Calculating Changes in CO_{2e} Emissions as a Result of Increased Cycling

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Abstract

UC Davis is (one of) the most bicycle friendly university campuses in the most bicycle friendly city in the U.S. As a result, it was hypothesized that motorized vehicle traffic in Davis would be significantly reduced compared to the national average. In this paper, we investigate the effect of heavy bicycle usage on the greenhouse gas (GHG) emissions of the city of Davis. This result was then compared to the emissions of the "average" American city. The analysis was done using data from the National Household Transportation Survey (NHTS), the American Community Survey (ACS), and the UC Davis Transportation and Parking Services Annual Campus Transportation Survey (CTS). These surveys provided data at multiple levels that allowed easy identification of different transportation patterns among various groups. Transportation data was then used in conjunction with life cycle analysis of the modes of transport to calculate a communitys transport related GHG emissions. It was found that the CO_{2e} emissions within the city of Davis were less than the national average, primarily due to the large decrease in drivers due to extra bicycle commutes.

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1 Notation

- ACS: American Community Survey
- AER: All Electric Range
- BCF: Bicycle Friendly Community
- BMR: Base Metabolic Rate
- CO_{2e}: Carbon Dioxide Equivalent emissions
- CTS: [UC Davis] Campus Transportation Survey
- CV: Conventional Vehicle
- d: commute distance
- d_{day}: Daily round-trip commute distance (km)
- ECF: European Cyclist Federation
- EIOA: Economic Input Output Analysis
- EIOLCA: Economic Input Output Life Cycle Analysis
- EPA: [United States] Environmental Protection Agency
- GHG: Greenhouse Gas(es)
- GWP: Global Warming Potential
- HEV: Hybrid Electric Vehicle
- ICE: Internal Combustion Engine
- L: Lifetime of vehicle (years)
- LCA: Life Cycle Analysis
- M_{CO2}: Manufacturing Related CO2e emissions
- m: Transportation mode, vehicle type
- NHTS: National Household Travel Survey
- P: Population
- P(m): Fraction of population owning vehicle m
- P(mc): Fraction of population using vehicle m for commutes
- PHEV: Plug-in Hybrid Electric Vehicle
- RMR: Resting Metabolic Rate
- T: Total number of commutes
- T(d): Number of commutes of distance d
- t_{mode} fraction of commutes of length d by vehicle m
- TAPS: [UC Davis] Transportation and Parking Services

2 Introduction

Since their invention, conventional vehicles (CV)s have become the developed worlds prefered mode of transportation. Now, developing nations are increasing the number of vehicles on the road even further. As a result, CO_{2e} and other GHG emissions due to transportation have become a serious problem with dire consequences for the environment. The goal of this study was to investigate the effect increased bicycle commuting and decreased driving would have on greenhouse gas emissions of a community. This was done by comparing Davis, a city with a high bicycle commuter rate, to an average city based on the national data to determine the resulting change in GHG emissions.

In the past many studies have looked into the importance of biking, not only for personal health reasons (i.e. exercise) but also for the health of the environment. Many papers have been written on the GHG emissions of bicycles compared to cars. The previous research reviewed here focused on factors influencing the energy intensity of biking, including the additional energy required by a cyclist, the impact of infrastructure on biking (and vise-versa), and the amount of Americans who bike. The research also discussed light road vehicle CO_{2e} emissions and lifecycle assessment for different drivetrain architectures. These studies will aid in the assessment of the potential benefits bicycles may have on the environment compared to other forms of travel.

To make use of the data from previous research, it was important to apply it to real world communities. Davis was a prime candidate due to its high cycling rate and general bicycle-friendliness. The statistics that were deemed important to the analysis were population, the percent of the population using each mode of transportation, the distance traveled by each transportation mode, and the overall life cycle carbon intensity of each transportation mode. It was hypothesized that a car would have both higher production-related CO_{2e} emissions as well as higher usage CO_{2e} emissions. The CO_{2e} emissions from production of a car and bike were found to be 7162 kg CO_{2e} and 111 kg CO_{2e} respectively. It was also important to look at the usage energy from a car and a bicycle. Combining information gained from a literature review and an LCA (below), the use-phase CO_{2e} emissions were determined to be 304 gCO_{2e}/km for a car and 88.1 gCO_{2e}/km for a bike. Even though the results showed that usage emissions from biking cannot be neglected, it was demonstrated that these emissions were much less than those from driving, from both production and usage.

This data was used in accordance with the transportation mode distribution to determine the amount of CO_{2e} released based on the population in an average city from national data, Davis data and data for the UC Davis community. It was predicted that the average city (which was scaled down national data) would result in the emission of the most CO_{2e} due to the high amount of commuter vehicles. Based on data from the NHTS, the fraction of Americans who bike to work was less than 1% in 2009, while driving accounted for 90% of all commutes. While in Davis, these percentages were 22% for bikers and 68% for drivers. It would make sense, then, that commute related CO_{2e} emissions would be higher nationally than in a more bicycle friendly community. In this report, this hypothesis was investigated by looking at the preferred transportation modes of three separate communities.

3 Background

In recent years, the United States has seen an increase rate of bicycle commuting as a primary means to get to work. In 2008, 0.55% of Americans used a bicycle as their primary commuting vehicle, a 14% increase from 2007[3]. This survey compared 70 large cities, and only 27 were determined to be bicycle friendly communities (BFC). The 70 cities had a higher biking rate than the US as a whole, 0.93% compared to the national average of 0.55%. It was interesting that while some of the cities increased the percentage of bikers, there were some that showed little or no change in the rate of cycling. Figure [1] shows the growing split between the percentage of commutes done by bike between the BFCs and non-BFCs.

Figure 1.

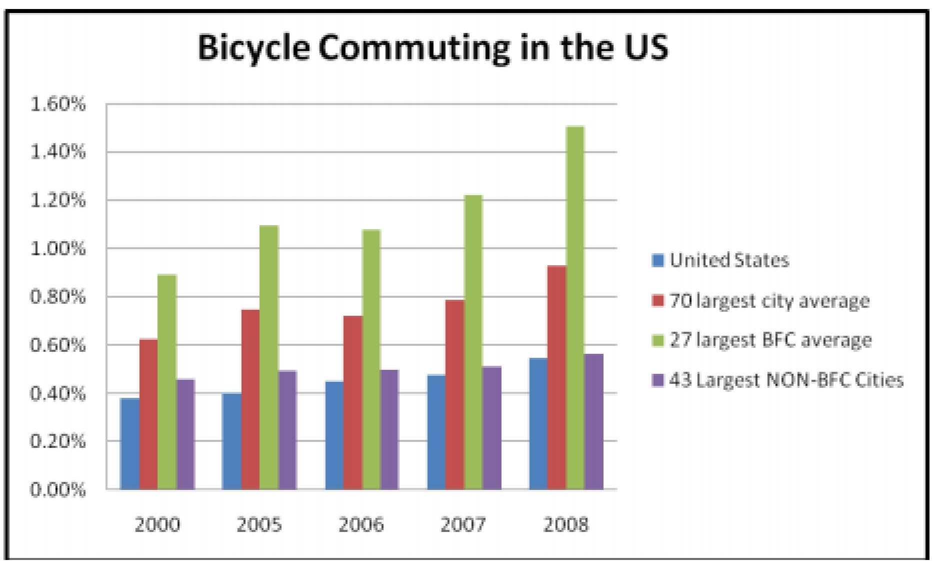


Figure 1: Shows the percentage of bikers commuting in the US[3].

It was also interesting to directly compare the most bike friendly cities with each other, rather than simply take an average. Figure [2] shows the 27 most cyclist-friendly cities and their bicycle commute percentages.

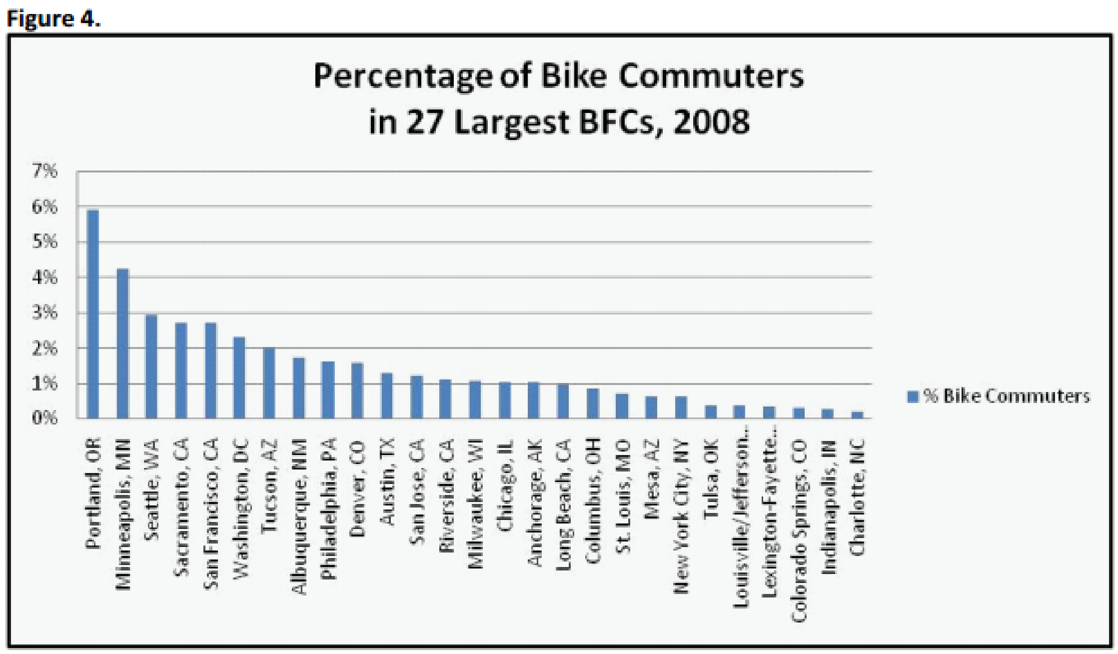


Figure 2: The percentage of bikers in the most bicycle friendly communities[3]. Note that this figure does not include Davis because its population is to small.

In the grand scheme, these percentages are small. It begs the question: how do we get even more people to choose a bicycle as their primary means of commuting? We begin to answer this by first observing what it is about the BFC cities that makes people want to bike. What kind of weather do these cities have, what is their terrain like, how is their bike infrastructure, what policies promoting cycling have they implemented, and which came first, the bike or the bike lane? (Figure [4]) These are all factors that likely influence the percentage of biking in a city. Data from the Federal Highway Administration[3] showed that cities with increased spending on bike lanes and related projects significantly increased the percentage of the population that chose to commute by bike. This corroborates the data from McGuckins (2012)[40] analysis of the NHTS that showed that one of the major reasons people cite for why they do not bike commute is concern for safety. (See figure [3])

Another factor people consider when deciding whether or not to bike is the state of the infrastructure for biking. Nelson (2007)[41] found that an inadequate quantity of bicycle infrastructure affected the number of people who chose to bike. The research found that the number of bikers and the quantity of facilities for bikers (namely pathways) were correlated. However, Nelson was unable to determine whether the bikers caused the need for more infrastructure or if the infrastructure was built to encourage more biking. Furthermore, some bike lanes in the cities studied were determined to be for recreational use rather than commuter use. In general though, from the study Nelson completed[41], it was concluded that

Walking and Biking in California

Figure 11 Barriers to Biking More[13]

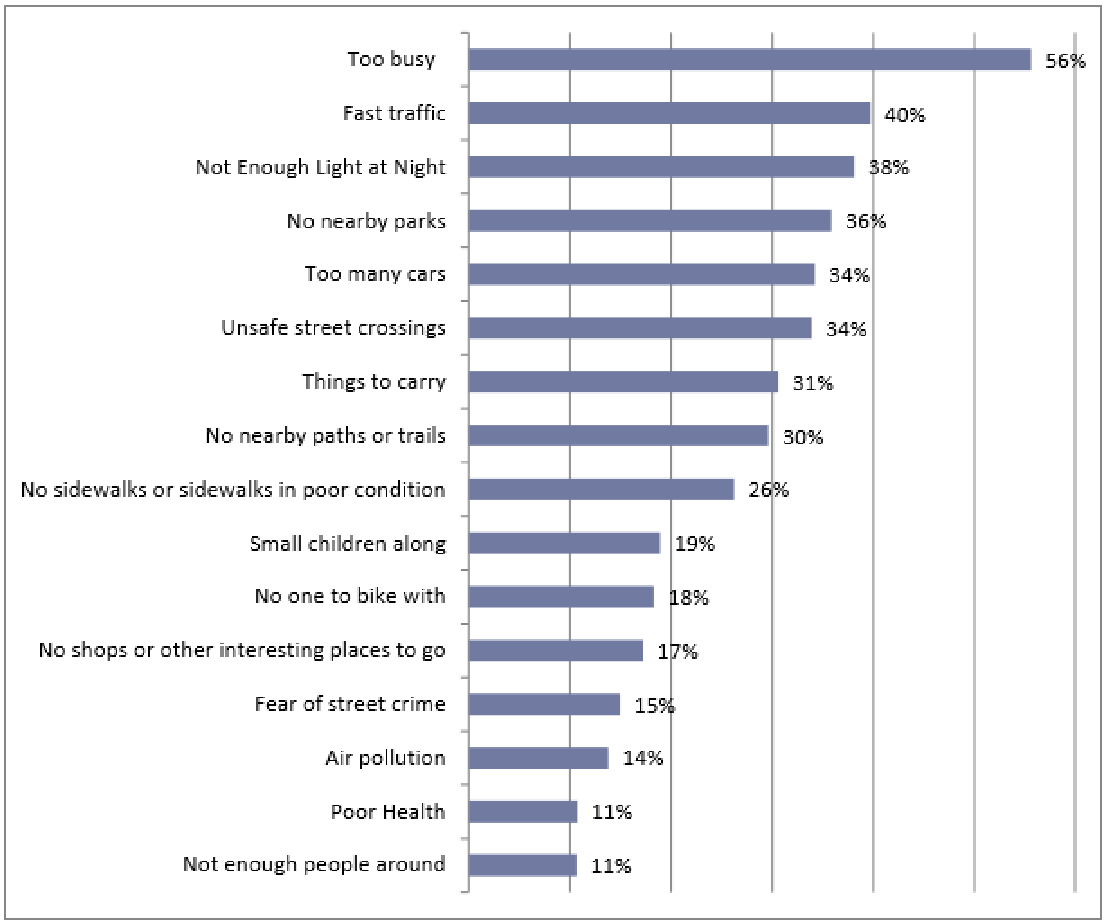


Figure 3: Shows the reasons given in NHTS for not biking more often. Figure from [40]

