time	Roads, indirect support
Roadway Maintenance	Direct processes, material production	◈	Continuous	Roads, indirect support
Herbicide Production	Production processes	◈	Continuous	Manufacturing facilities, indirect support
Salt Production	Production processes	◈	Continuous	Manufacturing facilities, indirect support
Roadway Lighting	Electricity consumption	◈	Continuous	Power plants, indirect support
Parking Construction & Maintenance	Direct processes, material production	◈	One-time	Manufacturing facilities, indirect support
Fuels				
Refining & Distribution	Direct processes, fuel production	◈	Continuous	Extraction region, refining region, transport network

◈ indicates that indirect energy inputs and emission outputs from the supply chain are included

Table 85 through Table 87 detail the temporal and geographic differences in each of the life-cycle components for onroad, rail, and air modes. Although this study used several different LCA methods and data sources to compute energy inputs and emissions, specific energy and emission pathways were evaluated. These are direct energy use, material production, parts production, or a particular process (such as building construction or asphalt paving). In addition to these causes, the LCA method often provided indirect effects such as material extraction and transport. The geographic region identifies where the energy input or emission output occurs which includes both direct and indirect contributions.

Table 86 – Rail Life-cycle Component Temporal and Geographic Differentiation

Life-cycle Component	Input/Output Contributor		Temporal	Geographic
Vehicle				
Manufacturing	Manufacturing processes	⟐	One-time	Manufacturing facilities, indirect support
Operation (Propulsion)	Diesel fuel or Electricity use		Continuous	Train route
Operation (Idling)	Diesel fuel or Electricity use		Continuous	Train route
Operation (Auxiliaries)	Diesel fuel or Electricity use		Continuous	Train route
Maintenance	Manufacturing processes for parts	⟐	One-time	Manufacturing facilities, indirect support
Cleaning	Electricity use		Continuous	Power plants
Flooring	Manufacturing processes	⟐	One-time	Manufacturing facilities, indirect support
Insurances	Insurance facilities requirements	⟐	Continuous	Power plants, indirect support
Infrastructure				
Station Construction	Material production, direct process	⟐	One-time	Manufacturing facilitites, train route, indirect support
Station Lighting	Electricity use		Continuous	Power plants
Station Escalators	Electricity use		Continuous	Power plants
Train Control	Electricity use		Continuous	Power plants
Station Parking Lighting	Electricity use		Continuous	Power plants
Station Miscellaneous	Electricity use		Continuous	Power plants
Station Maintenance	Material production, direct process	⟐	Continuous	Manufacturing facility, train route, indirect support
Station Cleaning	Electricity use		Continuous	Power plants
Station Parking	Direct processes, material production	⟐	One-time	Manufacturing facility, train route, indirect support
Track/Power Construction	Material production, direct process	⟐	One-time	Manufacturing facility, train route, indirect support
Track Maintenance	Material production, direct process	⟐	Continuous	Manufacturing facility, train route, indirect support
Insurances	Insurance facilities requirements	⟐	Continuous	Power plants, indirect support
Fuels				
Electricity Production	Material extraction, refining, transport	⟐	Continuous	Extraction region, refining region, transport network
T&D Losses	Electricity production lost		Continuous	Power plants

⟐ indicates that indirect energy inputs and emission outputs from the supply chain are included

Any impact assessment framework which uses these life-cycle data must consider the temporal differentiations in the context of the system. The one-time emissions relate to the life-cycle component and have been normalized to effects per PMT (or vehicle-life, or VMT) and not system lifetime. The one-time emissions from different components may repeatedly occur in this framework during the system's lifetime. For example, within the total effects of the Caltrain rail network, vehicle manufacturing one-time emissions may reoccur every 25 years while station construction will reoccur every 50 years.

Table 87 – Air Life-cycle Component Temporal and Geographic Differentiation

Life-cycle Component	Input/Output Contributor		Temporal	Geographic
Vehicle				
Aircraft Manufacturing	Manufacturing processes	⟐	One-time	Manufacturing facilities, indirect support
Engine Manufacturing	Manufacturing processes	⟐	One-time	Manufacturing facilities, indirect support
Operation, APU	Fuel combustion		Continuous	Airport
Operation, Startup	Fuel combustion		Continuous	Airport
Operation, Taxi Out	Fuel combustion		Continuous	Airport
Operation, Take Off	Fuel combustion		Continuous	Airport
Operation, Climb Out	Fuel combustion		Continuous	Near airport
Operation, Cruise	Fuel combustion		Continuous	Flight route, upper atmosphere
Operation, Approach	Fuel combustion		Continuous	Near airport
Operation, Taxi In	Fuel combustion		Continuous	Airport
Maintenance	Manufacturing processes for parts	⟐	Continuous	Manufacturing facilities, indirect support
Insurances	Insurance facilities requirements	⟐	Continuous	Power plants, indirect support

Table 87 – Air Life-cycle Component Temporal and Geographic Differentiation

Life-cycle Component	Input/Output Contributor		Temporal	Geographic
Infrastructure				
Airport Construction	Material production, direct process	⟐	One-time	Manufacturing facilities, airports, indirect support
Runway/Taxiway/Tarmac Construction	Material production, direct process	⟐	One-time	Manufacturing facilities, airports, indirect support
Runway Lighting	Electricity use		Continuous	Power plants
Deicing Fluid Production	Material production	⟐	Continuous	Manufacturing facilities, indirect support
Ground Support Equipment Operation	Energy use		Continuous	Airport
Airport Maintenance	Material production	⟐	Continuous	Manufacturing facilities, airports, indirect support
Runway/Taxiway/Tarmac Maintenance	Material production, direct process	⟐	Continuous	Manufacturing facilities, airports, indirect support
Parking	Material production, direct process	⟐	One-time	Manufacturing facilities, airports, indirect support
Insurances	Insurance facilities requirements	⟐	Continuous	Power plants, indirect support
Fuels				
Refining & Distribution	Material extraction, refining, transport	⟐	Continuous	Extraction region, refining region, transport network

⟐ indicates that indirect energy inputs and emission outputs from the supply chain are included

The geographic differentiation also requires further analysis for locating continuous-source or point-source emissions from this study. While continuous-source emissions are based on the route of the vehicle, point-source emissions are not. The electricity used in any system comes from an electricity grid composed of many different power generation facilities. The electricity used for a particular system may come from a single power plant at any given time (while California may have more hydro power and is considered to have a cleaner statewide mix, the electrons used to power the CAHSR system may come from a coal plant near the network). Manufacturing facilities for system parts and materials could be located anywhere in the world. Additionally, the inclusion of supply chain effects results in massive geographic considerations.

1.10 Data Uncertainty, Quality, and Sensitivity

The use of various data points and extensive sources to evaluate multiple modes requires evaluation of model data in an uncertainty framework. Uncertainty in LCAs is discussed by Huijbregts 1998 and separated into three components: model, choice, and parameters.

1.10.1 Model and Choice Uncertainty

Model and choice uncertainty are related to system boundary selection, functional units, process and hybrid flows, geographic variation of parameters, component methodology, and the attribution of inventory components to particular modes [Huijbregts 1998]. It is not feasible to evaluate model and choice uncertainty in a quantitative framework. Instead, each of the issues mentioned is discussed with background provided on how uncertainty is addressed and minimized.

System Boundary Selection

The selection of an appropriate system boundary is critical in any LCA. The system boundary must provide a balance between capturing major environmental components outside of product use and managing analytical resources so the assessment can be completed in a timely and cost-effective manner. The system boundary in this analysis includes more components than any previous passenger transportation LCA but does not include all possible components. Within the cradle-to-grave framework, components such as vehicle design and end-of-life have not been included. As mentioned in previous sections, components with the largest expected contributions to total inventory were first considered. Because expectations and results do not necessarily correlate, back-of-the-envelope calculations were performed on these phases to determine their relative magnitude contributions to other phases prior to inclusion. The components included within the system boundary of this study are expected to have the largest contribution to total inventory.

Functional Units

The normalization of LCI results is necessary for comparison of any product or process in an LCA. There are several drawbacks to use of a single functional unit, some of which have already been mentioned (e.g., geographic and temporal masking). Other drawbacks to a single functional unit include normalization biases. Comparing all modes and their components by VMT hides the number of passengers transported, the ultimate purpose of the mode. Additionally, normalization per PMT does not take into account the value of that trip. Comparing emissions from automobiles and aircraft per PMT ignores the realization that neither mode could substitute for the other. The values of those trips are very different. Results have been reported in three functional units (per vehicle lifetime, VMT, and PMT) to relieve the biases that can result from reporting a single functional unit and to provide a range of environmental factors which can be used in further analyses.

Process and Hybrid Flows

In addition to appropriate LCA system boundary selection, it is necessary to appropriately select and evaluate component processes and sub-processes. A limitation of process-based LCA is the large resource requirements in multi-level process evaluation which inhibits full supply chain evaluation. The use of hybrid LCA in this assessment reduces some of the uncertainty associated with process flow selection and evaluation. It is not always possible, however, to use hybrid LCA, and for several components, process-based assessment was necessary. To pick appropriate processes associated with a component, literature reviews were performed and comparisons were completed against other studies which analyzed particular components within this work.

Additionally, process-based assessments could be compared against results from EIO-LCA and SimaPro when the process matched these software's processes [EIO-LCA 2008, SimaPro 2006].

Geographic Variation of Parameters

This study is intended to provide a comprehensive environmental LCI of passenger transportation in the U.S., however, certain modes (particularly commuter rail) are regionalized. Additionally, factors for other modal components may not represent U.S. averages. Careful attention has been given to using U.S. representative factors for onroad and rail modes. For rail modes, California and Massachusetts factors have been used when possible, particularly for electricity generation. The uncertainty due to regional variations is not expected to be significant but should not be ignored. Automobile emissions in cold environments are likely to be different than conditions in warm environments. Similarly, a commuter rail network in New York City will have different environmental factors than San Francisco Bay Area systems. These variations are discussed in the data quality assessment (§1.10.2).

Component Methodology

The use of EIO-LCA to complement process-based shortcomings reduces uncertainty associated with assessment methodology. While process-based LCA is more accurate, the intense requirements often prohibit full evaluation. EIO-LCA is then used to fill in the remaining information. For major component contributors, process-based LCA was used. For all modes, vehicle operation is a key environmental contributor and energy inputs and emissions outputs were determined from process-based analysis. This does not capture production of the fuel which is where EIO-LCA is then used. The major uncertainty with EIO-LCA is the similarity of the process under study to an economic sector in the model. If EIO-LCA did not provide a representative sector for a process then its use was avoided.

Attribution

Passenger transport modes do not operate on infrastructures completely isolated from other transport and non-transport infrastructures. While cars and buses use roadways, so do motorcycles and freight vehicles. Commercial aircraft carry not only passengers but also some freight and mail. The interdependency of passenger transportation infrastructure with other infrastructure creates a need for environmental attributions in this assessment. Careful attention is given to appropriate energy and emissions infrastructure overlaps. For onroad, roadway construction is deemed proportional to automobile VMT during its lifetime (separating automobiles and buses from other vehicles such as vans, motorcycles, and trucks). Since roadway damage, and the resulting maintenance, is proportional to the fourth power of axle load, automobiles contribute negligible damage to roadways despite their dominating share of VMT [Huang 2004]. The apportioned energy and emissions from roadway maintenance applies only to buses after accounting for vehicle damage. Similarly, because an aircraft transports freight and mail, total emissions from a flight cannot be attributed in their entirety to passengers. Freight and mail fractions by weight were determined and removed from all life-cycle air components (§1.8.1.5). Allocation steps such as these were necessary to prevent overcharging of mode inventory.

1.10.2 Parameter Uncertainty and Data Quality

To evaluate the degree of variability of model parameters, a data quality assessment should be performed in conjunction with a sensitivity analysis to determine the critical parameters on final results. These two tools complement each other by providing insight into which parameters are critical in each analysis. The data quality assessment provides an overall qualitative assessment of parameters identifying which are subject to the largest degree of uncertainty. The sensitivity analysis evaluates variations in parameters and the effect on overall results (providing information which can be used in the data quality assessment). The sensitivity analysis is described in §1.10.4.

A data quality assessment is performed to assess the degree to which parameters are likely to vary and identify which parameters should be monitored most closely. This method is based on Huijbregts 1998, Weidema 1996, and Lindfors 1995 who identify pedigree matrix criteria for scoring certain attributes of model components. The pedigree matrix specifies qualitative criteria to assess a score which can then be used to compute a ranking of components (shown in Table 88). The ranking provides a measure for which components should be given more attention in uncertainty assessment due to a combination of variability and impacts to overall results. The ranking is determined by comparing the averages for each component analyzed.

Table 88 – Data Quality Assessment Pedigree Matrix

Criteria	Indicator Score				
	1	2	3	4	5
Impact on Final Result	Parameter is the top contributor to final result	Parameter is within the top 5 contributors to final result	Parameter is within the top 10 contributors to final result	Parameter is not likely to affect final results significantly	Parameter contribution is unknown
Acquisition Method	Measured data	Calculated data based on measurements	Calculated data partly based on assumptions	Qualified estimate (by industrial expert)	Nonqualified estimate
Independence of Data Supplier	Verified data, information from public or other independent source	Verified information from enterprise with interest in the study	Independent source, but based on nonverified information from industry	Nonverified information from industry	Nonverified information from the enterprise interested in the study
Representation	Representative data from sufficient sample of sites over and adequate period to even out normal fluctuations	Representative data from smaller number of sites but for adequate periods	Representative data from adequate number of sites, but from shorter periods	Data from adequate number of sites, but shorter periods	Representativeness unknown or incomplete data from smaller number of sites and/or from shorter periods
Temporal Correlation	Less than three years of difference to year of study	Less than five years of difference	Less than 10 years of difference	Less than 20 years of difference	Age unknown or more than 20 years of difference
Geographical Correlation	Data from area under study	Average data from larger area in which the area of study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological Correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study, but from different enterprises	Data from processes and materials under study, but from different technology	Data on related processes or materials, but same technology	Data on related processes or materials, but different technology
Range of Variation	Estimate is a fixed and deterministic number	Estimate is likely to vary within a 5% range	Estimate is likely to vary within a 10% range	Estimate is likely to vary more than 10%	Estimate is likely to vary under unknown ranges

Adapted from Huijbregts 1998, Lindfors 1995, Weidema 1996, and Facanha 2006.

The criteria of the pedigree matrix are used to score onroad, rail and air mode parameters. Given the large number of model parameters, scoring is completed based on life-cycle components. This approach is justified by the large contributions of specific parameters to component inventories as identified in previous sections. The overall score for the component then directly relates to those parameters identified within. Table 91 shows the scoring and ranking for the mode groupings where the lower the ranking (closer to 1), the more attention should be given to verifying the associated parameters by the categories scored.

Table 89 – Data Quality Assessment Scoring Matrix for Onroad Modes

Component Category	EIO-LCA Used Exclusively?	Ranking	Average	Impact on Final Result	Acquisition Method	Independence of Data Supplier	Representation	Temporal Correlation	Geographical Correlation	Technological Correlation	Range of Variation
Vehicles											
Manufacturing	✓	7	3.0	4	4	3	3	3	2	1	4
Operation (Active)		1	1.4	1	3	1	1	1	1	1	2
Operation (Inactive)		2	1.6	3	3	1	1	1	1	1	2
Maintenance	✓	4	2.8	3	4	2	3	3	2	1	4
Insurance	✓	5	2.9	3	4	3	3	3	2	1	4
Infrastructure											
Roadway Construction & Maintenance		7	3.0	5	3	3	2	2	2	3	4
Roadway Lighting		3	2.1	3	3	2	2	1	2	1	3
Parking Construction & Maintenance		5	2.9	3	3	3	2	3	2	3	4
Fuels											
Fuel Production	✓	7	3.0	4	4	3	3	3	2	1	4

Table 90 – Data Quality Assessment Scoring Matrix for Rail Modes

Component Category	EIO-LCA Used Exclusively?	Ranking	Average	Impact on Final Result	Acquisition Method	Independence of Data Supplier	Representation	Temporal Correlation	Geographical Correlation	Technological Correlation	Range of Variation
Vehicles											
Manufacturing	✓	3	2.3	3	2	2	2	2	3	2	2
Operation (Active)		1	1.5	1	2	3	1	1	1	1	2
Operation (Inactive)		2	2.0	2	3	3	2	1	1	1	3
Maintenance	✓	3	2.3	3	2	2	2	2	3	2	2
Insurance	✓	11	3.5	3	4	3	4	3	3	4	4
Infrastructure											
Station Construction & Maintenance	✓	7	2.4	1	3	3	2	3	2	1	4
Station Operation		8	2.5	2	3	3	3	1	3	2	3
Station Parking Construction & Maintenance		3	2.3	3	3	3	2	1	2	1	3
Track/Power Delivery Construction & Maintenance		3	2.3	3	3	3	2	1	2	1	3
Insurance	✓	11	3.5	3	4	3	4	3	3	4	4
Fuels											
Electricity Production		8	2.5	2	3	3	3	3	2	2	2
Diesel Fuel Production (Caltrain)	✓	10	3.0	4	4	3	3	3	2	1	4

Table 91 – Data Quality Assessment Scoring Matrix for Air Modes

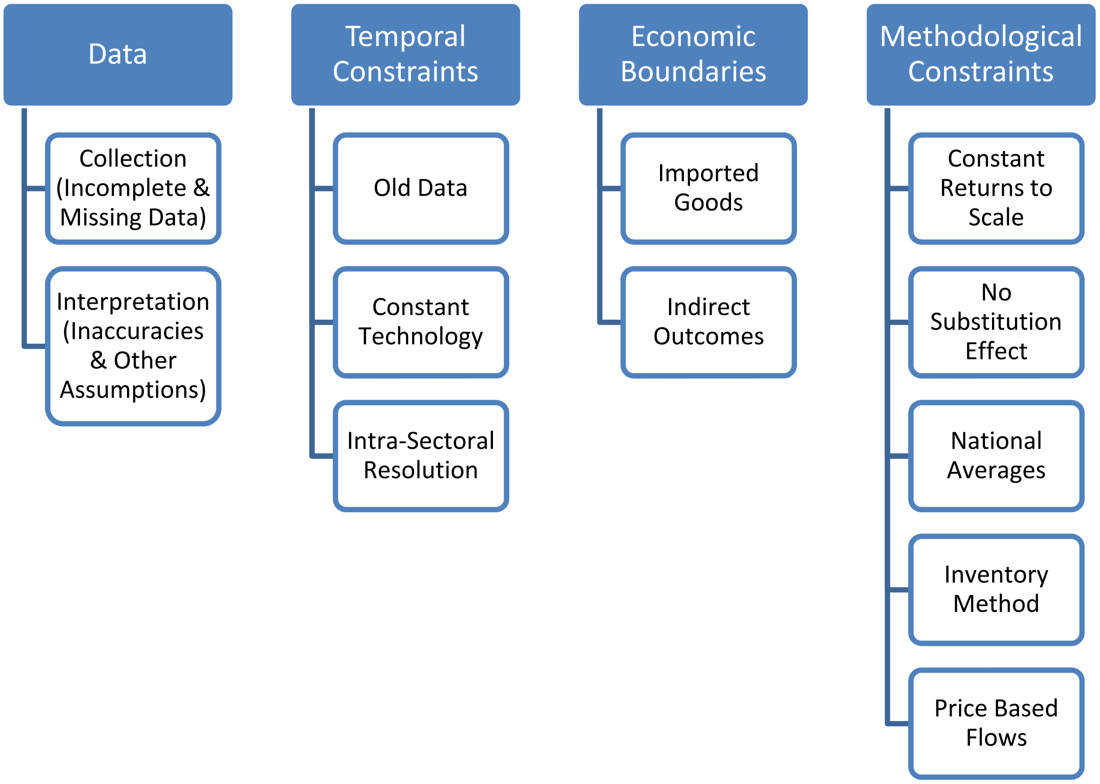
Component Category	EIO-LCA Used Exclusively?	Ranking	Average	Impact on Final Result	Acquisition Method	Independence of Data Supplier	Representation	Temporal Correlation	Geographical Correlation	Technological Correlation	Range of Variation
Vehicles											
Manufacturing	✓	7	2.8	2	4	3	3	3	3	1	3
Operation (Active)		2	2.3	1	3	3	2	1	3	3	2
Operation (Inactive)		1	2.0	2	2	2	2	1	2	3	2
Maintenance	✓	4	2.5	2	3	2	2	1	3	3	4
Insurance	✓	10	3.3	4	4	3	3	3	4	2	3
Infrastructure											
Airport Construction	✓	12	3.4	4	3	3	3	3	4	4	3
Runway/Taxiway/Tarmac Construction		3	2.4	3	3	2	2	2	3	2	2
Airport Operation		5	2.6	1	3	3	5	2	2	2	3
Airport Maintenance	✓	9	3.1	4	4	3	4	2	2	3	3
Airport Parking Construction & Maintenance		5	2.6	4	4	2	2	2	3	2	2
Insurance	✓	10	3.3	4	4	3	3	3	4	2	3
Fuels											
Fuel Production	✓	8	2.9	2	4	3	3	3	2	2	4

For all modes, vehicle operational components have the lowest rankings. The data quality assessment provides not only rankings but also a way to identify parameter uncertainty categories which require further attention. The uncertainty categories which consistently show higher numbers reveal areas of the analysis where further data assessment is required.

1.10.3 Uncertainty for Input-Output Analysis

The economic input-output modeling approach for determining direct and indirect environmental performance has uncertainty in parameter variation. While this approach serves as one of the only mechanisms for evaluating the entire supply chain, it relies on assumptions about the quality of data, timescale, process boundary, and estimation methodology, all of which have some degree of uncertainty [Pacca 2003]. Figure 17 shows four major categories of input-output analysis uncertainty and components within them that may contribute.

Figure 17 – Input-Output Analysis Uncertainties [Pacca 2003]



The uncertainty associated with each of the categories in Figure 17 varies and is dependent on several factors. Input-output tables are based on the reported transactions of industry which fall into specific economic sectors. The data are collected by the U.S. Census and packaged into transaction tables for use in input-output tables. It may be the case that a non-representative sample was collected or that data were collected and packaged for the wrong sector. While the later is less unlikely, Lenzen 2001 provides a framework for estimating the basic errors of input-output analysis from knowledge of survey data sources. Additionally, verification is typically performed against processed-based results to confirm the estimate.

Temporally, the data from input-output analysis can be dated depending on when it was collected and for what period the analysis is performed. Because U.S. data is collected every five years, it is possible that estimation is taking place for a process or service that is five years old. If there are rapid changes in the sector during that time then variability increases. Similarly, if costs fluctuate rapidly from month to month or year to year then historical data must be evaluated. This is often the case with primary materials and fuels. The costs of these items fluctuate depending on supply and demand as well as production costs resulting in potentially rapid jumps.

The economic boundaries of any input-output analysis dictate the boundaries of the process or service studied. EIO-LCA assumes that products and processes occur in the U.S. and are somewhat independent from non-domestic support. While this independence is rarely the case, it is often reasonable to assume that the non-domestic products or processes are reasonable estimations for their domestic counterparts. One of the most difficult issues that arise is the use of economic sectors when estimating a product or process. There is not always a clear overlap between the two and sometimes economic sectors are too broad. This may occur because of aggregation of economic data in the input-output tables. When this occurs, process or hybrid-based LCA is typically performed instead of assuming that broad economic sectors are representative of specific process within.

The methodology used to capture direct and indirect economic impacts in input-output analyses has its limitations. Input-output models, such as EIO-LCA are linear and do not assume increasing or decreasing returns to scale. This implies that these models provide average and not marginal estimates which may or may not be suitable. It is often the case that this is the only approach available given the complexity and constraints of performing the same analysis with process-based assessment. Among other methodological factors, input-output analysis assumes national average estimates and does not geographically differentiate. Although many products and processes are the same across the U.S., many are different as they are subject to differing suppliers, logistics, technology, and energy inputs. While input-output analysis does not typically capture this, a hybrid approach can be used where the major processes evaluated differ.

1.10.4 Sensitivity Analysis

Given the myriad of environmental data used and its representation and accuracy of specific processes, a sensitivity analysis is warranted to determine the effects of certain key parameters on final outputs. While many parameters were used to estimate mode performance, certain parameters have stronger influence on final outputs. Given the large number of parameters included and the many basis to evaluate variability (including temporal correlation, geographic correlation, process representation, technological representation, general variability, etc., which are qualitatively evaluated in §1.9, §1.10.1, §1.10.2, and §1.10.3), breakeven points are determined to illustrate the coalescence in variability of factors where mode performance is equivalent. Additionally, occupancy ranges, a trip mile-to-mile equivalency, renewable electricity, and improved fuel economy cases are evaluated against average conditions.

1.10.4.1 Breakeven Point Discussion

The number of passengers on a vehicle at any given time, which is used as one method for normalizing environmental performance, is the strongest influencing factor when evaluating results per PMT. A sedan is chosen to represent automobiles and a midsize aircraft is chosen to represent aircraft in this discussion because they are responsible for 55% of automobile and 80% of aircraft domestic PMT [BTS 2007, FHWA 2008]. Considering energy inputs and GHG emissions, sedan performance would have to increase by approximately 1.5 to 4.5 times to be equivalent to a peak bus, train, or aircraft per PMT. For this to be possible, average occupancy rates would have to increase from 1.6 passengers to between 2.4 and 3.5 passengers (excluding buses). Another possibility would be to improve operational fuel economy from 28 mpg by a factor of 2.1 to 3.1 to meet rail and air. More likely would be a combination of the two factors. For buses, occupancy rates would have to change to around 8 PMT/VMT to meet sedans, 19 to meet rail, and 15 to meet air energy and GHG performance. From an energy and GHG perspective, rail modes offer the best performance and would have to decrease by 1.9, 3.7, and 1.3 times to meet a sedan, off-peak bus, and midsize aircraft (but increase by 2.1 times to match the peak bus). At a decrease in occupancy of 20%, the rail systems would be equivalent to a midsize aircraft while at a 74% would be equivalent to a sedan. The midsize aircraft would have to decrease occupancy by 1.5 and 2.9 times to meet a sedan and the off-peak bus but increase by 2.8 and 1.3 times to have the same energy and GHG performance as peak buses and rail. The midsize aircraft is one of the most active operation dominated modes. The average midsize aircraft is modeled with 101 passengers and 141 seats [BTS 2007]. At 127 passengers, the midsize aircraft is equivalent to rail in energy consumption and GHG emissions. Technological advancements which improve fuel consumption in the cruise mode from 2.1 to 1.9 MJ/PMT and GHG emission from 140 to 120 g GGE/PMT make the aircraft competitive with rail systems.

While energy and GHG emissions are strongly dictated by operational fuel consumption, CAP emissions are often affected by non-operational components. The electric rail systems produce larger SO_2 emissions per PMT than the other modes as a result of electricity generation. These modes are equivalent to their Caltrain diesel-fueled counterpart with 70% reductions in electricity use (reductions of 62% and 74% are necessary to meet onroad and air modes). For VOCs, the elimination of cutback-type asphalt coupled with 84% reductions in evaporative and operational emissions brings sedan emissions near other modes. With the dominating automobile PM_{10} emissions resulting from asphalt production for road and parking construction, material substitution or increased recycled material content would be needed to drastically reduce total emissions. Sedan CO emissions, which are currently 16 times larger than the other modes and almost all from vehicle operation, would need to be reduced from 12 g/PMT to 0.8 g/PMT to compete with other modes.

1.10.4.2 Occupancy Ranges

The variations in passenger occupancy for all modes are the primary determinants of environmental performance when evaluating results per PMT. Evaluation of performance per PMT is necessary when considering the ultimate goal of each system, to move people. The modes presented in this thesis are evaluated under average occupancy conditions with the exception of buses. While evaluating at the average is useful, it is important to recognize that for many of these modes, the average occupancy may exist less frequently than the off-peak and peak occupancy. Furthermore, extremes exist beyond off-peak and peak occupancies which capture the best and worst case for operation. For the automobiles, the absolute worst case is when the vehicle has only one passenger which is when PMT equal VMT. For transit modes, vehicle operation with zero passengers (or just the operator) is the worst and represents when the mode is consuming energy and producing emissions but not transporting passengers (essentially infinitely poor environmental performance), counter to its purpose. Opposite to these worst case scenarios is maximum occupancy. For automobiles this would exist when all seats are full (ignoring safety aspects and crowding more passengers into a vehicle than there are seats). For mass transit vehicles, this situation occurs when all seats and standing room are full and the vehicle is operating at maximum capacity. At these maximum occupancies, environmental performance is at its best and PMT is much greater than VMT effectively reducing energy consumption and emissions per PMT to its minimum.

An assessment of modal environmental performance is performed with single, low and high occupancy conditions. For automobiles, the low occupancy is specified as one passenger while the high is specified as the number of seats (5 for sedans, 7 for SUVs, and 3 for pickups). For mass transit modes, the low was not specified as one passenger because the resulting performance is equivalent to per VMT performance. Instead, an occupancy rate was used that might exemplify poor ridership. For buses, the low was specified at 5 passengers and the high at 60 passengers which is standard for many transit agencies. Low rail occupancy was specified as 25% of the number of seats while high as 110% the number of seats to include standing passengers. Aircraft low and high is specified as 50% and 100% of the number of seats. These specified and calculated occupancies are shown in Table 92.

