Written by James Strickland, M.Sc., in July 2006. Last updated 12 February 2009
Additional references, updates and corrections welcome, but be civil and please read all my little caveats at the bottom first. My email address should be easy to figure out from my name and the domain name, I do not spell it out here in order to avoid spam.

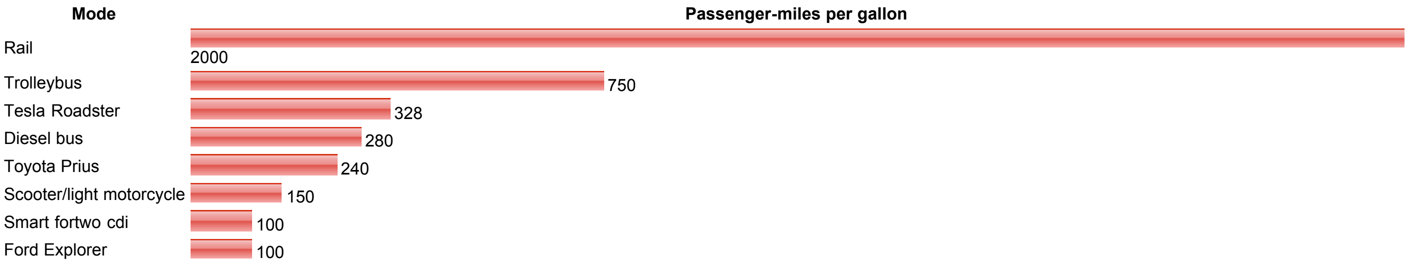
Energy Efficiency of different modes of transportation

I was once told by a transportation planner that "nobody cares about energy efficiency". Well, I always have. For a variety of reasons, I believe we should be rapidly moving towards more efficient transportation systems as soon as possible. Or, if possible, use human power or eliminate the need for urban transportation altogether, by reintegrating work, shopping and residential uses.

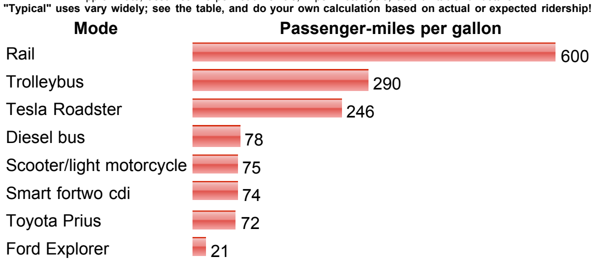
Ok, here are the pretty graphs, for those of you who like a quick, though overly simplified, summary. The data portrayed here should be interpreted primarily to give a sense of "order of magnitude"; **the "typical efficiency" figures in particular will vary significantly depending on what you consider typical**. The "typical" usage is either from ridership data or is estimated. Please see below for the detailed data table supporting the graphs.

Urban service

Maximum efficiency possible in urban service
Approximate, assumes seats filled for all vehicles plus standees for mass transit modes, see full table for details. **Maximums are mainly of theoretical interest.**

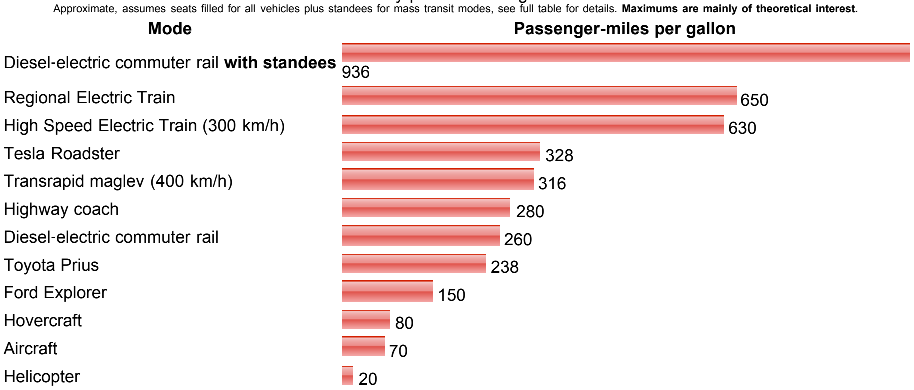


Typical efficiency in urban service
Approximate, assumes 1.5 per road vehicle, 1 per motorcycle, see full table for details.
"Typical" uses vary widely; see the table, and do your own calculation based on actual or expected ridership!



Long distance service

Maximum efficiency possible in long distance service
Approximate, assumes seats filled for all vehicles plus standees for mass transit modes, see full table for details. **Maximums are mainly of theoretical interest.**



Typical efficiency in long distance service
Approximate, assumes 1.5 per road vehicle, 1 per motorcycle, see full table for details.
"Typical" uses vary widely; see the table, and do your own calculation based on actual or expected ridership!

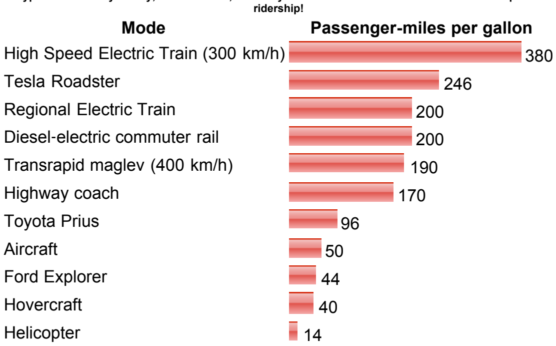


Table of vehicle efficiencies

The following table shows energy efficiency per vehicle and per passenger, the latter calculated in "typical" usage, in use with all seats filled, and "crush" capacity (with a lot of people standing, if appropriate). Crush capacities given may or may not be realistic. Results are sorted by crush capacity, as that gives an upper limit on efficiency. Comparing "all seated" figures would be better in many ways but is unfair for services designed to be used by standees, as such vehicles devote relatively little space to seating.

Different modes have their place, but comparing efficiency across modes when there is a choice is useful. The background colour indicates mode; green indicates rail or maglev, gray indicates a road vehicle (most roads are asphalt), dark blue is for water vehicles (including hovercraft, as that's where they usually operate) and light blue is for aircraft (sky).

