Life Cycle Assessment of Transportation Options for Commuters

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Abstract

In order to compare modes of transportation in terms of their environmental impact, a complete life cycle assessment (LCA) was conducted. Using Carnegie-Mellon's EIO-LCA methodology the manufacturing, assembly, operation, and infrastructure life stages were considered for energy input required. Building upon available research for the impact of vehicle and public transportation, the impact of these phases was calculated for walking, bicycling, and electric-bicycling. Electric bicycles use less than 10% of the energy required to power a sedan for each mile traveled and emit 90% fewer pollutants per passenger-mile-traveled than a bus operating off peak. Both habits and financial motivators impact the efficiency at which a form of transportation operates. For example, due to the amount of time a public bus runs off-peak, its average emissions per passenger-mile-traveled is greater than the emissions of a Boeing 737 per passenger-mile-traveled. These relationships and factors are explored in the concluding section.

Introduction

American commuters travel an average of 15 miles to work each way, usually alone, and often in vehicles that are designed to transport more than the single passenger (US Department of Transportation). In light of an energy-conscious society, ride-sharing, fuel-efficient vehicles, telecommunication technologies all aim to reduce the impact of commuting. Still we may question why a 3000-pound vehicle is used to transport a 150-pound person. Each type of transportation option requires a certain input of energy, not only to operate but also to manufacture and assemble. In addition, energy is required to construct and maintain the infrastructure required for operation. The energy and material input required for production and operation of any product has a certain environmental impact.

The analysis of the total energy input over the life of a vehicle is known as life cycle assessment. This study quantifies the energy input and environmental impact of various transportation options using life cycle assessment. It synthesizes the literature available for LCAs of automobiles, trains, and airplanes, and includes an original assessment of walking, bicycling and using an electric bicycle. While the electric bicycle examined is based on a generic Pietzo[2] model available, the study was conducted to academic standards without bias from the company.

LCA Methodology

A common example of how an LCA can provide value to society is comparing the total impacts of paper versus plastic bags. To manufacture, paper bags are less environmentally toxic to produce, but plastic bags tend to be re-used more times once in circulation. However, it is easier to recycle paper than plastic, and ultimately paper is biodegradable, while the plastic used for bags is not. In this example, it is not clear the magnitude of each of the effects, and thus the cumulative impact cannot be predicted. With an LCA, one can answer this question and conclude that paper bags have a less total impact on the environment, and that reusable cloth bags are far superior to both alternatives (Lave 1995).

In the case of commuter transport, an inclusive analysis of environmental impact must address production, operation, maintenance, repair, insurance, infrastructure, and disposal of both vehicle and procedure. During production, the energy and material inputs required to manufacture the vehicle are included. The operation phase consists of fuel production as well as utilization. Maintenance, repair, and insurance include all aspects, including office space required, to keep a vehicle as safe as possible on the road. Infrastructure is typically not included in an LCA, but Chester found the significant impact of road-related activities for transportation. Road surfacing, salting and pesticides, and gasoline distribution facilities are required for effective operation of any road vehicle, but with varying amounts. Finally, disposal includes the impact of waste materials and is often neglected in comparisons within an industry because of standard practices in reuse and recycling of materials. Data for disposal is very difficult to gather, and so it is assumed that impacts are similar for all types of vehicles (Chester 2008).

There are two different LCA models that are used in combination to generate the results of this paper. The process model approach is the conventional method in which one identifies and quantifies the inputs and outputs through mass-balance calculations. The second approach, developed by Carnegie Mellon University's Green Design Institute is called Economic Input-Output Analysis (EIO-LCA). It uses an industry-based equilibrium of the US economy that allows sector information to be publically available for including the entire supply chain associated

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[2] Pietzo's hybrid e-bikes are a commuter transport alternative. More information can be found at www.pietzo.com.

with a product or service. This approach was developed to overcome the challenges presented by the process model approach. The results generated here use a combination of both approaches where applicable (Chester 2008).

A Hybrid LCA model is generated so that advantages of each approach are utilized. EIO-LCA uses dollar values (producer prices) to weigh the impact a specific sector, and associates the economic output from the chosen sector with energy input and environmental impacts. It is a macro-view of the economy which makes it impossible to compare two specific manufacturing processes within one industry. But EIO-LCA is useful when the order of magnitude of materials and processing are substantially different. Furthermore, the operation phase of a vehicle cannot be accurately calculated with EIO-LCA due to the price fluctuations of fuel. A process-based model can, however, be used to calculate the impact of driving a vehicle. Chester validates the use of a hybrid model for transport vehicles further in his dissertation (Chester 2008).

The EIO-LCA model was thus chosen for use in all phases except operation to analyze a Pietzo Hybrid-Electric Bicycle. The analysis was specifically conducted to match the inputs and system boundaries of the forms of transportation evaluated in Chester's work such that a significant comparison can be made. The data available from Pietzo and various other sources was converted into 1997 dollars in order to use the most recent data available for the EIO-LCA economic tables. However, the age of the tables does not present a statistically significant problem because, for mechanical components analyzed here, the technology and processes have not changed substantially.

Functional Unit

The functional unit used for reporting the results of transport vehicle LCA studies is passenger-mile-traveled. This allows a significant comparison to be made because a bus will use much more energy to produce and operate than a smaller car. However, a bus has higher occupancy and its impact is therefore spread across more value added in terms of miles traveled. Automobiles experience vehicle-miles-traveled (VMT), but this is not an appropriate unit for comparing forms of transportation that carry different number of people. However, the relationship between VMT and PMT is as follows.

$$PMT = VMT \times \frac{occupancy}{vehicle} \tag{1}$$

Thus, a bus with 20 people that travels 5 miles has completed 100 passenger-miles-traveled (PMT). A bicycle that travels 5 miles has only completed 5 PMTs.

