SUPPORTING INFORMATION FOR:

ENVIRONMENTAL ASSESSMENT OF PASSENGER TRANSPORTATION SHOULD INCLUDE INFRASTRUCTURE AND SUPPLY CHAINS

Mikhail V. Chester [1,2]
Post Doctoral Associate
510-332-0145
mchester@cal.berkeley.edu

Arpad Horvath [1]
Associate Professor
510-642-7300
horvath@ce.berkeley.edu

1 Department of Civil and Environmental Engineering
760 Davis Hall
University of California, Berkeley
Berkeley, CA 94720, USA

2 Author to whom any correspondence should be addressed

Supporting Information Table of Contents

1. Scope of Work

Many studies have quantified the environmental inventory of specific life-cycle stages and particular modes. Few studies have evaluated total environmental inventory for a specific mode let alone multiple modes. Table S1 shows selected studies associated with passenger transportation and in which component the study was performed. Onroad modes are the most studied mode across all components. The focus of other modes tends to be in the operation of the vehicles. Few studies have gone further to evaluate the infrastructure of the systems.

Table S1 - Selected Literature

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

Sources: A. 19 (Economic); B. 60 (Economic); C. 62 (Economic); D. 78 (Economic); E. 72 (Economic); F.54 (Economic); G. 55 (Economic); H. 46 (Economic); I. 70 (Economic); J. 73 (Freight); K. 75; L. 58; M. 61 (Freight); N. 64 (Freight); O. 33; P. 37; Q. 14; R. 18; S. 59; T. 20; U. 42; V. 22; W. 28; X. 36; Y. 27; Z. 2; AA. 50; AB. 68; AC. 44; AD. 35; AE. 52; AF. 5; AG. 12; AH. 16; AI. 53; AJ. 74; AK. 41; AL. 17; AM. 21; AN. 51; AO. 34 (Freight); AP. 63.

2. Modal Representation and Characteristics

The sedan, SUV, and pickup (where a sedan represents the lowest weight and best fuel economy at 3,200 lbs and 28 mpg, the SUV is 4,600 lbs and averages 17 mpg, and the pickup is 5,200 lbs, gets 16 mpg and is one of the top selling vehicles in the U.S.) are chosen to represent the range in the U.S. light duty vehicle fleet (which includes automobiles, SUVs, pickup trucks, and vans) and critical performance characteristics (32, 85, 87). The sedan SUV, and pickup are modeled after the 2005 Toyota Camry, Chevrolet Trailblazer, and Ford F-150. These vehicles were the highest selling in their respective classes with 430,000, 240,000, and 850,000 sales in the U.S. in that year (32). It is estimated that the vehicles travel 11,000 miles per year.

The bus is modeled after a typical 40-foot urban diesel vehicle and achieves a 4.3 miles per gallon fuel economy and performs 42,000 miles per year (30, 39).

The difficulty of selecting a single rail system for all U.S. commuter rail travel is rooted in the unique service niche, operating conditions, and geographic region, among many other factors. The subway is modeled after the San Francisco Bay Area's heavy rail electric Bay Area Rapid Transit (BART) system. BART infrastructure is composed of roughly 20 miles of underground track, 23 miles of aerial track, and 44 miles of surface track (91). The commuter rail system is modeled after the San Francisco Bay Area's Caltrain, a heavy rail diesel locomotive with similar vehicles and infrastructure to Amtrak. The California and Massachusetts electric Light Rail system are modeled after San Francisco's Muni Metro and the Boston metropolitan area's Green Line. These two light rail systems are similar in vehicle and infrastructure design. For the electric modes, the two San Francisco systems operate with a 47% natural gas, 23% nuclear, 13% hydro, 15% renewable, and 2% other and the Boston Green Line with a 44% natural gas, 22% coal, 16% petroleum, 12% nuclear, and 6% other electricity mixes (20, 81). The generalization, particularly of the subway system, to other networks does present representativeness questions. Assuming similar vehicle and infrastructure material requirements between BART and the New York City subway but altering the electricity mix reveals an increase of 1.5 times for greenhouse gas (GHG) emissions (the New York City subway emits 1.5 times more than BART per passenger mile traveled (PMT)), 3.2 times for CO, 5 times for NO_X, and 1.3 times for SO_2.

Air modes are evaluated by small, medium and large aircraft (similar to the Embraer 145, Boeing 737, and Boeing 747) which represent the range of impacts from aircraft sizes, passenger occupancy, and short to long haul segment performance (86). The three specific aircraft models make up 30% of vehicle miles traveled (VMT) and 26% of PMT of all domestic flights. Assuming the Boeing 737 is representative of the Airbus A300s, Boeing 717, 727, 757, 777, and the McDonnell Douglas DC9 and the Boeing 747 is representative of the Boeing 767 then they make up 80% of VMT and 92% of PMT (86).

3. Fundamental Environmental Factors for Onroad Modes

The fundamental environmental factors for onroad modes are shown in Table S2 with their sources. These factors are the basis for energy and emission inventory calculations for automobiles and buses. Data sources in Table S2 are provided in the Supporting Information References section.

Table S2 - Fundamental Environmental Factors for Onroad Modes (Sources, Energy, & GHG)

Grouping	Component	Sources	LCA Approach	Energy		GHG (CO_2e)	
Vehicles							
Manufacturing	Sedan	26 (#336110), 1	EIO-LCA	121	GJ/veh.	10	mt/veh.
	SUV	26 (#336110), 1	EIO-LCA	103	GJ/veh.	9	mt/veh.
	Pickup	26 (#336110), 1	EIO-LCA	146	GJ/veh.	12	mt/veh.
	Bus	26 (#336120), 39	EIO-LCA	114	GJ/veh.	129	mt/veh.
Sedan	Running	58, 32, 30	Process	4.8	MJ/VMT	367	g/VMT
Operation	Startup	30	Process				
	Brake Wear	30	Process				
	Tire Wear	30	Process				
	Evaporative	30	Process				
SUV	Running	58, 32, 30	Process	7.8	MJ/VMT	478	g/VMT
Operation	Startup	30	Process				
	Brake Wear	30	Process				
	Tire Wear	30	Process				
	Evaporative	30	Process				
Pickup	Running	58, 32, 30	Process	8.3	MJ/VMT	618	g/VMT
Operation	Startup	30	Process				
	Brake Wear	30	Process				
	Tire Wear	30	Process				
	Evaporative	30	Process				
Bus	Running	30	Process	32	MJ/VMT	2,373	g/VMT
Operation	Brake Wear	30	Process				
	Tire Wear	30	Process				
	Evaporative	30	Process				
	Idling	15, 11, 30	Process	65	MJ/hr	4,614	g/hr
Maintenance	Vehicle	26 (#8111A0)	EIO-LCA	5.2	TJ/$M	423	mt/$M
	Tire	26 (#326210)	EIO-LCA	15.1	TJ/$M	1090	mt/$M
	Repair Stations	10	Process			205	mt/yr
Insurance	Vehicle Insurance	26 (#524100)	EIO-LCA	1.0	TJ/$M	84	mt/$M
Infrastructure							
Construction	Roads & Highways	65, 29, 57, 7	Hybrid	76	MJ/ft^2	6	kg/ft^2
Maintenance	Roads & Highways	65, 29, 57, 7	Hybrid	7.3	MJ/ft^2	614	g/ft^2
Vegetation Control	Herbicide Production	26 (#325180), 31	EIO-LCA	529	MJ/lb	31	kg/lb
Deicing	Salt Production	26 (#325190), 76	EIO-LCA	883	MJ/ton	77	kg/ton
Lighting	Electricity Production	23, 20	Process	205	PJ/yr	758	g/kWh
Parking	Road/Surface Parking	65, 29	Hybrid	86	MJ/ft^2	7.1	kg/ft^2
	Garage Parking	65, 29	Hybrid	8	MJ/ft^2	53	kg/ft^2
Fuels							
Gasoline Production	Refining & Distribution	26 (#324110)	Hybrid	19	MJ/gal	1.7	kg/gal
Diesel Production	Refining & Distribution	26 (#324110)	Hybrid	18	MJ/gal	1.6	kg/gal