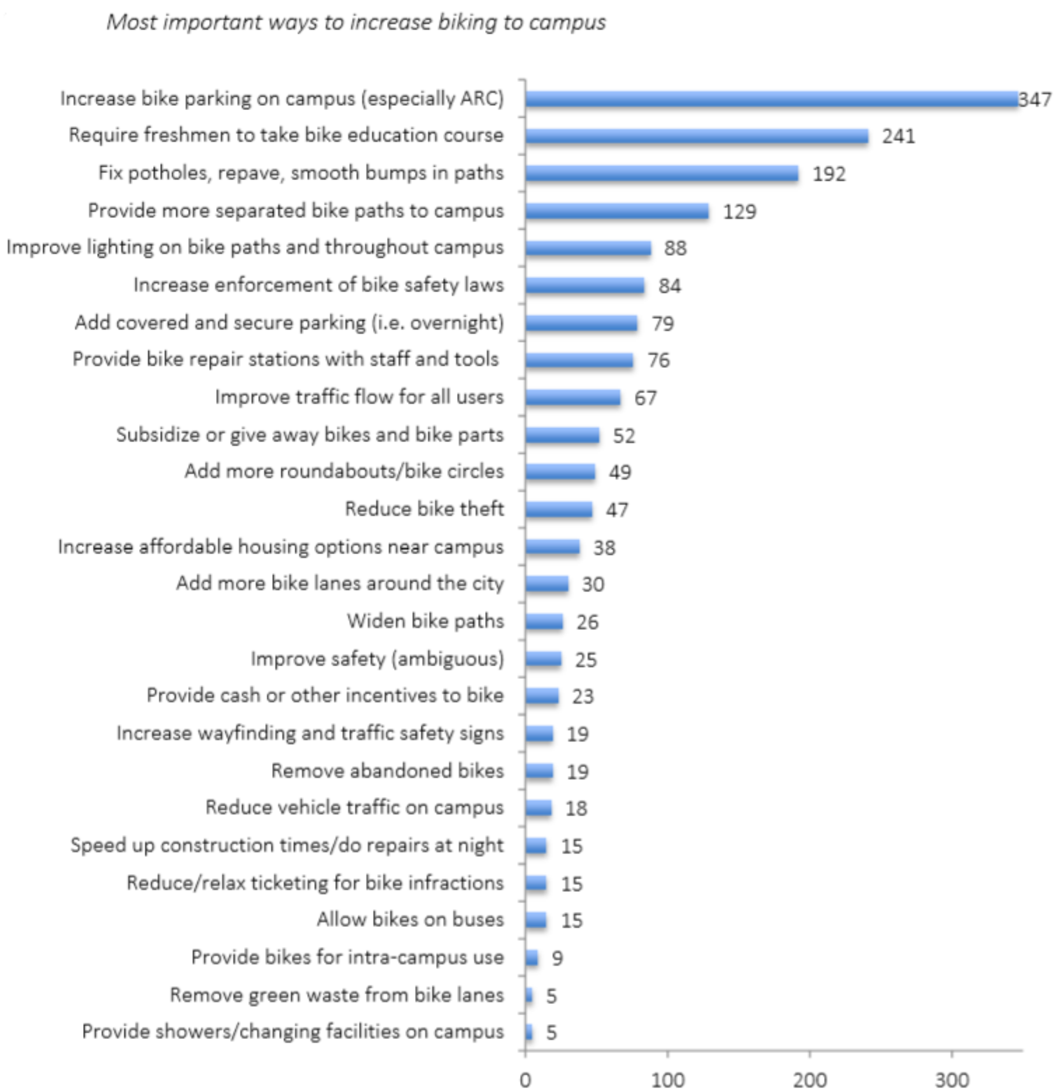


Figure 4: The reasons why people bike in Davis.[43]

if pathways are built, they will be used, but to encourage increased bicycle commuting, the bike lanes should be placed on existing streets.

It was also found that most people bike for leisure, (table [1]) not for commuting[Bik]. These trips were not considered as a reduction in CO_{2e} emissions. Biking for leisure does not replace driving to work, therefore while a worker might bike for recreation or exercise, it did not decrease or offset CO_{2e} released from commuting.

% of Active Bicyclists By Trip Purpose

Purpose	Harris Poll	NPTS[19]	Phoenix	Port land	Seattle	Pennsyl vania[20]	Madison
Work	7.0%	10%	11%	12.2%	14.3%	6%	N/A
School	N/A	14%	N/A	2.8%	N/A	6%	N/A
Utility[21]	N/A	20%	54%	26.1%	24.1%	18%	23%
Recreation	75.8%	55%	84%	95.6%	90.8%	70%	63%

Table 1: The percentage of people who bike for different reasons.[Bik] These surveys showed that commuting was by far the smallest use for bicycles while recreation was the greatest.

Not only was it important to look at how many people bike for what reasons, but it was also important to understand the energy use associated with biking and where the 'fuel' for cycling comes from. An article from The Guardian, *Whats the carbon footprint of...cycling a mile?*[30] found the carbon footprint of cycling 1.6 kilometers based on the carbon intensity of various foods. It was assumed that a person burned 31 kcal/km (130 kJ/km) (compared to our 23.6kcal/km = 99kJ/km). This energy use depends on many factors, so variations were to be expected. The energy needed to ride comes from food, which has its own carbon footprint. Berners-Lee[30] discussed the CO_{2e} emitted by biking 1.6km on energy obtained different foods. Among these were: 65g CO_{2e} when powered by bananas, 90g CO_{2e} when powered by cereal with milk, 200g CO_{2e} when powered by bacon, and 260g CO_{2e} when powered by cheeseburgers. According to Berners-Lee, "At the ridiculous high end of the scale, however, is getting your cycling calories by piling up your plate with asparagus that has been flown by air from the other side of the world. At [1.7kg per km] this is like driving a car that does six miles to the gallon (a shade over a mile per litre). You'd be better off in a Hummer."[30] Each of these numbers show that bicycling can be a significant indirect source of CO_{2e} emissions. The calculated use-phase emissions of a bicycle was 88.1 gCO_{2e}/km. This was in reasonable agreement with the numbers above, since it is unlikely that most cyclists are powered by such carbon-intense foods as air-freighted asparagus.

4 The Data

Data was collected from various sources to determine energy expenditure (and hence CO_{2e} emissions) from each transportation mode nationally compared to Davis and UC Davis. To calculate the energy expenditure from each mode of transportation, information was needed about the number of commuters using each vehicle type, the distance traveled by each vehicle, and the CO_{2e} intensity per distance for that vehicle.

The data for the community comparison portion of the project was composed of three main surveys. For the UC Davis community, the UC Davis TAPS 2013-2014 Campus Transportation Survey[43], for the city of Davis from the U.S. Census Bureaus American Community Survey[9], and for the U.S. as a whole from the National Highway Traffic Safety Administrations (NHTSA) 2009 National Household Travel Survey (NHTS)[4]. As a result of using separate surveys, a major challenge was to get the data into equivalent forms. For example, the NHTS and CTS used distance to measure commutes, whereas the ACS used time. This created problems for commutes that contain a combination of highway and city driving, as it introduced error related to assuming an average speed to convert time to distance. Another difference between the data sets was the resolution of the data, for example, whether distance was split in 1 or 5 km increments.

To estimate the energy intensity of each mode of transport, an LCA was performed piecewise. OpenLCA 1.4.1 was used along with the NEEDS[17], USDA[16], and NREL US LCI[8] databases to estimate the production CO_{2e} intensity for bikes and CVs. The difficult part of an LCA is finding data for the inputs, for the LCA performed below, the data came from many different sources. For the use-phase data, fewer sources were needed for estimating vehicle emissions. However, determining the energy intensity of biking required analyzing the US Food Production sector to determine the CO_{2e} intensity of a kcal (4.2 kJ) of food energy. This required a substantial amount of data, along with the use of OpenLCA.

4.1 National: NHTS

U.S. National average data was obtained from the Federal Highway Administration's 2009 NHTS trip length by mode table[4] to serve as a reference point to compare to Davis. Data was selected using the filters shown in table [5]. To make the data comparable to the ACS, the data was filtered for workers making trips to work or school such that the trips could be classified as a commute. It was relatively simple to create a table of the number of trips by transportation mode and trip length (table [6]) which was then converted into percentages as in table [2]. That data was directly used to calculate the amount of CO_2 emitted for each transportation mode. Overall it can be seen that 90% of commutes nationally were driven, 4.6% were walked, 4.5% were by public transit or other, while only 0.8% were biked. The average bike commute distance was calculated to be 7 km, and the average vehicle commute was 14.7 km.

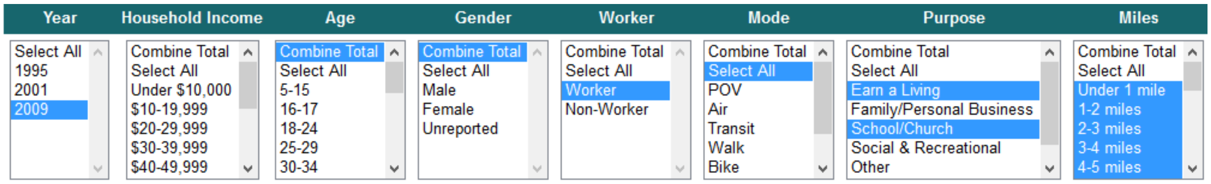


Figure 5: Screenshot from nhts.ornl.gov showing the filters used to find data[4].

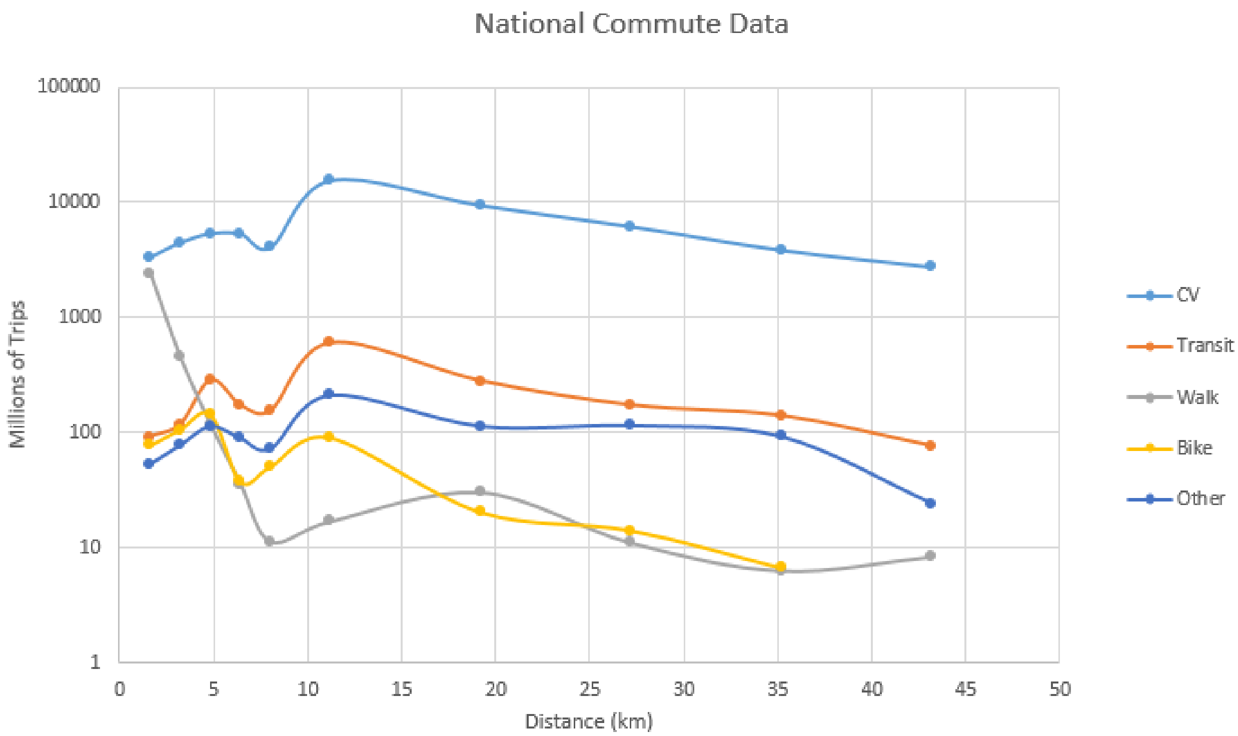


Figure 6: The national distribution of transportation mode, it shows that driving is by far the dominate mode of transport in the U.S, with only walking coming close for trips less than 1.6km. Note log scale

km	Range	0-1.6	1.6-3.2	3.2-4.8	4.8-6.4	6.4-8	8-15.5	16.1-22.5	24.1-30.6	32.2-38.6	40.2-46.7	
km	Length	1.6	3.2	4.8	6.4	8	11.2	19.2	27.2	35.2	43.2	Total Percent
Percent of Trips	Car	55.90%	85.66%	89.05%	94.13%	93.38%	94.43%	95.52%	95.18%	94.02%	96.21%	90.03%
Percent of Trips	Transit	1.54%	2.24%	4.73%	3.02%	3.54%	3.63%	2.82%	2.65%	3.40%	2.66%	3.11%
Percent of Trips	Walk	40.39%	8.60%	1.96%	0.63%	0.26%	0.10%	0.30%	0.17%	0.15%	0.29%	4.62%
Percent of Trips	Bike	1.29%	2.03%	2.38%	0.66%	1.16%	0.54%	0.20%	0.22%	0.16%	-	0.81%
Percent of Trips	Else	0.89%	1.48%	1.89%	1.57%	1.67%	1.29%	1.15%	1.78%	2.26%	0.84%	1.44%

Table 2: The percentage of commutes using different modes of transportation. Each column shows the percent of trips of that length that were done using the listed mode.

4.2 Local: ACS

The American Community Survey[9] was used to acquire transportation mode mix data for the city of Davis. As expected, Davis showed commute patterns different than those of the National and UC Davis communities. According to the ACS, there are 28,000 ± 1500 workers above 16 years old living in Davis. Of these, 68% drive to work as their normal means of commuting, which is lower than the national average by over 22%. Unlike the NHTS and CTS, the ACS used the category "Taxicab, motorcycle, bicycle, or other means rather than separating out bicycles. However, we felt that it was valid to assume that the vast majority of those in this category were biking, especially for Davis. The 22% of workers in Davis who used a bicycle as their primary means to get to work was 21 points above the national average. This increase was due almost entirely to the higher number of bikers, as can be seen in table [13].

Another issue encountered with the ACS was the unit of commute length. It used time (minutes) to measure commute distance, meaning a method to convert commute-minutes to commute-km was required. For biking, this was relatively easy, as it was assumed that nearly all bike commute trips happened within the city of Davis. This allowed us to say that the average speed of a biker would not vary significantly, and that the distribution of biker speeds would be closely grouped around the mean. To determine the average speed, Google Maps[24] trip time estimates were used for trips of various lengths within Davis. Table [3] below shows the distance and estimated commute time given by Google Maps, and the calculated speed. From this table [3], it was found that the average biker speed was 18.6 km/h. Then the average bike commute distance for commutes in Davis was found to be 4.9 km, which was less than the national average. In one study, Adams[28] found that the average speed of cyclists on the UC Davis campus was 16.1 km/hr, slightly lower than the speed speed found from Google Maps. This may have been due to increased congestion on campus, causing cyclists to slow down to avoid collisions with pedestrians and other bikers.