The conversion factor for occupancy is the average occupancy of the vehicle. For example, on buses, the off-peak occupancy is 3 people while the on-peak occupancy is around 40. The weighted average – based on number of miles traveled at whole number occupancy levels – is 10.5, which is thus used as the conversion factor for buses.

Uncertainty in LCA

Life cycle analyses are subject to considerable uncertainty due to the massive amount of data required to obtain results. At each step, uncertainty in the data propagates through to the results. However, because the accuracy of the data is often unknown, it is impossible to calculate the exact degree of accuracy of the results. As a result, LCA results are often reported with reference to order of magnitude differences.

In an attempt to reduce the uncertainty in comparisons, LCA studies, including this one, are conducted as comparisons that are as methodically similar as possible. For example, the same uncertain data for steel production should be used for automobile, bus and airplane steel use. This way, error is negated and the comparison is still valid.

Uncertainty in LCA studies becomes more critical when two similar manufacturing processes are being compared for total impact. Specificity is more relevant when the differences will not be a whole order of magnitude apart. This study, however, does not address specific processes.

Methodology

The results of this LCA report the total energy input per passenger mile traveled and the amount of emissions of greenhouse gases and criteria air pollutants. The goal is to inform and motivate individuals to make behavior choices, as well as be used to influence policy decisions that relate directly or indirectly to environmental impact.

The energy inputs for the life cycle of one passenger-mile-traveled include electricity and fuel for vehicle production and operation and infrastructure construction and maintenance. All electricity and fuel inputs have been converted to the common unit of energy kilojoules for the purpose of comparison. One kilowatt-hour (the unit of electricity that costs, in Massachusetts, about 14 cents) is equal to 3600 kilojoules (EIA 2009).

The associated environmental impacts are, in some cases tied to the energy consumption – as in the case of operating an automobile – and in others related to the processes of manufacturing – such as producing the lithium-ion batteries of an electric bicycle. The emissions of interest are as follows [EIO-LCA 2009]:

- Greenhouse Gases (GHG) – the gases, that trap heat in the atmosphere resulting in global climate change. These gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. Each of these has a different Global Warming Potential (GWP) as defined by the International Panel on Climate Change and accepted by the US Environmental Protection Agency. The GWP is defined as the cumulative radiative forcing effects of a gas over a specific time horizon. The units reported are in equivalent emissions of CO_2, or CO_2Eq [EPA 2007].
- Sulfur Dioxide (SO_2) – SO_2 released into the atmosphere acts as a respiratory irritant and leads to acid precipitation in the water cycle in the form of sulfuric acid (H_2SO_4). Plants and aquatic wildlife are most susceptible to destruction from acid precipitation, but it also can reach humans by way of the food chain.
- Carbon Monoxide (CO) – when exposed to CO in the air, humans experience a reduction in the oxygen carrying capacity of red blood cells. CO is the result of incomplete combustion of fossil-fuels (complete combustion would release only CO_2) and is released from every powerplant globally.
- Nitrogen Oxides (NO_x) – nitrogen oxides are produced during combustion, and exist in various forms, the most common being NO_2. NO_x reacts with ammonia to product nitric acid, a component of acid rain. NO_x also reacts with volatile organic compounds to produce ozone at an atmospheric height that causes respiratory problems to people. Meanwhile, some NO_xs destroy the ozone layer that protects the earth from ultraviolet radiation, and contributes to climate change.
- Volatile Organic Compounds (VOC) – an important aspect of indoor and outdoor air quality is the presence of VOC. VOC are also soluble in water, and can affect people through ingestion. The most common VOC is methane, which is emitted during combustion of oil or natural gas. Methane is also emitted from landfill decomposition.
- Lead – lead is a heavy metal found in old paints, plumbing, and most notably in the lead-acid car batteries. Lead can leach out during manufacturing and production, and even small quantities have health impacts for people. Ingestion of food or water contaminated with lead can result in negative effects in many organs as well as fertility.
- Particulate Matter (PM_{10}) – PM_{10} is used to refer to particles in liquids or gas of 10 micrometers or less. These may be in the form of ash, dust, or sea spray and occur naturally as well as from human activities. Combustion releases particulate matter that has impacts for human respiration. Particles greater than about 10 micrometers tend not to be inhaled, but these smaller particulates contribute to lung disease and asthma cases.

Each of the pollutants described has been chosen according to the US Environmental Protection Agency's identification of criteria air pollutants. While others have negative human impacts, such as mercury or other heavy metals, these are the most common for the given set of activities. The most commonly recognized characterization of pollution is the greenhouse gas equivalent metric, which will be used for the following comparisons.

Single Passenger Transport

Walking

There are some people who live close enough to their job to choose to walk. Additional factors that tend to influence this decision are ability to park at the job's location, the income level of the commuter, and the desire for physical exercise during the walk. Walking speeds are between two and three miles per hour and only in cases of extreme congestion allows the commuter to get to work more quickly. Weather often presents a barrier to this form of transportation as some climates are too warm, others are too cold, and some wish to not arrive at work exposed to the elements for an extended period of time.

However, walking is a form of transportation that requires no inputs with the exception of the food that the commuter eats. It has been assumed that, in the United States, a commuter will not change her eating habits if she switches from driving to walking to work, given a reasonable walking distance and assuming sufficient nutrition is available. In addition, the health value of daily exercise has not been included in the impact calculations, monetarily or otherwise. The only quantifiable emissions that result from walking to work daily are the carbon dioxide emissions that result from a faster breathing rate than would be otherwise if the commuter was at rest (Gordon 2004). Note that jogging or running has not been calculated because we work under the assumption that a commuter would not like to jog in work attire or arrive to work out of breath and in need of a shower.

