Title

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

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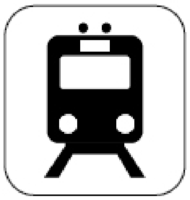

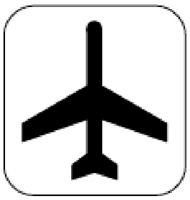

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This document is based on models 20071027/onroad, 20071015/rail, and 20071206/air. Document version “its_report_06.doc”.

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Version History

This working paper is meant to provide the background purpose, methodology, and preliminary results of this assessment. The results in this paper provide draft final results meaning they are subject to further analysis. Changes in the analysis which have been published in re-released working papers are documented in this section.

Report Number	Publication Date	Documentation
Working Paper 1	December 2007	Release of draft final inventory Models used: 20071027/onroad, 20071015/rail, 20071206/air

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List of Acronyms and Symbols

$I_{IO-\gamma}^{\alpha,\beta}$	Impact for mode (α), system component (β), and functional unit (γ) Modes (α) are onroad (autos and buses), rail, and air Functional units are impacts per vehicle lifetime, VMT, and PMT Impacts (IO = Input or Output) include: ➥ Energy inputs ➥ Greenhouse Gases (GHG in Carbon Dioxide Equivalence) outputs ➥ Criteria Pollutants (SO_2, CO, NO_X, VOC, Pb, PM) outputs
$	U.S. dollars in 2005 unless otherwise stated
§	Section
B	Billion
BART	Bay Area Rapid Transit
CAHSR	California High Speed Rail
CAP	Criteria air pollutants
CO	Carbon Monoxide
EF	Emission Factor
EIOLCA	Economic Input-Output Life-cycle Assessment
GGE	Grams of Greenhouse Gas Equivalence
GHG	Greenhouse Gases
Green Line	Massachusetts Bay Transportation Authority Green Line Light Rail
J	Joule
LCA	Life-cycle Assessment
LTO	Landing-Takeoff Cycle
M	Million
Muni	San Francisco Municipal Railway Light Rail
NO_X	Nitrogen Oxides
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
Pb	Lead
PKT	Passenger Kilometers Traveled
PMT	Passenger Miles Traveled
PM_X	Particulate Matter (subscript denotes particle diameter in microns, 10^{-6} meters)
SO_2	Sulfur Dioxide
VKT	Vehicle Kilometers Traveled
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compounds
Wh	Watt-hour (watt = joule · second^{-1})
g	Gram
mt	Metric tonne

Powers of Ten

k	Kilo (10^3)
M	Million or Mega (10^6)
B	Billion (10^9)
G	Giga (10^9)
T	Tera (10^{12})
P	Peta (10^{15})
E	Exa (10^{18})

1 Abstract

The passenger transportation modes of auto, bus, heavy rail, light rail and air are critical systems relied upon for business and leisure. When considering their environmental effects, most studies and policy focus on the fuel use of the vehicles, and ignore the energy and other resource inputs and environmental outputs from the life cycles of necessary infrastructures, fuels, and vehicles.

The goal of this project is to develop comprehensive life-cycle assessment (LCA) models to quantify the energy inputs and emissions from autos, buses, heavy rail, light rail and air transportation in the U.S. associated with the entire life cycle (design, raw materials extraction, manufacturing, construction, operation, maintenance, end-of-life) of the vehicles, infrastructures, and fuels involved in these systems. Energy inputs are quantified as well as greenhouse gas and criteria air pollutant outputs. Inventory results are normalized to effects per vehicle-lifetime, VMT, and PMT.

Current results show that energy and greenhouse gas emissions increase by as much as 1.3X for automobiles, 1.4X for buses, 2.6X for light rail, 2.1X for heavy rail, and 1.3X for air. Criteria air pollutant emissions increase up to 25X for automobiles, 7X for buses, 220X for light rail, 98X for heavy rail, and 11X for air.

2 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 1998a, Maddison 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 analyzing 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 these 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 quantification of 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 infrastructure and vehicles.

3 Methodology

The passenger transportation sectors play a key role in the economy of moving people between sources and destinations, but 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 [GREET 2004]. 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 infrastructure and vehicles. 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 lifecycle (Table 1). These studies tend to quantify social costs at each stage without considering the full environmental costs.

Table 1 - Scope of Work

		Design	Production	Operation	End-of-Life
Automobile	Roadways	N	M,N	M,N	N
	Cars & Trucks	K,L,N	K,L,N,M,J	A,B,C,D,E,F,G,H,K,L,N,M,J	K,L,N,M
	Fuel (Gasoline)			A	
Air	Airports			O	
	Aircraft			G,H,I	
	Fuel (Kerosene)				
Light Rail	Tracks	N	N	N	N
	Locomotives & Cars	N	J,N	H,J,N	N
	Fuel (Electric)				
Heavy Rail	Tracks	N	N	N	N
	Locomotives & Cars	N	J,N	H,J,N,P	N
	Fuel (Diesel, Electric)				
Bus	Roadways	N	M,N	M,N	N
	Vehicles			Q, R	
	Fuel (Diesel, Electric)				

Sources: A. Delucchi 1997; B. Madison 1996; C. Mayeres 1996; D. Verhoef 1994; E. Small 1995; F. Levinson 1996; G. Levinson 1998b; H. INFRAS 1994; I. Schipper 2003; J. Stodolsky 1998; K. Sullivan 1998; L. MacLean 1998; M. Marheineke 1998; N. Nocker 2000; O. FAA 2007; P. Fritz 1994; Q. Clark 2003; R. Cohen 2003

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.

3.1 Life-cycle Assessment (LCA)

The vehicles, infrastructure, 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).

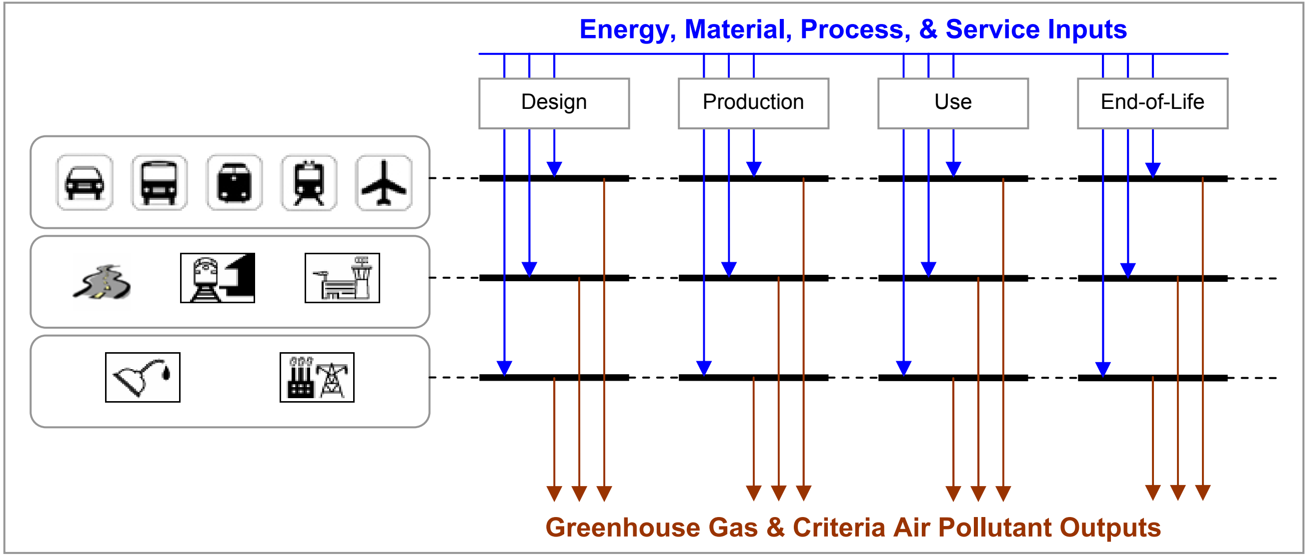
LCA has become the necessary systematic method in pollution prevention and life-cycle engineering to analyze the environmental implications associated with products, processes, and services through the different stages of the life cycle: design, materials and energy acquisition, transportation, manufacturing, 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 15 years [Fava 1991, Bare 2003, ISO 2000]. The LCA methodology consists of four stages (Figure 1): definition 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. EIOLCA 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) [EIOLCA 2005]. 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 the stages of the LCA that will be analyzed.

Figure 1 - A conceptual model of the life-cycle components of each mode



3.2 Environmental Effects Studied

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, fuels associated with each mode.

The emissions are of concern because:

- Greenhouse Gases – global climate change and its effects
- Sulfur Dioxide (SO_2) – respiratory irritant, precursor for acid deposition
- Carbon Monoxide (CO) – asphyxiate
- Nitrogen Oxides (NO_X) – respiratory irritant, contributes to ground level ozone formation
- Volatile Organic Compounds (VOC) – potentially carcinogenic, contributes to ground level ozone formation
- Particulate Matter (PM) – affects respiratory system, cardiovascular system, and damages lung tissue
- Lead (Pb) – neurotoxin

4 Data Sources

Across the five modes and twelve vehicles, 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. The following tables summarize these data sources for the purpose of availability and reproducibility. The tables are arranged by life-cycle component where for each stage, both the data source and LCA type (process, EIOLCA, hybrid) is reported.

Table 2 - Onroad data sources

	Data Sources	LCA Type
Vehicle		
Manufacturing		
Manufacturing	AN 2005	EIOLCA
Operation		
Running	EPA 2006, Mobile 2003	Process
Startup	Mobile 2003	Process
Braking	Mobile 2003	Process
Tire Wear	Mobile 2003	Process
Evaporative Losses	Mobile 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, EPA 2001	Hybrid
Roadway Maintenance	FTA 2006, PaLATE, 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, EPA 2001	Hybrid
Operation		
Herbicides & Salt Production	EPA 2001b, TRB 1991	EIOLCA
Fuel		
Gasoline & Diesel Production	EIA 2007, EIA 2007b	EIOLCA

Table 3 - Rail data sources

	Data Sources	LCA Type
Vehicles		
Manufacturing		
Vehicle Manufacturing	SimaPro, Breda 2007, Breda 2007b	Process
Operation		
Propulsion, Idling, Auxiliaries	Fels 1977, FTA 2005, Caltrain 2007c, Fritz 1994, Anderrson 2006, Deru 2007	Process
Maintenance		
Vehicle	SimaPro	Process
Cleaning	SFG 2006, EERE, BuiLCA	Process
Flooring Replacement	SFG 2006	EIOLCA
Insurance		
Operator Health and 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, MBTA 2007, FAA 2007	Process
Station Maintenance	BART 2006, BART 2007e, Bombardier 2007, Guggemos 2005	Hybrid
Station Parking	SFC 2007b, Caltrain 2004, MBTA 2007, PaLATE, EPA 2001	Hybrid
Operation		
Station Lighting	Fels 1977, Deru 2007	Process
Station Escalators	EERE 2007, FTA 2005, Fels 1977, Deru 2007	Process
Train Control	Fels 1977, Deru 2007	Process
Station Parking Lighting	Deru 2007	Process
Station Miscellaneous	Fels 1977, MEOT 2005, EIA 2005	Process
Station Cleaning	Paulsen, Deru 2007	Process
Insurance		
Non-Operator Health and 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
Transmission and Distribution Losses	Deru 2007	Process

Table 4 - Air data sources

	Data Sources	LCA Type
Vehicle		
Manufacturing		
Airframe	Janes 2004, AIA 2007, Boeing 2007	EIOLCA
Engine	Jenkins 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		
Lubrication and Fuel Changes	EPA 1998, BTS 2007b	EIOLCA
Battery Repair and Replacement	EPA 1998, BTS 2007b	EIOLCA
Chemical Application	EPA 1998, BTS 2007b	EIOLCA
Parts Cleaning	EPA 1998, BTS 2007b	EIOLCA
Metal Finishing	EPA 1998, BTS 2007b	EIOLCA
Coating Application	EPA 1998, BTS 2007b	EIOLCA
Painting	EPA 1998, BTS 2007b	EIOLCA
Depainting	EPA 1998, BTS 2007b	EIOLCA
Engine	EPA 1998, BTS 2007b	EIOLCA
Insurance		
Vehicle Incidents	BTS 2007b	EIOLCA
Flight Crew Health & Benefits	BTS 2007b	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, EPA 2001	Hybrid
Airport Maintenance		
Airport Parking	MWA 2007, PaLATE, 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	Process

5 Life-cycle Inventory of Automobiles and Urban Buses

Cars, light trucks, 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: sedan, SUV, and pickup truck. Additionally, a typical diesel-powered urban transit bus is evaluated.

5.1 Vehicles

To select the most typical vehicles representing the three automobile categories, vehicle sales data is evaluated for 2005 [Wards 2006]. Table 5 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 high weight (and is the highest selling vehicle). The sedan averages 1.58 people per car, the SUV 1.74, and the pickup 1.46 [Davis 2006].

Table 5 - 2005 automobile sales by vehicle type

	Sedan		Sport Utility		Pickup	
Rank	Model	Number	Model	Number	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 [FHA 2004].

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 6.

Table 6 - Onroad 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

5.1.1 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 EIOLCA which serves as a good estimate for the total direct and indirect impacts of the process. This sector in EIOLCA is used to determine the total inventory for the three automobiles. To determine automobile production costs, the base invoice price is used. This is the price the manufacturer sells the vehicle at to the dealer. A 20% markup 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 EIOLCA produces the vehicle environmental inventory. The general mathematical framework is shown in Equation Set 1.

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.

Figure 2 – Automobile manufacturing
Source: http://images.jupiterimages.com/

Equation Set 1 – Onroad vehicle manufacturing

$$I_{IO-vehicle-lifetime}^{onroad,manufacturing} = I = \text{Impact determined from EIOLCA}$$

$$I_{IO-VMT}^{onroad,manufacturing} = I \times \frac{vehicle-life}{VMT}$$

$$I_{IO-PMT}^{onroad,manufacturing} = I \times \frac{vehicle-life}{VMT} \times \frac{VMT}{PMT}$$

5.1.2 Operation

Emissions from vehicle operation are computed using the EPA Mobile 6.2 model [EPA 2003]. This software is designed to allow input of vehicle, operational, and fuel characteristics while driving to estimate environmental inventory. Typical operational factors do not disaggregate emissions into specific components such as driving, startup, tires and brakes, evaporative, and idling. Instead, emission factors, which are based on hundreds of operating condition parameters, are presented as representative of typical driving conditions. This does not allow for specific questions to be answered such as when and where these emissions occurred. This analysis disaggregates operational emissions by using the Mobile software. Not only are emissions from driving presented but also from startup, braking, tire wear, evaporative losses, and idling (in the case of the bus). It is important to consider these specific conditions for different reasons. Cold start emissions are the time when your 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, your 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

Oxidation Reactions:

$$2 \cdot H_N C_M + \tfrac{1}{2} \cdot (N+4 \cdot M) \cdot O_2 \rightarrow N \cdot H_2O + M \cdot CO_2$$

$$2 \cdot CO + O_2 \rightarrow 2 \cdot CO_2$$

Reduction Reaction:

$$2 \cdot NO_X \rightarrow N_2 + X \cdot O_2$$

PM emissions do not typically distinguish between 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 in order 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 6.2 for the bus [EPA 2006]. 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 500 ppm is used. The average emission values are used from the summer and winter scenarios. Table 7 summarizes these emission values. Energy consumption in the fuel is computed from fuel economy estimates and the fuel's energy content.

Table 7 – Emissions (g/VMT) from Mobile

	Sedan			SUV			Pickup			Bus		
	Summer	Winter	Average	Summer	Winter	Average	Summer	Winter	Average	Summer	Winter	Average
Operational Emissions												
CO_2	365	368	367	482	477	479	479	476	477	2,373	2,374	2,373
SO_2	0.02	0.21	0.11	0.03	0.03	0.03	0.03	0.03	0.03	0.74	0.74	0.74
CO	9.5	12.4	10.9	9.6	13.8	11.7	9.6	14.0	11.8	4.4	4.5	4.5
NO_X	0.80	0.89	0.85	0.76	0.92	0.84	1.00	1.21	1.10	17.65	17.99	17.82
VOC	0.28	0.35	0.31	0.33	0.43	0.38	0.35	0.46	0.41	0.55	0.56	0.55
Lead	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PM_{10}	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.66	0.68	0.67
Non-Operational Emissions												
Startup - CO	2.4	12.1	7.3	3.7	14.6	9.1	4.4	14.7	9.5	0.0	0.0	0.0
Startup - NO_X	0.15	0.19	0.17	0.16	0.21	0.19	0.20	0.26	0.23	0.00	0.00	0.00
Startup - VOC	0.22	0.48	0.35	0.28	0.62	0.45	0.30	0.66	0.48	0.00	0.00	0.00
Brake Wear - PM_{10}	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Tire Wear - PM_{10}	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Evaporative Losses - VOC	0.81	0.29	0.55	0.72	0.28	0.50	0.72	0.28	0.50	0.00	0.00	0.00

Multiplying the average emission factors in Table 7 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.

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].

5.1.3 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, EIOLCA 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

$$I_{IO-vehicle-lifetime}^{onroad,maintenance} = I = \text{Impact determined from EIOLCA}$$

$$I_{IO-VMT}^{onroad,maintenance} = I \times \frac{vehicle-life}{VMT}$$

$$I_{IO-PMT}^{onroad,maintenance} = I \times \frac{vehicle-life}{VMT} \times \frac{VMT}{PMT}$$

5.1.4 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. In order 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 vehicles repair facilities

$$I_{IO-VOC/CO2}^{onroad,auto-repair} = \frac{emission_{CA}}{yr} \times \frac{vehicles_{US}}{vehicles_{CA}} = \frac{emission_{US}}{yr}$$

$$I_{IO-vehicle-lifetime}^{onroad,auto-repair} = I_{IO-VOC/CO2}^{onroad,auto-repair} \times fleet-share_{vehicle} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{vehicle-life}$$

$$I_{IO-VMT}^{onroad,auto-repair} = I_{IO-VOC/CO2}^{onroad,auto-repair} \times fleet-share_{vehicle} \times \frac{yr}{VMT_{vehicle}}$$

$$I_{IO-PMT}^{onroad,auto-repair} = I_{IO-VOC/CO2}^{onroad,auto-repair} \times fleet-share_{vehicle} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

5.1.5 Insurance

The money paid towards 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 is 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 EIOLCA sector Insurance Carriers is used to estimate the inventory from this service for each vehicle type. The lifetime insurance costs (in \$1997) is computed and input into this sector for the environmental inventory as shown in Equation Set 5.

Equation Set 5 – Onroad vehicle insurance

$$I_{IO-vehicle-lifetime}^{onroad,insurance} = \text{Impact determined from EIOLCA}$$

$$I_{IO-VMT}^{onroad,insurance} = I_{IO-vehicle-lifetime}^{onroad,insurance} \times \frac{vehicle-life}{VMT}$$

$$I_{IO-PMT}^{onroad,insurance} = I_{IO-vehicle-lifetime}^{onroad,insurance} \times \frac{vehicle-life}{VMT} \times \frac{VMT}{PMT}$$

5.1.6 Vehicle Results

The environmental inventories for the life-cycle components associated with the vehicles are presented in Table 8 to Table 11 with all 3 functional units.

Table 8 – Sedan vehicle inventory

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
V, Manufacture	Energy	3.3 GJ	17 kJ	11 kJ
	GHG	0.15 mt GGE	0.78 g GGE	0.49 g GGE
	SO_2	0.36 kg	1.9 mg	1.2 mg
	CO	0.16 kg	0.88 mg	0.56 mg
	NO_X	0.20 kg	1.0 mg	0.66 mg
	VOC	5.4 kg	29 mg	18 mg
	PM_{10}	0.043 kg	0.23 mg	0.14 mg
	Pb	-	-	-
V, Operation (Running)	Energy	890 GJ	4,800 kJ	3,000 kJ
	GHG	69 mt GGE	370 g GGE	230 g GGE
	SO_2	21 kg	110 mg	72 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	VOC	3.4 kg	18 mg	11 mg
V, Evaporative Losses	VOC	100 kg	550 mg	350 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	2.0 GJ	10 kJ	6.6 kJ
	GHG	2.8 mt GGE	15 g GGE	9.4 g GGE
	SO_2	33 kg	180 mg	110 mg
	CO	7.7 kg	41 mg	26 mg
	NO_X	9.7 kg	52 mg	33 mg
	VOC	-	-	-
	PM_{10}	1.6 kg	8.8 mg	5.6 mg
	Pb	3,300 kg	17,000 mg	11,000 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 9 - SUV vehicle inventory

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
V, Manufacture	Energy	4.6 GJ	27 kJ	15 kJ
	GHG	0.21 mt GGE	1.2 g GGE	0.69 g GGE
	SO_2	0.51 kg	3.0 mg	1.7 mg
	CO	0.23 kg	1.4 mg	0.78 mg
	NO_X	0.28 kg	1.6 mg	0.93 mg
	VOC	7.7 kg	45 mg	26 mg
	PM_{10}	0.061 kg	0.36 mg	0.20 mg
	Pb	-	-	-
V, Operation (Running)	Energy	1,300 GJ	7,800 kJ	4,500 kJ
	GHG	82 mt GGE	480 g GGE	280 g GGE
	SO_2	4.6 kg	27 mg	16 mg
	CO	2,000 kg	12,000 mg	6,700 mg
	NO_X	140 kg	840 mg	480 mg
	VOC	65 kg	380 mg	220 mg
	PM_{10}	18 kg	110 mg	61 mg
	Pb	-	-	-
V, Operation (Start)	CO	1,600 kg	9,100 mg	5,200 mg
	NO_X	32 kg	190 mg	110 mg
	VOC	78 kg	450 mg	260 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	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	2.0 GJ	12 kJ	6.7 kJ
	GHG	2.9 mt GGE	17 g GGE	9.5 g GGE
	SO_2	34 kg	200 mg	110 mg
	CO	7.9 kg	46 mg	26 mg
	NO_X	10.0 kg	58 mg	33 mg
	VOC	-	-	-
	PM_{10}	1.7 kg	9.8 mg	5.7 mg
	Pb	3,300 kg	19,000 mg	11,000 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 10 - Pickup vehicle inventory

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
V, Manufacture	Energy	3.2 GJ	18 kJ	13 kJ
	GHG	0.14 mt GGE	0.82 g GGE	0.56 g GGE
	SO_2	0.35 kg	2.0 mg	1.4 mg
	CO	0.16 kg	0.93 mg	0.64 mg
	NO_X	0.19 kg	1.1 mg	0.76 mg
	VOC	5.3 kg	31 mg	21 mg
	PM_{10}	0.042 kg	0.24 mg	0.17 mg
	Pb	-	-	-
V, Operation (Running)	Energy	1,400 GJ	8,300 kJ	5,700 kJ
	GHG	82 mt GGE	480 g GGE	330 g GGE
	SO_2	4.6 kg	27 mg	18 mg
	CO	2,000 kg	12,000 mg	8,100 mg
	NO_X	190 kg	1,100 mg	760 mg
	VOC	70 kg	410 mg	280 mg
	PM_{10}	18 kg	110 mg	73 mg
	Pb	-	-	-
V, Operation (Start)	CO	1,600 kg	9,500 mg	6,500 mg
	NO_X	39 kg	230 mg	160 mg
	VOC	83 kg	480 mg	330 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	VOC	2.6 kg	15 mg	10 mg
V, Evaporative Losses	VOC	86 kg	500 mg	340 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	2.0 GJ	12 kJ	8.0 kJ
	GHG	2.9 mt GGE	17 g GGE	11 g GGE
	SO_2	34 kg	200 mg	140 mg
	CO	7.9 kg	46 mg	31 mg
	NO_X	10.0 kg	58 mg	40 mg
	VOC	-	-	-
	PM_{10}	1.7 kg	9.8 mg	6.7 mg
	Pb	3,300 kg	19,000 mg	13,000 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 11 - Bus vehicle inventory

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	11,000 GJ	22,000 kJ	2,100 kJ
	GHG	1,200 mt GGE	2,400 g GGE	230 g GGE
	SO_2	370 kg	740 mg	70 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}	370 kg	740 mg	71 mg
	Pb	-	-	-
V, Operation (Start)	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
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	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	13 GJ	27 kJ	2.6 kJ
	GHG	19 mt GGE	38 g GGE	3.6 g GGE
	SO_2	230 kg	460 mg	43 mg
	CO	52 kg	100 mg	10.0 mg
	NO_X	66 kg	130 mg	13 mg
	VOC	-	-	-
	PM_{10}	11 kg	23 mg	2.1 mg
	Pb	22,000 kg	45,000 mg	4,200 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	-	-	-

5.2 Infrastructure

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.

5.2.1 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]. PaLATE allows specification of parameters for the design, initial construction, maintenance, and equipment us 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 12.

Figure 3 – Roadway construction
Source: http://eroundlake.com/

Table 12 - AASHTO roadway geometry by functional class

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). The roadway miles by functional class are shown in Table 13 and are extrapolated out ten years based on historical mileage [BTS 2005]. Ten years represents the expected lifetime of the road so all infrastructure analyses evaluate roadways over this horizon.

Table 13 - Roadway mileage by functional class at 10-year horizon

Interstate Urban Paved Road Miles (2005-2014)	28,509
Interstate Rural Paved Road Miles (2005-2014)	31,371
Major Arterial Urban Paved Road Miles (2005-2014)	62,940
Major Arterial Rural Paved Road Miles (2005-2014)	102,332
Minor Arterial Urban Paved Road Miles (2005-2014)	109,123
Minor Arterial Rural Paved Road Miles (2005-2014)	134,934
Collector Urban Paved Road Miles (2005-2014)	113,735
Collector Rural Paved Road Miles (2005-2014)	555,127
Local Urban Paved Road Miles (2005-2014)	753,078
Local Rural Paved Road Miles (2005-2014)	819,766

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 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 constructions impacts of all environmental inventory computed, normalization can occur to the functional units. This is done using VMT data by vehicle type again extrapolated to 2014 [BTS 2005]. Equation Set 6 details the inventory calculations to the functional units for roadway construction.

Equation Set 6 – Onroad infrastructure roadway construction

$$I_{IO}^{onroad,road-construction} = \sum_{road-types} I_{road-type}\left[in\frac{effect_{road-life}}{road-mi}\right]\times mi$$

$$I_{IO-vehicle-life}^{onroad,road-construction} = I_{IO}^{onroad,road-construction}\times\frac{road-life}{VMT_{vehicle}}\times\frac{VMT}{vehicle-life}$$

$$I_{IO-VMT}^{onroad,road-construction} = I_{IO}^{onroad,road-construction}\times\frac{road-life}{VMT_{vehicle}}$$

$$I_{IO-PMT}^{onroad,road-construction} = I_{IO}^{onroad,road-construction}\times\frac{road-life}{VMT_{vehicle}}\times\frac{VMT_{vehicle}}{PMT_{vehicle}}$$

5.2.2 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). 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

$$DF = DamageFactor = \left(\frac{vehicle-weight}{\#-axles}\right)^4$$

$$DF_{sedan} = \left(\frac{3{,}200lbs}{2}\right)^4 = 6.9\times10^{12}$$

$$DF_{SUV} = \left(\frac{4{,}600lbs}{2}\right)^4 = 2.9\times10^{13}$$

$$DF_{pickup} = \left(\frac{5{,}200lbs}{2}\right)^4 = 4.7\times10^{13}$$

$$DF_{bus} = \left(\frac{25{,}000lbs}{2}\right)^4 = 2.4\times10^{16}$$

$$DF_{freight-truck} = \left(\frac{62{,}000lbs}{5}\right)^4 = 2.3\times10^{16}$$

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 14. As a result, only the maintenance on roadways attributed to bus traffic is considered.

Table 14 - Roadway damage fraction calculations by vehicle and functional class

	Sedan	Pickup	SUV	Van	Motorcycle	Other Bus	Transit Bus	Freight
Interstate (Urban)	0.16%	0.39%	0.26%	0.06%	0.00%	1.60%	0.00%	97.54%
Interstate (Rural)	0.06%	0.15%	0.10%	0.02%	0.00%	1.28%	0.00%	98.39%
Arterial (Urban)	0.33%	0.83%	0.54%	0.12%	0.00%	1.98%	0.00%	96.20%
Arterial (Rural)	0.14%	0.34%	0.22%	0.05%	0.00%	1.35%	0.00%	97.91%
Collector (Urban)	0.33%	0.82%	0.53%	0.12%	0.00%	1.92%	2.99%	93.30%
Collector (Rural)	0.17%	0.42%	0.27%	0.06%	0.00%	3.04%	5.57%	90.48%
Local (Urban)	0.32%	0.79%	0.52%	0.11%	0.00%	1.90%	4.05%	92.31%
Local (Rural)	0.18%	0.44%	0.29%	0.06%	0.00%	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 §5.2.1.

To determine what portion of total maintenance inventory is attributable to bus operations requires use of the damage factors. For every VMT by vehicle type, it is multiplied by the damage factor for the vehicle type to compute total damage. Next, the ratio of bus damage to roadways to total damage is taken and multiplied by the total impact. This yields the portion of inventory attributed on roadways to buses based on damage as shown in Equation Set 8.