Table 92 – Passenger Modal Occupancy for Sensitivity Analysis

	Mode	Single	Low	Average	High
Onroad	Sedan	1 Pax	1	1.58	5
	SUV		1	1.74	7
	Pickup		1	1.46	3
	Bus		5	10.5	60
Rail	BART	1 Pax	133	146	583
	Caltrain		110	155	482
	Muni		15	22	66
	Green Line		30	54	70
	CAHSR		88	263	385
Aircraft	Embraer 145	1 Pax	25	33	49
	Boeing 737		70	101	141
	Boeing 747		185	305	370

Onroad low and high specified from size of vehicle. Rail specified as 25% low and 110% high (excluding the Green Line) and aircraft 50% low and 100% high of the number of seats.

The single occupancy conditions show when PMT and VMT are equal and the almost worse case environmental performance (the worse being when public transit vehicles have no passengers). Figure 18 and Figure 19 show the energy consumption and GHG emissions per PMT/VMT for both operational and life-cycle modal inventories (the figures are presented with a logarithmic scale).

Figure 18 – Single Occupancy Modal Energy Performance (MJ/PMT or VMT)

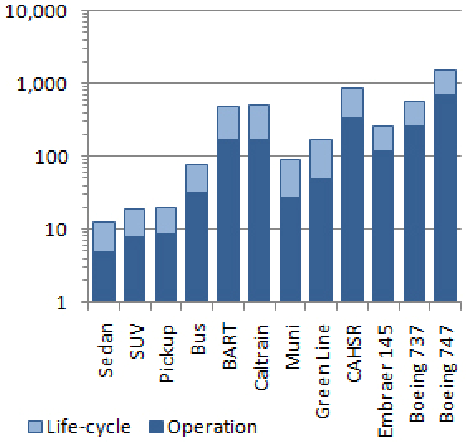


Figure 19 – Single Occupancy Modal GHG Performance (g CO_2e/PMT or VMT)

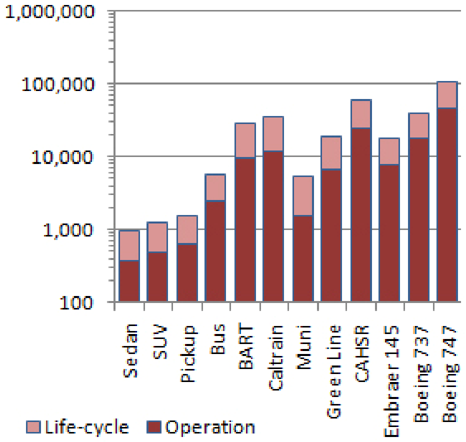


Table 93 shows single occupancy modal performance for CAP in both operation and the life-cycle. While a significant difference can be seen comparing some modes, a more surprising result are the smaller contrasts. For example, CO emissions from automobiles are larger than emissions from buses and Muni and not far from several other modes.

Table 93 – Single Occupancy Modal CAP Performance (mg/PMT or VMT)

	SO_2 (mg)		CO (mg)		NO_X (mg)		VOC (mg)		PM (mg)	
	Oper.	LC	Oper.	LC	Oper.	LC	Oper.	LC	Oper.	LC
Sedan	21	560	18,000	20,000	1,000	1,800	1,200	1,900	130	380
SUV	27	710	21,000	23,000	1,300	2,100	1,400	2,300	130	400
Pickup	35	670	28,000	29,000	1,700	2,500	2,300	3,100	130	390
Bus	22	1,900	4,500	11,000	18,000	22,000	550	3,200	710	1,400
BART	52,000	90,000	5,200	77,000	3,000	42,000	1,400	30,000	570	8,000
Caltrain	50	40,000	13,000	68,000	220,000	250,000	9,100	32,000	6,000	15,000
Muni	8,400	18,000	850	14,000	490	5,800	220	3,300	92	1,100
Green Line	40,000	64,000	7,500	39,000	8,800	22,000	510	6,800	400	2,700
CAHSR	130,000	180,000	13,000	83,000	9,500	43,000	2,800	25,000	1,400	6,100
Embraer 145	2,800	7,700	9,700	26,000	21,000	26,000	2,400	4,800	220	1,100
Boeing 737	5,900	16,000	24,000	61,000	59,000	71,000	2,300	7,100	380	2,200
Boeing 747	15,000	51,000	17,000	140,000	180,000	220,000	3,900	21,000	820	7,600

Oper. = Operation, LC = Life-cycle

Using the ranges from Table 92, environmental performance per PMT is evaluated in Figure 20 through Figure 27. All of the passenger occupancy variability figures show modal operation and life-cycle (which includes operation) performance and the range of variation from the minimum and maximum occupancies. For both energy and emissions, aircraft tend to show the largest variations in performance, most of which decreases the performance per PMT (energy and emissions increase per PMT). This is due to aircraft current operation conditions which are around 70% of passenger capacity. BART, which shows the least variation towards worse performance, shows large variation towards improved performance. This is due to the sensitivity occupancies selected where BART, at average occupancy, already operates near the specified minimum (which is again based on 25% of the number of seats).

Figure 20 – Passenger Occupancy Variability on Modal Energy Performance (MJ/PMT)

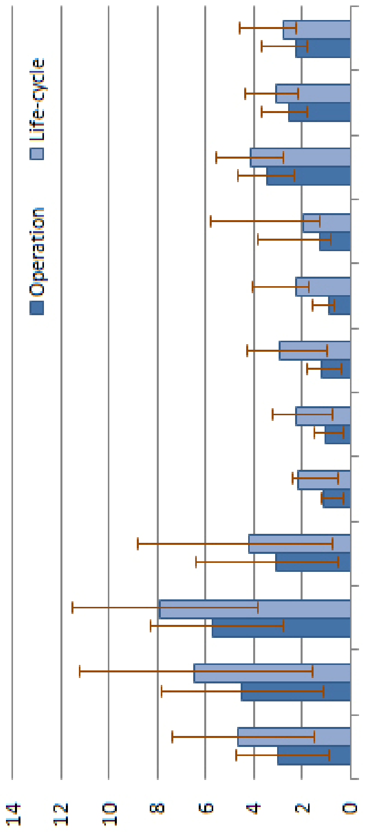


Figure 21 – Passenger Occupancy Variability on Modal GHG Performance (g CO_2e/PMT)

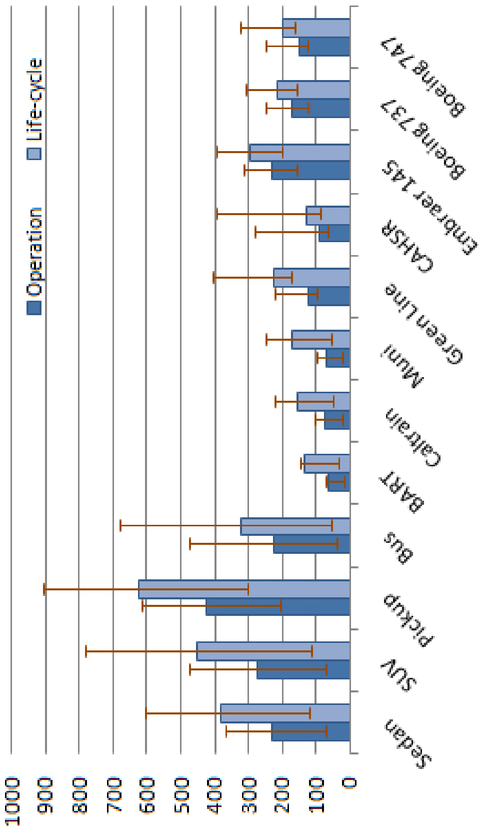


Figure 22 illustrates the importance of electricity generation SO_2 emissions on electric rail system emissions. Autos, buses, Caltrain, and aircraft, the petroleum-consuming modes, dominate NO_X emissions but are subject to large performance variations based on occupancy. Although aircraft, at the average, are often lower NO_X emitting per PMT than auto modes, the large variations could switch this ordering.

Figure 22 – Passenger Occupancy Variability on Modal SO_2 Performance (mg/PMT)

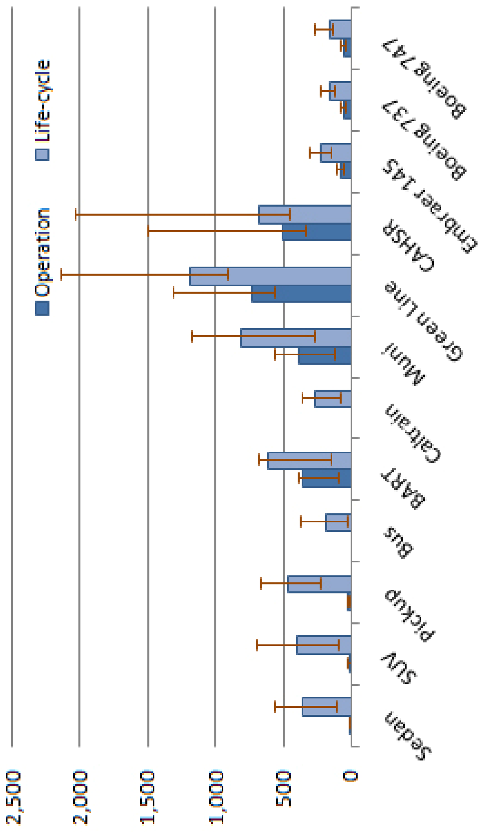
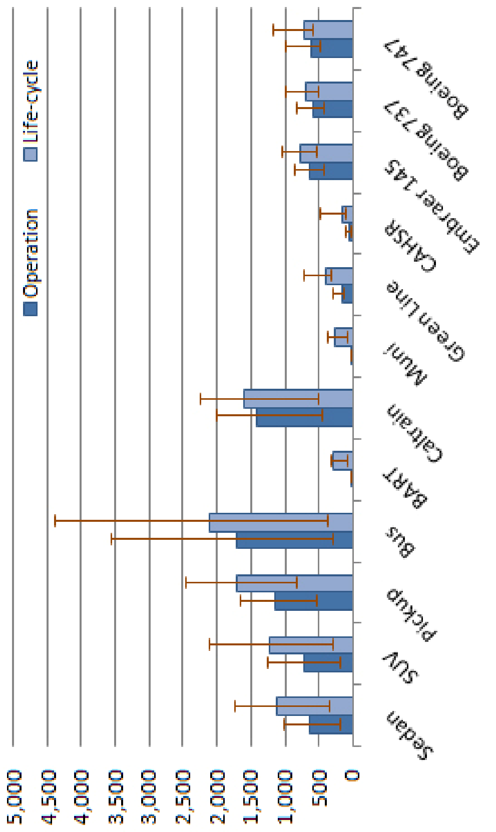


Figure 23 – Passenger Occupancy Variability on Modal NO_X Performance (mg/PMT)



As mentioned earlier, auto and non-auto modes produce similar CO emissions per VMT but due to the larger variations in occupancy result in large performance differences per PMT. Figure 24 shows average auto CO emissions at roughly 11 to 20 g/PMT for the different vehicles which all operate at around 1.5 passengers per vehicle. The occupancy rates of the non-auto modes produces much better CO performance as shown in Figure 25.

Figure 24 – Passenger Occupancy Variability on Auto CO Performance (mg/PMT)

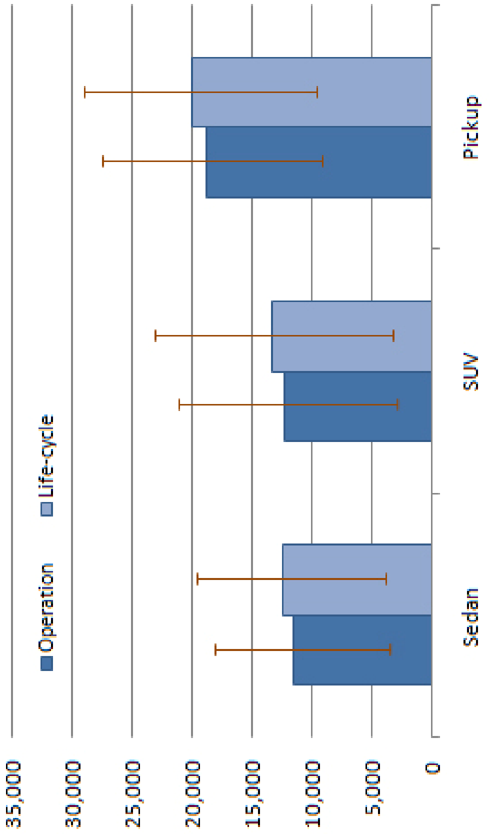
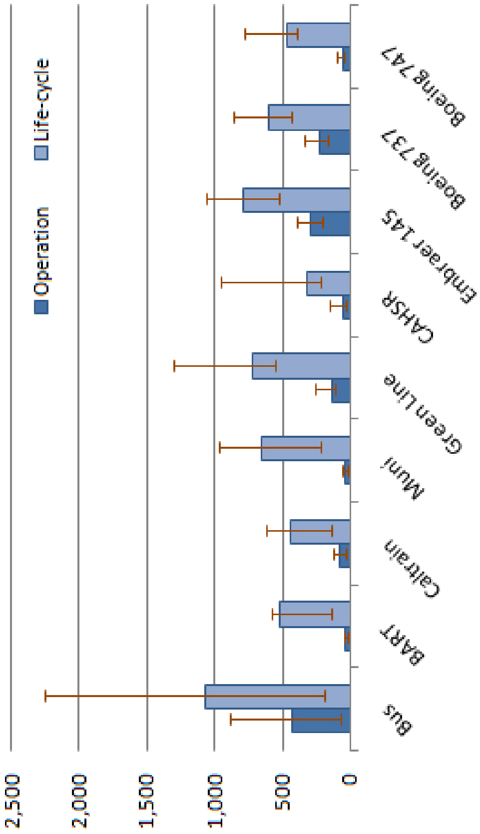


Figure 25 – Passenger Occupancy Variability on Bus, Rail, and Air CO Performance (mg/PMT)



Automobiles tend to dominate VOC and PM emissions and variations in occupancy are not typically large enough for the non-auto modes to switch rankings. Only at maximum auto occupancy is environmental performance for the two pollutants comparable to the other modes. This effect highlights the importance of targeting automobiles for air basin VOC and PM reductions given their typical dominating performance and share of PMT in a region.

Figure 26 – Passenger Occupancy Variability on Modal VOC Performance (mg/PMT)

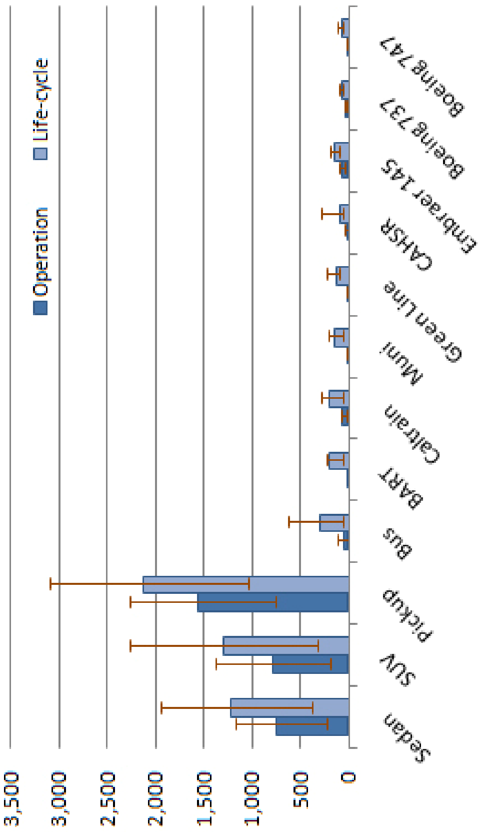
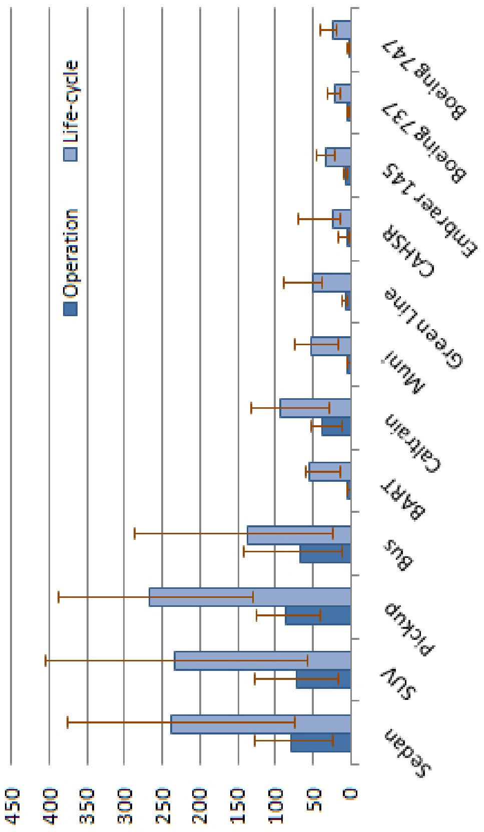


Figure 27 – Passenger Occupancy Variability on Modal PM Performance (mg/PMT)



1.10.4.3 Trip Modal Equivalencies

The environmental performance of each mode can be used in comparison against other modes to determine travel equivalencies. For example, a mile traveled in a car can be evaluated against a mile traveled in not only an SUV and pickup but also rail and air modes. While mode tradeoffs are not always feasible since modal infrastructure is not in place everywhere (e.g., rail or bus) and modes serve specific niche purposes (e.g., air), this is not always the case. For many trips, several mode options may exist and the travelers must weigh a plethora of variables including time, cost, and comfort to decide which to choose. The life-cycle inventory presented in this thesis provides metrics for which modal environmental equivalencies can be evaluated. Using the inventory, a PMT in any mode for energy inputs or emission output can be compared to a PMT in any other mode. Figure 28 through Figure 33 show PMT equivalencies for sedans, BART, the Boston Green Line, off-peak and peak bus, and a midsize aircraft (Boeing 737). For each of these modes, energy input and GHG and CAP emission outputs (with the exception of lead) are shown. All figures are shown with logarithmic scales. For each figure, a value of one means that a PMT for that mode is equivalent to a PMT in the other mode's environmental performance. A value less than one means that the dependent mode outperforms the independent mode (and vice-versa when the value is greater than one).

Figure 28 evaluates a sedan against several other modes. Comparing against the pickup, energy and emissions are typically less than one. This means that that driving a sedan one PMT is equivalent to driving a pickup less than one PMT (the sedan environmentally outperforms the pickup for energy and all emissions). Comparing the sedan against Caltrain in VOC emissions shows a value of about 6. This means that one PMT in a sedan produces the same amount of VOCs as 6 PMT on Caltrain, or Caltrain environmentally outperforms the sedan by a factor of 6 for that pollutant.

The BART PMT equivalencies show that for most comparative mode's environmental categories, a BART mile is greater. This is due to the strong environmental performance of BART such that when compared against other modes, the equivalent emissions result at less than one PMT for that mode. There are however, a few exceptions, particularly for SO_2 emissions with onroad modes and peak bus emissions in general. For auto and off-peak buses, the SO_2 emitted from roughly two PMT are equivalent to the SO_2 from BART at one PMT. This is the result of electricity generation emissions in vehicle operation. Peak buses, with a 40-passenger occupancy, have the strongest environmental performance resulting in equivalencies of around 20 PMT for SO_2 and CO compared to BART (20 PMT on a peak bus is equivalent to one PMT on BART).

Figure 28 – Sedan PMT Equivalency

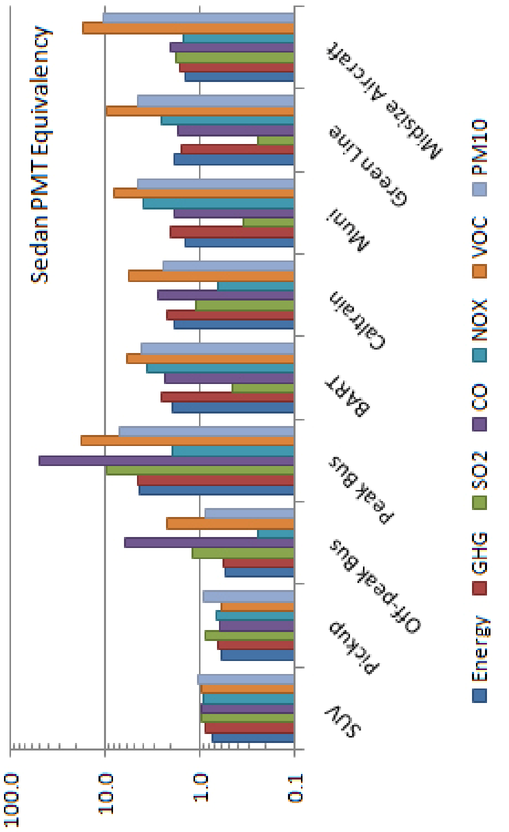
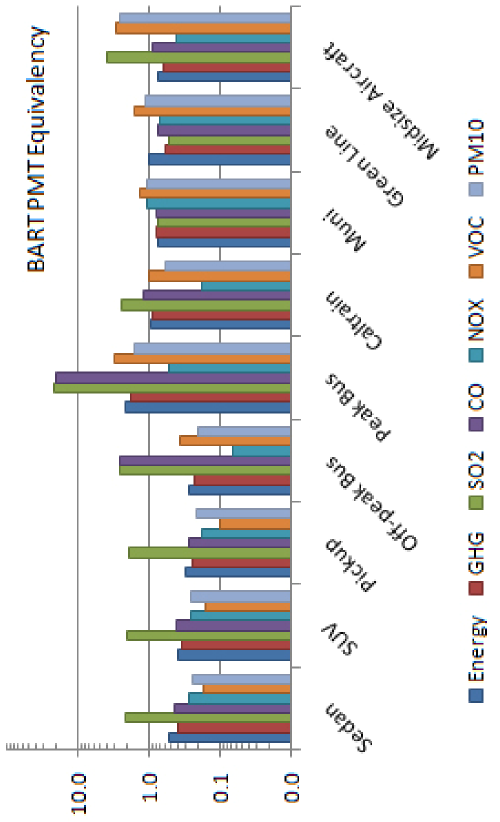


Figure 29 – BART PMT Equivalency



The Green Line shows similar SO_2 effects to BART where outside of this pollutant, the LRT system generally outperforms the auto and off-peak bus. A Green Line PMT is roughly equivalent to 1.5 BART and Caltrain PMT for GHG and NO_X (and 4.5 against Caltrain SO_2). Due to the linearity in the passenger occupancy assumption, the off-peak bus shows a factor of 8 for energy and all emissions against the peak bus (one PMT on an off-peak bus is equivalent to 8 on a peak bus). Compared against autos, one PMT on an off-peak bus is equivalent to 1.5 PMT for energy and GHG, 0.8 PMT for SO_2, 0.2 PMT for CO, around 4 for NO_X, 0.4 PMT for VOCs, and 1.2

for PM$_{10}$. The off-peak bus shows worse energy performance than all other modes. For NO$_X$ emissions, one PMT on this mode is equivalent to roughly 15 PMT on BART and Muni.

Figure 30 – Green Line PMT Equivalency

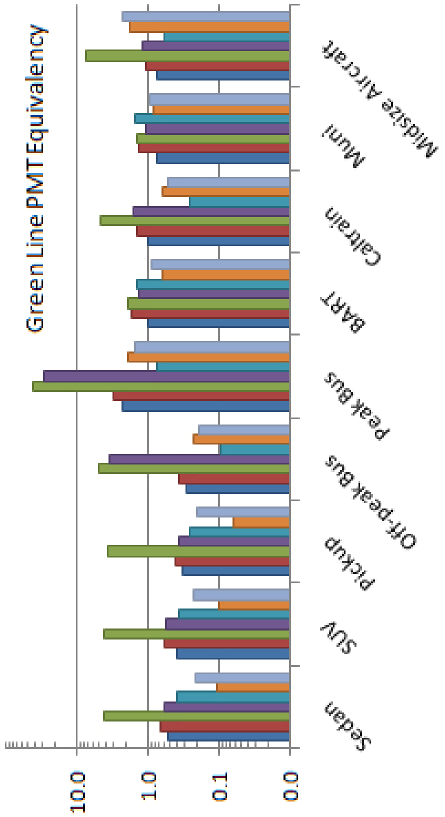
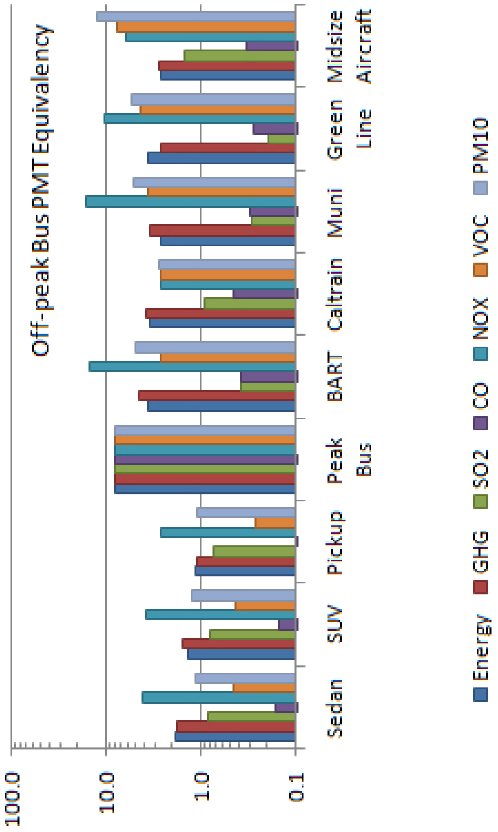


Figure 31 – Off-Peak Bus PMT Equivalency



Again, due to the linearity in assumptions, the peak bus factors are one-eighth those of the off-peak bus. The midsize aircraft outperforms the auto modes by 0.1 to 0.7 PMT per aircraft PMT but doesn't fair as well against other modes. For energy and GHG, one aircraft PMT is equivalent to roughly 1.3 rail PMT. For SO$_2$, VOC, and PM$_{10}$, one aircraft PMT is equivalent to roughly 0.3 rail PMT.

Figure 32 – Peak Bus PMT Equivalency

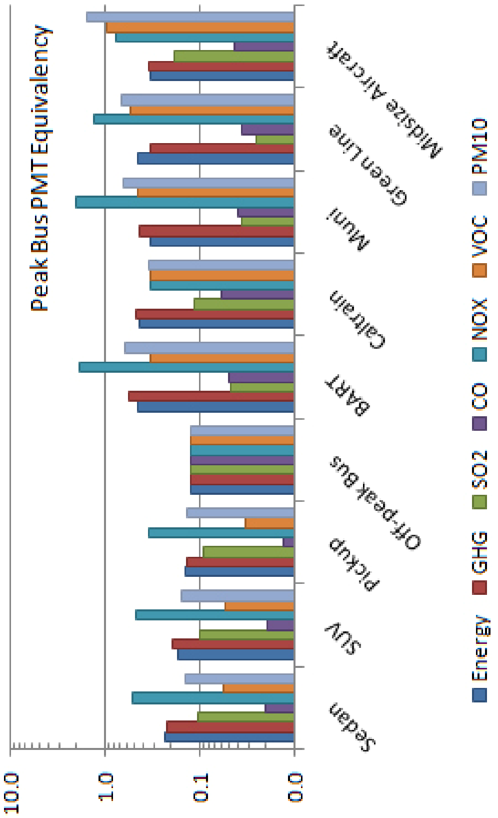
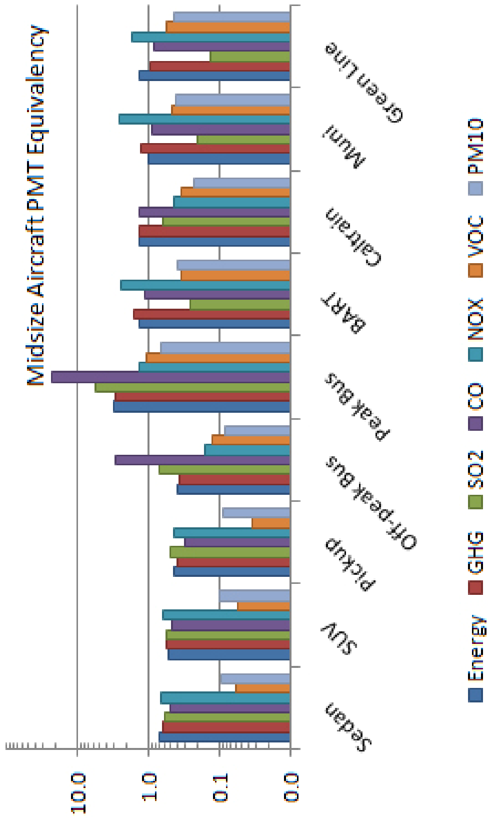


Figure 33 – Midsize Aircraft PMT Equivalency



1.10.4.4 Renewable Electricity Generation

The environmental performance of the electric rail modes is strongly affected by the electricity mix in the region they operate. A fossil fuel-intensive mix will typically result in larger emissions per VMT than a region with more hydro and renewables. For the commuter rail modes evaluated, all operate directly on electricity with the exception of Caltrain. Four out of the five rail modes operate in California which has a cleaner electricity mix than other states. Additionally, the electric rail commuter systems BART and Muni operate in the San Francisco Bay Area in PG&E’s region which has an even cleaner mix than the entire state (PG&E’s mix has a smaller percentage of electricity generation from natural gas and a higher percentage from nuclear and renewable) as shown in Table 37 [Deru 2007, PGE 2008]. The Muni and Green Line systems which have similar physical characteristics contrast the effects of dirtier electricity on environmental performance. While these differing electricity mixes provide a contrast of operating condition performance, an ideal scenario can be imagined where these systems operate in an electricity mix which is 100% renewable.