The results show that walking to work releases 37 grams of CO_2 per mile traveled. 28 grams is a result of the person's breathing rate; a person sitting at rest for an entire day will release about 10.3 grams of CO_2. The remaining 9 grams of greenhouse gas-equivalent emissions is due to the infrastructure (sidewalks and lights) that are required for commuting. Arguably, paved sidewalks are not an absolute requirement for walking, but in the same way paved roads are not essential for driving. Both are used in the United States.

Bicycling

Bicycling, like walking, avoids the congestion of traffic jams, although bicycle lanes are not completely unaffected by the cars on the road. Still, bicycles allow the user to engage in physical activity that is not too strenuous to be a commuting option (like jogging or running), eliminates the need to park a car at work, and is significantly cheaper to purchase and maintain than even an inexpensive car by more than a factor of one thousand. Bicycles usually operate at about 14 miles per hour, four times the speed of an average runner because energy is not wasted from the impact of the foot on the ground.

To consider the life cycle of a conventional bicycle, the phases considered are production, maintenance, and operation. The processes of bicycle production are fairly well established and so generic production prices were used with the EIO-LCA database to generate results. Data for the maintenance of bicycles was obtained from a locally-owned bicycle repair shop in the greater Boston area, and the same EIO database was used. Finally, the carbon dioxide emissions for operation of a bicycle were calculated based on average breathing rate of a human cycling at the reasonable speed of 16 miles per hour (Gordon 2004). As with walking, food intake is assumed constant, and CO_2 emissions are the *additional* CO_2 release from the rider being at rest.

The lifetime of a bicycle was assumed to be 15 years – equivalent to that of a sedan – because bicycles are more likely to be stolen or sold than scrapped by the user who bought it new. Bike shops routinely reuse parts or refurbish bikes for resale. In actuality the lifetime of a bicycle may be even longer, but for conservative calculations, this number was chosen in order to be consistent with the average automobile. According to estimates made by the US Census, there are between 411,000 and 750,000 bicycle commuters in the United States. An average, approximately 600,000 commuters, is assumed (Kifer 2002).

Roadway maintenance is included in the LCA discussion of automobiles. To be consistent it should also be addressed for both bicycles and electric bicycles. However, as shown in Table 18 of Chester's dissertation, a motorcycle contributes effectively 0% to the roadway damage and therefore maintenance required (Chester 2008). This is a function of the weight of the vehicle, and as a result can be neglected for both bicycles and electric bicycles, which are a factor of ten lighter than motorcycles. Parking for bicycles has also been neglected based on order of magnitude. For example, there are 2733 spaces for cars in the parking lot at Alewife Station, at the end of Boston's public transport route. There is parking for 300 bicycles, with the estimated cost of one parking spot being one hundred times that of the total cost one bicycle spot (WalkBikeJersey 2009). Thus, roadway maintenance and parking space requirements have been neglected.

For roadway construction, bicycles were allocated a portion of the same type of road that is constructed for cars. Using area (road width) as the conversion factor, the construction of bike lanes follows the procedure detailed in the literature (Chester 2008). This is assumed necessary because without bike lanes, riders tend to be hesitant to use bicycling as a form of commuter transport. Furthermore, the impact of herbicides and salting is also included for the area of bike lanes assumed, again using extrapolated data from Chester.

More detail on the assumptions used for analysis of a conventional bicycle can be found in Appendix A. In summing the life cycle inventories of a bicycle, we find that bicycles require 319 kJ of energy input and releases 33 grams of greenhouse gases per passenger mile traveled.

Electric Bicycles

In addition to the considerations of a conventional bicycle, electric bicycles require a battery, electricity, and less human effort. The impact of roadway construction, herbicides and pesticides, are the same as for a conventional bicycle.

The producer prices for lithium-ion batteries was obtained as an average of various manufacturers and calculated from consumer costs using a typical 30% margin. More specific data was not available.

Using emissions factors for electricity, (United States averages) emissions can be obtained per kilowatt-hour (kWh) of electricity produced (Deru and Torcellini 2007). The mining process of the fuels combusted in a power plant were not included in order to maintain a consistent system boundary to the other vehicles reported by Chester. In the case of electricity, the only cost of distribution is loss of electricity in the system. It is estimated that, in the United States, about 10% of electricity is lost due to voltage drops across the lines. Furthermore, because the amount of electricity used for charging the lithium ion batteries of electric bicycles is so small compared to the US total electricity use the allocation of construction of electricity lines is negligible.

The energy input required for an electric bicycle is 12% higher than that of a conventional bicycle, but actually results in exactly the same amount of emissions. While these relative numbers appear interesting, it is important to recognize that errors in available data could affect the figures drastically. Assuming accuracy to be within +/- 10%, it is difficult to ascertain anything significant from only these results. Both values are more significant when compared with cars and other forms of transport.

Personal Vehicle Transport

Personal vehicle transport is defined as transport types that are owned by the individual operating them. In many cases, only the owner benefits from the transportation, but sometimes more people are present. Breathing rates, in all cases, were neglected in the carbon dioxide release because occupants are generally at rest. Much of the following analysis is summarized from the literature.

Automobiles

The automobile is often considered the most desirable form of commuter transport because of convenience, relatively inexpensive fuel costs, and status. The average automobile has less than two people riding it in at any given time, and weighs between three- and five- thousand pounds (Chester 2008). These automobiles rely on the combustion of gasoline, refined from crude oil, to motor their way to and from the commuter's home and work. Their impact on the environment is significant.