Equation Set 8 – Onroad infrastructure roadway maintenance

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

$$I_{IO}^{onroad,road-maintenance} = \sum_{road-types} \left(I_{road-type} \times \frac{D_{bus,road-type}}{D_{all,road-type}} \right)$$

$$I_{IO-vehicle-lifetime}^{onroad,road-maintenance} = I_{IO}^{onroad,road-maintenance} \times \frac{road-life}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{vehicle-life}$$

$$I_{IO-VMT}^{onroad,road-maintenance} = I_{IO}^{onroad,road-maintenance} \times \frac{road-life}{VMT_{vehicle}}$$

$$I_{IO-PMT}^{onroad,road-maintenance} = I_{IO}^{onroad,road-maintenance} \times \frac{road-life}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

5.2.3 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]. 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. VOC emissions are calculated separately using the same methodology described in §5.2.1. The life-cycle impacts of the parking garages are computed as a steel-framed structure based on square-foot estimates [Guggemos 2005].

Figure 4 – Surface lot
Source: http://www.denverinfill.com/

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

$$I_{IO}^{onroad,parking} = Annual\,impact\;\;from\;parking\;construction\,and\,ma\,\mathrm{int}\,enance$$

$$I_{IO-vehicle-lifetime}^{onroad,parking} = I_{IO}^{onroad,parking} \times share_{VMT,vehicle} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{vehicle-life}$$

$$I_{IO-VMT}^{onroad,parking} = I_{IO}^{onroad,parking} \times share_{VMT,vehicle} \times \frac{yr}{VMT_{vehicle}}$$

$$I_{IO-PMT}^{onroad,parking} = I_{IO}^{onroad,parking} \times share_{VMT,vehicle} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

5.2.4 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 to 2005. 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

$$I_{IO-vehicle-lifetime}^{onroad,road/parking-lighting} = E_{road/parking-lighting,yr} \times \frac{EF_{IO}}{E} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{vehicle-life}$$

$$I_{IO-VMT}^{onroad,road/parking-lighting} = E_{road/parking-lighting,yr} \times \frac{EF_{IO}}{E} \times \frac{yr}{VMT_{vehicle}}$$

$$I_{IO-PMT}^{onroad,road/parking-lighting} = E_{road/parking-lighting,yr} \times \frac{EF_{IO}}{E} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

5.2.5 Herbicides and Salting

Herbicides are routinely used for vegetation management along roadways. The U.S. is the world's largest consumer and producer 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 8% of U.S. herbicide consumption. This amounted to $792M (in $2001) in pesticide expenditures. Assuming that herbicide use was split evenly among the commercial, industrial, and government sectors 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).

Over 70% of U.S. roadways are in potential snow and ice regions 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].

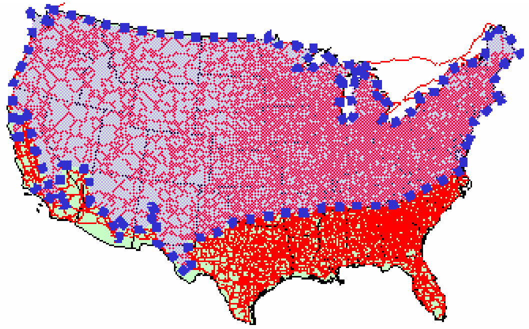


Figure 5 – Roadways in potential snow regions
Source: FHWA 2007

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 EIOLCA 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 EIOLCA 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

$$I_{IO}^{onroad,herbicide/salting} = \text{herbicide or salt production impact in 2005}$$

$$I_{IO-vehicle-lifetime}^{onroad,herbicide/salting} = I_{IO}^{onroad,herbicide/salting} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{vehicle-life}$$

$$I_{IO-VMT}^{onroad,herbicide/salting} = I_{IO-EIOLCA}^{onroad,herbicide/salting} \times \frac{yr}{VMT_{vehicle}}$$

$$I_{IO-PMT}^{onroad,herbicide/salting} = I_{IO-EIOLCA}^{onroad,herbicide/salting} \times \frac{yr}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

5.2.6 Infrastructure Results

Table 15 - Onroad infrastructure results to sedans

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
I, Roadway Construction	Energy	140 GJ	740 kJ	470 kJ
	GHG	9.7 mt GGE	52 g GGE	33 g GGE
	SO_2	17 kg	88 mg	56 mg
	CO	28 kg	150 mg	93 mg
	NO_X	54 kg	290 mg	180 mg
	VOC	98 kg	520 mg	330 mg
	PM_{10}	180 kg	980 mg	620 mg
	Pb	0.00076 kg	0.0041 mg	0.0026 mg
I, Roadway Maintenance	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	PM_{10}	-	-	-
	Pb	-	-	-
I, Herbicides / Salting	Energy	1.8 GJ	9.3 kJ	5.9 kJ
	GHG	0.000019 mt GGE	0.00010 g GGE	0.000065 g GGE
	SO_2	0.0025 kg	0.013 mg	0.0083 mg
	CO	0.00014 kg	0.00074 mg	0.00047 mg
	NO_X	0.00026 kg	0.0014 mg	0.00086 mg
	VOC	0.000093 kg	0.00050 mg	0.00031 mg
	PM_{10}	-	-	-
	Pb	0.000100 kg	0.00053 mg	0.00034 mg
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	7.7 GJ	41 kJ	26 kJ
	GHG	1.6 mt GGE	8.5 g GGE	5.4 g GGE
	SO_2	38 kg	200 mg	130 mg
	CO	10 kg	54 mg	34 mg
	NO_X	16 kg	84 mg	53 mg
	VOC	4.9 kg	26 mg	16 mg
	PM_{10}	14 kg	72 mg	46 mg
	Pb	0.000099 kg	0.00053 mg	0.00033 mg

Table 16 - Onroad infrastructure results to SUVs

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
I, Roadway Construction	Energy	130 GJ	740 kJ	420 kJ
	GHG	8.9 mt GGE	52 g GGE	30 g GGE
	SO_2	15 kg	88 mg	51 mg
	CO	25 kg	150 mg	84 mg
	NO_X	49 kg	290 mg	160 mg
	VOC	90 kg	520 mg	300 mg
	PM_{10}	170 kg	980 mg	560 mg
	Pb	0.00070 kg	0.0041 mg	0.0023 mg
I, Roadway Maintenance	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	PM_{10}	-	-	-
	Pb	-	-	-
I, Herbicides / Salting	Energy	1.8 GJ	10 kJ	5.9 kJ
	GHG	0.000019 mt GGE	0.00011 g GGE	0.000065 g GGE
	SO_2	0.0025 kg	0.014 mg	0.0083 mg
	CO	0.00014 kg	0.00082 mg	0.00047 mg
	NO_X	0.00026 kg	0.0015 mg	0.00086 mg
	VOC	0.000094 kg	0.00054 mg	0.00031 mg
	PM_{10}	-	-	-
	Pb	0.00010 kg	0.00058 mg	0.00033 mg
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	7.1 GJ	41 kJ	24 kJ
	GHG	1.5 mt GGE	8.5 g GGE	4.9 g GGE
	SO_2	35 kg	200 mg	120 mg
	CO	9.4 kg	54 mg	31 mg
	NO_X	14 kg	84 mg	48 mg
	VOC	4.5 kg	26 mg	15 mg
	PM_{10}	12 kg	72 mg	42 mg
	Pb	0.000091 kg	0.00053 mg	0.00030 mg

Table 17 - Onroad infrastructure results to pickups

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
I, Roadway Construction	Energy	130 GJ	740 kJ	500 kJ
	GHG	8.9 mt GGE	52 g GGE	36 g GGE
	SO_2	15 kg	88 mg	61 mg
	CO	25 kg	150 mg	100 mg
	NO_X	49 kg	290 mg	200 mg
	VOC	90 kg	520 mg	360 mg
	PM_{10}	170 kg	980 mg	670 mg
	Pb	0.00070 kg	0.0041 mg	0.0028 mg
I, Roadway Maintenance	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	PM_{10}	-	-	-
	Pb	-	-	-
I, Herbicides / Salting	Energy	1.8 GJ	10 kJ	7.0 kJ
	GHG	0.000019 mt GGE	0.00011 g GGE	0.000077 g GGE
	SO_2	0.0025 kg	0.014 mg	0.0098 mg
	CO	0.00014 kg	0.00082 mg	0.00056 mg
	NO_X	0.00026 kg	0.0015 mg	0.0010 mg
	VOC	0.000094 kg	0.00054 mg	0.00037 mg
	PM_{10}	-	-	-
	Pb	0.00010 kg	0.00058 mg	0.00040 mg
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	7.1 GJ	41 kJ	28 kJ
	GHG	1.5 mt GGE	8.5 g GGE	5.8 g GGE
	SO_2	35 kg	200 mg	140 mg
	CO	9.4 kg	54 mg	37 mg
	NO_X	14 kg	84 mg	58 mg
	VOC	4.5 kg	26 mg	18 mg
	PM_{10}	12 kg	72 mg	50 mg
	Pb	0.000091 kg	0.00053 mg	0.00036 mg

Table 18 - Onroad infrastructure results to urban buses

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
I, Roadway Construction	Energy	360 GJ	730 kJ	69 kJ
	GHG	26 mt GGE	52 g GGE	4.9 g GGE
	SO_2	42 kg	84 mg	8.0 mg
	CO	69 kg	140 mg	13 mg
	NO_X	140 kg	270 mg	26 mg
	VOC	660 kg	1,300 mg	120 mg
	PM_{10}	460 kg	920 mg	88 mg
	Pb	0.0020 kg	0.0039 mg	0.00037 mg
I, Roadway Maintenance	Energy	110 GJ	210 kJ	20 kJ
	GHG	5.4 mt GGE	11 g GGE	1.0 g GGE
	SO_2	1,500 kg	3,000 mg	290 mg
	CO	20 kg	39 mg	3.7 mg
	NO_X	84 kg	170 mg	16 mg
	VOC	-	-	-
	PM_{10}	26 kg	52 mg	4.9 mg
	Pb	0.00084 kg	0.0017 mg	0.00016 mg
I, Herbicides / Salting	Energy	4.7 GJ	9.4 kJ	0.89 kJ
	GHG	0.000052 mt GGE	0.00010 g GGE	0.0000098 g GGE
	SO_2	0.0066 kg	0.013 mg	0.0013 mg
	CO	0.00037 kg	0.00075 mg	0.000071 mg
	NO_X	0.00068 kg	0.0014 mg	0.00013 mg
	VOC	0.00025 kg	0.00050 mg	0.000048 mg
	PM_{10}	-	-	-
	Pb	0.00027 kg	0.00053 mg	0.000051 mg
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

5.3 Fuel Production (Gasoline and Diesel)

5.3.1 Onroad fuels production

The life-cycle inventory for gasoline and diesel fuel production is calculated using EIOLCA. The Petroleum Refineries (#324110) economic sector is an accurate representation of the petroleum refining process. Table 19 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 19 - 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)	24	28	17	16
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	81,000

Using the cost of fuel and the lifetime gallons consumed, a total lifetime cost is determined. This is then input into EIOLCA for environmental inventory. The EIOLCA 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 EIOLCA.

Equation Set 12 – Onroad fuel production

$$I_{IO-vehicle-lifetime}^{onroad,\,fuel-production} = I_{IO}^{onroad,\,fuel-production} = \text{Production Impact determined from EIOLCA}$$

$$I_{IO-VMT}^{onroad,\,fuel-production} = I_{IO}^{onroad,\,fuel-production} \times \frac{vehicle-life}{VMT_{vehicle}}$$

$$I_{IO-PMT}^{onroad,\,fuel-production} = I_{IO}^{onroad,\,fuel-production} \times \frac{vehicle-life}{VMT_{vehicle}} \times \frac{VMT_{vehicle}}{PMT_{vehicle}}$$

5.3.2 Onroad fuel production results

Table 20 - Onroad fuel production for sedans

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
F, Petroleum Refining	Energy	85 GJ	450 kJ	290 kJ
	GHG	0.0022 mt GGE	0.012 g GGE	0.0075 g GGE
	SO_2	340 kg	1,800 mg	1,200 mg
	CO	21 kg	110 mg	72 mg
	NO_X	30 kg	160 mg	100 mg
	VOC	12 kg	66 mg	42 mg
	PM_{10}	-	-	-
	Pb	14 kg	74 mg	47 mg

Table 21 - Onroad fuel production for SUVs

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
F, Petroleum Refining	Energy	130 GJ	750 kJ	430 kJ
	GHG	0.0033 mt GGE	0.019 g GGE	0.011 g GGE
	SO_2	520 kg	3,000 mg	1,700 mg
	CO	32 kg	190 mg	110 mg
	NO_X	46 kg	270 mg	150 mg
	VOC	19 kg	110 mg	63 mg
	PM_{10}	-	-	-
	Pb	21 kg	120 mg	70 mg

Table 22 - Onroad fuel production for pickups

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
F, Petroleum Refining	Energy	140 GJ	790 kJ	540 kJ
	GHG	0.0035 mt GGE	0.021 g GGE	0.014 g GGE
	SO_2	550 kg	3,200 mg	2,200 mg
	CO	34 kg	200 mg	140 mg
	NO_X	49 kg	280 mg	190 mg
	VOC	20 kg	120 mg	80 mg
	PM_{10}	-	-	-
	Pb	22 kg	130 mg	88 mg

Table 23 - Onroad fuel production for urban buses

Life-Cycle Component	I/O	per Vehicle-Life	per VMT	per PMT
F, Petroleum Refining	Energy	980 GJ	2,000 kJ	190 kJ
	GHG	0.025 mt GGE	0.051 g GGE	0.0048 g GGE
	SO_2	3,900 kg	7,900 mg	750 mg
	CO	250 kg	490 mg	47 mg
	NO_X	350 kg	700 mg	67 mg
	VOC	140 kg	290 mg	27 mg
	PM_{10}	-	-	-
	Pb	160 kg	320 mg	30 mg

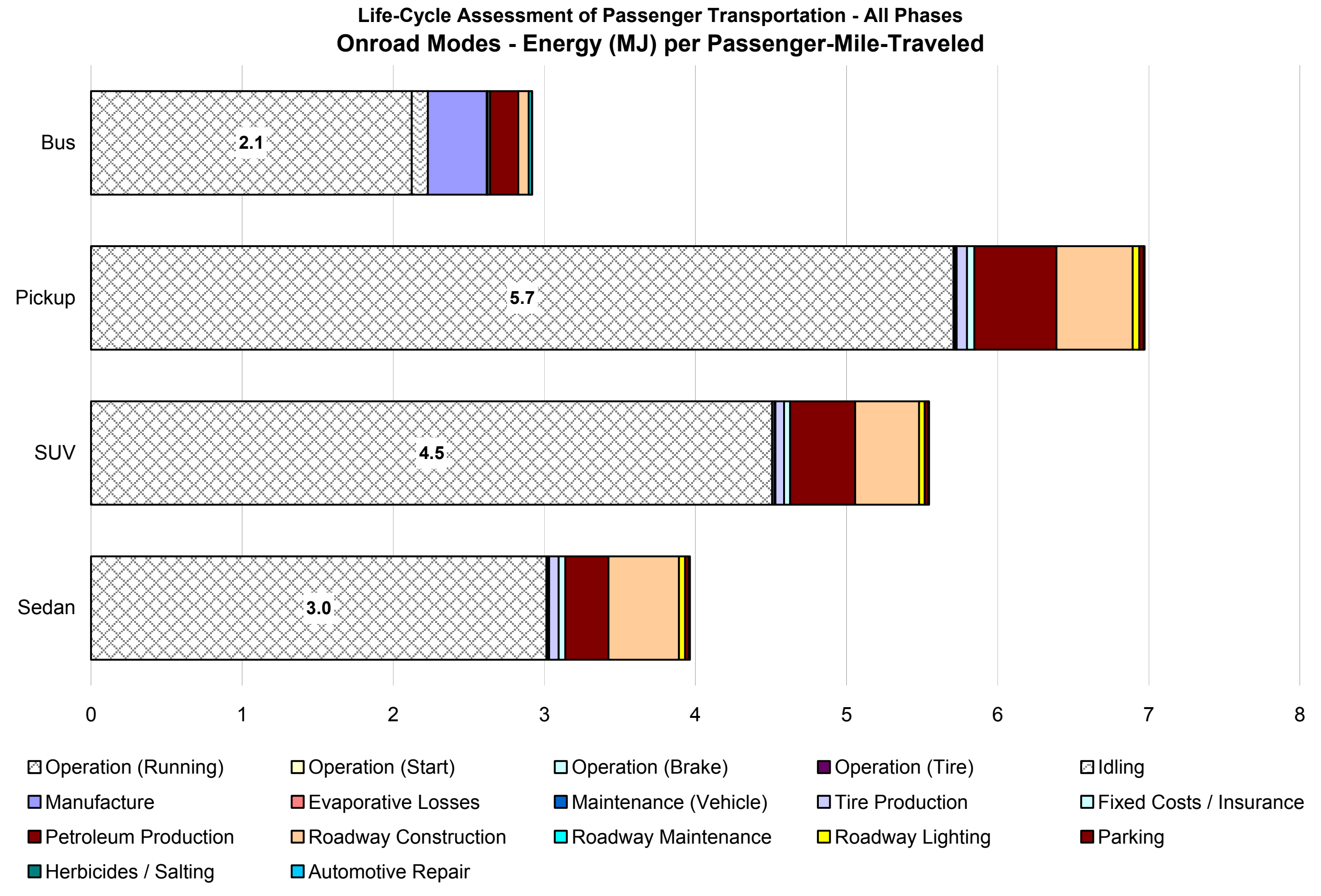
5.4 *Onroad Summary*

While non-operational environmental results show themselves in the onroad life-cycle assessment, it is not necessarily apparent where these results originate. In this section, key findings are discussed including the root of their causes.

5.4.1 Energy and Greenhouse Gas 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 attribution of these components increases energy consumption and GHG emission per PMT by 10% to 40%.

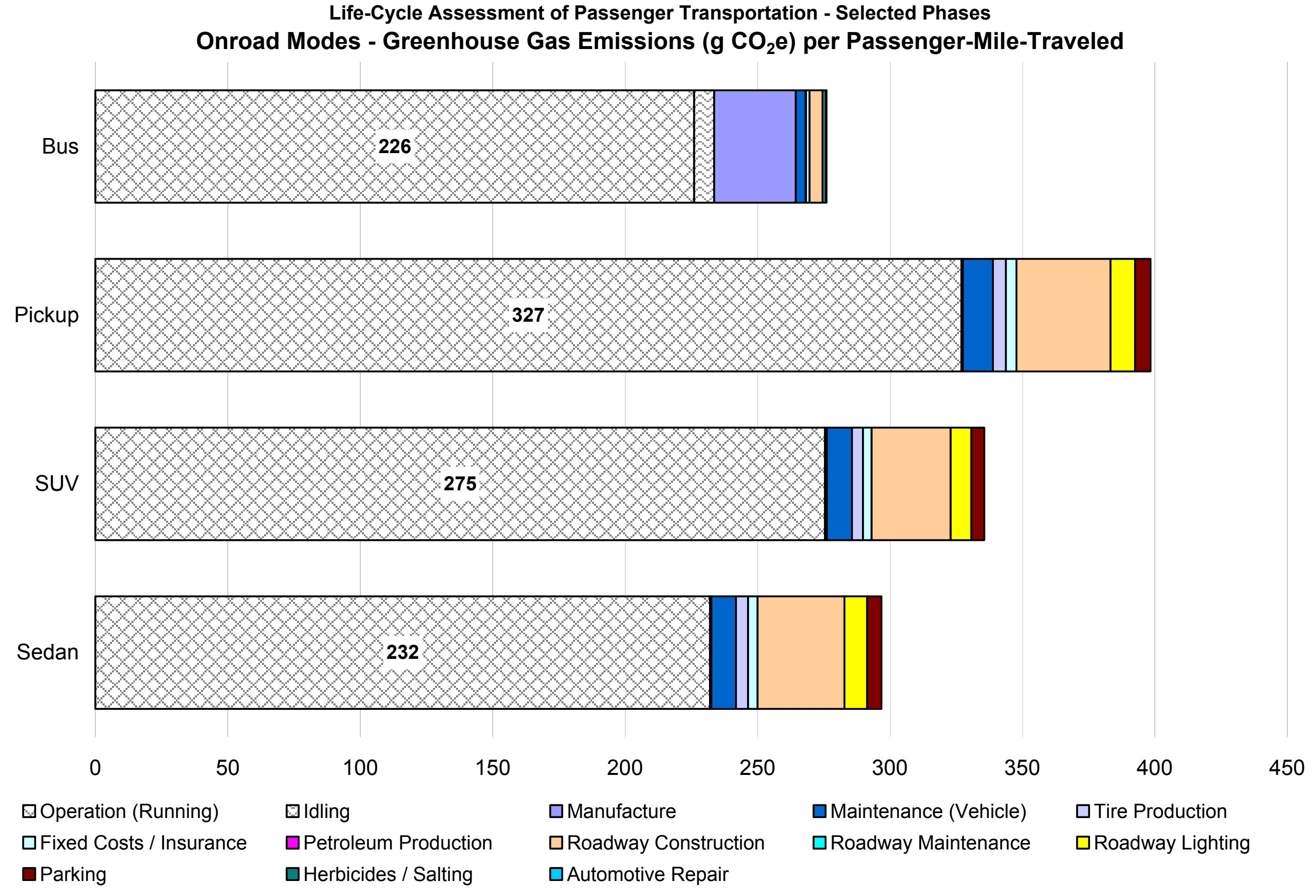
Table 24 - Onroad energy inventory



<u>Vehicle Manufacturing</u>

The large energy requirements to manufacture an urban bus have significant effects when normalized over the lifetime of the vehicle. The energy, and resulting GHG emissions, is the result of not just direct manufacturing but also the production of motor vehicle parts and the steel that goes in them. While the bus consumes 2.1 MJ/PMT in direct operational diesel fuel combustion, an additional 0.4 MJ/PMT are the result of vehicle manufacturing (bus factors are based on an average occupancy of 10.5 passengers). For GHG emissions, vehicle manufacturing accounts for 21 g CO_2e/PMT out of the total 276 g CO_2e/PMT.

Table 25 - Onroad GHG inventory



Vehicle Maintenance

The effects of vehicle maintenance are shown in the GHG inventory 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 [EIOLCA]. While vehicle maintenance does not show as largely for the bus, it accounts for between 3% and 6% of total automobile emission (11 to 15 g CO_2e/PMT).

Roadway Construction and Maintenance

Construction and operation of roadways is the most significant contributor to the life-cycle energy and GHG inventory. The impact of roadways affects all four modes but most significantly the automobiles which are attributed a larger share of construction 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].

Roadway Lighting

The consumption of over 200,000 TJ of electricity to light roadways and parking lots in 2001 and the GHG emissions to product 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.

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 so burdens on the 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 §5.3, 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 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.

5.4.2 Criteria Air Pollutants

The CAP per vehicle type is shown in Table 26. The life-cycle effects of certain components actually constitute the bulk of emissions which is contrary to dominating tail-pipe expectations. 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 §5.1.2, 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. The inclusion of this property shows in the vehicle inventory for these three pollutants as large fractions of total emissions. It is most strongly felt with CO where cold start emissions are 65% to 80% as large as running emissions.

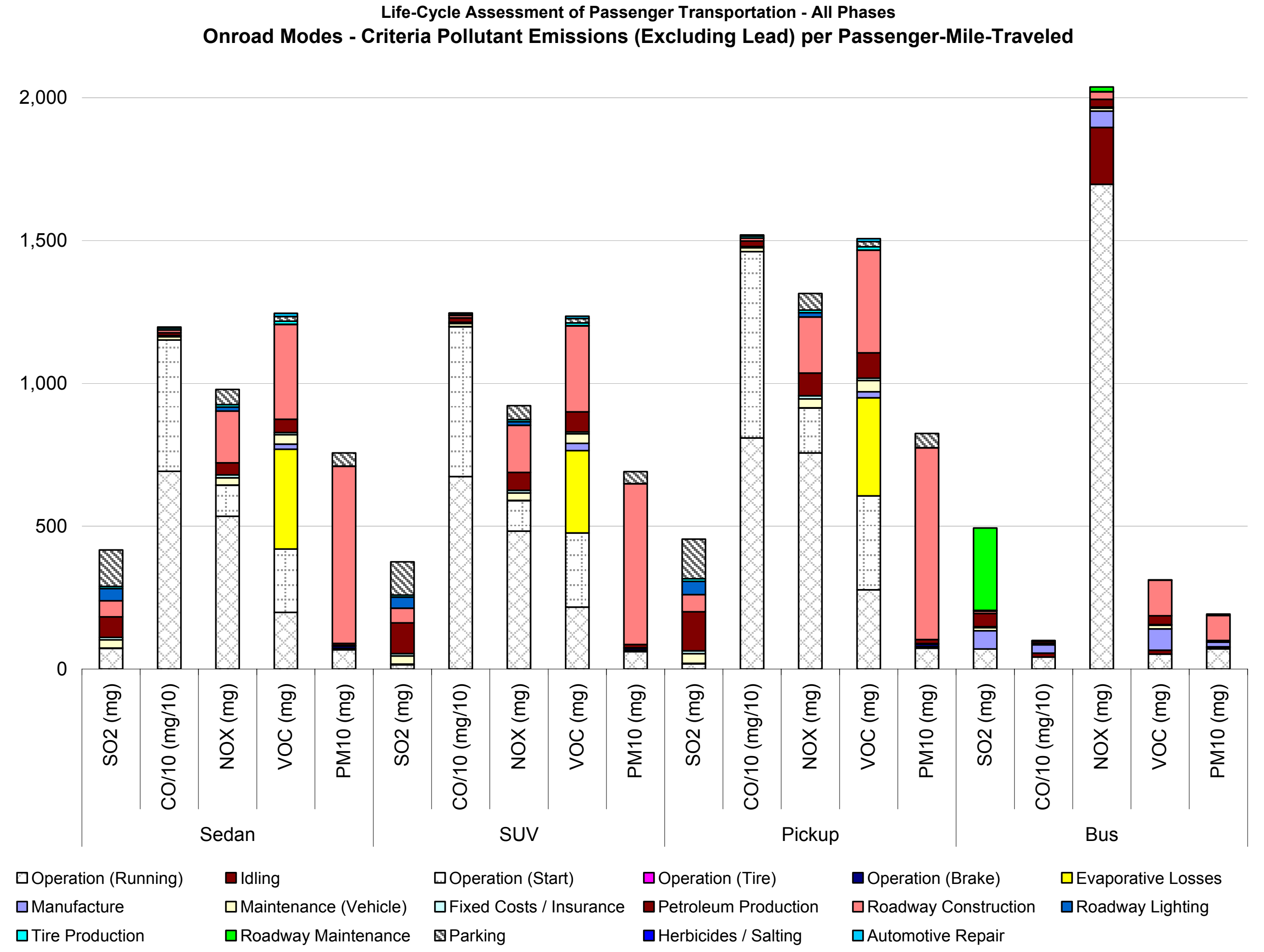
Evaporative Losses

Evaporative losses, primarily from running, resting, and hot soak, contribute heavily to total VOC emissions from automobiles. These emissions constitute 36% to 45% of total operation VOC emissions, the largest is with 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 [EIOLCA]

Table 26 - Onroad criteria air pollutants inventory



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 almost as large (for the sedan) or over 3 times larger (for the SUV and pickup) than tail-pipe emissions. NO_X emissions in this component are responsible for 160 to 200 mg/PMT of the 1,000 to 1,300 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 §5.2.1, are emitted when the diluent in the asphalt mix volatilizes during placement. These emissions are about 25% of total automobile VOC emissions and about 50% of bus emissions. The fugitive dust emissions during asphalt placement overwhelm tailpipe PM_{10} emissions for the automobile modes. Roadway construction emissions are 10 times larger than tail-pipe emissions for the automobile.

Roadway Lighting

SO_2, from the production of fossil fuel derived electricity, shows in the automobile inventories. Lighting SO_2 is over 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 as attributed to the damage from urban bus travel overwhelms operational emissions. The origin of the SO_2 emissions is the production of hot-mix asphalt at the plant. Roadway maintenance SO_2 emissions for buses is 290 mg/PMT as compared to the 70 g/PMT released in diesel fuel combustion

Parking Construction and Maintenance

Similar to roadway construction, parking construction and maintenance strong 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 much smaller (yet still significant).

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. For sedans, the contribution from petroleum production is as large as tail-pipe SO_2 emissions. For SUVs and pickups, it is 7 times larger than tail-pipe emissions. NO_X is also the result of electricity generation. VOCs result from both direct refinery emissions as well as oil and gas extraction processes [EIOLCA].

Figure 6 – Refinery electricity consumption

Source: http://www.emersonprocess.com/

6 Life-cycle 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 real system which is expected to compete with air 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.

6.1 Vehicles (Trains)

<u>BART</u>

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.