Distance (km)	Time (min)	Speed (km/h)
5.1	17	18.2
4.0	14	17.2
2.1	6	20.9
3.2	10	19.3
1.6	5	19.3
4.5	15	18.0
4.8	16	18.1
6.4	21	18.4
5.5	18	18.2

Table 3: Estimated speed based on time and distance for a cyclist in Davis[24]. The average was found to be 18.6 km/h.

Vehicle commutes presented a much larger problem however, since there are several neighboring cities to Davis within range of about half of the commute times. Commutes of 15-35 minutes made up 47% of all commutes[9], while according to Google Maps[24] it takes 15 minutes to drive across the whole of Davis. Meanwhile, Woodland, CA is an 18 minute drive, Sacramento, CA is a 21 minute drive, and Vacaville, CA is a 25 minute drive. (Note, these commute times were for almost no congestion on the highways.) This was a problem as it meant these commutes consisted of a combination of highway and city driving, implying a large variation in speed. Using an overall average speed would mean that commutes only within Davis would be estimated to be much faster than they were, while it would be found that highway speeds were much lower than expected. This would skew the trip distances by making inter-city trips appear shorter and intra-city commutes seem longer. The resulting distances would then not be directly comparable to those found in the NHTS.

To address this problem, it was assumed that all vehicle trips of less than 15 minutes were within Davis, then the same method was used to calculate average speed as was for bikes. The results are shown in table [4], and gave an average city driving speed in Davis of 34 km/h[24]. For longer vehicle commutes, a destination in central (downtown) Davis was assumed, then the travel time to the nearby cities of Woodland, Sacramento, and Vacaville was determined. The commute distance and times were from Google Maps[24] and are shown in table [5]. To get the overall commute speed, the highway travel distance between Davis and the other cities were found and the average speed was assumed to be the speed limit of 65 MPH (105 km/h). This was done as it was found that traffic between Davis and the surrounding cities was minimal for all times of the day[24]. According to the NHTS[47], the average commute speed for cars was 47 km/h, which shows that an average commute has a lower composition of highway driving or greater congestion than was found around Davis. Given the commute times to each city, the following expression was used to find the average speed

$$V_{avg} = t_{highway} * 105\frac{km}{h} + t_{city} * 34\frac{km}{h} \tag{1}$$

where V_{avg} is the average speed, $t_{highway}$ is the fraction of the time spent on highways, and t_{city} is the fraction of time spent on city streets. These speeds were then used to convert the commute times found in the ACS into distances traveled. As an example calculation, the Davis-Woodland highway distance is 12.6km = 7min, but the total Woodland commute is 19 mins. Then 36.8% of it is highway driving, and 63.2% is city driving, so we have

$$0.368 * 105\frac{km}{h} + 0.632 * 33.8 = 60\frac{km}{h}$$

for Woodland-Davis Commute.

Then the problem that occurred was that a 10 minute bike commute and a 10 minute driving commute do not have the same distance traveled. This meant that within Davis, the number of vehicle trips of one km could not be directly compared to the number of bike trips of one km. Instead the comparison was made between biking and driving trips of 5 minutes, resulting in a vehicle traveling 2.9km and a bike traveling 1.4km. The ACS data was left categorized by time, not distance since the percentages of trips of a given length were also given in terms of time groups. It was found that this did not affect the calculations of the total CO_{2e} emissions from each source for comparison with the NHTS data.

Distance (km)	Time (min)	Speed (km/h)
1.6	3	32.0
3.2	5	38.4
3.2	6	32.0
4.8	10	28.8
6.4	13	29.5
8.1	17	28.6
10.0	15	40.0
8.1	13	37.4

Table 4: The average speed of a car traveling a specific distance within Davis and the associated time[24]. The average city driving speed was found to be 34km/h.

City	Distance (km)	Commute Time (min)
Sacramento	25.80	30.00
Vacaville	30.60	24.00
Woodland	17.70	19.00

Table 5: The distances and commute times from Davis to surrounding cities.[24]

4.3 UC Davis: TAPS CTS

UC Davis constitutes about half of the population of the city of Davis, 35,400 to 66,000 respectively, and hence was important to take into account, as the UC community did not show the same commuting trends as the residents of the city itself[11;9]. The UC Davis Transportation and Parking Services (TAPS) Campus Transportation Survey (CTS)[43] provided the data below (Table [6]) that shows the percent of trips of each distance made by each mode of transport[43].

Overall, it can be seen that 48.2% of the UC Davis community bikes to campus, 23.7% drive, 19.3% take public transit, and only 4% walk (table [13]). This data was used to calculate the CO_{2e} emissions from the UC Davis community, and added to the data from the city of Davis to be compared with the national average.

Distance group		Usual mode of those physically traveling to campus								
(miles)	(km)	Physically Traveling	Bike	Walk or Skate	Drive alone	Carpool or Ride	Bus	Train	Weighted Sample	Projected Population
Up to 1	Up to 1.609	96.10%	78.00%	14.10%	1.30%	1.40%	5.20%	0.00%	631	7,734
1 - 2.9	1.609 - 4.667	91.80%	58.40%	2.30%	9.90%	2.00%	27.50%	0.00%	1657	20,397
3 - 4.9	4.828 - 7.886	90.80%	47.70%	1.10%	23.20%	6.70%	21.10%	0.30%	375	4,625
5 - 9.9	8.047 - 15.93	79.20%	8.00%	0.00%	78.00%	14.00%	0.00%	0.00%	50	620
10 - 19.9	16.09 - 32.03	84.20%	1.00%	0.80%	74.20%	13.80%	9.00%	1.30%	391	4,860
20 or more	32.19 or more	77.20%	0.60%	0.30%	71.70%	10.60%	4.20%	12.50%	311	3,880
Overall		90.00%	48.20%	4.00%	23.70%	4.70%	18.00%	1.30%	3415	42,115
Weighted Sample		3,074	1,483	121	730	145	553	41	3,415	
Projected Population		37,904	18,286	1,498	8,999	1,786	6,824	510		42,115

Table 6: The transportation mode based on distance away from the UC Davis campus[43].

5 Literature Review

In order to use the data above, a way was needed of quantifying the CO_{2e} emissions per distance traveled by a vehicle and a bike so that it could be determined if CO_{2e} emissions were reduced in Davis. Doing this required understanding of the emissions, from both bikes and motorized vehicles, from manufacturing as well as during use. This was achieved through Life Cycle Analysis (LCA), but before performing our own LCA of a bike and a car, a literature review was done to provide a point of reference and reasonable values of parameters, along with methods of estimating fuel useage. The literature results were found to be fairly consistent, with biking constantly being an order of magnitude less CO_{2e} intensive than driving. The majority of a car's CO_{2e} emissions were also generally found to result from fuel burning during the use phase.

5.1 Previous Bicycle LCAs

The European Cyclists Federation (ECF)[5], in conjunction with the European Union performed an in depth analysis and literature survey to determine the energy required to manufacture a bike. Manufacturing emissions came from Hendriksen & Gijlswijk[35]. They assumed the average bike had a mass of 19.9kg, was made of mostly aluminium (with some steel and rubber thrown in), that it had a lifetime of 8 years and would be ridden 2400km/year. The number they calculated was 5g CO_{2e}/km (96kg CO_{2e} total) as a result of energy intensity of manufacturing and maintenance of a bicycle. For fuel emissions, it was calculated[35] that at 16km/hr, a biker burns 4 kcal/(kg hr) (17 kJ/(kg hr)) compared to 1.5kcal/(kg hr) (6.3kJ/(kg hr)) for a driver. Based on the average CO_{2e} intensity of a kcal in the UK, they found that the extra food consumed by a biker was equivalent to 16g CO_{2e}/km. This made the overall energy use of a bike 21g CO_{2e}/km.

A Masters thesis project completed by Dave Shreya investigated complete life cycle assessment of different modes of transportation for commuters. Shreya[32] used the EIO-LCA database to calculate the production energy intensity of a bike (319kJ) and data from a bike shop to estimate energy intensity of repairs. Unlike Hendriksen & Gijlswijk, Shreya assumed food consumption to be constant and instead calculated the increased CO_{2e} released by the biker as a result of increased respiration of biking at 16 MPH (25.75km/hr). Shereya assumed a lifetime of 15 years for the bike, compared to the ECFs 8 years. In the end, Shreya found that biking cost 20.5 g CO_{2e}/km, agreeing with the ECFs number.

5.2 Conventional Vehicle LCAs

While one might think that the manufacturing of a car of any type, especially a hybrid or electric vehicle, would have a significant environmental cost compared to the emissions generated by driving over the lifetime, studies have found that it is actually quite minimal and so is often neglected. Anecdotally, a common question is: Are electric/hybrid vehicles actually better for the environment even though they need to manufacture a large battery that contains large quantities of chemicals? Most life cycle analysis come to the conclusion that only about 10-15% of a conventional vehicle's emissions are a result of the manufacturing and disposal phases of its life. The remaining 85-90% then is due solely to the fuel consumption of the vehicle during the use phase.[38;5;32]

Since the use phase contributes to a large portion of emissions intensity over the lifetime of the vehicle, it would be advantageous to increase the energy intensity of manufacturing, for example by adding a battery, to in turn decrease the emissions during the use phase. Samaras and Meisterling[46] found that the battery accounts for only 2-5% of the life cycle emissions of a PHEV (Plug-in Hybrid Electric Vehicle), depending on its AER (All Electric Range), proportional to battery size. Rydh and Sandn[45] found that it takes 1700 MJ of primary energy per kWh capacity of a Li-ion battery. This 50% increase in the manufacturing CO_{2e} emissions is still a small increase compared to the total use phase emissions and the resulting emissions savings from a reduction in fuel use.

Figure [7] shows the reduction in lifecycle CO_{2e}/km due to electrifying the drivetrain of a vehicle. It can be seen that there is an almost imperceptible change in the production energy use of HEVs (Hybrid Electric Vehicle) and PHEVs compared to CVs (Conventual Vehicle) due to the battery and a significant reduction in the use phase emissions. Of course, for a PHEV, the reduction in CO_{2e} emissions is related to the the electricity generation method, which is represented by the large error bars in the plot below. It can be seen however, that even the worst case scenario for a PHEV is still better than a CV.

The plot [7] shows that all forms of personal four-wheeled motorized transportation use significantly more energy and are more GHG intensive overall and per distance traveled than biking. Even with the best case, a PHEV 90 (a plug in hybrid with an AER of 90 miles (145km)) being charged primarily from renewably generated electricity, the emissions per km are still much more than that of a bike.

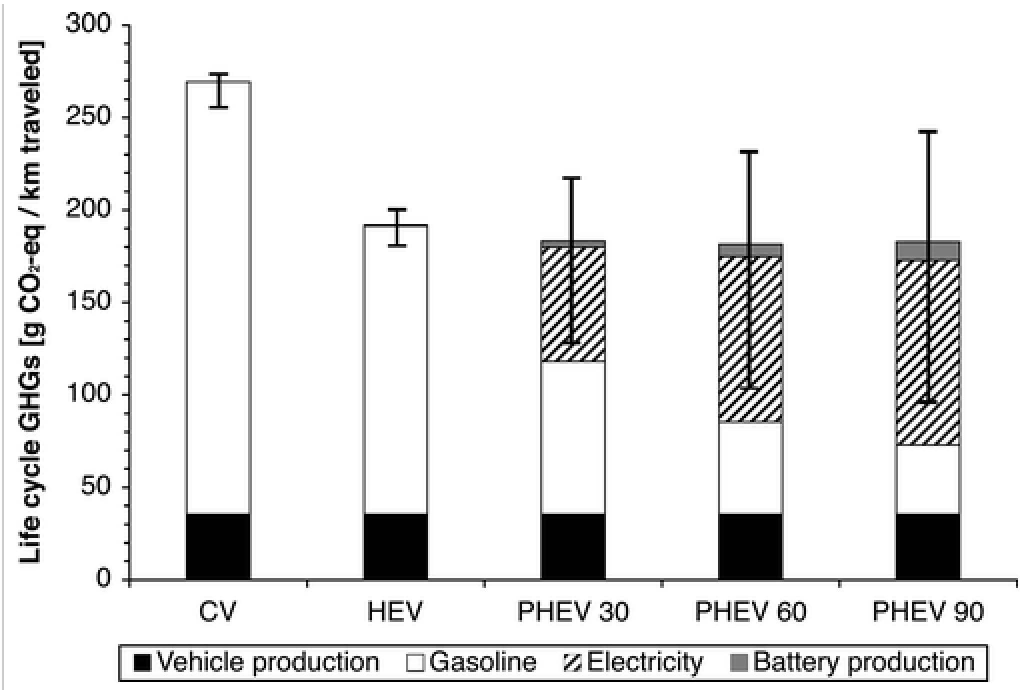


Figure 7: Lifecycle GHG for different vehicle types on per distance basis. Figure from Samaras and Meisterling[46].