The data and calculations for personal vehicle transport were conducted by Mickhail V. Chester in for his doctoral thesis, "Life-cycle Environmental Inventory of Passenger Transportation in the United States" and reviewed by the Institute of Transportation Studies at the University of California, Berkeley. The processes and related infrastructure of automobile transport are extremely complex and have been verified by experts in the life-cycle analysis field. This paper does not attempt to argue with or improve upon the calculations presented, but aims to explain implications of their results.

In order to model personal automobiles, one make and model was chosen for each of the following three classes: sedan, sports utility vehicle (SUV), and pickup. The make and model was chosen based on number of vehicles sold in 2005 in each class. Data was collected on each vehicle for model specifications, fuel efficiency, average passenger occupancy, lifetime, vehicle-miles traveled (VMT) (EPA, Davis 2006) and is aggregated in Error! Reference source not found..

Table 1: Data collected for personal vehicle transport.

	Weight (lbs)	Average Occupancy (#)	Mileage (MPG)	Lifetime (Years)	Annual VMT	Annual PMT	Invoice Price
Sedan (Toyota Camry)	3200	1.58	28	16.9	11,100	17,000	$21,000
SUV (Chevrolet TrailBlzer)	4600	1.74	17	15.5	11,100	19,000	$29,000
Pickup (Ford F-Series)	5200	1.46	16	15.5	11,100	16,000	$20,000

Table 2: Energy and GHG inventory for personal vehicle transport.

	Energy (MJ/PMT)	GHG (g CO2E/PMT)	CO (g/PMT)	SO2 (mg/PMT)	Nox (mg/PMT)	VOC (mg/PMT)	PM10 (mg/PMT)
Sedan (Toyota Camry)	4.7	380	12	350	1100	1200	240
SUV (Chevrolet TrailBlzer)	6.5	450	13	410	1200	1300	230
Pickup (Ford F-Series)	7.9	620	20	460	1700	2100	270

Additional details on the assumptions used to obtain the results are available in Appendix B.

Although it is not expressed in these tables, he data reported from the EPA Mobile 6.2 indicates that the startup of the car – the period of time during which the catalytic converter is not warmed up and working at its optimal conditions – compromises 40% of the total CO emissions and 17% of the NO_x emissions (normalized per vehicle mile traveled). As a result those "quick trips" are the worst for the environment because the emissions cannot be justified with the distance traveled. The relative comparison with other forms of transport (walking, bicycling, electric bicycling) result in even more drastic differences when comparing only the startup period. However, the absolute values of this comparison are impossible to quantify due to the uncertainty around temperature conditions, vehicle environment, and age and state of the vehicle.

Many Passenger Transport

The many passenger transport options evaluated are bus, rail, and airplane. Each of these is operated by an external provider and runs on a schedule as opposed at the convenience of the commuter. In addition, the emissions of each are distributed across the multiple passengers that use the form of transport at a given time.

Bus

The values for the total life cycle inventory of a bus are calculated in the same way described for personal automobiles because it is also an on-road vehicle. A 40-foot bus is assumed to be typical of public transport in the United States, with an average occupancy of 10.5 passengers (5 during off-peak and 40 during peak times). The average is weighted with time. A bus lasts for 12 years as this is the industry retirement age, and travels 42,000 miles per year. The most significant different for operational emissions for a bus is the high percentage of time spent idling. Therefore, bus idling fuel and running fuel were computed differently, with associated emissions factors. The average speed of a bus while moving is 12 miles per hour.

Rail

Three types of rail systems were analyzed: BART, Muni, and the Green Line. Because each system in the United States has been developed slightly differently to achieve the purposes desired by the specific city, there is a fairly wide range in results. The three systems evaluated here represent typical short-distance heavy and light rail systems. These systems are San Francisco's Bay Area Rapid Transit System (BART), Municipal Railway (Muni), and Boston's Green Line. Average occupancy of each was assumed to be 146, 22, and 54 respectively. Each phase of the life cycle was evaluated, including the infrastructure required for operation. More details are in Appendix C.

When totaled, these inventories provide insight into the relative impact of each phase of a rail's life cycle. Emissions are primarily due to electricity consumption, both of the train as well as of the supporting infrastructure. As a result, it can be noticed that SO_2 emissions are higher relative to other emissions when compared to onroad vehicles. For these commuter systems, no one train system is significantly better than another for all CAP categories. Each system performs slightly differently under its own circumstance.

Air Travel

Air travel consumed 9% of total transportation energy consumption in 2005 (Davis 2007). The vehicle chosen to represent a standard aircraft is a Boeing 737, a midsize, medium-haul aircraft. The Boeing 737 is also representative of the Airbus A300s, Boeing 717,727,757, 777, and the McDonnell Douglas DC9. The Boeing 737 has an empty operating weight of 81,800 lbs. Each life cycle phase was analyzed and details are explained in Appendix D.

Each flight does not only carry passengers, but hauls a certain amount of freight and mail. The allocation must therefore be adjusted in order to avoid unfair association of emissions for each *passenger* mile traveled. Studying the various forms of freight transport is left for another paper. The Boeing 737 carries about 101 passengers, whose weight and weight of luggage totals about 19,000 lbs. Meanwhile freight compromises an additional 360 lbs and mail another 150 lbs. The passengers and their luggage are therefore representative of 97% of the aircrafts load. (Larger aircrafts allocate only 83% of the total load to passengers and luggage.)