Table 94 shows the baseline rail modes discussed in §1.7 and the corresponding performance in a 100% renewable environment. The 100% renewable mix does not account for life-cycle energy consumption and emissions so that if the electricity is generated from solar then manufacturing of the solar panels is not considered. This means that no primary energy is consumed and no emissions result from the production of the renewable electricity. For all modes, vehicle and infrastructure operation electricity consumption was assumed 100% renewable and negated from the inventory.

Table 94 – Effect of a 100% Renewable Electricity Mix on Rail Environmental Performance

	Energy MJ/PMT	GHG g CO_2e/PMT	CO mg/PMT	SO_2 mg/PMT	NO_X mg/PMT	VOC mg/PMT	PM_{10} mg/PMT
BART (Bay Area)	1.1 (2.2)	64 (140)	36 (530)	360 (620)	21 (290)	9.5 (200)	3.9 (55)
BART (Renewable)	1.1 (2.2)	0 (65)	0 (480)	0 (190)	0 (260)	0 (190)	0 (51)
Caltrain (Bay Area)	1.1 (2.3)	74 (160)	83 (440)	0.32 (260)	1400 (1600)	59 (210)	38 (95)
Caltrain (Renewable)	1.1 (2.3)	74 (130)	83 (390)	0.32 (140)	1400 (1600)	59 (190)	38 (90)
Muni (Bay Area)	1.2 (3)	69 (170)	39 (660)	380 (810)	22 (270)	10 (150)	4.2 (52)
Muni (Renewable)	1.2 (3)	0 (69)	0 (600)	0 (180)	0 (230)	0 (130)	0 (46)
Green Line (MA)	0.87 (2.3)	120 (230)	140 (720)	730 (1200)	160 (410)	9.3 (130)	7.4 (50)
Green Line (Renewable)	0.87 (2.3)	0 (56)	0 (510)	0 (140)	0 (170)	0 (110)	0 (40)
CAHSR (CA)	1.3 (2)	94 (130)	48 (320)	500 (680)	36 (160)	11 (96)	5.5 (23)
CAHSR (Renewable)	1.3 (2)	0 (32)	0 (260)	0 (95)	0 (120)	0 (84)	0 (18)

Operational energy and emissions with life-cycle performance in parenthesis.

For every mode, GHG and CAP emissions decrease from the baseline electricity mix to the 100% renewable mix. For the electric modes, operational emissions go to zero for the renewable mix while life-cycle emissions typically decrease. The reduction depends on several factors but is primarily dictated by how much of the total emissions in the baseline mix resulted from electricity generation. Some of the largest reductions in emissions are seen with SO_2. For all of the rail modes, a large fraction of the SO_2 was produced during electricity generation which is no longer the case in the renewable mix. Caltrain exhibits some of the smallest decreases between mixes due to its primary direct operating input being diesel fuel. There are reductions however in the life-cycle for Caltrain since all of its infrastructure operation components consume electricity.

The application of a 100% renewable mix to the rail modes highlights two key points: the first being that even with no emissions from electricity generation, there are still emissions in the life-cycle, and second, that emissions reductions vary but can show only small decreases as a result of a strong energy dependence on fossil fuels. This assessment assumes that many of the non-operational components, which are also driven by electricity generation somewhere in the supply chain, are not affected by a clean electricity mix. While this would not be entirely accurate, there is validity in that many of the supply chain activities could take place outside of the improved electricity mix. In all likelihood, Table 94 would show even larger reductions if emissions from electricity generation in indirect activities were removed. While reductions almost always occur, the size of the reductions varies and is sometimes small. The U.S. electricity mix is over 70% fossil and no transportation life-cycle process is completely independent of this [Deru 2007]. While some major components in a mode can be targeted for operation in a cleaner electricity mix, somewhere in the supply chain energy generation is based on fossil fuels. This interdependency plays a key role in shaping the environmental performance of every mode when evaluating the life-cycle.

1.10.4.5 Improved Corporate Average Fuel Economy Standards

The Energy Independence and Security Act of 2007 which was signed into law on December 19, 2007 requires automakers to improve their CAFE to 35 mi/gal by 2020 [TLOC 2007]. While previous CAFE standards have allowed loopholes for light duty trucks including SUVs and pickups, this legislation seeks to push almost all automobiles to improved economy. The effect of this legislation would significantly reduce fuel consumption of sedans, SUVs, and pickups reducing energy consumption and resulting emissions per VMT and PMT. While the legislation specifies average fuel economies for a fleet, it would likely improve environmental performance of the average automobiles in this thesis.

Applying the 35 mi/gal standard to the automobiles in this study improves direct vehicle operation performance ultimately reducing life-cycle energy consumption and emissions. Table 95 shows operational and life-cycle energy consumption and vehicle emissions per PMT for both the baseline and improved fuel economy conditions.

Table 95 – Effect of a 35 mi/gal Standard on Automobiles

	Energy MJ/PMT	GHG g CO_2e/PMT	CO mg/PMT	SO_2 mg/PMT	NO_X mg/PMT	VOC mg/PMT	PM_{10} mg/PMT
Sedan (28 mi/gal)	3 (4.7)	230 (380)	12 (12)	13 (350)	640 (1100)	740 (1200)	81 (240)
Sedan (35 mi/gal)	2.4 (4)	190 (330)	9.2 (10)	10 (340)	510 (970)	340 (1100)	51 (80)
SUV (17 mi/gal)	4.5 (6.5)	270 (450)	12 (13)	15 (410)	730 (1200)	790 (1300)	73 (230)
SUV (35 mi/gal)	2.2 (3.8)	130 (280)	5.9 (6.9)	7.5 (340)	350 (800)	240 (860)	64 (220)
Pickup (16 mi/gal)	5.7 (7.9)	420 (620)	19 (20)	24 (460)	1100 (1700)	1500 (2100)	86 (270)
Pickup (35 mi/gal)	2.6 (4.4)	190 (350)	8.6 (9.6)	11 (370)	520 (1000)	460 (1200)	35 (190)

Operational energy and emissions with life-cycle performance in parenthesis.

The effect of such an economy increase varies by automobile and input or output. The sedan which in the baseline case has the highest fuel economy shows less improvement than the SUV and pickup which had the lowest fuel economies. For the SUV and pickup, the improved fuel economy is more than twice that of the baseline. This results in significant environmental benefit per VMT and PMT. This benefit shows up with the operational factors and carries to the life-cycle factors. The improved fuel economy is manifested in the vehicles which would have particular characteristics (e.g., less mass or less acceleration) that would allow the automobile to travel further on a volume of gasoline. This would show in the vehicle manufacturing phase of the life-cycle but is presumed to be small in comparison to the baseline. The effect of these characteristics carries not just into vehicle operation but also fuel production. In these cases, less gasoline would be produced since automobiles would travel their lifetime distances using less fuel. In addition to the direct emissions decreases in vehicle operation, side effects such as evaporative fuel losses (VOCs), cold start emissions (CO), and electricity generation in fuel production (SO_2) would also decrease.

2 Case Study: Environmental Life-cycle Inventories of Metropolitan Regions

A Comparison of the San Francisco Bay Area, Chicago, and New York City

2.1 Executive Summary

This case study applies the life-cycle methodology and results from Chapter 1 to metropolitan passenger transportation networks to contrast the environmental performance of the systems. The environmental performance is linked to economic externalities, specifically the human healthcare costs of pollutants from passenger transport as well as GHG costs.

With a growing concern for the impact of transportation on humans and the environment, more attention is being given to the quality of environmental performance of vehicles and transit networks. In the U.S., the transportation sector is responsible for about 30% of national energy consumption and passenger transport is roughly two-thirds of this, or 20% of national consumption [BTS 2008]. GHG emissions are positively correlated to this consumption considering a near complete share of fossil-carbon fuels as the energy input. Additionally, CAP emissions from urban passenger transport are of particular concern due to their proximity of release to the population [Matthews 2001, English 1999, NYT 2006]. The energy inputs and emission outputs are not constrained purely to vehicle operation (see Chapter 1). The operation of any transportation mode is supported by a vast infrastructure which also consumes energy and releases emissions in its processes. For example, an automobile must be manufactured and maintained, processes that require energy and material inputs and result in emission outputs. Additionally, roads must be constructed and maintained and fuels must be produced, on top of many other infrastructure components. The inclusion of these non-operational components in the environmental inventory of each mode moves analysis towards total inventory accounting.

These life-cycle inventories are used in the evaluation of each passenger transit mode based on the LCI in Chapter 1.

Regional travel surveys are used to evaluate the energy consumption and emissions from passenger modes in metropolitan areas. The San Francisco Bay Area, Chicago, and New York regions are chosen because of their richness in transit options and the public availability of data. The Bay Area Travel Survey (BATS) was conducted in 2000 and consists of 15,000 households and 270,000 trips [MTC 2000]. The Chicago Metropolitan Agency for Planning's Travel Tracker Survey was conducted in 2007 and 2008 and consists of 14,000 households and 170,000 trips [CMAP 2008]. The Regional Travel Household Interview Survey (RTHIS) was conducted in 1997 and 1998 for the New York City, Northern New Jersey, and Southwestern Connecticut regions and captures 11,000 households and 110,000 trips [NYMTC 1998]. Given the large number of trips captured, it is assumed that these datasets are a representative sample of the entire system. The surveys capture critical parameters necessary to evaluate the environmental performance of the mode chosen such as distance traveled, time of day, passengers on personal transit vehicles (public transit occupancy is determined from other sources), vehicle types, and others. A summary of PMT mode splits for each region is shown in Appendix G.

The environmental performance for each trip is computed and normalized per VMT and PMT. While the three regions are similar in their abundance of transit options, they also have many characteristics which make them different from each other. The normalization of results per VMT and PMT is meant to compare travel in a uniform approach. For each trip, the energy consumption and GHG and CAP (CO, NO_X, SO_2, PM, and VOC, while Pb is excluded due to a lack of data) emissions are computed for both vehicle operation and the life-cycle. Energy consumption and emissions are adjusted for vehicle age and vehicle speed using emission trend reports and energy consumption and emissions versus vehicle speed profiles [Parrish 2006, Ross 1994, Granell 2004, Anderson 1996].

It is estimated that life-cycle energy varies from 6.3 MJ/PMT in the Bay Area to 5.7 MJ/PMT in Chicago and 5.3 MJ/PMT in New York for an average trip. Life-cycle GHG emissions range from 480 g CO_2e/PMT in the Bay Area to 440 g CO_2e/PMT for Chicago and 410 g CO_2e/PMT in New York. All three regions are heavily influenced by auto and rail travel (BART in the Bay Area, subway and commuter rail in Chicago, and subways in New York). The improved energy and GHG performance of Chicago and New York is the result of auto travel characteristics and high rail ridership. CAP emissions vary depending on the pollutant and sometimes the difference is as large as 25% between regions. Life-cycle CAP emissions are between 11% and 380% larger than their operational counterparts.

While energy and emissions for an average vehicle are useful metrics in evaluating entire system performance, it is important to consider off-peak and peak operating conditions as well as personal and public transit vehicles. It is expected that peak travel is cleaner than off-peak performance due to increased vehicle occupancies. This expectation is not always the case as energy and emissions, particularly from auto travel, get worse as vehicles operate in congestion [Ross 1994, Granell 2004]. The increased ridership does not necessarily make up for this resulting in off-peak travel sometimes cleaner than peak travel. For example, Chicago off-peak trip energy consumption is 5.5 MJ/PMT while peak trip energy consumption is 5.9 MJ/PMT. The off-peak and peak effects can partly be explained by disaggregating passenger and public transit. The large share of auto PMT (roughly 90% of all trips in the three regions) has strong effects on overall system performance. The Bay Area is the only region that shows significant auto occupancy increases from off-peak (1.6 passengers/auto) to peak (1.8 passengers/auto). Public transit occupancy increases significantly in the peak improving its environmental performance during that time.

The social costs of travel range from ¢51 (in ¢2007) per auto passenger per trip during peak in New York to ¢6 per public transit passenger per trip during peak hours in the Bay Area and New York. Average personal transit costs are between ¢28 and ¢41 while public transit is as high as ¢24 in Chicago (due to high NO_X emissions from commuter rail trains). The economic externalities represent a range of costs that if internalized by the trip taker could affect mode choice, i.e. the more a passenger is charged, the more likely they are to switch to cleaner modes.

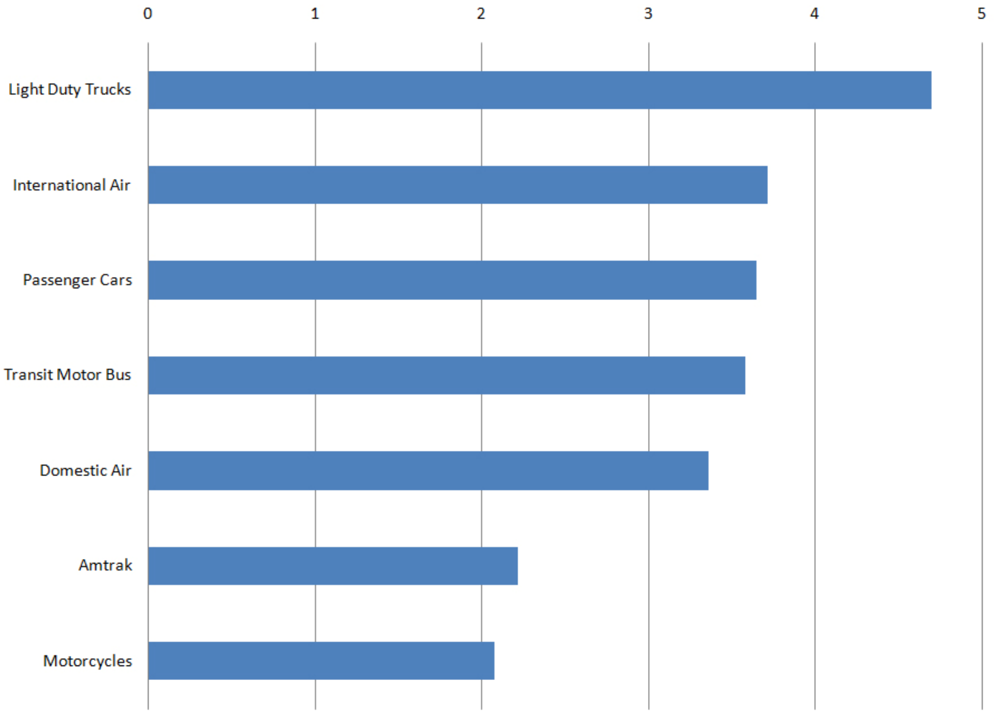
2.2 Introduction

Comparative assessments of the environmental performance of passenger transportation modes are numerous but rarely are life-cycle assessments presented for complete comparisons. In urban regions many transit options may exist and it is not easy to assess among each option's performance considering the many influencing variables (vehicle occupancy, fuel types, vehicle age, emissions control devices, and vehicle speed). Is it environmentally better to take a bus or train for a commute or is it better to carpool or take a bus that only has five passengers on it? These questions are sometimes answered by evaluating critical performance factors such as fuel economy of the vehicle. However, the variations in environmental performance of passenger transit modes are contingent on many physical (fuel consumption, emissions controls, occupancy rates), geographic (electricity mixes), and temporal (vehicle age) factors, just to name a few. Additionally, evaluating vehicle operation environmental performance also ignores the life-cycle components of the vehicles, infrastructure, and fuels which are necessary requirements for any transit mode. The energy and emissions associated with raw materials extraction and processing, supply chain transport, vehicle manufacturing, vehicle maintenance, infrastructure construction, infrastructure operation, fuel production, as well as many others (see Chapter 1) should be included in any environmental inventory to comprehensively evaluate the performance of a mode.

This case study evaluates three transit-rich U.S. metropolitan centers to determine the environmental performance of passenger transportation modes within each region. The objective is not to determine the total inventory for the region but to analyze the quality of travel in a normalized unit (effect per vehicle or passenger mile traveled). By normalizing performance to these functional units (vehicle miles traveled are further referred to as VMT and passenger miles traveled as PMT), it is possible to compare each region's modes against each other as well as against the other region's modes.

Modal characteristics from one metropolitan region to the next are not the same. Cross-modal comparisons are often done on "typical" vehicles and do not capture the variations which may make one region's mode strikingly different from another region. For example, a bus can be compared against an automobile or aircraft as shown in Figure 34. This is often done by taking the entire environmental inventory for a sector (e.g., total energy consumption) and dividing by the total PMT of that sector. Another common approach is to look at a "representative" system from a particular region and perform the same calculation. Both approaches mask the operating nuances of a particular mode in varying operating conditions and configurations. It may even fail to capture the best and worst operating configurations since these approaches tend toward the mean. For example, by looking at the average U.S. urban public transit bus (diesel powered), the relative performance of an electric bus is completely masked. To evaluate GHG emissions in this scenario, total emissions for all urban buses are likely computed based on the amount of fuel consumed. It is not common practice to include the upstream emissions from the electricity produced to operate electric buses, thus biasing the GHG emissions.

Figure 34 – Energy Intensity of Various Modes (MJ/PMT) [BTS 2007, Table 4-20]



The economic societal impact of passenger transportation is affected by many factors including direct human health complications, energy security, loss of environmental habitats, damage to crop production, indirect effects of global warming, and many others. While many of these impacts are difficult to determine, direct human health impacts are quantifiable by reviewing the cost of treating patients in hospitals who were exposed to transportation emissions [Matthews 2000, Matthews 2001]. These externalities are real costs and are not borne by the passenger in the transit vehicle. In most cases, those impacted live in urban areas and do not have the option of avoiding exposure, resulting in inequitable burdens [Matthews 2001, English 1999, NYT 2006]. The healthcare costs of treating the effects of respiratory illnesses from CAPs as well as premature death are used to determine the human health externalities associated with passenger transportation in these metropolitan regions. Additionally, the externalities associated with GHG emissions are included on an indirect human health impact basis.

This study evaluates the specific modal environmental performance of several metropolitan regions not from the top down (by comparing total inventory data and system-wide usage) but from the bottom up (by building life-cycle inventories specific to each region's transit). The environmental performance is evaluated from both the operational and life-cycle energy and emissions. With sparse evaluations of the total environmental inventory and associated costs, this work intends to provide some clarity on the quality and impact of specific modes and trip habits in the regions.

2.3 Background

The evaluation of metropolitan inventories often centers on computation of total inventories with the goal of estimating exposure or verifying emission rates of vehicles. Inventories are usually not compared against each other to contrast the environmental performance of passenger travel in multiple regions. The onset of travel surveys in the past few decades provides a mechanism for estimating regional transit inventories in major metropolitan regions in the U.S. at a different resolution than some common approaches. These surveys often report sufficient data to estimate critical operating characteristics of the vehicles as well as the passengers they deliver. While these surveys were not always intended to be used for such application, they can provide improved estimates of travel and vehicle behavior in a region from high-level estimates based on total VMT and passengers transported, or even micro-simulations of travel on corridors in sub-regions.

While many studies use various approaches to estimate a total inventory for a region, the objective of this work is to evaluate normalized environmental performance of transit networks across regions. The objective is not to determine the total energy consumption and emissions from passenger travel in each region but to consider the energy and emission quality of travel in each region by normalizing environmental performance to a per VMT and PMT basis. Past studies estimated inventories from total VMT by mode [Lyons 2003, EMFAC 2007], from simulations (where activity data may come from travel surveys or sensors) [Mensink 2000, Reynolds 2000, Anderson 1996], monitoring [Parrish 2006], or from regional fuel consumption [Singer 1999].

The travel surveys chosen are large and assumed representative of their larger systems. The travel captured in the survey therefore, is assumed to reflect that of the larger region. The normalization approach is used because the intention is not to estimate impact of emissions and because all of the metropolitan regions have some major differing characteristics (e.g., size, constraining geography, cost of transport, etc.).

Furthermore, no known study to date computes environmental inventories from an environmental life-cycle perspective. Typically, only operational components (petroleum and electricity consumption) are included because the emissions that occur with the vehicle are the ones that are assumed to have the highest impact and because of a general lack of availability of life-cycle data for transportation modes. Only recently have life-cycle inventories from some transit modes become available [MacLean 1998, Chapter 1]. The inclusion of non-operational components creates a comprehensive inventory with all components required to support a mode.

2.4 Methodology

To compare the three regions, metropolitan surveys were used to elicit passenger transportation characteristics. Travel surveys have been performed in many metropolitan regions in the U.S. over the past several decades [MTC 2005, MTC 2000, CMAP 2008, NYMTC 1998]. These surveys are large datasets which bring together socio-economic and transit characteristics of a large sampling of households in a region. Typically, each household is asked to detail their trip characteristics (including mode of travel, cost, duration, and passengers in the vehicle) over several days. The Bay Area Travel Survey (BATS) was conducted in 2000 and consists of 15,000 households and 270,000 trips [MTC 2000]. The Chicago Metropolitan Agency for Planning's Travel Tracker Survey was conducted in 2007 and 2008 and consists of 14,000 households and 170,000 trips [CMAP 2008]. The Regional Travel Household Interview Survey (RTHIS) was conducted in 1997 and 1998 for the New York City, Northern New Jersey, and Southwestern Connecticut regions and captures 11,000 households and 110,000 trips [NYMTC 1998]. These travel surveys were chosen for analysis because they have been completed recently and represent metropolitan regions with transit-rich options. The use of the term trip in this case study is defined by the individual modal travel segments between an origin and destination. A person traveling from home to work who walks to a bus, takes a bus close to the workplace, and walks the remaining distance is treated as having had three trips.

Given the richness of each dataset and methods for data collection, it is assumed that the surveys are a representative sample of each region's passenger transport system. The diversity of transit options in each region and environmental performance of different trip types warrant the comparison. The results of the analysis show energy consumption and GHG and CAP emissions. This environmental performance is normalized into several functional units including per VMT and PMT results. Given the assumption that the surveys are representative of the larger systems and the normalization of results, total environmental inventories were not computed for the entire system (e.g., total GHG emissions for the San Francisco Bay Area). Instead, the resolution stayed at the depth of particular trip types disaggregating both private and public modes.

2.4.1 Trip Characteristics

The travel survey datasets serve as the foundation of the analysis. They are used to determine the environmental effectiveness of passenger travel in the region. This is done by assessing individual trip characteristics in each dataset and the mode's environmental performance. The mode, generalized mode, vehicle year (if an automobile is used), party size, distance, trip time, and if travel occurred during peak times is identified for each record in each dataset. The mode refers to the specific metropolitan region's travel choices while the generalized mode groups travel by similar vehicles (e.g., BATS identifies around 20 unique bus services in the Bay Area and a generalized bus mode is applied to all of them based on a similar bus type). A description of the generalized modes is shown in Table 96. The generalized modal assignments for each of the travel surveys are shown in Table 107, Table 108, and Table 109 of Appendix D. The number of passengers for auto modes is specified for all datasets while transit occupancy must be specified (this is discussed in §2.4.2, §2.4.3, and §2.4.4). Peak travel times are specified as 7:00a to 10:00p and 3:00p to 7:00p. If the majority of travel occurs in one of these windows then it is tagged as peak travel.

Table 96 – Generalized Modal Coding for All Regions

Generalized Mode Assignment	Generalized Mode Description
1	Airplane
2	Bicycle
3	Employer Shuttle Bus
4	Dial-a Ride Bus
5	School Bus
6	Urban / Commuter Bus
9	Automobile (Tagged Explicitly as Carpool)
10	Ferry
11	Inter-Urban Rail
12, 14	Commuter Rail
13	Subway
15, 16	Light Rail
17	Taxi
18	Walk
100	Automobile (Undefined)
101	Automobile (Sedan)
102	Automobile (Light Duty Gasoline Truck)
103	Automobile (SUV)
104	Automobile (Van)
105	Automobile (Motorcycle / Moped)
200	Electric Urban Bus

These characteristics were needed to evaluate the environmental performance in the region but not always specified. It wasn’t uncommon for some data to be filled in while others were left blank (e.g., an auto trip between two regions would have a distance specified but a similar auto trip would not), likely the result of households not providing all of the information that they were asked to provide. In other cases, necessary data were completely missing such as in the BATS 2000 survey which doesn’t report trip distances. Several techniques were used as discussed to address the data quality issues. For each metropolitan region, the data quality goal was to have, for each trip, the mode, vehicle year, occupancy, distance, travel time, and peak indicator. These parameters would allow for the computation of trip emissions per VMT and

PMT adjusted for vehicle age and speed (peak travel occurs at lower speeds, potentially resulting in greater fuel consumption and emissions).

2.4.2 Specific San Francisco Bay Area Data Adjustments

Trip distances are not included in the BATS 2000 dataset. A previous BATS survey however, conducted in 1990, does report distances. Using the BATS 1990 dataset and origin-destination combinations by mode types, it was possible to populate the BATS 2000 dataset with trip distances. It was assumed that using the 1990 distances for year 2000 data was reasonable because trip distances should not have significantly changed during that period. Additionally, San Francisco Municipal Railway's LRT (Muni Metro) trip distances needed to be addressed but 1990 data could not be used since the LRT mode was not disaggregated from the bus mode for this service provider in the earlier dataset. To determine Muni Metro trip distances, track lengths between origin-destination were estimated [GE 2007].

Survey respondents were asked to identify start and end times for each trip segment so durations could be computed. Some dataset records however, did not have start or end times and durations needed to be estimated differently. To populate the missing trip times, average durations were used based on origin-destination combinations for each mode.

2.4.3 Specific Chicago Data Adjustments

A similar approach was used from §2.4.2 when trip distances were absent. An average distance for each origin-destination pair and mode was computed and applied to empty distance records.

2.4.4 Specific New York City Data Adjustments

The RTHIS dataset aggregates trip data at the multi-segment level and not individual segment level. Trips (which include multiple segments of potentially multiple modes) are given a single distance and duration and individual segment data are not reported. To compute the environmental inventory, individual segments with their own distance traveled and trip times were needed so that modal factors could be applied. For example, a trip reported in the dataset might show the traveler walking to a bus, taking a bus to a region, and then walking from the bus terminal to the destination. The total trip distance would be reported as well as the travel time (which includes both walking segments and the bus segment). It was necessary to disaggregate this trip into individual segments identifying the distance and time taken on both walking segments and the bus segment. To do this, weighted averages were used based on the modes chosen. While many trips in the RTHIS dataset were multi-modal, many were uni-modal. Using these single mode trips, average trip distances and durations were determined for each mode (e.g., the average walking trip is 1.4 miles and takes 13 minutes while the average bus trip is 4.5 miles and takes 38 minutes). With these modal averages, it was possible to disaggregate the trips into their individual segmental factors. If this walk-bus-walk trip had a total distance of 3 miles and a duration of 20 minutes then it was assumed that the first walking segment was the weighted average walking distance of the total trip distance ($3 \times 1.4 \div (1.4 + 4.5 + 1.4) = 0.7$) and the same for the duration. Using this approach, every multi-segment trip was disaggregated into its individual modal components.

2.4.5 Modal Environmental Performance

Modal environmental performance is estimated for energy inputs as well as GHGs, CO, NO_X, SO_2, PM, and VOC outputs. Two sets of environmental factors are used: operational (the direct energy and emissions resulting from vehicle operation during propulsion and idling and for auxiliary systems) and life-cycle (the energy and emissions invested in constructing and operating the modal infrastructure and fuels as well as the indirect factors associated with these components and the vehicle). Both the operational and life-cycle factors are determined primarily from the methodology described in Chapter 1. This LCA, however, evaluated specific modes in a specific geographic region. Many more modes in differing regions are included in this case study. Environmental factors were assigned to all generalized modes starting with operational factors. Most of the onroad factors were estimated in Mobile 6.2 while nonroad factors were estimated from a variety of sources [Chapter 1, EPA 2003, Farrell 2002, Corbett 2002, FTA 2005, EPA 1999c]. The life-cycle environmental factors are more difficult to estimate since no known repository of factors exists outside of the LCI presented in Chapter 1. This assessment estimates energy and emissions from automobiles, buses, rail, and aircraft and is based on representative vehicles for each mode. To create a life-cycle inventory for travel in each metropolitan region, generalizations were necessary from the inventory in Chapter 1 to the multitude of modes found in each dataset. While operational factors could be estimated based on previous studies, life-cycle factors were supplemented from components in Chapter 1. For non-operational components, diesel automobiles were assumed equal to gasoline automobiles, the school bus was assumed equivalent to an urban bus, the subways are equivalent to San Francisco's BART while commuter rail is equivalent to Caltrain. For several modes, including ferries and motorcycles, non-operational components weren't included since no previous analysis would provide a reasonable estimate of the total inventory for that system or mode and it couldn't be inferred from other modes.