Figure 7 - BART train
Source: http://subwaynut.com/

<u>Muni</u>

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]

<u>Caltrain</u>

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.

Figure 8 - Caltrain train
Source: http://railroadpictures.net/

<u>Boston Green Line</u>

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].

<u>California High Speed Rail</u>

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].

6.1.1 Manufacturing

To estimate manufacturing energy and emissions, process-based LCA software SimaPro is used [SimaPro]. SimaPro provides data on 3 distinctly different passenger rail vehicles: a light rail system, and 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 27 for manufacturing of a train.

Table 27 – Life-cycle inventory of rail vehicle manufacturing in SimaPro (impacts per train)

		Light Rail Transit (CA Mix)	Light Rail Transit (MA Mix)	High Speed Rail (CA Mix)	Long Distance Rail (CA Mix)
System Representation		Muni Metro	Boston Green Line	CA High Speed Rail	BART, Caltrain
Impact	Unit				
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 ($PM_{2.5 \le d \le 10}$)	kg	440	440	1,900	1,200
Particulate Matter <2.5μ ($PM_{<2.5}$)	kg	240	250	1,200	800
Particulate Matter ≤10μ ($PM_{\le 10}$)	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.

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 263 for High Speed Rail [FTA 2005, CAHSR 2005]

Equation Set 13 - Rail vehicle manufacturing

$$I_{IO}^{rail,vehicle-manufacturing} \times \frac{Weight_{vehicle}}{Weight_{simapro-vehicle}} = \text{Production impact determined from SimaPro}$$

$$I_{IO-train-life}^{rail,vehicle-manufacturing} = I_{IO}^{rail,vehicle-manufacturing}$$

$$I_{IO-PMT}^{rail,vehicle-manufacturing} = I_{IO}^{rail,vehicle-manufacturing} \times \frac{train-lifetime}{PMT_{train}}$$

$$I_{IO-VMT}^{rail,vehicle-manufacturing} = I_{IO}^{rail,vehicle-manufacturing} \times \frac{train-lifetime}{VMT_{train}}$$

6.1.2 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 remains 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 data operational energy consumption 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 given several assessments performed in the late 1970s during the U.S. energy crisis [Fels 1977, 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 1977, 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 1977]. 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 1977].

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 starts 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 28 summarizes the Caltrain operational factors computed from the drive cycles and emission data.

Table 28 - Caltrain operational factors for a train

Inventory Parameter	Active	Idling	Hot Start
Average Fuel Consumption (MJ/VMT)	147	9	10
Average CO_2 Emissions (kg/VMT)	10.1	0.6	0.7
Average SO_2 Emissions (g/VMT)	1.5	0.1	0.1
Average CO Emissions (g/VMT)	9.8	1.4	1.5
Average NO_X Emissions (g/VMT)	190	12	18
Average HC Emissions (g/VMT)	6	2	2
Average PM_{10} Emissions (g/VMT)	5.1	0.5	0.4

The electricity consumption of the proposed California High Speed Rail system is based on several estimates. Using data from the Swedish X2000 high speed rail system (which exhibits similar speeds and ridership to the California proposed system), operational components are broken out. The X2000 consumes 0.075 kWh/PKT in total of which 0.002 kWh/PKT is consumed during idling [Anderrson 2006]. Using similar methodology to Muni, auxiliary electricity consumption is estimated at 0.004 kWh/PKT. This results in a propulsion factor of 0.068 kWh/PKT. Converting to VMT factors, this is 29 kWh/VMT propulsion, 1.4 kWh/VMT idling, and 1.6 kWh/VMT auxiliaries.

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]. Electricity emission factors are reported based on the fuel mix and are shown in Table 29 [Deru 2007].

Table 29 - Electricity generation emission factors by state (per kWh)

	California	Massachusetts
g CO_2e	264	509
mg SO_2	1,411	3,012
mg CO	136	570
mg NO_X	102	670
mg VOC	30	39
µg Pb	2	25
mg PM_{10}	15	30

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

Equation Set 14 - Rail vehicle operation

$$EF = \text{Electricity generation emission factor}$$

$$I_{rail,vehicle,operation,IO-train-life} = \frac{kWh}{VMT} \times \frac{VMT}{train-life} \times \frac{EF}{kWh}$$

$$I_{rail,vehicle,operation,IO-PMT} = \frac{kWh}{VMT} \times \frac{VMT}{PMT} \times \frac{EF}{kWh}$$

$$I_{rail,vehicle,operation,IO-VMT} = \frac{kWh}{VMT} \times \frac{EF}{kWh}$$

6.1.3 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 30 shows the impacts for the three train types and the different mixes.

Table 30 – Life-cycle inventory of rail vehicle maintenance in SimaPro (per train per lifetime)

		Light Rail Transit (CA Mix)	Light Rail Transit (MA Mix)	High Speed Rail (CA Mix)	Long Distance Rail (CA Mix)
System Representation		Muni Metro	Boston Green Line	CA High Speed Rail	BART, Caltrain
Impact	Unit				
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 (routine maintenance)

$$I_{IO}^{rail,vehicle-maintenance} \times \frac{Weight_{vehicle}}{Weight_{simapro-vehicle}} = \text{Maintenance Impact determined from SimaPro}$$

$$I_{IO-train-lifetime}^{rail,vehicle-maintenance} = I_{IO}^{rail,vehicle-maintenance}$$

$$I_{IO-PMT}^{rail,vehicle-maintenance} = I_{IO}^{rail,vehicle-maintenance} \times \frac{train-lifetime}{PMT_{train-life}}$$

$$I_{IO-VMT}^{rail,vehicle-maintenance} = I_{IO}^{rail,vehicle-maintenance} \times \frac{train-lifetime}{VMT_{train-life}}$$

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, BuiLCA]. 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)

$$EF = \text{emission factor (per kWh) for electricity production}$$

$$I_{rail,vehicle,cleaning,IO-train-life} = \frac{kWh}{ft^2-cleaning} \times \frac{ft^2}{train} \times \frac{cleanings}{yr} \times \frac{yr}{train-life} \times EF$$

$$I_{rail,vehicle,cleaning,IO-PMT} = \frac{kWh}{ft^2-cleaning} \times \frac{ft^2}{train} \times \frac{cleanings}{yr} \times \frac{yr}{PMT_{train}} \times EF$$

$$I_{rail,vehicle,cleaning,IO-VMT} = \frac{kWh}{ft^2-cleaning} \times \frac{ft^2}{train} \times \frac{cleanings}{yr} \times \frac{yr}{VMT_{train}} \times EF$$

Two floor types are considered for the 5 systems: carpet and plastic composite. The replacement of carpet (BART, Caltrain, California HSR) 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 [EIOLCA]. Using the flooring replacement costs and vehicle dimensions, yearly replacement costs are determined. Using the EIOLCA sector Carpet and Rug Mills (#314110) and Resilient Floor Covering Manufacturing (#326192), total impacts are computed.

Equation Set 17 - Rail vehicle maintenance (flooring replacement)

$$EF = \text{emission factor (per \$) for flooring material production determined from EIOLCA}$$

$$I_{rail,vehicle,flooring,IO-train-life} = \frac{\cos t_{replacement}}{yr} \times \frac{yr}{train-life} \times EF$$

$$I_{rail,vehicle,flooring,IO-PMT} = \frac{\cos t_{replacement}}{yr} \times \frac{yr}{PMT_{train}} \times EF$$

$$I_{rail,vehicle,flooring,IO-VMT} = \frac{\cos t_{replacement}}{yr} \times \frac{yr}{VMT_{train}} \times EF$$

6.1.4 Insurance

Insurance remains a significant portion of system operating costs covering operator health and casualty/liability with regards to the vehicles. To provide this insurance, buildings are constructed, office operations are performed, energy is consumed, and emissions are produced. The EIOLCA 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 31.

Table 31 – Rail vehicle insurance costs ($\$_{2005}$/yr-train)

	BART	Caltrain	Muni	Boston T	High Speed
Operator Health	22,000	17,000	31,000	100,000	310,000
Vehicle Casualty and Liability	48,000	37,000	39,000	60,000	390,000

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 (as discussed in §6.2.7). 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 31. Again, using the EIOLCA 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

$$EF = \text{emission factor (per \$) for insurance services determined from EIOLCA}$$

$$\alpha = \text{fraction of total insurance cost attributable to vehicles}$$

$$I_{rail,vehicle,insurance,IO-train-life} = \frac{total - \cos t}{yr} \times \alpha \times \frac{yr}{train - life} \times EF$$

$$I_{rail,vehicle,flooring,IO-PMT} = \frac{total - \cos t}{yr} \times \alpha \times \frac{yr}{PMT} \times EF$$

$$I_{rail,vehicle,flooring,IO-VMT} = \frac{total - \cos t}{yr} \times \alpha \times \frac{yr}{VMT} \times EF$$

6.1.5 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 32 summarizes these factors for each system.

Table 32 - Rail vehicle performance data

	BART	Caltrain	Muni	Boston T	High Speed
Vehicle Lifetime	26	30	27	27	30
Annual VMT (2005) in 10^6	8.6	5.5	1.3	3.3	22
Annual PMT (2005) in 10^6	1,300	120	200	180	14,000

Table 33 - BART vehicle inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Manufacture	Energy	140 TJ	42 MJ	0.29 MJ
	GHG	12,000 mt GGE	3,600 g GGE	25 g GGE
	SO_2	51,000 kg	15,000 mg	100 mg
	CO	130,000 kg	39,000 mg	270 mg
	NO_X	29,000 kg	8,400 mg	57 mg
	VOC	21,000 kg	6,200 mg	42 mg
	Pb	42 kg	12 mg	84 µg
	PM_{10}	11,000 kg	3,100 mg	22,000 µg
V, Operation (Active)	Energy	350 TJ	100 MJ	0.69 MJ
	GHG	25,000 mt GGE	7,400 g GGE	51 g GGE
	SO_2	140,000 kg	39,000 mg	270 mg
	CO	13,000 kg	3,800 mg	26 mg
	NO_X	9,800 kg	2,800 mg	20 mg
	VOC	2,900 kg	850 mg	5.8 mg
	Pb	0.18 kg	0.051 mg	0.35 µg
	PM_{10}	1,500 kg	430 mg	2,900 µg
V, Operation (Idling)	Energy	180 TJ	51 MJ	0.35 MJ
	GHG	13,000 mt GGE	3,800 g GGE	26 g GGE
	SO_2	69,000 kg	20,000 mg	140 mg
	CO	6,600 kg	1,900 mg	13 mg
	NO_X	5,000 kg	1,400 mg	10.0 mg
	VOC	1,500 kg	430 mg	3.0 mg
	Pb	0.090 kg	0.026 mg	0.18 µg
	PM_{10}	750 kg	220 mg	1,500 µg
V, Operation (HVAC)	Energy	48 TJ	14 MJ	0.096 MJ
	GHG	3,500 mt GGE	1,000 g GGE	7.0 g GGE
	SO_2	19,000 kg	5,500 mg	38 mg
	CO	1,800 kg	530 mg	3.6 mg
	NO_X	1,400 kg	390 mg	2.7 mg
	VOC	400 kg	120 mg	0.81 mg
	Pb	0.024 kg	0.0071 mg	0.049 µg
	PM_{10}	200 kg	59 mg	410 µg
V, Maintenance	Energy	7.2 TJ	2.1 MJ	0.014 MJ
	GHG	620 mt GGE	180 g GGE	1.3 g GGE
	SO_2	2,500 kg	740 mg	5.1 mg
	CO	6,700 kg	2,000 mg	13 mg
	NO_X	1,400 kg	420 mg	2.9 mg
	VOC	1,100 kg	310 mg	2.1 mg
	Pb	2.1 kg	0.61 mg	4.2 µg
	PM_{10}	540 kg	160 mg	1,100 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 34 - Caltrain vehicle inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Manufacture	Energy	25 TJ	20 MJ	0.13 MJ
	GHG	1,500 mt GGE	1,200 g GGE	8.0 g GGE
	SO_2	5,800 kg	4,700 mg	30 mg
	CO	1,700 kg	1,400 mg	9.2 mg
	NO_X	3,200 kg	2,600 mg	17 mg
	VOC	800 kg	640 mg	4.2 mg
	Pb	6.6 kg	5.4 mg	35 µg
	PM_{10}	1,600 kg	1,300 mg	8,400 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	1,700 kg	1,400 mg	9.1 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	230 kg	190 mg	1.2 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	93 kg	75 mg	0.49 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	21 TJ	17 MJ	0.11 MJ
	GHG	940 mt GGE	760 g GGE	4.9 g GGE
	SO_2	2,600 kg	2,100 mg	14 mg
	CO	2,300 kg	1,900 mg	12 mg
	NO_X	2,200 kg	1,800 mg	11 mg
	VOC	3,400 kg	2,700 mg	18 mg
	Pb	9.1 kg	7.4 mg	48 µg
	PM_{10}	650 kg	530 mg	3,400 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
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 35 – 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	2,000 mt GGE	1,200 g GGE	54 g GGE
	SO_2	11,000 kg	6,300 mg	290 mg
	CO	1,000 kg	600 mg	28 mg
	NO_X	780 kg	450 mg	21 mg
	VOC	230 kg	130 mg	6.2 mg
	Pb	0.014 kg	0.0081 mg	0.37 µg
	PM_{10}	120 kg	68 mg	3,100 µg
V, Operation (Idling)	Energy	14 TJ	8.2 MJ	0.37 MJ
	GHG	1,000 mt GGE	600 g GGE	27 g GGE
	SO_2	5,500 kg	3,200 mg	150 mg
	CO	530 kg	310 mg	14 mg
	NO_X	400 kg	230 mg	11 mg
	VOC	120 kg	69 mg	3.1 mg
	Pb	0.0071 kg	0.0041 mg	0.19 µg
	PM_{10}	60 kg	35 mg	1,600 µg
V, Operation (HVAC)	Energy	4.8 TJ	2.8 MJ	0.13 MJ
	GHG	350 mt GGE	210 g GGE	9.4 g GGE
	SO_2	1,900 kg	1,100 mg	50 mg
	CO	180 kg	110 mg	4.8 mg
	NO_X	140 kg	79 mg	3.6 mg
	VOC	41 kg	24 mg	1.1 mg
	Pb	0.0024 kg	0.0014 mg	0.065 µg
	PM_{10}	20 kg	12 mg	540 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
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 36 - 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
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 37 - CAHSR vehicle inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
V, Manufacture	Energy	44 TJ	0.0044 MJ	0.000017 MJ
	GHG	2,100 mt GGE	0.22 g GGE	0.00082 g GGE
	SO_2	10,000 kg	1.0 mg	0.0039 mg
	CO	8,400 kg	0.85 mg	0.0032 mg
	NO_X	5,600 kg	0.57 mg	0.0022 mg
	VOC	1,700 kg	0.17 mg	0.00066 mg
	Pb	25 kg	0.0026 mg	0.0097 µg
	PM_{10}	3,100 kg	0.32 mg	1.2 µg
V, Operation (Active)	Energy	1,000,000 TJ	100 MJ	0.39 MJ
	GHG	75,000,000 mt GGE	7,600 g GGE	29 g GGE
	SO_2	400,000,000 kg	40,000 mg	150 mg
	CO	38,000,000 kg	3,900 mg	15 mg
	NO_X	29,000,000 kg	2,900 mg	11 mg
	VOC	8,600,000 kg	870 mg	3.3 mg
	Pb	520 kg	0.053 mg	0.20 µg
	PM_{10}	4,300,000 kg	440 mg	1,700 µg
V, Operation (Idling)	Energy	51,000 TJ	5.2 MJ	0.020 MJ
	GHG	3,800,000 mt GGE	380 g GGE	1.4 g GGE
	SO_2	20,000,000 kg	2,000 mg	7.7 mg
	CO	1,900,000 kg	200 mg	0.74 mg
	NO_X	1,400,000 kg	150 mg	0.56 mg
	VOC	430,000 kg	44 mg	0.17 mg
	Pb	26 kg	0.0026 mg	0.010 µg
	PM_{10}	220,000 kg	22 mg	84 µg
V, Operation (HVAC)	Energy	55,000 TJ	5.6 MJ	0.021 MJ
	GHG	4,100,000 mt GGE	410 g GGE	1.6 g GGE
	SO_2	22,000,000 kg	2,200 mg	8.3 mg
	CO	2,100,000 kg	210 mg	0.80 mg
	NO_X	1,600,000 kg	160 mg	0.60 mg
	VOC	470,000 kg	47 mg	0.18 mg
	Pb	28 kg	0.0028 mg	0.011 µg
	PM_{10}	230,000 kg	24 mg	90 µg
V, Maintenance	Energy	28 TJ	0.0028 MJ	0.000011 MJ
	GHG	1,300 mt GGE	0.13 g GGE	0.00051 g GGE
	SO_2	1,200 kg	0.12 mg	0.00046 mg
	CO	2,600 kg	0.26 mg	0.00100 mg
	NO_X	2,500 kg	0.26 mg	0.00098 mg
	VOC	4,000 kg	0.41 mg	0.0015 mg
	Pb	1.8 kg	0.00019 mg	0.00071 µg
	PM_{10}	390 kg	0.039 mg	0.15 µg
V, Maintenance (Cleaning)	Energy	0.12 TJ	0.000012 MJ	0.000000045 MJ
	GHG	8.5 mt GGE	0.00086 g GGE	0.0000033 g GGE
	SO_2	46 kg	0.0046 mg	0.000018 mg
	CO	4.4 kg	0.00044 mg	0.0000017 mg
	NO_X	3.3 kg	0.00033 mg	0.0000013 mg
	VOC	0.98 kg	0.000099 mg	0.00000038 mg
	Pb	0.000059 kg	0.0000000060 mg	0.000000023 µg
	PM_{10}	0.49 kg	0.000050 mg	0.00019 µg
V, Maintenance (Flooring)	Energy	1.8 TJ	0.00019 MJ	0.00000071 MJ
	GHG	140 mt GGE	0.015 g GGE	0.000056 g GGE
	SO_2	260 kg	0.027 mg	0.00010 mg
	CO	1,400 kg	0.14 mg	0.00053 mg
	NO_X	260 kg	0.027 mg	0.00010 mg
	VOC	240 kg	0.024 mg	0.000091 mg
	Pb	0.13 kg	0.000013 mg	0.000049 µg
	PM_{10}	91 kg	0.0092 mg	0.035 µg
V, Insurance (Employees)	Energy	7.9 TJ	0.00080 MJ	0.0000030 MJ
	GHG	640 mt GGE	0.065 g GGE	0.00025 g GGE
	SO_2	1,600 kg	0.16 mg	0.00061 mg
	CO	7,100 kg	0.72 mg	0.0028 mg
	NO_X	1,800 kg	0.18 mg	0.00069 mg
	VOC	1,300 kg	0.13 mg	0.00051 mg
	Pb	-	-	-
	PM_{10}	340 kg	0.034 mg	0.13 µg
V, Insurance (Vehicles)	Energy	9.8 TJ	0.00099 MJ	0.0000038 MJ
	GHG	810 mt GGE	0.081 g GGE	0.00031 g GGE
	SO_2	2,000 kg	0.20 mg	0.00076 mg
	CO	8,900 kg	0.90 mg	0.0034 mg
	NO_X	2,200 kg	0.23 mg	0.00086 mg
	VOC	1,700 kg	0.17 mg	0.00064 mg
	Pb	-	-	-
	PM_{10}	420 kg	0.043 mg	0.16 µg

6.2 Infrastructure (Stations, Tracks, and Insurance)

Rail infrastructure is evaluated by 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.

6.2.1 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.

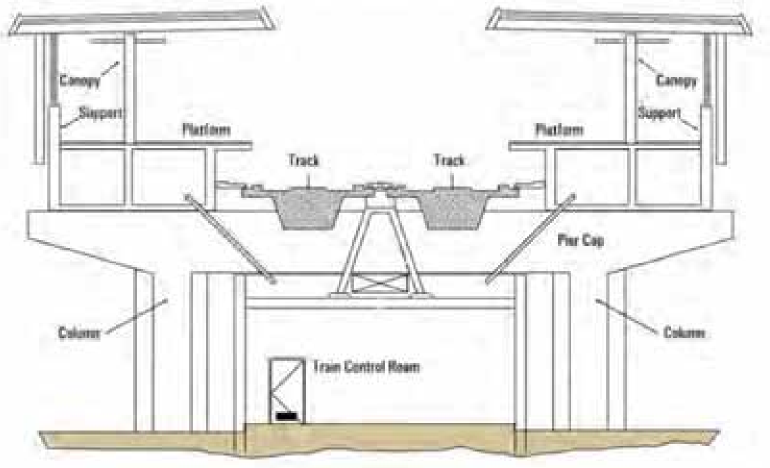


Figure 9 - Typical BART aerial structure
Source: BART 2007e

BART

There are 43 stations in the BART system where 14 are aerial platforms, 13 are surface, and 16 are 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 9. 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.

Caltrain

Caltrain exhibits small station requirements as two platforms are constructed at grade on the side of the tracks (Figure 10). The platforms are constructed 300 ft long and 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).

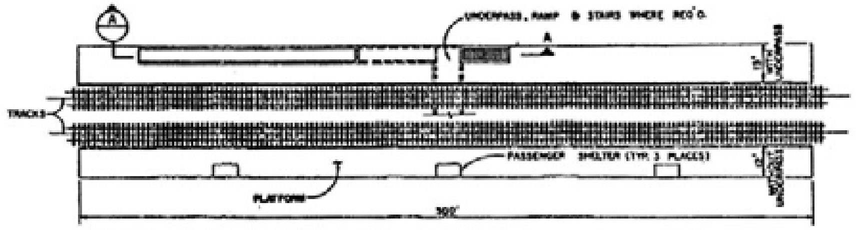


Figure 10 - Typical Caltrain station
Source: Caltrans 1988

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 (Figure 11). 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.

Figure 11 - Typical Muni at-grade station
Source: Muni 2007b

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 §6.2.5). 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 (see Figure 12). 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.

Figure 12 - At-grade Green Line station
Source: Mikhail Chester, 9/2007

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, environmental inventory is determined through a hybrid LCA approach. The inventory includes concrete production, steel rebar production, concrete placement, and aggregate production. Table 38 summarizes the material requirements and their associated costs for each system.

Table 38 - 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 EIOLCA 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. EIOLCA is suitable for estimating the production life-cycle impacts because the material match 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 by to the functional units as shown in Equation Set 19.

Equation Set 19 - Rail infrastructure station construction

$$I_{IO}^{rail,stations} = \text{Construction impact for stations}$$

$$I_{IO-vehicle-lifetime}^{rail,stations} = I_{IO}^{rail,stations} \times \frac{VMT_{train}}{train-life} \times \frac{station-life}{VMT_{station}}$$

$$I_{IO-VMT}^{rail,stations} = I_{IO}^{rail,stations} \times \frac{station-life}{VMT_{station}}$$

$$I_{IO-PMT}^{rail,stations} = I_{IO}^{rail,stations} \times \frac{station-life}{PMT_{station}}$$

6.2.2 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

Figure 13 – BART Lake Merritt station
Source: http://www.ibabuzz.com/

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 such as with the Green Line with only a few lamps on only 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 1977]. 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 tends 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 1977]. 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

$$I^{rail,station-lighting}_{IO-train-life} = \left(Electricity_{aerial+atgrade+underground}\ in\left[\frac{kWh}{station-yr}\right]\right) \times \frac{VMT_{train}}{train-life} \times \frac{yr}{VMT_{system}}$$

$$I^{rail,station-lighting}_{IO-VMT} = \left(Electricity_{aerial+atgrade+underground}\ in\left[\frac{kWh}{station-yr}\right]\right) \times \frac{yr}{VMT_{system}}$$

$$I^{rail,station-lighting}_{IO-PMT} = \left(Electricity_{aerial+atgrade+underground}\ in\left[\frac{kWh}{station-yr}\right]\right) \times \frac{yr}{PMT_{system}}$$

$$Electricity_{aerial+atgrade+underground} = Electricity_{aerial} + Electricity_{atgrade} + Electricity_{underground}$$

$$Electricity_{aerial} = Electricity_{aerial,BART}$$

$$Electricity_{atgrade,caltrain} = Electricity_{atgrade,CAHSR} = Electricity_{atgrade,BART}$$

$$Electricity_{atgrade,Muni} = Electricity_{atgrade,Green\ Line} = \frac{4 lamps}{station} \times \frac{0.15kW}{lamp} \times \frac{12hrs}{day} \times \frac{365days}{yr}$$

$$Electricity_{underground} = Electricity_{underground,BART} \times \alpha \quad where \quad \alpha = \%\,station\ for\ system$$

Escalators

The effect of escalators in a train system is not insignificant accounting for up to 24% of station electricity consumption [Fels 1977]. 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 of escalators is 4.7 kW [EERE 2007].

Equation Set 21 - Rail infrastructure station operation – escalators

$$I_{rail,\inf,station-operation-escalators,IO-train-life} = 4.7kW \times \frac{hrs}{day} \times \frac{days}{yr} \times \frac{VMT}{train-life} \times \frac{yr}{VMT}$$

$$I_{rail,\inf,station-operation-escalators,IO-VMT} = 4.7kW \times \frac{hrs}{day} \times \frac{days}{yr} \times \frac{yr}{VMT}$$

$$I_{rail,\inf,station-operation-escalators,IO-PMT} = 4.7kW \times \frac{hrs}{day} \times \frac{days}{yr} \times \frac{yr}{PMT}$$

Train Control

Systems required for train operation and safety can consume up to 17% of total station electricity consumption [Fels 1977]. Per year, BART consumes 47,000 kWh per mile of track for train control systems [Fels 1977]. 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

$$Electricity_{train-control} = E_{TC} = 47{,}000 \cdot kWh \cdot mi_{track}^{-1} \cdot yr^{-1}$$

$$I_{rail,\inf,station-operation-train\,control,IO-train-life} = E_{TC} \times track\,mileage_{system} \times \frac{VMT}{train-life} \times \frac{yr}{VMT}$$

$$I_{rail,\inf,station-operation-train\,control,IO-VMT} = E_{TC} \times track\,mileage_{system} \times \frac{yr}{VMT}$$

$$I_{rail,\inf,station-operation-train\,control,IO-PMT} = E_{TC} \times track\,mileage_{system} \times \frac{yr}{PMT}$$

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. This results 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 §6.2.4. 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

$$Electricity_{parking-lighting} = E_{PL} = 0.9 \cdot kWh \cdot ft^{-2} \cdot yr^{-1}$$

$$I_{rail,\inf,station-operation-parking-lighting,IO-train-life} = E_{PL} \times ft^{2}_{yr} \times \frac{VMT}{train-life} \times \frac{yr}{VMT}$$

$$I_{rail,\inf,station-operation-parking-lighting,IO-VMT} = E_{PL} \times ft^{2}_{yr} \times \frac{yr}{VMT}$$

$$I_{rail,\inf,station-operation-parking-lighting,IO-PMT} = E_{PL} \times ft^{2}_{yr} \times \frac{yr}{PMT}$$

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 1977]. 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

$$Electricity_{miscellaneous,station-type} = E_{M,s} = kWh \cdot station^{-1} \cdot yr^{-1}$$

$$I_{rail,\inf,station-operation-miscellaneous,IO-train-life} = \sum_{s} \left(E_{M,s} \times \#_{stations} \times \%_{shared} \right) \times \frac{VMT}{train-life} \times \frac{yr}{VMT}$$

$$I_{rail,\inf,station-operation-miscellaneous,IO-VMT} = \sum_{s} \left(E_{M,s} \times \#_{stations} \times \%_{shared} \right) \times \frac{yr}{VMT}$$

$$I_{rail,\inf,station-operation-miscellaneous,IO-PMT} = \sum_{s} \left(E_{M,s} \times \#_{stations} \times \%_{shared} \right) \times \frac{yr}{PMT}$$

Station Operation Inventory

Having computed electricity consumption for each of the operational components, state 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

$$Electricity_{station-operation,component} = E_{s,c} = kWh \cdot unit^{-1} \text{ where unit is train lifetime, VMT, or PMT}$$

$$Emission\,Factor_{state} = EF$$

$$I_{rail,\inf,station-operation-miscellaneous,IO} = E_{s,c} \times EF$$

6.2.3 Station Maintenance and Cleaning

Maintenance of railway stations includes the 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 relived at the end of the facilities life.