Passenger-mpg will vary dramatically based on vehicle occupancy, as vehicle efficiency generally varies little with passenger load but passenger-mpg is directly proportional to passenger load. Also, the energy-equivalency calculations have some inherent error, due to variation among fuels, for example. See the text below for a discussion of comparing electric vehicles to fuelled vehicles, as well as life-cycle issues. Figures generally including heating/cooling and energy used in "idling", but some have not or cannot be verified in this regard. In addition, there are no doubt varying degrees of error in reported figures. Lastly, there are variations in type of service provided which make simple vehicle comparisons impossible. For example, the Airbus 320 figure presented is based on a longer average stage length than the Boeing 737 figure presented; one cannot conclude solely from this that the A320 is more efficient than the B737. (Especially as there are a bunch of different models!)

Service	Source figure(s)	Average energy usage			Typical passenger load		All seated		Crush Capacity	
		MJ/km	L/100 km gasoline equivalent	mpg gasoline equivalent	Passengers	Passenger-mpg gasoline equivalent	Passengers	Passenger-mpg gasoline equivalent	Passengers	Passenger-mpg gasoline equivalent
Generic "subway"	2.61 kWh/vehicle-km (From table 3, Environment Canada fact sheet 93-1)	9.40	29.4	8.00	?	?	66	528	315 Crush capacity for Bombardier T-1 car	2520
Siemens Combino 28 tonne 27 m LRV	Table 3 (page 7) of Siemens study of Combino in service in Basel over 56 days; 7215.7 km, 19.1 km/h average service, estimated average load 65 people (5 t), 18 908 kWh consumed, 7870 kWh (41.6%) recovered through regenerative braking, net consumption 1.53 kWh/vehicle-km; vehicle dimensions are those of the prototype, in-service Basel vehicles are 43 x 2.3 m, weight 47.5 t.	5.51	17.2	13.6	65	887	67	914	180	2460
Siemens Combino 28 tonne 27 m LRV	Table 3 (page 7) of Siemens study of Combino in service in Potsdam over 41 days; 6633.3 km, 27.1 km/h average service, estimated average load 65 people (5 t), 17 575 kWh consumed, 5358 kWh (30.5%) recovered through regenerative braking, net consumption 1.84 kWh/vehicle-km	6.62	20.7	11.3	65	738	67	760	180	2040
Siemens SD160 (42 tonne 24.82 m LRV in service with Calgary Transit, Calgary, Alberta, Canada)	3.23 kWh/vehicle-km Note: Calgary's system is entirely powered by wind turbines (Calgary Transit purchases power from a company which operates wind turbines in the foothills of the Canadian Rocky Mountains)	11.6	36.3	6.48	145 Peak hour downtown based on 11300 passengers per hour on 26 3-car trains	940	60	389	200	1296
London Underground	0.151 kWh/passenger-km (From page 9, London Underground Environment Report 2005 as well as average occupancy per train of 113, 6 car trains. in 2002-03 DfT report. Not an ideal mix of sources, but I have yet to find something better.	10.2	31.9	7.4	19	141	41	303	152	1125

	Anyways, this yields 2.84 kWh/vehicle-km. Note that only 40% of LU rolling stock has regenerative braking.									
Go Transit commuter train - F59PH hauling 10 bi-level coaches	Fuel economy of 761 L/100 km (diesel) from table 3, Environment Canada fact sheet 93-1. I have yet to find independent confirmation of fuel burn of a 3000 hp locomotive. Bi-level coach capacity available from Bombardier or Wikipedia.	289	904	0.260	1000	260	1620	421	3600	936
Colorado Railcar pulling two bi-level coaches	Results from actual service condition trial: 128 gallons diesel, 144 miles; DMU seats 92, crush 200, from photo it is clear the coaches were Bombardier bi-levels, seating 162, crush capacity 360.	79.8	249	0.942	300	283	416	392	920	867
SkyTrain (rail rapid transit in Vancouver, BC, Canada)	BC Transit 1994/95 fiscal year operating statistics: 53,920,000 kWh for 22,338,000 vehicle-km	8.69	27.2	8.65	30	260	40	346	90 The claim is 110, but I think that's a bit much	779
TGV Atlantique trainset (300 km/h, seats 485)	1997 EC study "Estimating Emissions from Railway Traffic", page 74: 13.20 kWh/train-km assuming 4 intermediate stops St. Pierre des Corps - Bordeaux: **maximum speed 220 km/h** (suggests efficiency possible at lower speeds)	47.52	149	1.58	291	460	485	767	485	767
2005 (and later) New Flyer Low Floor Trolley Bus in operation in Vancouver, BC, Canada	Trans Link Bus Technology and Alternative Fuels Demonstration Project - Phase 2 Results, page 6: 2.14 kWh/vehicle-km ($0.14/km).	7.70	24.06	9.77	30	293	34	332	77	752
Danish Railways trains across the Øresund link (official site) between Denmark and Sweden, from Copenhagen to Malmö at speeds up to 180 km/h, average 10 km between stops.	6.7 kWh/train-km, average load factor 41% (From page 28, Energy consumption and related air pollution for Scandinavian electric passenger trains)	24.1	75.4	3.12	97 41% occupancy	303	237	740	237	740
1982 New Flyer Trolley Bus (Fleet of 244 in Vancouver, BC, Canada)	BC Transit 1994/95 fiscal year operating statistics: 35,454,170 kWh for 12,966,285 vehicle-km	9.84	30.8	7.64	30	229	34	260	90	688
Swedish Railways Regina electric multiple-unit train	2-car trains in regional service with speeds up to 200 km/h, distance between stops 25 km on average: 5.91 kWh/train-km, average load factor 35%. (From page 26, Energy consumption and related air pollution for Scandinavian electric passenger trains)	21.3	66.5	3.54	63 35% occupancy	223	180	637	180	637
	1997 EC study "Estimating Emissions									