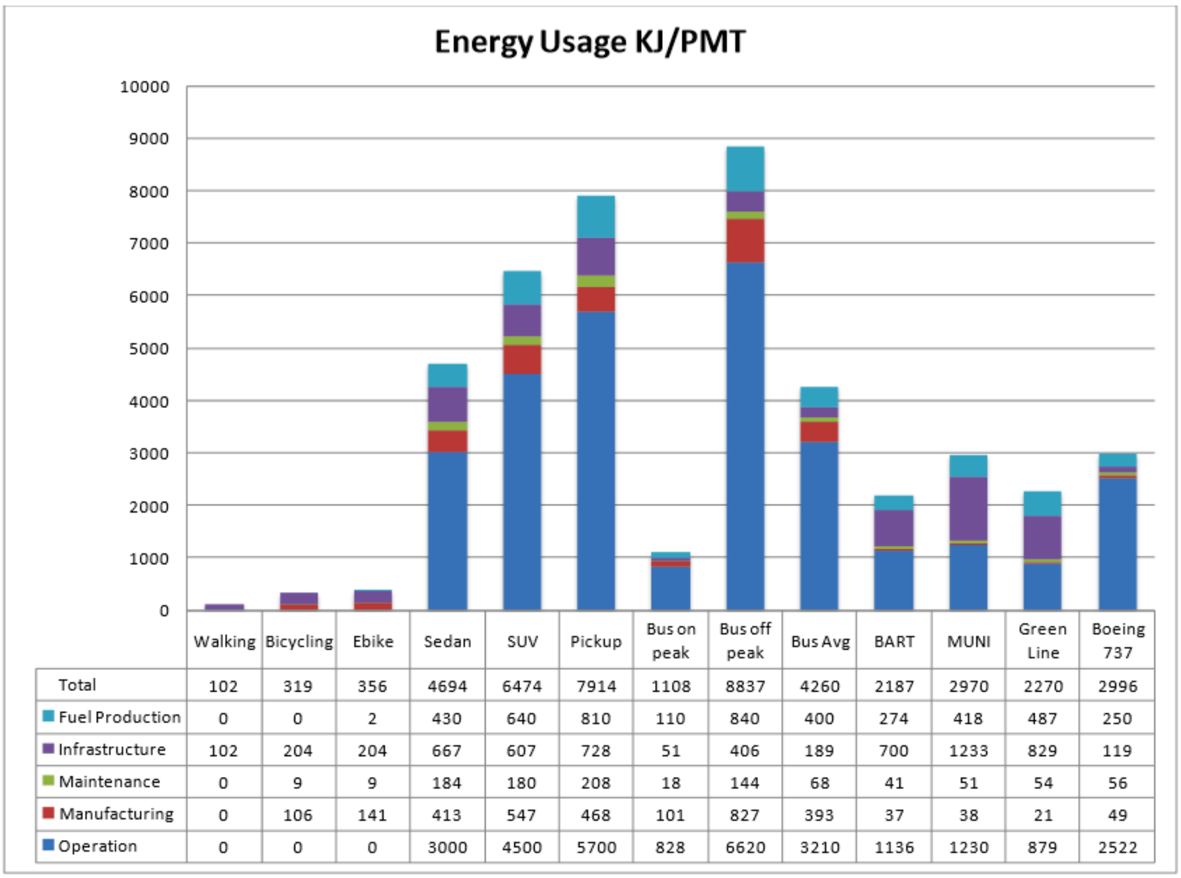
The ECF[5] used numbers from the Environment and Energy Management Agency of France (Agence de l'Environnement et de la Maitrise de l'nergie) for personal vehicle energy intensity. The assessment took raw materials and manufacturing energy into account, but not maintenance. Based on this, they found that production resulted in 5.5 tons of CO_{2e}/ton of car, or 42g CO_{2e}/km for an average sized car of 1.19 tons. The direct energy usage from fuel and the energy intensity of production of the fuel was taken into account[5]. However, the ECF also accounted for significant variations in fuel efficiency based on the road type on which vehicles are driven, as can be seen in Table [7]. For example, a highway commute of 15 km uses significantly less fuel than an urban commute of the same distance.

To get an average fuel use per distance, the ECF used a driving mix of 70% urban, 25% on "roads" and 5% on highways. The result was 229g CO_{2e}/km for fuel usage. This is similar to the value found by Samaras and Meisterline, as can be seen from figure [7] above. This corresponds to about 18% of total emissions due to production of the vehicle. The overall CO_{2e} intensity of an average vehicle was then found to be 271g CO_{2e}/km, or 13 times that of a bike. This is also agrees with Shreya (2010), who found that a sedan is 14.7 times more CO_{2e} intense than cycling. The energy usage for different types of transportation can be seen in Figure [8][32].

Car	Energy Use	Emission Factors			
		CO2	NOX	PM10	SO2
	MJ/Km	g/Km	g/Km	g/Km	g/Km
Gasoline					
Total	2.69	194	0.35	0.008	0.006
Urban	3.59	259	0.48	0.012	0.008
Extra urban	2.25	162	0.27	0.005	0.005
Motorway	2.58	186	0.38	0.008	0.006
Diesel					
Total	2.42	180	0.57	0.061	0.003
Urban	3.11	231	0.85	0.097	0.004
Extra urban	2.09	155	0.46	0.043	0.002
Motorway	2.41	179	0.54	0.060	0.003
LPG					
Total	2.48	165	0.47	0.008	0.000
Urban	3.48	232	0.62	0.010	0.000
Extra urban	2.20	146	0.46	0.006	0.000
Motorway	2.38	159	0.45	0.008	0.000
Total					
Total	2.60	188	0.43	0.023	0.005
Urban	3.49	252	0.56	0.030	0.007
Extra urban	2.21	160	0.33	0.014	0.004
Motorway	2.50	182	0.44	0.028	0.004

Source : STREAM[31]

Table 7: Shows the energy use per kilometer, including production of raw material and manufacturing energy consumption, but not maintenance, and CO_{2e} intensity of driving on various road types. Figure from the ECF[5].



	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

Figure 8: Shows the total energy use in kJ per mile, and what fraction of that energy use is associated with different parts of the vehicle's lifecycle. Figure from Shreya 2010[32].

6 Methods, Procedures and Analysis

The analysis of the transportation data from the various surveys[4;43;9] provided information on transit patterns for the US as a whole, for the city of Davis (excluding students), and for the UC Davis community. These data were used to find the distribution of transportation modes by distance. To convert the transportation mode distribution and distance data into CO_{2e} emissions, an LCA was performed to estimate the CO_{2e} produced by manufacturing a bike and a car. A 'separate' LCA was also done for the use phase of a bike and car that took into account the emissions from burning fuel and the emissions resulting from the extra food intake of a biker in addition to their increased breathing rate. This information was used to calculate the total energy intensity of commuting for each transportation mode distribution.

6.1 Transportation Mode Distribution Analysis

The survey data was analyzed in Excel to determine the percent of trips that were a certain length and the percentage of each transportation mode at that length. The resulting distributions and percentages are shown in tables [11, 12, 10]. The data was then combined with the results of the LCA to calculate the CO_{2e} produced by each transportation mode traveling each distance. Davis and UC Davis were analyzed separately not only because they were from two separate surveys, but also to determine if Davis' reputation as a bicycle friendly city was earned, or simply a result of such a large number of bicycling students. To compare the City of Davis to an "average" American city, we used the national (NHTS) averages and applied the same population to both the Davis and national distributions.

6.2 Transportation Mode Energy Intensity and LCA

The production and use CO_{2e} emissions for each transportation mode were calculated separately. When calculating the overall CO_{2e} released by each transportation mode, two estimates were made, one including production-related CO_{2e} and the other only including use-phase CO_{2e}. This was done since it was found that 93% of bike commuters also own cars, but do not use them as their primary means of work-related travel[9]. Thus even if a person used a bike to commute, the car sitting in their driveway would still contribute production CO_{2e} emissions. However, only 51% of Americans own a bike[39]. It follows that many commuters contributed to both bicycle and vehicle production CO_{2e}. The results of the comparison, therefore, should not change based on the CO_{2e} emitted from production since this number should be constant for the vast majority of the population.

Another reason for adopting this approach was that if CO_{2e} production was included in per-kilometer GHG intensity, those who drive less would not properly account for manufacturing-related CO_{2e}. That method may be applicable to full life-time LCAs, but this analysis was attempting to analyze the carbon intensity of a commute, not the lifetime of a vehicle. Thus if a vehicle was purchased and used only for one commute the total contribution should be

ALL of the production CO_{2e} + the small amount of use-phase CO_{2e}, not a small percentage of the manufacturing CO_{2e} based on an assumed lifetime of the vehicle. Since we wish to determine the change in CO_{2e} emissions, accounting for the production emissions would have the same effect on both sides of the comparison, and so would not change our result. The formula used to calculate CO_{2e} emissions based only on 'fuel' usage was:

$$\Sigma_{d=0}^{d_{max}} P * \frac{T(d)}{T} * t_{mode} * d * fuel \frac{gCO2_e}{km} \tag{2}$$

where P is the population, $T(d)$ is the number of trips of distance d, T is the total number of trips, t_{mode} is the fraction of trips of length d traveled by the vehicle type, and *fuel* is the CO_{2e} emissions per kilometer of the vehicle.

In the interest of providing numbers comparable to other LCAs, whole-lifetime CO_{2e} emissions were also calculated. The formula [3] used for calculating the cumulative lifetime CO_{2e} emissions if production emissions were included as a lump sum was

$$P\left[P(m) * M_{CO2} + P(mc) * fuel \frac{gCO2_e}{km} * d_{day} \frac{km}{day} \frac{5}{7} \frac{days}{week} * 365.25 \frac{days}{year} \frac{L}{life}\right] \tag{3}$$

where $P(m)$ is the fraction of the population that owns that vehicle type, $P(mc)$ is the fraction of the population that uses that vehicle type to commute to work, M_{CO2} is the manufacturing related CO_{2e} emissions in kg, d_{day} is the round trip daily commute in km, and L is the lifetime of the vehicle in years. This calculated the amount of CO_{2e} that would have been emitted regardless of the owners actual choice of transportation method to work plus the emissions due to travel. (The expression for including production CO_{2e} emissions per kilometer is given in eq. [4].)

The expression for bicycles was similar, simply replacing the commute percentages and carbon intensity. Nationally, 51% of Americans own at least one bike[39], but only 0.8% use their bikes to commute to work. A lifetime of 15 years was assumed for a bicycle.

The values found give insight into the importance of biking and the actual emissions released from driving or biking. The most common way, though, of looking at life cycle CO_{2e} emissions due to transportation is to divide out the production related CO_{2e} over the total distance the vehicle was assumed to travel. This was done by finding the total manufacturing related CO_{2e} caused by all commuters for each mode. For example, if 50% of commuters bike, then the bike manufacturing emissions were

$$50\% * P * M_{CO2}$$

Next, the total distance driven by that population in a day was found using the (national) transportation mode distribution. This was then multiplied by the estimated lifetime of the vehicle in days to find the total distance an average vehicle would travel. This was used to divide the total production CO_{2e} emissions to determine the average gCO_{2e}/km. The average vehicle commute length, nationally, was found to be 29.4 km/day[4] (round trip), and the lifetime of a car in the US was 20 years[7]. The result was that, nationally, an average vehicle had a lifetime "mileage" of 155,000 kilometers. This result was derived from NHTS[4] data, and applied to all communities to ensure that the CO_{2e} per kilometer traveled was the same for each. NHTS data was used because the average vehicle age was known nationally. The age of a vehicle in Davis and UC Davis then, was given in terms to kilometers traveled, not in terms of years to allow for an equal comparison with the national data. The expression was as follows:

$$\frac{M_{CO2}}{km} = \frac{P(m) * M_{CO2}}{\Sigma_{d=0}^{d_{max}} d * \frac{T(d)}{T} * L * 365.25} \tag{4}$$

This method assumed that only those vehicles used for commutes contributed to production CO_{2e}, which is one reason it was not used as the primary method to assess the change in commute carbon intensity.

To apply the above expressions and calculate the total CO_{2e} emissions for vehicles and bikes, information about the production and use-phase emissions of each transportation mode was needed. This was found by performing an LCA. The LCA was performed using OpenLCA (version 1.4.1), the NREL US Life Cycle Inventory Database[8], the NEEDS database[17], and the USDA LCA Commons Database[16]. Our LCA, in agreement with the literature and expectations, found that the manufacturing of cars produces an order of magnitude more GHG emissions than bicycle production.

6.2.1 LCA Inputs and Assumptions

Many of the LCA input parameters were based on extrapolations from a representative product. As much real data was used as possible, but some best guess approximations were still required. Additionally, the end of life or disposal emissions for both bicycles and vehicles was neglected. This should not affect the results as a comparison, as the disposal for bicycles and cars should approximately reflect the same energy intensity disparity as the production and use phase. Maintenance was also neglected due to a lack of data and that other studies[32;5;46] have found that it is insignificant compared to the fuel use.

6.2.2 Conventional Vehicle Production

The manufacturing related emissions of a "typical" commuter automobile based on average components, literature, and best guesses was modeled. Table [8] shows the materials and the quantities that were used as inputs for the LCA for making a car with the accompanying supply chain tree shown in figure [9].

Material	Quantity	Unit
Automotive Paint	23	m^2
Sheet Steel	1,827	kg
Scrap Steel	-412*	kg
Process Water	4,000	kg
Electricity	2,442	kWh
Electronics	5	kg
Glass	86	kg
Polybutadiene	48	kg
PET Plastic	15	kg
PVC Plastic	25	kg
Titanium	100	kg
Train Transport	4,467,200	kg*km
Truck Transport	60,000	kg*km

Table 8: The material and energy inputs used for the LCA for car manufacturing. *Note that negative value represents flow out.

The "Automotive Paint" category was actually composed of three processes, "Automotive painting, pretreatment," "Automotive painting", electrocoating, per vehicle," and Automotive painting, top coat, per vehicle." These processes were from the NREL US Life Cycle Inventory Database[8]. The total vehicle weight (the sum of all the materials in the chart above that make up the vehicle itself) was 1474kg. This number was based on the value found in Ungureanu[48] of a typical total vehicle mass of 1418kg and the referenced value in [[5]] of 1190kgm. These were checked by comparing the mass of the 2015 Toyota Corolla[12] (1280kg) with the 2015 Ford Explorer[14] (2070kg), giving an average of 1675 kg. Of the cars total mass, 1200kg of it was assumed to be steel, there were 1827kg of input[8] steel because 34% of the original steel becomes scrap during manufacturing[48].

The mass of the tires was assumed to be all polybutadiene[8], an artificial rubber. Each tire was based on the 12kg mass of the Goodyear Wrangler Radial tire 235/75R15 105S[23]. The mass of plastics in a vehicle was determined based on the estimated weight of the dashboard, seats, roof rails, bumpers, and other interior components. This estimation was justified by noting that if there were 100kg of plastics[17;8], it would only account for 160 kg of manufacturing CO_{2e}, so it makes a small contribution compared to the steel. Titanium was included as a stand-in for various other metals involved in the production of a vehicle.

The transportation was estimated by assuming all cars were made in Detroit with US steel from the South-East, requiring an average train transport distance of 600km*1827 kg (steel). The final vehicle was also assumed to be transported by train, an average distance of halfway across the US (2500km)[24], resulting in additional rail travel[8] of $1474kg * 2500km$. Also included in transport was 600kg*100km of truck hauling[8] for smaller parts and inter-factory transport for components such as engines. Note that producing the car in Europe and transporting it across the Atlantic only adds 140kg (about 2%) CO_{2e} to the manufacturing carbon intensity.

The amount of glass[17] in the vehicle was estimated using the mass of a replacement windshield for a Jeep Wrangler of 13.6kg[25]. This was then used to extrapolate the total mass of glass on an average vehicle. While this estimate may be a little high, especially for a smaller vehicle, the LCA databases used did not contain a process for the laminated glass found in automobile windshields and only calculated carbon intensity based on soda-lime container glass. Since the production of laminated vehicle glass is more complicated than the forming of pure glass, slightly overestimating the quantity of glass may provide a more accurate measure of the production CO_{2e} for vehicle glass.

In 2013, Ford used 15 GWh of electricity[18] and sold 6,330,000 vehicles[10], implying they used 2,370 kWh per vehicle. Ford self-reported using 2,442kWh per vehicle, presumably because they had access to more precise numbers. According to Fords Sustainability Report[18], they have been reducing the amount of energy required to produce a vehicle, meaning the number used here was one of the lower possible values. Similarly, Ford also reported having used $24.9Mm^3$ of water in 2013[18], and used $4m^3$ (4000 kg) of water[17] per vehicle manufactured.