Equation Set 26 - Rail infrastructure station maintenance

$$I_{rail,\inf,ma\operatorname{int},IO-train-life}$$

$$= I_{rail,\inf,stations,IO} \times 5\% + (100 - life_{station}) \times \frac{I_{rail,\inf,stations,IO}}{yr} \times \frac{VMT}{train-life} \times \frac{reconstruction-yrs}{VMT}$$

$$I_{rail,\inf,ma\operatorname{int},IO-VMT} = I_{rail,\inf,stations,IO-VMT} \times 5\% + (100 - life_{station}) \times \frac{I_{rail,\inf,stations,IO}}{yr} \times \frac{reconstruction-yrs}{VMT}$$

$$I_{rail,\inf,ma\operatorname{int},IO-PMT} = I_{rail,\inf,stations,IO-PMT} \times 5\% + (100 - life_{station}) \times \frac{I_{rail,\inf,stations,IO}}{yr} \times \frac{reconstruction-yrs}{PMT}$$

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]. 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

$$EF = \text{emission factor for electricity production}$$

$$I_{rail,\inf,cleaning,IO-train-life} = \frac{440{,}000MJ}{m^2-yr} \times \frac{EF}{MJ} \times \frac{m^2}{station} \times \frac{\#stations}{system} \times \frac{VMT}{train-life} \times \frac{system-yr}{VMT}$$

$$I_{rail,\inf,cleaning,IO-VMT} = \frac{440{,}000MJ}{m^2-yr} \times \frac{EF}{MJ} \times \frac{m^2}{station} \times \frac{\#stations}{system} \times \frac{system-yr}{VMT}$$

$$I_{rail,\inf,cleaning,IO-PMT} = \frac{440{,}000MJ}{m^2-yr} \times \frac{EF}{MJ} \times \frac{m^2}{station} \times \frac{\#stations}{system} \times \frac{system-yr}{PMT}$$

6.2.4 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 the 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 39 [SFC

2007b, Caltrain 2004, MBTA 2007]. For CAHSR, it was assumed that 1,000 parking spaces would be constructed at each of the 25 stations.

Table 39 - Rail station parking

	BART	Caltrain	Muni	Boston T	High Speed
Number of Spaces	45,890	7,814	0	2,000	25,000
Parking System Area (ft^2)	15,000,000	2,600,000	0	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 39. 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]. 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

$$I_{IO} = \text{emission factor for system parking area construction and maintenance}$$

$$I_{rail,\inf,parking,IO-train-life} = I_{IO} \times \frac{VMT}{train-life} \times \frac{parking-area-life}{VMT}$$

$$I_{rail,\inf,parking,IO-VMT} = I_{IO} \times \frac{parking-area-life}{VMT}$$

$$I_{rail,\inf,parking,IO-PMT} = I_{IO} \times \frac{parking-area-life}{PMT}$$

6.2.5 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 far more environmentally intensive than other tracks, accurate estimation procedures were not easily identified and therefore excluded for all systems.

<u>BART</u>

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 14) 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 1980's 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.

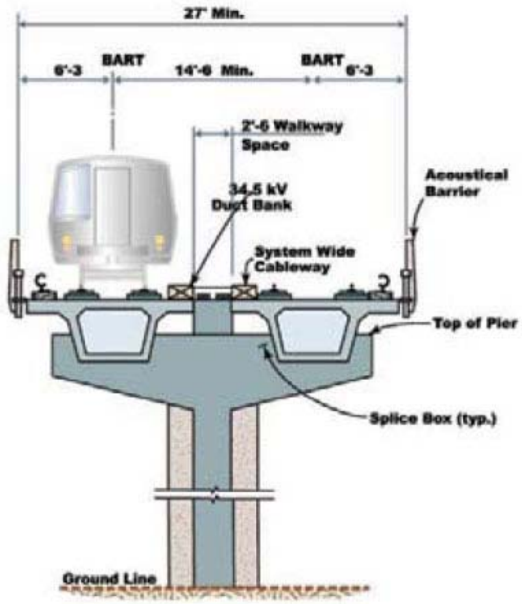


Figure 14 – BART aerial support
Source: SVRTC 2006

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.

Figure 15 – New York City aerial support similar to Green Line

Source: Griest 1915

Muni and 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 theses 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 15, is assigned a weight of 2,250 lbs of steel per linear foot of structure [Griest 1915].

Track Construction Inventory

The total track material requirements are shown in Table 1. 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 EIOLCA 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 EIOLCA, 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 40.

Table 40 - Rail infrastructure track construction material requirements

	BART	Caltrain	Muni	Green Line	CAHSR
Volume of Ballast (10^6 ft^3)	16	29			63
Cost of Ballast ($$M_{1997}$)	1.0	1.9			4.2
Volume of Concrete (10^6 ft^3)	16	2.4			340
Cost of Concrete ($$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 Structure ($$M_{1997}$)	2.0		3.9	2.4	34
Cost of Substations ($$M_{1997}$)	19		1.8	1.1	4,500

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 EIOLCA 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

$$I^{rail,track-construction}_{IO-yearly} = \frac{I^{rail,track-construction}_{IO-lifetime}}{track-lifetime} = \text{Yearly construction impact for tracks determined in EIOLCA}$$

$$I^{rail,track-construction}_{IO-train-lifetime} = I^{rail,track-construction}_{IO-yearly} \times \frac{VMT_{train}}{train-life} \times \frac{year_{system}}{VMT_{system}}$$

$$I^{rail,track-construction}_{IO-VMT} = I^{rail,track-construction}_{IO-yearly} \times \frac{year_{system}}{VMT_{system}}$$

$$I^{rail,track-construction}_{IO-PMT} = I^{rail,track-construction}_{IO-yearly} \times \frac{year_{system}}{VMT_{system}}$$

6.2.6 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 41) [SimaPro]. 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 41 - Rail infrastructure track maintenance SimaPro factors (per meter per year)

		High Speed Rail (CA Mix)
System Representation		CA High Speed Rail
Impact	Unit	
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

$$I_{IO}^{rail,track-maintenance} = \text{Yearly maintenance impact for tracks determined in SimaPro (in meters per year)}$$

$$I_{IO-train-lifetime}^{rail,track-maintenance} = I_{IO}^{rail,track-maintenance} \times \frac{system}{meters_{track}} \times \frac{years}{track-life} \times \frac{VMT_{train}}{train-life} \times \frac{system}{VMT_{system}}$$

$$I_{IO-VMT}^{rail,track-maintenance} = I_{IO}^{rail,track-maintenance} \times \frac{system}{meters_{track}} \times \frac{years}{track-life} \times \frac{system}{VMT_{system}}$$

$$I_{IO-PMT}^{rail,track-maintenance} = I_{IO}^{rail,track-maintenance} \times \frac{system}{meters_{track}} \times \frac{years}{track-life} \times \frac{system}{PMT_{system}}$$

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

$$EF = \text{emission factor (per gallon of fuel) for equipment use}$$

$$I_{IO-train-lifetime}^{rail,track-maintenance} = \frac{gal}{yr} \times EF \times \frac{VMT}{train-life} \times \frac{system-yr}{VMT}$$

$$I_{IO-VMT}^{rail,track-maintenance} = \frac{gal}{yr} \times EF \times \frac{system-yr}{VMT_{system}}$$

$$I_{IO-PMT}^{rail,track-maintenance} = \frac{gal}{yr} \times EF \times \frac{system-yr}{PMT_{system}}$$

6.2.7 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 (§6.1.4), non-vehicle insurances are calculated. These are summarized in Table 42. Equation Set 18 summarizes the framework used for calculating environmental impacts from the insurance infrastructure.

Table 42 – Rail non-vehicle insurance costs ($$_{2005}$/yr-train)

	BART	Caltrain	Muni	Boston T	High Speed
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	1,100,000

6.2.8 Rail Infrastructure Results

Similar to the rail vehicle results (§6.1.5), 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 32.

Table 43 - 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	280 mt GGE	80 g GGE	0.55 g GGE
	SO_2	1,500 kg	430 mg	2.9 mg
	CO	140 kg	41 mg	0.28 mg
	NO_X	110 kg	31 mg	0.21 mg
	VOC	32 kg	9.2 mg	0.063 mg
	Pb	0.0019 kg	0.00056 mg	0.0038 µg
	PM_{10}	16 kg	4.6 mg	32 µg
I, Station Escalators	Energy	0.93 TJ	0.27 MJ	0.0019 MJ
	GHG	68 mt GGE	20 g GGE	0.14 g GGE
	SO_2	370 kg	110 mg	0.73 mg
	CO	35 kg	10 mg	0.070 mg
	NO_X	26 kg	7.7 mg	0.053 mg
	VOC	7.9 kg	2.3 mg	0.016 mg
	Pb	0.00047 kg	0.00014 mg	0.00095 µg
	PM_{10}	4.0 kg	1.2 mg	7.9 µg
I, Station Train Control	Energy	1.6 TJ	0.47 MJ	0.0032 MJ
	GHG	120 mt GGE	34 g GGE	0.24 g GGE
	SO_2	630 kg	180 mg	1.3 mg
	CO	60 kg	18 mg	0.12 mg
	NO_X	45 kg	13 mg	0.090 mg
	VOC	13 kg	3.9 mg	0.027 mg
	Pb	0.00081 kg	0.00024 mg	0.0016 µg
	PM_{10}	6.8 kg	2.0 mg	14 µg
I, Station Parking Lighting	Energy	22 TJ	6.4 MJ	0.044 MJ
	GHG	1,600 mt GGE	470 g GGE	3.2 g GGE
	SO_2	8,700 kg	2,500 mg	17 mg
	CO	830 kg	240 mg	1.7 mg
	NO_X	620 kg	180 mg	1.2 mg
	VOC	190 kg	54 mg	0.37 mg
	Pb	0.011 kg	0.0033 mg	0.023 µg
	PM_{10}	94 kg	27 mg	190 µg
I, Station Miscellaneous	Energy	0.40 TJ	0.12 MJ	0.00079 MJ
	GHG	29 mt GGE	8.5 g GGE	0.058 g GGE
	SO_2	150 kg	45 mg	0.31 mg
	CO	15 kg	4.3 mg	0.030 mg
	NO_X	11 kg	3.3 mg	0.022 mg
	VOC	3.3 kg	0.97 mg	0.0067 mg
	Pb	0.00020 kg	0.000059 mg	0.00040 µg
	PM_{10}	1.7 kg	0.49 mg	3.4 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
I, Station Parking	Energy	22 TJ	6.3 MJ	0.044 MJ
	GHG	1,400 mt GGE	420 g GGE	2.9 g GGE
	SO_2	16,000 kg	4,600 mg	32 mg
	CO	7,300 kg	2,100 mg	15 mg
	NO_X	16,000 kg	4,700 mg	32 mg
	VOC	21,000 kg	6,200 mg	43 mg
	Pb	0.25 kg	0.074 mg	0.51 µg
	PM_{10}	48,000 kg	14,000 mg	96,000 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 44 - Muni infrastructure inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Construction	Energy	0.43 TJ	0.25 MJ	0.011 MJ
	GHG	43 mt GGE	25 g GGE	1.1 g GGE
	SO_2	130 kg	76 mg	3.5 mg
	CO	350 kg	200 mg	9.3 mg
	NO_X	180 kg	100 mg	4.7 mg
	VOC	110 kg	66 mg	3.0 mg
	Pb	0.020 kg	0.012 mg	0.53 µg
	PM_{10}	23 kg	13 mg	610 µg
I, Station Lighting	Energy	8.0 TJ	4.6 MJ	0.21 MJ
	GHG	590 mt GGE	340 g GGE	16 g GGE
	SO_2	3,100 kg	1,800 mg	83 mg
	CO	300 kg	170 mg	8.0 mg
	NO_X	230 kg	130 mg	6.0 mg
	VOC	67 kg	39 mg	1.8 mg
	Pb	0.0041 kg	0.0024 mg	0.11 µg
	PM_{10}	34 kg	20 mg	900 µg
I, Station Escalators	Energy	0.82 TJ	0.47 MJ	0.022 MJ
	GHG	60 mt GGE	35 g GGE	1.6 g GGE
	SO_2	320 kg	190 mg	8.5 mg
	CO	31 kg	18 mg	0.82 mg
	NO_X	23 kg	13 mg	0.61 mg
	VOC	6.9 kg	4.0 mg	0.18 mg
	Pb	0.00042 kg	0.00024 mg	0.011 µg
	PM_{10}	3.5 kg	2.0 mg	92 µg
I, Station Train Control	Energy	4.9 TJ	2.9 MJ	0.13 MJ
	GHG	360 mt GGE	210 g GGE	9.6 g GGE
	SO_2	1,900 kg	1,100 mg	51 mg
	CO	190 kg	110 mg	4.9 mg
	NO_X	140 kg	81 mg	3.7 mg
	VOC	42 kg	24 mg	1.1 mg
	Pb	0.0025 kg	0.0015 mg	0.067 µg
	PM_{10}	21 kg	12 mg	560 µg
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	490 mt GGE	290 g GGE	13 g GGE
	SO_2	2,600 kg	1,500 mg	70 mg
	CO	250 kg	150 mg	6.7 mg
	NO_X	190 kg	110 mg	5.0 mg
	VOC	57 kg	33 mg	1.5 mg
	Pb	0.0034 kg	0.0020 mg	0.091 µg
	PM_{10}	29 kg	17 mg	760 µg
I, Station Maintenance	Energy	0.13 TJ	0.075 MJ	0.0034 MJ
	GHG	13 mt GGE	7.4 g GGE	0.34 g GGE
	SO_2	39 kg	23 mg	1.0 mg
	CO	110 kg	61 mg	2.8 mg
	NO_X	53 kg	31 mg	1.4 mg
	VOC	34 kg	20 mg	0.90 mg
	Pb	0.0060 kg	0.0035 mg	0.16 µg
	PM_{10}	6.8 kg	4.0 mg	180 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
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	59 kg	34 mg	1.6 mg
	CO	330 kg	190 mg	8.7 mg
	NO_X	630 kg	370 mg	17 mg
	VOC	41 kg	24 mg	1.1 mg
	Pb	-	-	-
	PM_{10}	26,000 kg	15,000 mg	690,000 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 45 - 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	1,000 mt GGE	810 g GGE	5.2 g GGE
	SO_2	5,300 kg	4,300 mg	28 mg
	CO	510 kg	420 mg	2.7 mg
	NO_X	380 kg	310 mg	2.0 mg
	VOC	110 kg	93 mg	0.60 mg
	Pb	0.0069 kg	0.0056 mg	0.036 μg
	PM_{10}	58 kg	47 mg	300 μg
I, Station Escalators	Energy	0.26 TJ	0.21 MJ	0.0014 MJ
	GHG	19 mt GGE	16 g GGE	0.10 g GGE
	SO_2	100 kg	83 mg	0.54 mg
	CO	9.9 kg	8.0 mg	0.052 mg
	NO_X	7.4 kg	6.0 mg	0.039 mg
	VOC	2.2 kg	1.8 mg	0.012 mg
	Pb	0.00013 kg	0.00011 mg	0.00070 μg
	PM_{10}	1.1 kg	0.90 mg	5.8 μg
I, Station Train Control	Energy	25 TJ	20 MJ	0.13 MJ
	GHG	1,800 mt GGE	1,500 g GGE	9.6 g GGE
	SO_2	9,800 kg	7,900 mg	51 mg
	CO	940 kg	760 mg	4.9 mg
	NO_X	710 kg	570 mg	3.7 mg
	VOC	210 kg	170 mg	1.1 mg
	Pb	0.013 kg	0.010 mg	0.067 μg
	PM_{10}	110 kg	86 mg	560 μg
I, Station Parking Lighting	Energy	8.4 TJ	6.8 MJ	0.044 MJ
	GHG	620 mt GGE	500 g GGE	3.2 g GGE
	SO_2	3,300 kg	2,700 mg	17 mg
	CO	320 kg	260 mg	1.7 mg
	NO_X	240 kg	190 mg	1.2 mg
	VOC	71 kg	57 mg	0.37 mg
	Pb	0.0043 kg	0.0035 mg	0.022 μg
	PM_{10}	36 kg	29 mg	190 μg
I, Station Miscellaneous	Energy	3.1 TJ	2.5 MJ	0.016 MJ
	GHG	230 mt GGE	190 g GGE	1.2 g GGE
	SO_2	1,200 kg	1,000 mg	6.4 mg
	CO	120 kg	96 mg	0.62 mg
	NO_X	89 kg	72 mg	0.46 mg
	VOC	26 kg	21 mg	0.14 mg
	Pb	0.0016 kg	0.0013 mg	0.0084 μg
	PM_{10}	13 kg	11 mg	70 μg
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	8.5 TJ	6.9 MJ	0.044 MJ
	GHG	570 mt GGE	460 g GGE	3.0 g GGE
	SO_2	6,000 kg	4,800 mg	31 mg
	CO	2,800 kg	2,200 mg	14 mg
	NO_X	6,000 kg	4,900 mg	32 mg
	VOC	8,000 kg	6,500 mg	42 mg
	Pb	0.095 kg	0.077 mg	0.50 μg
	PM_{10}	18,000 kg	15,000 mg	94,000 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
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 46 - Green Line infrastructure inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Construction	Energy	18 TJ	13 MJ	0.24 MJ
	GHG	1,800 mt GGE	1,300 g GGE	24 g GGE
	SO_2	5,500 kg	3,900 mg	72 mg
	CO	15,000 kg	11,000 mg	190 mg
	NO_X	7,400 kg	5,300 mg	98 mg
	VOC	4,700 kg	3,400 mg	62 mg
	Pb	0.83 kg	0.60 mg	11 μg
	PM_{10}	950 kg	680 mg	13,000 μg
I, Station Lighting	Energy	7.1 TJ	5.1 MJ	0.094 MJ
	GHG	1,000 mt GGE	720 g GGE	13 g GGE
	SO_2	6,000 kg	4,300 mg	79 mg
	CO	1,100 kg	810 mg	15 mg
	NO_X	1,300 kg	950 mg	17 mg
	VOC	76 kg	54 mg	1.0 mg
	Pb	0.050 kg	0.035 mg	0.65 μg
	PM_{10}	60 kg	43 mg	790 μg
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	16 TJ	11 MJ	0.21 MJ
	GHG	2,200 mt GGE	1,600 g GGE	29 g GGE
	SO_2	13,000 kg	9,400 mg	170 mg
	CO	2,500 kg	1,800 mg	33 mg
	NO_X	2,900 kg	2,100 mg	39 mg
	VOC	170 kg	120 mg	2.2 mg
	Pb	0.11 kg	0.078 mg	1.4 μg
	PM_{10}	130 kg	95 mg	1,700 μg
I, Station Maintenance	Energy	19 TJ	13 MJ	0.25 MJ
	GHG	1,900 mt GGE	1,300 g GGE	25 g GGE
	SO_2	5,700 kg	4,100 mg	76 mg
	CO	15,000 kg	11,000 mg	200 mg
	NO_X	7,800 kg	5,600 mg	100 mg
	VOC	5,000 kg	3,500 mg	65 mg
	Pb	0.88 kg	0.63 mg	12 μg
	PM_{10}	1,000 kg	720 mg	13,000 μg
I, Station Cleaning	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-
I, Station Parking	Energy	0.75 TJ	0.54 MJ	0.0100 MJ
	GHG	51 mt GGE	36 g GGE	0.67 g GGE
	SO_2	470 kg	340 mg	6.3 mg
	CO	220 kg	160 mg	2.9 mg
	NO_X	480 kg	340 mg	6.3 mg
	VOC	640 kg	460 mg	8.4 mg
	Pb	0.0077 kg	0.0055 mg	0.10 μg
	PM_{10}	1,400 kg	1,000 mg	19,000 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	1.6 TJ	1.1 MJ	0.020 MJ
	GHG	110 mt GGE	81 g GGE	1.5 g GGE
	SO_2	39 kg	28 mg	0.51 mg
	CO	210 kg	150 mg	2.8 mg
	NO_X	410 kg	290 mg	5.4 mg
	VOC	27 kg	19 mg	0.35 mg
	Pb	-	-	-
	PM_{10}	17,000 kg	12,000 mg	220,000 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 47 - CAHSR infrastructure inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
I, Station Construction	Energy	11 TJ	0.0011 MJ	0.0000041 MJ
	GHG	1,100 mt GGE	0.11 g GGE	0.00041 g GGE
	SO_2	3,300 kg	0.33 mg	0.0013 mg
	CO	8,800 kg	0.89 mg	0.0034 mg
	NO_X	4,400 kg	0.45 mg	0.0017 mg
	VOC	2,800 kg	0.29 mg	0.0011 mg
	Pb	0.50 kg	0.000050 mg	0.00019 µg
	PM_{10}	570 kg	0.058 mg	0.22 µg
I, Station Lighting	Energy	0.15 TJ	0.000015 MJ	0.000000057 MJ
	GHG	11 mt GGE	0.0011 g GGE	0.0000042 g GGE
	SO_2	58 kg	0.0059 mg	0.000022 mg
	CO	5.6 kg	0.00056 mg	0.0000021 mg
	NO_X	4.2 kg	0.00042 mg	0.0000016 mg
	VOC	1.2 kg	0.00013 mg	0.00000048 mg
	Pb	0.000075 kg	0.0000000076 mg	0.000000029 µg
	PM_{10}	0.63 kg	0.000064 mg	0.00024 µg
I, Station Escalators	Energy	0.066 TJ	0.0000067 MJ	0.000000025 MJ
	GHG	4.8 mt GGE	0.00049 g GGE	0.0000019 g GGE
	SO_2	26 kg	0.0026 mg	0.0000099 mg
	CO	2.5 kg	0.00025 mg	0.00000096 mg
	NO_X	1.9 kg	0.00019 mg	0.00000072 mg
	VOC	0.56 kg	0.000056 mg	0.00000021 mg
	Pb	0.000034 kg	0.0000000034 mg	0.000000013 µg
	PM_{10}	0.28 kg	0.000028 mg	0.00011 µg
I, Station Train Control	Energy	110,000 TJ	11 MJ	0.043 MJ
	GHG	8,200,000 mt GGE	830 g GGE	3.2 g GGE
	SO_2	44,000,000 kg	4,400 mg	17 mg
	CO	4,200,000 kg	430 mg	1.6 mg
	NO_X	3,200,000 kg	320 mg	1.2 mg
	VOC	940,000 kg	95 mg	0.36 mg
	Pb	57 kg	0.0057 mg	0.022 µg
	PM_{10}	480,000 kg	48 mg	180 µg
I, Station Parking Lighting	Energy	19 TJ	0.0019 MJ	0.0000074 MJ
	GHG	1,400 mt GGE	0.14 g GGE	0.00054 g GGE
	SO_2	7,500 kg	0.76 mg	0.0029 mg
	CO	730 kg	0.073 mg	0.00028 mg
	NO_X	540 kg	0.055 mg	0.00021 mg
	VOC	160 kg	0.016 mg	0.000063 mg
	Pb	0.0098 kg	0.00000099 mg	0.0000038 µg
	PM_{10}	82 kg	0.0083 mg	0.032 µg
I, Station Miscellaneous	Energy	0.034 TJ	0.0000034 MJ	0.000000013 MJ
	GHG	2.5 mt GGE	0.00025 g GGE	0.00000096 g GGE
	SO_2	13 kg	0.0014 mg	0.0000051 mg
	CO	1.3 kg	0.00013 mg	0.00000049 mg
	NO_X	0.96 kg	0.000097 mg	0.00000037 mg
	VOC	0.29 kg	0.000029 mg	0.00000011 mg
	Pb	0.000017 kg	0.0000000018 mg	0.0000000067 µg
	PM_{10}	0.14 kg	0.000015 mg	0.000056 µg
I, Station Maintenance	Energy	11 TJ	0.0011 MJ	0.0000044 MJ
	GHG	1,100 mt GGE	0.11 g GGE	0.00043 g GGE
	SO_2	3,400 kg	0.35 mg	0.0013 mg
	CO	9,300 kg	0.94 mg	0.0036 mg
	NO_X	4,700 kg	0.47 mg	0.0018 mg
	VOC	3,000 kg	0.30 mg	0.0011 mg
	Pb	0.52 kg	0.000053 mg	0.00020 µg
	PM_{10}	600 kg	0.061 mg	0.23 µg
I, Station Cleaning	Energy	0.12 TJ	0.000012 MJ	0.000000045 MJ
	GHG	8.5 mt GGE	0.00086 g GGE	0.0000033 g GGE
	SO_2	46 kg	0.0046 mg	0.000018 mg
	CO	4.4 kg	0.00044 mg	0.0000017 mg
	NO_X	3.3 kg	0.00033 mg	0.0000013 mg
	VOC	0.98 kg	0.000099 mg	0.00000038 mg
	Pb	0.000059 kg	0.0000000060 mg	0.000000023 µg
	PM_{10}	0.49 kg	0.000050 mg	0.00019 µg
I, Station Parking	Energy	22 TJ	0.0022 MJ	0.0000083 MJ
	GHG	1,400 mt GGE	0.15 g GGE	0.00055 g GGE
	SO_2	16,000 kg	1.6 mg	0.0060 mg
	CO	7,200 kg	0.73 mg	0.0028 mg
	NO_X	16,000 kg	1.6 mg	0.0061 mg
	VOC	21,000 kg	2.1 mg	0.0081 mg
	Pb	0.25 kg	0.000025 mg	0.000096 µg
	PM_{10}	47,000 kg	4.8 mg	18 µg
I, Track/Power Construction	Energy	5,300 TJ	0.54 MJ	0.0020 MJ
	GHG	480,000 mt GGE	48 g GGE	0.18 g GGE
	SO_2	1,300,000 kg	140 mg	0.52 mg
	CO	4,200,000 kg	420 mg	1.6 mg
	NO_X	1,600,000 kg	160 mg	0.61 mg
	VOC	1,100,000 kg	110 mg	0.44 mg
	Pb	750 kg	0.076 mg	0.29 µg
	PM_{10}	290,000 kg	29 mg	110 µg
I, Track Maintenance	Energy	96 TJ	0.0097 MJ	0.000037 MJ
	GHG	4,000 mt GGE	0.40 g GGE	0.0015 g GGE
	SO_2	3,700 kg	0.38 mg	0.0014 mg
	CO	1,900 kg	0.19 mg	0.00074 mg
	NO_X	6,600 kg	0.67 mg	0.0025 mg
	VOC	1,300 kg	0.13 mg	0.00050 mg
	Pb	4.4 kg	0.00044 mg	0.0017 µg
	PM_{10}	1,100 kg	0.11 mg	0.43 µg
I, Insurance (Employees)	Energy	37 TJ	0.0038 MJ	0.000014 MJ
	GHG	3,000 mt GGE	0.31 g GGE	0.0012 g GGE
	SO_2	7,500 kg	0.76 mg	0.0029 mg
	CO	34,000 kg	3.4 mg	0.013 mg
	NO_X	8,400 kg	0.85 mg	0.0032 mg
	VOC	6,300 kg	0.63 mg	0.0024 mg
	Pb	-	-	-
	PM_{10}	1,600 kg	0.16 mg	0.61 µg
I, Insurance (Facilities)	Energy	27 TJ	0.0027 MJ	0.000010 MJ
	GHG	2,200 mt GGE	0.22 g GGE	0.00085 g GGE
	SO_2	5,400 kg	0.55 mg	0.0021 mg
	CO	25,000 kg	2.5 mg	0.0095 mg
	NO_X	6,100 kg	0.62 mg	0.0024 mg
	VOC	4,500 kg	0.46 mg	0.0018 mg
	Pb	-	-	-
	PM_{10}	1,200 kg	0.12 mg	0.45 µg

6.3 Fuels

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, diesel fuel, and electricity in Massachusetts), electricity and fuel production energy is evaluated. For electricity, transmission and distribution loses are included.

6.3.1 Electricity in California and Massachusetts

The energy required to produce a unit of electricity in each state 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 48 per kilowatt-hour of delivered electricity. Additionally, there is an 8.4% transmission and distribution loss in California and 9.6% in Massachusetts.

Table 48 - Electricity generation factors for CA and MA [Deru 2007]

	Input/Output	Precombustion Factors
California	$kWh_{primary}$ / kWh	0.14
	g CO_2e / kWh	63
	mg SO_2 / kWh	1,370
	mg CO / kWh	95
	mg NO_X / kWh	156
	mg VOC / kWh	7
	µg Pb / kWh	1.2
	mg PM_{10} / kWh	5
Massachusetts	$kWh_{primary}$ / kWh	0.32
	g CO_2e / kWh	69
	mg SO_2 / kWh	838
	mg CO / kWh	236
	mg NO_X / kWh	238
	mg VOC / kWh	9
	µg Pb / kWh	1.9
	mg PM_{10} / kWh	7

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 49 - Rail vehicle and infrastructure electricity consumption

	BART	Caltrain	Muni	Green Line	High Speed
Vehicle Consumption (GWh/train-life)	160	0.017	13	18	310,000
Infrastructure Consumption (GWh/train-life)	8.0	14	5.7	7.6	31,000

Using the precombustion factors in Table 48, the transmission and distribution losses percentages, and the vehicle and infrastructure electricity consumption factors in Table 49, the electricity inventory is computed as shown in Equation Set 32.