TGV Duplex trainset (300 km/h bi-level, seats 545)	from Railway Traffic", page 74: 18.00 kWh/train-km assuming 3 intermediate stops Paris-Lyon	64.80	203	1.160	436 80% occupancy according to this EU report, page 3.	506	545	632	545	632
Service	**Source figure(s)**	**Average energy usage**			**Typical passenger load**		**All seated**		**Crush Capacity**	
		MJ/km	**L/100 km** gasoline equivalent	**mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent
Swedish Railways X2000 200 km/h tilting train measured between Stockholm and Göteborg	11.87 kWh/train-km, average load factor 55% (From page 24-25, Energy consumption and related air pollution for Scandinavian electric passenger trains)	42.7	133.5	1.76	176	310	320	563	320	563
Swedish Railways Regina electric multiple-unit train	2-car trains in regional service with speeds up to 180 km/h, distance between stops 10 km on average: 6.25 kWh/train-km, average load factor 20%. (From page 27, Energy consumption and related air pollution for Scandinavian electric passenger trains)	22.5	70.3	3.35	34 20% occupancy	114	167	560	167	560
ICE first-generation trainset (280 km/h, seats 645 with 12 coaches)	1997 EC study "Estimating Emmissions from Railway Traffic", page 71: 24.09 kWh/train-km averaged over all routes	86.72	271	0.8669	290	252	645	559	645	559
Transrapid Magnetic levitation train @ 300 km/h	Manufacturer energy consumption page: 47 Wh/seat-km for 300 km service with 3 intermediate stops @ 300 km/h. Shanghai Transrapid has 440 seats according to Wikipedia.	74.4	233	1.01	?	?	440	444	440	444
TGV Paris Sud-Est trainset (first generation TGV, 270 km/h, seats 368 prior to refurbishment)	1997 EC study "Estimating Emmissions from Railway Traffic", page 74: 17.70 kWh/train-km assuming 3 intermediate stops Paris-Lyon	63.72	199	1.180	294	347	368	434	368	434
AVE 300 km/h trainset on Madrid-Seville line	1997 EC study "Estimating Emmissions from Railway Traffic", page 76: 15.88 kWh/train-km, average load factor 85%, 313 seats	57.17	179	1.315	266	350	313	412	313	412
Colorado Railcar (not pulling any coaches)	Colorado Railcar FAQ page: seats 92, max capacity 200, 2 mpg diesel	34.9	140	1.67	?	?	92	154	200	335
Tesla Roadster	Table on manufacturer's page on efficiency: 2.18 km/MJ.	0.46	1.43	164	1	164	2	328	2	328
Transrapid Magnetic levitation train @ 400 km/h	Manufacturer energy consumption page: 66 Wh/seat-km for 300 km service with 3 intermediate stops @ 400 km/h. Shanghai Transrapid has 440 seats according to Wikipedia.	104.5	327	0.719	?	?	440	316	440	316
Diesel bus in local and express	BC Transit 1994/95 fiscal year operating statistics: 29,161,885 L diesel fuel for 45,582,954	24.3	76.0	3.1	25	78	34	105	90	279

Service	Source figure(s)	Average energy usage			Typical passenger load		All seated		Crush Capacity	
service in Vancouver, BC, Canada	45,582,954 vehicle-km. All buses 40' except for a small number (<3% of fleet) of 60'	24.3	76.0	3.1	25	78	34	105	90	279
MCI 102DL3 diesel bus in commuter service in Santa Barbara, California, USA	Demonstration of Caterpillar C-10 Dual-Fuel Engines in MCI 102DL3 Commuter Buses", National Renewable Energy Laboratory, page 7: 6.0 mpg diesel	15.0	46.8	5.0	40	200	55	276	55	276
Service	**Source figure(s)**	**Average energy usage**			**Typical passenger load**		**All seated**		**Crush Capacity**	
		MJ/km	**L/100 km** gasoline equivalent	**mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent
Toyota Prius	GreenHybrid Mileage Database: 47.6 mpg Note the large variation in results. I suspect the lower figures are due to high-speed driving, not what hybrids are useful for.	1.58	4.94	47.6	1.5	72	5	238	5	238
MCI 102DL3 CNG/diesel bus in commuter service in Santa Barbara, California, USA	Demonstration of Caterpillar C-10 Dual-Fuel Engines in MCI 102DL3 Commuter Buses", National Renewable Energy Laboratory, page 7: 4.8 mpg diesel-equivalent using CNG	18.6	58.1	4.04	40	162	55	222	55	222
VW Golf TDI (1.9L diesel, automatic)	Actual highway trip: 72.27 L, 1447 km, 4.99 L/100 km diesel	1.90	5.93	39.6	1.5	59.4	4 adults in moderate comfort	158	5	198
Ford Explorer (4.6L V8 gasoline, automatic)	Ford web site **highway** rating	3.49	10.9	21.6	2	43.2	7	151	7	151
Wasp Scooter Air cooled 4-stroke one-cylinder 0.149L, 7.2hp, automatic with CVT	Dealer Web Site	1.00	3.13	75	1	75	2 Weight limit: 350 pounds	150	2	150
Corporate Average Fuel Economy standard in effect for passenger cars **since 1990**	NHTSA Automotive Fuel Economy Program Annual Update FY 2003, Table I-1	2.73	8.54	27.5	1.5	41.3	5 Cars typically have front bucket seats nowadays	138	5	138
Suzuki GS500 (motorcycle with 0.5 L gasoline engine)	Various sources, including Wikipedia, Motorcycle Fuel Economy Guide and Suzuki GS FAQ; take optimistic 60 mpg as value	1.25	3.9	60	1	60	2	120	2	120
Corporate Average Fuel Economy standard for passenger cars when first enacted in 1978	NHTSA Automotive Fuel Economy Program Annual Update FY 2003, Table I-1	4.18	13.1	18	1.5	27	6 North American cars typically had bench seats in front	108	6	108
Smart fortwo cdi (0.8 L diesel, 40 hp, 6-speed)	Natural Resources Canada Fuel Consumption Guide: 3.8 L/100 km **highway**	1.44	4.51	52.1	1.5	78.2	2	104	2	104
Service	**Source figure(s)**	**Average energy usage**			**Typical passenger load**		**All seated**		**Crush Capacity**	
		MJ/km	**L/100 km** gasoline equivalent	**mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent
SeaBus (cross-harbour passenger	BC Transit 1994/95 fiscal year operating									