Based on our assumptions and calculations from OpenLCA (1.4.1), the production of an average vehicle was found as 7162 kg CO_{2e}. This result agrees well with the ECF[5] who found that there is 8.107 tons of CO_{2e} released during the production phase of a car of equivalent mass.

6.2.3 Conventional Vehicle Use

The use phase of a conventional vehicle contributes a significant portion of the car's total CO_{2e} footprint. Calculating the emissions released by a vehicle is dependant on its fuel efficiency, which in turn depends on the type of road and the conditions the vehicle is driving in. Different vehicles also have widely varying fuel economies, which makes coming up with an exact amount of CO_{2e} released per km impossible to do other than on a vehicle by vehicle basis. The Bureau of Transportation Statistics[21] divides fuel economy into two classes, short wheelbase ($\leq$ 307cm) vehicles and long wheelbase (>307cm). In 2012, short

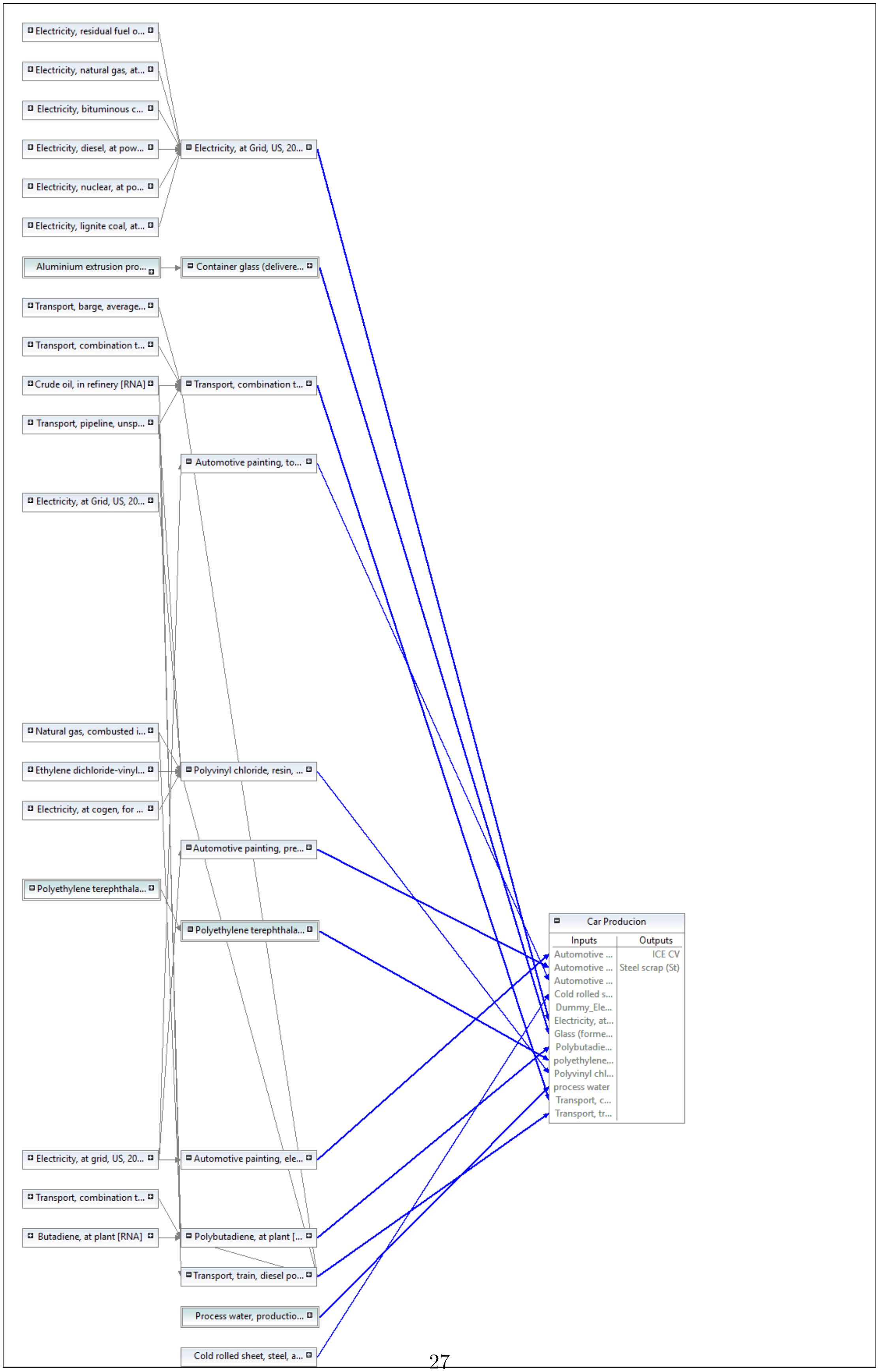


Table 9: Tree diagram of the supply chain for the car production process in OpenLCA. It shows the interlocking linkages between the different processes and flows that go into making a car.

wheelbase vehicles had an average fuel economy of 23.3MPG (9.9 km/L) and long wheelbase vehicles had an average fuel economy of 17.1 MPG (7.27 km/L)[21].

In 2012, there were 183,000,000 short wheelbase vehicles registered and they traveled 3,320,651 million km[19]. There were also 50,589,000 long wheelbase vehicles registered in 2012 that traveled a total of 967,357 million km[20]. Of the total 233.6 million light-duty vehicles registered in 2012, 78.3% of them were short wheelbase vehicles and 21.7% were long wheelbase. The average fuel economy for light duty vehicles in 2012 was then given by

$$21.7\%\frac{7.27km}{L} + 78.3\%\frac{9.9km}{L} = \frac{9.3km}{L}$$

The next step was to calculate the CO_{2e} released by a vehicle traveling one km by determining the mass of gasoline burnt. According to the EIA[15], burning one gallon of gasoline produces 19.64 lbs of CO_{2e}, or 1L of gasoline creates 2352.4g CO_{2e}. Taking $\frac{2352gCO_{2e}}{L}\frac{1L}{9.3km}$, an average vehicle emits 253 g CO_{2e} per km traveled. This is an overall average, taking into account the fuel efficiencies of driving on highways and in cities, since the fuel economy was calculated by dividing the total distance traveled by these vehicles by the quantity of fuel they used. The value found above compares well with the estimate by the ECF[5], who found 229gCO_{2e}/km and with Samaras and Meisterling[46] who found 270 gCO_{2e}/km.

In addition to the direct fuel burning related CO_{2e} emissions, there is a carbon intensity associated with the production of gasoline. Using OpenLCA 1.4.1 and the predefined regular gasoline input/output analysis from the NEEDS database, it was found that production of one kg of gasoline results 0.689 kg of CO_{2e} emissions[17]. From these numbers, the direct fuel burning related to CO_{2e} emissions are:

$$\frac{0.689kg\ CO_{2e}}{kg\ gas}\frac{0.735kg\ gas}{L}\frac{1000g}{kg}\frac{1L}{9.9km} = \frac{51.15g\ CO_{2e}}{km}$$

Which represents the carbon intensity as a result of gasoline lifecycle emissions. This brought the total per kilometer emissions of driving to 304 gCO_{2e}/km.

6.2.4 Bicycle Production

Similar to the conventional vehicle, modeling of the manufacturing of a typical bicycle was based on average components, literature values, and best approximations. Table [10] shows the inputs, components, and energy influencing the LCA.

According to an LCA sponsored by the bicycle manufacturer Specialized Bikes[36], one of their high-end aluminum framed bikes has a GWP of 315 kgCO_{2e}, most of which was due to the artificial aging of the aluminum frame. From communications with bicycle parts suppliers, it was found that the electrical energy used for forming, cutting, and treating the aluminum tubes was about 6.5kWh/bike while the water use was 1.5kg of water for hydroforming.

For welding, many large bike manufacturers use TIG (Gas Tungsten Arc) welding according to Jeffrey Bock, a custom bike manufacturer[31]. However, another common method is brazing, which uses natural gas rather than electricity and is more akin to soldering than welding. To save cost, some manufacturers use a combination of both[31]. A TIG welder uses about 8.3kW[26]. An average bike has about 19 joints that require welding[31], and if we assume it takes 15 seconds to weld each joint, then the energy required to weld a bike frame together is $19 * 8.3kW * 10sec/60^2 sec/hr = 0.66kWh$. This brings the electricity usage of bike manufacturing to 6.7kWh per bike.

Material	Quantity	Unit
Aluminum	13.5	kh
Automotive Painting	1	m^2
Sheet Steel	13.5	kg
Electricity	6.7	kWh
Natural Gas	10	m^3
Polybutadiene	2	kg
Truck Transport	53,500	kg*km
Freighter Transport	156,000	kg*km
Process Water	1.5	kg
Steel Scrap	-0.5*	kg

Table 10: The material and energy inputs used for the LCA for bicycle manufacturing. *Note that negative value represents flow out.

It was assumed that the total mass of a bike is 15kg, which was smaller than the ECFs 19.9kg, and larger than high-end road bikes that might weigh as little as 8kg[31]. Of that weight, it was assumed most of it (13kg) would be the primary frame material, be it steel or aluminium. The remaining 2 kg consisted of the tires, seat, and handlebar grips which were assumed to be made of mostly synthetic rubber (polybutadiene). The same automotive painting process was used for bike painting, but reducing the amount to a square meter.

Many frames are not made in the United States, but are manufactured in places like Taiwan, China, Cambodia or Vietnam[29]. It was assumed that bikes were manufactured in China[29] and shipped to Los Angeles (10,400 km) where they were then trucked to their destination in the U.S., traveling an average of 2500km in the U.S. An extra 800km was added to account for parts being shipped to the assembly factory[36]. The scrap for manufacturing a bicycle is considerably less than that for an automobile[31;36]. The frame produces "significantly less than [0.5 kg][31] of scrap" (Units converted from pounds) while the chain produces the most, but it is recycled[36]. From this data, 0.5 kg was estimated for overall scrap.

With the inputs listed in table [10], it was found using OpenLCA that an aluminum framed bike resulted in 137kg CO_{2e} while a steel framed bike released 84.5 kg CO_{2e}. The difference in CO_{2e} was due only to the disparity in manufacturing energy intensity of the input steel and aluminum[48]. For the purposes of further analysis, the average, 111kgCO_{2e}, was taken for manufacturing a bicycle.

6.2.5 Bicycle Use

The energy source for a bicycle is expenditure of human metabolic energy (CO_{2e} released from breathing and food production). To calculate this it was necessary to know the amount of food energy (1 kcal/4.2kJ) a person uses while biking. According to Adams[28], the energy expended by a biker is dependant mainly on their speed and weight, while the wind direction also plays a large roll. The average American has a mass of 82kg[6], and the average cycling speed found by Adams[28] was 16km/h, which was close to the 18.6 km/h found from Google Maps[24]. Figure [9] shows the kcal expenditure of subjects biking at 16km/h vs their body weight. From the plot, we see that a person weighing 82kg would expend 6.1 kcal/min (25.5kJ/min) at 16km/h which is equivalent to 22.9kcal/km (95.8kJ/km).

From WolframAlpha[27] it was found that a biker weighing 82kg cycling at 16km/h would burn 6.7 kcal/min (28kJ/min), or 25.1kcal/km (105kJ/km), only an 8.8% difference from the Adams[28] value. These models appear to be well correlated, and therefore the data from WolframAlpha was used for further predictions. The WolframAlpha calculator allowed more flexibility in speeds, as well as calculating the O_2 consumed by the biker. The caloric expenditure of a biker traveling at 18.6 km/h was found to be 8.0kcal/min (33.5kJ/min) or 30kcal/km (125.5 kJ/km) using the WolframAlpha[27] calculator.

This value however, needed to be compared to the energy that would have been used even had they been stationary (as in a car). According to Frankenfield et al.[34] the best of the equations commonly used to estimate the resting metabolic rate (RMR) is the Mifflin-St Jeor Equation. The equation is given by

$$RMR(kcal) = 9.99 * weight + 6.25 * height - 4.92 * age + 5 \tag{5}$$

for men and

$$RMR(kcal) = 9.99 * weight + 6.25 * height - 4.92 * age - 161 \tag{6}$$

for women[34]. The average height and weight for men in the US is 176cm and 88.7kg respectively, while for women the numbers are 162cm and 75.4kg.[6] The average age of a resident of

Davis is 25.2 years, compared to the California average (which was assumed to be effectively the same as nationally) of 35.0 years[22]. This gave an RMR of 1819kcal/day (7611 kJ/day) for men and 1653kcal/day (6916kJ/day) for women (using an age of 35 years.) Assuming a 50/50 split between men and women (its actually 51/49)[22], the average RMR for an American is 1736kcal/day (7263 kJ/day) or 0.69kcal/min (2.89kJ/min). If we subtract this from the metabolic energy expenditure from biking, we get

$$\frac{8kcal}{min} - \frac{0.69kcal}{min} = \frac{7.3kcal}{min} = \frac{23.6kcal}{km} = \frac{98.7kJ}{km} \;\; at \;\; 18.6km/h$$

which is the equivalent of $\frac{0.085\ Snickers\ Bars}{km}$.[27]

For 16km/h, the biker was calculated to use 1.3L/min (4.9L/km) of oxygen whereas a person at rest (or driving a car) would burn $\frac{225\ mL\ O_2}{kg\ hr}$.[27] The 82kg person considered would use $\frac{0.31\ L\ O_2}{min}$ while at rest, as when driving. The *additional* O_2 consumed by a biker then is $\frac{1.0\ L}{min} = \frac{3.8\ L}{km}$ at 16km/h. Then, it was found that biking at 18.6km/h (2.6km/h faster) resulted in

$$\frac{1.61L - 0.31L}{min} = \frac{1.3L}{min} = \frac{4.2L}{km}$$

Calculating the CO_{2e} as a result of breathing was completed using the molar mass ratios. 4.2L of oxygen has a mass of 6.0g[27] and the molar mass of oxygen is 32g/mol. The molar mass of carbon is 12g/mol, so CO_{2e} has a molar mass of 42g/mol. There are 0.188 mols of CO_{2e}, and from these values it was found a biker releases 7.9g CO_{2e}/km when traveling at 18.6 km/h.

One key piece of information that influences the CO_{2e} emissions of a biker is the carbon intensity of the food used as 'fuel'. The energy intensity of biking, from above, must now be converted into carbon intensity. This was a much more complex conversion than for calculating fuel-related emissions from a vehicle since food types vary significantly and have large differences in their carbon footprints, which are difficult to calculate. A combination of LCA and EIOA methods from literature were used to estimate the value, as this alone is the subject of many studies[42;37;2;33;49].