A summary of the fundamental specifications of each mode of transport is shown in Error! Reference source not found., and the results from the inventory are shown in Error! Reference source not found..

Table 3: Summary of data collected for many-passenger transport.

	Average Occupancy (#)	Lifetime (Years)	Annual VMT	Annual PMT	Invoice Price
Off-Peak Bus	4	12	42,000	440,000	$310,000
On-Peak Bus	40	12	42,000	440,000	$310,000
BART	146	26	8,600,000	1,300,000	n/a
Muni	22	27	5,500,000	120,000,000	n/a
Green Line	54	27	3,300,000	180,000,000	n/a
Boeing 737	101	30*	950 miles/flight	9,500 miles/flight	$66M

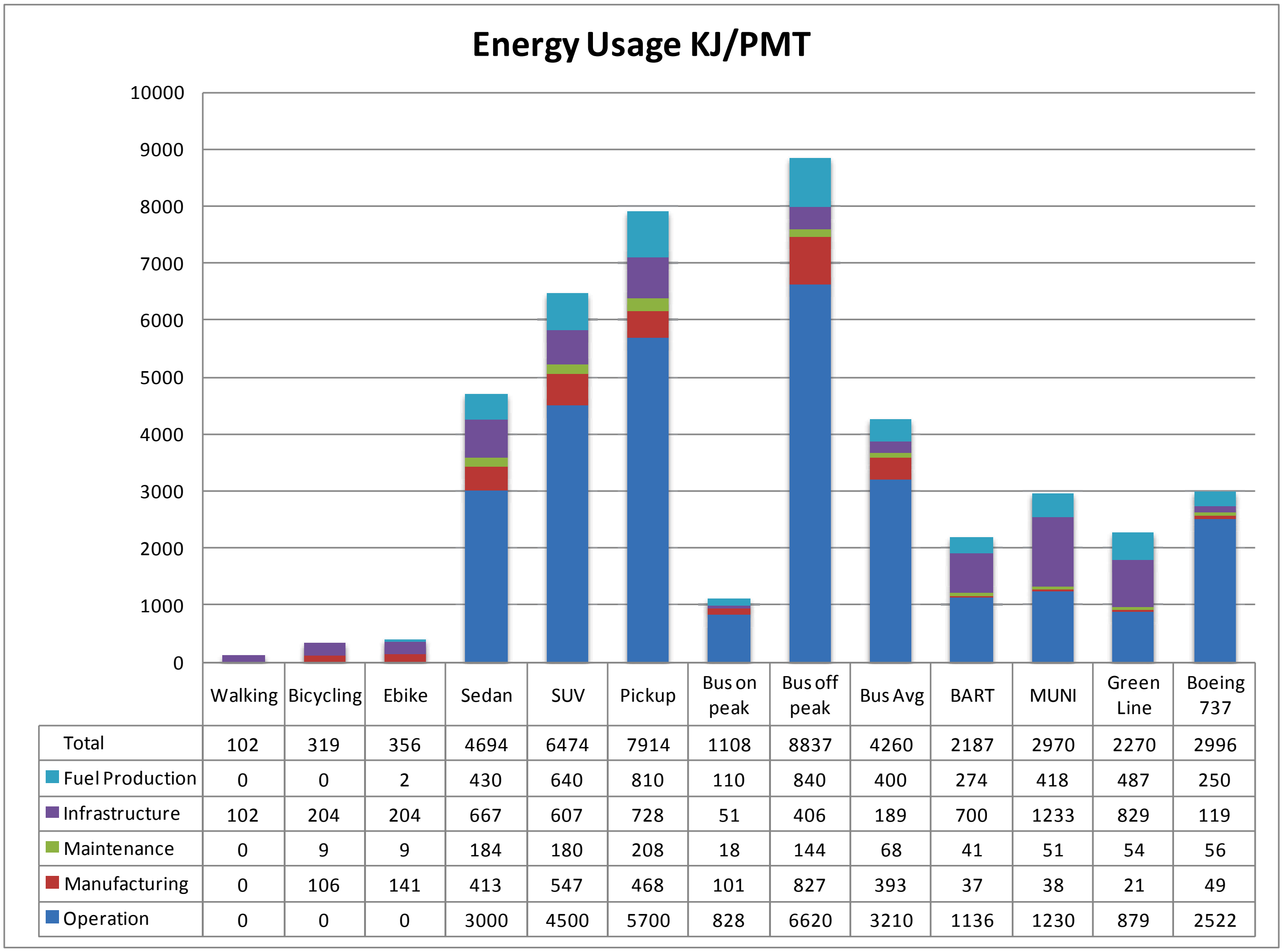
*The age of an aircraft is assumed to be 30 years, and for the engine 20 years.

Table 4: Summary of energy and GHG emissions for many-passenger transport modes.

	Energy (MJ/PMT)	GHG (g CO2E/PMT)	CO (g/PMT)	SO2 (mg/PMT)	Nox (mg/PMT)	VOC (mg/PMT)	PM10 (mg/PMT)
Off-Peak Bus	8.8	680	2.2	380	4400	630	290
On-Peak Bus	1.1	85	0.28	47	550	79	36
BART	2.2	140	530	619	290	200	55
Muni	3	170	660	810	270	150	52
Green Line	2.3	230	720	1200	410	130	50
Boeing 737	3	210	600	160	700	70	22