ferry in service with Translink, Vancouver, BC, Canada)	statistics: 1,118,718 L diesel fuel for 140,948 vehicle-km	302	944	0.25	140	35	400	100	400	100
Smart fortwo cdi (0.8 L diesel, 40 hp, 6-speed)	Natural Resources Canada Fuel Consumption Guide: 4.0 L/100 km **city**	1.52	4.75	49.5	1.5	74.3	2	99	2	99
Ford Explorer (4.6L V8 gasoline, automatic)	Ford web site **city** rating. This is meant to be a typical SUV-in-city example - see above for highway rating	5.34	16.7	14.1	1.5	21.2	7	98	7	98
Griffon 2000TD hovercraft	Griffon specifications page: 35 knots, 45 L/h, 25 passengers	22.5	70.3	3.34	15	50.1	25	83.5	25	83.5

Service	Source figure(s)	Average energy usage			Typical passenger load		All seated		Crush Capacity	
		MJ/km	L/100 km gasoline equivalent	mpg gasoline equivalent	Passengers	Passenger-mpg gasoline equivalent	Passengers	Passenger-mpg gasoline equivalent	Passengers	Passenger-mpg gasoline equivalent
Diamond DA-42 Twin Star (economy)	Aircraft Flight Manual, 60% (economy) power setting (4.4 gph per engine) at 10000 ft, cruise 138 knots; **will overstate efficiency as taxi, takeoff and climb not included in calculation**	4.22	13.2	17.8	2	35.6	4 I'm assuming it's owner-flown, not charter	71.2	4	71.2
Airbus 320 in service with JetBlue, 1358 mile average stage length	2004 annual report, page 30: 18,911,051,000 available seat miles, 83.2% load factor, 241,087,000 gallons Jet A consumed	168	526	0.447	130	58.1	156	69.7	156	69.7
Honda Gold Wing (motorcycle with 1.8 L 6-cylinder gasoline engine)	Motorcycle Fuel Economy Guide: 32.7 mpg	2.30	7.18	32.7	1	32.7	2	65.4	2	65.4
Griffon 8000TD hovercraft	Griffon specifications page: 40 knots, 230 L/h, 80 passengers	101	314	0.747	40	29.9	80	59.8	80	59.8
Bombardier Q300 (DHC-8-300)	Actual airline flight plan CYVR-CYZP: burnoff 2457 pounds, 468 mile great circle route, 2:06 gate to gate.	63.4	198	1.19	30	35.6	50	59.3	50	59.3
Boeing 737 "next generation" in service with Southwest Airlines, 607 mile average stage length	2005 annual report, page 11: 85,172,795,000 available seat miles, 60,223,100,000 revenue passenger miles, 1,287,000,000 gallons Jet A consumed, 70.7% average load factor, 194 737-300 (137 seats), 25 737-500 (122 seats), 226 737-700 (137 seats)	175	547	0.430	97	41.7	137	58.9	137	58.9
Diamond DA-42 Twin Star (80% power)	Aircraft Flight Manual, 80% power setting (6.2 gph per engine) at 10000 ft, cruise 156 knots; **will overstate efficiency as taxi, takeoff and climb not included in calculation**	5.26	16.4	14.3	2	28.6	4 I'm assuming it's owner-flown, not charter	57.2	4	57.2
Eclipse 500	Mission profiles on Eclipse web site: medium range 566 nm, 844 pounds fuel burned.	7.11	22.2	10.6	3	31.8	5	53.0	5 Optional 6-seat cabin, one pilot	53.0
	BC Ferries Fuel Savings Plan, June 15, 2006, Appendix A shows round trip fuel									

BC Ferries Spirit class car ferries	consumption of 8400 L, distance between Swartz Bay and Tsawwassen is 24 nautical miles. No doubt a passenger-only ferry of equivalent capacity would be far more efficient! There is the question of goods shipment, however.	3063	9572	0.0246	1000	24.6	2100	51.7	2100	51.7
Cessna 172	Actual flight data - long distance summer round trip: 363.2 US gallons for 4024 nautical miles	5.97	18.7	12.6	1	12.6	4	50.4	4	50.4
Service	**Source figure(s)**	**Average energy usage**			**Typical passenger load**		**All seated**		**Crush Capacity**	
		MJ/km	**L/100 km** gasoline equivalent	**mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent	**Passengers**	**Passenger-mpg** gasoline equivalent
Columbia 400 turbocharged 310 hp fixed gear 4-place single	Trip calculated using Airplane Flight Manual, pages 5-15 (climb), 5-30 (cruise), 5-35 (descent). 600 nm trip, standard atmosphere, zero wind, sea level airports, super-economy cruise (48% power 14 gph 200 kts) at 25000 feet: 21.4 min 13.9 gal 49 nm climb 1.88 h 26.32 gal 376 nm cruise 50 min 14 gal 175 nm descent 3h 4 min 54.2 gal 600 nm (681.8 sm) Assuming the minimum IFR reserve requirement of 45 minutes reserve at a holding speed consuming 9gph, fuel required is 61.0 gal (about 2/3 tanks - max usable fuel 98 gal), weighing 366 pounds. Typical payload is 1100 pounds, thus 4 passengers and baggage must weigh less than 734 pounds (184 pounds each).	5.98	18.7	12.58	2	25.2	4 I'm assuming it's owner-flown, not charter	50.3	4	50.3
Porsche Boxster S (3.2L, 5 speed Tiptronic)	Porsche web site, estimated combined fuel consumption based on 18 mpg city, 27 mpg highway	3.42	10.7	22.0	1.5	33.0	2	44.0	2	44.0
Columbia 400 turbocharged 310 hp fixed gear 4-place single	Trip calculated using Airplane Flight Manual, pages 5-15 (climb), 5-30 (cruise), 5-35 (descent). 600 nm trip, standard atmosphere, zero wind, sea level airports, maximum continuous power cruise (85% power 25 gph 235 kts) at 25000 feet: 21.4 min 13.9 gal 49 nm climb 1.60 h 40.0 gal 376 nm cruise 50 min 14 gal 175 nm descent 2h 47 min 67.9 gal 600 nm (681.8 sm) Assuming the minimum IFR reserve requirement of 45 minutes reserve at a holding speed consuming 9gph, fuel required is 74.7 gal (about 3/4 tanks - max usable fuel 98 gal), weighing 448 pounds. Typical payload is 1100 pounds, thus 4 passengers and baggage must weigh less than 652 pounds (163 pounds each).	7.49	23.4	10.0	2	20.1	4 I'm assuming it's owner-flown, not charter	40.2	4	40.2
Beechcraft Duchess	Approximation based on 18 gph, 150 knot	7.94	24.8	9.5	2	19	4 I'm assuming it's owner-flown, not	38	4	38