(Note: where EIO-LCA is used (Source 26), the economic sector is provided in parenthesis. Sector descriptions are as follows: #336110 – Automobile & Light Truck Manufacturing, #336120 – Heavy Duty Vehicle Manufacturing, #8111A0 – Automotive Repair & Maintenance, #326210 – Tire Manufacturing, #524100 – Insurance Carriers, #325180 – Other Basic Inorganic Chemical Manufacturing, #325190 – Other Basic Organic Chemical Manufacturing, #324110 – Petroleum Refineries)

Table S2 - Fundamental Environmental Factors (SO_2, CO, NO_X) for Onroad Modes (cont'd)

Grouping	Component	SO_2		CO		NO_X	
Vehicles							
Manufacturing	Sedan	23	kg/veh	124	kg/veh	23	kg/veh
	SUV	20	kg/veh	105	kg/veh	20	kg/veh
	Pickup	28	kg/veh	149	kg/veh	28	kg/veh
	Bus	1600	kg/veh	302	kg/veh	392	kg/veh
Sedan	Running	0.02	g/VMT	11	g/VMT	0.8	g/VMT
Operation	Startup			7	g/VMT	0.2	g/VMT
	Brake Wear						
	Tire Wear						
	Evaporative						
SUV	Running	0.03	g/VMT	12	g/VMT	1.0	g/VMT
Operation	Startup			9	g/VMT	0.2	g/VMT
	Brake Wear						
	Tire Wear						
	Evaporative						
Pickup	Running	0.03	g/VMT	16	g/VMT	1.4	g/VMT
Operation	Startup			12	g/VMT	0.3	g/VMT
	Brake Wear						
	Tire Wear						
	Evaporative						
Bus	Running	0.02	g/VMT	4	g/VMT	17.8	g/VMT
Operation	Brake Wear						
	Tire Wear						
	Idling			80	g/hr	121	g/hr
Maintenance	Vehicle	1090	kg/$M	4340	kg/$M	994	kg/$M
	Tire	1960	kg/$M	15.2	mt/$M	2030	kg/$M
	Repair Stations						
Insurance	Vehicle	207	kg/$M	934	kg/$M	233	kg/$M
Infrastructure							
Construction	Roads & Hwys	12	g/ft^2	23	g/ft^2	30	g/ft^2
Maintenance	Roads & Hiwys	1	g/ft^2	2236	mg/ft^2	2.8	g/ft^2
Vegetation Control	Herbicide Prod.	86	g/lb	81	g/lb	37	g/lb
Deicing	Salt Production	122	g/ton	322	g/ton	108	g/ton
Lighting	Electricity Prod.	4	g/kWh	365	mg/kWh	1.3	g/kWh
Parking	Road/Surface	14	g/ft^2	26	g/ft^2	39	g/ft^2
	Garage	222	g/ft^2	380	g/ft^2	465	g/ft^2
Fuels							
Gasoline	Refining	3.2	g/gal	4.6	g/gal	1.9	g/gal
Diesel	Refining	3.0	g/gal	4.3	g/gal	1.8	g/gal

4. Fundamental Environmental Factors for Rail Modes

The fundamental environmental factors for rail modes are shown in Table S3 with their sources. These factors are the basis for energy and emission inventory calculations for BART, Caltrain, Muni, and the Green Line. Data sources in Table S3 are provided in the Supporting Information References section.

Table S3 - Fundamental Environmental Factors for Rail Modes **(Sources, Energy, and GHG)**
Vehicle and Fuel Components

Grouping	Component	Source	LCA Approach	Energy		GHG (CO_2e)	
Vehicles							
Manufacturing	BART/Caltrain	71 (Long Distance Train)	Process	30	TJ/train	1841	mt/train
	Muni	71 (LRT w/CA Mix)	Process	7	TJ/train	338	mt/train
	Green Line	71 (LRT w/MA Mix)	Process	7	TJ/train	373	mt/train
BART Operation	Propulsion	71, 44, 20	Process	28	kWh/VMT	10	kg/VMT
	Idling	71, 44, 20	Process	14	kWh/VMT	5	kg/VMT
	Auxiliaries	71, 44, 20	Process	3.9	kWh/VMT	1	kg/VMT
Caltrain Operation	Propulsion	37, 9, 36, 44	Process	41	kWh/VMT	10	kg/VMT
	Idling	37, 9, 36, 44	Process	2.4	kWh/VMT	0.6	kg/VMT
	Auxiliaries	37, 9, 36, 44	Process	2.1	kWh/VMT	0.5	kg/VMT
Muni Operation	Propulsion	38, 36, 44, 20	Process	4.4	kWh/VMT	1.6	kg/VMT
	Idling	38, 36, 44, 20	Process	1.1	kWh/VMT	0.4	kg/VMT
	Auxiliaries	38, 36, 44, 20	Process	2.3	kWh/VMT	0.8	kg/VMT
Green Line Operation	Propulsion	38, 36, 44, 20	Process	7.9	kWh/VMT	5.0	kg/VMT
	Idling	38, 36, 44, 20	Process	4.0	kWh/VMT	2.5	kg/VMT
	Auxiliaries	38, 36, 44, 20	Process	1.2	kWh/VMT	0.8	kg/VMT
Maintenance	BART/Caltrain	71 (Long Distance Train)	Process	25	TJ/life	1128	mt/life
	Muni	71 (LRT w/CA Mix)	Process	1.3	TJ/life	64	mt/life
	Green Line	71 (LRT w/MA Mix)	Process	1.4	TJ/life	68	mt/life
Cleaning	Vacuuming (BA)	25, 8, 81, 20	Hybrid	1.1	Wh/ft^2	271	g/kWh
	Vacuuming (CA)	25, 8, 81, 20	Hybrid	1.1	Wh/ft^2	351	g/kWh
	Vacuuming (MA)	25, 8, 81, 20	Hybrid	1.1	Wh/ft^2	632	g/kWh
Flooring Replacement	Carpet Production	26 (#314110)	EIO-LCA	15	TJ/$M	1140	mt/$M
Insurances	Benefits & Liability	26 (#524100)	EIO-LCA	1.0	TJ/$M	84	mt/$M
Fuels							
Electricity Production	Bay Area Mix	81, 20	Process			271	g/kWh
	California Mix	81, 20	Process			351	g/kWh
	Massachusetts Mix	81, 20	Process			632	g/kWh
Diesel Production	Fuel Refining	26 (#324110)	Hybrid	18	MJ/gal	1.6	kg/gal

(Note: where EIO-LCA is used (Source 26), the economic sector used is provided in parenthesis.
Sector descriptions are as follows: #314110 – Carpet & Rug Mills, #524100 – Insurance Carriers)

Table S3 - Fundamental Environmental Factors for Rail Modes (Sources, Energy, and GHG)
Infrastructure Components (cont'd)