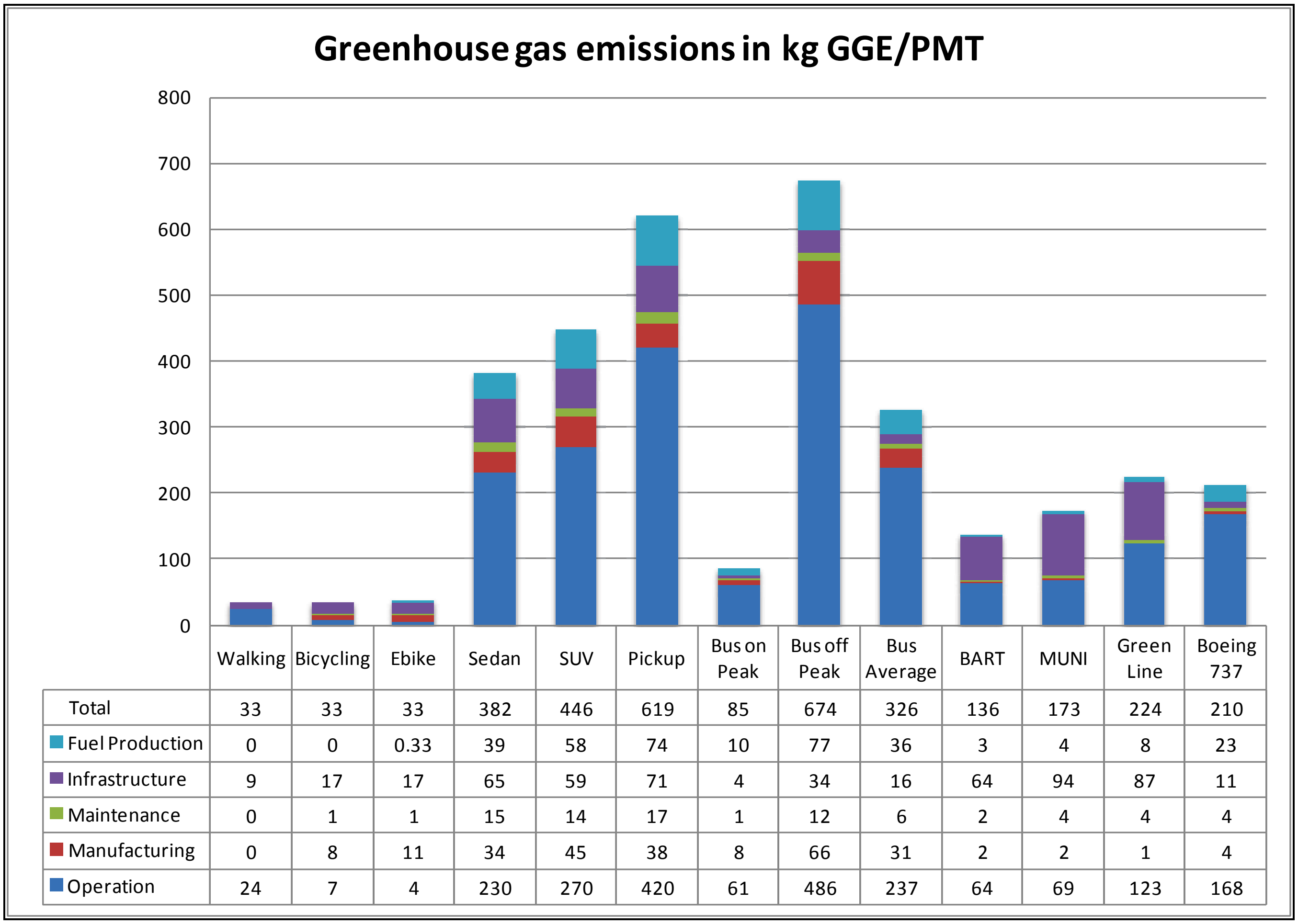
Summary of Results

In sum, electric bicycles use less than 10% of the energy required to power a sedan for each mile traveled, and emit 90% fewer pollutants per passenger-mile-traveled than a bus operating at off peak. Error! Reference source not found. shows the comparison of energy input per PMT and Error! Reference source not found. depicts the greenhouse gas emission per PMT for each form of transport studied.



	Walking	Bicycling	Ebike	Sedan	SUV	Pickup	Bus on peak	Bus off peak	Bus Avg	BART	MUNI	Green Line	Boeing 737
Total	102	319	356	4694	6474	7914	1108	8837	4260	2187	2970	2270	2996
🟦 Fuel Production	0	0	2	430	640	810	110	840	400	274	418	487	250
🟪 Infrastructure	102	204	204	667	607	728	51	406	189	700	1233	829	119
🟩 Maintenance	0	9	9	184	180	208	18	144	68	41	51	54	56
🟥 Manufacturing	0	106	141	413	547	468	101	827	393	37	38	21	49
🟦 Operation	0	0	0	3000	4500	5700	828	6620	3210	1136	1230	879	2522

Figure 1: Energy input per PMT for commuter transport options



	Walking	Bicycling	Ebike	Sedan	SUV	Pickup	Bus on Peak	Bus off Peak	Bus Average	BART	MUNI	Green Line	Boeing 737
Total	33	33	33	382	446	619	85	674	326	136	173	224	210
🟦 Fuel Production	0	0	0.33	39	58	74	10	77	36	3	4	8	23
🟪 Infrastructure	9	17	17	65	59	71	4	34	16	64	94	87	11
🟩 Maintenance	0	1	1	15	14	17	1	12	6	2	4	4	4
🟥 Manufacturing	0	8	11	34	45	38	8	66	31	2	2	1	4
🟦 Operation	24	7	4	230	270	420	61	486	237	64	69	123	168

Figure 2: Greenhouse gas emissions per PMT for commuter transport options.