[illegible]	cruise						charter			
Piper Navajo	Approximation based on 40 gph, 180 knot cruise	14.7	46.1	5.1	2	10.2	7	35.7	7	35.7
Beechcraft King Air B-100	Approximation based on 100 gph, 270 knot cruise	24.5	76.6	3.1	2	6.2	9	27.9	9	27.9
Cunard Queen Mary 2 ocean liner	Cunard's technical specs show 3 tonnes/hour of heavy fuel oil for each of 4 diesel generators, producing a cruise speed of about 25 knots. (To travel faster - over 30 knots - QM2 can run two 25 MW gas turbine generators, each burning about 6 tonnes/hour of marine gas oil.) The crew of 1238 is not included in the passenger count. Heavy fuel oil has an energy density of 9203 kcal/kg, or 38.5 MJ/kg, according to the IEA. 38.5 MJ/kg at 12 tonnes/hour is 462 GJ/h, at 25 knots this is 18480 MJ/nm, or about 10000 MJ/km.	10,000	31,250	0.00753 More amusingly expressed as 40 feet per gallon	2000	15.0	2620	19.7	3090	23.2
Porsche Carrera GT (5.7L V10 605 hp, 6 speed manual)	Porsche web site, Natural Resources Canada Fuel Consumption Guide: 22.7 L/100 km **city** (just for interest)	7.27	22.7	10.3	1.5	15.5	2	20.6	2	20.6
Sikorsky S-76C++ twin turbine helicopter (Turbomeca Arriel 2S2)	Mission performance tables, 145 knots @ 4000 feet, 620 pph	45.5	142	1.65	9	14.9	12	19.8	12	19.8
Bell Longranger IV Helicopter powered by 650shp Allison 250C30P	Approximation based on 250 pph, 110 knot cruise	25.5	79.7	2.95	2	5.89	6 not including pilot	17.7	6	17.7
Concorde	Page 90 of "Flying Concorde" by Brian Calvert suggests fuel load typically in the 75 to 95 ton range, page 180 states average fuel load New York - London was 14 tons below max (81 tons). Guess: reserve of 11 tons, so fuel used New York - London (~3500 statute miles) is 70 tons (22,000 USgal). Page 188 states typical load 80%. This article states fuel capacity is 209,946 pounds, fuel flow is 45,000 pph in cruise at Mach 2.04, and 220,000 pph with "reheat", which (according to "Flying Concorde") is used on takeoff and for the acceleration from Mach 0.95 at 28000 feet through some point shy of Mach 1.7. NOVA Aircraft Specifications gives independent confirmation of fuel flow: 6771 gal/h in cruise.	473	1480	0.16	80	12.7	100	15.9	100	15.9

The fine print

km = kilometre (1,000 metres)
MJ = MegaJoule (1,000,000 Joules)
L = Litre
mpg = statute miles (5,280 feet or roughly 1,609 metres) per U.S. gallon (3.785 L)
knot = 1 nautical mile (6,000 feet) per hour, or 1.852 km/h
One kW is 1000 Joules per second, so 1 kWh is 3,600,000 Joules, or 3.6 MJ

The L/100 km and mpg figures are stated in terms of gasoline, to allow easier comparison with the most commonly used metric (pun intended) in the U.S. Unfortunately there is quite a variation in quoted energy density among different sources, see for example hypertextbook on diesel and gasoline. The Wikipedia energy density entry lists gasoline as 29.0 MJ/L, yet the Wikipedia Petrol entry claims it to be 32.0 MJ/L. Similarly, the former lists diesel as 34 MJ/L, the latter as 40.9 MJ/L. So, Wikipedia is not even consistent with itself. These are not small discrepancies. Other sources give even higher energy densities, one listing diesel as high as 39.6 MJ/L. The discrepancy could be in part due to different composition of diesel fuel in different countries. Nevertheless... the best I can do here is use a "reasonable" figure and introduce an error bar. Here's what I will use:
Gasoline: 32 MJ/L
Diesel: 38 MJ/L
Jet A: 36 MJ/L
with a big whopping plus or minus 10% error bar.

After all that, here are the conversion factors:
from MJ/km to L/100 km: 100/32 = 3.125
from km/MJ to mpg: 32 * 3.785 / 1.609 = 75.28

Energy usage will vary with passenger load, significantly in the case of aircraft but not very significantly in the case of land vehicles. Energy usage will also vary with weather conditions and tire pressures for rubber-tired vehicles and engine condition for those powered by internal combustion engines and ... a whole bunch of other factors which really are just going to make life miserable if you try to worry about them all, just don't worry, be happy, add a little bit more to the error bars if you like.

Speaking of such difficulties - the "typical" occupancy is a difficult question to answer, but the numbers I have used are not all arbitrary. See, e.g., this European Environment Agency report, page 4, for average occupancy rates of high-speed trains.