Grouping	Component	Source	LCA Approach	Energy		GHG (CO_2e)	
Infrastructure							
Station Construction	Concrete Production	26 (#327320), 80	EIO-LCA	6.5	GJ/yd^3	609	kg/yd^3
	Concrete Placement	43	Process	5.7	MJ/yd^3	35	kg/yd^3
	Steel Production	26 (#331111), 77	EIO-LCA	5.9	MJ/yd^3	543	g/yd^3
Station Lighting (per station)	BART	36, 4	Process	450,000	kWh/yr	351	g/kWh
	Caltrain	36	Process	120,000	kWh/yr	351	g/kWh
	Muni	36, 38	Process	2,600	kWh/yr	351	g/kWh
	Green Line	Observation, 23	Process	2,600	kWh/yr	632	g/kWh
Station Escalators (per station)	BART	36, 4	Process	280,000	kWh/yr	351	g/kWh
	Caltrain	24, 38	Process	4.7	kW	351	g/kWh
	Muni	24, 38	Process	4.7	kW	351	g/kWh
	Green Line	24, 38	Process	4.7	kW	632	g/kWh
Train Control (per station)	BART	36, 4	Process	190,000	kWh/yr	351	g/kWh
	Caltrain	36	Process	210,000	kWh/yr	351	g/kWh
	Muni	36, 38	Process	130,000	kWh/yr	351	g/kWh
	Green Line	36, 38	Process	52,000	kWh/yr	632	g/kWh
Parking Lighting (per station)	BART	Estimation	Process	0.9	kWh/ft^2-yr	351	g/kWh
	Caltrain	Estimation	Process	0.9	kWh/ft^2-yr	351	g/kWh
	Green Line	Estimation	Process	0.9	kWh/ft^2-yr	632	g/kWh
Station Miscellaneous (per station)	BART	36, 4	Process	47,000	kWh/yr	351	g/kWh
	Caltrain	36	Process	27,000	kWh/yr	351	g/kWh
	Muni	36, 38	Process	160,000	kWh/yr	351	g/kWh
	Green Line	36, 38	Process	160,000	kWh/yr	632	g/kWh
Station Maintenance	For all systems, assumed 5% of station construction.						
Station Cleaning	Mopping, BA Mix	66, 81, 20	Hybrid	0.6	kWh/ft^2-yr	0.2	kg/ft^2-yr
	Mopping, CA Mix	66, 20	Hybrid	0.6	kWh/ft^2-yr	0.2	kg/ft^2-yr
	Mopping, MA Mix	66, 20	Hybrid	0.6	kWh/ft^2-yr	0.4	kg/ft^2-yr
Parking	BART	65, 29	Hybrid	80	MJ/ft^2	6.7	kg/ft^2
	Caltrain	65, 29	Hybrid	80	MJ/ft^2	6.7	kg/ft^2
	Green Line	65, 29	Hybrid	80	MJ/ft^2	6.7	kg/ft^2
Track & Power Delivery	Aggregate Production	26 (#212320), 77	Hybrid	193	MJ/ton	14	kg/ton
	Concrete Production	26 (#327320), 80	EIO-LCA	6,500	MJ/yd^3	609	kg/yd^3
	Concrete Placement	43	Process	5.7	MJ/yd^3	35	kg/yd^3
	Steel Production	26 (#331111), 77	EIO-LCA	5.9	MJ/yd^3	543	g/yd^3
	Wood Production	26 (#321113), 40	EIO-LCA	138	MJ/tie	12	kg/tie
	Power Structure Production	26 (#335929)	EIO-LCA	9	TJ/$M	728	mt/$M
	Substation Production	26 (#335311)	EIO-LCA	10	TJ/$M	807	mt/$M
Track Maintenance	For all systems, assumed 5% of track construction.						
Insurances	Benefits & Liability	26 (#524100)	EIO-LCA	1.0	TJ/$M	84	mt/$M

(Note: where EIO-LCA is used (Source 26), the economic sector used is provided in parenthesis. Sector descriptions are as follows: #327320 – Ready-Mix Concrete Manufacturing, #331111 – Iron & Steel Mills, #212320 – Sand, Gravel, Clay, & Refractory Mining, #321113 – Sawmills, #335929 – Other Communication & Energy Wire Manufacturing, #335311 – Electric Power & Specialty Transformer Manufacturing, #524100 – Insurance Carriers)

Table S3 - Fundamental Environmental Factors for Rail Modes (SO_2, CO, NO_X)
Vehicle and Fuel Components (cont'd)

Grouping	Component	SO_2		CO		NO_X	
Vehicles							
Manufacturing	BART/Caltrain	6.9	mt/train	2.1	mt/train	3.8	mt/train
	Muni	1.7	mt/train	2.8	mt/train	1.0	mt/train
	Green Line	1.9	mt/train	2.8	mt/train	1.1	mt/train
BART	Propulsion	81	g/VMT	6.8	g/VMT	7.5	g/VMT
Operation	Idling	41	g/VMT	3.5	g/VMT	3.8	g/VMT
	Auxiliaries	11	g/VMT	0.9	g/VMT	1.0	g/VMT
Caltrain	Propulsion	0.0	g/VMT	10	g/VMT	190	g/VMT
Operation	Idling	0.0	g/VMT	1	g/VMT	12	g/VMT
	Auxiliaries	0.0	g/VMT	0.5	g/VMT	10	g/VMT
Muni	Propulsion	13	g/VMT	1.1	g/VMT	1.2	g/VMT
Operation	Idling	3.3	g/VMT	0.3	g/VMT	0.3	g/VMT
	Auxiliaries	6.6	g/VMT	0.6	g/VMT	0.6	g/VMT
Green Line	Propulsion	33	g/VMT	6.9	g/VMT	7.8	g/VMT
Operation	Idling	17	g/VMT	3.5	g/VMT	3.9	g/VMT
	Auxiliaries	5	g/VMT	1.0	g/VMT	1.2	g/VMT
Maintenance	BART/Caltrain	3.1	mt/life	2.8	mt/life	2.6	mt/life
	Muni	0.2	mt/life	0.2	mt/life	0.2	mt/life
	Green Line	0.2	mt/life	0.2	mt/life	0.2	mt/life
Cleaning	Vacuuming (Bay Area)	2353	mg/kWh	206	mg/kWh	174	mg/kWh
	Vacuuming (CA)	2910	mg/kWh	243	mg/kWh	267	mg/kWh
	Vacuuming (MA)	4170	mg/kWh	867	mg/kWh	979	mg/kWh
Flooring	Carpet Production	2.1	mt/$M	11	mt/$M	2.1	mt/$M
Insurances	Benefits & Liability	207	kg/$M	934	kg/$M	233	kg/$M
Fuels							
Electricity	Bay Area	2353	mg/kWh	206	mg/kWh	174	mg/kWh
	CA	2910	mg/kWh	243	mg/kWh	267	mg/kWh
	MA	4170	mg/kWh	867	mg/kWh	979	mg/kWh
Diesel	Fuel Refining	3.0	g/gal	4.3	g/gal	1.8	g/gal

Table S3 - Fundamental Environmental Factors for Rail Modes (SO2, CO, NOX)

Infrastructure Components (cont'd)

Grouping	Component	SO_2		CO		NO_X	
Infrastructure							
Station Construction	Concrete Production	1.9	kg/yd^3	5.1	kg/yd^3	2.4	kg/yd^3
	Concrete Placement	82	g/yd^3	241	g/yd^3	312	g/yd^3
	Steel Production	0.9	g/yd^3	5.0	g/yd^3	0.9	g/yd^3
Station Lighting (per station)	BART	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Caltrain	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Muni	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Green Line	4.2	g/kWh	867	mg/kWh	979	mg/kWh
Station Escalators (per station)	BART	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Caltrain	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Muni	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Green Line	4.2	g/kWh	867	mg/kWh	979	mg/kWh
Train Control (per station)	BART	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Caltrain	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Muni	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Green Line	4.2	g/kWh	867	mg/kWh	979	mg/kWh
Parking Lighting (per station)	BART	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Caltrain	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Green Line	4.2	g/kWh	867	mg/kWh	979	mg/kWh
Station Miscellaneous (per station)	BART	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Caltrain	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Muni	2.9	g/kWh	243	mg/kWh	267	mg/kWh
	Green Line	4.2	g/kWh	867	mg/kWh	979	mg/kWh
Station Maintenance	For all systems, assumed 5% of station construction.						
Station Cleaning	Mopping (Bay Area)	1.3	g/ft^2-yr	0.1	g/ft^2-yr	0.1	g/ft^2-yr
	Mopping (CA)	1.7	g/ft^2-yr	0.1	g/ft^2-yr	0.2	g/ft^2-yr
	Mopping (MA)	2	g/ft^2-yr	0.5	g/ft^2-yr	0.6	g/ft^2-yr
Parking	BART	13	g/ft^2	24	g/ft^2	33	g/ft^2
	Caltrain	13	g/ft^2	24	g/ft^2	33	g/ft^2
	Green Line	13	g/ft^2	24	g/ft^2	33	g/ft^2
Track & Power Delivery	Aggregate Production	30	g/ton	38	g/ton	20	g/ton
	Concrete Production	1900	g/yd^3	5100	g/yd^3	2400	g/yd^3
	Concrete Placement	82	g/yd^3	241	g/yd^3	312	g/yd^3
	Steel Production	0.9	g/yd^3	5.0	g/yd^3	0.9	g/yd^3
	Wood Production	22	g/tie	626	g/tie	39	g/tie
	Power Structure Production	3.3	mt/$M	8.3	mt/$M	1.8	mt/$M
	Substation Production	1.8	mt/$M	7.8	mt/$M	1.6	mt/$M
Track Maintenance	For all systems, assumed 5% of track construction.						
Insurances	Benefits & Liability	207	kg/$M	934	kg/$M	233	kg/$M

5. Fundamental Environmental Factors for Air Modes

The fundamental environmental factors for air modes are shown in Table S4 with their sources. These factors are the basis for energy and emission inventory calculations for small, midsize, and large aircraft. Data sources in Table S4 are provided in the Supporting Information References section.

