Title
Environmental Life-cycle Assessment of Passenger Transportation An Energy, Greenhouse Gas, and Criteria Pollutant Inventory of Rail and Air Transportation

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Publication Date
2008-12-01

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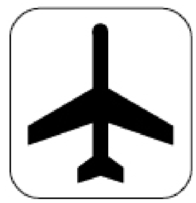
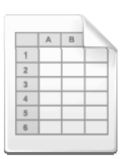
Environmental Life-cycle Assessment of Passenger Transportation

An Energy, Greenhouse Gas, and Criteria Pollutant Inventory of Rail and Air Transportation



Report to the University of California Transportation Center

December 2007



This document is accompanied by a Microsoft Excel spreadsheet decision support tool. Please contact the authors via email if you would like a copy of the latest version or more information.

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List of Acronyms and Symbols

§	Section
CAHSR	California High Speed Rail
CAP	Criteria air pollutants
CO	Carbon Monoxide
EIOLCA	Economic Input-Output Life-cycle Assessment
GGE	Grams of Greenhouse Gas Equivalence
GHG	Greenhouse Gases
J	Joule
LCA	Life-cycle Assessment
LTO	Landing-Takeoff Cycle
NO_X	Nitrogen Oxides
Pb	Lead
PMT	Passenger Miles Traveled
PM_X	Particulate Matter (subscript denotes particle diameter in microns, 10^{-6} meters)
SO_2	Sulfur Dioxide
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compounds
Wh	Watt-hour (watt = joule · second^{-1})
g	Gram
mt	Metric tonne
HRT	Heavy Rail Transit

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 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 other components. Vehicle manufacturing and maintenance, infrastructure construction and operation, and fuel production are rarely included in environmental factors for transportation systems.

The goal of this project is to develop a comprehensive life-cycle assessment model to quantify the energy inputs and emissions from rail and air transportation in the U.S. associated with the life-cycle components (raw materials extraction, manufacturing, construction, operation, maintenance) 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 passenger-mile traveled.

Results show that energy and greenhouse gas emissions increase by as much as 2.1 times for heavy rail, 1.4 times for high speed rail, and 1.3 times for air when life-cycle components are included. Criteria air pollutant emissions increase between 1.1-29 times for heavy rail, 1.2-1.4 times for high speed rail, and 1.5-9 times for air.

2 Background

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 rail or air at economically reasonable prices for their trips. Within urban areas, infrastructure is typically in place for cars, buses, metro, electric trolleys, 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 comprehensive, systematic study of the life-cycle environmental effects of rail and air in the United States has not yet been published. The environmental impacts of passenger rail and air transportation 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 vehicles, infrastructure, and fuels.

The passenger transportation sectors play a key role in the economy of moving people for work and leisure trips, and are some of the largest energy consumers and polluters in our society [Greene 1997, Mayeres 1996]. Some statistics have been compiled comparing the environmental impacts of these modes of transportation, but few consider anything beyond the operational impact of the vehicle [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 vehicles and infrastructure. 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 rail and air modes has not yet been published. To appropriately address the environmental impacts of these modes, it is necessary to accurately quantify the entire life cycle of the vehicles, infrastructure, and fuels. Informed decisions should not be made on partial data acting as indicators for whole system performance. Some studies have been completed for rail and air 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
Air	Airports			O	
	Aircraft			G,H,I	
	Fuel (Kerosene)				
Heavy Rail	Tracks	N	N	N	N
	Locomotives & Cars	N	J,N	H,J,N,P	N
	Fuel (Diesel, Electric)				

Sources: G. Levinson 1998b; H. INFRAS 1994; I. Schipper 2003; J. Stodolsky 1998; N. Nocker 2000; O. FAA 2007; P. Fritz 1994

With increasing environmental regulation and pressures from 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 vehicle or infrastructure. 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 in the system.

2.1 Life-cycle Assessment

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

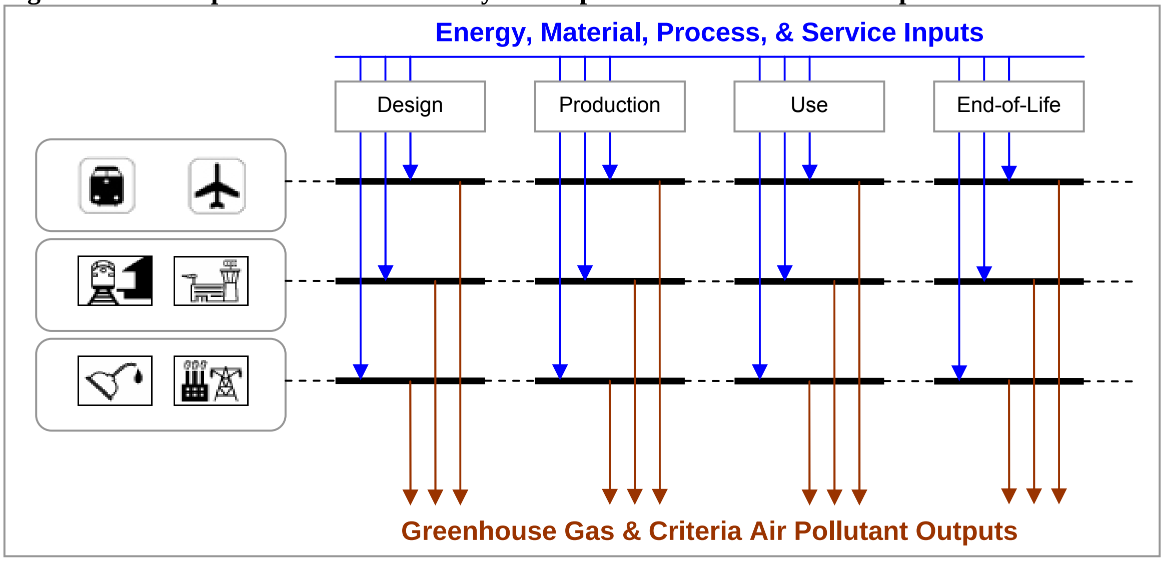
LCA is a systematic method in pollution prevention and life-cycle engineering to analyze the environmental implications associated with products, processes, and services through the different stages of the life-cycle: design, materials and energy acquisition, transportation, manufacturing, construction, 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 two decades [Fava 1991, Bare 2003, ISO 2000]. The LCA methodology consists of four stages: 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 used 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 2007]. 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 life-cycle stages that are analyzed for each transportation system.

Figure 1 - A conceptual model of the life-cycle components of rail and air transportation



2.2 Environmental Effects Studies

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

The emissions of concern are:

- Greenhouse Gases – global climate change
- 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

3 Environmental Inventory

3.1 Rail Transportation

The rail assessment analyzes the San Francisco Bay Area Caltrain (Caltrain) heavy rail commuter line from Gilroy to San Francisco and the proposed California High Speed Rail (CAHSR) system connecting Sacramento to San Diego. Both systems are considered heavy rail transit. Caltrain vehicles are powered by diesel fuel while CAHSR is electric-powered. Caltrain's fleet consists of 34 locomotives and 110 passenger cars all with an expected lifetime of 30 years [Caltrain 2007, Caltrain 2004]. There are 34 stations which are primarily of raised platform design. For the stations, minimal materials are required as passengers typically load and unload from a platform slightly below the train's door level (Figure 2). There are 77 miles of track in the Caltrain rail network, almost all of which are constructed at-grade. 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 [Levinson 1996]. 42 electric-powered trains will provide service with speeds averaging 220 mph [Levinson 1996]. The CAHSR network will consist of 25 stations constructed as platforms next to tracks. 570 miles of track are considered at-grade with the remaining designed as retained-fill or elevated [SVRTC 2006, PB 1999].