Equation Set 32 - Rail electricity precombustion and transmission and distribution losses

$$\mathrm{E}_{\mathrm{system,i}} = \text{Yearly electricity consumption in system for i where i} \in \{\text{vehicles, infrastructure}\}$$

$$\mathrm{E}_{\mathrm{precombustion}} = \text{kwh of precombustion energy per kwh of delivered energy}$$

$$I_{IO-train-life}^{rail,electricity-precombustion} = E_{system,i} \times E_{precombusion} \times EF_{precombustion} \times \frac{VMT_{train}}{train-life} \times \frac{yr_{system}}{VMT_{system}}$$

$$I_{IO-VMT}^{rail,electricity-precombustion} = E_{system,i} \times E_{precombusion} \times EF_{precombustion} \times \frac{yr_{system}}{VMT_{system}}$$

$$I_{IO-PMT}^{rail,electricity-precombustion} = E_{system,i} \times E_{precombusion} \times EF_{precombustion} \times \frac{yr_{system}}{PMT_{system}}$$

$$I_{IO-train-life}^{rail,electricity-T\&D} = \left(\frac{E_{system,i} \times (1 - \% \cdot loss_{T\&D})}{\% - loss_{T\&D}} \right) \times EF_{combustion} \times \frac{VMT_{train}}{train-life} \times \frac{yr_{system}}{VMT_{system}}$$

$$I_{IO-VMT}^{rail,electricity-T\&D} = \left(\frac{E_{system,i} \times (1 - \% \cdot loss_{T\&D})}{\% - loss_{T\&D}} \right) \times EF_{combustion} \times \frac{yr_{system}}{VMT_{system}}$$

$$I_{IO-PMT}^{rail,electricity-T\&D} = \left(\frac{E_{system,i} \times (1 - \% \cdot loss_{T\&D})}{\% - loss_{T\&D}} \right) \times EF_{combustion} \times \frac{yr_{system}}{PMT_{system}}$$

6.3.2 Diesel

The production of diesel fuel for Caltrain operations is handled with EIOLCA 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 EIOLCA [EIA 2007, EIA 2007b, EIOLCA]. Normalization of inventory output from EIOLCA to the functional units is the same as other methods which rely on EIOLCA output.

6.3.3 Rail Fuels Results

Rail fuel results are summarized in the following tables.

Table 50 - 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	1,400 mt GGE	420 g GGE	2.9 g GGE
	SO_2	31,000 kg	9,100 mg	63 mg
	CO	2,200 kg	630 mg	4.3 mg
	NO_X	3,600 kg	1,000 mg	7.1 mg
	VOC	160 kg	48 mg	0.33 mg
	Pb	0.026 kg	0.0076 mg	0.052 µg
	PM_{10}	110 kg	31 mg	210 µg
F, T&D Losses (Vehicles)	Energy	52 TJ	15 MJ	0.10 MJ
	GHG	350 mt GGE	100 g GGE	0.70 g GGE
	SO_2	1,900 kg	550 mg	3.8 mg
	CO	180 kg	53 mg	0.36 mg
	NO_X	140 kg	39 mg	0.27 mg
	VOC	40 kg	12 mg	0.081 mg
	Pb	0.0024 kg	0.00071 mg	0.0049 µg
	PM_{10}	20 kg	5.9 mg	41 µg
F, Supply Chain (Infrastructure	Energy	4.1 TJ	1.2 MJ	0.0083 MJ
	GHG	72 mt GGE	21 g GGE	0.14 g GGE
	SO_2	1,600 kg	460 mg	3.2 mg
	CO	110 kg	32 mg	0.22 mg
	NO_X	180 kg	52 mg	0.36 mg
	VOC	8.2 kg	2.4 mg	0.017 mg
	Pb	0.0013 kg	0.00039 mg	0.0026 µg
	PM_{10}	5.4 kg	1.6 mg	11 µg
F, T&D Losses (Infrastructure)	Energy	2.6 TJ	0.77 MJ	0.0053 MJ
	GHG	18 mt GGE	5.2 g GGE	0.036 g GGE
	SO_2	95 kg	28 mg	0.19 mg
	CO	9.1 kg	2.7 mg	0.018 mg
	NO_X	6.8 kg	2.0 mg	0.014 mg
	VOC	2.0 kg	0.59 mg	0.0041 mg
	Pb	0.00012 kg	0.000036 mg	0.00025 µg
	PM_{10}	1.0 kg	0.30 mg	2.1 µg

Table 51 - 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	120 mt GGE	67 g GGE	3.1 g GGE
	SO_2	2,500 kg	1,500 mg	67 mg
	CO	180 kg	100 mg	4.7 mg
	NO_X	290 kg	170 mg	7.7 mg
	VOC	13 kg	7.7 mg	0.35 mg
	Pb	0.0021 kg	0.0012 mg	0.057 μg
	PM_{10}	8.7 kg	5.0 mg	230 μg
F, T&D Losses (Vehicles)	Energy	4.3 TJ	2.5 MJ	0.11 MJ
	GHG	29 mt GGE	17 g GGE	0.76 g GGE
	SO_2	150 kg	89 mg	4.1 mg
	CO	15 kg	8.5 mg	0.39 mg
	NO_X	11 kg	6.4 mg	0.29 mg
	VOC	3.3 kg	1.9 mg	0.087 mg
	Pb	0.00020 kg	0.00012 mg	0.0053 μg
	PM_{10}	1.7 kg	0.96 mg	44 μg
F, Supply Chain (Infrastructure	Energy	2.9 TJ	1.7 MJ	0.078 MJ
	GHG	51 mt GGE	30 g GGE	1.4 g GGE
	SO_2	1,100 kg	650 mg	30 mg
	CO	78 kg	45 mg	2.1 mg
	NO_X	130 kg	74 mg	3.4 mg
	VOC	5.9 kg	3.4 mg	0.16 mg
	Pb	0.00094 kg	0.00055 mg	0.025 μg
	PM_{10}	3.8 kg	2.2 mg	100 μg
F, T&D Losses (Infrastructure)	Energy	1.9 TJ	1.1 MJ	0.050 MJ
	GHG	13 mt GGE	7.3 g GGE	0.34 g GGE
	SO_2	67 kg	39 mg	1.8 mg
	CO	6.5 kg	3.8 mg	0.17 mg
	NO_X	4.9 kg	2.8 mg	0.13 mg
	VOC	1.5 kg	0.84 mg	0.038 mg
	Pb	0.000088 kg	0.000051 mg	0.0023 μg
	PM_{10}	0.73 kg	0.43 mg	19 μg

Table 52 - Caltrain fuel inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
F, Supply Chain (Vehicles)	Energy	26 TJ	21 MJ	0.14 MJ
	GHG	2,300 mt GGE	1,900 g GGE	12 g GGE
	SO_2	4,500 kg	3,600 mg	23 mg
	CO	6,400 kg	5,200 mg	34 mg
	NO_X	2,600 kg	2,100 mg	14 mg
	VOC	2,900 kg	2,400 mg	15 mg
	Pb	-	-	-
	PM_{10}	460 kg	380 mg	2,400 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	130 mt GGE	100 g GGE	0.66 g GGE
	SO_2	2,800 kg	2,200 mg	14 mg
	CO	190 kg	160 mg	1.0 mg
	NO_X	310 kg	250 mg	1.6 mg
	VOC	14 kg	12 mg	0.076 mg
	Pb	0.0023 kg	0.0019 mg	0.012 μg
	PM_{10}	9.4 kg	7.6 mg	49 μg
F, T&D Losses (Infrastructure)	Energy	4.6 TJ	3.7 MJ	0.024 MJ
	GHG	31 mt GGE	25 g GGE	0.16 g GGE
	SO_2	170 kg	130 mg	0.87 mg
	CO	16 kg	13 mg	0.084 mg
	NO_X	12 kg	9.7 mg	0.063 mg
	VOC	3.6 kg	2.9 mg	0.019 mg
	Pb	0.00022 kg	0.00017 mg	0.0011 μg
	PM_{10}	1.8 kg	1.5 mg	9.4 μg

Table 53 - 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	8.9 TJ	6.3 MJ	0.12 MJ
	GHG	170 mt GGE	120 g GGE	2.2 g GGE
	SO_2	2,100 kg	1,500 mg	27 mg
	CO	580 kg	420 mg	7.7 mg
	NO_X	590 kg	420 mg	7.7 mg
	VOC	22 kg	16 mg	0.29 mg
	Pb	0.0047 kg	0.0034 mg	0.062 µg
	PM_{10}	16 kg	12 mg	220 µg
F, T&D Losses (Infrastructure)	Energy	2.9 TJ	2.1 MJ	0.038 MJ
	GHG	44 mt GGE	31 g GGE	0.58 g GGE
	SO_2	260 kg	190 mg	3.4 mg
	CO	49 kg	35 mg	0.65 mg
	NO_X	58 kg	41 mg	0.76 mg
	VOC	3.3 kg	2.4 mg	0.044 mg
	Pb	0.0022 kg	0.0015 mg	0.028 µg
	PM_{10}	2.6 kg	1.9 mg	34 µg

Table 54 - CAHSR fuel inventory

Life-Cycle Component	I/O	per Train-Life	per VMT	per PMT
F, Supply Chain (Vehicles)	Energy	160,000 TJ	16 MJ	0.063 MJ
	GHG	2,800,000 mt GGE	290 g GGE	1.1 g GGE
	SO_2	62,000,000 kg	6,300 mg	24 mg
	CO	4,300,000 kg	430 mg	1.6 mg
	NO_X	7,000,000 kg	710 mg	2.7 mg
	VOC	320,000 kg	33 mg	0.12 mg
	Pb	52 kg	0.0052 mg	0.020 µg
	PM_{10}	210,000 kg	21 mg	81 µg
F, T&D Losses (Vehicles)	Energy	100,000 TJ	10 MJ	0.040 MJ
	GHG	700,000 mt GGE	70 g GGE	0.27 g GGE
	SO_2	3,700,000 kg	380 mg	1.4 mg
	CO	360,000 kg	36 mg	0.14 mg
	NO_X	270,000 kg	27 mg	0.10 mg
	VOC	80,000 kg	8.1 mg	0.031 mg
	Pb	4.8 kg	0.00049 mg	0.0019 µg
	PM_{10}	40,000 kg	4.1 mg	16 µg
F, Supply Chain (Infrastructure	Energy	16,000 TJ	1.6 MJ	0.0062 MJ
	GHG	280,000 mt GGE	28 g GGE	0.11 g GGE
	SO_2	6,100,000 kg	620 mg	2.4 mg
	CO	420,000 kg	43 mg	0.16 mg
	NO_X	700,000 kg	70 mg	0.27 mg
	VOC	32,000 kg	3.2 mg	0.012 mg
	Pb	5.1 kg	0.00052 mg	0.0020 µg
	PM_{10}	21,000 kg	2.1 mg	8.1 µg
F, T&D Losses (Infrastructure)	Energy	10,000 TJ	1.0 MJ	0.0039 MJ
	GHG	69,000 mt GGE	7.0 g GGE	0.027 g GGE
	SO_2	370,000 kg	37 mg	0.14 mg
	CO	35,000 kg	3.6 mg	0.014 mg
	NO_X	27,000 kg	2.7 mg	0.010 mg
	VOC	7,900 kg	0.80 mg	0.0031 mg
	Pb	0.48 kg	0.000048 mg	0.00018 µg
	PM_{10}	4,000 kg	0.40 mg	1.5 µg

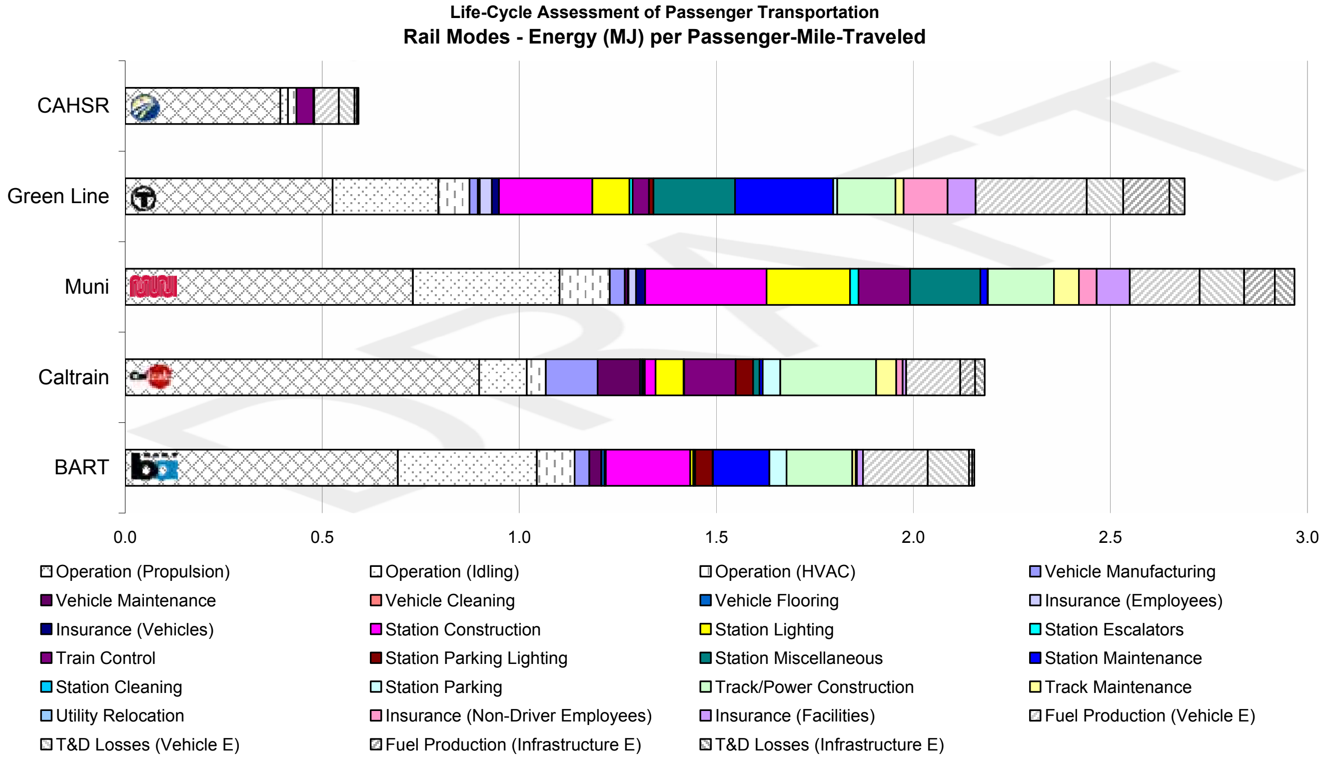
6.4 Rail Summary

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.

6.4.1 Energy and Greenhouse Gas Emissions

While over 25 life-cycle components have been included in the rail inventory, only a few have major contributions to total energy consumption GHG emissions for a system. 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. Table 55 shows the rail energy inventory for each of the five modes normalized to MJ per passenger-mile. Table 56 shows the same for the GHG emissions inventory.

Table 55 - Rail energy inventory

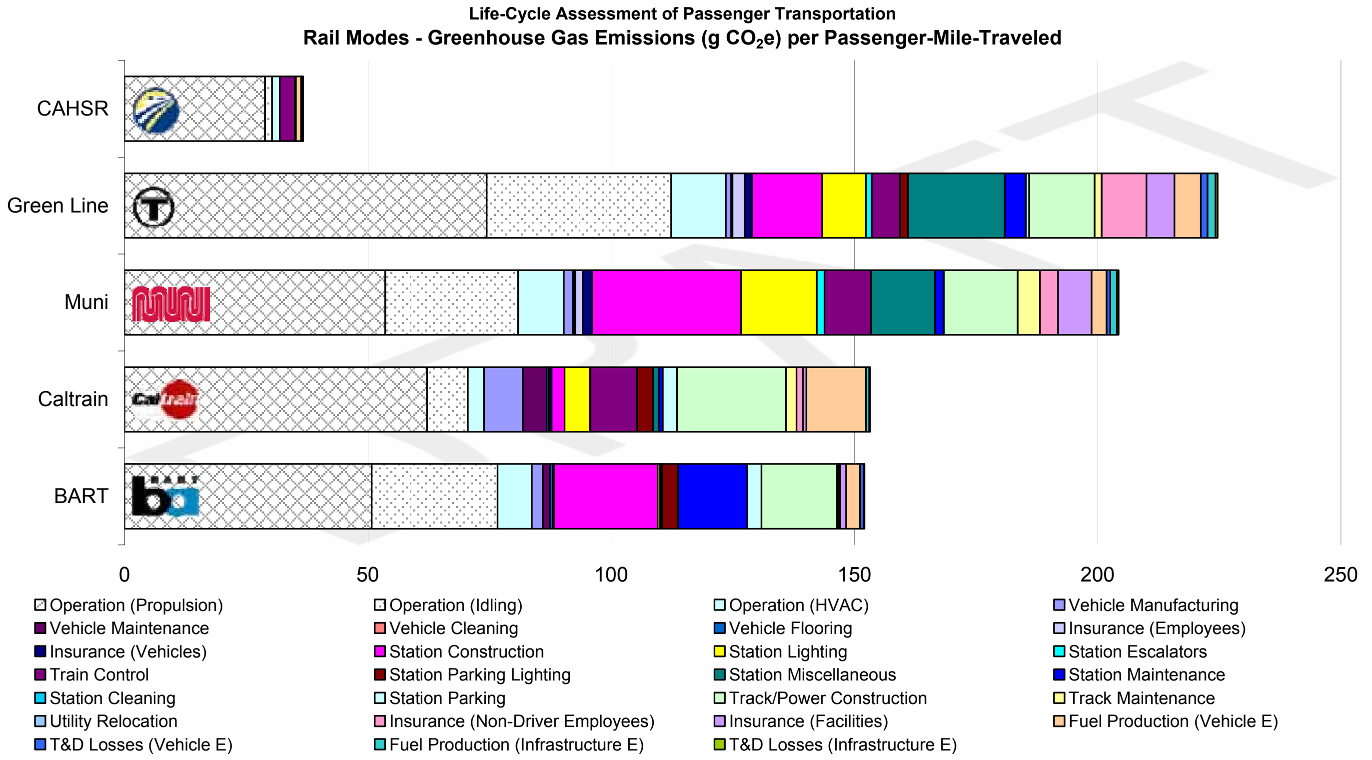


<u>Vehicle Operation</u>

Before discussing the life-cycle components, it is interesting to consider the disaggregating of operational components. Total operational energy consumption for BART, Muni, Caltrain, and the Green Line hover around 1 MJ/PMT with CAHSR at approximately 0.4 MJ/PMT. Looking at the three components of this energy (propulsion, idling, and auxiliaries) shows how that energy is used. Propulsion energy accounts for between 60% and 90%, idling between 5% and 30%, and auxiliaries 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.

A similar distribution holds 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 system.

Table 56 - Rail GHG emission inventory



Vehicle Manufacturing

Train production shows in each of the 4 commuter modes (not CAHSR) but most significantly with Caltrain since it is one of the most materials intensive. The construction of the Caltrain train (including locomotive and passenger cars) requires 25 TJ while BART requires 19 TJ and Muni and the Green Line about 1.5 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]. Emissions from production of the trains (1,500 mt GGE for Caltrain, 1,100 mt GGE for BART, 71 mt GGE for Muni, and 85 mt GGE for the Green Line) 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, 50X 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 0.2 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.

<u>Track and Power Delivery Construction</u>
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. 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.

<u>Station Lighting and Miscellaneous Station Electricity</u>
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.

<u>Station Maintenance</u>
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.

<u>Fuel Production and Transmission and Distribution Losses</u>
The precombustion electricity factors discussed in §6.3.1 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 EIOLCA 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 (Table 48) 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 (EIOLCA assumes a national average mix) for insurance carriers is the reason for large GHG emissions.

6.4.2 Criteria Air Pollutants

Sulfur Dioxide (SO_2)

The operational emissions of SO_2 are much larger for electric fuel systems than Caltrain. This is the result of electricity production where low concentrations of sulfur in coal lead to emissions. While operational emissions account for between 50% and 80% of total SO_2 emissions for electric-powered systems, they are only 4% of total emissions for Caltrain. Total emissions amount to between 300 mg/PMT (Caltrain) and 1,200 mg/PMT (Green Line). Caltrain's low value is due to its use of diesel fuel however life-cycle components account for over 99% of total SO_2 emissions. 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 requirements 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 7% and 20% (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. Similarly, station maintenance is large because of station reconstruction. The insurance components affect CO emissions due to truck transportation required to sustain insurance operations. CO emissions are lowest for CAHSR (22 mg/PMT) due to the long distances traveled resulting in high PMT. For the commuter systems, emissions range from 420 (Caltrain) to 720 (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. The release of NO_X, from diesel equipment use, and VOCs, from the asphalt diluent evaporation, makes significant contributions to total emissions for BART and Caltrain. Muni and Green Line do not experience this effect due to their small parking infrastructure. Total NO_X emissions for the 4 commuter systems are between 280 (Muni) and 1,500 (Caltrain) mg/PMT while VOCs amount to between 130 (Green Line) and 200 (BART)

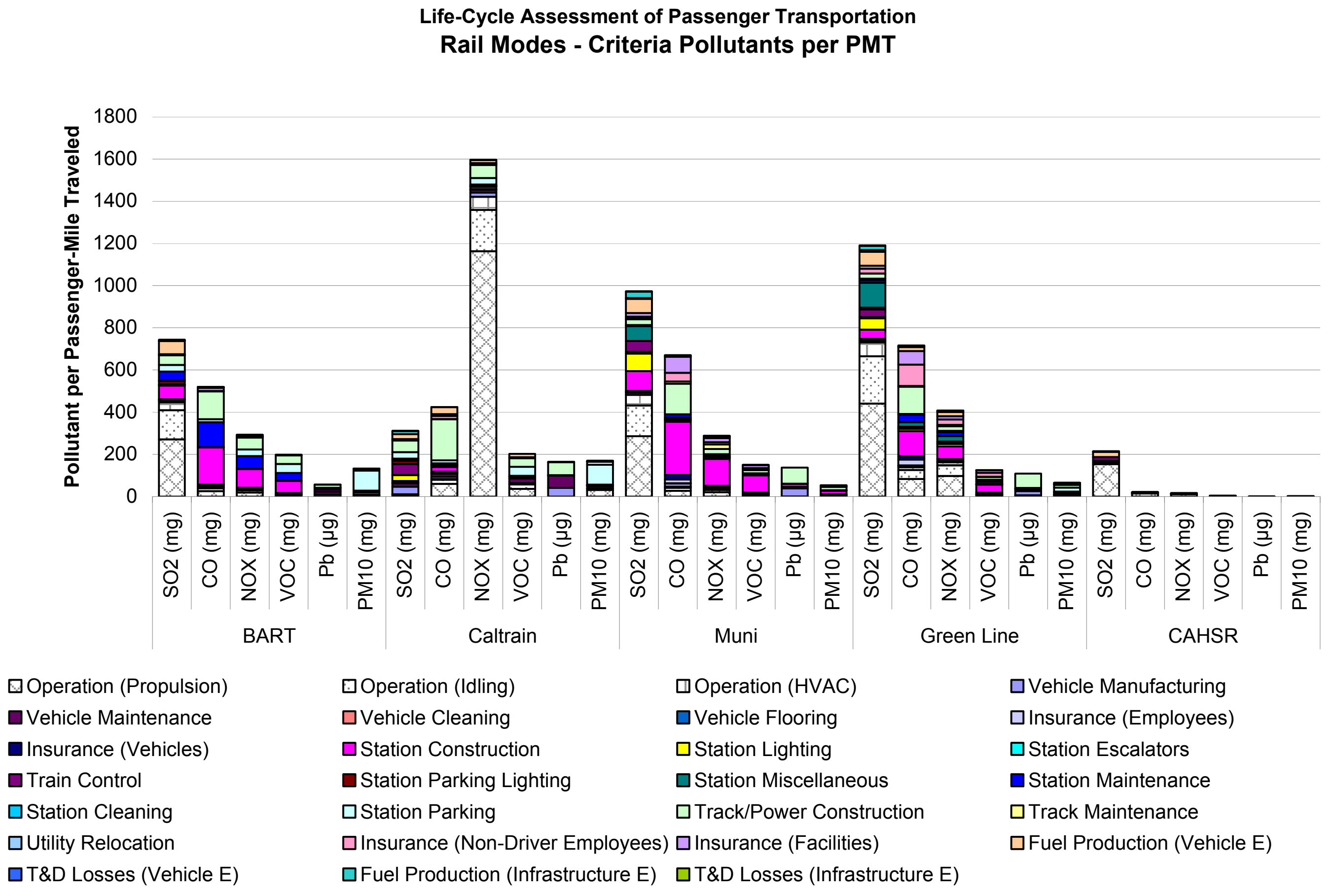
Figure 16 – Roadway paving emissions
Source: http://www.ehponline.com/

mg/PMT. While 90% of Caltrain NO_X emissions are due to vehicle operation, only 11% to 40% of total emissions on the other 3 commuter systems are due to operation. The majority of emissions are found in the life-cycle. The same holds true for VOCs where operational emissions range from 7% to 30% of total emissions for the 4 commuter systems.

Lead (Pb)

Few lead emissions are found in operational emissions of the vehicle. The majority of emissions come from vehicle manufacturing, vehicle maintenance, and track construction. The manufacturing and maintenance of vehicles requires large amounts of metals (particularly steel and aluminum) which when produced, emit lead. The lead emissions in track construction come again from steel manufacturing. Lead emissions from non-operational components are between 20 and 220 times larger than operational components for the 4 commuter systems.

Table 57 - Rail CAP inventory



Particulate Matter (PM_{10})

Station parking and track maintenance are the two largest contributors to PM emissions. Fugitive dust emissions from asphalt paving have a large impact for BART and Caltrain. A large PM contribution from track maintenance is due to the diesel equipment used to repair track. Operational PM composes between 4% and 82% of total PM emissions. CAHSR has the lowest life-cycle PM emissions at 2.3 mg/PMT while the 4 commuter modes range from 50 mg/PMT (Muni) to 170 mg/PMT (Caltrain).

Summary

While CAHSR performs significantly better than the 4 commuter modes on a per passenger-mile basis, the system is not necessarily functionally comparable since it is not an urban commuter network. Looking at the 4 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 58 details the CAP emissions for each system with both their life-cycle and operational effects.

Table 58 - Rail inventory of Criteria Air Pollutants (operational emissions in parenthesis)

	BART	Caltrain	Muni	Green Line	CAHSR
SO_2 (mg/PMT)	740 (450)	300 (11)	970 (480)	1,200 (730)	220 (170)
CO (mg/PMT)	520 (43)	420 (83)	670 (46)	720 (140)	22 (16)
NO_X (mg/PMT)	290 (32)	1,600 (1,400)	280 (35)	410 (160)	17 (12)
VOC (mg/PMT)	200 (9.6)	200 (59)	150 (10)	130 (9.3)	4.7 (3.7)
Pb (µg/PMT)	57 (0.58)	150 (0)	140 (0.63)	110 (6.1)	0.57 (0.22)
PM_{10} (mg/PMT)	130 (4.9)	170 (38)	740 (5.2)	280 (7.4)	2.3 (1.8)

7 Life-cycle Inventory of Air

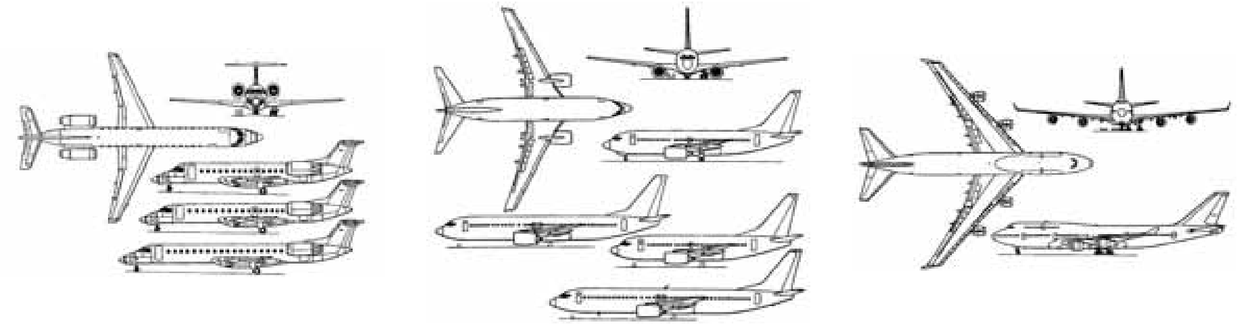
Figure 17 – Boeing 747
Source: http://content.answers.com/

Air travel in the U.S. was responsible for 2.5M TJ of energy consumption in 2005 [Davis 2007]. This was 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].

7.1 *Vehicles (Aircraft)*

Three representative aircraft are chosen to model the entire commercial passenger fleet: the Embraer 145 (short-haul, μ=34 passengers per flight), Boeing 737 (medium-haul, μ=94 passengers per flight), and Boeing 747 (long-haul, μ=305 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 makeup 80% of VMT and 92% of PMT. Figure 18 shows schematics of each aircraft and specifications.



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

Figure 18 - Aircraft Parameters Source: Janes 2004

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

Figure 19 – Embraer 145
Source: http://www.modelairplaneinternational.com/

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].