Table S4 - Fundamental Environmental Factors for Air Modes (Sources, Energy, & GHG)

Grouping	Component	Source	LCA Approach	Energy		GHG (CO_2e)	
Vehicles							
Manufacturing	Small Aircraft	26 (#336411), 48, 49	EIO-LCA	63	TJ/plane	5.1	kg/plane
	Midsize Aircraft	26 (#336411), 6, 49	EIO-LCA	213	TJ/plane	17	kg/plane
	Large Aircraft	26 (#336411), 6, 49	EIO-LCA	776	TJ/plane	63	kg/plane
	Small Aircraft Engine	26 (#336412), 49	EIO-LCA	7	TJ/eng	592	mt/eng
	Midsize Aircraft Engine	26 (#336412), 49	EIO-LCA	14	TJ/eng	1140	mt/eng
	Large Aircraft Engine	26 (#336412), 49	EIO-LCA	27	TJ/eng	2192	mt/eng
Small Aircraft Operation	APU Operation	33	Process	70	TJ/LTO	4,645	mt/LTO
	Startup	33	Process				
	Taxi Out	33	Process	884	TJ/LTO	58,793	mt/LTO
	Take Off	33	Process	230	TJ/LTO	15,302	mt/LTO
	Climb Out	33	Process	606	TJ/LTO	40,302	mt/LTO
	Cruise	47, 3, 69, 67	Process	79	MJ/VMT	5.3	kg/VMT
	Approach	33	Process	411	TJ/LTO	27,365	mt/LTO
	Taxi In	33	Process	325	TJ/LTO	21,629	mt/LTO
Medium Aircraft Operation	APU Operation	33	Process	105	TJ/LTO	6,977	mt/LTO
	Startup	33	Process				
	Taxi Out	33	Process	756	TJ/LTO	50,302	mt/LTO
	Take Off	33	Process	212	TJ/LTO	14,120	mt/LTO
	Climb Out	33	Process	560	TJ/LTO	37,264	mt/LTO
	Cruise	22, 47, 69, 67	Process	223	MJ/VMT	15.0	kg/VMT
	Approach	33	Process	376	TJ/LTO	25,006	mt/LTO
	Taxi In	33	Process	279	TJ/LTO	18,552	mt/LTO
Large Aircraft Operation	APU Operation	33	Process	146	TJ/LTO	9,728	mt/LTO
	Startup	33	Process				
	Taxi Out	33	Process	200	TJ/LTO	13,336	mt/LTO
	Take Off	33	Process	88	TJ/LTO	5,877	mt/LTO
	Climb Out	33	Process	225	TJ/LTO	14,984	mt/LTO
	Cruise	22, 69, 67	Process	783	MJ/VMT	52.6	kg/VMT
	Approach	33	Process	135	TJ/LTO	8,953	mt/LTO
	Taxi In	33	Process	74	TJ/LTO	4,910	mt/LTO
Maintenance	Aircraft	26 (Various Sectors)	EIO-LCA	25	TJ/\$M	1762	mt/\$M
	Engine	26 (#336412)	EIO-LCA	5.1	TJ/\$M	411	mt/\$M
Insurance	Crew Health and Benefits	26 (#524100)	EIO-LCA	1.0	TJ/\$M	84	mt/\$M
	Aircraft liability	26 (#524100)	EIO-LCA	1.0	TJ/\$M	84	mt/\$M
Infrastructure							
Construction	Airports	26 (#230220)	EIO-LCA	549	MJ/ft^2	43	kg/ft^2
	Runway	29, 65	Hybrid	136	MJ/ft^2	10	kg/ft^2
	Taxiway/Tarmac	29, 65	Hybrid	95	MJ/ft^2	6.8	kg/ft^2
Operation	Runway Lighting	20, 23	Process	471	GWH/yr	758	g/kWh
	Deicing Fluid Production	26 (#325998)	EIO-LCA	76	MJ/gal	6	kg/gal
	GSE Operation	33	Process	47	MJ/LTO	4	kg/LTO
Maintenance	Airports		Hybrid	28	TJ/ft^2	2	mt/ft^2
Parking	Airports	29, 65	Hybrid	35	MJ/ft^2	2.2	kg/ft^2
Insurance	Non-Crew Health and Benefits	26 (#524100)	EIO-LCA	1.0	TJ/\$M	84	mt/\$M
	Infrastructure Liability	26 (#524100)	EIO-LCA	1.0	TJ/\$M	84	mt/\$M
Fuels							
Production	Jet Fuel Refining	26 (#324110)	EIO-LCA	25	TJ/\$M	2200	mt/\$M

(Note: LTO = Landing-Takeoff Cycle. Where EIO-LCA is used (Source 26), the economic sector used is provided in parenthesis. Sector descriptions are as follows: #336411 – Aircraft Manufacturing, #336412 – Aircraft Engine & Engine Parts Manufacturing, #524100 – Insurance Carriers, #230220 – Commercial & Institutional Buildings, #325998 – Other Miscellaneous Chemical Product Manufacturing, #324110 – Petroleum Refineries)

Table S4 - Fundamental Environmental Factors for Air Modes (cont'd) (SO_2, CO, NO_X)

Grouping	Component	SO_2		CO		NO_X	
Vehicles							
Aircraft Manufacturing	Small	13	mt/pla	51	mt/pla	11	mt/pla
	Midsize	45	mt/pla	171	mt/pla	38	mt/pla
	Large	164	mt/pla	625	mt/pla	137	mt/pla
Engine Manufacturing	Small	1.7	mt/eng	5	mt/eng	1.3	mt/eng
	Midsize	3.2	mt/eng	10	mt/eng	2.5	mt/eng
	Large	6.2	mt/eng	19	mt/eng	4.9	mt/eng
Small Aircraft Operation	APU Operation	4.3	mt/LTO	28	mt/LTO	20	mt/LTO
	Startup						
	Taxi Out	26	mt/LTO	315	mt/LTO	74	mt/LTO
	Take Off	6.7	mt/LTO	4	mt/LTO	103	mt/LTO
	Climb Out	17.6	mt/LTO	10	mt/LTO	232	mt/LTO
	Cruise	1.7	g/VMT	2.3	g/VMT	13	g/VMT
	Approach	11.9	mt/LTO	28	mt/LTO	70	mt/LTO
	Taxi In	9.4	mt/LTO	116	mt/LTO	27	mt/LTO
Medium Aircraft Operation	APU Operation	2.5	mt/LTO	45	mt/LTO	12	mt/LTO
	Startup						
	Taxi Out	21.9	mt/LTO	535	mt/LTO	65	mt/LTO
	Take Off	6.2	mt/LTO	4	mt/LTO	82	mt/LTO
	Climb Out	16.3	mt/LTO	11	mt/LTO	190	mt/LTO
	Cruise	4.8	g/VMT	8.3	g/VMT	52	g/VMT
	Approach	10.9	mt/LTO	29	mt/LTO	68	mt/LTO
	Taxi In	8.1	mt/LTO	197	mt/LTO	24	mt/LTO
Large Aircraft Operation	APU Operation	0.7	mt/LTO	12	mt/LTO	2	mt/LTO
	Startup						
	Taxi Out	5.8	mt/LTO	48	mt/LTO	22	mt/LTO
	Take Off	2.6	mt/LTO	0	mt/LTO	63	mt/LTO
	Climb Out	6.5	mt/LTO	1	mt/LTO	121	mt/LTO
	Cruise	16.7	g/VMT	16.1	g/VMT	207	g/VMT
	Approach	3.9	mt/LTO	2	mt/LTO	34	mt/LTO
	Taxi In	2.1	mt/LTO	18	mt/LTO	8	mt/LTO
Maintenance	Aircraft	3.1	mt/$M	7.9	mt/$M	2.1	mt/$M
	Engine	1160	kg/$M	3500	kg/$M	912	kg/$M
Insurance	Crew Health and Benefits	207	kg/$M	934	kg/$M	233	kg/$M
	Aircraft liability	207	kg/$M	934	kg/$M	233	kg/$M
Infrastructure							
Construction	Airports	75	g/ft^2	390	g/ft^2	143	g/ft^2
	Runway	72	g/ft^2	58	g/ft^2	131	g/ft^2
	Taxiway/Tarmac	50	g/ft^2	41	g/ft^2	92	g/ft^2
Operation	Runway Lighting	4	g/kWh	0.4	g/kWh	1.3	g/kWh
	Deicing Fluid Production	23	g/gal	36	g/gal	24	g/gal
	GSE Operation	2.6	g/LTO	255	g/LTO	35	g/LTO
Maintenance	Airports	4	mt/ft^2	19	mt/ft^2	7	mt/ft^2
Parking	Airports	46	g/ft^2	10	g/ft^2	26	g/ft^2
Insurance	Non-Crew Health and Benefits	207	kg/$M	934	kg/$M	233	kg/$M
	Infrastructure Liability	207	kg/$M	934	kg/$M	233	kg/$M
Fuels							
Production	Jet Fuel Refining	4220	kg/$M	6020	kg/$M	2460	kg/$M