The fundamental environmental factors for the Chicago and New York rail modes are based on California rail systems. These factors must be corrected since the emissions from California's electricity production (more specifically the San Francisco Bay Area) are based on a less fossil-intense state mix [PGE 2008, Deru 2007]. While all three states produce around 50% of their electricity from fossil fuels, 30% of California's electricity comes from hydro and renewable compared to 0.5% in Illinois and 19% in New York. To adjust for this, the Chicago and New York life-cycle rail component's emissions were computed based on their state's electricity mix.

The operational and life-cycle factors for the modes in this study that were not included in the LCI in Chapter 1 are shown in Table 97 and Table 98.

Table 97 – Operational Environmental Factors

Mode	Energy (MJ/VMT)	GHG (g CO_2e/VMT)	CO (g/VMT)	NO_X (g/VMT)	SO_2 (g/VMT)	PM (g/VMT)	VOC (g/VMT)
Light Duty Diesel Vehicle (LDDV)	4.7	342	1.6	1.4	0.1	0.2	0.6
Light Duty Diesel Truck (LDDT)	7.7	567	1.4	1.4	0.2	0.2	0.8
School Bus	22	1,626	2.7	12	0.5	0.8	0.8
Motorcycle	2.7	176	16	1.6	0.0	0.0	1.9
San Francisco Electric Urban Bus	18	351	0.2	0.3	2.9	0.0	0.0
Ferry	1,164	80,540	808	4,202	25	97	87
Chicago CTA Train	166	23,737	6.4	37	55	1.1	0.4
Chicago Metro Train	165	11,438	13	220	1.7	6.0	9.1
New York City Subway	166	16,523	23	23	83	1.0	0.8
New York / New Jersey PATH Rail	166	16,523	23	23	83	1.0	0.8
Newark Subway	166	16,523	23	23	83	1.0	0.8
New York City Commuter Rail	165	11,438	13	220	1.7	6.0	9.1

Table 98 – Life-cycle Environmental Factors

Mode	Energy (MJ/VMT)	GHG (g CO_2e/VMT)	CO (g/VMT)	NO_X (g/VMT)	SO_2 (g/VMT)	PM (g/VMT)	VOC (g/VMT)
Light Duty Diesel Vehicle (LDDV)	Non-operational factors assumed equivalent to sedan.						
Light Duty Diesel Truck (LDDT)	Non-operational factors assumed equivalent to light duty gasoline truck.						
School Bus	33	2,519	9.1	14	4.4	3.3	1.4
Motorcycle	No non-operational factors used. Life-cycle factors assumed equal to operational.						
San Francisco Electric Urban Bus	29	1,243	6.7	1.9	6.8	2.5	0.7
Ferry	No non-operational factors used. Life-cycle factors assumed equal to operational.						
Chicago CTA Train	321	36,528	78	226	94	12	18
Chicago Metro Train	353	27,983	68	469	45	16	29
New York City Subway	321	28,123	214	146	121	11	23
New York / New Jersey PATH Rail	321	28,123	214	146	121	11	23
Newark Subway	321	28,123	214	146	121	11	23
New York City Commuter Rail	353	26,094	93	373	47	16	31

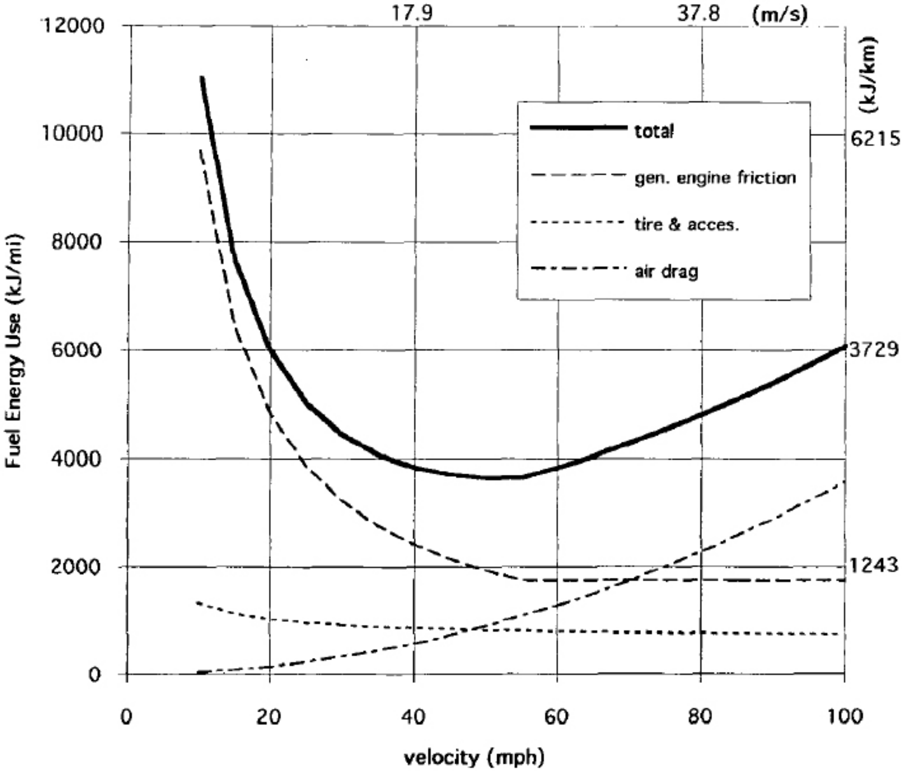
2.4.6 Vehicle Age Adjustments

The base energy and emission factors used for automobiles are modeled for 2005 vehicles and the differing ages of vehicles in the datasets should be adjusted since emissions change over time. While fuel economy has remained somewhat stagnant for the past decade, several studies indicate that CAP from the transportation sector have been steadily decreasing as the vehicle fleet, with more stringent emissions standards and improved fuel programs, turns over [Parrish 2006, Granell 2004]. While the computation of CAP emissions from vehicles is under some debate, it is suggest that during the past couple decades, CO emissions have decreased 4.9% annually, NO_X 1.4%, and VOCs 5.9% [Parrish 2006]. Furthermore, the Mobile 6.2 model estimates that this trend will continue resulting in a PM decrease of 4.5% annually during the next few decades [Granell 2004]. Assuming that fuel consumption and GHG emissions have not changed significantly during the past decade and CAP have decreased by the percentages described, the baseline emission factors were adjusted accounting for vehicle age. While some of the trends are not based on per VMT data but for the entire transportation inventory, it was presumed that using these values was a conservative estimate since total U.S. VMT has consistently increased. This means that emissions per mile have been decreasing at a higher rate [BTS 2008]. Depending on the year the dataset was conducted, vehicles are as young as 2008. For vehicles older than 2005, their emissions were greater than the baseline factors and younger vehicles were lower. The U.S. EPA has introduced more stringent fuel sulfur content standards around 2005 resulting in a decrease of SO_2 emission for many vehicle types [EPA 2007]. These standards primarily affect heavy duty diesel vehicles. Reducing the fuel's sulfur content (which acts as a poison to catalytic converters) enables the implementation of improved emissions control devices. Since all datasets are assumed to represent travel in 2007 in this case study, all heavy duty diesel vehicles with an age of three years or younger were adjusted for reduced SO_2 emissions. It was assumed that SO_2 emissions decreased from their baseline performance by a factor of three [Granell 2004]. The trends in vehicle emissions are shown in Figure 39 through Figure 41 of Appendix E.

2.4.7 Vehicle Speed Adjustments (Free Flow and Congestion Effects)

Fuel consumption and emissions profiles are not always linear with vehicle speed. While many operating characteristics affect these profiles, there is typically an optimal speed where fuel consumption and certain emissions are minimized per VMT. Below and above these speeds, energy and emissions increase resulting in a parabolic curve. This is illustrated in Figure 35 which shows the fuel energy use by different vehicle work components and speed [Ross 1994].

Figure 35 – Fuel Consumption and Vehicle Speed [Ross 1994]



A similar profile results when you look at CO, NO_X, and HC due to the air-fuel ratio at different speeds and catalytic converter operation. For PM and SO_2, emissions remain fairly constant with speed [Granell 2004]. These emission profiles are shown in Figure 42 through Figure 47 of Appendix F.

The energy and emission versus speed profiles were used to adjust base environmental factors for the operating speed of automobiles during their trip. The base environmental factors (determined in Mobile 6.2) are average factors for a particular driving cycle [EPA 2008]. They represent an average of a range of fuel consumption and emissions during the driving cycle which is not representative of all trips. Using the energy and emission profiles as well as the average vehicle speed during the trip (determined from the total distance traveled and trip time), the base environmental factors were adjusted for each trip. This adjustment would capture peak congestion effects where vehicles operate at lower speeds causing higher emission rates for GHGs, CO, NO_X, and HCs.

2.4.8 Vehicle Occupancy Rates

The number of passengers in each vehicle during each trip is needed for occupancy results but not always populated in the datasets. This absence of data exists for some personal transit trips and all public transit trips. The populating of occupancy rates for the two types of trips was done in two different ways. For personal transit trips, average occupancy rates for each mode type were determined. As the sample size was large and diverse, it was assumed to be representative and could therefore be applied to the missing data. For public transit trips, no occupancy data existed within the dataset so the Federal Transit Administration's National Transit Database (NTD) was employed [FTA 2005]. The NTD is a repository of transit data submitted by each public agency reporting overall characteristics of their network by mode. Transit agencies submit this data annually and report information such as the number of vehicles in operation, total vehicle miles, and total passenger miles as well as many other performance data. For each mode in each metropolitan region, NTD average occupancy rates were computed. This occupancy was applied to all of the transit agencies trips within a dataset. The occupancy rates used for each agency are shown in Table 107, Table 108, and Table 109 of Appendix D.

While average vehicle occupancies are useful for evaluating aggregate performance, off-peak and peak occupancies are necessary to evaluate the shifts in energy and emissions during critical travel times. The NTD reports total VMT and PMT allowing for an average occupancy to be determined. To determine the off-peak and peak occupancy, a percentage adjustment is calculated from the off-peak and peak VMT for the mode and applied to the average occupancy. The occupancies computed from the percentage adjustment represent the average off-peak and peak occupancies such that based on the VMT, result in an average occupancy as reported in the NTD. The mathematical formulation for computing these occupancies is shown in Appendix H.

2.4.9 External Costs

The economic externalities of trips in all regions are estimated from Matthews 2000 which gathered literature on the economic costs from healthcare for treating transportation related respiratory illnesses as well as premature death. A range of values is reported for each pollutant and converted to 2007 dollars. After the environmental inventory has been computed for each trip, the externalities are determined from the costs below. These costs are assumed to be U.S. averages and applicable to all of the metropolitan regions under consideration.

Table 99 – Environmental Externalities of GHG and CAP Pollutants ($\$_{1992}$/mt) [Matthews 2000]

	CO_2	CO	NO_X	SO_2	PM	VOC
Minimum	2	1	220	770	950	160
Median	14	520	1,060	1,800	2,800	1,400
Mean	13	520	2,800	2,000	4,300	1,600
Maximum	23	1,050	9,500	4,700	16,200	4,400

The applicability of these factors is based on the assumption that the human health impacts are uniform in any geographic region. The emissions of a metric tonne of PM in a population-dense region versus a sparse region would yield different impacts which are not captured here. Given that all three surveys were completed in dense metropolitan regions, it is assumed that the use of these factors is sound and that they don’t over-represent the impacts from each trip.

2.5 Results

2.5.1 System-wide Environmental Performance

The average energy consumption and emissions from a mile traveled in each region varies significantly. The effect of mode splits, vehicle types, vehicle occupancy, vehicle age, and off-peak and peak performance results in differing overall performance for each region. When average regional characteristics are evaluated, both operational and life-cycle performance can vary significantly as shown in Table 100 and Table 101. Life-cycle energy and GHG emissions are around 68% larger than operational. CAP life-cycle performance varies from almost insignificant increases to up to 350% larger than their operational components (see Chapter 1 for a description of non-operational life-cycle component contributors for the modes).

Table 100 – Personal and Public Transit Inventory (Energy and GHG Emissions)

			Energy (MJ)			**GHG (g CO_2e)**		
			A	**OP**	**P**	**A**	**OP**	**P**
San Francisco Bay Area	Oper.	per VMT	16	21	10	1,100	1,300	720
		per PMT	4.8	4.2	5.5	340	300	400
	LC	per VMT	26	34	14	1,700	2,300	1,000
		per PMT	6.3	5.8	7.0	480	440	530
Chicago	Oper.	per VMT	16	10	21	1,200	780	1,600
		per PMT	4.2	3.9	4.4	310	290	320
	LC	per VMT	28	17	38	2,400	1,400	3,200
		per PMT	5.7	5.5	5.9	440	430	460
New York	Oper.	per VMT	16	13	19	1,300	1,000	1,500
		per PMT	3.8	4.1	3.6	280	300	270
	LC	per VMT	26	21	31	2,100	1,600	2,500
		per PMT	5.3	5.6	5.1	410	430	390

Oper. = Vehicle Operation, LC = Life-cycle (Including Operation),
A = All (Off-Peak and Peak) Times, OP = Off-Peak Times, and P = Peak Times

Table 101 – Personal and Public Transit Inventory (CAP Emissions)

			CO (g)			NO$_X$ (g)			SO$_2$ (g)			PM (g)			VOC (g)		
			A	OP	P	A	OP	P	A	OP	P	A	OP	P	A	OP	P
San Francisco Bay Area	Oper.	VMT	39	29	54	13	19	3	1.7	2.6	0.5	.40	.58	.17	2.7	2.4	3.1
		PMT	28	20	39	1.1	1.1	1.2	0.0	0.0	0.0	.09	.09	.09	1.8	1.5	2.3
	LC	VMT	44	35	56	15	22	5	3.8	5.6	1.4	1.0	1.3	.49	4.6	4.9	4.2
		PMT	29	21	40	1.6	1.6	1.7	0.4	0.4	0.3	.26	.26	.27	2.3	2.0	2.8
Chicago	Oper.	VMT	36	24	45	12	6	18	0.7	0.5	0.9	.40	.25	.54	2.4	1.9	2.8
		PMT	27	18	35	1.3	1.0	1.5	0.0	0.0	0.0	.09	.09	.09	1.5	1.3	1.7
	LC	VMT	40	27	52	32	15	46	3.4	2.0	4.6	1.2	.77	1.6	4.2	3.1	5.1
		PMT	28	19	36	1.9	1.7	2.1	0.4	0.4	0.3	.26	.26	.26	2.0	1.8	2.2
New York	Oper.	VMT	40	25	51	16	10	20	2.2	1.7	2.6	.47	.35	.56	2.3	1.9	2.5
		PMT	28	18	36	1.5	1.1	1.8	0.0	0.0	0.0	.09	.09	.09	1.4	1.3	1.5
	LC	VMT	49	32	61	25	16	32	4.4	3.4	5.2	1.1	.90	1.3	4.0	3.4	4.4
		PMT	29	19	37	2.0	1.7	2.3	0.3	0.4	0.3	.26	.26	.25	1.9	1.8	2.0

Oper. = Vehicle Operation, LC = Life-cycle (Including Operation),
A = All (Off-Peak and Peak) Times, OP = Off-Peak Times, and P = Peak Times

For energy and GHG emissions, the three regions perform almost identically during all times per VMT considering only vehicle operation (around 16 MJ and 1.2 kg CO_2e). The varying ridership of the regions results in New York (3.8 MJ and 280 g CO_2e per PMT) and Chicago (4.2 MJ and 310 g CO_2e per PMT) having the best operational performance followed by the Bay Area (4.8 MJ and 340 g CO_2e per PMT). The strong New York performance is somewhat influenced by high subway ridership at 220 passengers per train and Chicago by the HRT Metra commuter rail system which has an average occupancy of 250 passengers per train [FTA 2005]. For life-cycle performance, energy across the three regions is again fairly similar per VMT (around 27 MJ) but GHG emissions differ with the Bay Area the largest (480 g CO_2e), followed by Chicago (440 g CO_2e), and New York the smallest (410 g CO_2e). With such a strong dependence on public transit in all three regions, rail systems have an effect on overall results. The GHG emissions per PMT on the rail systems in the three regions can vary by train type (§2.4.5). For example, the Bay Area's electric BART train's life-cycle emissions are 20 kg CO_2e/VMT while a New York City subway trains emits 28 kg CO_2e/VMT in the life-cycle (see Chapter 1). Because the BART train carries around 150 passengers on average compared to 220 for a subway train in New York, the increased occupancy is the primary reduction factor for decreased PMT modal emissions.

For CAP emissions, no metropolitan region stands alone as the best or worst performer across all pollutants. CO emissions are largest per VMT in New York (49 g life-cycle) and per PMT are relatively equal across regions (28 g life-cycle). For all regions, CO emissions are dominated by automobile travel accounting for 99% of total operational emissions in the Bay Area, 100% in Chicago, and 99% in New York.

Life-cycle NO_X emissions vary significantly between regions and are dominated by auto travel but affected by diesel rail and ferry service. Life-cycle NO_X emissions are around 18% larger than operational per VMT for the Bay Area, 164% for Chicago (due to a larger share of subway travel and the emissions from electricity generation), and 58% for New York. Per VMT, life-cycle NO_X emissions for Chicago (32 g) are 28% larger than New York (25 g). For Chicago, 11% of total emissions are from diesel commuter rail systems while for New York, ferry traffic accounts for 3% and subways and commuter rail 4% (the vast majority of NO_X emissions in all regions is attributed to autos). Again, the larger per VMT New York emissions are offset by high occupancy rates in comparison to the other regions. Per PMT, the regions vary between 1.6 and 2.0 g.

SO_2 emissions in non-operational components are more pronounced in the regional inventories than other CAP emissions, the result of electricity generation in vehicle manufacturing and maintenance, infrastructure construction and operation, and fuel production. For automobiles, life-cycle emissions are around 2100% larger than operation, and for electric rail, about 70% larger. Because of the strong influence of electricity generation on total emissions, it is important to understand each region's particular electricity mix when comparing system-wide or individual modal performance. New York is the worst performing region per VMT (4.4 g) followed by the Bay Area (3.8 g) and Chicago (3.4 g). This is again attributed primarily to auto travel followed by subways in New York, BART in the Bay Area, and rail in Chicago. The life-cycle PMT performance results in relatively equal emissions across regions of 0.35 g.

While operational PM emissions for the three regions are nearly the same (0.4 to 0.47 g/VMT), life-cycle emissions vary between 1.0 and 1.2 g/VMT due largely to automobiles and subway systems. For automobiles, the emissions at hot mix asphalt plants, and for subways, the production of concrete, are the major components contributing to non-operational PM emissions in the system (see Chapter 1). Considering passenger delivery, the three systems emit roughly 0.26 g/PMT.

Life-cycle VOC emissions for the systems (approximately 4.0-4.6 g/VMT) are around 75% larger than operational emissions. System-wide VOC emissions are dominated by automobiles and subways. Per PMT, auto emissions are around 6 times larger than emissions from rail systems (see Chapter 1). Operational emissions comprise around one-half of an automobile's life-cycle emissions and releases of volatile organic diluents from asphalts during roadway construction roughly comprise the other half. For rail systems, the release of VOCs during cement production for concrete in the infrastructure is the major contributor. Normalizing per PMT, the Bay Area emits 2.3 g, Chicago 2.0 g, and New York 1.9 g.

2.5.2 Trip Externalities

The societal costs associated with different types of travel in different regions vary significantly but are all considerable if internalized by the trip takers. For the average trip, the life-cycle health and GHG costs per passenger per trip are ¢28 for the Bay Area, ¢27 for Chicago, and ¢30 for New York (all costs are in ¢2007). It is assumed that the emissions that occur from transport in each region are more likely to have high impacts since they occur in densely populated areas and thus using the associated healthcare costs is reasonable. A breakdown of per trip costs is shown in Table 102 which disaggregates off-peak from peak travel as well as personal and public transit.

Table 102 – Personal and Public Transit Mean External Costs (¢$_{2007}$)

			Personal and Public Transit			Personal Transit			Public Transit		
			A	**OP**	**P**	**A**	**OP**	**P**	**A**	**OP**	**P**
San Francisco Bay Area	Oper.	per Trip	72	88	49	35	26	46	880	1,100	320
		per Pax-Trip	23	18	30	27	21	34	12	13	5
	LC	per Trip	96	120	60	42	34	54	1,200	1,500	500
		per Pax-Trip	28	23	35	33	26	41	16	19	6
Chicago	Oper.	per Trip	66	37	93	30	21	38	660	530	710
		per Pax-Trip	21	16	27	24	16	30	12	25	7
	LC	per Trip	140	75	200	36	28	45	1,800	1,500	1,900
		per Pax-Trip	27	21	33	28	21	36	24	53	14
New York / New Jersey / Southwest Connecticut	Oper.	per Trip	92	59	110	44	31	56	460	370	510
		per Pax-Trip	24	18	30	34	23	43	7	12	5
	LC	per Trip	140	96	170	54	40	66	800	670	880
		per Pax-Trip	30	24	35	41	31	51	11	19	6

Oper. = Vehicle Operation, LC = Life-cycle (Including Operation),
A = All (Off-Peak and Peak) Times, OP = Off-Peak Times, and P = Peak Times

While evaluating the costs per VMT can be useful for understanding the cleanliness of vehicle fleets, the trip costs are more informative when evaluating a traveler's behavior. The higher the cost, the more likely that passenger is to switch to a cleaner mode, if forced to internalize these social costs. Per PMT, the life-cycle costs for off-peak and peak travel can vary by up to 50%. The average off-peak trip costs around ¢23 while the average peak trip ¢34. Personal transit trips have the highest costs per PMT at ¢33 for the Bay Area, ¢28 for Chicago and ¢41 for New York. Although a particular region may rank the lowest in certain emissions, it is possible for this city to have higher overall external costs (which are an aggregate of the costs associated with all of the emissions) due to the non-uniform unit costs of each emission (for example, the mean NO_X cost in $1992/mt is 2,800 while CO is 520, as shown in Table 99). Auto trips fluctuate from a low of ¢21/PMT in Chicago to a high of ¢51/PMT in New York. Auto costs actually increase in peak per PMT due to congestion effects increasing emissions and a ridership change which doesn't make up for this increase. Around half of the auto costs in off-peak or peak are attributed to CO emissions. Public transit external costs are highest in the off-peak and lowest in the peak. While auto costs are not significantly different in the three regions, transit costs vary with differences in the transit fleet and ridership. In the life-cycle, per PMT, public transit costs range from a low of ¢6 in the Bay Area and New York during peak travel times to a high of ¢53 in Chicago during off-peak times. Chicago experiences higher public transit social costs during off-peak and peak times compared to the other two regions due to diesel commuter rail emissions. Per VMT, the external costs of operating a public transit vehicle range from a low (in the Bay Area during peak) of $5.00 to a high (in Chicago during peak) of $18. The Bay Area experiences the strongest variation between off-peak ($15) and peak travel per VMT for public transit.

2.5.3 Off-Peak and Peak Performance

The travel characteristics during off-peak and peak travel vary significantly for the regions. Not only is it expected that passenger occupancy increases during peak times for each VMT but the mode split is also likely to be different. While the general expected trend is for systems to be less efficient in the off-peak than on average and most efficient during peak, this is not always true. Table 101 disaggregates average (denoted with an "A" for all times which includes off-peak and peak), off-peak (OP), and peak (P) environmental factors. Comparing the average, off-peak, and peak factors, it is possible to determine when each system is operating at improved environmental performance. The mode split is the primary cause of regional performance changes between off-peak and peak and is less so the result of changes in occupancy.

For energy and GHG emissions, the Bay Area follows the expected trend with life-cycle variations from 34 MJ and 2.3 kg CO_2e per VMT in the off-peak to 14 MJ and 1.0 kg CO_2e per VMT in peak. Per PMT does not follow the expected trend with increases of 18% (1.2 MJ) in energy from off-peak to peak and 17% (93 g CO_2e) for GHG emissions. Chicago and New York show increases per VMT from off-peak to peak but New York is the only system that shows a per PMT decrease. Off-peak travel for these two regions performs better than peak travel per VMT because passengers choose cleaner modes during the off-peak but then switch to dirtier modes during peak. The dirtier modes, which tend to be public transit, also have much higher occupancy rates which for New York, makes up for the dirtier mode selection. For Chicago, life-cycle energy and GHG emissions in the off-peak (5.5 MJ and 430 g CO_2e) are 10% smaller than peak (5.9 MJ and 460 g CO_2e). For New York, life-cycle energy and GHG emissions in the off-peak (5.6 MJ and 430 g CO_2e) are 1.1 times larger than peak (5.1 MJ and 390 g CO_2e).

Off-peak to peak travel shows a common increasing trend from off-peak to peak for most pollutants as a result of congestion effects. The CAP emissions per VMT show that travelers tend to switch to dirtier modes during peak times resulting in larger emissions per VMT (except for the San Francisco Bay Area). The normalization per PMT shows that not enough passengers take these dirtier modes to result in lower emissions per PMT. In the Bay Area, CO and VOC emissions increase per PMT in the peak. Life-cycle CO peak emissions (40 g/PMT) are 1.9 times larger than off-peak emissions (21 g/PMT) and life-cycle VOC peak emissions (2.8 g/PMT) are 1.4 times larger than off-peak emissions (2.0 g/PMT). This is predominantly the result of automobile travel where CO and VOC emissions increase due to congestion effects (vehicles in peak have higher emissions per VMT since they are operating further from optimal) and are not offset by the same magnitude from the increase in passengers. This effect is also felt in Chicago and New York. For many CAP emissions, the dominance of automobile emissions and the effects of congestion in peak increase emissions per PMT from off-peak.

2.5.4 Personal and Public Transit Performance

While all three regions are rich in public transit options, the mix of personal and public transit vehicles and modal ridership results in unique performance for each system. Furthermore, the particular characteristics of each region's fleet and operating conditions (vehicle age, congestion, etc.) result in further changes.

The personal transit fleet is defined primarily by automobiles. Table 103 details the environmental performance of personal transit in each region during all times, off-peak times, and peak times. Considering purely vehicle performance (and ignoring passenger occupancies to normalize by PMT), variations among regions are explained by differences in vehicle age and shares in free flow versus congestion operation. Per VMT and per PMT, Bay Area autos have the highest energy consumption and GHG emissions. While the average auto emissions fluctuate due to differing operating conditions, the normalization per PMT is founded in differing occupancies across regions. The Bay Area is the only region which shows significant increases in auto ridership from off-peak (1.6 passengers/auto) to peak (1.8 passengers/auto). Chicago auto occupancy decreases from off-peak to peak from 1.7 to 1.6 passengers/auto and New York stays relatively constant at 1.7 passengers/auto. The Chicago decrease can possibly be explained by the public transit dependence where passengers are more inclined to switch to bus and rail instead of traveling by auto during peak times.

Table 103 – Personal Transit Inventory (Energy and GHG Emissions)

			Energy (MJ)			GHG (g CO_2e)		
			A	OP	P	A	OP	P
San Francisco Bay Area	Oper.	per VMT	6.6	5.8	7.6	470	410	550
		per PMT	5.0	4.5	5.6	360	320	400
	LC	per VMT	8.7	7.9	10	660	600	730
		per PMT	6.5	6.0	7.2	500	460	540
Chicago	Oper.	per VMT	5.3	5.0	5.7	390	370	420
		per PMT	4.3	3.8	4.7	310	280	350
	LC	per VMT	7.3	6.9	7.6	570	540	590
		per PMT	5.8	5.2	6.3	450	410	490
New York	Oper.	per VMT	5.2	5.4	5.1	380	390	370
		per PMT	4.0	4.1	4.0	290	300	290
	LC	per VMT	7.2	7.3	7.0	550	560	540
		per PMT	5.6	5.6	5.6	430	430	430

Oper. = Vehicle Operation, LC = Life-cycle (Including Operation),
A = All (Off-Peak and Peak) Times, OP = Off-Peak Times, and P = Peak Times

Table 104 – Personal Transit Inventory (CAP Emissions)

			CO (g)			NO_X (g)			SO_2 (g)			PM (g)			VOC (g)		
			A	OP	P	A	OP	P	A	OP	P	A	OP	P	A	OP	P
San Francisco Bay Area	Oper.	VMT	40	29	55	1.4	1.3	1.6	.02	.02	.02	.12	.12	.12	2.6	2.1	3.2
		PMT	30	22	40	1.1	1.0	1.2	.02	.02	.02	.09	.09	.09	2.0	1.6	2.3
	LC	VMT	41	30	56	2.1	1.9	2.3	.46	.46	.46	.36	.36	.36	3.3	2.8	3.9
		PMT	31	23	41	1.6	1.5	1.7	.35	.35	.35	.27	.28	.27	2.5	2.2	2.9
Chicago	Oper.	VMT	38	25	50	1.6	1.1	2.0	.02	.02	.02	.12	.12	.12	2.1	1.8	2.4
		PMT	30	19	40	1.2	0.9	1.6	.02	.02	.02	.09	.09	.10	1.7	1.3	1.9
	LC	VMT	39	26	51	2.2	1.7	2.6	.43	.43	.43	.34	.34	.34	2.8	2.4	3.1
		PMT	31	20	41	1.7	1.3	2.1	.34	.32	.35	.27	.26	.28	2.2	1.8	2.5
New York	Oper.	VMT	41	25	54	1.9	1.2	2.5	.02	.02	.02	.12	.12	.12	2.0	1.8	2.2
		PMT	32	19	41	1.5	0.9	1.9	.02	.02	.02	.09	.09	.09	1.6	1.4	1.8
	LC	VMT	43	27	55	2.6	1.8	3.1	.44	.44	.44	.35	.35	.35	2.7	2.5	2.9
		PMT	33	20	42	2.0	1.4	2.5	.35	.34	.35	.27	.27	.28	2.1	1.9	2.3

Oper. = Vehicle Operation, LC = Life-cycle (Including Operation),
A = All (Off-Peak and Peak) Times, OP = Off-Peak Times, and P = Peak Times

The public transit environmental inventory is strongly affected by a few modes in each fleet, and variations across regions are significant. The Bay Area public transit system is the only network which experiences decreases in energy consumption and GHG emissions from off-peak to peak travel per VMT. This is not the case with the Chicago and New York systems where energy and emissions increase during peak periods. Per PMT however, all systems experience increased environmental efficiency with largest requirements in the off-peak and lowest requirements in the peak as shown in Table 105.