Conclusions

The results reported in the previous section show the significant environmental as well as economic (in terms of energy purchased) benefit of using human-powered forms of transportation. According to this study, walking, conventional bicycling and electric bicycling are release exactly the same amount of greenhouse gas emissions. While an electric bicycle consumes more energy (both to produce and to operate) and releases the associated greenhouse gases, a conventional bicycle requires the operator to work harder and breathe more heavily. In effect, the impact of the electric bicycle is entirely negligible. All forms of personal transport are at least three times better than any other form of commuter transport.

Clearly, a bus operating on peak is the most environmentally friendly form of non-personal transport, but the average bus operation is an order of magnitude worse than any form of personal transport. It is interesting to note that even a Boeing 737 operates at a lower greenhouse gas per passenger-mile-traveled average than does a bus. The difference here may be attributed to the private sector for air travel versus the public service provided by a bus. A discussion of the environmental impact of public transport, while outside the scope of this study, may be required.

Finally, it is important to recognize that the results of this study will change as bicycling behavior changes. While the amount of energy required to produce a bicycle will probably remain constant, the more that bicycles are used, the greater the average passenger-mile-traveled per bicycle will be. As a result, the fraction (energy use per PMT) will be reduced. The assumed PMT for a bicycle is less than one-third that of an automobile. Even if this value increases by only 50% (still less than half the miles traveled by an automobile), the energy and emissions per PMT will be reduced by one third. Behavior trends are an important factor in this analysis.

Ultimately, this study is relevant for understanding the impact of various types of commuter transport. Electric bicycling, conventional bicycling, and walking each have about the same impact when considering commuting to work. Walking is the most energy intensive form of personal transport from the human's perspective, but since most Americans consume ample calories, an increase in food intake was ignored. Accordingly, walking releases the most amount of carbon dioxide from breathing. Thus, while an electric bicycle consumes energy and releases emissions to manufacture and operate, the amount is the same order of magnitude as a humans breathing activities during a brisk walk. To reiterate, the exact accuracy of any life-cycle assessment cannot be guaranteed, but the overall impact and comparisons are very interesting to understand and consider when making individual choices.

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Appendices

Appendix A

For conventional bicycling, the following life-cycle phases were considered:

- Manufacturing – Using EIO-LCA sectors appropriate for each component of the bicycle, a bicycle was constructed to be of a similar mid-range standard as the Pietzo electric bicycle. Without the electric motorized component of the bicycle, the total manufacturing energy was slightly less. Each component was analyzed as follows:
  - Bicycle frame, fenders, and rack: Alumina refining, Aluminum extruded part manufacture (Sector # 331316 and 331311)
  - Helmet: Foam product manufacturing (Sector # 3261A0)
  - Tires: Tire manufacturing (Sector #32621)
  - Tire rims, gears, bicycle lock: Iron and steel mills, Rolled steel shape manufacturing (Sector # 311221 and 311111)
  - Lights and reflectors: Electric lamp and bulb manufacturing (Sector # 335110)
  - For the Electric Bicycle only – Lithium-ion Battery: Battery and storage manufacturing (Sector # 335911)
- Operation
  - A conventional bicycle requires only human power to operate. The emissions associated with human power include only the CO_2 released through breathing.
  - An electric bicycle uses electricity in the form of kWh to operate. The United States average emissions factor was used (Deru and Torcellini)

Because bicycle ridership is dependent on safe spaces to ride, a portion of the roadway infrastructure impact must be allocated to bicycles. The following assumptions were made:

- Bicycles do not require new road construction because they use existing roadways. In some cases roads may be expanded to accommodate a bike lane and thus only additional width is required.
- A bicycle lane is about 4 feet wide (in Boston, MA) on each side. This increases the average width of a road by 40%.
- Bicycle lanes will be added only to roads that are experience significant bicycle traffic. In an extremely conservative estimation, 10,000 miles of bike lanes will be added. This is conservative because many roads in commuter cities already have existing bicycle lanes, while rural roads may already be wide enough and simply require painting to indicate bicycle lanes.
- Using the same Roadway Construction Factors from the PaLATE software that was used by Chester for roadway infrastructure calculations for automobiles, the appropriate allocation to bicycle lanes was determined.
- To convert to impact per vehicle mile traveled, the VMT for electric bicycles was extrapolated to 2014 (assuming a 10 year lifetime for the roadway) to ascertain the number of bicycle miles traveled during the period.

Appendix B

Each phase of the life-cycle of an electric bicycle was considered via a combination of the EIO database and the process model approach. They are described as follows (Chester 2008):