Figure 20 – Boeing 737
Source: http://www.gadget-box.com/

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 34 passengers per flight, the Boeing 737 travels 850 miles with 94 passengers per flight, and the Boeing 747 travels 7,600 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]

7.1.1 Manufacturing

The aircraft and its engines are considered separately when computing the environmental inventory for aircraft manufacturing. The EIOLCA 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 EIOLCA 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 [Jenkins 1999]. Both the Embraer 145 and Boeing 737 have 2 engines while the Boeing 747 has 4 engines. Inputting the cost parameters into the EIOLCA sectors and normalizing to the functional units (as shown in Equation Set 33) produces the aircraft manufacturing inventory.

Figure 21 – Airplane manufacturing facility
Source: http://cache.eb.com/

Equation Set 33 – Aircraft manufacturing

$$I_{IO}^{rail,aircraft/engine-manufacturing} \times \frac{aircraft/engine-life}{yr}$$

$$= \text{Yearly impact for aircraft and engine manufacturing determined in EIOLCA}$$

$$I_{IO-aircraft-life}^{air,aircraft/engine-manufacturing} = I_{IO}^{air,aircraft/engine-manufacturing} \times \frac{VMT_{aircraft}}{aircraft-life} \times \frac{yr_{system}}{VMT_{system}}$$

$$I_{IO-VMT}^{air,aircraft/engine-manufacturing} = I_{IO}^{air,aircraft/engine-manufacturing} \times \frac{yr_{system}}{VMT_{system}}$$

$$I_{IO-PMT}^{air,aircraft/engine-manufacturing} = I_{IO}^{air,aircraft/engine-manufacturing} \times \frac{yr_{system}}{VMT_{system}}$$

7.1.2 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 22). 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…).

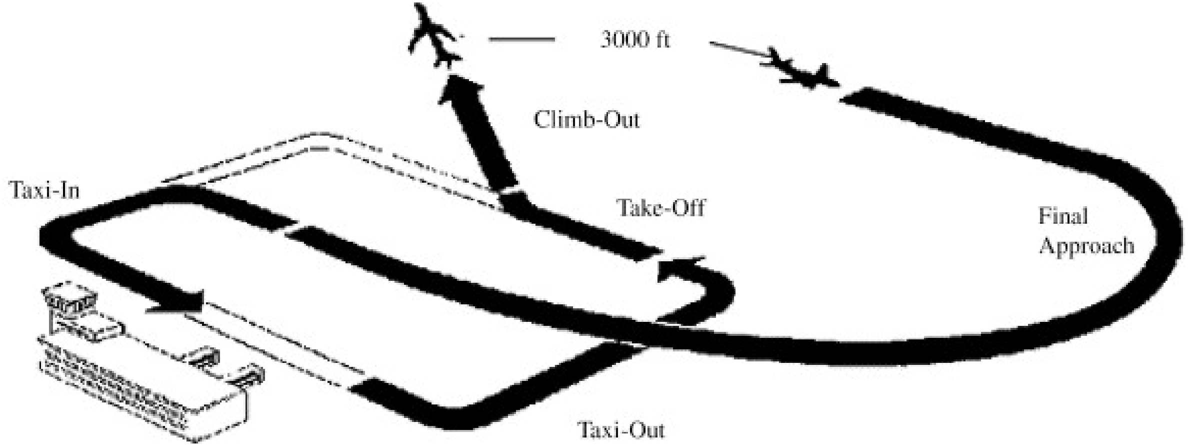


Figure 22 – Landing-Takeoff cycle
Source: http://www.grida.no/climate/ipcc/aviation/105.htm

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]

<u>At or Near-Airport Operations</u>

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 §7.1 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 §7.2). 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 59. The fuel sulfur content is specified as 0.068% with a SO_X emission factor of 1.36 g/kg.

Table 59 - EDMS emission factors by stage (emissions per kg of fuel burned)

	Fuel Flow (kg/s)	CO (g/kg)	THC (g/kg)	NMHC (g/kg)	VOC (g/kg)	NOX (g/kg)	PM (g/kg)
Embraer 145							
Taxi Out	0.056	16.7	2.42	2.42	2.29	3.92	0.15
Takeoff	0.3967	0.805	0.26	0.26	0.2465	21.06	0.267
Climb	0.3324	0.805	0.26	0.26	0.2465	17.916	0.239
Approach	0.124	3.16	0.617	0.617	0.5844	7.9889	0.2199
Taxi In	0.056	16.7	2.42	2.42	2.292	3.927	0.1538
Boeing 737							
Taxi Out	0.13	33.17	2.1986	2.1986	2.082	3.9996	0.242
Takeoff	0.995551	0.891	0.0433	0.0433	0.041	18.15	0.216
Climb	0.835	0.891	0.0433	0.0433	0.041	15.89	0.186
Approach	0.308	3.664	0.077	0.077	0.073	8.5119	0.204
Taxi In	0.13	33.17	2.1986	2.1986	2.08	3.9996	0.242
Boeing 747							
Taxi Out	0.215	11.185	0.636	0.636	0.602	5.127	0.315
Takeoff	2.577	0.106	0.135	0.135	0.127848	33.33	0.538
Climb	2.0909	0.106	0.135	0.135	0.127848	25.228	0.545
Approach	0.687	0.867	0.241	0.241	0.228	11.896	0.304
Taxi In	0.215	11.185	0.636	0.636	0.602	5.127	0.315

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

$$I^{air,aircraft-airport-operation}_{IO-stage} = \frac{I_{EDMS}}{\#_{LTO-aircraft}}$$

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

$$I^{air,aircraft-airport-operation}_{IO-stage-VMT} = I^{air,aircraft-airport-operation}_{IO-stage} \times \frac{flight}{VMT_{aircraft}}$$

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

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 60.

Table 60 - Aircraft cruise emission factors per VMT

	Embraer 145	Boeing 737	Boeing 747
Fuel Consumption (kg)	2.4	4.8	16.7
Energy Consumption (MJ)	80	220	780
GHG Emissions (kg)	5.2	15	53
SO_2 Emissions (g)	1.7	4.8	17
CO Emissions (g)	2.3	8.3	16
NO_X Emissions (g)	13.17	52.39	207.26
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

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

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

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

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

7.1.3 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 EIOLCA which reasonably estimates effects of aircraft maintenance. As a result, maintenance items were disaggregated and assigned best-fit EIOLCA sectors as shown in Table 61.

Table 61 - Aircraft maintenance components and corresponding EIOLCA sectors

	% of Total Maintenance Costs	EIOLCA Sector Number	EIOLCA Sector Name
Airframe Maintenance			
Lubrication & Fuel Changes	10%	324191	Petroleum 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 62.

Table 62 - Aircraft maintenance component costs ($/hr 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 61 and then input into their corresponding EIOLCA sector. Engine maintenance inventory is computed with the EIOLCA 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

$$I_{IO}^{air,aircraft/engine-maintenance} = \sum_{components} I_{EIOLCA} \times \frac{aircraft-life}{yr}$$

$$I_{IO-aircraft-life}^{air,aircraft/engine-maintenance} = I_{IO}^{air,aircraft/engine-maintenance} \times \frac{PMT}{aircraft-life} \times \frac{yr_{system}}{PMT}$$

$$I_{IO-VMT}^{air,aircraft/engine-maintenance} = I_{IO}^{air,aircraft/engine-maintenance} \times \frac{yr_{system}}{VMT}$$

$$I_{IO-PMT}^{air,aircraft/engine-maintenance} = I_{IO}^{air,aircraft/engine-maintenance} \times \frac{yr_{system}}{PMT}$$

7.1.4 Insurance

Similar to other modes' inventory calculations, insurance on aircraft is computed from liability and benefits through EIOLCA. 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 63).

Table 63 - Aircraft insurance costs in $M/aircraft-life

	Embraer 145	Boeing 737	Boeing 747
Pilot and Flight Crew Benefits	0.9	16	12
Vehicle Casualty and Liability	0.4	3.4	1.1

7.1.5 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 64 [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 64 - Weight of Passengers, freight, and mail on aircraft (per flight)

Aircraft Size	# Pax	Weight of Pax & Luggage (lbs)	Weight of Freight (lbs)	Weight of Mail (lbs)	% Weight to Pax
Small	32	6,107	7	5	100%
Medium	103	19,639	584	166	96%
Large	182	34,573	6,456	743	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 vehicle inventory to account for the passenger's effect.

7.1.6 Air Vehicle Results

Table 65 - Air vehicle inventory for Embraer 145

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Aircraft Manufacture	Energy	63,000 GJ	4,700 kJ	150 kJ
	GHG	5,100 mt GGE	380 g GGE	12 g GGE
	SO_2	13,000 kg	990 mg	31 mg
	CO	51,000 kg	3,800 mg	120 mg
	NO_X	11,000 kg	830 mg	26 mg
	VOC	8,400 kg	620 mg	19 mg
	Pb	11 kg	0.82 mg	0.026 mg
	PM_{10}	3,100 kg	230 mg	7.2 mg
V, Engine Manufacture	Energy	22,000 GJ	1,600 kJ	51 kJ
	GHG	1,800 mt GGE	130 g GGE	4.1 g GGE
	SO_2	5,000 kg	370 mg	12 mg
	CO	15,000 kg	1,100 mg	35 mg
	NO_X	3,900 kg	290 mg	9.1 mg
	VOC	2,300 kg	170 mg	5.2 mg
	Pb	4.3 kg	0.32 mg	0.0099 mg
	PM_{10}	1,100 kg	83 mg	2.6 mg
V, Operation, APU	Energy	14,000 GJ	1,100 kJ	33 kJ
	GHG	960 mt GGE	71 g GGE	2.2 g GGE
	SO_2	890 kg	66 mg	2.0 mg
	CO	5,700 kg	420 mg	13 mg
	NO_X	4,100 kg	300 mg	9.4 mg
	VOC	540 kg	40 mg	1.2 mg
	Pb	-	-	-
	PM_{10}	-	-	-
V, Operation, Startup	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	14,000 kg	1,000 mg	33 mg
	Pb	-	-	-
	PM_{10}	-	-	-
V, Operation, Taxi	Energy	180,000 GJ	13,000 kJ	420 kJ
	GHG	12,000 mt GGE	900 g GGE	28 g GGE
	SO_2	5,300 kg	390 mg	12 mg
	CO	65,000 kg	4,800 mg	150 mg
	NO_X	15,000 kg	1,100 mg	35 mg
	VOC	8,900 kg	660 mg	21 mg
	Pb	-	-	-
	PM_{10}	600 kg	44 mg	1.4 mg
V, Operation, Take Off	Energy	47,000 GJ	3,500 kJ	110 kJ
	GHG	3,100 mt GGE	230 g GGE	7.3 g GGE
	SO_2	1,400 kg	100 mg	3.2 mg
	CO	810 kg	60 mg	1.9 mg
	NO_X	21,000 kg	1,600 mg	49 mg
	VOC	250 kg	18 mg	0.57 mg
	Pb	-	-	-
	PM_{10}	270 kg	20 mg	0.62 mg
V, Operation, Climb Out	Energy	120,000 GJ	9,200 kJ	290 kJ
	GHG	8,300 mt GGE	620 g GGE	19 g GGE
	SO_2	3,600 kg	270 mg	8.3 mg
	CO	2,100 kg	160 mg	4.9 mg
	NO_X	48,000 kg	3,500 mg	110 mg
	VOC	660 kg	49 mg	1.5 mg
	Pb	-	-	-
	PM_{10}	640 kg	47 mg	1.5 mg
V, Operation, Cruise	Energy	1,100,000 GJ	78,000 kJ	2,400 kJ
	GHG	71,000 mt GGE	5,200 g GGE	160 g GGE
	SO_2	22,000 kg	1,700 mg	52 mg
	CO	30,000 kg	2,300 mg	70 mg
	NO_X	180,000 kg	13,000 mg	410 mg
	VOC	3,800 kg	290 mg	8.9 mg
	Pb	-	-	-
	PM_{10}	900 kg	67 mg	2.1 mg
V, Operation, Approach	Energy	84,000 GJ	6,300 kJ	200 kJ
	GHG	5,600 mt GGE	420 g GGE	13 g GGE
	SO_2	2,500 kg	180 mg	5.7 mg
	CO	5,700 kg	420 mg	13 mg
	NO_X	14,000 kg	1,100 mg	33 mg
	VOC	1,100 kg	78 mg	2.4 mg
	Pb	-	-	-
	PM_{10}	400 kg	29 mg	0.92 mg
V, Operation, Taxi In	Energy	67,000 GJ	5,000 kJ	150 kJ
	GHG	4,400 mt GGE	330 g GGE	10 g GGE
	SO_2	1,900 kg	140 mg	4.5 mg
	CO	24,000 kg	1,800 mg	55 mg
	NO_X	5,600 kg	420 mg	13 mg
	VOC	3,300 kg	240 mg	7.5 mg
	Pb	-	-	-
	PM_{10}	220 kg	16 mg	0.51 mg
V, Maintenance, Lubrication & Fuel	Energy	5,300 GJ	390 kJ	12 kJ
	GHG	340 mt GGE	26 g GGE	0.80 g GGE
	SO_2	190 kg	14 mg	0.43 mg
	CO	620 kg	46 mg	1.4 mg
	NO_X	170 kg	13 mg	0.39 mg
	VOC	160 kg	12 mg	0.36 mg
	Pb	-	-	-
	PM_{10}	32 kg	2.4 mg	0.074 mg
V, Maintenance, Battery	Energy	650 GJ	49 kJ	1.5 kJ
	GHG	50 mt GGE	3.7 g GGE	0.12 g GGE
	SO_2	120 kg	9.2 mg	0.29 mg
	CO	640 kg	48 mg	1.5 mg
	NO_X	110 kg	7.9 mg	0.25 mg
	VOC	84 kg	6.2 mg	0.19 mg
	Pb	0.34 kg	0.026 mg	0.00080 mg
	PM_{10}	34 kg	2.5 mg	0.078 mg
V, Maintenance, Chemical Applicati	Energy	2,100 GJ	160 kJ	4.9 kJ
	GHG	190 mt GGE	14 g GGE	0.44 g GGE
	SO_2	360 kg	27 mg	0.84 mg
	CO	520 kg	39 mg	1.2 mg
	NO_X	210 kg	16 mg	0.49 mg
	VOC	240 kg	17 mg	0.54 mg
	Pb	-	-	-
	PM_{10}	38 kg	2.8 mg	0.087 mg
V, Maintenance, Parts Cleaning	Energy	1,900 GJ	140 kJ	4.3 kJ
	GHG	160 mt GGE	12 g GGE	0.37 g GGE
	SO_2	260 kg	19 mg	0.60 mg
	CO	680 kg	51 mg	1.6 mg
	NO_X	230 kg	17 mg	0.53 mg
	VOC	300 kg	23 mg	0.70 mg
	Pb	-	-	-
	PM_{10}	45 kg	3.4 mg	0.10 mg
V, Maintenance, Metal Finishing	Energy	3,100 GJ	230 kJ	7.2 kJ
	GHG	180 mt GGE	14 g GGE	0.42 g GGE
	SO_2	500 kg	37 mg	1.2 mg
	CO	470 kg	35 mg	1.1 mg
	NO_X	220 kg	16 mg	0.50 mg
	VOC	110 kg	7.8 mg	0.24 mg
	Pb	-	-	-
	PM_{10}	49 kg	3.6 mg	0.11 mg
V, Maintenance, Coating Applicatio	Energy	1,400 GJ	100 kJ	3.2 kJ
	GHG	100 mt GGE	7.6 g GGE	0.23 g GGE
	SO_2	190 kg	14 mg	0.45 mg
	CO	860 kg	63 mg	2.0 mg
	NO_X	170 kg	13 mg	0.40 mg
	VOC	250 kg	19 mg	0.58 mg
	Pb	0.34 kg	0.026 mg	0.00080 mg
	PM_{10}	64 kg	4.7 mg	0.15 mg
V, Maintenance, Depainting	Energy	3,100 GJ	230 kJ	7.2 kJ
	GHG	180 mt GGE	14 g GGE	0.42 g GGE
	SO_2	500 kg	37 mg	1.2 mg
	CO	470 kg	35 mg	1.1 mg
	NO_X	220 kg	16 mg	0.50 mg
	VOC	110 kg	7.8 mg	0.24 mg
	Pb	-	-	-
	PM_{10}	49 kg	3.6 mg	0.11 mg
V, Maintenance, Painting	Energy	4,200 GJ	310 kJ	9.7 kJ
	GHG	310 mt GGE	23 g GGE	0.70 g GGE
	SO_2	580 kg	43 mg	1.3 mg
	CO	2,600 kg	190 mg	5.9 mg
	NO_X	520 kg	39 mg	1.2 mg
	VOC	760 kg	56 mg	1.7 mg
	Pb	1.0 kg	0.077 mg	0.0024 mg
	PM_{10}	190 kg	14 mg	0.44 mg
V, Maintenance, Engine	Energy	1,500 GJ	110 kJ	3.6 kJ
	GHG	120 mt GGE	9.2 g GGE	0.29 g GGE
	SO_2	350 kg	26 mg	0.81 mg
	CO	1,100 kg	78 mg	2.4 mg
	NO_X	280 kg	20 mg	0.64 mg
	VOC	160 kg	12 mg	0.37 mg
	Pb	0.30 kg	0.022 mg	0.00070 mg
	PM_{10}	78 kg	5.8 mg	0.18 mg
V, Insurance, Incidents	Energy	300 GJ	22 kJ	0.68 kJ
	GHG	24 mt GGE	1.8 g GGE	0.056 g GGE
	SO_2	60 kg	4.4 mg	0.14 mg
	CO	270 kg	20 mg	0.62 mg
	NO_X	67 kg	5.0 mg	0.15 mg
	VOC	50 kg	3.7 mg	0.11 mg
	Pb	-	-	-
	PM_{10}	13 kg	0.94 mg	0.029 mg
V, Insurance, Health	Energy	660 GJ	49 kJ	1.5 kJ
	GHG	54 mt GGE	4.0 g GGE	0.13 g GGE
	SO_2	130 kg	9.9 mg	0.31 mg
	CO	600 kg	45 mg	1.4 mg
	NO_X	150 kg	11 mg	0.35 mg

Table 66 - Air vehicle inventory for Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Aircraft Manufacture	Energy	200,000 GJ	3,900 kJ	38 kJ
	GHG	17,000 mt GGE	320 g GGE	3.1 g GGE
	SO_2	43,000 kg	830 mg	8.1 mg
	CO	170,000 kg	3,200 mg	31 mg
	NO_X	36,000 kg	700 mg	6.7 mg
	VOC	27,000 kg	520 mg	5.0 mg
	Pb	36 kg	0.69 mg	0.0067 mg
	PM_{10}	10,000 kg	190 mg	1.9 mg
V, Engine Manufacture	Energy	41,000 GJ	790 kJ	7.6 kJ
	GHG	3,300 mt GGE	63 g GGE	0.61 g GGE
	SO_2	9,300 kg	180 mg	1.7 mg
	CO	28,000 kg	540 mg	5.2 mg
	NO_X	7,300 kg	140 mg	1.4 mg
	VOC	4,200 kg	81 mg	0.78 mg
	Pb	8.0 kg	0.15 mg	0.0015 mg
	PM_{10}	2,100 kg	40 mg	0.38 mg
V, Operation, APU	Energy	98,000 GJ	1,900 kJ	18 kJ
	GHG	6,500 mt GGE	120 g GGE	1.2 g GGE
	SO_2	2,300 kg	45 mg	0.43 mg
	CO	42,000 kg	810 mg	7.8 mg
	NO_X	11,000 kg	210 mg	2.1 mg
	VOC	2,400 kg	46 mg	0.45 mg
	Pb	-	-	-
	PM_{10}	-	-	-
V, Operation, Startup	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	44,000 kg	840 mg	8.2 mg
	Pb	-	-	-
	PM_{10}	-	-	-
V, Operation, Taxi	Energy	700,000 GJ	14,000 kJ	130 kJ
	GHG	47,000 mt GGE	900 g GGE	8.7 g GGE
	SO_2	20,000 kg	390 mg	3.8 mg
	CO	500,000 kg	9,600 mg	93 mg
	NO_X	60,000 kg	1,200 mg	11 mg
	VOC	31,000 kg	600 mg	5.8 mg
	Pb	-	-	-
	PM_{10}	3,600 kg	70 mg	0.68 mg
V, Operation, Take Off	Energy	200,000 GJ	3,800 kJ	37 kJ
	GHG	13,000 mt GGE	250 g GGE	2.4 g GGE
	SO_2	5,700 kg	110 mg	1.1 mg
	CO	3,800 kg	72 mg	0.70 mg
	NO_X	77,000 kg	1,500 mg	14 mg
	VOC	170 kg	3.3 mg	0.032 mg
	Pb	-	-	-
	PM_{10}	910 kg	18 mg	0.17 mg
V, Operation, Climb Out	Energy	520,000 GJ	10,000 kJ	97 kJ
	GHG	35,000 mt GGE	670 g GGE	6.4 g GGE
	SO_2	15,000 kg	290 mg	2.8 mg
	CO	9,900 kg	190 mg	1.8 mg
	NO_X	180,000 kg	3,400 mg	33 mg
	VOC	460 kg	8.8 mg	0.085 mg
	Pb	-	-	-
	PM_{10}	2,100 kg	40 mg	0.38 mg
V, Operation, Cruise	Energy	11,000,000 GJ	220,000 kJ	2,100 kJ
	GHG	750,000 mt GGE	14,000 g GGE	140 g GGE
	SO_2	240,000 kg	4,600 mg	44 mg
	CO	420,000 kg	8,000 mg	78 mg
	NO_X	2,300 kg	45 mg	0.43 mg
	VOC	23,000 kg	440 mg	4.3 mg
	Pb	-	-	-
	PM_{10}	9,600 kg	180 mg	1.8 mg
V, Operation, Approach	Energy	350,000 GJ	6,700 kJ	65 kJ
	GHG	23,000 mt GGE	450 g GGE	4.3 g GGE
	SO_2	10,000 kg	200 mg	1.9 mg
	CO	27,000 kg	530 mg	5.1 mg
	NO_X	64,000 kg	1,200 mg	12 mg
	VOC	550 kg	10 mg	0.10 mg
	Pb	-	-	-
	PM_{10}	1,500 kg	29 mg	0.28 mg
V, Operation, Taxi In	Energy	260,000 GJ	5,000 kJ	48 kJ
	GHG	17,000 mt GGE	330 g GGE	3.2 g GGE
	SO_2	7,600 kg	140 mg	1.4 mg
	CO	180,000 kg	3,500 mg	34 mg
	NO_X	22,000 kg	430 mg	4.1 mg
	VOC	12,000 kg	220 mg	2.1 mg
	Pb	-	-	-
	PM_{10}	1,300 kg	26 mg	0.25 mg
V, Maintenance, Lubrication & Fuel	Energy	62,000 GJ	1,200 kJ	12 kJ
	GHG	4,100 mt GGE	78 g GGE	0.76 g GGE
	SO_2	2,200 kg	42 mg	0.41 mg
	CO	7,300 kg	140 mg	1.4 mg
	NO_X	2,000 kg	38 mg	0.37 mg
	VOC	1,800 kg	35 mg	0.34 mg
	Pb	-	-	-
	PM_{10}	380 kg	7.3 mg	0.071 mg
V, Maintenance, Battery	Energy	7,700 GJ	150 kJ	1.4 kJ
	GHG	590 mt GGE	11 g GGE	0.11 g GGE
	SO_2	1,500 kg	28 mg	0.27 mg
	CO	7,600 kg	150 mg	1.4 mg
	NO_X	1,300 kg	24 mg	0.23 mg
	VOC	990 kg	19 mg	0.18 mg
	Pb	4.1 kg	0.078 mg	0.00076 mg
	PM_{10}	400 kg	7.6 mg	0.074 mg
V, Maintenance, Chemical Applicati	Energy	25,000 GJ	480 kJ	4.6 kJ
	GHG	2,200 mt GGE	43 g GGE	0.42 g GGE
	SO_2	4,300 kg	82 mg	0.80 mg
	CO	6,100 kg	120 mg	1.1 mg
	NO_X	2,500 kg	48 mg	0.46 mg
	VOC	2,800 kg	53 mg	0.52 mg
	Pb	-	-	-
	PM_{10}	440 kg	8.5 mg	0.082 mg
V, Maintenance, Parts Cleaning	Energy	22,000 GJ	420 kJ	4.1 kJ
	GHG	1,900 mt GGE	37 g GGE	0.36 g GGE
	SO_2	3,100 kg	59 mg	0.57 mg
	CO	8,100 kg	150 mg	1.5 mg
	NO_X	2,700 kg	52 mg	0.50 mg
	VOC	3,600 kg	69 mg	0.67 mg
	Pb	-	-	-
	PM_{10}	540 kg	10 mg	0.100 mg
V, Maintenance, Metal Finishing	Energy	37,000 GJ	710 kJ	6.8 kJ
	GHG	2,200 mt GGE	41 g GGE	0.40 g GGE
	SO_2	5,900 kg	110 mg	1.1 mg
	CO	5,600 kg	110 mg	1.0 mg
	NO_X	2,600 kg	49 mg	0.47 mg
	VOC	1,200 kg	24 mg	0.23 mg
	Pb	-	-	-
	PM_{10}	580 kg	11 mg	0.11 mg
V, Maintenance, Coating Applicatio	Energy	16,000 GJ	320 kJ	3.1 kJ
	GHG	1,200 mt GGE	23 g GGE	0.22 g GGE
	SO_2	2,300 kg	44 mg	0.42 mg
	CO	10,000 kg	190 mg	1.9 mg
	NO_X	2,100 kg	39 mg	0.38 mg
	VOC	3,000 kg	57 mg	0.55 mg
	Pb	4.1 kg	0.078 mg	0.00076 mg
	PM_{10}	750 kg	14 mg	0.14 mg
V, Maintenance, Depainting	Energy	37,000 GJ	710 kJ	6.8 kJ
	GHG	2,200 mt GGE	41 g GGE	0.40 g GGE
	SO_2	5,900 kg	110 mg	1.1 mg
	CO	5,600 kg	110 mg	1.0 mg
	NO_X	2,600 kg	49 mg	0.47 mg
	VOC	1,200 kg	24 mg	0.23 mg
	Pb	-	-	-
	PM_{10}	580 kg	11 mg	0.11 mg
V, Maintenance, Painting	Energy	49,000 GJ	950 kJ	9.2 kJ
	GHG	3,600 mt GGE	69 g GGE	0.67 g GGE
	SO_2	6,800 kg	130 mg	1.3 mg
	CO	30,000 kg	580 mg	5.6 mg
	NO_X	6,200 kg	120 mg	1.1 mg
	VOC	9,000 kg	170 mg	1.7 mg
	Pb	12 kg	0.23 mg	0.0023 mg
	PM_{10}	2,300 kg	43 mg	0.42 mg
V, Maintenance, Engine	Energy	29,000 GJ	560 kJ	5.4 kJ
	GHG	2,300 mt GGE	45 g GGE	0.43 g GGE
	SO_2	6,600 kg	130 mg	1.2 mg
	CO	20,000 kg	380 mg	3.7 mg
	NO_X	5,200 kg	100 mg	0.96 mg
	VOC	3,000 kg	58 mg	0.56 mg
	Pb	5.7 kg	0.11 mg	0.0011 mg
	PM_{10}	1,500 kg	28 mg	0.27 mg
V, Insurance, Incidents	Energy	3,100 GJ	60 kJ	0.58 kJ
	GHG	260 mt GGE	4.9 g GGE	0.048 g GGE
	SO_2	630 kg	12 mg	0.12 mg
	CO	2,900 kg	55 mg	0.53 mg
	NO_X	710 kg	14 mg	0.13 mg
	VOC	530 kg	10 mg	0.098 mg
	Pb	-	-	-
	PM_{10}	130 kg	2.6 mg	0.025 mg
V, Insurance, Health	Energy	14,000 GJ	280 kJ	2.7 kJ
	GHG	1,200 mt GGE	23 g GGE	0.22 g GGE
	SO_2	2,900 kg	55 mg	0.54 mg
	CO	13,000 kg	250 mg	2.4 mg
	NO_X	3,300 kg	62 mg	0.60 mg