Figure 2 – Caltrain San Jose station
Source: http://www.capitalcorridor.org/

3.1.1 Train Operational Components

Typical energy and emission factors for train operation do not disaggregate operational emissions. This is typically due to high level metering where only gross operational electricity (because it is monitored at substations) or fuel consumption is reported. This does not distinguish or provide any disaggregating on propulsion, idling, and auxiliary (lighting, HVAC, and other peripherals) energy specifics. In this research, the following components have been evaluated individually for vehicle operation:

- Propulsion
- Idling
- Auxiliaries

Figure 3 – German ICE-3 high speed train
Source: PB 1999

3.1.2 Vehicle Non-Operational Components

Outside of direct operational energy, there are several vehicle components which could significantly contribute to the environmental performance of the rail modes. Manufacturing and maintaining trains are important, but so are the insurance services associated with train crews and liability. Several of these components are detailed even further. The non-operational vehicle components included herein are:

- Manufacturing
- Maintenance – replacement and upkeep of train parts
- Maintenance – cleaning of trains
- Maintenance – replacement of flooring
- Insurance – train crew health insurance and benefits
- Insurance – liability

3.1.3 Infrastructure Components

The construction, operation, and maintenance of stations and tracks are each considered. The infrastructure supporting the train systems is vast with many components. Individual station operational components have been analyzed (lighting, escalators, train control, etc.). Also, insurance has been included.

- Station construction
- Station lighting
- Station escalator operation
- Station train control operation
- Parking lot construction
- Parking lot lighting
- Miscellaneous station operational items
- Station maintenance
- Station cleaning
- Track and power delivery construction
- Track maintenance
- Non-train crew health insurance and benefits
- Liability insurance on infrastructure components

3.1.4 Electricity Production, Transmission, and Distribution

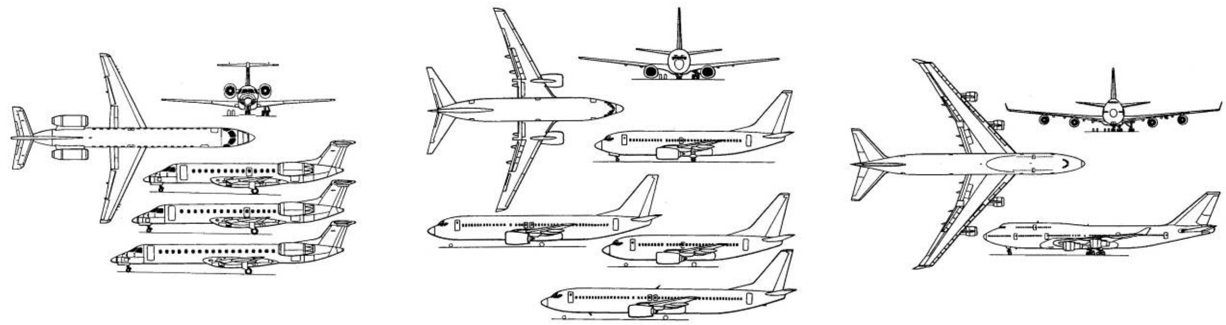
The electricity or fuel used by trains and infrastructure components do not capture the energy required to produce, transmit, and distribute the energy to the systems. Energy is required to produce electricity and diesel fuel. In electricity transmission and distribution, energy is lost. The extent of these effects is captured by EIO-LCA for fuel production and is in the work of Deru [2007] for electricity. For both systems, the energy production and transmission and distribution losses are evaluated for both vehicle and infrastructure energy consumption:

- Diesel fuel and electricity production for vehicle and infrastructure components
- Transmission and distribution losses

3.2 Air Transportation

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

Three representative aircraft are chosen to model the entire commercial passenger fleet: the Embraer 145 (short-haul), Boeing 737 (medium-haul), and Boeing 747 (long-haul) [BTS 2007]. These aircraft represent small, medium, and large aircrafts each designed for specific travel distances and passenger loads. The three aircraft make up 30% of VMT and 26% of PMT among all commercial aircraft [BTS 2007]. Assuming the Boeing 737 is representative of the Airbus A310 and 320 series, the Boeing 717, 727, 757, and the McDonnell Douglas DC9, and the Boeing 747 is representative of the Boeing 767, 777, and Airbus A300, then they makeup 80% of VMT and 92% of PMT. Figure 4 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 4 - Aircraft Parameters Source: Janes 2004

A representative airport (Washington Dulles) is used to determine environmental effects of airport construction, operation, and maintenance. Dulles airport is chosen as the average airport because it lies close to the average for number of passenger enplanements at the top 50 U.S. airports and accommodates several Boeing 747 flights each day [BTS 2006].

3.2.1 Aircraft Operational Components

The disaggregating of aircraft operational components is of particular concern because of environmental impact and the geographic differentiation of where pollutants are emitted. While most PMT are performed during the cruise cycle at high altitudes, this is where criteria air pollutant (CAP) emissions are less likely to have an effect. The few PMT performed during a flight at or near airports poses a much more serious effect for CAP emissions. The landing-takeoff (LTO) cycle is shown in Figure 5.

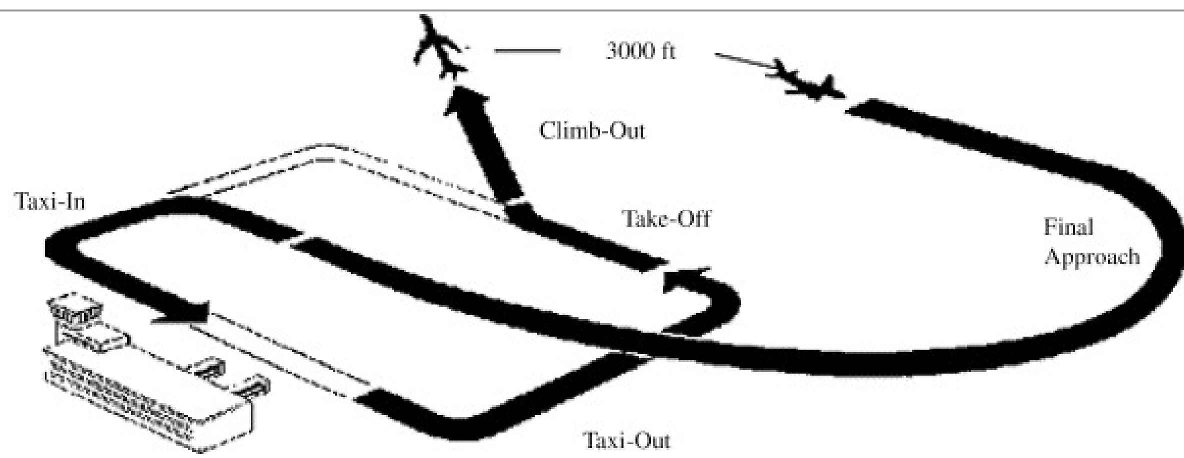


Figure 5 – Landing-Takeoff cycle
Source: http://www.grida.no/climate/ipcc/aviation/105.htm

Aircraft energy and emissions are computed for each of the LTO cycle components as well as during cruise. Additionally, the operation of an auxiliary power unit (APU) which is an onboard generator that supplies electricity for aircraft systems and bleed air to the main engine is included.

- APU operation
- Startup
- Taxi out
- Take off
- Climb out
- Cruise
- Approach
- Taxi in

3.2.2 Aircraft Non-Operational Components

The manufacturing, maintenance, and insurance associated with aircraft operation contribute to life-cycle environmental performance. Manufacturing is treated separately for the aircraft and its engines. Individual maintenance components are considered, such as parts replacement, painting, and engine work. Insurance is evaluated for both crew benefits and aircraft operational liability. The vehicle non-operational components included are:

- Aircraft Manufacturing
- Engine Manufacturing
- Crew health insurance and benefits
- Vehicle liability insurance
- Aircraft maintenance
  - Lubrication & fuel changes
  - Battery repair & replacement
  - Chemical milling, maskant, and application
  - Parts cleaning
  - Metal finishing
  - Coating application
  - Depainting
  - Painting
- Engine maintenance

3.2.3 Infrastructure Components

The impacts from airports are evaluated through construction of buildings, runways, taxiways, tarmacs, and parking, maintenance, operation of facilities, and insurance. Airport, runway, taxiway/tarmac, and parking construction are evaluated individually. Operation of airports is considered not just through direct electricity use but also production of deicing fluid and operation of ground support equipment (GSE). The infrastructure components included are:

- Airport buildings construction
- Runway construction
- Taxiway and Tarmac construction
- Parking lot construction
- Lighting electricity
- Deicing fluid production
- GSE operation
- Airport maintenance
- Airport personnel insurance & benefits
- Airport liability insurance

3.2.4 Fuel Production

The production of jet fuel is included to account for the energy and emissions that are associated with producing the operational energy. The production requirements capture both direct production requirements and indirect production requirements (in the supply chain).