6. Passenger Occupancies

The automobile modes average 1.58, 1.74, and 1.46 passengers at any time (83) while the off-peak and peak buses are specified as 5 and 40 passengers (84). The rail modes are representative commuter systems and include the San Francisco Bay Area's BART, Caltrain, and Muni Metro as well as Boston's Green Line. The BART and Caltrain systems are heavy rail transit (HRT) (electric and diesel, respectively). Rail occupancies are determined from the Federal Transit Administration's National Transit Database (38). Aircraft average occupancies are determined from the 2005 U.S. Department of Transportation's Air Carrier Statistics (86).

Table S5 – Passenger Occupancies

	Average	Sensitivity Low	Sensitivity High
Sedan	1.58	1	5
SUV	1.74	1	7
Pickup	1.46	1	3
Bus	Off-Peak: 5, Peak: 40	5	60
BART	146	133	583
Caltrain	155	110	482
Muni	22	15	66
Green Line	54	30	70
Small Aircraft	33	25	49
Midsize Aircraft	101	70	141
Large Aircraft	305	185	370

The sensitivity low and high specified occupancies are meant to illustrate realistic ridership ranges for the modes. Auto low is specified as one passenger while the high is specified as the number of seats. Bus low is specified as 5 passengers with a high of 60 passengers, the maximum allowed by federal regulation. Rail is specified as 25% of the number of seats for the low and 110% (to capture standing riders) for the high while aircraft is specified as 50% of the number of seats as the low and 100% of the number of seats as the high.

7. Methodology Detail

Additional methodological details, including evaluation steps used for each life-cycle component of each mode are found in reference *13*. To improve transparency of results, Tables S6 through S8 provide the sections within reference *13* where detailed component modeling information is found. For example, for assumptions specific to energy and emissions contributions from roadway construction to automobiles, see section 1.6.2.1 as shown in Table S6.

Table S6 – Additional Onroad Methodology

	Section
Vehicle Components	1.6.1
Manufacturing	1.6.1.1
Operation	1.6.1.2
Maintenance	1.6.1.3
Automotive Repair	1.6.1.4
Insurance	1.6.1.5
Infrastructure Components	1.6.2
Roadway Construction	1.6.2.1
Roadway Maintenance	1.6.2.2
Parking	1.6.2.3
Roadway & Parking Lighting	1.6.2.4
Herbicides & Salting	1.6.2.5
Fuel Components	1.6.3
Production	1.6.3.1
Distribution	1.6.3.2

Table S7 – Additional Rail Methodology

	Section
Vehicle Components	1.7.1
Manufacturing	1.7.1.1
Operation	1.7.1.2
Maintenance	1.7.1.3
Insurance	1.7.1.4
Infrastructure Components	1.7.2
Station Construction	1.7.2.1
Station Operation	1.7.2.2
Station Maintenance & Cleaning	1.7.2.3
Station Parking	1.7.2.4
Track Construction	1.7.2.5
Track Maintenance	1.7.2.6
Insurance	1.7.2.7
Fuel Components	1.7.3
Electricity Production	1.7.3.1
Diesel Production	1.7.3.2

The vehicle component sections within reference *13* provide additional information on the data, assumptions, calculations, attributions, and normalizations of energy and emissions from specific products, processes, and services for each component.

Table S8 – Additional Air Methodology

	Section
Vehicle Components	1.8.1
Manufacturing	1.8.1.1
Operation	1.8.1.2
Maintenance	1.8.1.3
Insurance	1.8.1.4
Infrastructure Components	1.8.2
Airport Construction	1.8.2.1
Runway, Taxiway, & Tarmac Construction	1.8.2.2
Operation	1.8.2.3
Maintenance	1.8.2.4
Parking	1.8.2.5
Insurance	1.8.2.6
Fuel Components	1.8.3
Production	1.8.3.1

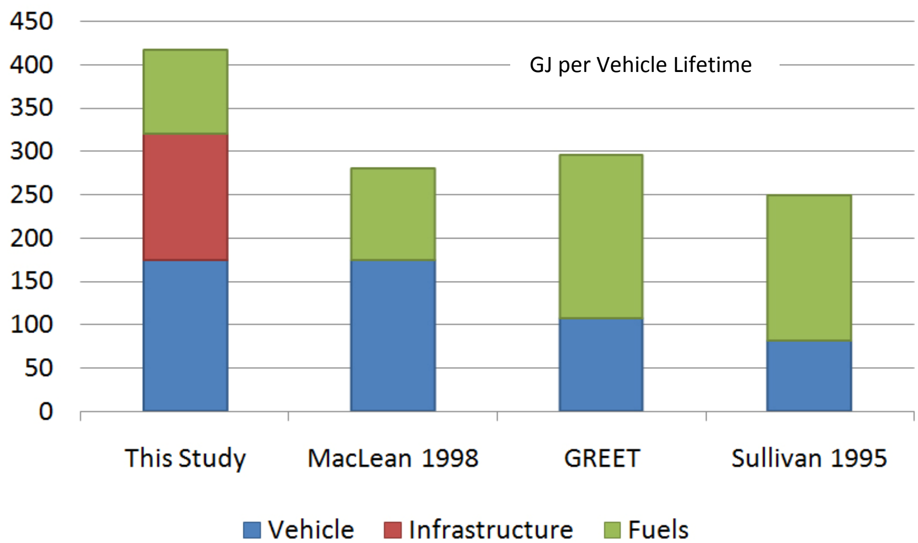
8. Life-cycle Assessment

A combination of two LCA models was used: 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, and the economic input-output analysis-based LCA (EIO-LCA) as a general equilibrium model of the U.S. economy that integrates economic and environmental databases for inventory analysis of the entire supply chain associated with a product or service (26). A hybrid LCA model (88) that combines the advantages of both process model-based LCA and EIO-based LCA (89, 90) was employed for the components of this analysis. An extensive discussion of the process, EIO-LCA, and hybrid-based approaches for each component is found in 13.

9. Comparison to Other Studies

Previous LCAs have quantified energy inputs or emission outputs for particular life-cycle phases, however, none have explored infrastructure components. As a comparison, results from this study are contrasted against several existing conventional gasoline sedan studies to illustrate the differences in scope and results. The energy consumption per vehicle lifetime results of non-operational sedan components from this study are shown with MacLean 1998, GREET (version 2.7a for vehicle manufacturing and version 1.8b for fuel production), and Sullivan 1995 in Figure S1. MacLean 1998's vehicle components include manufacturing, maintenance, and insurance while GREET and Sullivan 1995 include only manufacturing (58, 74, 92). All studies have been normalized to an equivalent lifetime vehicle kilometer traveled (VKT).