Table 105 – Public Transit Inventory (Energy and GHG Emissions)

			Energy (MJ)			GHG (g CO_2e)		
			A	**OP**	**P**	**A**	**OP**	**P**
San Francisco Bay Area	Oper.	per VMT	150	160	110	9,400	9,900	6,800
		per PMT	2.2	2.3	1.9	150	160	140
	LC	per VMT	260	270	180	16,000	18,000	12,000
		per PMT	3.4	3.6	2.4	230	250	170
Chicago	Oper.	per VMT	120	110	130	9,900	9,000	10,000
		per PMT	2.8	5.9	1.8	230	480	140
	LC	per VMT	240	210	250	21,000	19,000	22,000
		per PMT	4.5	9.8	2.8	370	820	220
New York	Oper.	per VMT	110	96	110	8,700	7,900	9,200
		per PMT	2.2	4.0	1.3	170	310	100
	LC	per VMT	180	170	190	15,000	14,000	15,000
		per PMT	3.1	5.8	1.8	250	460	140

Oper. = Vehicle Operation, LC = Life-cycle (Including Operation),
A = All (Off-Peak and Peak) Times, OP = Off-Peak Times, and P = Peak Times

Table 106 – Public Transit Inventory (CAP Emissions)

			CO (g)			NO_X (g)			SO_2 (g)			PM (g)			VOC (g)		
			A	OP	P	A	OP	P	A	OP	P	A	OP	P	A	OP	P
SF Bay Area	Oper.	VMT	30	33	17	160	180	66	25	26	18	4.2	4.7	1.9	4.9	5.3	2.7
		PMT	0.7	0.7	0.8	2.1	2.3	0.8	.20	.23	.08	.06	.07	.03	.08	.08	.07
	LC	VMT	75	80	48	190	210	83	50	53	34	9	10	5.3	22	24	15
		PMT	1.2	1.3	1.1	2.4	2.6	1.0	.45	.51	.19	.12	.13	.06	.29	.31	.18
Chic.	Oper.	VMT	11	8.9	12	120	97	130	7.8	10	7.1	3.4	2.8	3.6	5.1	4.0	5.5
		PMT	0.8	1.5	0.6	1.9	4.2	1.1	.14	.36	.06	.06	.15	.03	.11	.23	.08
	LC	VMT	53	47	55	340	280	360	34	33	34	11	9.2	11	19	16	20
		PMT	1.5	3.2	1.0	3.9	9.1	2.2	.49	1.2	.25	.17	.40	.09	.37	.82	.21
New York	Oper.	VMT	28	23	30	130	110	140	20	20	20	3.3	2.9	3.5	3.9	3.3	4.2
		PMT	1.6	2.7	1.0	1.8	3.1	1.1	.14	.29	.07	.06	.11	.03	.14	.25	.09
	LC	VMT	98	91	100	210	180	220	37	36	37	7.5	6.9	7.9	14	13	15
		PMT	2.4	4.2	1.4	2.5	4.5	1.5	.33	.67	.17	.12	.24	.07	.33	.62	.19

Oper. = Vehicle Operation, LC = Life-cycle (Including Operation),
A = All (Off-Peak and Peak) Times, OP = Off-Peak Times, and P = Peak Times

Per PMT, CAP emissions also experience reductions from off-peak to peak. The variations can be significant highlighting the sensitivity in environmental performance and how it is affected by ridership. Additionally, the dependence on particular modes in a region will have strong effects on particular emissions. In Chicago, the use of diesel commuter rail results in large off-peak NO_X emissions (9.1 g/PMT) while for New York, the strong dependence on taxis results in large off-peak CO emissions (4.2 g/PMT).

2.6 Discussion

This study identifies the critical environmental characteristics of several major urban transport networks and the influence that these parameters have on overall performance. While many factors have some effect on the system, a few have major influence on the cleanliness of the network. The choice to normalize performance by VMT and PMT highlights the importance of passenger transport’s objective to move people. While a regional inventory is useful, personal and public transport can ultimately be evaluated per mile traveled by the vehicles and passengers on board. From an environmental perspective, the passengers are sometimes ignored and environmental performance is compared at the vehicle level (vehicle energy consumption and tailpipe emissions do not change drastically with the mass of additional passenger since the bulk of the mass is with the vehicle). From a transportation environmental perspective, however, it is important to evaluate modal performance from a per PMT perspective (an even higher resolution than per VMT) to capture the ultimate goal of each mode, to move people. The normalization per VMT and PMT results in metrics that are determined from environmental stocks for each vehicle trip and passengers transported. While many factors can improve the environmental stock (reducing energy consumption and emissions), other factors can improve the number of passengers transported by vehicles, ultimately having the same effect of improving environmental performance per PMT.

The non-linear relationship of fuel consumption and emissions against vehicle speed is necessary in evaluating off-peak and peak conditions. While it may be expected that during peak times vehicles operate more passenger-dense so performance per PMT is reduced, this is not always true. Peak vehicle operation results in increased travel times during congestion, meaning that vehicles operate further from the optimum (see Figure 35 and Appendix F). Additionally, passenger occupancies do not change by a large enough margin to offset the increased emissions. During peak times, while more passengers occupy vehicles, per PMT, the vehicles have poorer performance than during off-peak times. With auto travel (personal transit) in all three regions, energy consumption, GHG emissions, and many CAP emissions are lower during off-peak than peak.

The regions chosen were selected partly based on the richness of transit options offered although system-wide performance is often the result of a few modes. For all three regions, auto and rail travel constitute a majority of energy and emissions. Automobiles are responsible for a 90% or more share of total PMT in the system and likely just under 100% of VMT. While public transit options are rich in these regions and likely used more heavily than other cities in the country, the dominance of automobile travel has strong effects on overall results. From an energy and GHG perspective, autos are 2-3 times worse than public transit and from a CAP perspective, this multiplier can be much larger (CO emissions are 31 g/PMT in the Bay Area on average for auto travel but only 1.2 g/PMT for public transit travel). The reliance on subway systems in all regions also has strong implications for overall results. Rail systems are responsible for 4.5% of total PMT in the Bay Area, 5.7% in Chicago, and 4.7% in New York, which is larger than buses (1.2% in the Bay Area, 1.6% in Chicago, and 2.6% in New York). The dominance of rail modes often results in high SO_2 (electricity generation for electric trains) and NO_X (electricity generation for electric trains and diesel fuel combustion with commuter rail) levels from public transport. Reduction strategies for these modes should be centered around low sulfur fuel inputs during electricity generation and the implementation of catalytic converters on diesel locomotives which would reduce the NO_X to inert N_2.

The internalization of human health and GHG passenger transport externalities could have profound implications on mode choice. While the average cost of a trip in any region is around ¢30, this fluctuates significantly based on the mode and time of day. The higher emissions during peak travel result in higher costs. Public transit trips, per passenger, are 85% less than personal transit trips in the Bay Area, 61% in Chicago, and 88% in New York. This means that personal transit trips, during peak times, are 6.8 times more costly than public transit trips in the Bay Area, 2.6 times in Chicago, and 8.5 times in New York.

Policies intended to improve the environmental performance of a region's passenger transport network must consider the energy consumption and emissions of vehicles as well as ridership. Improving one while ignoring the other does not acknowledge the objective of the system: to move passengers. Both must be addressed if quality and service are to be maintained while reducing impact of the system. Increasing the occupancy of personal vehicles presumably reduces emissions by removing other cars from the road (passengers who would have driven by themselves are now sharing a ride). If this is done simultaneously with incentives to drive more fuel efficient vehicles then both parameters have been improved. Tradeoffs between personal and public transit vehicles are often large. Personal transit energy consumption and GHG emissions are sometimes twice as large per PMT compared to public transit. For CAP emissions, this difference can be an order of magnitude. Incentives to switch to public transit from automobiles should be given higher priority than carpool incentives for many environmental factors. Additionally, policies which aim to reduce the emissions of public transit vehicles (such as biodiesel, compressed natural gas, and hydrogen buses), do not acknowledge the relatively minor impact these technologies will have on a system's overall environmental inventory. While it is important to develop and implement these technologies to address even a minor share of PMT, the impact of other modes should not be ignored. The dominating performance of autos and rail should lead to an evaluation of how best to improve environmental performance in a system optimal manner, and not at the agency level. A minor improvement to auto and rail performance, whether that is reduced energy consumption and emissions or increased ridership, will likely have a much larger effect for each region than an improvement to buses or even ferries (which are the worst performing vehicles per VMT or PMT).

Regional transit modes have been compared at many levels from an environmental viewpoint and the achievement of access and mobility of different modes is founded in many factors.

While some modes outperform others in certain conditions, all modes fill some niche that others may not be able to fill. Agendas which advocate switches from one mode to another based purely on environmental considerations should not ignore the functionally unique aspects of the modes. The geographic, time, and cost tradeoffs of different modes in different regions result in passenger choices based on their utility for the modes. A thorough understanding of a traveler’s utility would incorporate not only environmental considerations but also the many factors which result in passengers choosing the modes they do.

3 Contributions and Future Work

3.1 Contributions of Thesis

This thesis presents the most comprehensive environmental life-cycle inventory published to date of passenger transportation modes in the U.S.. Previous LCAs of automobiles do not include nearly as many components as this study. This is one of the first LCAs for buses, HRT, LRT, and aircraft. The total inventory reported in this work is a tool that can be used in place of, or in conjunction with, other environmental inventories for passenger transit modes. However, while typical vehicles were evaluated, these vehicles do not describe the performance of every vehicle in every operating condition. This inventory is representative of U.S. automobiles, buses, and aircraft, San Francisco Bay Area rail systems, a Massachusetts light rail system, and a proposed California high speed rail system.

The normalization of the reported data into multiple functional units is meant to present the findings in forms that can be easily used. Those wishing to evaluate other vehicles or even these vehicles in differing operating conditions should still find many components of this work complementary. For example, a diesel sedan's operating inputs and outputs could be determined in a separate study and combined with the non-operational vehicle components as well as infrastructure and fuel components to create a reasonable inventory for that vehicle. Additionally, an urban diesel bus could be evaluated with a drive cycle different from the one used in this work and combined with the non-operational vehicle components as well as the infrastructure and fuel components to create a system-specific inventory.

This inventory is intended to illuminate some answers that arise when modes are cross-compared with the goal of informing policy and decision makers. With mounting energy and environmental concerns, more in-depth questions are asked about the life-cycle performance of various modes. These questions are sometimes answered by analyses which look at vehicle operation and a few of the larger and easy to quantify supporting components. For example, the emissions from an electric urban bus which touts itself as a zero emission vehicle can be quantified by evaluating electricity consumption during operation and the emissions which result at the power plant from producing that electricity. While this high-level analysis has its merits and can sometimes answer particular questions, it is important to consider many other components as well as the supply chain of activities supporting that system. It is not unlikely to uncover a major environmental contributor in a component that would not be considered in a high-level analysis (e.g., the CO emissions from concrete production in railway infrastructure construction account for the large fraction of total emissions). The results of this work should provide a foundation upon which policy and decision makers can answer tougher cross-comparison questions without resorting to limited high-level analyses. An inventory has been developed which will help to answer questions not only about total environmental performance but also the quality of that performance.

The identification of major energy and emission components serves as a tool to tackle specific issues related to the quality of performance both geographically and temporally (§1.9). While emissions of a particular pollutant may be larger for the vehicle operation component in an inventory, other component emissions may be released closer to population centers resulting in a greater likelihood of exposure (e.g., the impacts of emissions from auto manufacturing may be greater than vehicle operation if manufacturing occurs in a dense region while driving typically does not). The disaggregation of components presents a founding inventory which could be used in impact assessment frameworks to determine where the greatest risks exist. Additionally, the temporal aspect is important in understanding the duration of exposure for a particular population. While some emissions are continuously released and may expose populations to acceptable exposure, others are released one time and may result in unacceptable exposure.

This inventory is an assessment of energy inputs and GHG and CAP emission outputs but creates a framework for the evaluation of other inputs and outputs. The methodology presented in this thesis is valid for the computation of other items of interest. Additional inputs include economic costs, water consumption, material requirements, and labor requirements. Additional outputs include toxic releases and hazardous wastes. Using the methodology and mathematical framework developed in this thesis, total inventories for any of these components could be determined for passenger transit modes provided data exists.

The metropolitan environmental inventory case study (§2) is the first to estimate life-cycle energy and emissions for an entire urban region. The San Francisco Bay Area, Chicago, and New York regions are compared based on many different metrics and show that the LCI developed for the modes can be applied to real-world data. The application of the inventory to multiple regions shows the adaptability of the results and its applicability in several geographic regions. While not all of the transit systems were the same as the systems estimated in the inventory, new modal inventories were created by adjusting performance data and electricity requirements. While the vehicle operational components changed, most other components provided reasonable estimates resulting in new life-cycle inventories for these other modes. The cross comparisons begin to answer some of the questions related to total environmental costs and when it is better or worse to travel on a particular mode.

While the main focus of this thesis is to report an energy and emissions inventory, it also quantifies some associated impacts from the inventory. The reporting of GHG emissions in a normalized greenhouse gas-equivalent unit (CO_2-equivalence) quantifies the global warming potential (GWP) of the releases. While there is not yet a definitive quantitative association of GHG releases and climate change, GWP is the metric used to estimate the contribution of an activity to expected climate change. Additionally, the use of Matthews 2000 to link passenger travel to direct human health impacts in §2 is another form of impact assessment. The release of CAPs in the three metropolitan regions has associated direct human health costs which have been quantified and reported for typical trips. These two impacts begin to touch on the range of effects which could be evaluated from the reported inventory.

There are many questions in the field of transportation and the environment which need comprehensive answers. It is intended that the contributions of this research provide a stepping stone for further analyses to continuously improve passenger transit modes for the goal of sustainable transportation.

3.2 Future Work

The foundation laid by the work in this thesis can be readily built upon by further analyses. These analyses include addition of other life-cycle components, refinement of data in the inventory, use of the framework for inclusion of other inputs and outputs, and analysis case studies using the inventory. The future work detailed below is certainly not all that could be done but represents several future projects currently considered by the author of this dissertation.

<u>CAHSR Updates</u>

The CAHSR inventory is modeled after a planned system proposed in the state of California. At the time of this dissertation's submittal, the CAHSR system does not have finalized infrastructure designs or specified vehicles [CAHSR 2005, PB 1999]. Several routes have been proposed and preliminary engineering design performed which served as the basis for CAHSR infrastructure environmental inventory. Vehicles are assumed to operate similar to European trains [Anderrson 2006, Bombardier 2007]. Total yearly train and passenger mileage is speculative but determines the environmental effectiveness of the mode when normalized per VMT or PMT. If plans for the CAHSR system proceed, the finalization of designs and accuracy of estimates should increase. The improved data will serve to improve the accuracy of the estimated environmental performance of the system.

<u>End-of-life Phase</u>

Given the time constraints in completing this work, the end-of-life phase for all components was excluded from the inventories. This was not meant to diminish the importance of environmental effects of end-of-life practices. The complexity of analyzing this phase for so many components led to its exclusion across all modes and life-cycle phases so that a common system boundary was enforced. While some data exist on some component's end-of-life practices, this was far from the case for the majority. Assuming that this phase has a net positive energy consumption and emissions for almost all processes, the inventories would increase so the results reported are conservative. The intricacies of mapping process, material, service, energy consumption, and emission flows in end-of-life components were not feasible in the time and resource constraints of this work but should be carefully studied later. For many reasons, it is critical to have a sound understanding of how to deal with transport vehicles and other system components at obsolescence.

<u>Automobile Carbon Monoxide Operational Emissions</u>

There is some debate around the accuracy of automobile CO emissions generated in the EPA's Mobile 6.2 software. The factors generated in Mobile 6.2 are used for sedan, SUV, pickup, and bus CO emissions during fuel combustion in the vehicle operation stage. A data source which estimates CO emissions disaggregating the three vehicle types was not readily discovered for verification against EPA's estimate so the Mobile 6.2 factors were used. These factors should be verified, and if found to be inaccurate, replaced.

Average and Marginal Analysis

For all systems inventoried in this thesis, average energy inputs and emission outputs are reported while marginal effects are not considered. In reality, many systems and processes operate with increasing or decreasing returns to scale. The marginal environmental effects are likely not equal to average effects in many circumstances. The difficulty of performing these estimates, the confidence in results, and a general unavailability of data were compelling reasons for reporting average effects. However, this is not to say that marginal effects cannot be computed. Future projects could be performed to estimate the average versus marginal effects of certain critical components in each mode to better inform policy makers of particular decisions.

Addition of Other Vehicles and Operating Conditions

With a methodological framework developed for life-cycle assessment of autos, buses, HRT, LRT, and aircraft, new inventories can be computed outside of the systems estimated in this thesis. For example, the auto inventory could be further specified by particular operating conditions instead of an average drive cycle. Electric rail system inventories could be estimated from the components in this work and specified electricity grid data. These improvements do not correspond only to vehicle operation but to any of the life-cycle components for the modes. While the inventories reported are valuable, the methodological framework allows anyone with the appropriate data to perform the necessary steps to create a tailored inventory for a particular system.

Additional Inputs and Outputs

In addition to creating customized modal inventories, the methodological framework allows for the estimation of inputs and outputs not determined in this work. This study focused on energy inputs and GHG and CAP emission outputs. However, many other inputs and outputs are critical to the overall performance of a transit system. These are not just environmental but also technical, social, and economic. This may include:

- Water consumption
- Material inputs (such as metals or wood)
- Labor inputs
- Cost inputs
- Toxic releases (such as carcinogenic emissions)
- Hazardous waste generation

Using the framework for each component and appropriate data, inventories for these items could be estimated to determine total inputs or outputs, and ultimately total impacts.

Impact Assessment

While life-cycle energy and emission inventories are necessary to understand the comprehensive performance of transit systems, the ultimate goal is to determine the impacts of the energy consumption and emissions releases. Impact must be further defined, but in the context of this thesis would be associated with energy and environmental costs. The impacts of our current transportation energy consumption habits (particularly the consumption of gasoline and ethanol) have profound implications for national security and reduction goals. The release of GHG emissions from passenger transportation are roughly 20% of total U.S. emissions and around 5% of global emissions [BTS 2008]. While the impacts from climate change are uncertain, the impacts of U.S. driving will be a major contributor to any change. Even a small reduction in GHG emissions from U.S. automobiles will have significant effects over large reductions from many countries. The release of CAP from transportation systems is of significant concern due to its direct effects on human health. Using this inventory, policies aimed at reducing emissions can more intelligently target components for improvement. These components can be evaluated for their geographic and temporal properties and how population exposure occurs.

4 References

[AAA 2006] American Automobile Association, *Your Driving Costs 2006 Pamphlet*, http://www.aaawin.com/news_safety/news_room/documents/DrivingCosts2006_000.pdf (accessed 6/4/2007).

[AASHTO 2001] *A Policy on Geometric Design of Highways and Streets: 2001*; American Association of State Highway and Transportation Officials, Washington, DC, 2001.

[AIA 2007] Aerospace Industries Association of America, *Aerospace Facts and Figures 2006-2007*, 54th Edition; ISBN 978-0-9721132-5-0, Arlington, VA, 2007.

[AN 2005] *2005 Market Data Book*; Automotive News.

[Anderrson 2006] Anderrson, E.; Lukaszewicz, P., *Energy Consumption and Related Air Pollution for Scandinavian Electric Passenger Trains*, Report KTH/AVE 2006:46, Department of Aeronautical and Vehicle Engineering, Royal Institute of Technology, KTH, Stockholm, Sweden ; http://www.kth.se/fakulteter/centra/jarnvag/publications/Energy_060925.pdf.

[Anderson 1996] Anderson, W.; Kanaroglou, P.; Miller, E.; Buliung, R.; Simulating Automobile Emissions in an Integrated Urban Model; *Transportation Research Record, Journal of the Transportation Research Board*, 1996, V.1520, pp.71-80; http://dx.doi.org/10.3141/1520-09.

[APTA 2006] *Public Transportation Fact Book 2006*, 57th Edition; American Public Transportation Association, Washington, DC, 2006; http://www.apta.com/research/stats/factbook/ (accessed 7/12/2007).

[ATA 2003] *2003 Annual Report*, Air Transportation Association; http://www.airlines.org/ (accessed 10/5/2007).

[Bare 2003] Bare, J.C., Norris, G.A., Pennington, D.W. and McKone, T., TRACI: the US EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. *Journal of Industrial Ecology*, 2003, V.6, pp.49–78; http://dx.doi.org/10.1162/108819802766269539.

[BART 2006] *2006 Short Range Transit Plan and Capital Improvement Program*; Bay Area Rapid Transit District, Office of Planning and Budget, Oakland, CA, January 2006; http://www.bart.gov/docs/FINAL_FY06_SRTP_CIP.pdf (accessed 11/29/2007).

[BART 2006c] *FY2006 Independent Audit of Basic Financial Statements*; Bay Area Rapid Transit District, Oakland, CA, 2006; http://www.bart.gov/docs/FY2006_financials.pdf (accessed 11/29.2007).

[BART 2007] Bay Area Rapid Transit System, *BART System Facts*, http://www.bart.gov/about/history/systemFacts.asp (accessed 4/26/2007).

[BART 2007e] *Seismic Retrofit of BART Aerial Structures and Stations Along the Concord, Richmond, Daly City, and Fremont Lines Project*; Bay Area Rapid Transit District, Oakland, CA, 5/3/2007; http://www.bart.gov/docs/eqs/Technical_Studies_Summary.pdf (accessed 10/15/2007).

[Bei 1978] Bei, R., San Francisco's Muni Metro, A Light-Rail Transit System, Light-Rail Transit: Planning and Technology, 1978, *Transportation Research Board,* Special Report 182.

[Boeing 2007] Boeing Company, *Boeing Commercial Plane Prices*, http://www.boeing.com/commercial/prices (accessed 4/2005 and 10/2007).

[Bombardier 2007] Bombardier, *ICE-3 Specifications*, http://www.bombardier.com/en/1_0/1_1/1_1_4_3_3.jsp (accessed 9/6/2007).

[Breda 2007] Ansaldobreda, *San Francisco Muni LRV Specifications*, http://www.ansaldobreda.it/files/prodotti/SanFrancisco.pdf (accessed 7/18/2007).

[Breda 2007b] Ansaldobreda, *Boston Green Line LRV Specifications*, http://www.ansaldobreda.it/files/prodotti/Boston.pdf (accessed 7/18/2007).

[BTS 2005] U.S. Department of Transportation, Bureau of Transportation Statistics, Research and Innovation Technology Administration, *National Transportation Statistics Series*, Washington, DC; http://www.bts.gov/publications/national_transportation_statistics/ (accessed 3/10/2006).

[BTS 2006] U.S. Department of Transportation, Bureau of Transportation Statistics, Research and Innovation Technology Administration, *State Transportation Statistics Series*, Washington, DC; http://www.bts.gov/publications/state_transportation_statistics/ (accessed 6/25/2007).

[BTS 2007] U.S. Department of Transportation, Bureau of Transportation Statistics, Research and Innovation Technology Administration, *Air Carrier Statistics and Financial Reports*, Aviation Data Library, Table T-100 and P-52, Washington, DC; http://www.transtats.bts.gov/databases.asp?Mode_ID=1 (accessed 2/1/2008).

[BTS 2008] U.S. Department of Transportation, Bureau of Transportation Statistics, Research and Innovation Technology Administration, *National Transportation Statistics Series*, Washington, DC; http://www.bts.gov/publications/national_transportation_statistics/ (accessed 4/17/2008).

[BuiLCA 2007] Vieira, P.; Horvath, A.; *BuiLCA: Building Life-cycle Assessment Tool*; Unpublished Doctoral Thesis; University of California, Berkeley, Berkeley, CA; Fall 2007.

[CAHSR 2005] Final Environmental Impact Report: August 2005; California High Speed Rail Authority, Sacramento, CA; http://www.cahighspeedrail.ca.gov/eir_final/FEIR/Vol1.asp (accessed 8/10/2006).

[Caltrain 2004] *Short Range Transit Plan 2004*; Caltrain, San Carlos, CA, 2004; http://www.caltrain.org/srtp.html (accessed 9/5/2006).

[Caltrain 2006] *Caltrain 2025*; Caltrain, San Carlos, CA, 2006; http://www.caltrain.org/caltrain2025.html (accessed 9/17/2007).

[Lenzen 2001] Lenzen, M.; Errors in Conventional and Input-Output Based Life-cycle Assessment; *Journal of Industrial Ecology*, 2001, V.4, N.4, pp.127-148; http://dx.doi.org/10.1162/10881980052541981.

[Caltrain 2007] Caltrain; *Commute Fleet*; http://www.caltrain.com/caltrain_commute_fleet.html (accessed 10/16/2007).

[Caltrain 2007c] Caltrain; *Timetable*; http://www.caltrain.org/timetable.html (accessed 6/23/2007).

[Caltrain 2007d] Caltrain; *Gallery Cars*; http://www.caltrain.org/caltrain_gallery_cars.html (accessed 6/24/2007).

[Caltrans 1988] *Evaluation of the Feasibility of Constructing a Peninsula Commute Service (Caltrain) Station in the South Bayshore/Hunters Point Area of San Francisco and of Closing the Paul Street Station*; California Department of Transportation, Sacramento, CA, 1988; http://www.sfcta.org/images/stories/Planning/CaltrainOakdaleStation/PDFs/caltrain1988bayviewstudy.pdf (accessed 9/17/2007).

[CARB 1997] *1997 Consumer and Commercial Products Survey*; California Air Resources Board, Consumer Products Program, Sacramento, CA, 1997; http://www.arb.ca.gov/consprod/regact/ccps/ccps.htm (accessed 3/6/2008).

[CARB 2002] *Notice of Public Hearing to Consider Amendments to the Public Transit Bus Fleet Rule and Emission Standards for New Urban Buses: Appendix C*: Orange County Bus Cycle; California Air Resources Board, Sacramento, CA, 2002; http://www.arb.ca.gov/regact/bus02/bus02.htm (accessed 4/21/2006).

[Carrington 1984] Carrington, B.; San Francisco Municipal Railway Modernisation, Part 2: The Muni Metro Emerges; *Modern Tramway and Light Rail Transit*, 1984, V.47, N.563, pp.373.

[CDC 1997] Centers for Disease Control, Agency for Toxic Substances and Disease Registry; *ToxFAQS™ for Methyl tert-Butyl Ether (MTBE)*; http://www.atsdr.cdc.gov/tfacts91.html (accessed 7/12/2008).

[Census 2002] U.S. Census Bureau; *Parking Lots and Garages: NAICS 812930*; http://www.census.gov/econ/census02/data/industry/E812930.HTM (accessed 3/12/2008).

[Clark 2003] Clark, N.; Gajendran, P.; A Predictive Tool for Emissions from Heavy-Duty Vehicles, *Environmental Science and Technology*, 2003, American Chemical Society, V.37, I.1, pp.7-15; http://dx.doi.org/10.1021/es0113192.

[Clarke 2005] Clarke, N.; *Idle Emissions from Heavy-Duty Diesel Vehicles*; Diesel Engine Emissions Reduction Conference, 2005, Energy Efficiency and Renewable Energy, U.S. Department of Energy; http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2005/poster1/2005_deer_clark.pdf (accessed 7/15/2008).

[CMAP 2008] Chicago Metropolitan Agency for Planning; *Travel Tracker Survey 2008*; http://www.cmap.illinois.gov/travel_tracker_survey.aspx.