3.2.5 Usage Attribution

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) on a given flight. The exact attribution of passengers, freight, and mail, by weight, is shown in Table 2 [BTS 2007].

Table 2 - 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%

The percentage attribution for each aircraft size is applied to vehicle inventory to account for the passenger's effect. The infrastructure components must also be reduced taking out freight and mail's contribution to overall environmental effects. 7% of all flights in the U.S. are dedicated freight flights [BTS 2007]. These flights carry high value commodities and emergency shipments. Infrastructure components are addressed individually for their passenger attribution. Airport terminal and parking construction and maintenance are attributed 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.

3.3 Methodological Framework

The impact from each life-cycle component for each mode is computed using a process LCA, EIO-LCA, or hybrid LCA approach before it is normalized to the functional units. The impact may be computed annually (such as with train propulsion) or over the lifetime of the component (such as with construction of stations). The contribution of the vehicle of interest on total impact is also analyzed for each component (for example, passenger aircraft are responsible for a portion of total flights to U.S. airports as freight is also a contributor). The specific considerations for each life-cycle component are discussed in detail in [Chester 2007].

After these various considerations are analyzed, the impact attributed to the vehicle of interest is determined for a time period (annual, lifetime) and is represented by:

$$I_{IO}^{\text{mod}\,e,component} \text{ where}$$

$$\text{I} = \text{Impact}$$

$$\text{IO} = \text{Input or Output (Energy, GHG, CAP)}$$

$$\text{mode} \in \{\text{air, heavy rail, high speed rail}\}$$

$$\text{component} = \text{life - cycle component normalized}$$

The impact is then reduced to the functional unit based on the following set of equations:

$$I_{IO-vehicle-lifetime}^{\text{mod}\,e,component} = I_{IO}^{\text{mod}\,e,component} \times \frac{VMT_{vehicle}}{vehicle-life} \times \frac{component-life}{VMT_{component}}$$

$$I_{IO-VMT}^{\text{mod}\,e,component} = I_{IO}^{\text{mod}\,e,component} \times \frac{component-life}{VMT_{component}}$$

$$I_{IO-PMT}^{\text{mod}\,e,component} = I_{IO}^{\text{mod}\,e,component} \times \frac{component-life}{PMT_{component}}$$

4 Results and Discussion

All modes have significant energy and emissions from non-operational components. While energy and GHG emissions from non-operational sources encompass a small increase as compared to operational components (with the exception of Caltrain where non-operational effects are larger than operational effects), CAPs represent magnitude increases. An understanding of where these effects occur in the life cycle is critical in any decision making or impact assessment framework.

Life-cycle components have been aggregated into several groupings: vehicle manufacturing, vehicle operation, vehicle maintenance, vehicle insurance, infrastructure construction, infrastructure operation, infrastructure maintenance, infrastructure parking, infrastructure insurance, and fuel production. The life-cycle component's groupings are shown in Appendix A.

The data, assumptions, and methodological framework used to compute each system's impacts are detailed in the [Chester 2007] supporting document.

4.1 Energy and Greenhouse Gas Emissions

For all modes but Caltrain, the energy and GHG inventory is strongly weighted towards vehicle operation but other life-cycle components have non-negligible contributions. The energy and GHG inventories are shown in Figure 6 and Figure 7. The operational and total life-cycle contributions are shown in Table 4.

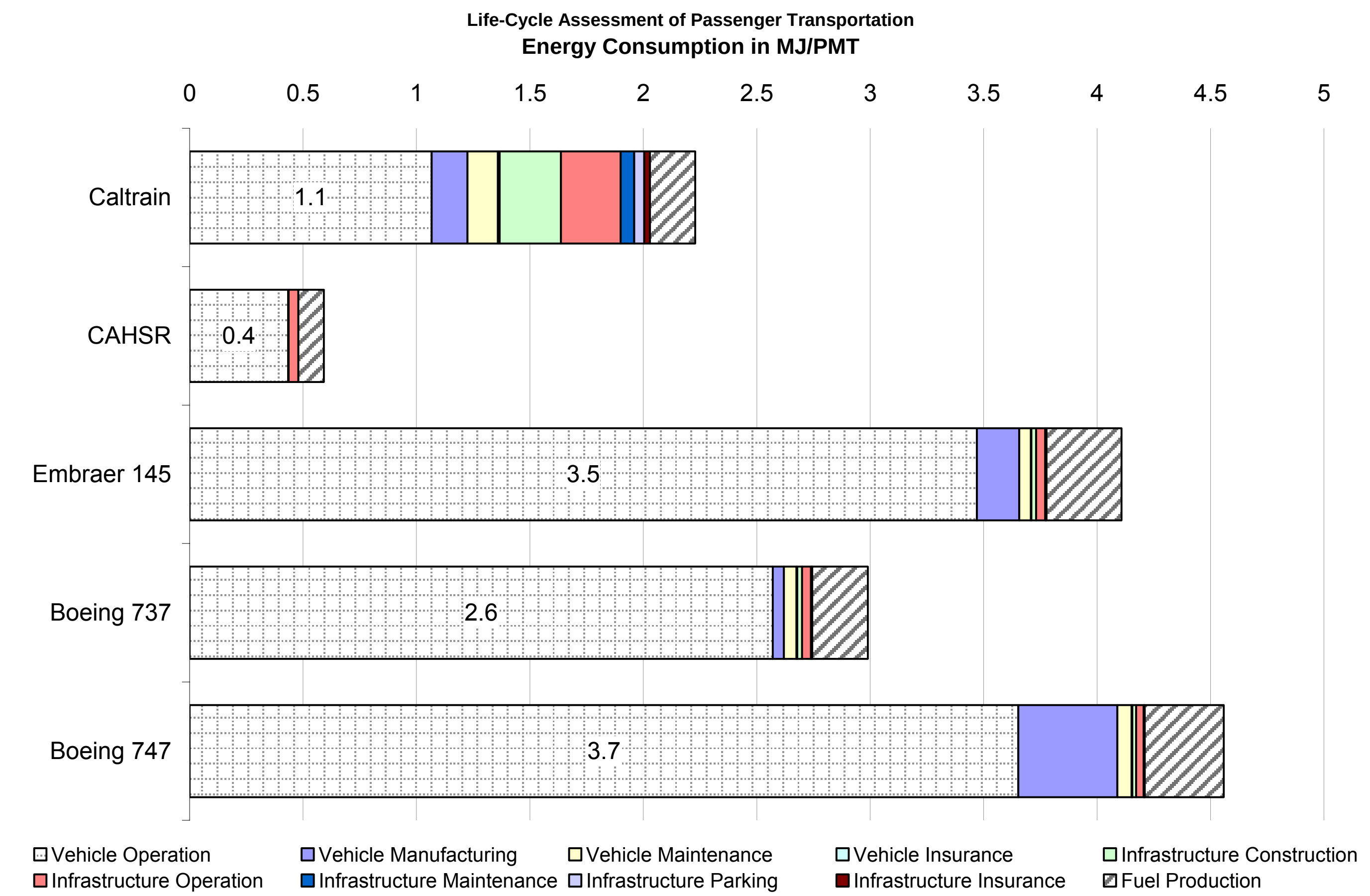


Figure 6 - Energy inventory

Vehicle Operation

As mentioned in §3.1.1, rail operational energy is disaggregated into propulsion, idling, and auxiliaries. Caltrain's 1.1MJ and 74g GHG per PMT are composed of 60% propulsion, 30% idling, and 10% auxiliaries. CAHSR's 0.4MJ and 32g GGE per PMT are composed of 90% propulsion, 5% idling, and 5% auxiliaries. The main difference between these two rail systems is the nature of their travel. Caltrain is a stop-and-go system which spends considerable time idling at stations while CAHSR travels long distances without stops and does not have large idling times.