Some sanity checks:

- The high speed rail energy usage figures can be compared with the maximum continuous rated power output of the trainset in each case. For example, the original TGV Paris-Sud-Est trainsets were 6450 kW (8650 hp). If maximum power were required to go 270 km/h (it isn't, obviously) then energy usage for an hour would be 6450 kWh and distance travelled would be 270 km, giving 23.89 kWh/km. The measured figure in service was 17.70 kWh/km, which is 74% of the theoretical maximum. This seems to be in the right ballpark.
- A generic figure for electric trains in the UK is given by the Association of Train Operating Companies on page 6 of their 2007 report: 1.99 kWh/vehicle-km, 0.108 kWh/passenger-km. These are similar to other reported and calculated figures.
- the Airbus 320 and Boeing 737 "fleet average" data match the computation by All Nippon Airways of fuel consumption by aircraft type found on page 16 of their Environmental Report 2004. The chart shows the A320 at approximately 0.1 pound per nm-seat, which is approximately 75 mpg gasoline equivalent - very close to the computed figure for JetBlue's A320 fleet. The ANA chart shows a B737-400 (Southwest doesn't operate -400s) as being slightly more efficient than an A320, whereas a B737-500 (Southwest operates many -500s) is noticeably less efficient. ANA also operates the DHC-8-400, which it shows as being roughly equivalent in efficiency to an A320. The chart presumes a 500 nm flight.
- Cruise fuel flow of a 737-400 is shown as 792 gallons per hour, which - assuming approximately a 400 knot cruise and 159 seats - works out to 86 passenger-mpg (gasoline equivalent) when full. A significant portion of fuel burned will be during climb - as much as an order of magnitude more per unit time - so this result seems to be in the "right ballpark" (see above re 737-400 vs 737-500).
- An approximation of fuel burn can be found by taking an aircraft's range and dividing it by its fuel capacity. For example, the A320 has a range of 2600 nm with 6300 US gal, that's 0.469 mpg (Jet A), 0.417 mpg gasoline equivalent. This will understate the maximum efficiency as the aircraft must land with a significant amount of fuel after achieving the given range. The computed figure for JetBlue's A320 fleet - 0.447 mpg - is very close to the estimated computed in this manner.

Some observations and conclusions

The first, most obvious and striking conclusion, is that - for passenger transportation - rail vehicles are more efficient than road (except trolleybuses and the electric Tesla Roadster), and far more efficient than aircraft. Magnetic levitation trains are included in the "rail vehicle" category - the Transrapid is the only in-service high-speed maglev in the world, and it is quite efficient.

Road vehicles are, in general, more efficient than aircraft. One must keep in mind, however, that on some routes aircraft will be more efficient than the table suggests, as they can travel the great circle distance whereas surface transport (road, rail) must go around lakes and mountains. On the other hand, almost all air travel involves a not-insubstantial distance travelled to the airport, perhaps negating or overwhelming the aforementioned advantage.

The exceptions to the "road is more efficient than air" observation are interesting: many two-seat sports cars and large motorcycles are less efficient than some aircraft.

The table suggests road vehicles are less efficient than rail, though electrically-propelled buses (trolleybuses) do come quite close in similar service, and surpass the efficiency of high-speed rail. When disallowing standees on rail, highway coaches approach the efficiency of rail, but nevertheless it does appear rail still wins out.

There is a wide variation in efficiency for ships based on different designs, but in general they fare worse than high occupancy road vehicles. When comparing against road vehicles as typically used, however, ships are surprisingly efficient; on a trip between Victoria, BC and Vancouver, BC the BC Ferries portion - in which the ship moves not only itself, with the cafeteria, restaurants, gift shop, arcade, children's play areas, observation deck, etc, but also all the cars and people - is **more** efficient than the portion that most people drive with only one or two people on board.

It is not surprising that ships containing a great deal of volume per person will be less efficient - the Queen Mary 2, for example, is effectively a floating hotel, with amenities including a spa, weight room, gym, playing field (!), planetarium, basketball court, book shop, restaurants, bars, disco... you get my point. It is not built for ultimate efficiency. Contrast with, for example, the SeaBus, which is more efficient than all aircraft studied and surpasses the efficiency of most cars in typical service (e.g. SeaBus half full versus SUV with 2 people in it). The SeaBus interior is just one big rectangular room filled with seats.

An aside: goods transportation is a different matter, as bulk cargo is orders of magnitude more dense than "people cargo", which in general consists primarily of air. I am under the impression that ships fare far better wrt goods transport, with ships being more efficient than rail being more efficient than trucks. Figures from the UK government agree: 0.7-1.2 MJ/tonne-km for road, 0.6 MJ/tonne-km for rail (bulk), 0.3 MJ/tonne-km for 3000 dwt coastal tanker at 14 knots, 0.12 MJ/tonne-km for 1226 TEU container ship at 18.5 knots.

Amusingly, a Toyota Prius with all seats filled is nearly as efficient as a full highway coach. This is really a testament to the engineering of the Prius. The other thing of note is that the Prius is *more* efficient in city driving than highway driving, no doubt due to less use of the internal combustion engine, less drag due to lower speeds, and more energy recovery through regenerative braking.

Update 18 March 2008: The high efficiency of the Tesla Roadster is quite impressive, *if indeed the real world experience bears out the current estimate*. I am inclined to accept the stated figure as roughly accurate, as the car itself is very small (space for two seats and not much more), and the advantages of all-electric drive are huge. The caveat is that the energy storage technology (lithium-ion batteries) is still exceedingly expensive, and thus only really marketable as part of a $100,000 supercar (0-60 mph in 3.9 seconds). The Tesla Roadster entered series production on 17 March 2008, so it is not a hypothetical vehicle. Note: the efficiency figure I use is the "gasoline equivalent", not the well-to-wheels calculation that Tesla presents. As with all electric entries in the table, the true energy cost depends on the source of the electric energy. Many jurisdictions are completely or nearly-completely renewable (generally jurisdictions with massive amounts of hydroelectric power), in which case the caveat about energy source does not apply. Many jurisdictions are nearly 100% coal-powered, in which case the caveat definitely does apply! For comparison with internal-combustion-engine vehicles, see my comments above regarding the energy cost of shipping and refining oil.

Direct vehicle comparisons

The table gives efficiency figures for each vehicle, then calculates the result per passenger. Looking just at the per-vehicle figure yields some amusing comparisons.