Figure S1 – Energy Comparison of Study Results to Previous Automobile LCAs



This study and MacLean 1998 evaluate similar vehicle components (manufacturing, maintenance, and insurance) using primarily EIO-LCA which captures both direct and indirect process. GREET and Sullivan 1995 use process-based LCA and include only vehicle manufacturing for their vehicle components (indirect components are not included, e.g., the energy required for steel production for the manufacturing facility) which explains the smaller results. Outside of this study, no known study to date includes infrastructure components in automobile LCAs. For fuel components, again, this study and MacLean 1998 use EIO-LCA to capture the gasoline fuel cycle explaining the similar results. GREET and Sullivan 1995 use a process-based approach and report larger results. The GREET results capture a 25% (for every 100 energy units of gasoline, an additional 25 were required to extract, refine, and transport) energy requirement for gasoline production compared to EIO-LCA's 16%.

10. Data Quality Assessment

A data quality assessment (DQA) is performed in conjunction with a sensitivity analysis to evaluate parameter uncertainty and the effects of variability on final results. Given the large data requirements of any LCA, steps must be taken to evaluate certain parameters (or groups of parameters) for contribution to the quality of final results. The DQA provides a measure for the degree of uncertainty in parameters to assist in identifying which components should be given the most attention in a sensitivity analysis (45, 56, 79). A pedigree matrix is first established with quality categories and scoring criteria (Table S9). Due to the extensive number of model parameters, individual modal components are evaluated

Table S9 - Data Quality Assessment Pedigree Matrix

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

Adapted from 34, 45, 56, and 79.

The grading matrices shown in Table S10, Table S11, and Table S12 provide not only the score but an average of the scores and ranking against other components. Generally, the lower the ranking (closer to 1), the higher the qualitative assessment that component received and the less uncertainty it has.

Table S10 - Data Quality Assessment Scoring Matrix for Onroad Modes

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

Table S11 - Data Quality Assessment Scoring Matrix for Rail Modes

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

Table S12 - Data Quality Assessment Scoring Matrix for Air Modes

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

The parameters evaluated in the sensitivity analysis were selected partially from the rankings provided in the DQA. While the sensitivity analysis and DQA address parameter uncertainty (45), model and choice uncertainty are discussed in reference 13.

11. Temporal and Geographic Considerations

The following tables identify, for each component included in the inventory, whether the emission is one-time or continuous and where geographically it occurs.

Table S13 - Onroad life-cycle component temporal and geographic differentiation

Life-cycle Component	Input/Output Contributor		Temporal	Geographic
Vehicle				
Manufacturing	Manufacturing processes	□	One-time	Manufacturing facilities, indirect support
Operation (Running)	Gasoline/Diesel fuel combustion		Continuous	Vehicle route
Operation (Start)	Gasoline/Diesel fuel combustion		Continuous	Vehicle route
Operation (Tire)	Tire wear		Continuous	Vehicle route
Operation (Brake)	Brake pad wear		Continuous	Vehicle route
Operation (Evaporative Losses)	Gasoline/Diesel fuel losses		Continuous	Vehicle route
Operation (Idling)	Gasoline/Diesel fuel combustion		Continuous	Vehicle route
Tire Production	Manufacturing processes	□	One-time	Manufacturing facilities, indirect support
Vehicle Maintenance	Manufacturing processes for parts	□	Continuous	Maintenance facilities, indirect support
Automotive Repair Stations	Cleaner & degreaser emissions		Continuous	Repair stations
Insurances	Insurance facilities requirements	□	Continuous	Power plants, indirect support
Infrastructure				
Roadway Construction	Direct processes, material production	□	One-time	Roads, indirect support
Roadway Maintenance	Direct processes, material production	□	Continuous	Roads, indirect support
Herbicide Production	Production processes	□	Continuous	Manufacturing facilities, indirect support
Salt Production	Production processes	□	Continuous	Manufacturing facilities, indirect support
Roadway Lighting	Electricity consumption	□	Continuous	Power plants, indirect support
Parking Construction & Maintenance	Direct processes, material production	□	One-time	Manufacturing facilities, indirect support
Fuels				
Refining & Distribution	Direct processes, fuel production	□	Continuous	Extraction region, refining region, transport network

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

Table S14 - Rail life-cycle component temporal and geographic differentiation

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

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

Table S15 - Air life-cycle component temporal and geographic differentiation

Life-cycle Component	Input/Output Contributor		Temporal	Geographic
Vehicle				
Aircraft Manufacturing	Manufacturing processes	□	One-time	Manufacturing facilities, indirect support
Engine Manufacturing	Manufacturing processes	□	One-time	Manufacturing facilities, indirect support
Operation, APU	Fuel combustion		Continuous	Airport
Operation, Startup	Fuel combustion		Continuous	Airport
Operation, Taxi Out	Fuel combustion		Continuous	Airport
Operation, Take Off	Fuel combustion		Continuous	Airport
Operation, Climb Out	Fuel combustion		Continuous	Near airport
Operation, Cruise	Fuel combustion		Continuous	Flight route, upper atmosphere
Operation, Approach	Fuel combustion		Continuous	Near airport
Operation, Taxi In	Fuel combustion		Continuous	Airport
Maintenance	Manufacturing processes for parts	□	Continuous	Manufacturing facilities, indirect support
Insurances	Insurance facilities requirements	□	Continuous	Power plants, indirect support
Infrastructure				
Airport Construction	Material production, direct process	□	One-time	Manufacturing facilities, airports, indirect support
Runway/Taxiway/Tarmac Construction	Material production, direct process	□	One-time	Manufacturing facilities, airports, indirect support
Runway Lighting	Electricity use		Continuous	Power plants
Deicing Fluid Production	Material production	□	Continuous	Manufacturing facilities, indirect support
Ground Support Equipment Operation	Energy use		Continuous	Airport
Airport Maintenance	Material production	□	Continuous	Manufacturing facilities, airports, indirect support
Runway/Taxiway/Tarmac Maintenance	Material production, direct process	□	Continuous	Manufacturing facilities, airports, indirect support
Parking	Material production, direct process	□	One-time	Manufacturing facilities, airports, indirect support
Insurances	Insurance facilities requirements	□	Continuous	Power plants, indirect support
Fuels				
Refining & Distribution	Material extraction, refining, transport	□	Continuous	Extraction region, refining region, transport network

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

12. Vehicle Year, Operation Year, and Component Lifetimes

Vehicle and Operation Year

Given the myriad of factors which determine the environmental performance of any mode, it is unrealistic to define an average vehicle model or operational performance. Table S16 identifies the vehicle year and fuel year for the evaluated modes in this study.

Table S16 – Vehicle Model Year, Operation Year, and Vehicle Lifetime

Vehicle	Vehicle Year	Operation Year	Vehicle Lifetime	Fuel Environmental Source
Sedan	2005	2007	16.9 (median)	30
SUV	2005	2007	15.5 (median)	30
Pickup	2005	2007	15.5 (median)	30
Bus	2005	2008	12	30, 63, 82
BART	1969-1992	2007	26	20, 36, 81
Caltrain	1994	2008	27	37, 82
Muni	1998	2008	30	20, 81
Green Line	1995	2007	27	20
Small Aircraft	2005	2005	30	3, 69, 67, 47
Midsize Aircraft	2005	2005	30	22, 47, 67, 69
Large Aircraft	2005	2005	30	22, 69, 67

All vehicles (with the exception of the aircraft) operate under EPA Tier 2 fuel conditions (82). For an extended explanation of vehicle lifetimes, please see reference 13.

Component Lifetimes

For onroad modes, the roadway wearing layers are specified as 10 years and the subbase layers as 50 years.

For rail modes, stations are specified as 80 years and station parking as 10 years. Track construction is split into several materials with individual lifetimes. These are track ballast at 25 years, concrete at 50 years, steel at 25 years, power structures at 35 years, and electricity substations at 20 years. The wood ties have lifetimes of 35 years for BART, 40 years for Caltrain, and 30 years for Muni and the Green Line.