For air modes, the operational breakdown (see §3.2.1) is affected by the size of the aircraft and the nature of travel. The smaller aircraft (Embraer 145) which performs short-haul flights, exhibits 67% energy consumption and GHG emissions in cruise with 11% in taxi out. The larger the aircraft and the longer the flights, the larger the emphasis is on the cruise effect (see Table 3).

Table 3 - Operational energy and GHG fractions for air modes

	Embraer 145	Boeing 737	Boeing 747
APU	1%	1%	1%
Taxi Out	11%	5%	2%
Take Off	3%	2%	1%
Climb Out	8%	4%	2%
Cruise	67%	83%	92%
Approach	5%	3%	1%
Taxi In	4%	2%	1%

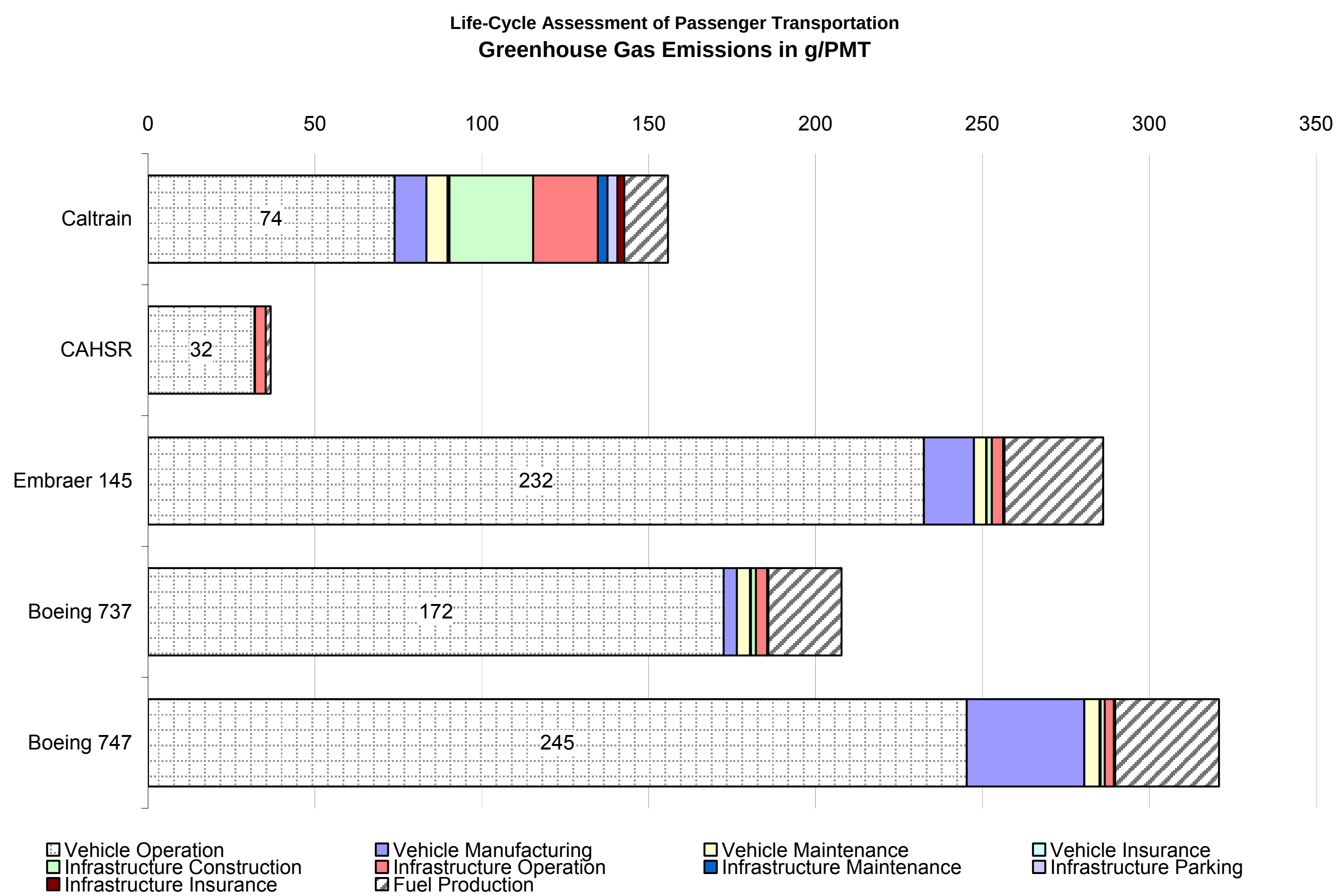


Figure 7 - GHG inventory

Vehicle Manufacturing

The effects of vehicle manufacturing on energy and GHG emissions show up most strongly with Caltrain, the Embraer 145, and the Boeing 747. This component accounts for 7%, 5% and 10% of Caltrain, Embraer 145 and Boeing 747's life-cycle energy consumption and 6%, 5% and 11% of GHG emissions. The magnitude of the effects results from several different reasons for the vehicles. For Caltrain, direct energy use during manufacturing as well as indirect energy requirements during the production of metals are the major contributors. For the Embraer 145, manufacturing energy and GHG emissions are small (in comparison to the 747) but are spread out over a small number of PMT in the lifetime of the aircraft. For the 747, a large manufacturing effect occurs and even with its long-haul nature, the lifetime impact is significant. For CAHSR this component accounts for less than 1% of life-cycle energy and GHG emissions and for the 737, 2%. For aircraft manufacturing, the primary energy and GHG factors are the electricity used at the manufacturing facilities and the diesel fuel consumed in truck transportation moving parts for assembly [EIOLCA 2007].

Table 4 – Total life-cycle inventory results (per PMT) (operational emissions in parenthesis)

	Caltrain	CAHSR	Embraer 145	Boeing 737	Boeing 747
Energy (MJ)	2.2 (1.1)	0.59 (0.43)	4.1 (3.5)	3.0 (2.6)	4.6 (3.7)
GGE (g CO_2e)	160 (74)	37 (32)	290 (230)	210 (170)	320 (250)
SO_2 (mg)	310 (11)	220 (170)	210 (84)	140 (58)	260 (79)
CO (mg)	420 (83)	22 (16)	740 (290)	550 (230)	720 (97)
NO_X (mg)	1,600 (1,400)	17 (12)	750 (630)	670 (590)	1,100 (970)
VOC (mg)	200 (59)	4.7 (3.7)	150 (71)	72 (22)	130 (22)
Pb (µg)	160	0.57 (0.22)	39	15	87
PM_{10} (mg)	170 (38)	2.3 (1.8)	43 (6.6)	32 (3.7)	52 (5.1)

Infrastructure Components

The low PMT for Caltrain, as compared to the other modes, effectively increases the contribution of infrastructure to total impacts for that mode. This is not so for the other modes as large vehicle or system PMT diminish the effects from infrastructure components. Infrastructure construction, operation, maintenance, and insurance account for 12%, 12%, 3%, and 2% of life-cycle energy consumption and 16%, 12%, 2%, and 2% of GHG emissions. The main drivers in infrastructure construction for Caltrain are the energy and GHG emissions associated with concrete and steel production for the stations and tracks. For operation, train control and station and parking lighting dominate overall effects. The energy required for concrete production in station reconstruction is the biggest contributor to infrastructure maintenance and the energy required to operate insurance facilities (such as buildings and computers) increases the insurance component's contribution.