Table 67 - Air vehicle inventory for Boeing 747

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
V, Aircraft Manufacture	Energy	640,000 GJ	76,000 kJ	420 kJ
	GHG	52,000 mt GGE	6,200 g GGE	34 g GGE
	SO_2	140,000 kg	16,000 mg	89 mg
	CO	520,000 kg	61,000 mg	340 mg
	NO_X	110,000 kg	13,000 mg	74 mg
	VOC	85,000 kg	10,000 mg	55 mg
	Pb	110 kg	13 mg	0.073 mg
	PM_{10}	32,000 kg	3,800 mg	21 mg
V, Engine Manufacture	Energy	140,000 GJ	16,000 kJ	89 kJ
	GHG	11,000 mt GGE	1,300 g GGE	7.1 g GGE
	SO_2	31,000 kg	3,600 mg	20 mg
	CO	93,000 kg	11,000 mg	60 mg
	NO_X	24,000 kg	2,900 mg	16 mg
	VOC	14,000 kg	1,700 mg	9.1 mg
	Pb	26 kg	3.1 mg	0.017 mg
	PM_{10}	6,800 kg	810 mg	4.5 mg
V, Operation, APU	Energy	92,000 GJ	11,000 kJ	60 kJ
	GHG	6,100 mt GGE	730 g GGE	4.0 g GGE
	SO_2	460 kg	55 mg	0.30 mg
	CO	7,800 kg	920 mg	5.1 mg
	NO_X	1,500 kg	170 mg	0.95 mg
	VOC	700 kg	83 mg	0.45 mg
	Pb	-	-	-
	PM_{10}	-	-	-
V, Operation, Startup	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	3,200 kg	380 mg	2.1 mg
	Pb	-	-	-
	PM_{10}	-	-	-
V, Operation, Taxi	Energy	130,000 GJ	15,000 kJ	82 kJ
	GHG	8,400 mt GGE	1,000 g GGE	5.5 g GGE
	SO_2	3,700 kg	430 mg	2.4 mg
	CO	30,000 kg	3,600 mg	20 mg
	NO_X	14,000 kg	1,600 mg	9.0 mg
	VOC	1,600 kg	190 mg	1.1 mg
	Pb	-	-	-
	PM_{10}	850 kg	100 mg	0.55 mg
V, Operation, Take Off	Energy	56,000 GJ	6,600 kJ	36 kJ
	GHG	3,700 mt GGE	440 g GGE	2.4 g GGE
	SO_2	1,600 kg	190 mg	1.1 mg
	CO	130 kg	15 mg	0.082 mg
	NO_X	40,000 kg	4,700 mg	26 mg
	VOC	150 kg	18 mg	0.099 mg
	Pb	-	-	-
	PM_{10}	640 kg	76 mg	0.42 mg
V, Operation, Climb Out	Energy	140,000 GJ	17,000 kJ	92 kJ
	GHG	9,400 mt GGE	1,100 g GGE	6.1 g GGE
	SO_2	4,100 kg	490 mg	2.7 mg
	CO	320 kg	38 mg	0.21 mg
	NO_X	76,000 kg	9,100 mg	50 mg
	VOC	390 kg	46 mg	0.25 mg
	Pb	-	-	-
	PM_{10}	1,600 kg	200 mg	1.1 mg
V, Operation, Cruise	Energy	5,500,000 GJ	650,000 kJ	3,600 kJ
	GHG	370,000 mt GGE	44,000 g GGE	240 g GGE
	SO_2	120,000 kg	14,000 mg	76 mg
	CO	110,000 kg	13,000 mg	73 mg
	NO_X	1,600 kg	190 mg	1.1 mg
	VOC	29,000 kg	3,400 mg	19 mg
	Pb	-	-	-
	PM_{10}	4,700 kg	550 mg	3.0 mg
V, Operation, Approach	Energy	85,000 GJ	10,000 kJ	55 kJ
	GHG	5,600 mt GGE	670 g GGE	3.7 g GGE
	SO_2	2,500 kg	290 mg	1.6 mg
	CO	1,600 kg	190 mg	1.0 mg
	NO_X	21,000 kg	2,500 mg	14 mg
	VOC	410 kg	49 mg	0.27 mg
	Pb	-	-	-
	PM_{10}	550 kg	65 mg	0.36 mg
V, Operation, Taxi In	Energy	46,000 GJ	5,500 kJ	30 kJ
	GHG	3,100 mt GGE	370 g GGE	2.0 g GGE
	SO_2	1,300 kg	160 mg	0.88 mg
	CO	11,000 kg	1,300 mg	7.2 mg
	NO_X	5,100 kg	600 mg	3.3 mg
	VOC	600 kg	71 mg	0.39 mg
	Pb	-	-	-
	PM_{10}	310 kg	37 mg	0.20 mg
V, Maintenance, Lubrication & Fuel	Energy	16,000 GJ	1,900 kJ	10 kJ
	GHG	1,000 mt GGE	120 g GGE	0.67 g GGE
	SO_2	550 kg	66 mg	0.36 mg
	CO	1,800 kg	220 mg	1.2 mg
	NO_X	510 kg	60 mg	0.33 mg
	VOC	470 kg	55 mg	0.30 mg
	Pb	-	-	-
	PM_{10}	96 kg	11 mg	0.063 mg
V, Maintenance, Battery	Energy	2,000 GJ	230 kJ	1.3 kJ
	GHG	150 mt GGE	18 g GGE	0.098 g GGE
	SO_2	370 kg	44 mg	0.24 mg
	CO	1,900 kg	230 mg	1.3 mg
	NO_X	320 kg	38 mg	0.21 mg
	VOC	250 kg	30 mg	0.16 mg
	Pb	1.0 kg	0.12 mg	0.00067 mg
	PM_{10}	100 kg	12 mg	0.065 mg
V, Maintenance, Chemical Applicati	Energy	6,300 GJ	750 kJ	4.1 kJ
	GHG	570 mt GGE	67 g GGE	0.37 g GGE
	SO_2	1,100 kg	130 mg	0.71 mg
	CO	1,500 kg	180 mg	1.0 mg
	NO_X	630 kg	75 mg	0.41 mg
	VOC	700 kg	83 mg	0.46 mg
	Pb	-	-	-
	PM_{10}	110 kg	13 mg	0.073 mg
V, Maintenance, Parts Cleaning	Energy	5,600 GJ	660 kJ	3.6 kJ
	GHG	480 mt GGE	57 g GGE	0.32 g GGE
	SO_2	770 kg	92 mg	0.50 mg
	CO	2,000 kg	240 mg	1.3 mg
	NO_X	680 kg	81 mg	0.45 mg
	VOC	910 kg	110 mg	0.59 mg
	Pb	-	-	-
	PM_{10}	140 kg	16 mg	0.088 mg
V, Maintenance, Metal Finishing	Energy	9,300 GJ	1,100 kJ	6.1 kJ
	GHG	550 mt GGE	65 g GGE	0.36 g GGE
	SO_2	1,500 kg	180 mg	0.98 mg
	CO	1,400 kg	170 mg	0.92 mg
	NO_X	650 kg	77 mg	0.42 mg
	VOC	310 kg	37 mg	0.20 mg
	Pb	-	-	-
	PM_{10}	150 kg	17 mg	0.095 mg
V, Maintenance, Coating Applicatio	Energy	4,200 GJ	490 kJ	2.7 kJ
	GHG	300 mt GGE	36 g GGE	0.20 g GGE
	SO_2	580 kg	68 mg	0.38 mg
	CO	2,600 kg	300 mg	1.7 mg
	NO_X	520 kg	62 mg	0.34 mg
	VOC	750 kg	89 mg	0.49 mg
	Pb	1.0 kg	0.12 mg	0.00067 mg
	PM_{10}	190 kg	23 mg	0.12 mg
V, Maintenance, Depainting	Energy	9,300 GJ	1,100 kJ	6.1 kJ
	GHG	550 mt GGE	65 g GGE	0.36 g GGE
	SO_2	1,500 kg	180 mg	0.98 mg
	CO	1,400 kg	170 mg	0.92 mg
	NO_X	650 kg	77 mg	0.42 mg
	VOC	310 kg	37 mg	0.20 mg
	Pb	-	-	-
	PM_{10}	150 kg	17 mg	0.095 mg
V, Maintenance, Painting	Energy	13,000 GJ	1,500 kJ	8.1 kJ
	GHG	910 mt GGE	110 g GGE	0.59 g GGE
	SO_2	1,700 kg	210 mg	1.1 mg
	CO	7,700 kg	910 mg	5.0 mg
	NO_X	1,600 kg	180 mg	1.0 mg
	VOC	2,300 kg	270 mg	1.5 mg
	Pb	3.1 kg	0.37 mg	0.0020 mg
	PM_{10}	570 kg	68 mg	0.37 mg
V, Maintenance, Engine	Energy	38,000 GJ	4,500 kJ	25 kJ
	GHG	3,000 mt GGE	360 g GGE	2.0 g GGE
	SO_2	8,500 kg	1,000 mg	5.6 mg
	CO	26,000 kg	3,000 mg	17 mg
	NO_X	6,700 kg	790 mg	4.4 mg
	VOC	3,900 kg	460 mg	2.5 mg
	Pb	7.3 kg	0.87 mg	0.0048 mg
	PM_{10}	1,900 kg	220 mg	1.2 mg
V, Insurance, Incidents	Energy	460 GJ	55 kJ	0.30 kJ
	GHG	38 mt GGE	4.5 g GGE	0.025 g GGE
	SO_2	93 kg	11 mg	0.060 mg
	CO	420 kg	50 mg	0.27 mg
	NO_X	100 kg	12 mg	0.068 mg
	VOC	77 kg	9.2 mg	0.051 mg
	Pb	-	-	-
	PM_{10}	20 kg	2.3 mg	0.013 mg
V, Insurance, Health	Energy	5,100 GJ	600 kJ	3.3 kJ
	GHG	420 mt GGE	50 g GGE	0.27 g GGE
	SO_2	1,000 kg	120 mg	0.67 mg
	CO	4,600 kg	550 mg	3.0 mg
	NO_X	1,200 kg	140 mg	0.75 mg

7.2 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.

Figure 23 – Dulles aerial view
Source: GE 2007

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 2005].

In order 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.

7.2.1 Airport Construction

Figure 24 – Dulles construction, circa 1961
Source: http://www.faa.gov/

Airport construction is a heavy construction activity which has not been heavily studied from an environmental standpoint. The materials and process required to construction 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 EIOLCA sector Commercial and Institutional Buildings (#230220) and output is normalized to the functional units as shown in Equation Set 37 [EIOLCA].

Equation Set 37 – Airport buildings inventory

$$I_{IO}^{air,airport-construction} = \frac{I_{EIOLCA}}{airport-life} \times \frac{PMT_{aircraft-size-yr}}{PMT_{US-yr}}$$

$$I_{IO-aircraft-life}^{air,airport-construction} = I_{IO}^{air,airport-construction} \times \frac{yr_{system}}{PMT_{system}} \times \frac{PMT_{aircraft}}{aircraft-life}$$

$$I_{IO-VMT}^{air,airport-construction} = I_{IO}^{air,airport-construction} \times \frac{yr_{system}}{VMT_{system}}$$

$$I_{IO-PMT}^{air,airport-construction} = I_{IO}^{air,airport-construction} \times \frac{yr_{system}}{VMT_{system}} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}$$

7.2.2 Runway, Taxiway and Tarmac Construction and Maintenance

The production and placement of concrete for runways, taxiways, and tarmac construction and maintenance has 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]. This is 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 of the airports can accommodate large aircraft [Sandel 2006]. Runway construction is estimated with PaLATE and EPA VOC data [PaLATE, 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 at an airport 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 environmental impact [PaLATE].

Figure 25 – Dulles terminals
Source: GE 2007

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.

Equation Set 38 – Airport infrastructure runway, taxiway, and tarmac construction and maintenance

$$I^{air,runway/taxiway/tarmac}_{IO,aircraft} = I^{air,runway/taxiway/tarmac}_{IO,system} \times \frac{PMT_{aircraft-size-yr}}{PMT_{US-yr}}$$

$$= \text{Yearly construction \& maintenance impact attributed to aircraft size}$$

$$I^{air,runway/taxiway/tarmac}_{IO-vehicle-lifetime} = I^{air,runway/taxiway/tarmac}_{IO,aircraft} \times \frac{yr}{PMT_{US}} \times \frac{PMT_{aircraft}}{aircraft-life}$$

$$I^{air,runway/taxiway/tarmac}_{IO-VMT} = I^{air,runway/taxiway/tarmac}_{IO,aircraft} \times \frac{yr}{VMT_{US}}$$

$$I^{air,runway/taxiway/tarmac}_{IO-PMT} = I^{air,runway/taxiway/tarmac}_{IO,aircraft} \times \frac{yr}{VMT_{US}} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}$$

7.2.3 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 EIOLCA sector Other Miscellaneous Chemical Product Manufacturing (#325998) captures production of these fluids [EIOLCA]. 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 EIOLCA.

Ground Support Equipment

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

Typical GSE 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 airport GSE populations specified so it is necessary to determine the number and configuration of each vehicle type at Dulles. This is done 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.

Figure 26 – Ground support equipment at San Francisco International Airport
Source: Mikhail Chester, June 14, 2007

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

$$\mathrm{I}^{\mathrm{air,operation,i}} = \text{Yearly impact of airport infrastructure operation component i}$$

$$I_{IO-aircraft}^{air,operation,i} = I^{air,operation,i} \times \frac{PMT_{aircraft-size-yr}}{PMT_{US-yr}}$$

$$I_{IO-vehicle-lifetime}^{air,parking} = I_{IO-aircraft}^{air,parking} \times \frac{yr}{PMT_{US}} \times \frac{PMT_{aircraft}}{aircraft-life}$$

$$I_{IO-VMT}^{air,parking} = I_{IO-aircraft}^{air,parking} \times \frac{yr}{VMT_{US}}$$

$$I_{IO-PMT}^{air,parking} = I_{IO-aircraft}^{air,parking} \times \frac{yr}{VMT_{US}} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}$$

7.2.4 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.

7.2.5 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, 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.

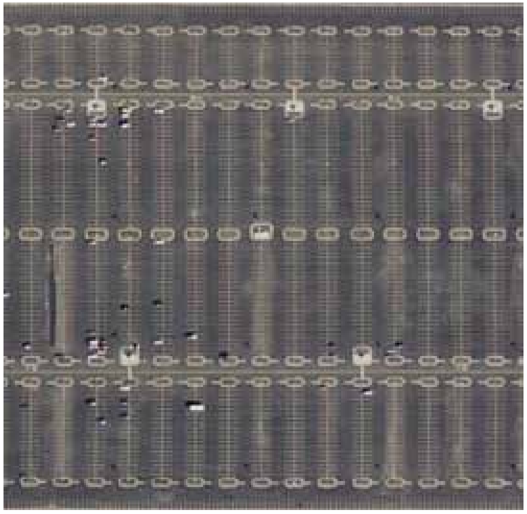


Figure 27 – Dulles parking (purple lot)
Source: GE 2007

Equation Set 40 – Airport infrastructure parking

construction and maintenance

$$I_{PaLATE/VOC} = \mathrm{Im}\,pact\ \ from\ parking\ construction\ and\ ma\,\mathrm{int}\,enance$$

$$I_{IO,aircraft}^{air,parking} = \frac{I_{PaLATE/VOC}}{parking-area-life} \times \frac{PMT_{aircraft-size-yr}}{PMT_{US-yr}}$$

$$I_{IO-vehicle-lifetime}^{air,parking} = I_{IO,aircraft}^{air,parking} \times \frac{yr}{PMT_{US}} \times \frac{PMT_{aircraft}}{aircraft-life}$$

$$I_{IO-VMT}^{air,parking} = I_{IO,aircraft}^{air,parking} \times \frac{yr}{VMT_{US}}$$

$$I_{IO-PMT}^{air,parking} = I_{IO,aircraft}^{air,parking} \times \frac{yr}{VMT_{US}} \times \frac{VMT_{aircraft}}{PMT_{aircraft}}$$

7.2.6 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 equal then half of this amount went towards employee benefits. 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 EIOLCA to compute impact.

Table 68 - Airport insurance costs ($M/aircraft-life)

	Embraer 145	Boeing 737	Boeing 747
Benefits for Non-Flight Crew Personnel	1.7	13	14
Non-Vehicle Casualty and Liability	0.2	1.5	1.6

Normalization calculations are shown in Equation Set 41.

Equation Set 41 – Airport insurance

$$I_{IO,aircraft}^{air,airport-insurance} = \frac{I_{EIOLCA}}{airport-life} \times \frac{PMT_{aircraft-size-yr}}{PMT_{US-yr}}$$

$$I_{IO-aircraft-life}^{air,airport-insurance} = I_{IO,aircraft}^{air,airport-insurance} \times \frac{yr_{system}}{PMT_{system}} \times \frac{PMT_{aircraft}}{aircraft-life}$$

$$I_{IO-VMT}^{air,airport-insurance} = I_{IO,aircraft}^{air,airport-insurance} \times \frac{yr_{system}}{VMT}$$

$$I_{IO-PMT}^{air,airport-insurance} = I_{IO,aircraft}^{air,airport-insurance} \times \frac{yr_{system}}{VMT} \times \frac{VMT}{PMT}$$

7.2.7 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 §7.1.5) 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 is 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.

7.2.8 Air Infrastructure Results

Table 69 - Aircraft infrastructure inventory for Embraer 145

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Construction, Airports	Energy	500 GJ	37 kJ	1.1 kJ
	GHG	39 mt GGE	2.9 g GGE	0.089 g GGE
	SO_2	68 kg	5.0 mg	0.16 mg
	CO	350 kg	26 mg	0.82 mg
	NO_X	130 kg	9.6 mg	0.30 mg
	VOC	65 kg	4.8 mg	0.15 mg
	Pb	-	-	-
	PM_{10}	27 kg	2.0 mg	0.061 mg
I, Construction, Runways	Energy	2,500 GJ	180 kJ	5.7 kJ
	GHG	180 mt GGE	13 g GGE	0.41 g GGE
	SO_2	1,300 kg	96 mg	3.0 mg
	CO	1,100 kg	78 mg	2.4 mg
	NO_X	2,400 kg	180 mg	5.5 mg
	VOC	-	-	-
	Pb	0.15 kg	0.011 mg	0.00034 mg
	PM_{10}	3,800 kg	280 mg	8.7 mg
I, Construction, Tarmacs	Energy	6,400 GJ	480 kJ	15 kJ
	GHG	460 mt GGE	34 g GGE	1.1 g GGE
	SO_2	3,400 kg	250 mg	7.9 mg
	CO	2,800 kg	210 mg	6.4 mg
	NO_X	6,200 kg	460 mg	14 mg
	VOC	-	-	-
	Pb	0.38 kg	0.028 mg	0.00088 mg
	PM_{10}	2,400 kg	180 mg	5.6 mg
I, Operation, Runway Lighting	Energy	1,200 GJ	86 kJ	2.7 kJ
	GHG	240 mt GGE	18 g GGE	0.56 g GGE
	SO_2	1,200 kg	91 mg	2.8 mg
	CO	120 kg	8.7 mg	0.27 mg
	NO_X	400 kg	30 mg	0.93 mg
	VOC	10 kg	0.78 mg	0.024 mg
	Pb	0.019 kg	0.0014 mg	0.000044 mg
	PM_{10}	13 kg	1.00 mg	0.031 mg
I, Operation, Other Electricity	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-
I, Operation, Deicing Fluid Producti	Energy	1,800 GJ	140 kJ	4.2 kJ
	GHG	140 mt GGE	10 g GGE	0.31 g GGE
	SO_2	560 kg	41 mg	1.3 mg
	CO	870 kg	64 mg	2.0 mg
	NO_X	580 kg	43 mg	1.3 mg
	VOC	280 kg	21 mg	0.64 mg
	Pb	-	-	-
	PM_{10}	87 kg	6.5 mg	0.20 mg
I, Operation, Ground Support Equip	Energy	15,000 GJ	1,100 kJ	34 kJ
	GHG	1,100 mt GGE	82 g GGE	2.6 g GGE
	SO_2	820 kg	61 mg	1.9 mg
	CO	80,000 kg	6,000 mg	190 mg
	NO_X	11,000 kg	820 mg	26 mg
	VOC	3,000 kg	220 mg	6.8 mg
	Pb	-	-	-
	PM_{10}	480 kg	36 mg	1.1 mg
I, Maintenance, Airports	Energy	25 GJ	1.8 kJ	0.057 kJ
	GHG	1.9 mt GGE	0.14 g GGE	0.0045 g GGE
	SO_2	3.4 kg	0.25 mg	0.0078 mg
	CO	18 kg	1.3 mg	0.041 mg
	NO_X	6.5 kg	0.48 mg	0.015 mg
	VOC	3.3 kg	0.24 mg	0.0075 mg
	Pb	-	-	-
	PM_{10}	1.3 kg	0.099 mg	0.0031 mg
I, Maintenance, Runways	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-
I, Maintenance, Tarmacs	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-
I, Parking	Energy	1,200 GJ	89 kJ	2.8 kJ
	GHG	77 mt GGE	5.7 g GGE	0.18 g GGE
	SO_2	1,600 kg	120 mg	3.6 mg
	CO	360 kg	27 mg	0.83 mg
	NO_X	900 kg	67 mg	2.1 mg
	VOC	1,200 kg	92 mg	2.9 mg
	Pb	0.015 kg	0.0011 mg	0.000035 mg
	PM_{10}	2,000 kg	150 mg	4.7 mg
I, Insurance, Non-Operator	Energy	1,100 GJ	80 kJ	2.5 kJ
	GHG	88 mt GGE	6.5 g GGE	0.20 g GGE
	SO_2	220 kg	16 mg	0.50 mg
	CO	970 kg	72 mg	2.2 mg
	NO_X	240 kg	18 mg	0.56 mg
	VOC	180 kg	13 mg	0.42 mg
	Pb	-	-	-
	PM_{10}	46 kg	3.4 mg	0.11 mg
I, Insurance, Liability	Energy	120 GJ	8.9 kJ	0.28 kJ
	GHG	9.9 mt GGE	0.73 g GGE	0.023 g GGE
	SO_2	24 kg	1.8 mg	0.056 mg
	CO	110 kg	8.1 mg	0.25 mg
	NO_X	27 kg	2.0 mg	0.063 mg
	VOC	20 kg	1.5 mg	0.047 mg
	Pb	-	-	-
	PM_{10}	5.1 kg	0.38 mg	0.012 mg

Table 70 - Aircraft infrastructure inventory for Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Construction, Airports	Energy	6,200 GJ	120 kJ	1.1 kJ
	GHG	480 mt GGE	9.2 g GGE	0.089 g GGE
	SO_2	840 kg	16 mg	0.16 mg
	CO	4,400 kg	84 mg	0.82 mg
	NO_X	1,600 kg	31 mg	0.30 mg
	VOC	810 kg	16 mg	0.15 mg
	Pb	-	-	-
	PM_{10}	330 kg	6.4 mg	0.061 mg
I, Construction, Runways	Energy	30,000 GJ	570 kJ	5.5 kJ
	GHG	2,100 mt GGE	40 g GGE	0.39 g GGE
	SO_2	16,000 kg	300 mg	2.9 mg
	CO	13,000 kg	240 mg	2.3 mg
	NO_X	28,000 kg	550 mg	5.3 mg
	VOC	-	-	-
	Pb	1.8 kg	0.034 mg	0.00033 mg
	PM_{10}	45,000 kg	860 mg	8.4 mg
I, Construction, Tarmacs	Energy	77,000 GJ	1,500 kJ	14 kJ
	GHG	5,500 mt GGE	110 g GGE	1.0 g GGE
	SO_2	41,000 kg	790 mg	7.6 mg
	CO	33,000 kg	640 mg	6.2 mg
	NO_X	74,000 kg	1,400 mg	14 mg
	VOC	-	-	-
	Pb	4.6 kg	0.088 mg	0.00085 mg
	PM_{10}	29,000 kg	560 mg	5.4 mg
I, Operation, Runway Lighting	Energy	14,000 GJ	270 kJ	2.6 kJ
	GHG	2,900 mt GGE	56 g GGE	0.54 g GGE
	SO_2	15,000 kg	280 mg	2.7 mg
	CO	1,400 kg	27 mg	0.26 mg
	NO_X	4,800 kg	93 mg	0.90 mg
	VOC	130 kg	2.4 mg	0.023 mg
	Pb	0.23 kg	0.0044 mg	0.000043 mg
	PM_{10}	160 kg	3.1 mg	0.030 mg
I, Operation, Other Electricity	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-
I, Operation, Deicing Fluid Producti	Energy	22,000 GJ	420 kJ	4.1 kJ
	GHG	1,600 mt GGE	31 g GGE	0.30 g GGE
	SO_2	6,700 kg	130 mg	1.2 mg
	CO	10,000 kg	200 mg	1.9 mg
	NO_X	7,000 kg	130 mg	1.3 mg
	VOC	3,300 kg	64 mg	0.62 mg
	Pb	-	-	-
	PM_{10}	1,000 kg	20 mg	0.19 mg
I, Operation, Ground Support Equip	Energy	170,000 GJ	3,300 kJ	32 kJ
	GHG	13,000 mt GGE	260 g GGE	2.5 g GGE
	SO_2	9,900 kg	190 mg	1.8 mg
	CO	970,000 kg	19,000 mg	180 mg
	NO_X	130,000 kg	2,600 mg	25 mg
	VOC	35,000 kg	680 mg	6.6 mg
	Pb	-	-	-
	PM_{10}	5,800 kg	110 mg	1.1 mg
I, Maintenance, Airports	Energy	310 GJ	5.9 kJ	0.057 kJ
	GHG	24 mt GGE	0.46 g GGE	0.0045 g GGE
	SO_2	42 kg	0.81 mg	0.0078 mg
	CO	220 kg	4.2 mg	0.041 mg
	NO_X	81 kg	1.5 mg	0.015 mg
	VOC	40 kg	0.78 mg	0.0075 mg
	Pb	-	-	-
	PM_{10}	17 kg	0.32 mg	0.0031 mg
I, Maintenance, Runways	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-
I, Maintenance, Tarmacs	Energy	-	-	-
	GHG	-	-	-
	SO_2	-	-	-
	CO	-	-	-
	NO_X	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM_{10}	-	-	-
I, Parking	Energy	15,000 GJ	290 kJ	2.8 kJ
	GHG	960 mt GGE	18 g GGE	0.18 g GGE
	SO_2	20,000 kg	380 mg	3.6 mg
	CO	4,500 kg	86 mg	0.83 mg
	NO_X	11,000 kg	220 mg	2.1 mg
	VOC	15,000 kg	300 mg	2.9 mg
	Pb	0.19 kg	0.0036 mg	0.000035 mg
	PM_{10}	25,000 kg	480 mg	4.7 mg
I, Insurance, Non-Operator	Energy	13,000 GJ	250 kJ	2.4 kJ
	GHG	1,100 mt GGE	20 g GGE	0.20 g GGE
	SO_2	2,600 kg	50 mg	0.48 mg
	CO	12,000 kg	220 mg	2.2 mg
	NO_X	2,900 kg	56 mg	0.54 mg
	VOC	2,200 kg	41 mg	0.40 mg
	Pb	-	-	-
	PM_{10}	550 kg	11 mg	0.10 mg
I, Insurance, Liability	Energy	1,400 GJ	28 kJ	0.27 kJ
	GHG	120 mt GGE	2.3 g GGE	0.022 g GGE
	SO_2	290 kg	5.6 mg	0.054 mg
	CO	1,300 kg	25 mg	0.24 mg
	NO_X	330 kg	6.3 mg	0.061 mg
	VOC	240 kg	4.7 mg	0.045 mg
	Pb	-	-	-
	PM_{10}	62 kg	1.2 mg	0.011 mg

Table 71 - Aircraft infrastructure inventory for Boeing 747

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
I, Construction, Airports	Energy	1,800 GJ	210 kJ	1.1 kJ
	GHG	140 mt GGE	16 g GGE	0.089 g GGE
	SO$_2$	240 kg	28 mg	0.16 mg
	CO	1,300 kg	150 mg	0.82 mg
	NO$_X$	460 kg	54 mg	0.30 mg
	VOC	230 kg	27 mg	0.15 mg
	Pb	-	-	-
	PM$_{10}$	94 kg	11 mg	0.061 mg
I, Construction, Runways	Energy	7,200 GJ	860 kJ	4.7 kJ
	GHG	520 mt GGE	61 g GGE	0.34 g GGE
	SO$_2$	3,800 kg	450 mg	2.5 mg
	CO	3,100 kg	370 mg	2.0 mg
	NO$_X$	7,000 kg	830 mg	4.5 mg
	VOC	-	-	-
	Pb	0.43 kg	0.051 mg	0.00028 mg
	PM$_{10}$	11,000 kg	1,300 mg	7.2 mg
I, Construction, Tarmacs	Energy	19,000 GJ	2,200 kJ	12 kJ
	GHG	1,300 mt GGE	160 g GGE	0.88 g GGE
	SO$_2$	10,000 kg	1,200 mg	6.5 mg
	CO	8,100 kg	960 mg	5.3 mg
	NO$_X$	18,000 kg	2,200 mg	12 mg
	VOC	-	-	-
	Pb	1.1 kg	0.13 mg	0.00073 mg
	PM$_{10}$	7,100 kg	850 mg	4.7 mg
I, Operation, Runway Lighting	Energy	3,400 GJ	400 kJ	2.2 kJ
	GHG	720 mt GGE	85 g GGE	0.47 g GGE
	SO$_2$	3,600 kg	430 mg	2.3 mg
	CO	350 kg	41 mg	0.23 mg
	NO$_X$	1,200 kg	140 mg	0.77 mg
	VOC	31 kg	3.6 mg	0.020 mg
	Pb	0.056 kg	0.0067 mg	0.000037 mg
	PM$_{10}$	39 kg	4.7 mg	0.026 mg
I, Operation, Other Electricity	Energy	-	-	-
	GHG	-	-	-
	SO$_2$	-	-	-
	CO	-	-	-
	NO$_X$	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM$_{10}$	-	-	-
I, Operation, Deicing Fluid Producti	Energy	5,400 GJ	640 kJ	3.5 kJ
	GHG	400 mt GGE	47 g GGE	0.26 g GGE
	SO$_2$	1,600 kg	190 mg	1.1 mg
	CO	2,500 kg	300 mg	1.7 mg
	NO$_X$	1,700 kg	200 mg	1.1 mg
	VOC	820 kg	97 mg	0.53 mg
	Pb	-	-	-
	PM$_{10}$	260 kg	30 mg	0.17 mg
I, Operation, Ground Support Equip	Energy	43,000 GJ	5,100 kJ	28 kJ
	GHG	3,300 mt GGE	390 g GGE	2.1 g GGE
	SO$_2$	2,400 kg	290 mg	1.6 mg
	CO	240,000 kg	28,000 mg	150 mg
	NO$_X$	33,000 kg	3,900 mg	21 mg
	VOC	8,700 kg	1,000 mg	5.7 mg
	Pb	-	-	-
	PM$_{10}$	1,400 kg	170 mg	0.93 mg
I, Maintenance, Airports	Energy	88 GJ	10 kJ	0.057 kJ
	GHG	6.8 mt GGE	0.81 g GGE	0.0045 g GGE
	SO$_2$	12 kg	1.4 mg	0.0078 mg
	CO	63 kg	7.4 mg	0.041 mg
	NO$_X$	23 kg	2.7 mg	0.015 mg
	VOC	12 kg	1.4 mg	0.0075 mg
	Pb	-	-	-
	PM$_{10}$	4.7 kg	0.56 mg	0.0031 mg
I, Maintenance, Runways	Energy	-	-	-
	GHG	-	-	-
	SO$_2$	-	-	-
	CO	-	-	-
	NO$_X$	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM$_{10}$	-	-	-
I, Maintenance, Tarmacs	Energy	-	-	-
	GHG	-	-	-
	SO$_2$	-	-	-
	CO	-	-	-
	NO$_X$	-	-	-
	VOC	-	-	-
	Pb	-	-	-
	PM$_{10}$	-	-	-
I, Parking	Energy	4,300 GJ	510 kJ	2.8 kJ
	GHG	270 mt GGE	32 g GGE	0.18 g GGE
	SO$_2$	5,600 kg	660 mg	3.6 mg
	CO	1,300 kg	150 mg	0.83 mg
	NO$_X$	3,200 kg	380 mg	2.1 mg
	VOC	4,400 kg	520 mg	2.9 mg
	Pb	0.053 kg	0.0063 mg	0.000035 mg
	PM$_{10}$	7,200 kg	850 mg	4.7 mg
I, Insurance, Non-Operator	Energy	3,100 GJ	370 kJ	2.1 kJ
	GHG	260 mt GGE	31 g GGE	0.17 g GGE
	SO$_2$	630 kg	75 mg	0.41 mg
	CO	2,900 kg	340 mg	1.9 mg
	NO$_X$	710 kg	84 mg	0.46 mg
	VOC	530 kg	63 mg	0.34 mg
	Pb	-	-	-
	PM$_{10}$	130 kg	16 mg	0.088 mg
I, Insurance, Liability	Energy	350 GJ	42 kJ	0.23 kJ
	GHG	29 mt GGE	3.4 g GGE	0.019 g GGE
	SO$_2$	71 kg	8.4 mg	0.046 mg
	CO	320 kg	38 mg	0.21 mg
	NO$_X$	80 kg	9.5 mg	0.052 mg
	VOC	59 kg	7.0 mg	0.039 mg
	Pb	-	-	-
	PM$_{10}$	15 kg	1.8 mg	0.0099 mg

7.3 Fuel Production

7.3.1 Fuel Production Inventory

The production of jet fuel requires energy and produces emissions. EIOLCA is used to determine these impacts [EIOLCA]. The EIOLCA 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 is in EIOLCA used to determine production factors.