[Cobas-Flores 1998] Cobas-Flores, E.; Lave, L.; Hendrickson, C.; McMichael, F.; Bustani, A.; Motor Vehicles and Passenger Car Bodies Sector: Life Cycle Assessment Using Economic Input-Output Analysis; *Society of Automotive Engineers Congress 1998*, Paper #980475, Detroit, MI; http://www.sae.org/technical/papers/980475.

[Cobas-Flores 1998b] Cobas-Flores, E.; Bustani, A.; Mackay, P.; Ramirez, B.; Yester, S.; Sullivan, J.; Williams, R.; An Analysis of the Vehicle End-of-Life in the United States; *Society of Automotive Engineers Congress 1998*, Paper #982213, Detroit, MI; http://www.sae.org/technical/papers/982213.

[Cohen 2003] Cohen, J.; Hammitt, J.; Levy, J.; Fuels for Urban Transit Buses, *Environmental Science and Technology*, 2003, American Chemical Society, V.37, pp.1477-1484; http://dx.doi.org/10.1021/es0205030.

[Corbett 2002] Corbett, J.; Farrell, A.; Mitigating Air Pollution Impacts from Passenger Ferries; *Transportation Research Part D*, 2002, V.7, I.3, pp.197-211; http://dx.doi.org/10.1016/S1361-9209(01)00019-0.

[Curran 1996] Curran, M.A., 1996. In: Curran, M.A., Editor, 1996. *The History of LCA*; McGraw-Hill, New York, USA, P1.1–1.9.

[Davis 2006] Davis, S.; Diegel, S.; *Transportation Energy Data Book*, Edition 25; Oak Ridge National Laboratory, National Transportation Research Center, Knoxville, TN.

[Davis 2007] Davis, S.; Diegel, S.; *Transportation Energy Data Book*, Edition 26; Oak Ridge National Laboratory, National Transportation Research Center, Knoxville, TN.

[Davis 2008] Davis, S.; Diegel, S.; *Transportation Energy Data Book*, Edition 27; Oak Ridge National Laboratory, National Transportation Research Center, Knoxville, TN.

[Delucchi 1997] Delucchi, M.; *The Annualized Social Cost of Motor-Vehicle Use in the U.S. Based on 1990-1991 Data: Summary of Theory, Data, Methods, and Results*; In Greene, D.L. (1997) “The Full Costs and Benefits of Transportation – Contributions to Theory, Method and Measurement”.

[Deru 2007] Deru, M.; Torcellini, P.; *Source Energy and Emission Factors for Energy Use in Buildings*; National Renewable Energy Laboratory, 2007, Technical Report # NREL/TP-550-38617; http://dx.doi.org/10.2172/884990.

[Di Carlo 1998] Di Carlo, S.; Serra, R.; Goglia, G.; Diana, D.; Environmental Impact of a Car: An Analysis of the Life Cycle Assessment Techniques Used for Evaluating the Environmental Impact of a Petrol Driven Car; *Society of Automotive Engineers Congress 1998*, Paper #982186, Detroit, MI; http://www.sae.org/technical/papers/982186.

[Economist 2005] Economist Magazine; *Cars in China: Dream Machines*; June 2, 2005; http://www.economist.com/world/displaystory.cfm?story_id=4032842 (accessed 6/5/2005).

[EEA 2006] *Emission Inventory Guidebook*; Activities 080501-080504; European Environment Agency, 12/2006; http://reports.eea.europa.eu/EMEPCORINAIR4/ (accessed 5/8/2007).

[EERE 2002] *U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate*; U.S. Department of Energy, Energy Efficiency and Renewable Energy, Prepared by Navigant Consulting, Inc., 9/2002; http://www.eere.energy.gov/buildings/publications/pdfs/corporate/lmc_vol1.pdf (accessed 6/25/2008).

[EERE 2007] *2007 Buildings Energy Data Book*; U.S. Department of Energy, Energy Efficiency and Renewable Energy, 2007; http://buildingsdatabook.eere.energy.gov/.

[EERE 2007b] U.S. Department of Energy, Energy Efficiency and Renewable Energy; *Estimating Appliance and Home Electronic Energy Use*; http://www.eere.energy.gov/consumer/your_home/appliances/index.cfm/mytopic=10040 (accessed 4/21/2007).

[EIA 2005] *Electric Power Annual 2005*; U.S. Department of Energy, Energy Information Administration, Washington, DC, 2005; http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html (accessed 5/12/2006).

[EIA 2007] U.S. Department of Energy, Energy Information Administration; *Diesel Fuel Components History*; http://tonto.eia.doe.gov/oog/info/gdu/dieselpump.html (accessed 2/22/2007).

[EIA 2007b] U.S. Department of Energy, Energy Information Administration; *U.S. No 2 Diesel Retail Sales by All Sellers*; http://tonto.eia.doe.gov/dnav/pet/hist/ddr001A.htm (accessed 2/22/2007).

[EIO-LCA 2008] *Economic Input-Output Analysis-Based Life-Cycle Assessment Software*; Carnegie Mellon University, Green Design Initiative; http://www.eiolca.net/.

[EMFAC 2007] California Air Resources Board; *Emission Factors (EMFAC) Model 2007*; http://www.arb.ca.gov/msei/onroad/latest_version.htm.

[English 1999] English, P.; Neutra, R.; Scalf, R.; Sullivan, M.; Waller, L.; Zhu, L.; Examining Associations between Childhood Asthma and Traffic Flow Using a Geographic Information System; *Environmental Health Perspectives*, 1999, V.107, N.9, pp.761-767; http://www.jstor.org/stable/3434663.

[EPA 1997] *Technical Highlights: Emission Factors for Locomotives*: December 1997; Report # EPA420-F-97-051, U.S. Environmental Protection Agency, Washington, DC; http://www.epa.gov/oms/regs/nonroad/locomotv/frm/42097051.pdf (accessed 11/12/2007).

[EPA 1998] *Profile of the Air Transportation Industry*: October 1998; Report # EPA/310-R-97-001; Environmental Protection Agency, Office of Compliance: Washington, DC; http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/airtrans.pdf (accessed 5/4/2007).

[EPA 1999] *Technical Support for Development of Airport Ground Support Equipment Emission Reductions*: May 1999; Report # EPA/420-R-99-007; U.S. Environmental Protection Agency, Office of Transportation and Air Quality: Washington, DC; http://www.epa.gov/otaq/stateresources/policy/transp/airports/r99007.pdf (accessed 8/1/2006).

[EPA 1999b] *Evaluation of Air Pollutant Emissions from Subsonic Commercial Jet Aircraft*; April 1999; Report # EPA420-R-99-013, U.S. Environmental Protection Agency, Washington, DC; http://www.epa.gov/oms/regs/nonroad/aviation/r99013.pdf (accessed 1/22/2006).

[EPA 1999c] *Final Regulatory Impact Analysis: Control of Emissions from Marine Diesel Engines*: 1999; Report # EPA420-R-99-026; U.S. Environmental Protection Agency, Washington, DC; http://www.epa.gov/oms/regs/nonroad/marine/ci/fr/ria.pdf (accessed 4/13/2006).

[EPA 2000] *Airport Deicing Operations*: August 2000; Report # EPA/821-R-00-016; U.S. Environmental Protection Agency, Washington, DC; http://www.epa.gov/waterscience/guide/airport/airport.pdf (accessed 6/30/2006).

[EPA 2001] *Asphalt Paving*: April 2001; Emission Inventory Improvement Program, Technical Report Series Volume 3, Chapter 17; U.S. Environmental Protection Agency, Washington, DC; http://www.epa.gov/ttn/chief/eiip/techreport/volume03/iii17_apr2001.pdf (accessed6/25/2006).

[EPA 2003] *Mobile 6.2 Emissions Modeling Software*: U.S. Environmental Protection Agency, Washington, DC, 2003.

[EPA 2004] *Pesticides Industry Sales and Usage: 2000 and 2001 Market Estimates*: May 2004; U.S. Environmental Protection Agency, Office of Prevention, Pesticides, and Toxic Substances, Washington, DC; http://www.epa.gov/oppbead1/pestsales/01pestsales/market_estimates2001.pdf (accessed 5/18/2008).

[EPA 2005] *Estimating and Projecting Impervious Cover in the Southeastern United States*: May 2005; Report # EPA/600-R-05-061; U.S. Environmental Protection Agency, Washington, DC; http://www.epa.gov/ATHENS/publications/reports/Exum600R05061EstimatingandProjectingImpervious.pdf (accessed 12/5/2007).

[EPA 2006] U.S. Department of Energy, Energy Efficiency and Renewable Energy; *Fuel Economy Ratings*; http://www.fueleconomy.gov/ (accessed 12/3/2007).

[EPA 2007] U.S. Environmental Protection Agency; *Tier 2 Vehicle and Gasoline Sulfur Program*; http://www.epa.gov/tier2/ (accessed 2/12/2008).

[EPA 2008] U.S. Environmental Protection Agency; *Dynamometer Driver's Aid*; http://www.epa.gov/nvfel/testing/dynamometer.htm (accessed 3/15/2008).

[EPA 2008b] U.S. Environmental Protection Agency; *Six Common Air Pollutants*; http://www.epa.gov/air/urbanair/ (accessed 6/25/2008).

[EPA 2008c] U.S. Environmental Protection Agency; *Climate Change: Greenhouse Gas Emissions*; http://www.epa.gov/climatechange/emissions/index.html (accessed 6/25/2008).

[Nazaroff 2001] Nazaroff, W.; Alvarez-Cohen, L.; *Environmental Engineering Science*: 2001; John Wiley & Sons, Inc., New York, NY; ISBN 0-471-14494-0.

[FAA 1996] *Airport Pavement Design and Evaluation*: January 30, 1996; Report # 150-5320-6D; U.S. Federal Aviation Administration; Washington, DC, 1996 (accessed 7/19/2007).

[FAA 1998] *Impact of New Large Aircraft on Airport Design*: March 1998; Report # DOT/FAA/AR-97/26; U.S. Federal Aviation Administration: Washington, DC, 1998; http://www.tc.faa.gov/its/worldpac/techrpt/ar97-26.pdf (accessed 2/16/2006).

[FAA 2007] *Emission Data Modeling System, 5.0.2*; Federal Aviation Administration: Washington, DC, 2007.

[Facanha 2006] Facahna, C.; *Life-cycle Air Emissions of Freight Transportation in the United States*; Unpublished Doctoral Thesis; University of California, Berkeley, Berkeley, CA, Fall 2006.

[Facanha 2007] Facanha, C.; Horvath, A.; Evaluation of Life-Cycle Air Emission Factors of Freight Transportation; *Environmental Science and Technology*, 2007, American Chemical Society, V.41, N.20, pp.7138-7144; http://dx.doi.org/10.1021/es070989q.

[Farrell 2002] Farrell, A.; Corbett, J.; Winebrake, J.; Controlling Air Pollution from Passenger Ferries: Cost-Effectiveness of Seven Technological Options; *Journal of the Air and Waste Management Association*, 2002, V.52, pp.1399-1410; http://secure.awma.org/journal/Abstract.aspx?id=988.

[Farrell 2006] Farrell, A., Plevin, R., Turner, B., Jones, A., O'Hare, M., Kammen, D., Ethanol Can Contribute to Energy and Environmental Goals; *Science*, 2006, V.311, N.5760, pp.506-508; http://dx.doi.org/10.1126/science.1121416.

[Fava 1991] Fava, J. A., Denison, R., Jones, B., Curran, M. A., Vigon, B., Selke, S., & Barnum, J., *A Technical Framework for Life Cycle Assessments*: 1991; SETAC.

[Fels 1978] Fels, M.; Breakdown of Rapid Rail Energy Costs: A Study of Three Systems; *Energy* 1978, V.3, pp.507-522; http://dx.doi.org/10.1016/0360-5442(78)90012-9.

[FHWA 2004] *2004 Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance*; Federal Highway Administration, Washington, DC, 2004; http://www.fhwa.dot.gov/policy/2004cpr/index.htm (accessed 5/6/2006).

[FHWA 2008] *Highway Statistics*; U.S. Department of Transportation, Federal Highway Administration, Office of Highway Policy Information, Washington, DC, 2005 (accessed 9/7/2007).

[FHWA 2000] U.S. Federal Highway Administration; *Speeding Counts*; http://safety.fhwa.dot.gov/speed_manage/docs/speeding_counts.pdf (accessed 3/2/2007).

[FHWA 2007] Federal Highway Administration; Office of Operations; *Snow and Ice*; http://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm (accessed 7/2/2008).

[FRA 1997] *High Speed Ground Transport for America*; Federal Railroad Administration, 1997; http://www.fra.dot.gov/us/content/515 (accessed 8/12/2006).

[Friedman 2007] Friedman, T.; *No, No, No, Don't Follow Us*; New York Times; November 4, 2007; http://www.nytimes.com/2007/11/04/opinion/04friedman.html (accessed 3/3/2008).

[Fritz 1994] Fritz, S.; Exhaust Emissions from Two Intercity Passenger Locomotives; *Journal of Engineering for Gas Turbines and Power*, 1994, V.16, pp.774-786.

[FTA 2005] *National Transit Database 2005*; Federal Transit Authority, 2005; http://www.ntdprogram.gov/ntdprogram/ (accessed 5/12/2007).

[FTA 2005b] National Transit Summaries and Trends 2005; Federal Transit Authority, 2005.

[FTA 2006] *U.S. Non-Rail Vehicle Market Viability Study*; Project Number MI-26-7008-05.1; Federal Transit Authority; January 19, 2006; http://www.trb.org/news/blurb_detail.asp?id=5881 (accessed 9/20/2007).

[Gauntt 2000] Gauntt, J.; Zarembski, A.; Analysis of Wood Cross-Tie Price Sensitivities, 2000; *Proceedings of the American Railway Engineering and Maintenance-of-Way Association*; http://www.arema.org/eseries/scriptcontent/custom/e_arema/library/2000_Conference_Proceedings/00003.pdf.

[GE 2007] *Google Earth 4.2*; Google: Mountainview, CA, 2007. http://earth.google.com/.

[Gediga 1998] Gediga, J.; Beddies, H.; Florin, H.; Loser, R.; Schuckert, M.; Haldenwanger, S.; Process Modeling in the Life Cycle Design: Environmental Modeling of Joining Technologies within the Automotive Industry; *Society of Automotive Engineers Congress 1998*; Paper # 982190; Detroit, MI; http://www.sae.org/technical/papers/982190.

[Granell 2004] Granell, J.; Ho, C.; Tang, T.; Claggett, M.; Analysis of Mobile 6.2’s PM Emission Factor Estimating Function; *EPA’s 13th International Emission Inventory Conference*; http://www.epa.gov/ttn/chief/conference/ei13/index.html.

[Greene 1992] Greene, D.; Energy-Efficiency Improvement Potential of Commercial Aircraft; *Annual Review of Energy and the Environment*, 1992, V.17, pp.537-573; http://dx.doi.org/10.1146/annurev.eg.17.110192.002541.

[Greene 1997] Greene D., Jones D.; Delucchi M.; *The Full Costs and Benefits of Transportation – Contributions to Theory, Method and Measurement*, 1997. Springer.

[GREET 2008] *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model*; Argonne National Laboratory, U.S. Department of Energy; http://www.transportation.anl.gov/modeling_simulation/GREET/ (accessed 7/20/2008).

[Griest 1915] Griest, M.; Design of Steel Elevated Railways, N.Y. Rapid Transit System; *Engineering News*, 1915, pp.971-977.

[Guggemos 2005] Guggemos, A.; Horvath, A.; Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings; *ASCE Journal of Infrastructure Systems*, 2005, V.11, I.2, pp.93-101. http://dx.doi.org/10.1061/(ASCE)1076-0342(2005)11:2(93).

[Healy 1973] Healy, T.; *Energy Requirements of the Bay Area Rapid Transit System*; California Department of Transportation, Division of Transportation Planning, 1973.

[Hendrickson 1998] Hendrickson, C.; Horvath, A.; Joshi, S.; Lave, L.; Economic Input-Output Models for Environmental Life Cycle Assessment; *Environmental Science and Technology*, 1998, American Chemical Society, V.32, N.7, pp.184A-191A.

[Huang 2004] Huang, Y.; *Pavement Analysis and Design*, 2nd ed.; Prentice Hall: Upper Saddle River, NJ, 2004.

[Huijbregts 1998] Huijbregts, M.; Application of Uncertainty and Variability in LCA – Part 1: A General Framework for the Analysis of Uncertainty and Variability in Life Cycle Assessment;

International Journal of Life Cycle Assessment, 1998, V.3, N.5, pp.273-280; http://www.scientificjournals.com/sj/lca/abstract/ArtikelId/1337.

[INFRAS 1994] INFRAS, IWW, *External Effects of Transport*; Project for the International Union of Railways (UIC), 1994; ISBN 2-901585-28-0.

[IPCC 1999] United Nations Intergovernmental Panel on Climate Change; *Aviation and the Global Atmosphere*; http://www.grida.no/climate/ipcc/aviation/index.htm (accessed 5/20/2008).

[IPCC 2006] United Nations Intergovernmental Panel on Climate Change; *2006 Guidelines for National Greenhouse Gas Inventories*; http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (accessed 4/5/2007).

[IPI 2007] International Parking Institute; *Frequently Asked Questions*; http://www.parking.org/Value/FAQ/Default.aspx (accessed 1/17/2007).

[ISO 2005] International Organization for Standardization; *ISO 14000*; http://www.iso.org/ (accessed 6/20/2008).

[Janes 2004] *Jane's All the World's Aircraft, 2003-2004*; London: Sampson Low, Marston, 2005.

[Jenkinson 1999] Jenkinson, L.; Simpson, P.; Rhodes, D., *Civil Jet Aircraft Design*; American Institute of Aeronautics and Astronautics, Arlington, VA, 1999.

[Jorgensen 1997] Jorgensen, M.; Sorenson, S.; *Estimating Emissions from Railway Traffic, Report for the Project MEET: Methodologies for Estimating Air Pollutant Emissions from Transport*; INFRETS: French National Institute for Transport and Safety Research, Joinville, France; http://www.inrets.fr/infos/cost319/MEETDeliverable17.PDF (accessed 5/15/2006).

[Kaniut 1997] Kaniut, C.; Cetiner, H.; Pranzeck, J.; Life Cycle Assessment of a Complete Car: The Mercedes Benz Approach; *Society of Automotive Engineers Congress 1997*, Paper # 971166; Detroit, MI; http://www.sae.org/technical/papers/971166.

[Keoleian 1993] Keoleian G.; Kar K., Manion M.; Bulkley J.; *Industrial Ecology of the Automobile – A Life Cycle Perspective*, 1997. Society of Automotive Engineers, Inc. Warrendale, PA. ISBN 1-56091-985-X.

[Kesgin 2006] Kesgin, U.; Aircraft Emissions at Turkish Airports; *Energy*, 2006, V.31, I.2-3, pp.372-384; http://dx.doi.org/10.1016/j.energy.2005.01.012.

[Keyser 1991] Keyser, B.; Welding BART's Aluminum Rail Transit Cars; *Welding Journal*, 1991, V.70, N.11, pp.39-42.

[Lave 1977] Lave, C.; Environmental and Conservation Concerns in Transportation: Energy, Noise, and Air Quality; *Transportation Research Record*, Report 648, 1977.

[Lee 2001] Lee, J.; Lukachko, S.; Waitz, I.; Schafer, A.; Historical and Future Trends in Aircraft Performance, Cost, and Emissions; *Annual Review of Energy and the Environment*, 2001, V.26, pp.167-200. http://dx.doi.org/10.1146/annurev.energy.26.1.167.

[Levinson 1996] Levinson, D.; Gillen, D.; Kanafani, A.; and Mathieu, J., *The Full Cost of Intercity Transportation*; University of California, Berkeley, Institute of Transportation Studies, Report # UCB-ITS-RR-96-3, 1996; http://repositories.cdlib.org/its/reports/UCB-ITS-RR-96-3/.

[Levinson 1998b] Levinson, D.; Gillen, D.; Kanafani, A.; The Social Costs of Intercity Passenger Transportation: A Review and Comparison of Air and Highway; *Transportation Research Board 77th Annual Meeting*, Paper # 980274.

[Lindfors 1995] Lindfors, L.; *Nordic Guidelines on Life-Cycle Assessment*; Nordic Council of Ministers, 1995, ISBN 9789291206926.

[Lyons 2003] Lyons, T.; Kenworthy, J.; Moy, C.; dos Santos, F.; An International Urban Air Pollution Model for the Transportation Sector; *Transportation Research Part D*, 2003, V.8, I.3, pp.159-167; http://dx.doi.org/10.1016/S1361-9209(02)00047-0.

[MA 2005] Massachusetts Highway Department, 2005 Design Guide: Pavement Design Chapter, 2005; http://www.mhd.state.ma.us/downloads/designGuide/CH_9.pdf (accessed 2/20/2008).

[MacLean 1998] MacLean, H.; Lave, L.; A Life-Cycle Model of an Automobile; *Environmental Science and Technology*, 1998, American Chemical Society, V.32, I.13, pp.322A-330A; http://pubs.acs.org/cgi-bin/article.cgi/esthag-a/1998/32/i13/html/maclean.html.

[MacLean 2003] MacLean, H.; Lave, L.; Life-Cycle Assessment of Automobile/Fuel Options; *Environmental Science and Technology*, 2003, American Chemical Society, V.37, N.23, pp.5445-5452; http://dx.doi.org/10.1021/es034574q.

[Madison 1996] Maddison, D.; Pearce, D.; *5 Blueprint – The True Costs of Road Transpor*; Cserge, London, 1996.

[Marheineke 1998] Marheineke, T.; Friedrich, R.; Krewitt, W.; Application of a Hybrid-Approach to the Life Cycle Inventory Analysis of a Freight Transport Task; *Society of Automotive Engineers Congress 1998*, Paper # 982201, Detroit, MI; http://www.sae.org/technical/papers/982201.

[Marshall 2003] Marshall, J.; Riley, W.; McKone, T.; Nazaroff, W.; Intake Fraction of Primary Pollutants: Motor Vehicle Emissions in the South Coast Air Basin; *Atmospheric Environment*, 2003, V.37, I.24, pp.3455-3468; http://dx.doi.org/10.1016/S1352-2310(03)00269-3.

[Marshall 2005] Marshall, J.; Teoh, S.; Nazaroff, W.; Intake Fraction of Non-Reactive Vehicle Emissions in U.S. Urban Areas; *Atmospheric Environment*, 2005, V.39, I.7, pp.1363-1371; http://dx.doi.org/10.1016/j.atmosenv.2004.11.008.

[Matthews 2000] Matthews, S.; Lave, L.; Applications of Environmental Valuation for Determining Externality Costs; *Environmental Science and Technology*, 2000, American Chemical Society, V.34, pp.1390-1395; http://dx.doi.org/10.1021/es9907313.

[Matthews 2001] Matthews, S.; Hendrickson, H.; Horvath, A.; External Costs of Air Emissions from Transportation; *ASCE Journal of Infrastructure Systems*, 2001, V.7, N.1, pp.13-17; http://dx.doi.org/10.1061/(ASCE)1076-0342(2001)7:1(13).

[Mayeres 1996] Mayeres, I.; Ochelen, S.; Proost, S.; The Marginal External Costs of Urban Transport; *Transportation Research D*, 1996, V.1, N.2, pp.111-130.

[MBTA 2007] Massachusetts Bay Transportation Authority; *Schedules and Maps*; http://www.mbta.com/schedules_and_maps/subway/lines/?route=GREEN (accessed 7/26/2007).

[MBTA 2007b] Personal communications with Ray Martin, Track Engineer, Massachusetts Bay Transportation Authority, 10/2/2007.

[McCormick 2000] McCormick, R.; Graboski, M.; Alleman, T.; Yanowitz, J.; Idle Emissions from Heavy-Duty Diesel and Natural Gas Vehicles at High Altitude; *Journal of the Air and Waste Management Association*, 2000, V.50, N.11, pp.1992-1998.

[Mensink 2000] Mensink, C.; De Vlieger, I.; Nys, J.; An Urban Transport Emission Model for the Antwerp Area; *Atmospheric Environment*, 2000, V.34, I.27, pp.4595-4602; http://dx.doi.org/10.1016/S1352-2310(00)00215-6.

[MEOT 2005] *Beyond Lechmere Northwest Corridor Study*; Massachusetts Executive Office of Transportation, Boston, MA, 8/2005 (accessed 10/30/2007).

[MR 2007] Market Research; *Parking Garages Abstract*; http://www.marketresearch.com/product/display.asp?productid=145157 (accessed 2/9/2007).

[MTC 2000] San Francisco Bay Area Metropolitan Transportation Commission; *Bay Area Travel Survey 2000;* http://www.mtc.ca.gov/maps_and_data/datamart/survey/ (accessed 5/12/2006).

[MTC 2005] San Francisco Bay Area Metropolitan Transportation Commission; *Household Travel Surveys on the Web*; http://trb.mtc.ca.gov/urban/hhsurvey.html (accessed 5/18/2008).

[MTC 2006] *Bay Area Statistical Summary 2006*; Metropolitan Transportation Commission, Oakland, CA, 2006; http://www.mtc.ca.gov/library/statsum/statsum.htm (accessed 11/4/2007).

[Muni 2006] *Short Range Transit Plan for FY2006 to 2025*; San Francisco Municipal Railway, San Francisco, CA, 2006; http://www.sfmta.com/cms/rsrtp/srtpindx.htm (accessed 12/2/2007).

[Muni 2007] *2007 Operating Budget*; San Francisco Municipal Railway, San Francisco, CA, 2007; http://www.sfmta.com/cms/rbudget/budgindx.htm (accessed 1/5/2008).

[Muni 2007b] San Francisco Municipal Railway; *Discover the T-Third Pamphlet*; http://www.sfmta.com/cms/mroutes/documents/T3-Manual_v6na.pdf (accessed 5/8/2007).

[MWAA 2005] *Comprehensive Annual Financial Report*; Metropolitan Washington Airports Authority, Washington, DC, 2005; http://www.metwashairports.com/news_publications/publications/annual_reports (accessed 10/20/2007).

[MWAA 2007] Metropolitan Washington Airports Authority; *Facts About Washington Dulles International Airport*; http://www.metwashairports.com/dulles/about_dulles_international_2/facts_2 (accessed 10/22/2007).

[NASA 2008] National Aeronautics and Space Administration; *Glenn Research Center Fact Sheet*; http://www.nasa.gov/centers/glenn/about/fs10grc.html (accessed 3/12/2008).

[NGN 2002] Mayell, H.; Human Footprint Seen on 83% of Earth's Land; *National Geographic News*; 10/25/2002; http://news.nationalgeographic.com/news/2002/10/1025_021025_HumanFootprint.html (accessed 6/15/2008).

[Nocker 2000] Nocker, L.; Panis, L.; Torfs, R., ExternE: A European Accounting Framework for Life Cycle Impact Assessment and External Costs of Transport; *Proceedings of the 2000 Total Life Cycle Conference*, 2000, Paper # 2000-01-1480.

[NYMTC 1998] New York Metropolitan Transportation Council; *Regional Travel Household Interview Survey*, 1998; http://www.nymtc.org/BPM/bpmindex.html (accessed 3/20/2008).

[NYT 2006] Fernandez, M; *A Study Links Trucks' Exhaust to Bronx Schoolchildren's Asthma*; The New York Times, 10/29/2006; http://www.nytimes.com/2006/10/29/nyregion/29asthma.html (accessed 7/20/2008).

[Olivier 1991] Olivier, J.; *Inventory of Aircraft Emissions: A Review of Recent Literature*; National Institute of Public Health and Environmental Protection, Report # 736 301 008, Bilthoven, the Netherlands.

[Pacca 2003] Pacca, S.; *Global Warming Effect Applied to Electricity Generation Technologies*; Unpublished Doctoral Thesis, University of California, Berkeley, Berkeley, CA, Spring 2003.

[PaLATE 2004] Horvath, A; *PaLATE: Pavement Life-cycle Assessment Tool for Environmental and Economic Benefits*; University of California, Berkeley, Berkeley, CA, 2004; http://www.ce.berkeley.edu/~horvath/palate.html.

[Parrish 2006] Parrish, D.; Critical Evaluation of U.S. On-road Vehicle Emission Inventories; *Atmospheric Environment*, 2006, V.40, I.13, pp.2288-2300; http://dx.doi.org/10.1016/j.atmosenv.2005.11.033.

[Paulsen 2003] Paulsen, J.; The Maintenance of Floor Coverings and PVC Flooring in Sweden; *International Journal of Life-cycle Assessment*, 2003, V.8, I.6, pp.357-364; http://dx.doi.org/10.1065/lca2003.06.117.

[PB 1999] Parsons Brinkerhoff; *California High Speed Rail Corridor Evaluation*; California High Speed Rail Authority, December 1999, Sacramento, CA; http://www.cahighspeedrail.ca.gov/plan/default.asp (accessed 3/1/2007).

[Pehrson 2005] Pehrson, J.; Aircraft Particulate Matter Emissions, Past Practices: What was Available and How it was Used; Presentation at the *84th Annual Transportation Research Board Meeting*, 1/12/2005; http://www.trbav030.org/pdf/TRB05Ann_685_j_pehrson.pdf (accessed 4/5/2007).