Fuel Production

Fuel production is determined from diesel and electricity requirements for the rail modes and jet fuel requirements from the air modes. Caltrain and the air modes consume petroleum based fuels which are evaluated in EIOLCA. For every MJ of fuel produced, and additional 0.16MJ of energy are required [EIOLCA 2007]. This is composed of 0.09MJ of direct energy (extraction, transport, and refining) and 0.07MJ of indirect energy in the supply chain (to support the direct energy processes). The two rail systems are California-based which has a particular electricity generation mix. In California, for every 1kWh of electricity consumed, an additional 0.14kWh of energy was consumed to extract, process, and transport the fuel (if necessary) [Deru 2007]. Additionally, there is an 8.4% transmission and distribution loss in the state [Deru 2007].

Combining these two factors, for every kWh of electricity consumed, and additional 0.24kWh of energy are used. While Caltrain uses diesel fuel for operational energy, many other infrastructure components consume electricity. The fuel production shares of total life-cycle energy are 9% and 19% for Muni and CAHSR and 8% for the air modes. The fuel production energy requirements results in GHG emissions. This amounts to 8% of total life-cycle emissions for Caltrain, 4% for CAHSR, 10% for Embraer 145, 11% for Boeing 737, and 10% for Boeing 747.

4.2 *Criteria Air Pollutants*

While energy consumption and GHG emissions are typically dominated by the operational phases for rail and air, this is not the case for CAPs. For almost all modes and all pollutants, the majority of CAPs are found in non-operational phases required to facilitate the system. There are four life-cycle components which have dominating effects on total CAP inventory.

<u>Vehicle Manufacturing</u>

The manufacturing of aircraft results in large CAP emissions (where not so significantly for rail modes). About 70% of SO_2 and 40% of manufacturing NO_X result in electricity generation during aircraft manufacturing. Around 50% of CO emissions and 20% of VOC emissions in manufacturing result from truck transportation in transporting parts and materials for final assembly [EIOLCA 2007]. Vehicle manufacturing accounts for between 8% to 36% of SO_2, 7% to 48% of CO, 1% to 7% of NO_X, 9% to 42% of VOC, 58% to 90% of Pb, and 8% to 41% of PM_{10} total life-cycle emissions where the smaller percentage is the Boeing 737, the larger

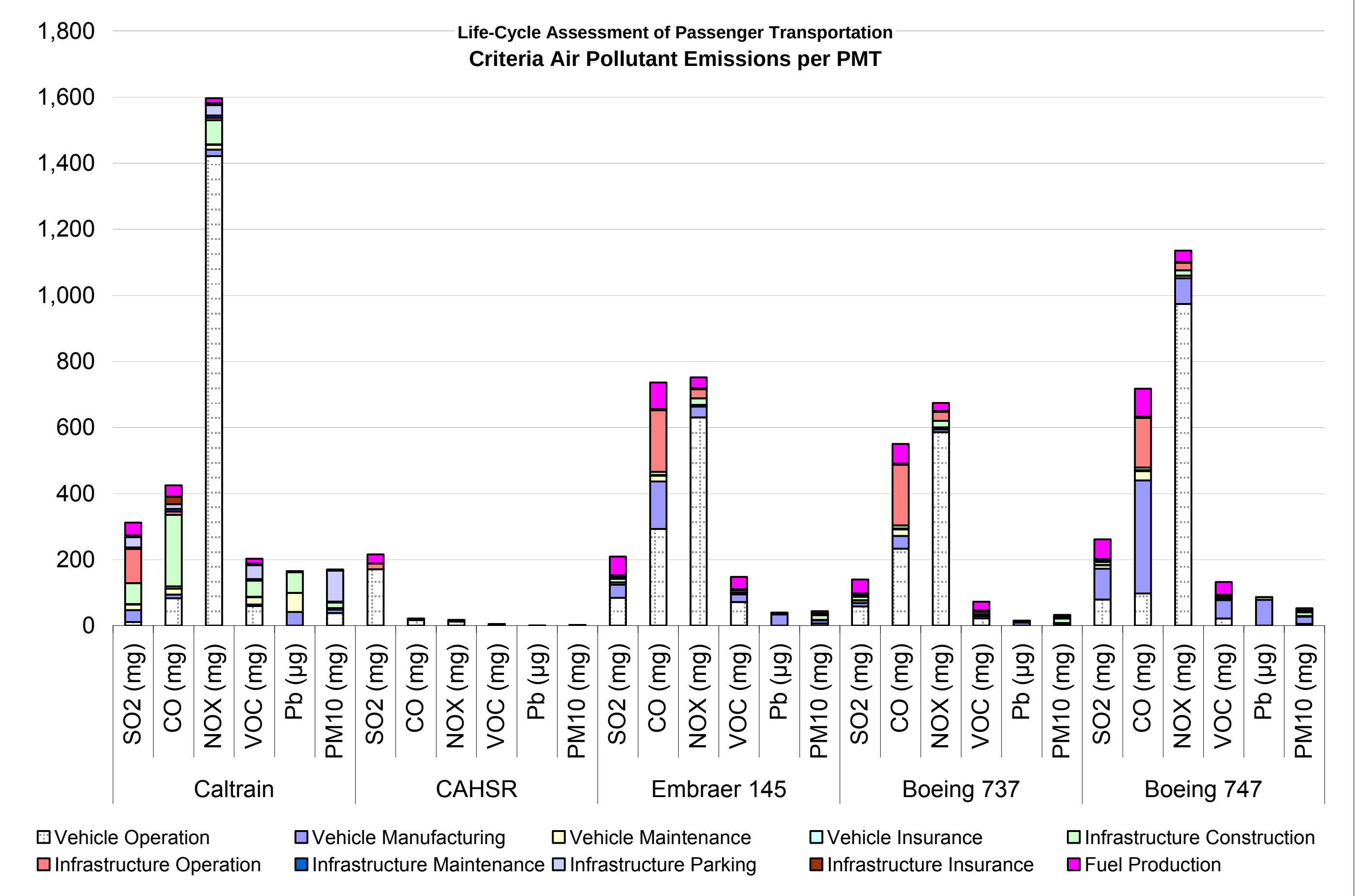


Figure 8 - CAP inventory

percentage is the Boeing 747, and the Embraer 145 lies between. The lead emissions, which make up the majority of total emissions, result from the production of nonferrous metals for the aircraft [EIOLCA 2007]. Vehicle manufacturing has less significance on total impacts for the rail modes.

Infrastructure Construction

Similar to energy and GHG emissions, the effects of station and track construction in the Caltrain system have large effects for the system. The low system PMT for Caltrain and the large infrastructure energy-intense material requirements result in large impacts when normalized per PMT. The individual pollutants are primarily the result of cement manufacturing and electricity generation in concrete and steel production. The large material requirements in the infrastructure have large impacts on all CAPs. Emissions from infrastructure construction account for 20% of total life-cycle SO_2, 51% of CO, 5% of NO_X, 24% of VOC, 38% of Pb, and 10% of PM_{10} emissions. Caltrain NO_X emissions are much larger than the other modes due to the use of decade-old diesel locomotives [Fritz 1994, Caltrain 2007].

Infrastructure Operation

The emissions of SO_2 from electricity generation in the Caltrain infrastructure and CO at airports from the operation of GSE significantly affect these modes. The Caltrain electricity requirements for station lighting, escalators, train control, parking lighting, and other miscellaneous services results in $14GWh_e$ consumed in a year [Chester 2007]. The production of this electricity, primarily from fossil fuels, emits large quantities of SO_2. The SO_2 from infrastructure electricity consumption in the Caltrain system is 33% of total life-cycle SO_2 emissions. Considering airports, the contribution from operation of 45,000 GSEs at all U.S. airports, each running off a fossil fuel or electricity, has large impacts for CO. The CO from airport operations is 21% to 33% of total life-cycle CO emissions.