Based on total fuel consumption (as described in §7.1.2), the production inventory is computed. Fuel production has also been reduced to the portion attributable only to passengers as described in §7.1.5.

7.3.2 Fuel Production Results

Table 72 - Aircraft fuel production inventory for Embraer 145

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
F, Refining & Distribution	Energy	150,000 GJ	11,000 kJ	350 kJ
	GHG	13,000 mt GGE	990 g GGE	31 g GGE
	SO_2	26,000 kg	1,900 mg	59 mg
	CO	37,000 kg	2,700 mg	85 mg
	NO_X	15,000 kg	1,100 mg	35 mg
	VOC	17,000 kg	1,200 mg	38 mg
	Pb	-	-	-
	PM_{10}	2,700 kg	200 mg	6.1 mg

Table 73 - Fuel production inventory for Boeing 737

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
F, Refining & Distribution	Energy	1,300,000 GJ	24,000 kJ	240 kJ
	GHG	110,000 mt GGE	2,200 g GGE	21 g GGE
	SO_2	220,000 kg	4,200 mg	40 mg
	CO	310,000 kg	6,000 mg	58 mg
	NO_X	130,000 kg	2,400 mg	24 mg
	VOC	140,000 kg	2,700 mg	26 mg
	Pb	-	-	-
	PM_{10}	23,000 kg	430 mg	4.2 mg

Table 74 - Fuel production inventory for Boeing 747

Life-Cycle Component	I/O	per Aircraft-Life	per VMT	per PMT
F, Refining & Distribution	Energy	570,000 GJ	68,000 kJ	370 kJ
	GHG	51,000 mt GGE	6,100 g GGE	33 g GGE
	SO_2	98,000 kg	12,000 mg	64 mg
	CO	140,000 kg	17,000 mg	91 mg
	NO_X	57,000 kg	6,800 mg	37 mg
	VOC	64,000 kg	7,500 mg	41 mg
	Pb	-	-	-
	PM_{10}	10,000 kg	1,200 mg	6.6 mg

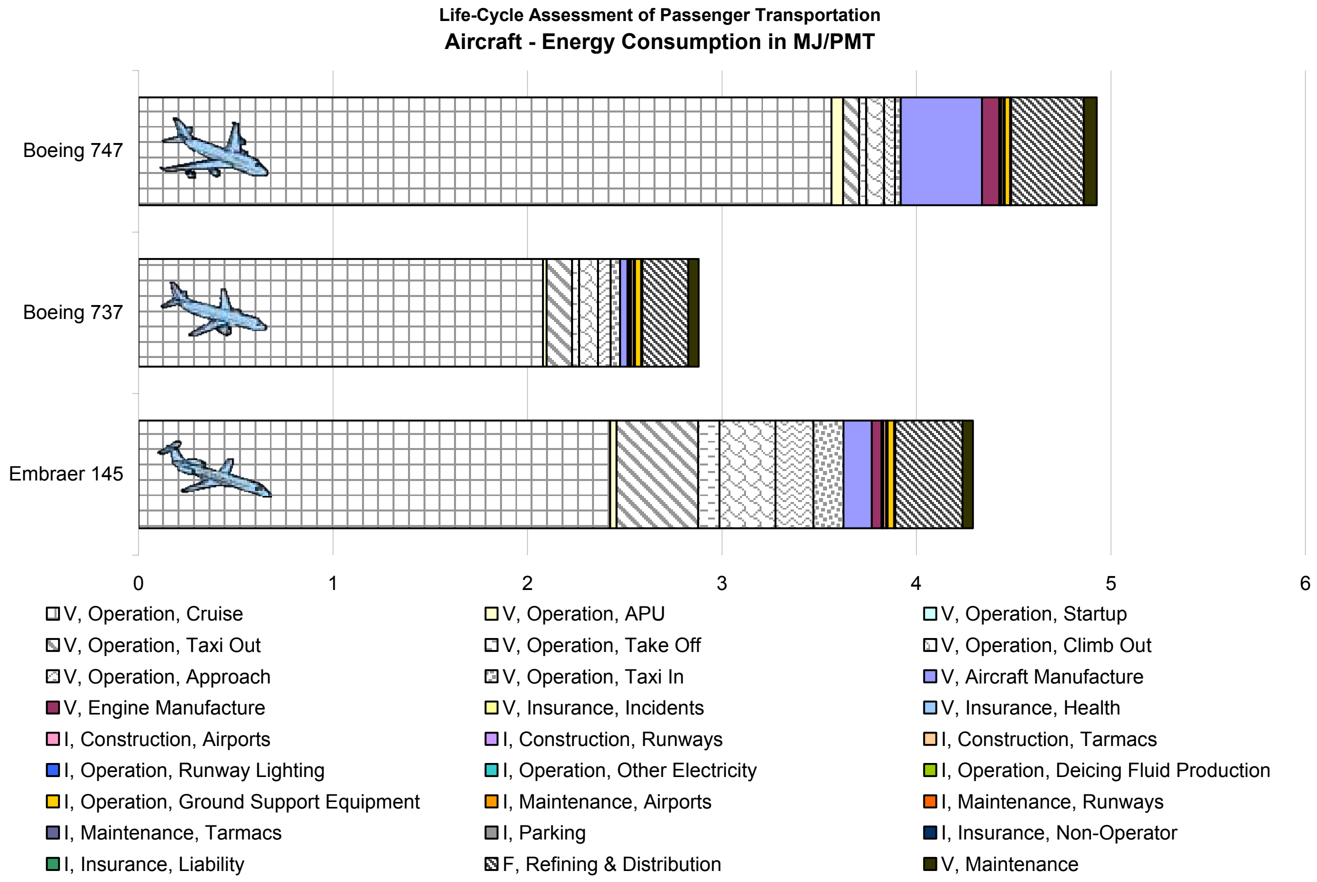
7.4 *Air Summary*

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

7.4.1 Energy and GHG Emissions

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

Table 75 - Air energy inventory



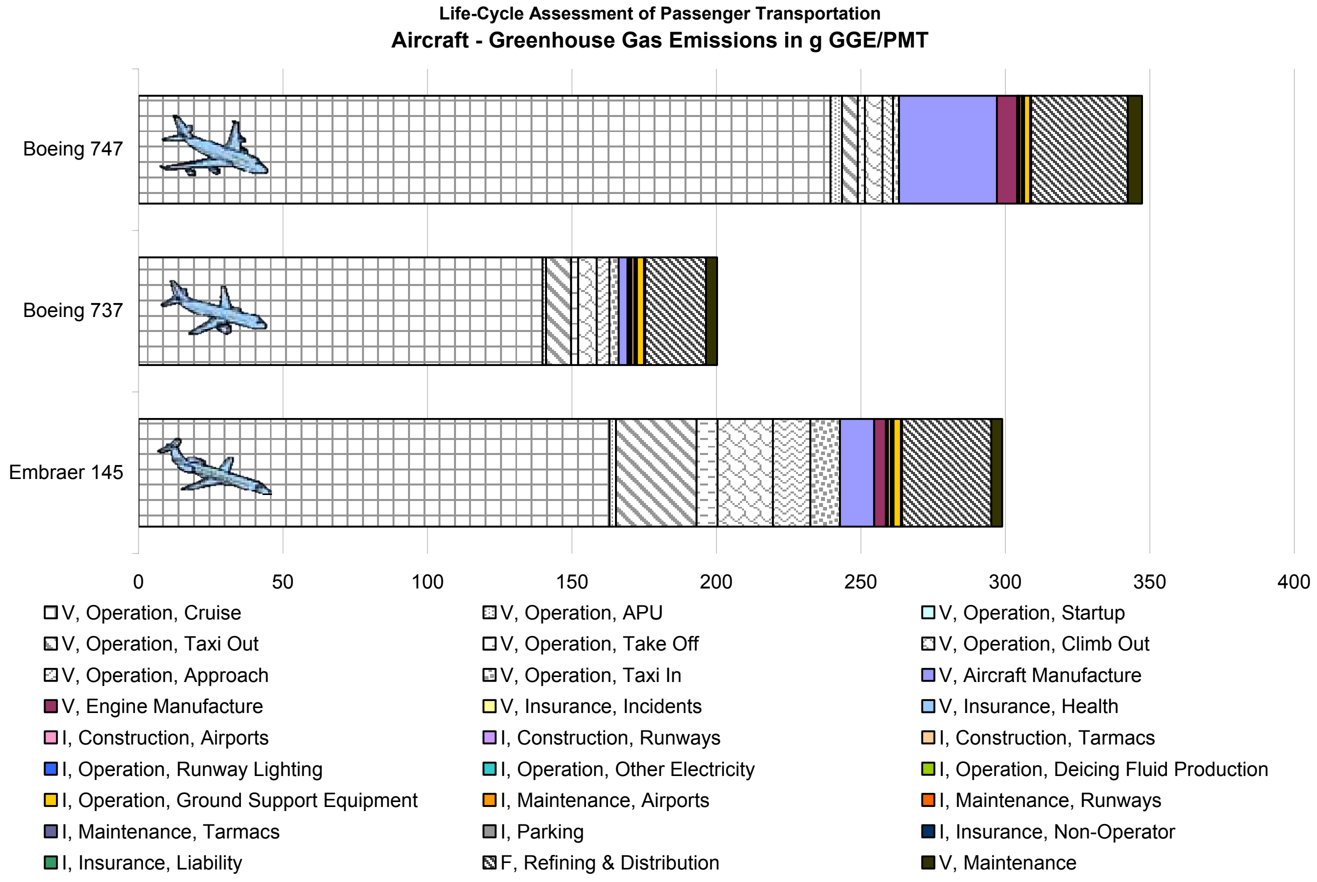
<u>Aircraft Operation</u>

The cruise phase accounts for between 60% (Embraer 145) and 70% (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 10% (Boeing 747) and 30% (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 is discussed in §7.4.2 is less important with energy and GHG emissions because impacts typically occur at macro scales.

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 50% larger than non-cruise operational emissions. The lowest manufacturing emissions (per PMT) are experienced with the 737. Given the medium-range nature of its flights coupled with manufacturing requirements significantly less than the 747 leads to a comparatively low factor.

Table 76 - Air GHG inventory



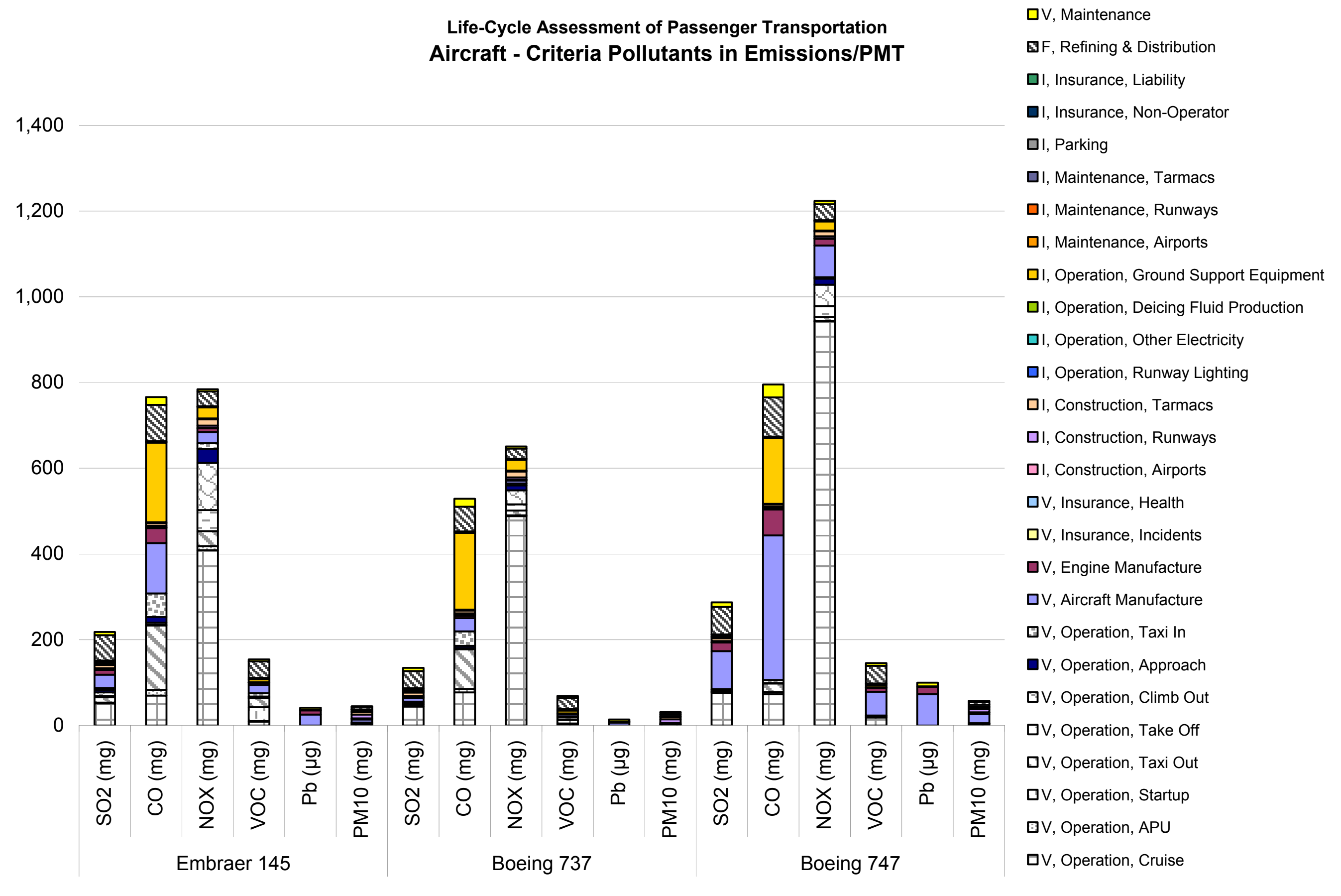
Fuel Production

For every 100 units of jet fuel produced, and additional 16 units are needed (in both direct and indirect supply chain support) [EIOLCA, SimaPro]. Given that operational phases dominate aircraft energy and GHG emissions, for every 100 energy units of fuel consumed, and addition 16 units of energy were used. Because most of this fuel production is fossil-based, the GHG emission correlation follows.

7.4.2 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.

Table 77 - Air CAP inventory



<u>Aircraft Manufacturing</u>
Total CO emissions are strongly controlled by aircraft manufacturing. Half of these CO emissions result from truck transportation in the movement of parts for final assembly and sub assembly [EIOLCA]. Aircraft manufacturing also shows with SO_2 emissions which are explained by the electricity requirements (which are heavily produced from sulfur-laden coal) in the process.

<u>GSE Operation</u>
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.

<u>Taxiway and Tarmac Construction</u>
Fugitive dust emissions from the construction and maintenance of taxiways and tarmacs has a strong effect on total inventory PM_{10} emissions.

<u>Fuel Production</u>
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.

Summary

The contribution of life-cycle components is very significant to total emissions from aircraft. The minimum magnitude increase is 2 for NO_X and the Embraer 145 comparing operation to total life-cycle impacts. PM_{10} emissions show very large increases, a magnitude of 9 to 15 for the different aircraft.

Table 78 - Air CAP inventory life-cycle impact contributions (per PMT)

	Embraer 145			Boeing 737			Boeing 747		
	Operational Emissions	Life-cycle Emissions	Magnitude Increase	Operational Emissions	Life-cycle Emissions	Magnitude Increase	Operational Emissions	Life-cycle Emissions	Magnitude Increase
SO_2 (mg)	88	218	2.5	56	134	2.4	85	287	3.4
CO (mg)	308	766	2.5	220	529	2.4	106	795	7.5
NO_X (mg)	659	784	1.2	565	651	1.2	1045	1224	1.2
VOC (mg)	75	155	2.1	21	69	3.3	23	146	6.2
Pb (µg)		41			14			100	
PM_{10} (mg)	7.0	45	6.4	3.5	31	9	5.6	58	10

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.

8 Future Work

This document provides the foundation for our life-cycle assessment of passenger transportation. Future revisions will incorporate critiques which may lead to changes in the values reported. These critiques may come in the form of various readers or other publication submissions. Several implementations of this data are planned and will be used to refine these results.

Many of the calculations rely on several assumptions which may be valid under certain conditions. A sensitivity analysis will be performed on critical assumptions and parameters to show their effects on final values.

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Appendix A

Roadway 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 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 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

Appendix B

PaLATE Roadway Construction Factors (described in §5.2.1)

PaLATE Factors (Per Mile)		Energy [MJ/mi]	Water Consumption [kg/mi]	CO_2e [Mg/mi]	NO_X [kg/mi]	PM_{10} [kg/mi]	SO_2 [kg/mi]	CO [kg/mi]
Interstate Construction Factors	Wearing - Materials Production	15,024,726	774	979	4,237	42,225	3,384	5,819
→ Urban or Rural	Wearing - Materials Transportation	5,863,583	32	438	7,258	1,401	461	624
	Wearing - Processes (Equipment)	98,893	11	7	173	39	11	37
	Subbase - Materials Production	3,276,827	1,162	232	468	3,325	228	306
	Subbase - Materials Transportation	989,774	5	74	3,942	768	237	329
	Subbase - Processes (Equipment)	169,939	19	13	256	30	17	55
Principal Arterial Construction Factors	Wearing - Materials Production	5,548,963	285	362	1,565	15,652	1,249	2,153
→ Urban	Wearing - Materials Transportation	4,724,203	26	353	2,720	524	188	245
	Wearing - Processes (Equipment)	36,668	4	3	64	14	4	14
	Subbase - Materials Production	1,638,413	581	116	234	1,663	114	153
	Subbase - Materials Transportation	494,887	3	37	1,971	384	118	164
	Subbase - Processes (Equipment)	84,969	10	6	128	15	8	28
Principal Arterial Construction Factors	Wearing - Materials Production	5,548,963	285	362	1,565	15,652	1,249	2,153
→ Rural	Wearing - Materials Transportation	4,724,203	26	353	2,720	524	188	245
	Wearing - Processes (Equipment)	36,668	4	3	64	14	4	14
	Subbase - Materials Production	1,638,413	581	116	234	1,663	114	153
	Subbase - Materials Transportation	494,887	3	37	1,971	384	118	164
	Subbase - Processes (Equipment)	84,969	10	6	128	15	8	28
Minor Arterial Construction Factors	Wearing - Materials Production	4,316,673	222	282	1,217	12,234	971	1,679
→ Urban	Wearing - Materials Transportation	4,575,831	25	342	2,129	410	153	196
	Wearing - Processes (Equipment)	28,673	3	2	50	11	3	11
	Subbase - Materials Production	1,518,530	538	108	217	1,541	106	142
	Subbase - Materials Transportation	458,676	3	34	1,827	356	110	152
	Subbase - Processes (Equipment)	78,752	9	6	118	14	8	26
Minor Arterial Construction Factors	Wearing - Materials Production	4,316,673	222	282	1,217	12,234	971	1,679
→ Rural	Wearing - Materials Transportation	4,575,831	25	342	2,129	410	153	196
	Wearing - Processes (Equipment)	28,673	3	2	50	11	3	11
	Subbase - Materials Production	1,518,530	538	108	217	1,541	106	142
	Subbase - Materials Transportation	458,676	3	34	1,827	356	110	152
	Subbase - Processes (Equipment)	78,752	9	6	118	14	8	26
Collector Construction Factors	Wearing - Materials Production	4,316,673	222	282	1,217	12,234	971	1,679
→ Urban	Wearing - Materials Transportation	4,575,831	25	342	2,129	410	153	196
	Wearing - Processes (Equipment)	28,673	3	2	50	11	3	11
	Subbase - Materials Production	1,518,530	538	108	217	1,541	106	142
	Subbase - Materials Transportation	458,676	3	34	1,827	356	110	152
	Subbase - Processes (Equipment)	78,752	9	6	118	14	8	26
Collector Construction Factors	Wearing - Materials Production	4,316,673	222	282	1,217	12,234	971	1,679
→ Rural	Wearing - Materials Transportation	4,575,831	25	342	2,129	410	153	196
	Wearing - Processes (Equipment)	28,673	3	2	50	11	3	11
	Subbase - Materials Production	1,518,530	538	108	217	1,541	106	142
	Subbase - Materials Transportation	458,676	3	34	1,827	356	110	152
	Subbase - Processes (Equipment)	78,752	9	6	118	14	8	26
Local Construction Factors	Wearing - Materials Production	3,384,765	174	221	954	9,556	762	1,314
→ Urban	Wearing - Materials Transportation	4,464,116	25	334	1,684	324	126	159
	Wearing - Processes (Equipment)	22,388	3	2	39	9	3	8
	Subbase - Materials Production	1,038,994	368	74	148	1,054	72	97
	Subbase - Materials Transportation	313,831	2	23	1,250	244	75	104
	Subbase - Processes (Equipment)	53,883	6	4	81	10	5	17
Local Construction Factors	Wearing - Materials Production	2,736,531	141	178	771	7,742	616	1,063
→ Rural	Wearing - Materials Transportation	4,386,148	24	328	1,374	264	107	133
	Wearing - Processes (Equipment)	18,143	2	1	32	7	2	7
	Subbase - Materials Production	839,187	298	59	120	852	58	78
	Subbase - Materials Transportation	253,479	1	19	1,010	197	61	84
	Subbase - Processes (Equipment)	43,521	5	3	65	8	4	14

Appendix C

Aircraft Size Groupings

Aircraft	Size Grouping	Aircraft	Size Grouping
Aerospatiale Caravelle Se-210	Small	Aerospatiale/British Aerospace Concorde	Medium
Aerospatiale Corvette	Small	Airbus A300	Medium
Aerospatiale/Aeritalia Atr-42	Small	Airbus A310	Medium
Aerospatiale/Aeritalia Atr-72	Small	Airbus A320	Medium
Beech 1900 A/B/C/D	Small	Airbus A330	Medium
Bombardier (Gates) Learjet 60	Small	Airbus A340	Medium
Bombardier Bd-700 Global Express	Small	Boeing 377	Medium
Bombardier Challenger 604	Small	Boeing 717	Medium
Bombardier Crj 705	Small	Boeing 720	Medium
British Aerospace (Hawker-Siddeley) Bae-748	Small	Boeing 727	Medium
British Aerospace Bae-146-100/Rj70	Small	Boeing 737	Medium
British Aerospace Bae-146-200	Small	Boeing 757	Medium
British Aerospace Bae-146-300	Small	Boeing 777	Medium
British Aerospace Bae-Atp	Small	British Aerospace Bac-111-200	Medium
British Aerospace Jetstream 31	Small	British Aerospace Bac-111-400	Medium
British Aerospace Jetstream 41	Small	Convair 880 (Cv-22/22m)	Medium
Canadair 601	Small	Convair 990 Coronado (Cv-30)	Medium
Canadair CL 44	Small	Ilyushin 62	Medium
Canadair RJ 100	Small	Ilyushin 76/Td	Medium
Canadair RJ 200	Small	Ilyushin 86	Medium
Canadair RJ 700	Small	Ilyushin 96	Medium
Canadar CRJ 900	Small	Ilyushin Il-18	Medium
Carstedt Cj-600a	Small	Mcdonnell Douglas Dc-10-20	Medium
Casa 235	Small	Mcdonnell Douglas Dc-10-30	Medium
Convair Cv-240	Small	Mcdonnell Douglas Dc-10-30cf	Medium
Convair Cv-340/440	Small	Mcdonnell Douglas Dc-10-40	Medium
Convair Cv-540	Small	MD DC10	Medium
Convair Cv-580	Small	MD DC2	Medium
Convair Cv-600	Small	MD DC3	Medium
Convair Cv-640	Small	MD DC4	Medium
Convair Cv-660	Small	MD DC6	Medium
Dassault Falcon 2000ex	Small	MD DC7	Medium
Dassault Falcon 50	Small	MD DC9	Medium
Dassault Falcon 900	Small	MD MD11	Medium
Dassault-Breguet Mystere-Falcon	Small	MD MD90	Medium
Dornier 228	Small	Boeing 707	Large
Dornier 328	Small	Boeing 747	Large
Dornier 328 Jet	Small	Boeing 767	Large
Dornier Do-28 Skyservant	Small	MD DC8	Large
Embraer 110	Small		
Embraer 120	Small		
Embraer 135	Small		
Embraer 140	Small		
Embraer 145	Small		
Embraer 170	Small		
Embraer 175	Small		
Embraer 190	Small		
Fokker 100	Small		
Fokker 50	Small		
Fokker 70	Small		
Fokker F28-1000 Fellowship	Small		
Fokker F28-4000/6000 Fellowship	Small		
Fokker Friendship F-27/Fairchild F-27/A/B/F/J	Small		
Gates Learjet Lear-23	Small		
Gates Learjet Lear-24	Small		
Gates Learjet Lear-25	Small		
Gates Learjet Lear-35	Small		
Gulfstream G450	Small		
Gulfstream I	Small		
Gulfstream I-Commander	Small		
Gulfstream V/ G-V Exec/ G-5/550	Small		
Hawker Siddeley 125	Small		
Hawker Siddeley 748	Small		
Lear 55	Small		
Rockwell Sabreliner	Small		
Rockwell Turbo-Commander 680-W/690	Small		
Saab-Fairchild 340/A	Small		
Saab-Fairchild 340/B	Small		
Tupolev Tu-154	Small		