[PGE 2008] Pacific Gas and Electric; *PG&E's Electric Power Mix Delivered to Retail Customers*; http://www.pge.com/myhome/edusafety/systemworks/electric/energymix/ (accessed 7/10/2008).

[Pikarsky 1991] Pikarsky, M.; Energy Implications of Fixed Rail Mass Transit; *Annual Review of Energy*, 1991, V.6, pp.339-356; http://dx.doi.org/10.1146/annurev.eg.06.110181.002011.

[Reynolds 2000] Reynolds, A.; Broderick, B.; Development of an Emissions Inventory Model for Mobile Sources; *Transportation Research Part D*, 2000, V.5, I.2, pp.77-101; http://dx.doi.org/10.1016/S1361-9209(99)00025-5.

[Romano 1999] Romano, D.; Gaudioso, D.; De Lauretis, R.; Aircraft Emissions: A Comparison of Methodologies Based on Different Data Availability; *Environmental Monitoring and Assessment*, 1999, V.56, pp.71-74; http://www.springerlink.com/content/q2174423m8h76u36/.

[Ross 1994] Ross, M.; Automobile Fuel Consumption and Emissions: Effects of Vehicle and Driving Characteristics; *Annual Review of Energy and the Environment*, 1994, V.19, pp.75-112; http://dx.doi.org/10.1146/annurev.eg.19.110194.000451.

[RSM 2002] R.S. Means; *Square Foot Costs 2002*; Reed Construction Data, Kingston, MA, 2002.

[Sandel 2006] Sandel Avionics; *List of Airports and Runways in ST3400 Airport Database*; http://www.sandel.com/ST3400_Airports_0606.pdf (accessed 9/4/2007).

[Schipper 2003] Schipper, Y.; Environmental Costs in European Aviation; *Transport Policy*, 2003, V.11 , pp.141-154.

[SFC 2005] Hoge, P.; St. John, K.; Squatriglia, C.; *BART Settlement Reached*; San Francisco Chronicle, 7/6/2005; http://www.sfgate.com/cgi-bin/article.cgi?file=/c/a/2005/07/06/BART.TMP (accessed 7/20/2005).

[SFC 2006] Gordon, R.; *BART Pulls the Rug Out*; San Francisco Chronicle, 11/24/2006; http://www.sfgate.com/cgi-bin/article.cgi?file=/c/a/2006/11/24/MNGP9MJ4ES1.DTL (accessed 1/12/2008).

[SFC 2007] Gordon, R.; Johnson, J.; *BART Parking Scarce as Ridership Soars*; San Francisco Chronicle, 5/2/2007; http://www.sfgate.com/cgi-bin/article.cgi?f=/c/a/2007/05/02/MNG76PJA7G1.DTL (accessed 6/1/2007).

[SFW 1998] Byrne, P.; *Rewarding Failure*; San Francisco Weekly, 12/2/1998; http://www.sfweekly.com/1998-12-02/news/rewarding-failure/ (accessed 7/30/2008).

[SimaPro 2006] *SimaPro 7.0*; Pré: Product Ecology Consultants, Amersfoort, Netherlands, 2006.

[Singer 1999] Singer, B.; Harley, R.; A fuel-based inventory of motor vehicle exhaust emissions in the Los Angeles area during summer 1997; *Atmospheric Environment*, 1999, V.34, I.11, pp.1783-1795; http://dx.doi.org/10.1016/S1352-2310(99)00358-1.

[Small 1995] Small, K. A.; Kazimi, C.; On the Costs of Air Pollution from Motor Vehicles; *Journal of Transport Economics and Policy*, 1995, V.29(1), pp.7-32.

[Stodolsky 1998] Stodolsky, F.; Gaines, L.; Cuenca, R.; Eberhardt, J.; Lifecycle Analysis for Freight Transport; *Proceedings of the Society of Automotive Engineer's 1998 Total Life Cycle Conference*, 1998, Paper # 982206.

[Suh 2004] Suh S.; Lenzen M.; Treloar G.; Hondo H.; Horvath A.; Huppes G.; Jolliet O.; Klann U.; Krewitt W.; Moriguchi Y.; Munksgaard J.; Norris G.; System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. *Environmental Science and Technology*, 2004, American Chemical Society, V.38, I.3, pp.567-664; http://dx.doi.org/10.1021/es0263745.

[Sullivan 1995] Sullivan, J.; Hu, J.; Life Cycle Energy Analysis for Automobiles; *Society of Automotive Engineers Congress*, 1995, Paper # 951829, Detroit, MI; http://www.sae.org/technical/papers/951829.

[Sullivan 1998] Sullivan, J.; Williams, R.; Yester, S.; Cobas-Flores, E.; Chubbs, S.; Hentges, S.; Pomper, S., Life Cycle Inventory of a Generic U.S. Family Sedan – Overview of Results U.S.CAR AMP Project; *1998 Proceedings of the Society of Automotive Engineer's Total Life Cycle Conference – Land, Sea & Air Mobility*, Paper # 982160; http://www.sae.org/technical/papers/982160.

[SVRTC 2006] *BART to Silicon Valley Draft Supplemental Environmental Impact Report*; Santa Clara Valley Transportation Authority, San Jose, CA, January 2007; http://www.vtabart-vta.org/seir.asp?area=SEIR (accessed 9/6/2007).

[TLOC 2007] The Library of Congress; *Energy Independence and Security Act of 2007*; http://thomas.loc.gov/cgi-bin/bdquery/z?d110:h.r.00006: (accessed 7/20/2008).

[TRB 1991] Highway Deicing: Comparing Salt and Calcium Magnesium Acetate; Transportation Research Board, Committee on the Comparative Costs of Rock Salt and Calcium Magnesium Acetate (CMA) for Highway Deicing; *Transportation Research Board*, 1991, Special Report 235; http://onlinepubs.trb.org/onlinepubs/sr/sr235.html.

[USGS 1999] U.S. Geological Survey; *Historical Steel Prices*, http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel/350798.pdf (accessed 7/19/2007).

[USGS 2007] Fenton, M.; *Iron and Steel Prices*; United States Geological Survey, http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel/350798.pdf (accessed 2/11/2008).

[Van Eck 1974] Van Eck, R.; Grief, N., The BART Car Systems and Maintenance Philosophies; *IEEE Transactions on Industry Applications*, 1974, V.1A-10, pp.553-559.

[Verhoef 1994] Verhoef, E.; External Effects and Social Costs of Road Transport; *Transportation Research A*, 1994, V.28A, I.4, pp.273-287.

[Wards 1998] Ward's Automotive Group; *1998 Ward's Automotive Facts and Figures*; Southfield, MI, 1998.

[Wards 2006] Ward's Automotive Group; *2006 Ward's Automotive Facts and Figures*; Southfield, MI, 2006.

[WBZ 2007] CBS Broadcasting; *Green Line Repair Work Near Fenway Winding Down*; WBZ TV News, 8/4/2007; http://wbztv.com/topstories/local_story_216141749.html (accessed 9/15/2007).

[Weidema 1996] Weidema, B.; Wesnaes, M., Data Quality Management for Life Cycle Inventories – An Example of Using Data Quality Indicators; *Journal of Cleaner Production*, 1996, V.4, N.3-4, pp.167-174 (http://dx.doi.org/10.1016/S0959-6526(96)00043-1).

[Woodmansey 1994] Woodmansey, G.; Patterson, J.; New Methodology for Modeling Annual-Aircraft Emissions at Airports; *ASCE Journal of Transportation Engineering*, 1994, V.120, I.3, pp.339-357; http://dx.doi.org/10.1061/(ASCE)0733-947X(1994)120:3(339).

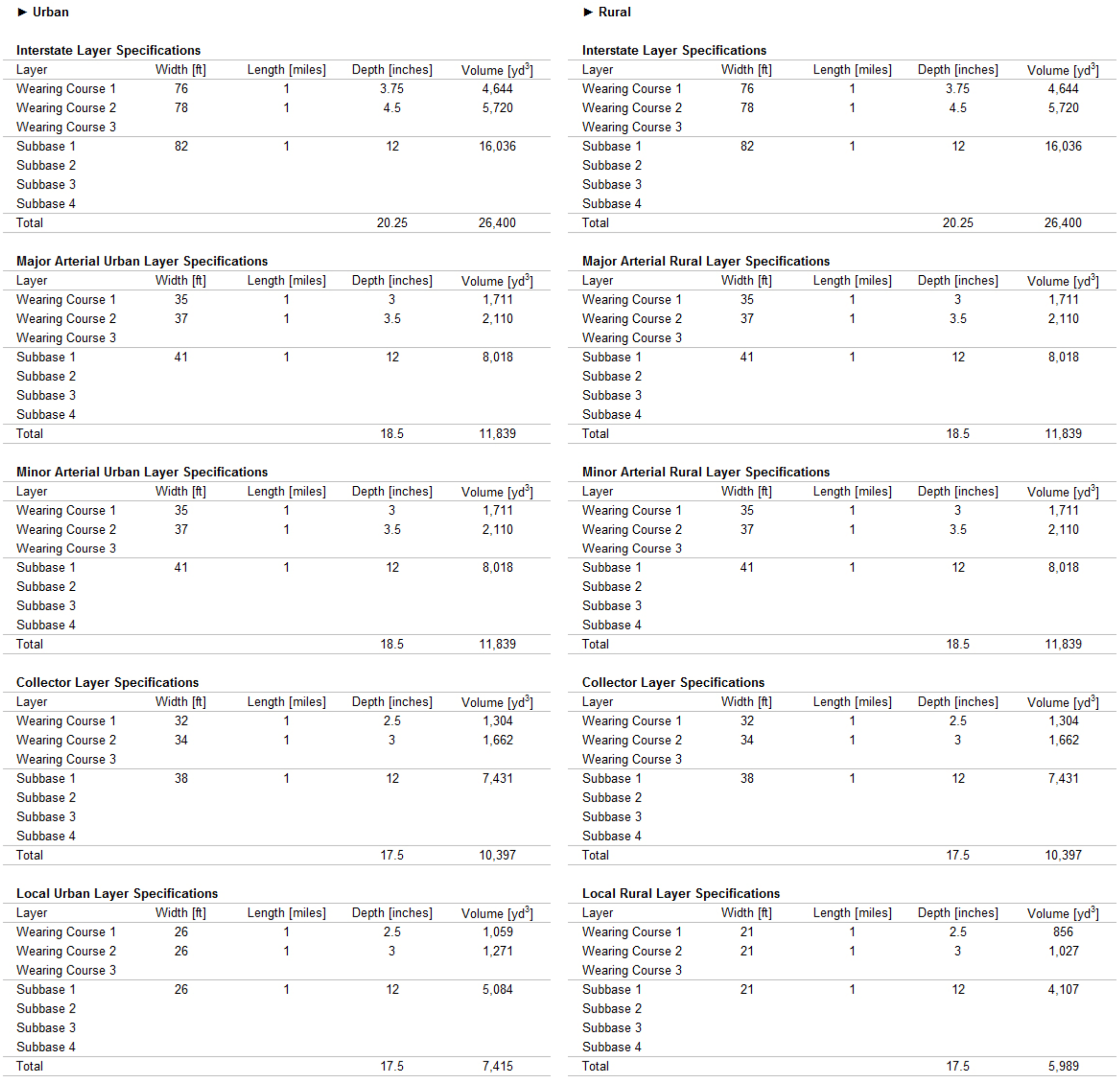
[WSDOT 2007] Washington State Department of Transportation; *Crushed Surfacing Price History*; http://www.wsdot.wa.gov/biz/construction/constructioncosts.cfm (accessed 11/12/2006).

[WSDOT 2007b] State Department of Transportation; *Structural Concrete Price History*; http://www.wsdot.wa.gov/biz/construction/constructioncosts.cfm (accessed 11/12/2006).

5 Appendices

5.1 Appendix A – LCI Roadway Layer Specifications

Figure 36 – Urban and Rural Roadway Classification Layer Specifications



► Urban

Interstate Layer Specifications

Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	76	1	3.75	4,644
Wearing Course 2	78	1	4.5	5,720
Wearing Course 3				
Subbase 1	82	1	12	16,036
Subbase 2				
Subbase 3				
Subbase 4				
Total			20.25	26,400

Major Arterial Urban Layer Specifications

Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	35	1	3	1,711
Wearing Course 2	37	1	3.5	2,110
Wearing Course 3				
Subbase 1	41	1	12	8,018
Subbase 2				
Subbase 3				
Subbase 4				
Total			18.5	11,839

Minor Arterial Urban Layer Specifications

Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	35	1	3	1,711
Wearing Course 2	37	1	3.5	2,110
Wearing Course 3				
Subbase 1	41	1	12	8,018
Subbase 2				
Subbase 3				
Subbase 4				
Total			18.5	11,839

Collector Layer Specifications

Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	32	1	2.5	1,304
Wearing Course 2	34	1	3	1,662
Wearing Course 3				
Subbase 1	38	1	12	7,431
Subbase 2				
Subbase 3				
Subbase 4				
Total			17.5	10,397

Local Urban Layer Specifications

Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	26	1	2.5	1,059
Wearing Course 2	26	1	3	1,271
Wearing Course 3				
Subbase 1	26	1	12	5,084
Subbase 2				
Subbase 3				
Subbase 4				
Total			17.5	7,415

► Rural

Interstate Layer Specifications

Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	76	1	3.75	4,644
Wearing Course 2	78	1	4.5	5,720
Wearing Course 3				
Subbase 1	82	1	12	16,036
Subbase 2				
Subbase 3				
Subbase 4				
Total			20.25	26,400

Major Arterial Rural Layer Specifications

Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	35	1	3	1,711
Wearing Course 2	37	1	3.5	2,110
Wearing Course 3				
Subbase 1	41	1	12	8,018
Subbase 2				
Subbase 3				
Subbase 4				
Total			18.5	11,839

Minor Arterial Rural Layer Specifications

Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	35	1	3	1,711
Wearing Course 2	37	1	3.5	2,110
Wearing Course 3				
Subbase 1	41	1	12	8,018
Subbase 2				
Subbase 3				
Subbase 4				
Total			18.5	11,839

Collector Layer Specifications

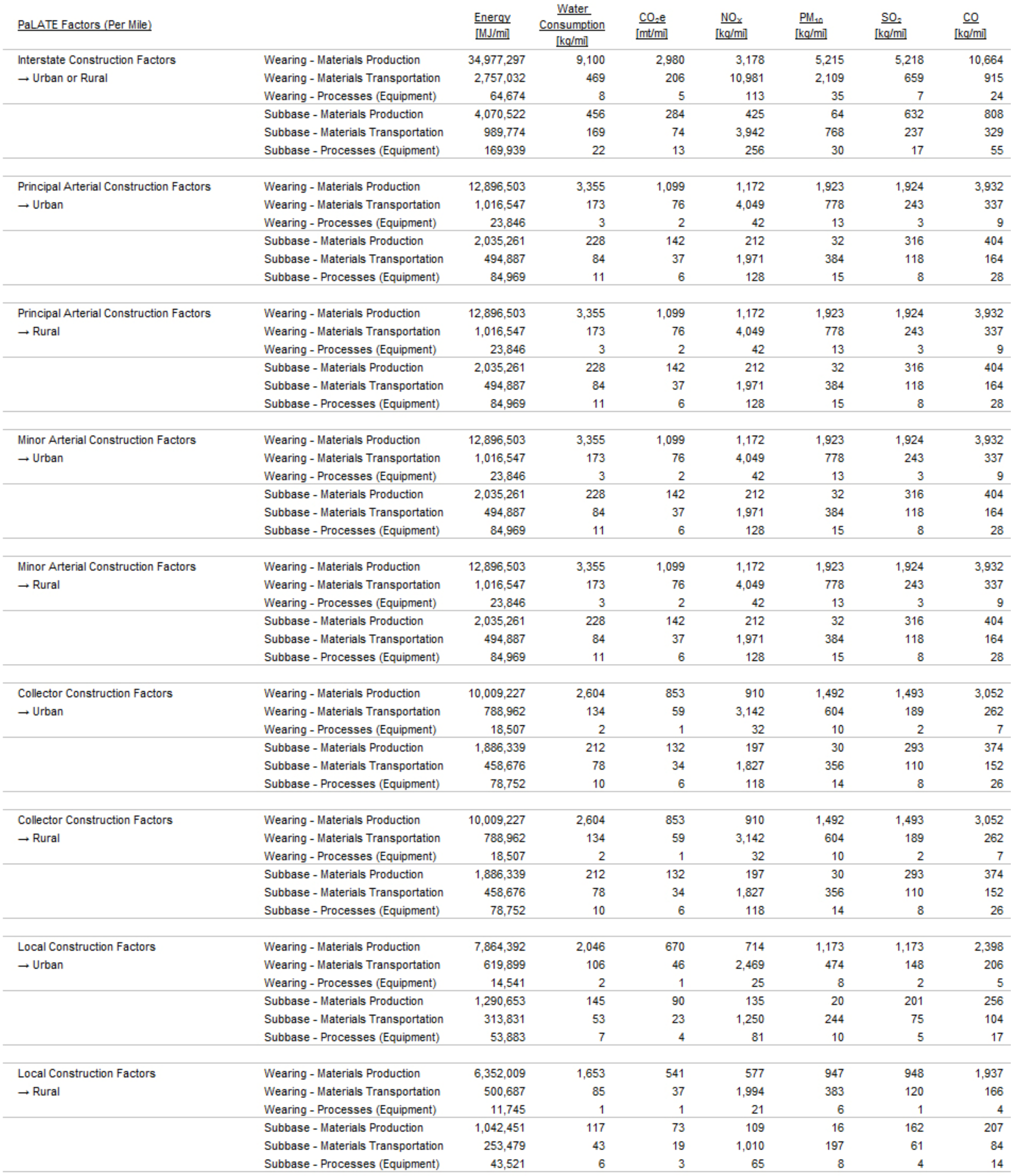
Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	32	1	2.5	1,304
Wearing Course 2	34	1	3	1,662
Wearing Course 3				
Subbase 1	38	1	12	7,431
Subbase 2				
Subbase 3				
Subbase 4				
Total			17.5	10,397

Local Rural Layer Specifications

Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	21	1	2.5	856
Wearing Course 2	21	1	3	1,027
Wearing Course 3				
Subbase 1	21	1	12	4,107
Subbase 2				
Subbase 3				
Subbase 4				
Total			17.5	5,989

5.2 Appendix B – LCI PaLATE Roadway Construction Factors

Figure 37 – Road Construction Environmental Performance (see §1.6.2.1)



PaLATE Factors (Per Mile)		Energy [MJ/mi]	Water Consumption [kg/mi]	CO_2e [mt/mi]	NO_x [kg/mi]	PM_{10} [kg/mi]	SO_2 [kg/mi]	CO [kg/mi]
Interstate Construction Factors	Wearing - Materials Production	34,977,297	9,100	2,980	3,178	5,215	5,218	10,664
→ Urban or Rural	Wearing - Materials Transportation	2,757,032	469	206	10,981	2,109	659	915
	Wearing - Processes (Equipment)	64,674	8	5	113	35	7	24
	Subbase - Materials Production	4,070,522	456	284	425	64	632	808
	Subbase - Materials Transportation	989,774	169	74	3,942	768	237	329
	Subbase - Processes (Equipment)	169,939	22	13	256	30	17	55
Principal Arterial Construction Factors	Wearing - Materials Production	12,896,503	3,355	1,099	1,172	1,923	1,924	3,932
→ Urban	Wearing - Materials Transportation	1,016,547	173	76	4,049	778	243	337
	Wearing - Processes (Equipment)	23,846	3	2	42	13	3	9
	Subbase - Materials Production	2,035,261	228	142	212	32	316	404
	Subbase - Materials Transportation	494,887	84	37	1,971	384	118	164
	Subbase - Processes (Equipment)	84,969	11	6	128	15	8	28
Principal Arterial Construction Factors	Wearing - Materials Production	12,896,503	3,355	1,099	1,172	1,923	1,924	3,932
→ Rural	Wearing - Materials Transportation	1,016,547	173	76	4,049	778	243	337
	Wearing - Processes (Equipment)	23,846	3	2	42	13	3	9
	Subbase - Materials Production	2,035,261	228	142	212	32	316	404
	Subbase - Materials Transportation	494,887	84	37	1,971	384	118	164
	Subbase - Processes (Equipment)	84,969	11	6	128	15	8	28
Minor Arterial Construction Factors	Wearing - Materials Production	12,896,503	3,355	1,099	1,172	1,923	1,924	3,932
→ Urban	Wearing - Materials Transportation	1,016,547	173	76	4,049	778	243	337
	Wearing - Processes (Equipment)	23,846	3	2	42	13	3	9
	Subbase - Materials Production	2,035,261	228	142	212	32	316	404
	Subbase - Materials Transportation	494,887	84	37	1,971	384	118	164
	Subbase - Processes (Equipment)	84,969	11	6	128	15	8	28
Minor Arterial Construction Factors	Wearing - Materials Production	12,896,503	3,355	1,099	1,172	1,923	1,924	3,932
→ Rural	Wearing - Materials Transportation	1,016,547	173	76	4,049	778	243	337
	Wearing - Processes (Equipment)	23,846	3	2	42	13	3	9
	Subbase - Materials Production	2,035,261	228	142	212	32	316	404
	Subbase - Materials Transportation	494,887	84	37	1,971	384	118	164
	Subbase - Processes (Equipment)	84,969	11	6	128	15	8	28
Collector Construction Factors	Wearing - Materials Production	10,009,227	2,604	853	910	1,492	1,493	3,052
→ Urban	Wearing - Materials Transportation	788,962	134	59	3,142	604	189	262
	Wearing - Processes (Equipment)	18,507	2	1	32	10	2	7
	Subbase - Materials Production	1,886,339	212	132	197	30	293	374
	Subbase - Materials Transportation	458,676	78	34	1,827	356	110	152
	Subbase - Processes (Equipment)	78,752	10	6	118	14	8	26
Collector Construction Factors	Wearing - Materials Production	10,009,227	2,604	853	910	1,492	1,493	3,052
→ Rural	Wearing - Materials Transportation	788,962	134	59	3,142	604	189	262
	Wearing - Processes (Equipment)	18,507	2	1	32	10	2	7
	Subbase - Materials Production	1,886,339	212	132	197	30	293	374
	Subbase - Materials Transportation	458,676	78	34	1,827	356	110	152
	Subbase - Processes (Equipment)	78,752	10	6	118	14	8	26
Local Construction Factors	Wearing - Materials Production	7,864,392	2,046	670	714	1,173	1,173	2,398
→ Urban	Wearing - Materials Transportation	619,899	106	46	2,469	474	148	206
	Wearing - Processes (Equipment)	14,541	2	1	25	8	2	5
	Subbase - Materials Production	1,290,653	145	90	135	20	201	256
	Subbase - Materials Transportation	313,831	53	23	1,250	244	75	104
	Subbase - Processes (Equipment)	53,883	7	4	81	10	5	17
Local Construction Factors	Wearing - Materials Production	6,352,009	1,653	541	577	947	948	1,937
→ Rural	Wearing - Materials Transportation	500,687	85	37	1,994	383	120	166
	Wearing - Processes (Equipment)	11,745	1	1	21	6	1	4
	Subbase - Materials Production	1,042,451	117	73	109	16	162	207
	Subbase - Materials Transportation	253,479	43	19	1,010	197	61	84
	Subbase - Processes (Equipment)	43,521	6	3	65	8	4	14

5.3 Appendix C – LCI Aircraft Size Groupings

Figure 38 – Aircraft Size Groupings Assignment

Small Aircraft
Aerospatiale Caravelle Se-210
Aerospatiale Corvette
Aerospatiale/Aeritalia Atr-42
Aerospatiale/Aeritalia Atr-72
Airbus A300
Beech 1900 A/B/C/D
Bombardier (Gates) Learjet 60
Bombardier Bd-700 Global Express
Bombardier Challenger 604
Bombardier Crj 705
Br. Ae. (Hawker-Siddeley) Bae-748
British Aerospace Bae-146-100/Rj70
British Aerospace Bae-146-200
British Aerospace Bae-146-300
British Aerospace Bae-Atp
British Aerospace Jetstream 31
British Aerospace Jetstream 41
Canadair 601
Canadair CL 44
Canadair RJ 100
Canadair RJ 200
Canadair RJ 700
Canadar CRJ 900
Carstedt Cj-600a
Casa 235
Convair Cv-240
Convair Cv-340/440
Convair Cv-540
Convair Cv-580
Convair Cv-600
Convair Cv-640
Convair Cv-660
Dassault Falcon 2000ex
Dassault Falcon 50
Dassault Falcon 900
Dassault-Breguet Mystere-Falcon
Dornier 228
Dornier 328
Dornier 328 Jet
Dornier Do-28 Skyservant

Small Aircraft (Continued)
Embraer 110
Embraer 120
Embraer 135
Embraer 140
Embraer 145
Embraer 170
Embraer 175
Embraer 190
Fokker 100
Fokker 50
Fokker 70
Fokker F28-1000 Fellowship
Fokker F28-4000/6000 Fellowship
Fokker Friendship F-27
Fokker Fairchild F-27/A/B/F/J
Gates Learjet Lear-23
Gates Learjet Lear-24
Gates Learjet Lear-25
Gates Learjet Lear-35
Gulfstream G450
Gulfstream I
Gulfstream I-Commander
Gulfstream V/ G-V Exec/ G-5/550
Hawker Siddeley 125
Hawker Siddeley 748
Lear 55
Rockwell Sabreliner
Rockwell Turbo-Commander 6XX
Saab-Fairchild 340/A
Saab-Fairchild 340/B
Tupolev Tu-154

Midsize Aircraft
Aerospatiale/Br. Ae. Concorde
Airbus A300
Airbus A310
Airbus A320
Airbus A330
Airbus A340
Boeing 377
Boeing 717
Boeing 720
Boeing 727
Boeing 737
Boeing 757
British Aerospace Bac-111-200
British Aerospace Bac-111-400
Convair 880 (Cv-22/22m)
Convair 990 Coronado (Cv-30)
Ilyushin 62
Ilyushin 76/Td
Ilyushin 86
Ilyushin 96
Ilyushin Il-18
Mcdonnell Douglas DC-10-20
Mcdonnell Douglas DC-10-30
Mcdonnell Douglas DC-10-30cf
Mcdonnell Douglas DC-10-40
MD DC10
MD DC2
MD DC3
MD DC4
MD DC6
MD DC7
MD DC9
MD MD11
MD MD90

Large Aircraft
Boeing 707
Boeing 747
Boeing 767
Boeing 777
MD DC8

5.4 Appendix D – Modal Assignments

Table 107 – Generalized Modal Codings and Occupancies for the San Francisco Bay Area

Mode Coding	Mode Description	Generalized Mode Assignment	Average Occupancy
1	Airplane	1	35
2	Bicycle	2	1
3	BUS - Employer Shuttle Bus	3	10
4	BUS - Dial-a-Ride	4	10
5	BUS - School Bus	5	20
6	BUS - AC Transit (AC)	6	10
7	BUS - AirBART (Coliseum BART station to Oakland Airport)	6	10
8	BUS - Benicia Transit (BT)	6	10
9	BUS - Central Contra Costa Transit Authority (County Connection)	6	6
10	BUS - Dumbarton Express BUS - (DBX)	6	10
11	BUS - Eastern Contra Costa - Tri Delta Transit (TriDelta)	6	10
12	BUS - Fairfield-Suisan Transit (FST)	6	10
13	BUS - Golden Gate Transit-Bus (GGT-B)	6	10
14	BUS - Napa Valley Intracity Neighborhood Express (VINE)	6	10
15	BUS - Napa Valley Transit (NVT)	6	10
16	BUS - Petaluma Transit (PT)	6	10
17	BUS - San Francisco Muni-Bus (MUNI-B)	200	15.7
18	BUS - Santa Clara Valley Transit Authority-Bus (VTA-B)	6	10
19	BUS - San Mateo County Transit (SAMTRANS)	6	10
20	BUS - Santa Rosa City BUS - (SR)	6	10
21	BUS - Sonoma County Transit (SCT)	6	10
22	BUS - Union City Transit (UCT)	6	10
23	BUS - Vacaville City Coach (VCC)	6	10
24	BUS - Vallejo Transit-Bus (VT-B)	6	10
25	BUS - Western Contra Costa County Transit (WestCat)	6	10
26	BUS - Wheels-Livermore Amador Valley Transit Authority (LAVTA)	6	10
27	Car, van, truck, (motorcycle, or moped)	8	
28	Carpool vehicle	9	
29	FERRY - Alameda/Oakland/Harbor Bay Ferry (BF)	10	107
30	FERRY - Golden Gate Transit-Ferry (GGT-F)	10	107
31	FERRY - Richmond FERRY	10	107
32	FERRY - Tiburon FERRY - (TF)	10	107
33	FERRY - Vallejo Transit-Ferry (VT-F)	10	107
34	RAIL - Amtrak	11	100
35	RAIL - Altamont Commuter Express (ACE)	12	42.5
36	RAIL - Bay Area Rapid Transit (BART)	13	148.6
37	RAIL - Caltrain	14	156.2
38	San Francisco Muni-Train (MUNI-T)	15	21.9
39	Santa Clara Valley Transit Authority-LRT (VTA-T)	16	13.1
40	Taxi	17	1
41	Walk	18	1
996	Other	996	2.43
999	Don't Know	999	2.43