Figure 9 – Ground support equipment at San Francisco International Airport
Source: Mikhail Chester, 6/14/2007

Fuel Production

Direct energy requirements in petroleum-based fuel production are the main contributors to fuel production SO_2, CO, NO_X, and VOCs in the Caltrain and air modes. The production of electricity from primarily fossil fuels results in emissions of these pollutants during fuel combustion. For Caltrain, SO_2 from fuel production accounts for 12% of total life-cycle SO_2, 8% of CO, and 8% of VOC emissions. For the air modes, fuel production accounts for 23% to 30% of SO_2, 12% to 12% of CO, 3% to 4% of NO_X, 25% to 38% of VOCs, and 12% to 13% of PM_{10} emissions.

5 Case Study: Rail and Air in the California Corridor

The life-cycle inventory provides a snapshot of normalized emissions but does not compute the total effects of particular trip choices. The California corridor is considered the network of road, rail, and air transport modes connecting Sacramento, the San Francisco Bay Area, Los Angeles, and San Diego. The 700 mile corridor connects the four major California urban areas and is experiencing increased congestion and delays for all modes [CAHSR 2005, Levinson 1996]. With population growth expected to increase for the next several decades, the state is exploring transportation network expansions, improvements, and additions, such as highway improvements and the high speed rail system. With growing concern of human health and environmental impacts, decision makers should consider the life-cycle emissions of these transportation options when setting policy.

The rail and air inventory presented in this assessment can be used to estimate total emissions of transportation alternatives in the California corridor. Certain inventory assumptions must be addressed prior to analysis. Specifically, Caltrain, the HRT San Francisco Bay Area commuter rail system, has been modeled and Amtrak, the HRT long distance inter-urban system operates on this route. The differences between the Caltrain and Amtrak systems are not technically that different. Both systems use similar diesel locomotives and have similar track and station layouts [Fritz 1994, Caltrans 1988]. While Caltrain serves as a commuter line and Amtrak serves as a long distance service, both systems operate with similar vehicles on a similar network, just one scaled larger than the other. Assuming the Caltrain life-cycle inventory serves as a reasonable approximation for Amtrak, this data is used to determine total emissions in the corridor.

5.1 Corridor Emissions

To evaluate corridor emissions, a trip from San Francisco to Los Angeles is considered for each of the three modes: heavy rail, high speed rail, and air. The heavy rail trip occurs on Amtrak, the high speed rail is CAHSR, and the air trip occurs on a midsize aircraft such as the Boeing 737. The trip distance is specified as 400 miles for all three systems. All other model assumptions are held constant including occupancy of the vehicles (the Amtrak train has 155 passengers, that of Caltrain, CAHSR has 263 passengers, and the aircraft transports 103 passengers) [Chester 2007].

The total trip energy consumption and GHG emission are shown in Figure 10 and Figure 11 for the three systems. Energy and GHG results are strongly correlated due to the dominating share of fossil energy in all life-cycle components. While the aircraft performs the worse (1,200 MJ and 80 kg GGE per trip), it is closely followed by Amtrak (890 MJ and 62 kg GGE per trip). The CAHSR system performs much better than the aircraft and Amtrak systems (240 MJ and 15 kg GGE per trip). For Amtrak, approximately one-half of the energy and GHG emissions are the result of non-operational phases due to the large infrastructure requirements of the system (assuming that Amtrak and Caltrain have scalable infrastructure components).

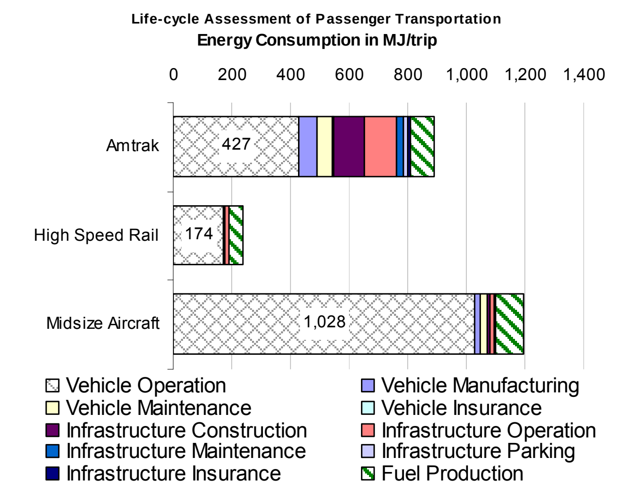


Figure 10 - California corridor trip energy consumption

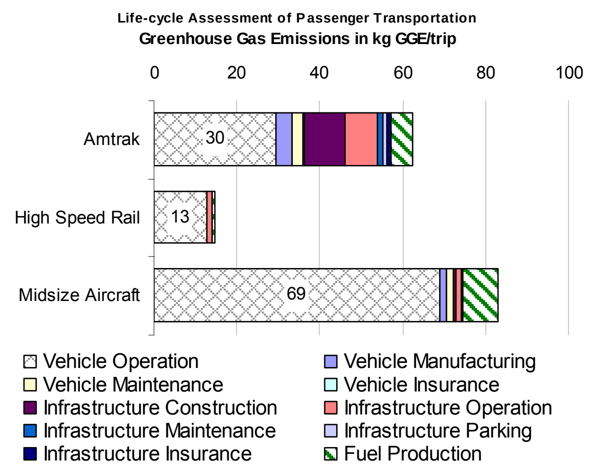


Figure 11 - California corridor trip GHG emission

The CAP emissions from Amtrak are the worse of the three modes from both an activity and impact perspective. While CAHSR has low CAP emissions for almost all pollutants (except SO_2 which results from the large operational electricity requirements) and the aircraft is somewhere in the middle for the two modes, Amtrak's effect is not only largest but also occurs close to people. The CAP emissions from Amtrak are likeliest to occur near population centers given its stop-and-go nature. This is dissimilar to CAHSR which is intended to connect only a few major urban centers, traveling in semi-remote areas between (and powered from a remotely located generation facility), and the aircraft which emits at high altitudes.

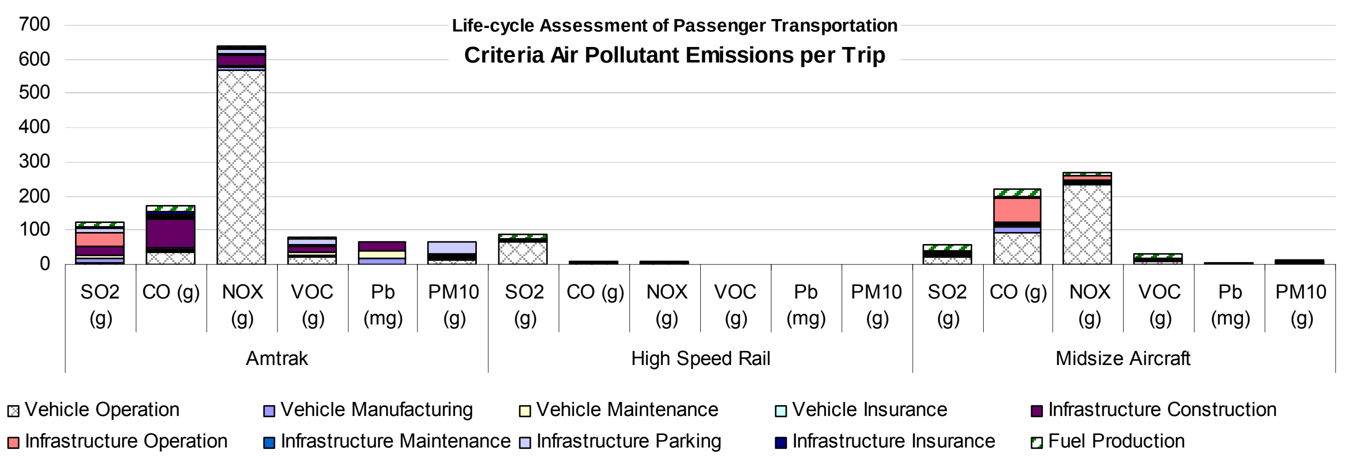


Figure 12 – California corridor trip CAP emissions

The emissions from the systems presented are highly dependent on several key variables which are explored in §5.2. The trip emissions presented provide a high-level analysis of the activities of the three systems under certain operating conditions which are explored further in later sections and in proposed future work.