The EPA estimated the energy use of the Food Manufacturing sector of the US economy to be 1116 TBtu or 1.177E18 J in 2002[2]. They also provided a table [11] that broke down the energy use by fuel. Using the table with Open LCA (1.4.1), the NEEDS[17], and USLCI[8] databases, a process was created with a dummy output that took the specified quantities of each fuel in table [11] as inputs. This provided not only the CO_{2e} resulting from combusting the fuels, but also CO_{2e} from the life cycle of the fuel itself. The energy used to produce food in 2002 was 1.177E18 J, which resulted in the emission of 9.31E11 kg CO_{2e}. Dividing this by the US population in 2002 of 288 million[27], gave 3.23 metric tons CO_{2e} per person

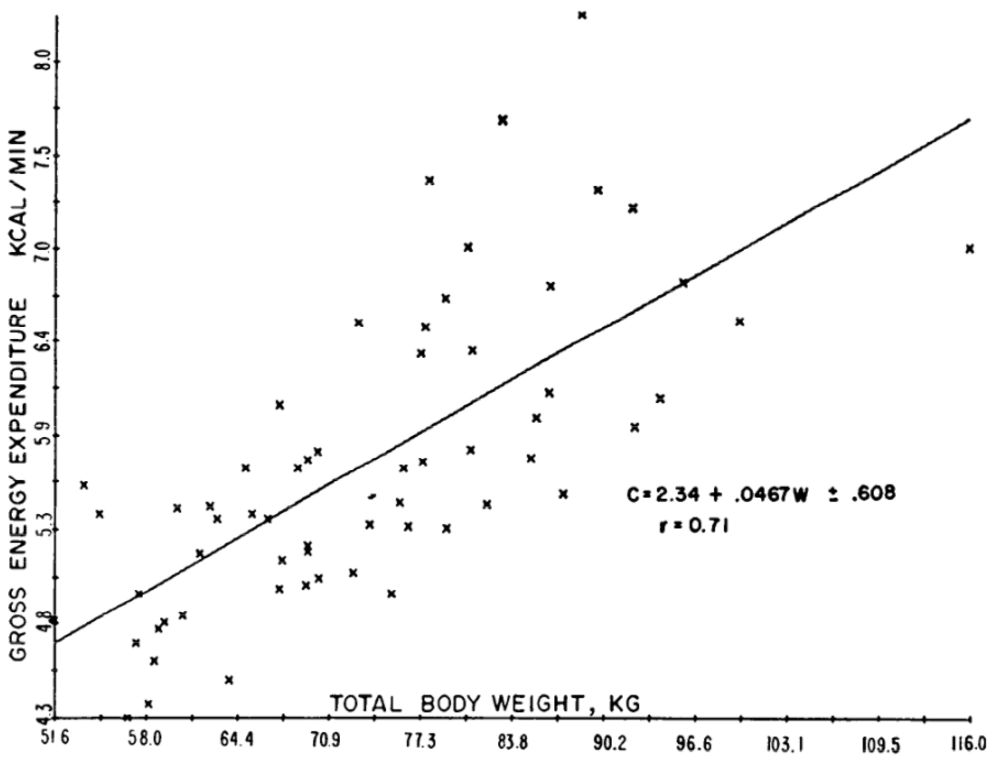


Figure 9: The energy expended from biking based on body weight[28].

per year. Eshel and Martin[33] estimated that the US produced 3774 kkcal (15,790 kJ) per person per day in 2002, meaning the energy intensity of a kcal was 3kJ/kcal ($\frac{0.7kJ\ input}{kJ\ food}$) and the carbon intensity was 2.35 gCO_{2e}/kcal (0.56 gCO_{2e}/kJ). Another analysis done by the EPA and evaluated by Kim and Neff[37] found that, excluding embodied energy, US food production resulted in 1.56t CO_{2e}/person per year.

	Total (kJ)*	Net Electricity (kJ)**	Residual Fuel Oil (kJ)	Distillate Fuel Oil (kJ)	Natural Gas (kJ)	LPG & NGL (kJ)***	Coal (kJ)	Coke & Breeze (kJ)	Other (kJ)
Food Manufacturing	1.18E+15	2.43E+14	1.37E+13	2.00E+13	6.07E+14	5.28E+12	1.94E+14	1.06E+12	9.50E+13
Iron and Steel	1.54E+15	1.94E+14	1.06E+12	1.06E+13	4.09E+14	-	3.80E+13	5.55E+14	3.28E+14
Transportation Equipment	4.47E+14	1.81E+14	6.33E+12	3.17E+12	2.14E+14	4.22E+12	8.44E+12	0.00E+00	2.95E+13

Table 11: The energy consumption of the food manufacturing industry and others by fuel type in 2002. Figure made with data from US EPA[2].

A thorough literature review was done by Kim and Neff[37] who looked at various calculators of dietary carbon footprints and compared them to literature values. The two base cases were the EPA study that excluded embodied energy (1.56 t/person per year) and a study done by Weber and Matthews[49]. In that study, they used EIOLCA to conclude that the carbon intensity of an Americans diet was 3.1 metric tons $\frac{CO_{2e}}{person*year}$ or 15% of US per capita CO_{2e} emissions[49;37]. Table [12] shows a comparison of the various calculators compared by Kim and Neff. They note that Carbonify.com had used a vegan diet as a baseline zero, and after contacting the author recived an average estimate of 3.3 metric tons/person/year. Kim and Neff[37] also noted that the Carbon Footprint calculator was seriously underestimating the CO_{2e}, giving the example that it considered a high-meat diet to be effectively the same as only the agricultural part of the diet in the EPAs analysis. Given this, if we take the average of the US Average category, excluding Carbon Footprints estimate, and using the corrected Carbonify result, we find that the carbon intensity of an American diet is 3.2 ton CO_{2e}/ person /year, agreeing well with the previous calculated result of 3.23 ton CO_{2e}/person/year.

According to the USDA, the average American consumes 2568 kcal (10,745 kJ) per day after adjusting for food spoilage and waste[13]. If the carbon intensity of the American diet was$\frac{3.2tCO_{2e}}{person*year}$, then:

$$2568kcal * 365.25 = \frac{937,962kcal}{year} = \frac{\frac{3{,}2{,}00{,}000gCO_{2e}}{year*person}}{\frac{937{,}962kcal}{person*year}} = \frac{3.4gCO_{2e}}{kcal} = \frac{0.8gCO_{2e}}{kJ}$$

Reported annual per-capita GHG emissions (metric tons CO_2e) for select diets.

	High red meat	U.S. Average or omnivorous	Vegetarian	Vegan
Calculators reviewed				
BIE	N/A[a]	2.59	2.41[b]	2.33[b]
Bon Appétit	3.24[b]	2.78[b]	1.85[b]	1.53[b]
Carbon Footprint	1.59	1.31[c]	0.47	0.19
Carbonify.com	N/A[a]	1.5[d]	N/A[a]	0[d]
Conservation International	N/A[a]	3.8[c]	2.7	2.0
The Nature Conservancy	5.26	3.72	1.36	0.82
Comparative figures				
EPA, agriculture only[e]		1.56		
Weber and Matthews		3.1		

a Calculator does not provide sufficient information to calculate emissions for this diet.

b Based on manual calculations. See Section 2.2.4 for assumptions.

c Defined as "omnivorous" or "a mix of red and white meat."

d The developer has since updated these estimations to 3.3 and 1.8 for U.S. average and vegan diets, respectively. These diet-related emissions estimates are bundled with household waste.

e As defined in Section 2.2.3.

Table 12: The carbon intensity of an Americans diet. This shows different calculators used to determine the carbon intensity of food in metric tons CO_{2e} per person per year. Figure from Kim 2009[37]

The carbon cost of the "fuel" for a biker was therefore

$$\frac{23.6kcal}{km}\frac{3.4gCO_{2e}}{kcal}+\frac{7.9gCO_{2e}}{km}=\frac{88.1gCO_{2e}}{km} \tag{7}$$

This was much higher than the value found by the ECF which was $37.5gCO_{2e}/km$[5] for the same 82kg biker, but traveling at 16 km/h. While some of this difference results from not including breathing CO_{2e}, most of it was due to a lower estimated energy expenditure per km found by the ECF.

7 Results and Discussion

The above analysis has demonstrated that biking, while it has a larger CO_{2e} footprint than expected, still helps to reduce the amount of CO_{2e} emitted. The national data[4] was used to construct an average city and compared to the results found within Davis and UC Davis. The methods and analysis above provided data for exploring the connections between biking, driving and CO_{2e} emissions. The values found for the production and use phase emissions were used to determine the amount of CO_{2e} emitted from each transportation mode nationally as well as within Davis.

The manufacturing of bicycles was found to result in 111 $kgCO_{2e}$. For CVs, this number was 7162 $kgCO_{2e}$, an order of magnitude greater. This difference was mainly due to the amount of steel used in a car versus a bicycle, as can be seen in figures [16, 15, 14]. Vehicle manufacturing also used around twice as much electricity per kg of product than bicycle production. The CO_{2e} released during use for a bicycle was found to be 88.1 gCO_{2e}/km when not including production CO_{2e} in the per-kilometer emissions, and 90.1 gCO_{2e}/km when including production. For a CVs, the use-phase resulted 304 gCO_{2e}/km from fuel use and fuel well-pump carbon intensity, and 46.3 gCO_{2e}/km resulting from production (for a 155,000 km lifetime). It can be noted from the previous literature review that the majority of commutes are driven, especially if the distance is over 1.6 km. Even so, a large fraction of people (39%) will drive even if the distance is less than 1.6 km[4].

7.1 Transportation Mode Distribution

From the NHTS, ACS and TAPS CTS data, it was clear that the majority of people drive, no matter the distance. The total percentages of commutes taken by each mode is shown in table [13]. Nationally 90% of people drive, while the next highest category was 4.6% with people who walk. Within the city of Davis 68% of people drive while the next biggest category was biking with 22%. If we compare the data from UC Davis TAPS with the data from the NHTS table [13], it is clear that the UC Davis community drives significantly less than the national average. It should be noted this is likely true of many college/university campuses. The table also shows that people in the city of Davis drive 22% (by population) less than the national average.

Mode	Davis	UC Davis	National
Drive	68.0%	29.2%	90.0%
Transit	6.1%	19.0%	3.1%
Walk	3.7%	4.9%	4.6%
Bike	22.2%	46.9%	0.8%

Table 13: The percentage of transportation modes used in the specified places.

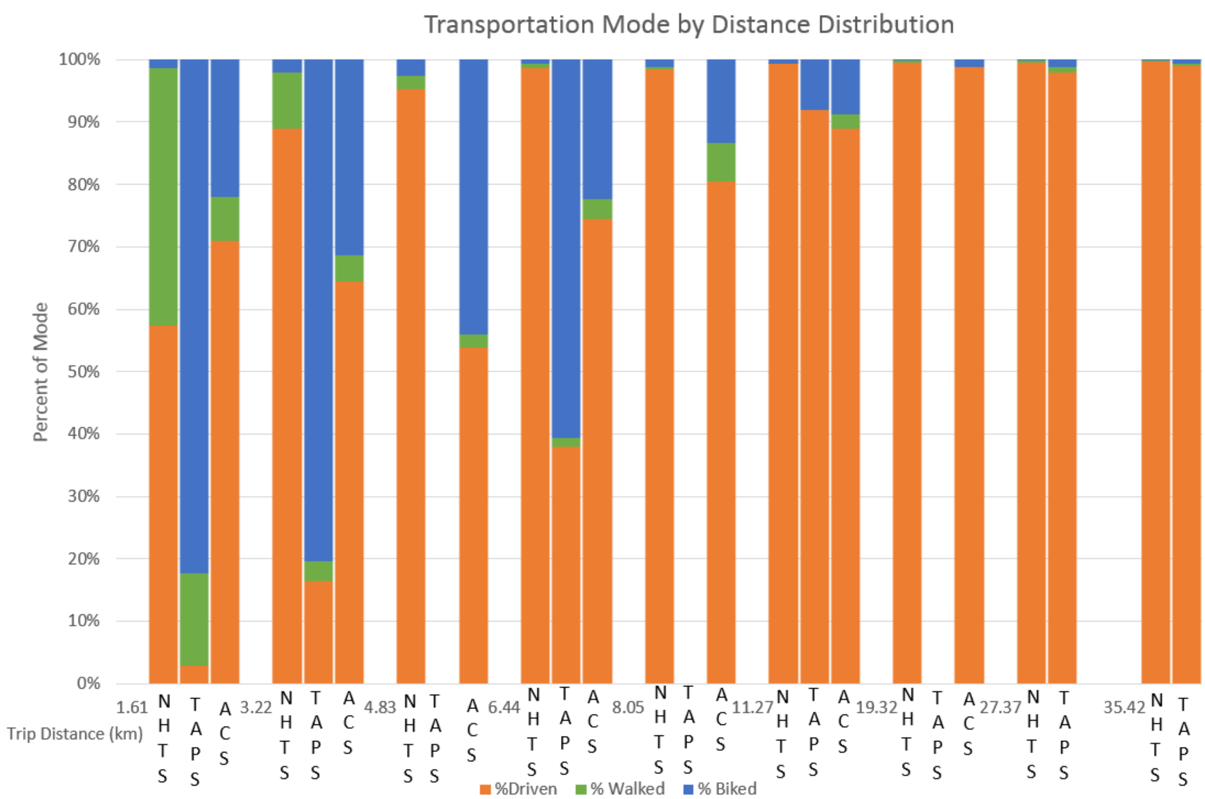


Figure 10: A comparison of the trip mode distribution separated by those who drive, walk and bike Nationally, at UC Davis, and Davis.

From figure [10], it can be seen that biking constituted a low percentage of total trips compared to driving for any distance in the national and Davis communities. It is interesting to note that a national average of only 1.3% bike when the trip length is 0-1.6km, while at UC Davis it was 78%. For trips of 0-1.6 km, the CO_{2e} released from driving for the national average was 150 times that of the CO_{2e} from biking. If an equal number of trips were made of the same distance for biking and driving, the CO_{2e} emissions would be 3.5 times less for the bikers than for the drivers. If all drivers switched to biking for trips of 1.6 km, or less, the total CO_{2e} emissions (both ways) would be reduced to 442kg from 1488kg, a 70% reduction per trip!

An overall comparison of the trip mode distribution by distance is shown in figure [10]. Some columns are missing due to the differences in resolution of each survey. Also, the ACS data only roughly corresponds to the distances listed since it provided commute time, not distance. This meant that it compared 5 minute bike commutes to 5 minute driving commutes, not 5 km to 5km commutes. The plot highlighted that driving was more common on the national level than for Davis or UC Davis by a significant margin, except for trips less than 1.6km where nationally, 40% of commuters walk.