- The Combino light rail vehicle is about the same energy efficiency as a Porsche Carrera GT; the Porsche seats 2, the Combino seats 67 and can carry 180. The efficiency advantage is huge, though the Porsche obviously accelerates better and has a higher top speed!
- The Colorado Railcar gets about the same mileage as a Sikorsky S-76C helicopter (but it seats 92, rather than 12). (Note: Colorado Railcar has gone bankrupt, so my references are no longer available. Interesting discussion here.)
- The S-76C helicopter is faster, you say? Well, how about comparing it to a TGV Duplex, which consumes 42% more energy per unit distance but has a slightly higher maximum speed and carries not just a little bit more but **45 times as many** passengers (making it 32 times as efficient). Plus, it seems the helicopter is lacking in a few passenger amenities: a restaurant/bar car, office, public telephones, family cubicles, washrooms (including handicap-access washrooms) and baby changing stations. :-)
- A subway car gets "8 mpg" whereas an Eclipse 500 jet gets about 10. The subway car seats an order of magnitude more people, but of course the Eclipse goes an order of magnitude faster! (Note: Eclipse has gone bankrupt, so my references are no longer available; indeed there is some doubt as to the long-term viability of the fleet, not just the web site. The fact remains, however, that a jet of this efficiency is possible.)

Many of these comparisons are only theoretical as there are no conditions under which one is choosing between the two to provide a particular service.

Lastly, one should take note that mass transit applications will rarely reach the theoretical maximum except perhaps for a short portion of the trip. Trip demand is almost never equally spread across all stops. This applies to all modes, but is usually more of a factor with rail and bus service than with air service. Those considering this an "aha!" invalidating mass transit figures should consider instead just how often they see 5 people in a VW Golf, or 7 in a Ford Explorer. Furthermore, how many trips are half as efficient as half the trip is driver only? (For example, picking children up from school, picking visitors up from the airport). The "max capacity versus max capacity" comparisons are still of use.

Dissenting opinions

In the United States it is claimed that Amtrak is no more efficient than private car trips over 75 miles, and intercity bus service is 3 times as efficient (consumes 1/3 as much energy). References are given but I have not looked them up yet (they are not something you can find in your neighbourhood library). I think it likely the discrepancy can be explained by the following factors:

- the calculation is comparing actual current usage, not the potential for each mode; a mostly-empty train is certainly not more efficient than a mostly-full bus
- many Amtrak long distance services incur significant delays, as they are at the mercy of the freight railroads and their needs. A lot of energy is consumed keeping a train air conditioned and lighted while sitting in a siding waiting for a freight train to approach and pass
- Amtrak provides sleeper service - essentially a rolling hotel - which is inherently energy-inefficient

Obvious solutions to these problems exist: for one, rather than thinking in terms of a standard 4200 hp locomotive hauling enough passenger cars to avoid looking extremely silly, consider using a modern DMU, including this model made in the United States.

The main point I want to make is that any comparison using energy efficiency as one of the criteria should examine **specific models on specific routes**, ideally using real-world data for those models on similar existing routes. Aggregates including composite types of service and different types of equipment are useless for comparison. The aggregate statistics I used in the table above are for determining the efficiency of a **specific** model in real-world conditions; for example I used JetBlue's 2004 annual report rather than their 2005 annual report because JetBlue was an all-A320 airline in 2004 but as of 2005 they operate the new Embraer 190.

Physical reasons supporting the conclusions

Physical laws dictate what is possible. Aircraft, while designed to fly through less-dense air high above the earth, and to have a small cross-sectional area relative to passenger-carrying capacity (low parasitic drag) do have the disadvantage of having to expend energy simply to stay up in the air (induced drag) as well as expending a lot of energy to get to altitude in the first place. Aircraft weight has a very large effect on performance, and aircraft must carry their fuel and hold it up in the air - a not insignificant factor on long flights, in which an aircraft's weight at take off may be more than 50% fuel!

Even the most efficient aircraft engines are only capable of converting about half of the energy in jet fuel into thrust. There is a lot of waste heat (and noise, though I think the noise is a small factor).

This is actually not bad, relative to internal combustion engines, which typically convert at best 1/3 of the energy in fuel into useful work. This is one reason why internal-combustion-engine-powered road vehicles fare relatively poorly in terms of energy efficiency. Contrast the BC Transit diesel bus data versus their trolleybus data - the trolleybus is nearly 3 times as efficient! This is primarily due to electric motors being on the order of 80-90% efficient. As well, the motors can be much smaller as they are primarily heat-limited and thus can put out far more power (double or triple) than the continuous rating for a short time - long enough to help in climbing a steep hill, for example. This is one reason trolleybus service survived in San Francisco. The motor can also be used as a generator, to recover energy when slowing. The limitation is that the trolleybus has to stay connected to overhead wires, which necessitates switches and crossovers and somewhat complex intersections. The power supply system must also be able to not only provide power but accept power from slowing buses. Please note also that the trolleybus comparison is actually likely to be biased *against* trolleybuses, as they are all used in heavily used frequent-stop service, whereas a not-insignificant portion of the BC Transit diesel bus fleet provides limited-stop express service at more efficient speeds.

The big differences between road and rail transportation are

- the far lower friction of steel wheel on steel rail versus rubber on road
- the reduced wind drag due to far lower cross-sectional area relative to passenger-carrying capacity

Life-cycle energy use considerations

There is an argument to be made that one should consider overall energy efficiency, including construction and maintenance of the vehicle, the surfaces and services associated with the vehicle, and delivery of energy to the vehicle. **I agree completely**. One has to start somewhere, however. Most "commercial" vehicles are used intensively, often more than 12 hours per day. If an aircraft isn't flying it is costing the airline a lot of money! Thus, with the exception of private cars, energy usage during operation is of primary importance. (I don't have proof of this, but the first table on this page gives some figures which claim manufacturing energy costs are a small fraction of operating energy costs).

There is not likely to be a huge difference in energy required to build the equivalent capacity in highway coaches versus rail cars. It is generally accepted, however, that rail cars last longer - usually twice as long - so when considering lifetime energy use rail cars have a very large advantage. The classic PCC streetcar was in daily use in some cities for 50 years. (A car in daily use that long would have been "rebuilt" at least once, but I ask you: how many 50 year old diesel buses are kept on the road in daily use?)