5.2 Modal Characteristic Adjustments

The adjustment of several highly sensitive parameters results in significant environmental characteristics for the trip for the three systems. The primary factor is vehicle occupancy. While total emissions do not change much based on the number of passengers (under the assumption that the vehicle will consume a certain amount of energy during its trip and the marginal passenger does not affect this amount significantly), the energy or emissions per PMT does. Under the standard occupancy assumptions, Table 4 shows the life-cycle inventory (again, assuming Caltrain represents Amtrak). The average Amtrak train transports 149 passengers, slightly less than the 155 for Caltrain [BTS 2007b]. For CAHSR, ridership is based on projections of a 75% occupancy rate and 350 seats per train [Levinson 1996]. The midsize aircraft carrying 101 passengers operates at 72% capacity [BTS 2007]. An additional 40 seats can be filled on the average flight reducing inventory effects per PMT.

A scenario is evaluated where Amtrak transports 149 passengers, CAHSR ridership projects have been overestimated, and aircraft are flying closer to full capacity. This scenario is not unreasonable considering the low ridership outcomes for many rail projects in the U.S. and the increasing propensity of airlines to schedule flights at or near capacity. CAHSR ridership is assumed to be at 50% occupancy and the midsize aircraft travels at 85% occupancy. The result of these occupancy adjustments does not significantly change Amtrak, increases the effect per PMT for CAHSR and decreases the effect per PMT for the aircraft. The adjusted inventory is shown in Table 5. In this scenario, CAHSR emissions increase by around 50% for all environmental impacts. The aircraft emissions decrease by around 10%. While a breakeven point for Amtrak and Caltrain will likely not be reached based on occupancy adjustments alone (due to the large infrastructure effects with Amtrak), an operational component equivalence can be found. Holding Amtrak's occupancy constant (since it is based on actual data while CAHSR ridership is based on projections), CAHSR would have to transport 100 passengers per train (around 30% occupancy) for this energy consumption and GHG emission equivalence. CAP behave differently in the operational stage at these occupancy levels due to differing fuel types and locomotive technology.

Table 5 – California corridor adjusted life-cycle inventory results for Scenario 1 (per PMT) (operational emissions in parenthesis)

	Amtrak	CAHSR	Midsize Aircraft
Energy (MJ)	2.3 (1.1)	0.89 (0.65)	2.6 (2.3)
GGE (g CO_2e)	160 (77)	55 (48)	180 (150)
SO_2 (mg)	320 (11)	320 (260)	120 (51)
CO (mg)	440 (86)	32 (25)	490 (210)
NO_X (mg)	1,700 (1,500)	26 (18)	590 (520)
VOC (mg)	210 (61)	7.0 (5.5)	64 (20)
Pb (μg)	170	0.85 (0.33)	13
PM_{10} (mg)	180 (40)	3.4 (2.8)	28 (3.3)

149, 175, and 115 passengers on Amtrak, CAHSR, & the aircraft

For the second scenario, the geographic constraints are introduced relating to inconsistencies in trip distance for the three systems. From San Francisco to Los Angeles, the trip for Amtrak is a different distance than the trip for CAHSR which is different than the distance the aircraft would fly. Trip distances of 400 miles for Amtrak, 450 miles for CAHSR, and 350 miles for the aircraft are introduced. Occupancy levels are kept at 155, 263, and 101 for the three systems. The trip distance adjustments do not have major effects on the rankings of the outcomes. The increased CAHSR distance is not far enough to make its total impacts close to that of Amtrak. Additionally, the decreased aircraft distance is not enough of a difference to make its total trip impacts less than that of Amtrak. The results are shown in Table 6.

Table 6 – California corridor adjusted life-cycle inventory results for Scenario 2 (per trip) (operational emissions in parenthesis)

	Amtrak	CAHSR	Midsize Aircraft
Energy (MJ)	890 (430)	270 (200)	1,000 (900)
GGE (kg CO_2e)	62 (30)	17 (14)	73 (60)
SO_2 (g)	120 (4.3)	97 (77)	49 (20)
CO (g)	170 (33)	9.7 (7.4)	190 (82)
NO_X (g)	640 (570)	7.7 (5.5)	240 (200)
VOC (g)	81 (24)	2.1 (1.6)	25 (7.9)
Pb (mg)	66	0.26 (0.100)	5.3
PM_{10} (g)	68 (15)	1.0 (0.83)	11 (1.3)

155, 263, and 101 passengers on Amtrak, CAHSR, & the aircraft

Aircraft size does have an impact on aircraft life-cycle performance. The midsized aircraft represents the optimal size for aircraft (evaluated per PMT). The small and large aircraft have significantly larger energy consumption and emissions than the midsize aircraft per PMT [Chester 2007]. When evaluating this effect on the California corridor trip, the improved performance of the midsized aircraft over the aircraft remains.

Figure 13 – Potential California high speed rail route
Source: CAHSR 2007

5.3 Case Study Discussion

The energy consumption and emissions resulting from the systems discussed in the California corridor can provide decision-makers with key environmental performance data for transportation planning. The three systems have life-cycle components that occur on different time scales and at different places than when and where the vehicles travel. This must be evaluated by decision and policy makers from the impact perspective. The first major difference is between the rail systems and aircraft where emissions occur at ground level or in the upper atmosphere where they may have more or less of an effect (GHG emissions released directly into the upper atmosphere may have more of an effect than those released at ground level while in terms of human health impacts, CAP releases at ground level will likely have larger effects than those released in the atmosphere). Life-cycle component considerations are also critical as emissions from each item may occur near population centers in more impacting bursts. For example, CO emissions from ground support equipment at airports may have more of an impact than the CO emissions from all three systems along their routes. These individually unique temporal and geographic considerations are critical in the full understanding of any transportation system's impact.

6 Future Work

The life-cycle inventory for the systems incorporates many data sets, assumptions, and a particular mathematical framework which should be evaluated with sensitivity and validation methods. The inventory presented in this document represents a best approach which is subject to change under a variety of conditions. A sensitivity analysis will be performed on several critical parameters for each system to present a probabilistic range for inventory values. This analysis will be presented in updates to [Chester 2007] and future publications. Additionally, validation of inventory values will occur against operational and other life-cycle studies if available.

An in-depth inventory of the Amtrak system would provide finer resolution environmental effects for comparisons in the case study. It is not expected that the Amtrak inventory will be significantly different than Caltrain's considering the strong similarities between the vehicles and infrastructure but verification of this assumption should occur prior to future analyses. While the system's are similar, their scales are not which could be a factor in the overall environmental performance.

This analysis sets the foundation for improved environmental factors for several transportation modes which can be used for both decision making and further analyses. The intention is for policy makers and others who use environmental factors (typically "tail-pipe") to have a more comprehensive data set for which to evaluate transportation networks. It is expected that this inventory will provide a new set of data for environmental analysis which can be applied to many different studies.

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Appendix A

Table 7 - Grouping of life-cycle components

Grouping	Rail	Air
Vehicles		
Manufacturing	• Train manufacturing	• Aircraft manufacturing • Engine manufacturing
Operation	• Propulsion • Idling • Auxiliaries	• APU operation • Startup • Taxi out • Take off • Climb out • Cruise • Approach • Taxi in
Maintenance	• Train maintenance • Train cleaning • Flooring replacement	• Aircraft maintenance • Engine maintenance
Insurance	• Crew health insurance and benefits • Train liability	• Crew health insurance and benefits • Aircraft liability insurance
Infrastructure		
Construction	• Station construction • Track construction	• Airport construction • Runway/Taxiway/Tarmac construction
Operation	• Station lighting • Escalators • Train control • Station parking lighting • Station miscellaneous	• Runway lighting • Deicing fluid production • GSE operation
Maintenance	• Station maintenance • Station cleaning	• Airport maintenance
Parking	• Station parking	• Airport parking
Insurance	• Non-crew health insurance and benefits • Infrastructure liability insurance	• Non-crew health insurance and benefits • Infrastructure liability insurance
Fuels		
Production	• Train electricity production • Train electricity T&D losses • Infrastructure electricity production • Infrastructure electricity T&D losses	• Jet fuel refining and distribution

Appendix B

Inventory effects per PMT. See Chester 2007 for methodology and assumptions.