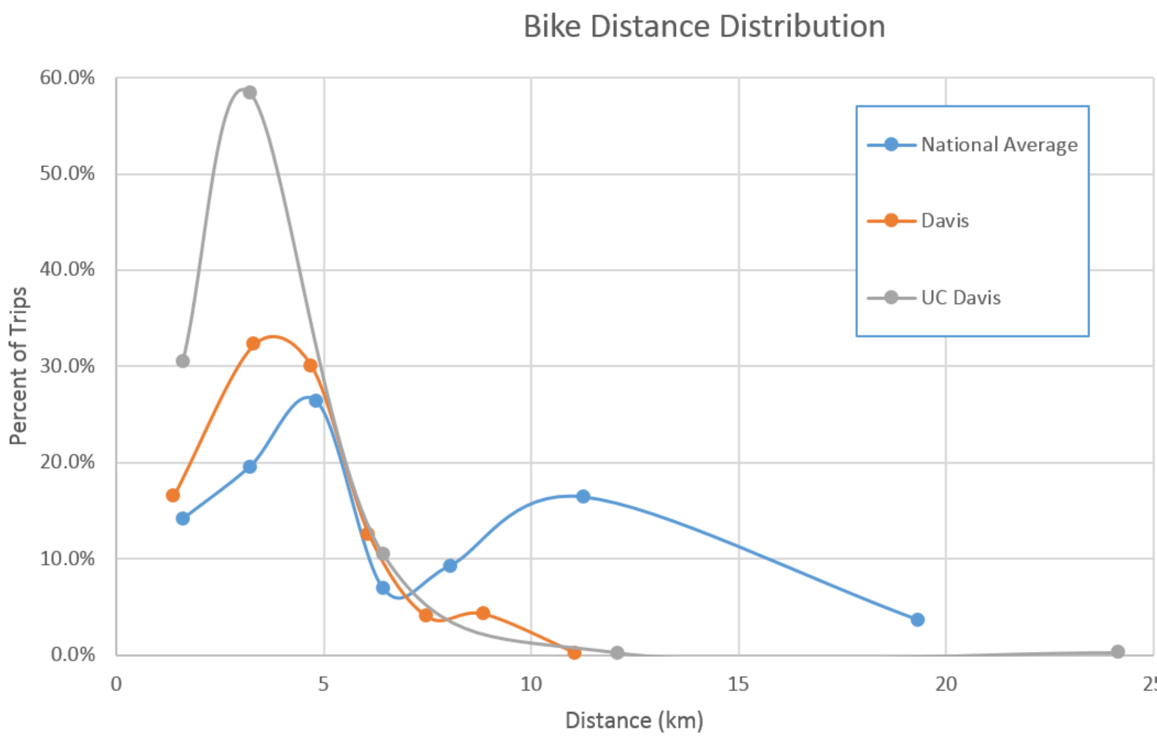


Figure 11: The transportation biking distribution for Davis and the National average.[4 9]

Another interesting finding was the distribution of trips of a vehicle type by the trip distance. Figure [11] shows the distribution of bike trips by distance. It shows what percent of all bike trips in Davis, UC Davis, and by the national average were of a given distance. As can be seen from the figure [11], both in Davis and nationally, the distribution did not simply decrease with distance, but there was a secondary peak for longer trips. This trend was especially pronounced for the national data, and fairly minor for Davis. Both the "For a living" and "Church/School" data sets displayed the same bimodal distribution for distances, implying this was not an artifact of summing the two curves. Potentially, the split may be a result of people biking short commutes because they find it practical or more economic, while others may cycle longer distances because they enjoy it. Other economic factors may also be involved, such as not being able to afford living closer to their place of work and thus not being able to afford the ownership costs of a vehicle. However, these economic considerations were beyond the scope of this paper.

The exception to the bimodal distribution was the UC Davis community. The curve showed a nicely decreasing fraction of bike trips as the distance from campus increased. It was expected that all the bike commutes would follow the trend seen in the UC Davis distribution, but contrary to intuition, it seemed to be an exception. The fact that each distribution's initial fall-off was at the same distance showed that, in general, no matter the community, most people agree that 6 to 7 kilometers is too far to commute by bike.

For vehicle transport, the distributions mostly followed a trend that one might expect. Figure [12] shows the driving distance distributions for the considered communities. Immediately apparent was that the UC Davis community did not follow the general trend of vehicle commuting that the city of Davis or the nation as a whole was found to. It was likely reflective of the fact that most trips to campus were quite short, only 1.6-4.6km (see table [6]). This range of distances was where most trips were found to be biked, as seen in figure [11]. This explained why the short distance driving commutes in UC Davis were less than the national average. This distance covered the majority of the city of Davis, so once a commute was longer than this, it was likely that the student/faculty would commute from nearby cities. In turn this would mean they were much more likely to drive, resulting in the greater fraction of vehicle commutes being farther than the national average.

The national data showed that most vehicle commutes were greater than 10km, which is likely due to urban sprawl and workers living rather far from their place of work. Once peaked at around 11km, the national distribution decreased nicely with distance as expected since a longer commute is not favorable for most workers.

The City of Davis had more short vehicle commutes than the national average, which was not surprising since the city is fairly small. The longer commutes then, represent people commuting to/from Davis from other cities. It would seem that the distribution implied that a large fraction of workers in Davis commute outside to other cities, based on the significant portion of commutes that were longer than the distance across Davis. One anomaly in the Davis data was the dip at about 33km. This drop in the percentage of vehicle trips could be caused by the location of major population centers. Similar economic considerations to those for the secondary peak in the bicycle commute distribution (figure [11]) could also go into explaining this discrepancy, but again, this was beyond the scope of this paper.

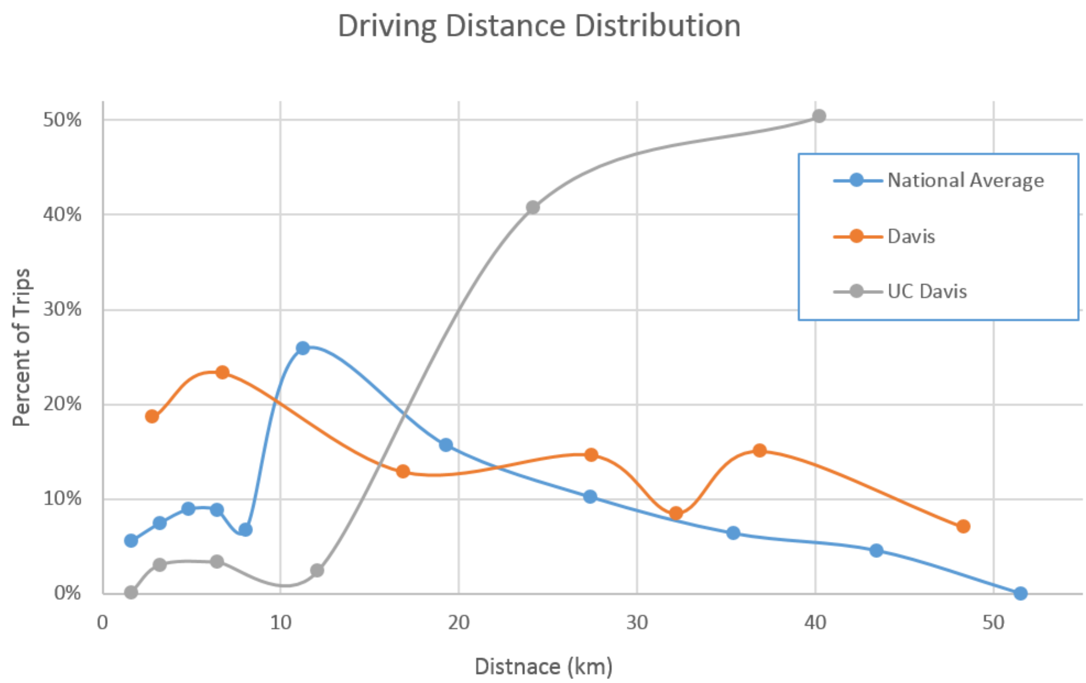


Figure 12: The transportation distribution by distance of cars in Davis versus Nationally.

7.2 Transportation Mode Energy Intensity

The carbon intensity of the different modes of transportation was found based on the manufacturing energy and energy used during operation of the transportation mode. Both values were important to the overall emissions of CO_{2e} for CVs and bicycles. An LCA was used to determine the amount of CO_{2e} emitted per car and per bicycle for the production phase. The usage phase emissions were calculated based on the energy intensity of the gasoline for cars and food energy (gasoline) for humans while biking.

7.2.1 Vehicle and Bicycle Production Results

It can be seen from figure [13] that the CO_{2e} intensity of car production is much greater than that for bicycle production. The figure shows the relative GWP of producing a car, a steel bike and an aluminium bike. The car represents 100% CO_{2e} emissions, while bike production is shown as releasing a percentage of the amount resulting from vehicle manufacturing. Also shown are the absolute quantities of CO_{2e} produced by the manufacturing process for each vehicle. For the CO_{2e} emissions from the production of one CV, 52 aluminum framed or 84 steel framed bikes could be built.

It was found that the largest source of the CO_{2e} emissions came from the production of steel (or aluminium) for both cars and bicycles. Bicycles, as expected, used much less steel than cars and therefore resulted in a smaller output of CO_{2e} from manufacturing. This can

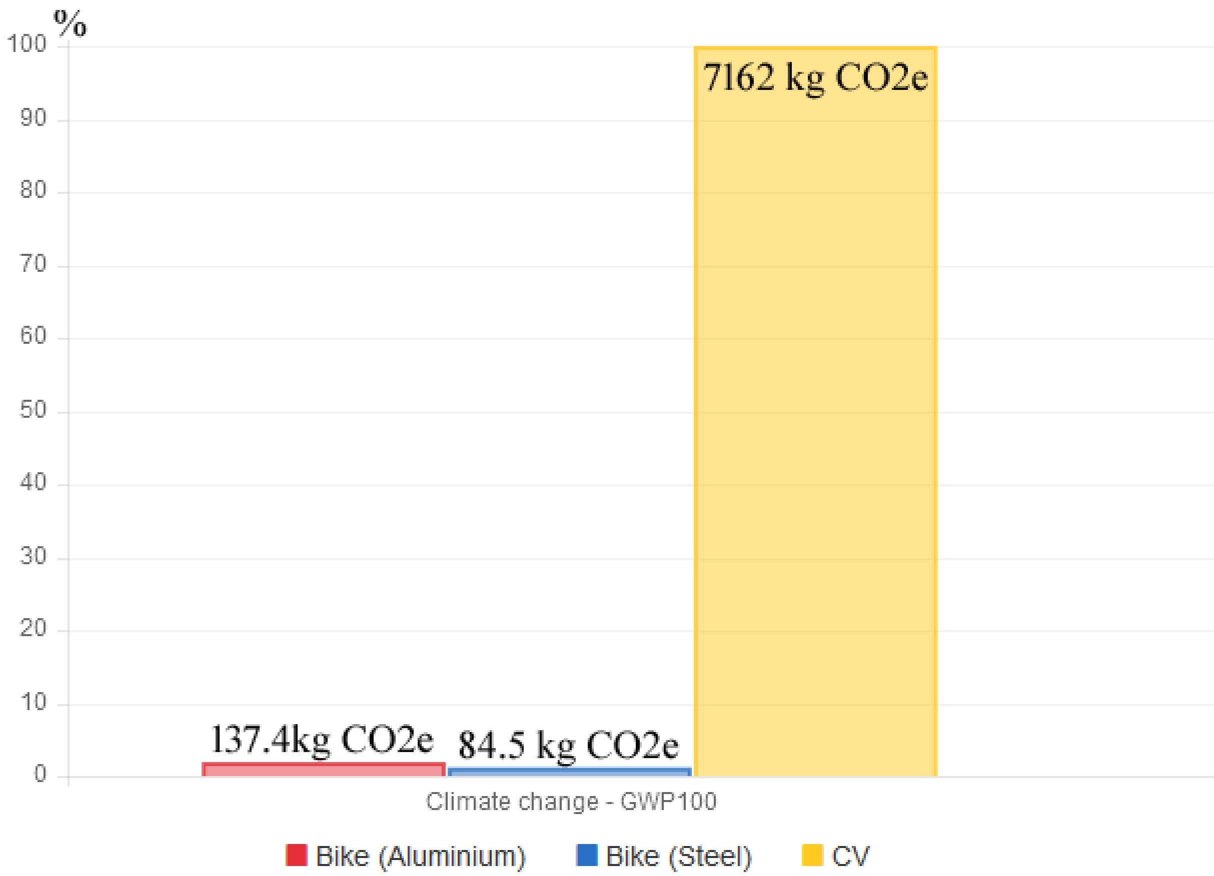


Figure 13: The CO_{2e} intensity of a car and two bikes, one of aluminum and one of steel. The basis was a car is at 100% production while the bikes were compared to this.

be seen in figures [14, 15, 16] that show the processes from the LCA for cars [16], for a steel bike [15], and for an aluminum bike [14] that produced the most CO_{2e} emissions. It can be seen from figures [14, 15] that the increased CO_{2e} resulting from the manufacturing of an aluminum bike is directly related to the greater carbon intensity of producing aluminum. Based on the LCA, for each kilogram of steel used for manufacturing, 2.6kg CO_{2e} emissions were released. For aluminum, each kilogram resulted in 6.6kg CO_{2e}.

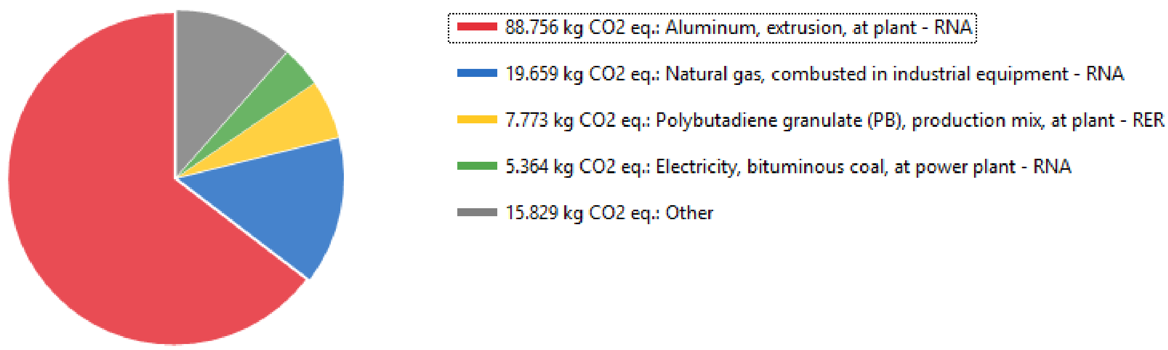


Figure 14: Sources of CO_{2e} emissions from manufacturing an aluminum bike.