Table 108 – Generalized Modal Codings and Occupancies for Chicago

Mode Coding	Mode Description	Generalized Mode Assignment	Average Occupancy
1	Walk	18	1
2	Bike	2	1
3	Auto/Van/Truck Driver	100	
4	Auto/Van/Truck Passenger	100	
5	CTA Bus	6	12
6	CTA Train	13	92
7	PACE Bus	6	12
8	Metra Train	14	245
9	Private Shuttle Bus	3	10
10	Dial-a-Ride/Paratransit	4	7
11	School Bus	5	20
12	Taxi	17	
14	Local Transit (NIRPC Region)	6	12
15	More Than One Transit Provider	0	
97	Other	996	
98	Don't Know	999	
99	Refused	999	

Table 109 – Generalized Modal Codings and Occupancies for New York

Mode Coding	Mode Description	Generalized Mode Assignment	Average Occupancy
11	Walk	18	1
12	Wheelchair	2	1
13	Skates	2	1
14	Bicycle	2	1
21	Auto Driver	100	
22	Auto Passenger	100	
23	Motorcycle/Moped	105	
31	Carpool	9	
41	Standard Local Bus	6	19
42	School Bus	5	20
43	Commuter Van or Shuttle Bus (Contracted)	3	7
44	Commuter Van or Jitney (Pay Fare)	4	7
45	Express Bus	6	20
46	Charter Bus	6	20
47	Airport Line	6	20
51	Amtrak, Greyhound, Airline, Helo	11	100
61	Subway	13	224
62	Path	15	166
63	Newark City Subway	13	24
71	Ferry	10	200
81	Comm Rail	14	230
91	Yellow/Medallion Cab	17	1
92	For Hire Van/Jitney	6	7
93	Car Service/Black Car	17	
94	Gypsy Cab	17	
97	Other	996	
98	Don'T Know	999	
99	Refused	999	

5.5 Appendix E – Emissions and Vehicle Age

Figure 39 – Onroad Vehicle Emissions from Several U.S. Inventories [Parrish 2006]

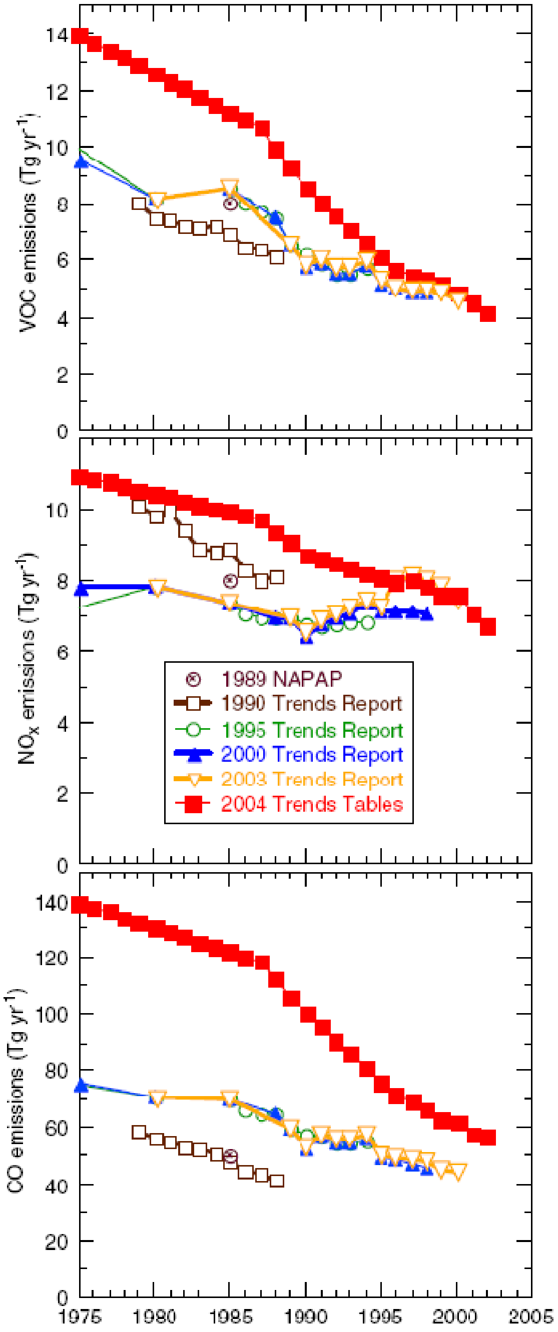


Figure 40 – PM$_{10}$ and PM$_{2.5}$ Emissions and Vehicle Year [Granell 2004]

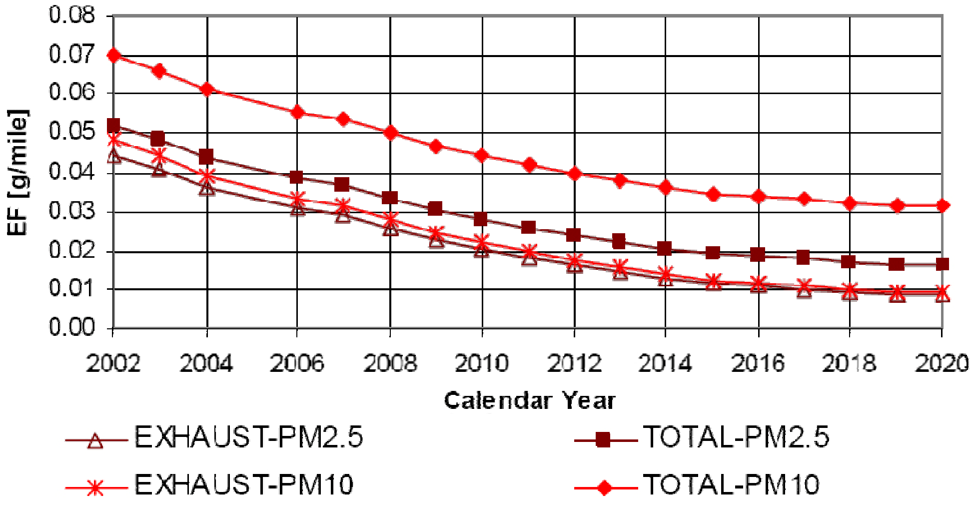
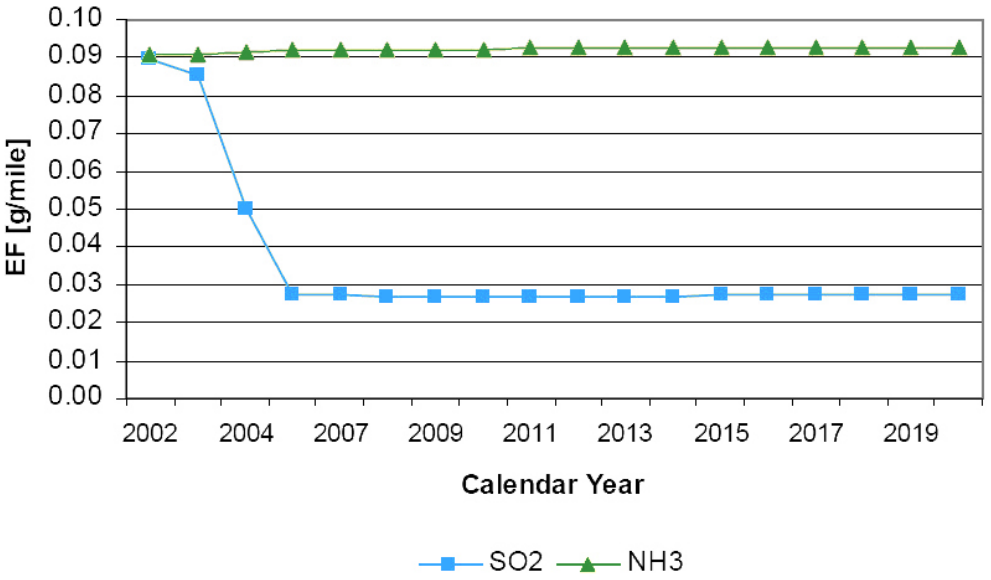
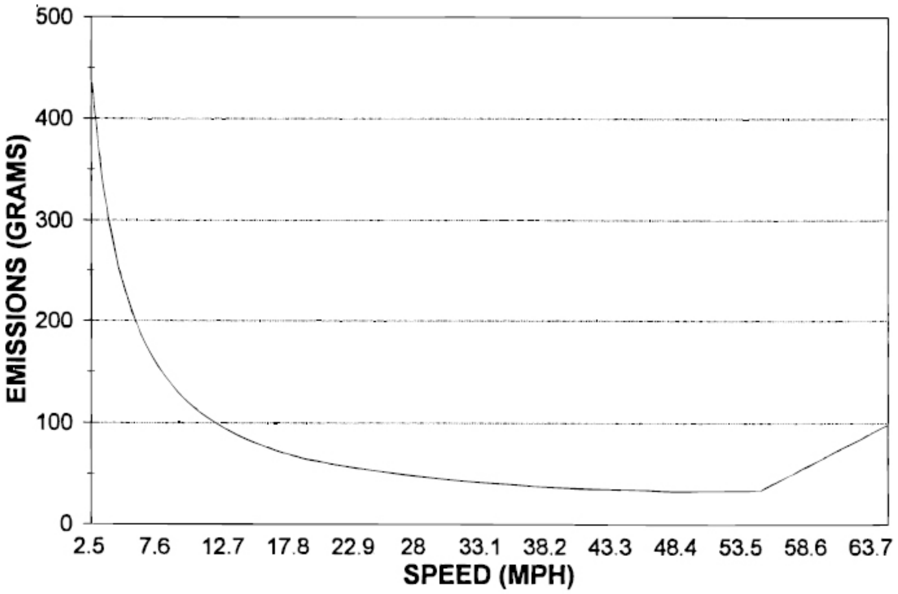


Figure 41 – SO$_2$ Emissions and Vehicle Year [Granell 2004]



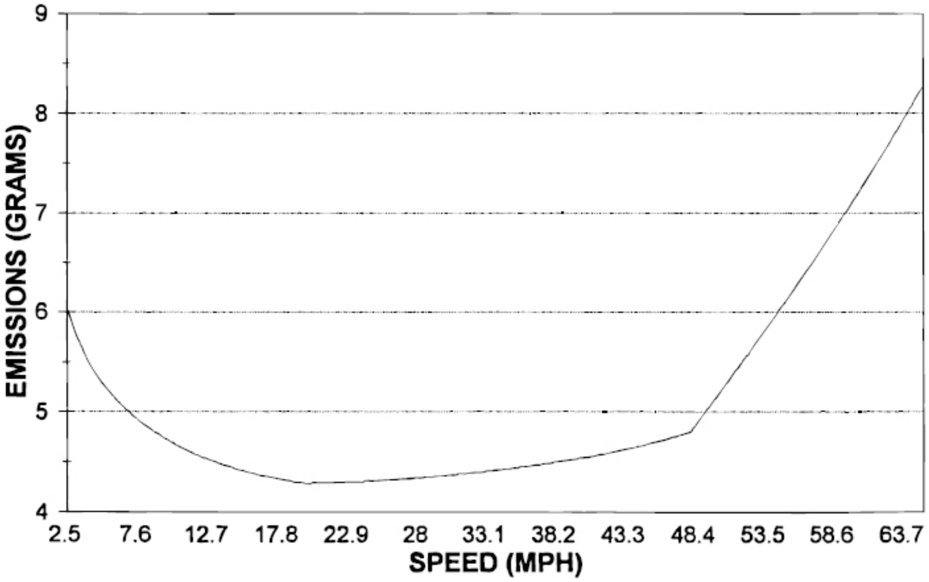
5.6 Appendix F – Emissions Profiles and Vehicle Speed

Figure 42 – CO Emissions and Vehicle Speed [Anderson 1996]



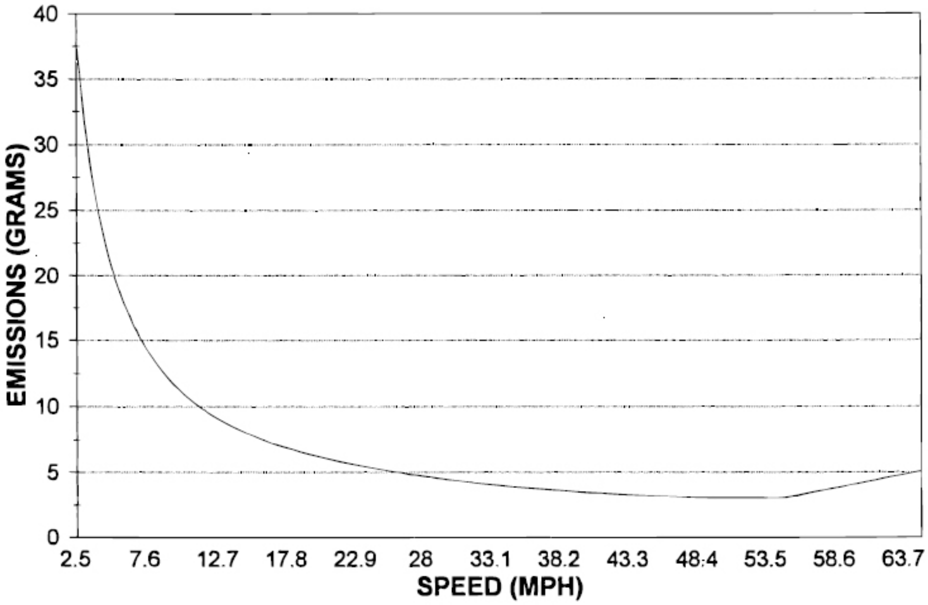
Generated in EPA Mobile 5.C for an Average Gasoline Vehicle

Figure 43 – NO$_X$ Emissions and Vehicle Speed [Anderson 1996]



Generated in EPA Mobile 5.C for an Average Gasoline Vehicle

Figure 44 – HC Emissions and Vehicle Speed [Anderson 1996]



Generated in EPA Mobile 5.C for an Average Gasoline Vehicle

Figure 45 – PM_{10} Emissions and Vehicle Speed [Granell 2004]

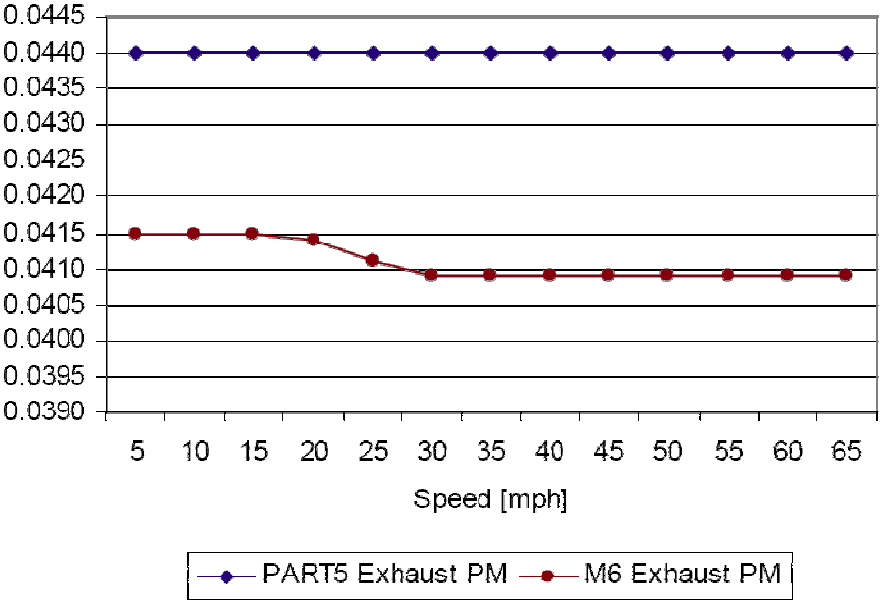


Figure 46 – $PM_{2.5}$ Emissions and Vehicle Speed [Granell 2004]

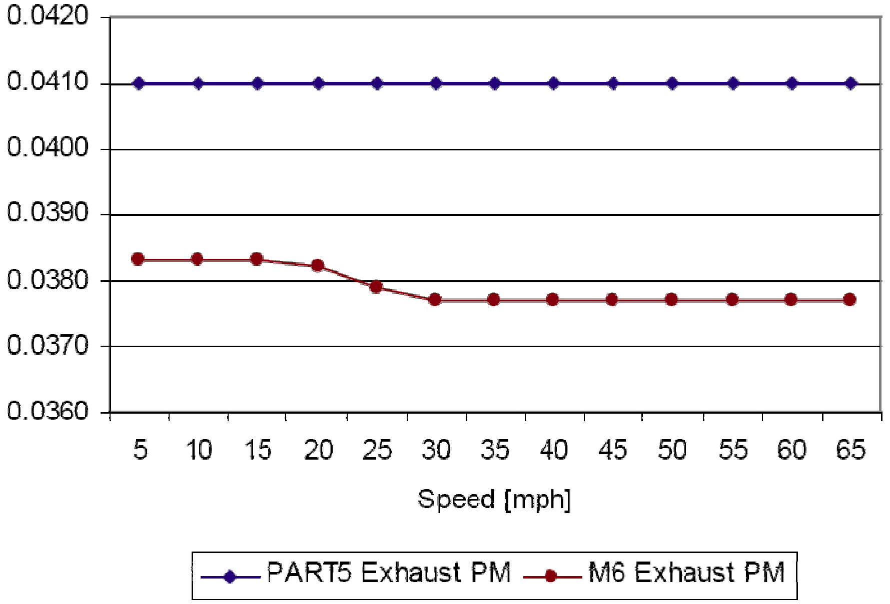
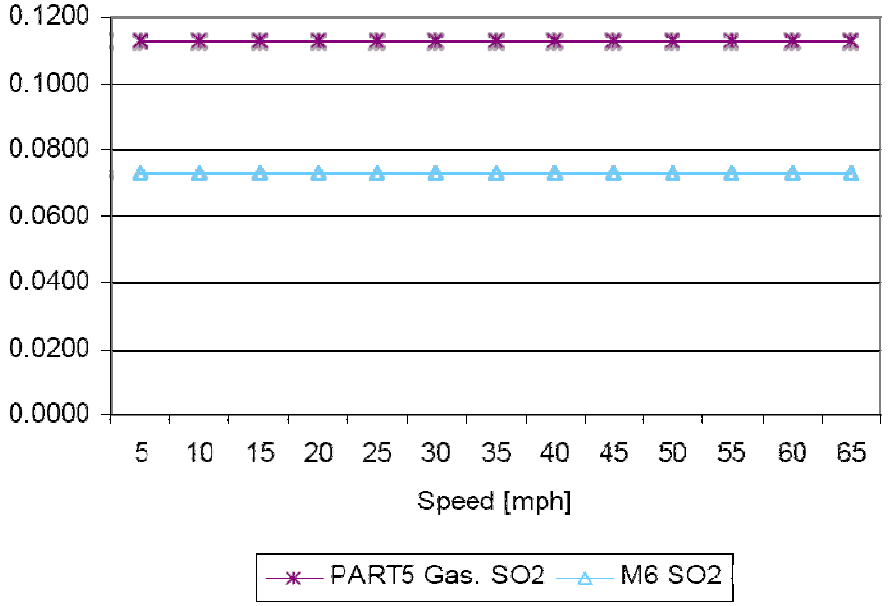


Figure 47 – SO_2 Emissions and Vehicle Speed [Granell 2004]



5.7 Appendix G – PMT Mode Splits for Each Region

All data in Table 110 are from the BATS 2000 travel survey. The survey captures 270,000 trips and is assumed to be a representative sample of travel in the San Francisco Bay Area region [MTC 2000].

Table 110 – San Francisco Bay Area Off-Peak and Peak Mode Splits by Generalized Mode

Generalized Mode	Off-Peak PMT	Peak PMT	Total PMT
Bicycle	2,756 (0.3%)	2,585 (0.4%)	5,341 (0.3%)
Employer Shuttle Bus	1,042 (0.1%)	636 (0.1%)	1,678 (0.1%)
Dial-a Ride Bus	27 (0.0%)	16 (0.0%)	43 (0.0%)
School Bus	2,092 (0.2%)	2,389 (0.4%)	4,482 (0.3%)
Urban / Commuter Bus	14,432 (1.6%)	4,935 (0.7%)	19,367 (1.2%)
Automobile (Tagged as Carpool)	-	-	-
Ferry	3,050 (0.3%)	184 (0.0%)	3,234 (0.2%)
Inter Urban Rail	2,550 (0.3%)	250 (0.0%)	2,800 (0.2%)
Commuter Rail	2,200 (0.2%)	80 (0.0%)	2,280 (0.1%)
Subway	45,242 (4.9%)	6,250 (0.9%)	51,492 (3.2%)
Commuter Rail	10,808 (1.2%)	852 (0.1%)	11,660 (0.7%)
Light Rail	1,943 (0.2%)	612 (0.1%)	2,555 (0.2%)
Light Rail	1,521 (0.2%)	342 (0.1%)	1,863 (0.1%)
Taxi	737 (0.1%)	238 (0.0%)	976 (0.1%)
Walk	7,177 (0.8%)	4,265 (0.6%)	11,442 (0.7%)
Automobile (Undefined)	14,587 (1.6%)	14,176 (2.1%)	28,763 (1.8%)
Automobile (Sedan)	503,106 (55%)	408,313 (60%)	911,418 (57%)
Automobile (Light Duty Gasoline Truck)	89,131 (9.7%)	73,649 (11%)	162,780 (10%)
Automobile (SUV)	95,203 (10%)	72,722 (11%)	167,925 (11%)
Automobile (Van)	100,603 (11%)	77,782 (11%)	178,384 (11%)
Automobile (Motorcycle / Moped)	-	-	-
Electric Urban Bus	5,105 (0.6%)	1,857 (0.3%)	6,963 (0.4%)
Undefined (Assumed Automobile)	13,650 (1.5%)	6,170 (0.9%)	19,820 (1.2%)
Undefined (Assumed Automobile)	2,180 (0.2%)	1,430 (0.2%)	3,610 (0.2%)
Total	919,141	679,735	1,598,876
Personal Transit	828,392 (90%)	661,093 (97%)	1,489,484 (93%)
Public Transit	90,749 (10%)	18,643 (3%)	109,392 (7%)

Percentages may not sum to 100% due to rounding.

All data in Table 111 are from the Chicago CMAP travel survey. The survey captures 170,000 trips and is assumed to be a representative sample of travel in the Chicago metropolitan region [CMAP 2008].

Table 111 – Chicago Off-Peak and Peak Mode Splits by Generalized Mode

Generalized Mode	Off-Peak PMT	Peak PMT	Total PMT
Bicycle	1,931 (0.4%)	2,640 (0.5%)	4,570 (0.4%)
Employer Shuttle Bus	1,007 (0.2%)	1,924 (0.3%)	2,931 (0.3%)
Dial-a Ride Bus	277 (0.1%)	221 (0.0%)	499 (0.0%)
School Bus	1,614 (0.3%)	8,828 (1.6%)	10,442 (1.0%)
Urban / Commuter Bus	5,862 (1.2%)	10,511 (1.9%)	16,374 (1.6%)
Automobile (Tagged as Carpool)	183,734 (39%)	141,281 (26%)	325,015 (32%)
Ferry	-	-	-
Inter Urban Rail	-	-	-
Commuter Rail	-	-	-
Subway	4,184 (0.9%)	8,808 (1.6%)	12,993 (1.3%)
Commuter Rail	8,780 (1.9%)	36,484 (6.6%)	45,264 (4.4%)
Light Rail	7 (0.0%)	20 (0.0%)	26 (0.0%)
Light Rail	-	-	-
Taxi	919 (0.2%)	801 (0.1%)	1,720 (0.2%)
Walk	21,076 (4.5%)	25,035 (4.5%)	46,111 (4.5%)
Automobile (Undefined)	140,558 (30%)	184,034 (33%)	324,592 (32%)
Automobile (Sedan)	39,407 (8.4%)	51,387 (9.3%)	90,794 (8.9%)
Automobile (Light Duty Gasoline Truck)	17,422 (3.7%)	23,450 (4.2%)	40,872 (4.0%)
Automobile (SUV)	27,170 (5.8%)	38,483 (6.9%)	65,653 (6.4%)
Automobile (Van)	16,485 (3.5%)	19,652 (3.5%)	36,137 (3.5%)
Automobile (Motorcycle / Moped)	130 (0.0%)	158 (0.0%)	288 (0.0%)
Electric Urban Bus	-	-	-
Undefined (Assumed Automobile)	27 (0.0%)	31 (0.0%)	58 (0.0%)
Undefined (Assumed Automobile)	-	-	-
Total	1,931 (0.4%)	2,640 (0.5%)	4,570 (0.4%)
Personal Transit	1,007 (0.2%)	1,924 (0.3%)	2,931 (0.3%)
Public Transit	277 (0.1%)	221 (0.0%)	499 (0.0%)

Percentages may not sum to 100% due to rounding.

All data in Table 112 are from the New York region RTHIS travel survey. The survey captures 110,000 trips and is assumed to be a representative sample of travel in the New York City region [NYMTC 1998].

Table 112 – New York Off-Peak and Peak Mode Splits by Generalized Mode

Generalized Mode	Off-Peak PMT	Peak PMT	Total PMT
Bicycle	403 (0.1%)	488 (0.1%)	891 (0.1%)
Employer Shuttle Bus	365 (0.1%)	734 (0.2%)	1,099 (0.2%)
Dial-a Ride Bus	137 (0.0%)	387 (0.1%)	524 (0.1%)
School Bus	5,008 (1.7%)	13,018 (3.3%)	18,026 (2.6%)
Urban / Commuter Bus	6,521 (2.2%)	11,700 (3.0%)	18,221 (2.6%)
Automobile (Tagged as Carpool)	17,300 (5.8%)	15,922 (4.1%)	33,222 (4.8%)
Ferry	352 (0.1%)	985 (0.3%)	1,337 (0.2%)
Inter Urban Rail	1,430 (0.5%)	1,483 (0.4%)	2,913 (0.4%)
Commuter Rail	-	-	-
Subway	5,868 (2.0%)	12,090 (3.1%)	17,958 (2.6%)
Commuter Rail	2,411 (0.8%)	7,456 (1.9%)	9,867 (1.4%)
Light Rail	374 (0.1%)	1,175 (0.3%)	1,549 (0.2%)
Light Rail	-	-	-
Taxi	2,332 (0.8%)	1,570 (0.4%)	3,903 (0.6%)
Walk	11,520 (3.9%)	15,780 (4.0%)	27,299 (4.0%)
Automobile (Undefined)	7,573 (2.6%)	9,284 (2.4%)	16,857 (2.4%)
Automobile (Sedan)	165,139 (56%)	212,746 (54%)	377,885 (55%)
Automobile (Light Duty Gasoline Truck)	14,643 (4.9%)	17,218 (4.4%)	31,861 (4.6%)
Automobile (SUV)	18,840 (6.3%)	24,796 (6.3%)	43,636 (6.3%)
Automobile (Van)	35,918 (12%)	43,837 (11%)	79,755 (12%)
Automobile (Motorcycle / Moped)	276 (0.1%)	333 (0.1%)	609 (0.1%)
Electric Urban Bus	-	-	-
Undefined (Assumed Automobile)	472 (0.2%)	509 (0.1%)	982 (0.1%)
Undefined (Assumed Automobile)	23 (0.0%)	98 (0.0%)	121 (0.0%)
Total	403 (0.1%)	488 (0.1%)	891 (0.1%)
Personal Transit	365 (0.1%)	734 (0.2%)	1,099 (0.2%)
Public Transit	137 (0.0%)	387 (0.1%)	524 (0.1%)

Percentages may not sum to 100% due to rounding.

5.8 Appendix H – Off-peak and Peak Occupancy Calculations

Variable Definition:

$$S_T = Average\ Stated\ Occupancy$$

$$P = Adjustment\ Percentage\ for\ Off - Peak\ or\ Peak\ Time$$

$$S_{OP} = Average\ Off - Peak\ Occupancy = S_T \times P$$

$$S_P = Average\ Peak\ Occupancy = S_T \times (1 + P)$$

$$VMT_{OP} = Total\ VMT\ for\ Mode\ in\ Off - Peak\ Travel$$

$$VMT_P = Total\ VMT\ for\ Mode\ in\ Peak\ Travel$$

Determination of Adjustment Percentage for a Mode:

$$S_T = \frac{S_{OP} \times V_{MTOP} + S_P \times VMT_P}{VMT_{OP} + VMT_P} = \frac{S_T \times P \times VMT_{OP} + S_T \times (1 + P) \times VMT_P}{VMT_{OP} + VMT_P}$$

$$VMT_{OP} + VMT_P = P \times VMT_{OP} + (1 + P) \times VMT_P$$

$$VMT_{OP} = P \times (VMT_{OP} + VMT_P)$$

$$P = \frac{VMT_{OP}}{VMT_{OP} + VMT_P}$$