In terms of fixed infrastructure rail has a very large advantage once sufficient capacity is required. Peak requirements have led to highways with 8, 10, even as many as 20 lanes, primarily due to travel by car. Even assuming one car every two seconds (closer than advised) without end for an hour, that is at most 1800 cars per lane. Suppose an occupancy of 2 people per car, which is actually far higher than is typical. That makes 3600 people per lane. There are subway (metro) services that carry 50,000 people in one hour. That's a factor of 14, making a two-track system in theory capable of the equivalent of a 28-lane highway. Even with far less extreme numbers the comparison is quite obviously in favour of rail requiring far less space, and thus less energy to initially build and to continuously maintain.

Comparing air with rail it would seem at first glance that aircraft have smaller fixed installation requirements - after all, they just need an airport at each end. One has to consider the vast quantity of land - and buildings - required for airports, however. Runway 26L/08R at Vancouver International Airport is 9940 x 200 feet x 1.5 feet (runway depth estimated) - 3 million cubic feet - and cost $100 million. The volume of a concrete railway sleeper is about 0.1 m^3, or about 3 cubic feet. Thus the volume of concrete in one runway is equal to the volume of concrete in a million concrete railway sleepers, which are normally spaced at 650 to 760 mm intervals. A million sleepers would thus support 650 km of railway track. Interestingly, with the railway there is an alternative: composite ties, which can be (and are) made of recycled post-consumer waste plastic. I don't think that's an option for aircraft runways.

Those looking at railway and trolleybus electrification will point out that a lot of energy went into producing the wire and posts and hangars and so on. That may be so, but it is pretty much a one-time cost, whereas the cost of delivery of fossil fuels is ongoing. Supertankers do not cross oceans by wind power. Drilling rigs do not operate for free.

But what of electric power generation? In the case of renewable sources, fixed electric power (rail, trolleybus) has a very large advantage over fossil-fuel powered sources. Where electric power is generated from coal or natural gas, however, the result is less clear. The power generation plant is nowhere near 100% efficient, and long-distance power transmission adds another 10% loss.

What, then, of "biofuels"? In some cases the "energy return on energy invested" (EROEI) makes biofuels either barely economic or, according to some, an actual net consumer of energy. Ethanol from corn seems to fit this description. Ethanol from sugar cane has a decent EROEI, however the difficulty is that there simply is not enough land to provide anywhere near enough fuel to maintain even a fraction of current transportation energy use. One need only look at Brazil, the largest producer and consumer of ethanol in the world, to see the problem: it's simply not possible to grow enough of it to support current "first world" energy usage, which is almost an order of magnitude greater than Brazil's. This short article makes that point.

Ok, now the biggie - the up and coming "hydrogen economy". I have news for you: most people suggesting the use of hydrogen as a replacement for fossil fuels are completely deluded. Hydrogen is as much a "source of energy" as electricity is, which is to say **IT ISN'T**! Hydrogen may be useful as an energy carrier, but there is no source of hydrogen you can obtain without a process which is, of course, not 100% efficient. In other words, you have to consume energy to produce hydrogen. The most common process is the electrolysis of water - turning electrical power and water into hydrogen and oxygen. The question should be "is there an advantage to using hydrogen as an energy carrier over electricity?" Given the relatively efficient long-distance energy transmission capable with electricity I think the answer is no. The cynic in me suggests that the existing oil industry, which knows how to move bulk cargo long distances and store it in tanks in various forms and distribute it at thousands of service stations, simply wants to maintain its viability. It is hard to make large convenience-store profits if no one has to stop at your convenience store any more, because they simply charge up their car at home or at work. They don't want "charge up", they want "fill up".

My plea

In my opinion a drastic decrease in energy usage - and thus in pollution and greenhouse gas emission - is possible by planning to use the different modes in the way they are best suited. For me, with respect to passenger movement, that means:

- abandoning urban development models that necessitate car use
- encouraging other methods of decreasing travel demand, such as telecommuting
- shifting spending on infrastructure. Diverting even as little as 1% of the road budget to support cycling would make it possible for cycling to be much safer and more comfortable. Imagine covered, completely grade-separated weather-protected cross-town bicycle "highways"!
- providing urban public transit service primarily with rail vehicles offering a frequent service (every 5 minutes or better), even in cities currently thought to be too small (100,000 people)
- avoiding abandonment of trolleybus services unless being replaced by rail; expand services where expansion makes sense
- providing local bus services or "ultra light rail" service to feed main urban rail lines
- operating more passenger-only ferries with better public transportation connections at each end, for shorter distances than would be efficiently served by air
- a dominant role for rail service (>80% market share) for intercity travel up to 3 hours, which with high speed rail could be as much as 800 km (500 miles) and with "maglev" could be as much as 1000 km (600 miles). (Maglev should be considered first in locations where existing passenger rail infrastructure is non-existent or inadequate. The TGV was a great success partly because it could run on existing lesser-quality rail at reduced speeds, but even those reduced speeds are faster than what the vast majority of North American rail infrastructure supports.)
- appropriate air service for transoceanic travel and distances beyond 1600 km (1000 miles)

Competition between modes is often counter-productive, and should be avoided. Governments should stop building highway expansions which compete with rail service, for example. Actually, governments should stop expanding roads, period. Road subsidies should stop. Public transit must be a viable (convenient, comfortable, safe) alternative for a far greater portion of the population than is currently the case.

The aim here is not just to decrease the rate at which fossil fuels are depleted, but rather to decrease overall energy usage such that the entire system can eventually be supported by renewable energy sources. That primarily means electrically-powered vehicles. The obvious exception to "electric propulsion everywhere" is aircraft, which will almost certainly have to rely on liquid fuels. Aircraft, I contend, should be the primary market for biofuels. Shifting air service emphasis to medium-to-long-haul routes would greatly ease congestion at some airports.

A transportation system that relies on a "non-renewable" resource is bound for collapse - the only question is whether we adapt in time, not whether we need to adapt.