Aircraft engines are assumed to have a lifetime of 20 years. Runway, taxiway, and tarmacs are specified as 10 years. Airports are assumed to have a 50 year lifetime.

For further explanation and background on the specified lifetimes, please see reference 13.

13. Supporting Information References

1. Automotive News 2005 *Market Data Book* (Detroit, MI)
2. Andersson E and Lukaszewicz P 2006 *Energy Consumption and Related Air Pollution for Scandinavian Electric Passenger Trains* (Stockholm, Sweden: Report # KTH/AVE 2006:46, Royal Institute of Technology, Department of Aeronautical and Vehicle Engineering, available at http://www.kth.se/fakulteter/centra/jarnvag/publications/Energy_060925.pdf)
3. Air Transportation Association 2003 *Economic Report: A Review of the U.S. Airline Industry* (Washington, DC)
4. Bay Area Rapid Transit 2006 *Short Range Transit Plan and Capital Improvement Program* (Oakland, CA, available at http://www.bart.gov/about/financials/)
5. Bei R 1978 *Light-Rail Transit: Planning and Technology* Transportation Research Board Special Report 182 18-23 (Washington, DC)
6. Boeing Airlines 2005 *Boeing Commercial Airplane Prices* (Chicago, IL: available online at http://www.boeing.com/commercial/prices/)
7. U.S. Department of Transportation 2005 *National Transportation Statistics* (Washington, DC: Bureau of Transportation Statistics, available online at http://www.bts.gov/publications/national_transportation_statistics/).
8. Vieira P S 2007 *Life-cycle Assessment of Commercial Buildings* (Berkeley, CA: Ph.D. Dissertation, University of California, Berkeley)
9. Caltrain 2008 *Caltrain Timetable* (San Carlos, CA: available online at http://www.caltrain.org/timetable.html)
10. California Air Resources Board 1997 *Consumer Products Program* (Sacramento, CA).
11. California Air Resources Board 2002 *Public Transit Bus Fleet Rule and Emission Standards for New Urban Buses* (Sacramento, CA: Appendix C – Orange County Bus Cycle)
12. Carrington B 1984 *Modern Tramway Light Rail Transit* **47** 373-381
13. Chester M V 2008 *Life-cycle Environmental Inventory of Passenger Transportation Modes in the United States* (Berkeley, CA: Ph.D. Dissertation, University of California, Berkeley, available online at http://repositories.cdlib.org/its/ds/UCB-ITS-DS-2008-1/)
14. Clark N N, Gajendran P, and Kern J 2003 *Environmental Science & Technology* **37** 7-15 (available at http://dx.doi.org/10.1021/es0113192)
15. Clark N N 2006 *Presentation at the 2006 Diesel Engine Emission Reduction Conference* (Detroit, MI)
16. Cobas-Flores E, Lave L B, Hendrickson C, McMichael F C, Bustani A 1998 *International Congress and Exposition* (Warrendale, PA: Society of Automotive Engineers: Paper # 980475)
17. Cobas-Flores E, Bustani A, Mackay P, Yester S G, Sullivan J L, Williams R L 1998 *Total Life Cycle Conference and Exposition* (Warrendale, PA: Society of Automotive Engineers, Paper # 982213)
18. Cohen J T, Hammitt J K, and Levy J I 2003 *Environmental Science & Technology* **37** 1477-1484 (available at http://dx.doi.org/10.1021/es0205030)
19. Greene D L, Jones D J, and Delucchi MA 1997 *The Full Costs and Benefits of Transportation* (New York, NY: Springer)
20. Deru M and Torcellini P 2007 *Source Energy and Emission Factors for Energy Use in Building*s (Golden, CO: U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO, available at http://www.nrel.gov/docs/fy06osti/38617.pdf).
21. Dicarlo S 1998 *Total Life Cycle Conference and Exposition* (Warrendale, PA: Society of Automotive Engineers, Paper # 982186)
22. European Environment Agency 2006 *EMEP/CORINAIR Emission Inventory Guidebook,* (Copenhagen, Denmark: available at http://reports.eea.europa.eu/EMEPCORINAIR4)
23. U.S. Department of Energy 2002 *U.S. Lighting Market Characterization* (Washington, DC: Office of Energy Efficiency and Renewable Energy, available at http://www.eere.energy.gov/buildings/info/documents/pdfs/lmc_vol1_final.pdf)
24. U.S. Department of Energy 2007 *Buildings Energy Data Book* (Washington, DC: Office of Energy Efficiency and Renewable Energy, available online at http://buildingsdatabook.eere.energy.gov/).
25. U.S. Department of Energy 2007 *Estimating Appliance and Home Electronic Energy Use* (Washington, DC: Office of Energy Efficiency and Renewable Energy, available online at http://www.eere.energy.gov/consumer/your_home/appliances/index.cfm/mytopic=10040)
26. Carnegie Mellon University 2008 *Economic Input-Output Analysis-Based Life-Cycle Assessment Software* (Pittsburgh, PA: Green Design Institute, available at http://www.eiolca.net/)

27. U.S. Environmental Protection Agency 1997 *Technical Highlights: Emission Factors for Locomotives* (Washington, DC: EPA Publication EPA420-F-97-051, available online at http://www.epa.gov/oms/regs/nonroad/locomotv/frm/42097051.pdf)
28. U.S. Environmental Protection Agency 1999 *Evaluation of Air Pollutant Emissions from Subsonic Commercial Jet Aircraft* (Washington, DC: EPA Publication EPA420-R-99-013, available online at http://www.epa.gov/oms/regs/nonroad/aviation/r99013.pdf)
29. U.S. Environmental Protection Agency 2001 *Emissions Inventory Improvement Program Technical Report Series* **3** ch.17 (Washington, DC: available online at http://www.epa.gov/ttn/chief/eiip/techreport/volume03/).
30. U.S. Environmental Protection Agency 2003 *Mobile 6.2: Mobile Source Emission Factor Model* (Washington, DC: Office of Transportation and Air Quality)
31. U.S. Environmental Protection Agency 2004 *Pesticide Industry Sales and Usage: 2000-2001 Market Estimates* (Washington, DC: Office of Prevention, Pesticides, and Toxic Substances)
32. U.S. Environmental Protection Agency 2008 *Fuel Economy Reporting* (available at http://www.fueleconomy.gov/)
33. U.S. Department of Transportation 2007 *EDMS 5.0.2: Emission and Dispersion Modeling System Software* (Washington, DC: Federal Aviation Administration**)**
34. Facanha C and Horvath A 2007 *Environmental Science & Technology* **41** 7138-7144 (available at http://dx.doi.org/10.1021/es070989q)
35. Farrell A E, Plevin R J, Turner B T, Jones A D, O'Hare M, and Kammen D M 2006 *Science* **311** 506-508 (available at http://dx.doi.org/10.1126/science.1121416)
36. Fels M 1978 *Energy* **3** 507-522 (available at http://dx.doi.org/10.1016/0360-5442(78)90012-9)
37. Fritz S G 1994 *Journal of Engineering for Gas Turbine and Power* **116** 774-783
38. U.S. Department of Transportation 2005 *National Transit Database* (Washington, DC: Federal Transit Administration, (available at http://www.ntdprogram.gov/ntdprogram/)
39. U.S. Department of Transportation 2006 *Non-Rail Vehicle Market Viability Study* (Washington, DC: Federal Transit Administration, Report # MI-26-7008-05.1, available at http://www.fta.dot.gov/documents/Non-Rail_Vehicle_Market_Study_FINAL_REPORT.pdf)
40. Zarembski A M and Gauntt J C 2000 *Presentation at the Proceedings of the 2000 AREMA Annual Conference* (Lanham, MD: Railway Tie Association)
41. Gediga J, Florin H, Schuckert M, and Beddies H 1998 *Total Life Cycle Conference and Exposition* (Warrendale, PA: Society of Automotive Engineers, Paper # 982190)
42. DiCarlo S 1998 *Total Life Cycle Conference and Exposition* (Warrendale, PA: Society of Automotive Engineers, Paper # 982186)
43. Guggemos A and Horvath A 2005 *ASCE J. of Infrastructure Systems* **11** 93-101 (available at http://dx.doi.org/10.1061/(ASCE)1076-0342(2005)11:2(93)).
44. Healy T 1973 *Energy Requirements of the Bay Area Rapid Transit System* (Sacramento, CA: California Department of Transportation, Division of Transportation Planning)
45. Huijbregts M A 1998 *International Journal of Life Cycle Assessment* **3** 273-280 (available at http://dx.doi.org/10.1007/BF02979835).
46. Banfi S, Maibach M, Doll C, and Rothengatter W 1994 *Externals Effects of Transport* (Paris, France: International Union of Railways)
47. Intergovernmental Panel on Climate Change 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* Volume 2: Energy, Chapter 3: Mobile Combustion (Geneva, Switzerland: United Nations Environment Programme).
48. Jane's Information Group 2004 *Jane's All The Worlds Aircraft 2003-2004* (Alexandria, VA).
49. Jenkinson L, Simpson P, and Rhodes D 1999 *Civil Jet Aircraft Design* (Reston, VA: American Institute of Aeronautics and Astronautics)
50. Jorgensen M, Sorenson S, 1997 *Estimating Emissions from Railway Traffic, Report for the Project MEET: Methodologies for Estimating Air Pollutant Emissions from Transport. INFRETS* (Joinville, France: French National Institute for Transport and Safety Research)
51. Kaniut C, Cetiner H, and Franzeck J 1997 *Society of Automotive Engineers*, (Warrendale, PA: Paper # 971166)
52. Lave C A 1977, *Transportation Research Record* **648** (Washington, DC: Transportation Research Board, National Academy of Sciences)
53. Lee J, Lukachko S, Waitz I, and Schafer A 2001 *Annual Review of Energy and the Environment* **26** 167-200 (available at http://dx.doi.org/10.1146/annurev.energy.26.1.167).
54. Levinson D, Gillen D, Kanafani A, and Mathieu J 1996 *The Full Cost of Intercity Transportation* (Berkeley, CA: University of California, Berkeley, Institute of Transportation Studies, Report # UCB-ITS-RR-96-3, available at http://repositories.cdlib.org/its/reports/UCB-ITS-RR-96-3/)