- Manufacturing – The manufacturing processes of an automobile consist of many different activities from material procreation to assembly, and are complex to analyze. EIO-LCA was used to determine the total inventory for each automobile, based on invoice prices. The invoice prices (assuming a 20% markup) were input into the Automobile and Light Truck Manufacturing (#336110) sector to calculate the impact per PMT for each class of vehicle. Automobile manufacturing energy ranges from 0.35 to 0.49 MJ/PMT for the three modes analyzed. The GHG emissions are 29 to 41 grams CO_2E/PMT.
- Operation – Chester used an inventory model from software developed by the EPA called Mobile 6.2 in order to calculate emissions associated with driving, startup, breaks, evaporative, and idling components of a vehicle's operation. Mobile 6.2 allows for a more accurate analysis of the car's fuel consumption not only by specific activity, but also by season and type of fuel input.
- Maintenance – Vehicle maintenance consists of both vehicle maintenance and tire maintenance. The costs of each for sedans and SUV were collected from the American Automobile Association (AAA) and are reported in **Error! Reference source not found.**. The costs for pickups was not available but was extrapolated based on vehicle weight. These values were used in the Automotive Repair and Maintenance sector (#8111A0) and Tire Manufacturing sector (#326210) respectively. Again, the energy and emissions results are normalized by PMT and the results show that it accounts for 2-3% of automobile emissions.
- Automotive Repair – This area includes the emissions as a result of the use of facilities to conduct automotive repair, and the energy required to operate such facilities. For example, the brake cleaners, carburetor cleaners, and engine degreasers release emissions must be attributed to a vehicle's infrastructure. Emissions data from California were added to the inventory and attributed to each class of vehicle based on use.
- Insurance – The EIO-LCA sector Insurance Carriers was used to estimate the operating energy and emissions of insurance for automobile. According to AAA a sedan costs $900 per year to insure and an SUV $920 per year. Using the same extrapolation based on weight, a pickup is assumed to cost $930 per year to insure.
- Roadway Infrastructure – While most automobile LCAs do not include roadways in their calculations, Chester recognizes that the supporting infrastructure contributes significantly to the inventories of interest. In this phase is roadway construction, roadway maintenance, parking construction and maintenance, roadway lighting, herbicides, salting, and repair facilities. In each case a certain percentage of total impact is allocated to the vehicle based on frequency of use or weight (as in the case of roadway maintenance, because lighter vehicles like sedans cause a fraction of a percent of the damage that occurs to existing roads). These impacts are generated using PaLATE, a pavement life-cycle assessment tool.
- Fuel Production – For automobiles, the inventory of gasoline and diesel was calculated using EIO-LCA. It is a simple calculation to obtain the amount of fuel required by the vehicle during its life, which is then converted to dollars and input into the supply chain in the Petroleum Refineries sector (#324110).
- Fuel Distribution – Gasoline and diesel both require distribution after refining, and the tanker trucking processes contribute to the emissions of the fuel's life cycle. Tanker trucks achieve 110 ton-miles per gallon and travel about 100 miles to distribution stations.

Finally the results from each phase described were aggregated and reported.

Appendix C

The life cycle phases were analyzed as follows (Chester 2008):

- Manufacturing – The process model LCA software SimaPro was used to calculate the manufacturing impact of each of the three rail systems. Manufacturing impact was prorated by train weights, and the values ranged from 1.4 TJ to 19 TJ for train construction.
- Operation – Electricity is the fuel used to power each of these train systems and includes both transit as well as auxiliary lighting systems and keeping the train “hot” and ready for use. Idling also occurs for trains which, like buses, make stops to allow passengers to get on and off. Once kWh per VMT has been calculated, emissions factors for electricity production are applied to generate criteria air pollutant data. Total operational energy consumption averages 1.1 MJ/PMT. The more fossil fuel intensive electricity mix increases the impact of Boston’s Green Line compared to the California Muni system.
- Maintenance – Maintenance includes routine maintenance, cleaning, and flooring replacement. SimaPro was also used, in the same manner as for train manufacturing, to calculate maintenance impact, again prorated by weight. Again, California and Massachusetts electricity mixes are applied and emissions factors allow calculation of CAP quantities.
- Insurance – For insurance, the EIO-LCA sector Insurance Carriers (#524100) was used. Total yearly insurance costs were prorated by the fraction of train operators in order to determine direct operational personnel insurance. Casual and liability insurance is also included, using a similar methodology. About 40% of the energy required by insurance carriers is in the form of electricity used for facilities and operations. The emissions are correspondingly from electricity generation.
- Infrastructure – Station and track construction and maintenance are fully allocated to the trains which use them. Each system has different specifications for its stations, and once analyzed, Chester determined the volume of concrete and weight of steel required. These were input to EIO-LCA sectors Ready-Mix Concrete Manufacturing (#327320), Iron and Steel Mills (#331111), and Sand, Gravel, Clay, and Refractory Mining (#212320). Energy consumption for station lighting, escalators, train control, parking lot lighting, and miscellaneous other electricity consumption were aggregated and included.

Appendix D

The following life-cycle phases were addressed (Chester 2008):

- Manufacturing – The EIO-LCA sectors Aircraft Manufacturing (#336411) and Aircraft and Engine Parts Manufacturing (#336411) were used, assuming a 10% markup on the invoice price, which includes overhead, profit, distribution, and marketing for both the aircraft and engine.
- Operation – The flight cycle of an aircraft was first broken down in to taxi-in, taxi-out, take-off, climb-out, cruising, and final approach. More broadly, emissions are either at or near-airport or cruising. The at or near-airport emissions were analyzed using the Federal Aviation Administration's (FAA) Emission Data Modeling Software (EDMS) [FAA 2007]. Cruising accounts for between 55% and 74% of total energy consumption, and emission factors for the Boeing 737 were determined from the European Environment Agency and are normalized by the functional unit.
- Maintenance – Because there is no sector in the EIO-LCA database to model aircraft maintenance, it was first disaggregated into components and analyzed individually by sector. For the Boeing 737, engine material costs are more than half that of the airframe itself.
- Insurance – Like the previous models discussed, insurance was calculated using EIO-LCA. The costs are reported by the US Department of Transportation and normalized by the functional unit.
- Infrastructure – Airport construction, operation, and maintenance are included in the aircraft's life-cycle inventory. The top 50 airports were studied, and Dulles airport was chosen as the average airport because its statistics are close to the average. As in road construction infrastructure, PaLATE was used to estimate emissions factors based on surface area requirements of the airport. Lighting, deicing fluid production, and ground support equipment were also included. Finally, parking and electricity for facilities was quantified and included.
- Fuel Production – The production of Jet-A is similar in process to the production of gasoline, but it operates with different emissions factor. Using EIO-LCA, the production inventory is computed.