Table 8 - Environmental inventory per PMT

I/O			Vehicle Manufacturing	Vehicle Operation	Vehicle Maintenance	Vehicle Insurance	Infrastructure Construction	Infrastructure Operation	Infrastructure Maintenance	Infrastructure Parking	Infrastructure Insurance	Fuel Production
Energy	Caltrain	Energy (MJ)	0.157996131	1.06722515	0.133943434	0.007233531	0.270407354	0.263861666	0.059231275	0.04436755	0.025058517	0.199165052
Energy	CAHSR	Energy (MJ)	1.68358E-05	0.43452288	1.15645E-05	6.68291E-06	0.002052665	0.043031626	4.13683E-05	8.333E-06	2.47785E-05	0.112561057
Energy	Embraer 145	Energy (MJ)	0.185960966	3.470627126	0.05129783	0.002114586	0.021554041	0.040178469	5.7427E-05	0.00277655	0.002732238	0.330702005
Energy	Boeing 737	Energy (MJ)	0.04912659	2.570696637	0.05519286	0.003382105	0.021214132	0.039509187	5.7427E-05	0.00277655	0.002686725	0.244951273
Energy	Boeing 747	Energy (MJ)	0.436479298	3.652855613	0.062228447	0.003374311	0.017634954	0.03246178	5.7427E-05	0.00277655	0.002207484	0.34806582
GHG	Caltrain	GHG (g)	9.576535773	73.87118386	6.285362726	0.592025927	25.08124852	19.36935194	2.930270075	2.958209146	2.050905834	13.0720728
GHG	CAHSR	GHG (g)	0.000819998	31.89711761	0.000571449	0.000546961	0.184843004	3.158832121	0.00197292	0.000553619	0.002027987	1.488687543
GHG	Embraer 145	GHG (g)	15.00793018	232.4891462	3.619418736	0.173067566	1.543093796	3.409874537	0.004455798	0.178010356	0.223619105	29.57497608
GHG	Boeing 737	GHG (g)	3.968347835	172.4880086	3.914438411	0.276807195	1.518873816	3.353073743	0.004455798	0.178010356	0.219894117	21.90621141
GHG	Boeing 747	GHG (g)	35.25533342	245.3028639	4.582393459	0.276169349	1.263842366	2.754972988	0.004455798	0.178010356	0.180670751	31.12783755
SO_2	Caltrain	SO_2 (mg)	36.11212269	10.81544471	17.07354819	1.453729144	63.30134306	103.3927278	4.447184663	31.24956079	5.036032119	38.82592686
CO		CO (mg)	10.97002198	82.71629654	18.30876887	6.559338262	216.8824853	9.943157787	7.653002878	14.43524937	22.72296618	34.60441211
NO_X		NO_X (mg)	19.79224273	1421.066126	14.38840725	1.636323142	72.67254314	7.45233298	6.856563709	31.555998	5.668577216	15.40637193
VOC		VOC (mg)	4.987607194	59.07373163	21.88248974	1.214952376	48.73761275	2.224286411	2.815635751	42.10786315	4.208857761	15.29493744
Pb		Pb (µg)	41.50193359	0	57.51881828	0	62.48885518	0.13427627	2.720070288	0.499157667	0	0.013266826
PM_{10}		PM_{10} (mg)	10.12469668	38.42768669	4.320102385	0.309005229	17.10794377	1.122549617	1.028458281	94.17803238	1.070460934	2.486469656
SO_2	CAHSR	SO_2 (mg)	0.003882086	170.2653765	0.000581671	0.001343071	0.521299551	16.86170352	0.002777828	0.006040262	0.004979755	27.74362286
CO		CO (mg)	0.003237317	16.37422225	0.001529318	0.006060041	1.611790236	1.621570319	0.004307627	0.002788929	0.02246904	1.964131633
NO_X		NO_X (mg)	0.002170165	12.27237454	0.001079595	0.001511766	0.607464972	1.215356553	0.004338857	0.006096992	0.005605231	3.093364525
VOC		VOC (mg)	0.000663216	3.662916834	0.001638053	0.00112247	0.438381039	0.362745609	0.001642486	0.008141652	0.004161824	0.170816242
Pb		Pb (µg)	0.009716879	0.221123866	0.000759737	0	0.288576686	0.021898316	0.001897059	9.62466E-05	0	0.02401119
PM_{10}		PM_{10} (mg)	0.001204622	1.848595516	0.000185479	0.000285484	0.111400019	0.183069924	0.000664176	0.018201219	0.001058499	0.106483394
SO_2	Embraer 145	SO_2 (mg)	40.09254036	83.78294542	6.743198192	0.42497018	10.95147379	5.963348135	0.007810664	3.636666594	0.549100295	56.7301814
CO		CO (mg)	143.8594168	292.5869861	17.38137338	1.917498302	9.566669946	186.5869076	0.040764227	0.83410399	2.477582972	80.9278891
NO_X		NO_X (mg)	32.93646162	630.0986561	4.675658647	0.478348077	19.94972275	27.73864001	0.014951842	2.082119111	0.618069414	33.07020053
VOC		VOC (mg)	23.18945902	71.36742762	4.756101165	0.355168315	0.150262297	7.432414947	0.007513115	2.87315795	0.458909908	36.69985668
Pb		Pb (µg)	33.52300051	0	4.462648186	0	1.213666215	0.043764989	0	0.034741287	0	0
PM_{10}		PM_{10} (mg)	9.227746822	6.617428657	1.276495454	0.090331826	14.23101727	1.33944707	0.003072194	4.668882422	0.116716971	5.861222533
SO_2	Boeing 737	SO_2 (mg)	10.52707238	58.02302248	7.455222446	0.6797045	10.77164918	5.86401225	0.007810664	3.636666594	0.539953526	42.02009643
CO		CO (mg)	38.56368724	232.9999681	19.42672714	3.066879241	9.420891669	183.478792	0.040764227	0.83410399	2.436312046	59.94336032
NO_X		NO_X (mg)	8.696992744	585.4113759	5.213711669	0.765078012	19.62238679	27.27657704	0.014951842	2.082119111	0.607773776	24.49512731
VOC		VOC (mg)	6.260672176	22.47659723	5.138387168	0.568062215	0.150262297	7.308607734	0.007513115	2.87315795	0.451265507	27.18361689
Pb		Pb (µg)	8.766208223	0	5.029543275	0	1.193449282	0.043035963	0	0.034741287	0	0
PM_{10}		PM_{10} (mg)	2.433651724	3.727181712	1.427101866	0.144478251	13.99498424	1.317134913	0.003072194	4.668882422	0.11477273	4.341412807
SO_2	Boeing 747	SO_2 (mg)	93.57722109	79.05908222	10.07881041	0.678138258	8.878132743	4.818025663	0.007810664	3.636666594	0.443639924	59.70885203
CO		CO (mg)	342.2272573	97.29248998	27.97312284	3.059812237	7.885876181	150.7509689	0.040764227	0.83410399	2.001737626	85.17708275
NO_X		NO_X (mg)	77.27385381	973.7910535	7.409490223	0.763315044	16.17560599	22.41114831	0.014951842	2.082119111	0.499362813	34.80658199
VOC		VOC (mg)	55.52782267	21.56898125	5.970379574	0.56675323	0.150262297	6.004943053	0.007513115	2.87315795	0.37077153	38.6268166
Pb		Pb (µg)	77.95057251	0	7.578431098	0	0.980569109	0.035359471	0	0.034741287	0	0
PM_{10}		PM_{10} (mg)	21.62543506	5.09996767	2.058105549	0.14414533	11.50960466	1.082192455	0.003072194	4.668882422	0.094300274	6.168971442