55. Levinson D M, Gillen D, Kanafani A 1998 *Proceedings of the Transportation Research Board 77th Annual Meeting* (Washington, DC: National Research Council, Paper # 980274)
56. Lindfors L G 1995 *Nordic Guidelines on Life-cycle Assessment*, (Copenhagen, Denmark: The Nordic Council, Report # Nord 1995:20)
57. Massachusetts Highway Department 2005 *Design Guide* Chapter 9: Pavement (Boston, MA: available at http://www.mhd.state.ma.us/downloads/designGuide/CH_9.pdf).
58. MacLean H L and Lave L B 1998 *Environmental Science & Technology* **32** 322A-330A
59. MacLean H L and Lave L B 2003 *Environmental Science & Technology* **37** 5445-5452 (available at http://dx.doi.org/ 10.1021/es034574q)
60. Maddison D, Pearce D 1996 *5 Blueprint – The True Costs of Road Transport* (London, England: Cserge).
61. Marheineke T, Friedrick R, and Krewitt W 1998 *Total Life Cycle Conference and Exposition* (Warrendale, PA: Society of Automotive Engineers, Paper # 982201)
62. Mayeres I, Ochelen S, Proost S 1996 *Transportation Research D* **1** 111-130
63. McCormick R L, Graboski M S, Alleman T L, Yanowitz J 2000 *J. of the Air & Waste Management Association* **50** 1992-1998
64. Nocker L, Panis L, and Torfs R 2000 *Total Life Cycle Conference and Exposition* (Warrendale, PA: Society of Automotive Engineers, Paper # 2000-01-1480)
65. Horvath A 2003 *Life-cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements* (Berkeley, CA: University of California Transportation Center, available at http://www.uctc.net/papers/final reports/year14/).
66. Paulsen J H 2003 *International J. of Life Cycle Assessment* **8** 357-364 (available at http://dx.doi.org/10.1065/lca2003.06.117).
67. Pehrson J 2005 *Presentation at the Transportation Research Board 84th Annual Meeting* (Washington, DC: National Research Council).
68. Pikarsky M 1981 *Annual Review of Energy and the Environment* **6** 339-356 (available at http://dx.doi.org/10.1146/annurev.eg.06.110181.002011)
69. Romano D, Gaudioso D, De Lauretis R 1999 *Environmental Monitoring and Assessment* **56** 51-74 (available at http://dx.doi.org/10.1023/A:1005972024261).
70. Schipper Y 2003 *Transportation Policy* **11** 141-154
71. Pré: Product Ecology Consultants 2006 *SimaPro 7.0 Software* (Amersfoort, Netherlands)
72. Small K and Kazimi C 1995 *J. of Transportation Economics and Policy* **29** 7-32
73. Stodolsky F, Gaines L, Cuenca R, and Eberhardt J 1998 *Total Life Cycle Conference and Exposition* (Warrendale, PA: Society of Automotive Engineers, Paper # 982206)
74. Sullivan J and Hu J 1995 *Society of Automotive Engineers* (Warrendale, PA: Paper # 951829)
75. Sullivan J L 1998 *Total Life Cycle Conference and Exposition* (Warrendale, PA: Society of Automotive Engineers, Paper # 982160)
76. National Research Council 1991 *Highway Deicing: Comparing Salt and Calcium Magnesium Acetate* (Washington, DC: Transportation Research Board Special Report 235, available at http://onlinepubs.trb.org/onlinepubs/sr/sr235.html)
77. U.S Geological Survey 2007 *Iron and Steel Prices in the U.S. through 1998,* (Washington, DC: U.S. Department of the Interior, available at http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel/)
78. Verhoef E 1994 *Transportation Research A* **28A** 273-287
79. Weidema B P and Wesnaes M S 1996 *J. of Cleaner Production* **4** 167-174 (available at http://dx.doi.org/10.1016/S0959-6526(96)00043-1).
80. Washington State Department of Transportation 2007 *Trends in Highway Material Costs: Structural Concrete* (available at http://www.wsdot.wa.gov/biz/construction/CostIndex/CostIndexPdf/StructuralConcrete.pdf)
81. Pacific Gas and Electric 2008 *PG&E's Electric Power Mix Delivered to Retail Customers* (available at http://www.pge.com/myhome/edusafety/systemworks/electric/energymix/)
82. U.S. Environmental Protection Agency 2008 *Tier 2 Vehicle and Gasoline Sulfur Program* (available at http://www.epa.gov/tier2/)
83. Davis S C and Diegel S W 2007 *Transportation Energy Data Book* (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Oak Ridge National Laboratory)
84. U.S. Department of Transportation 2004 *Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance* (Washington, DC: Federal Highway Administration, available at http://www.fhwa.dot.gov/policy/2004cpr/pdfs/cp2006.pdf)
85. Ward's Communications 2006 *Ward's Motor Vehicle Facts and Figures* (Southfield, MI**)**.
86. U.S. Department of Transportation 2005 *Air Carrier Statistics: 2005, Form 41, Table T-100* (Washington, DC: Bureau of Transportation Statistics, available at http://www.transtats.bts.gov/)

87. National Highway Traffic Safety Administration 2008 *Vehicle Safety Information* (available at http://www.safercar.gov/)
88. Suh S et al 2004 *Environmental Science & Technology* **38** 657-664 (available at http://dx.doi.org/10.1021/es0263745)
89. Hendrickson C, Lave L B, and Matthews S 2006 *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach* (Washington, DC: Resources for the Future)
90. Hendrickson H, Horvath A, Joshi S, Lave L B 1998 *Environmental Science and Technology* **32** 184A-191A
91. Bay Area Rapid Transit System 2007 *BART System Facts* (available at http://www.bart.gov/about/history/systemFacts.asp)
92. Argonne National Laboratory 2008 *Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation* (GREET) Model (Chicago, IL)