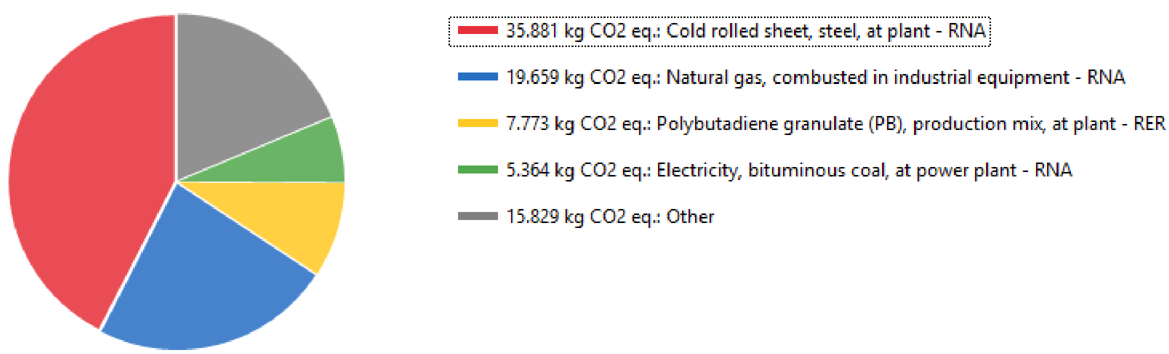


Figure 15: Sources of CO_{2e} emissions from manufacturing a steel bike.

7.2.2 Usage Energy for Vehicles and Bicycles

It can be seen from tables [10, 13] that the majority of transportation, 90% nationally, was made by car for an average distance of 16.9 km. Walking was only a major transportation mode for distances under 1.6 km. It was interesting to note that bicycling was never the major transportation mode except on the UC Davis campus. From figure [3][40], it can be seen that a primary reason given for not biking was that is not as quick as a car. The weather in some cities could also account for the lack of bike commuters. Walking was an important (national) mode of transportation for short trips, and could be the result of the lack of access to biking infrastructure[44] as suggested by figure [4][43]. Many people who bike

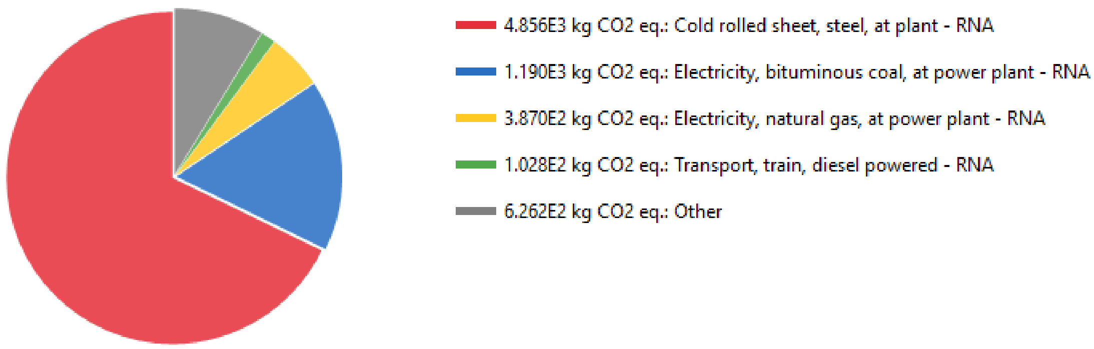


Figure 16: Sources of CO_{2e} emissions from conventional vehicle manufacturing.

do so for leisure and exercise[40], not necessarily to commute, so this does not account for any CO_{2e} reduction or change in energy use.

From the analysis, it was found that the energy usage of a car is 304 g CO_{2e}/km, which was composed mostly of direct fuel burning. Approximately 16% of the 304 g CO_{2e}/km was a result of the well-to-pump energy intensity of the gasoline. For a bike, the use-phase CO_{2e} emissions were calculated to be 88.1 gCO_{2e}/km. About 9% of this was due to CO_{2e} released from the bikers increased breathing above that of a driver (at RMR). The rest (80g CO_{2e}/km) of this was a result of the carbon intensity of the food production system in the United States. It was interesting that the carbon intensity of driving was "only" 3.5 times that of cycling. The analysis suggests this was a result of the high energy intensity of food production.

Based on the manufacturing-related CO_{2e} emissions of a bike (111 kgCO_{2e} on average), an average vehicle could drive 365 km on the production emissions of a bike. However, to reach CO_{2e} reductions from purchasing a bike to reduce ones driving, the bike must pay off its production emissions and the use-phase emissions. So one would have to cycle 514 km before purchasing a bike (if a car was already owned) would result in lowering overall CO_{2e} emissions.

7.3 CO_{2e} Emitted from Biking vs. Driving

The amount of CO_{2e} emitted from the use-phase of driving and biking in each community was calculated using the results of the above analysis. The CO_{2e} emitted nationally from driving was 113,575 kg CO_{2e}, while for biking it was 140.4 kg CO_{2e}. In Davis these numbers were 106,260 kgCO_{2e} and 2260 kg CO_{2e} respectively. In the UC Davis community it was found that 65,128 kg CO_{2e} was emitted by cars, while for bikes it was 4759 kg CO_{2e}. These values are shown in table [14], and the UC Davis and Davis values are also shown as a percent of the national average to serve as a comparison. This table took into account use-phase emissions only.

Community	UC Davis	Davis	National Average
Biking (kg CO2e)	4759	2261	140.37
Percemt of National	3390%	1611%	100%
Driving (kg CO2e)	65,128	106,260	113,576
Percent of National	57%	94%	100%
Ovearll CO2e	69,887	108,521	113,715.95
Percent of National	61%	95%	100%

Table 14: A comparison of the kg CO_{2e} emitted during the use-phase from driving based on the population.

From the table [14], it can be seen that Davis as a city did not have a significantly smaller carbon footprint than the national average, despite its large bike commuter community. The workers of Davis still produced 94% of the CO_{2e} that an average American did, even though the bike commute rate was 22 times higher in Davis. This can be explained by noting that in figure [12], Davis was found to have a higher fraction of vehicle commutes at a longer distance than was nationally typical. As a result, the reduced number of drivers seems to simply offset the additional CO_{2e} emissions resulting from other workers commuting farther. The same was true, to a lesser extent, of the UC Davis community. Even though from table [13] it can be seen that only 29% of commutes were driven compared to 90% nationally, the driving related CO_{2e} emissions from the UC Davis community were found to only be reduced by 43%. Figure [12] again explained this, as the UC Davis driven commutes were extremely weighted towards quite long distances, which significantly increased the driving related CO_{2e} emissions per commute. The overall CO_{2e} reduction (taking into account the increased biking related CO_{2e} and the reduced driving CO_{2e}) is also shown, so it can be seen that bike-related CO_{2e} accounted for 7% of the UC Davis community CO_{2e} emissions, while it only represented 2% of the city of Davis' CO_{2e}.

Table [15] shows how Davis as a whole (UC Davis and the city of Davis) fairs against the national average. The national values in table [15] didn't match the values seen in table [14] because the population used to calculate the national average in table [15] was set to match the population of Davis plus UC Davis, while in table [14] the population of the average national city was set to be the same as the (working) population of the city of Davis. It can be seen, that the increased biking in Davis and UC Davis result in the "real" population of Davis producing only one third of the national average CO_{2e} emissions from driving. The net result then, was that Davis produced only 69% of the commute related CO_{2e} emissions that an average American city of the same working population would. This 30% reduction in CO_{2e} emissions can be attributed to the high levels on cycling in this community.

Community	Davis+UC Davis	National Average
Biking (kg CO2e)	7020	318.00
Percemt of National	2207%	100%
Driving (kg CO2e)	171,388	257,168
Percent of National	67%	100%
Ovearll CO2e	178,408	257,486
Percent of National	69%	100%

Table 15: The CO_{2e} emissions in the entire city of Davis for biking versus the national average.

The CO_{2e} from biking nationally was lower than for Davis, 153.4 CO_{2e} to 2470.6 CO_{2e}, respectively, while it was 4,759 CO_{2e} in the UC Davis community. The increased CO_{2e} from Davis and UC Davis due to biking was expected, as there were significantly more bike commuters in those communities. This demonstrated that increasing bicycling CO_{2e} emissions in order to reduce driving related CO_{2e} emissions resulted in a net decrease in the carbon intensity of a commute.

The national value, based on a larger city population to match that of Davis and UC Davis combined, output 318kg CO_{2e} from bikes and 257,168 kg CO_{2e} from CVs. For Davis, bikes released 7020 kg CO_{2e} and cars emitted 171,388 kg CO_{2e} as shown in table [15]. The sum of the national CO_{2e} output was larger than that of Davis, mostly due to the amount of vehicle commutes. It was interesting that while those in Davis drove further, there were still fewer emissions from cars. This can be explained by noting the amount of bikers within the city and from the university, resulting in a sufficient reduction in the number of vehicle commutes to offset the longer driven distances.

7.3.1 Commute Carbon Intensity, Including Production

Knowing the emitted CO_{2e} from production and use-phase separately was interesting, but it was also useful to think about the overall emitted CO_{2e} over the life cycle, from production through use. To do this, the production-related CO_{2e} was added to the cumulative use-phase CO_{2e} in equation [3]. The results are shown in table [16]. Since the survey group focused on workers, CO_{2e} emissions were only calculated for commutes, which happen 5 days of the week. For the national transportation distribution, using a population equal to that of Davis and UC Davis combined, 63,400, the CO_{2e} emissions from the life cycle of all commuter vehicles (without disposal) was found to be 3.07E9 kg CO_{2e}.

The resulting cumulative lifetime bike commute related CO_{2e} emissions were 6.0E6 kg CO_{2e} for the national average. It was interesting to look at the effect that would be had if all drivers in a community decided to bike instead, as is shown in the third column in table

	Cumulative CO2		
	Cars (kg CO2)	Bikes (kg CO2)	Cars ->Bikes (kg CO2)
National Data	3.07E+09	6.04E+06	5.91E+08
Davis Data	2.04E+09	5.90E+07	2.93E+08

Table 16: The cumulative CO_{2e} emissions. This includes the production and use phase. The third column demonstrates the effect of everyone in the particular city biking (and only owning a bike) instead of driving.

[16]. If this were the case, then the bike commute related CO_{2e} emissions would be 5.9E8 kg CO_{2e}, still an order of magnitude less than that of driving. For these calculations, it was assumed that all owners of each vehicle type contributed to production CO_{2e}, but only commuters contributed to use-phase CO_{2e}, and that all distance traveled during the lifetime of the vehicle was representative of the national commute data.

Similar calculations were completed for the city of Davis (UC Davis + Davis), with different percentages of bikers and transportation mode distributions. The transportation mode distribution was determined from the population of Davis and UC Davis times the percentage of people commuting a certain distance. For Davis, the average vehicle commute distance was found to be 36km round trip while at UC Davis it was found to be 40 km. In Davis, 68% of people drive, while at UC Davis only 29% drive. The amount of CO_{2e} emitted from cars equated to 2.03E9 kg CO_{2e}. It was assumed that the CO_{2e} emitted from the production of cars came from those who commuted to work only. While people in the city of Davis might commute further, the overall CO_{2e} emissions were still less than the national average because of the amount of people commuting by bike.

Biking within Davis proved, as compared to the national data, to result in less CO_{2e} emissions. The average commute distance for biking at UC Davis was found to be 6.4 km round trip and at Davis was found as 8.1 km round trip. Within Davis, the CO_{2e} emissions from biking resulted in 59.3E6 kg CO_{2e}. It can be noted that the city of Davis has larger CO_{2e} emissions from biking, which is understandable based on the amount of bikers. If all drivers were to become bikes the overall CO_{2e} emissions would become 293E6 kg CO_{2e}. This, though, still does not exceed the amount of CO_{2e} released only by driving nationally. It can, therefore, be stated with confidence that biking is beneficial for the environment based on this data.

To compare the data calculated above to other LCAs, it was beneficial to look the production related CO_{2e} over the total distance the vehicle was assumed to travel. Based on the methods above, the result was that over 20 years, a vehicle was assumed to have a lifetime mileage of 155,000 kilometers. This assumed that only the vehicles used for commutes contributed to the production CO_{2e}. Nationally this gave 2.0 gCO_{2e}/km for bicycle production and 46.3 gCO_{2e}/km for vehicle production. This brought the total GHG emissions per kilometer for a vehicle to 366.4 gCO_{2e}/km, and 90.1 gCO_{2e}/km for bikes. Including these numbers in the transportation mode distribution increased the carbon intensity of a daily commute by 70,000 kg CO_{2e} per day in Davis, and 106,000 $kgCO_{2e}$ for an average city the same size as Davis. This also made biking appear more favorable, since the production emissions from vehicles contributed more CO_{2e}/km than bicycle manufacturing did. Bicycle emissions in Davis were reduced from 4.1% of daily commute CO_{2e} to 3.5%.

8 Recommendations and Future Work

From this study it was shown that bicycling does help lessen the amount of CO2e released into the atmosphere from commuting. Within Davis, the amount of CO2e emissions was found to be lower than nationally thanks to the smaller amount of drivers and larger amount of bikers.Therefore it can be concluded that it is important to increase the fraction of workers who choose to bike to work. The question then becomes how to increase the workers' bike commuting. Building infrastructure for ease of access and safe biking is a large portion of the problem. Doing this takes time, money, and resources and in turn would create pollution from the energy used to build the infrastructure. In general, the recommendation would be to start commuting more by bike because both the production and usage-phase of bikes is small compared to that of a car, and could potentially help decrease the release of GHGs into the atmosphere.

While many points were taken into account for this analysis, there were also many that were neglected because of the scope of the project. In the future it would be beneficial to add an economic analysis and the influence of money on buying a car or bike. This could also influence where people live and their means of transportation. It would also be beneficial to look at the CO_{2e} emissions of the maintenance of cars and bicycles. However, including these considerations is unlikely to change the fact that Davis was found to produce only 69% of the national average commute-related CO_{2e}.

9 Conclusion

It can be seen that the CO_{2e} emissions from bicycling are not negligible, but are significantly smaller than the CO_{2e} emissions from driving. The average city of about 60,000 people in the United States releases about 257,200 kg CO_{2e} per day from the usage of vehicles only. Compared to biking, which results in use-phase CO_{2e} emissions of only 318 kg CO_{2e} per day. It can be seen that it is beneficial to the atmosphere and to one's health to cycle more often.

The overall CO_{2e} emissions from owning a CV due to production are 7162 kg CO_{2e} per vehicle, while for bikes it is only 111 kg CO_{2e} per bike. The production of a car was found to be much more energy and carbon intensive than that of a bike. This was primarily due to the amount of steel used during the manufacturing process. Since there is less steel in a bike, it is therefore beneficial to produce fewer cars. The cumulative CO_{2e} released nationally by cars is 3.07E9 kg CO_{2e} while within Davis this number is 2.04E9 kg CO_{2e}. While these numbers are similar it is imperative to understand that within Davis there are fewer drivers, but they commute further, increasing the CO_{2e} emissions to a similar level as national average. The cumulative CO_{2e} released from bicycles is 6.04E6 kg CO_{2e} nationally and 5.04E7 kg CO_{2e} in Davis. While the numbers clearly demonstrate biking in Davis releases more CO_{2e}, this is primarily influenced by the number of bikers and more than makes up for this increase by the decrease in vehicle CO_{2e} emissions.

The total GHG emissions per kilometer for a vehicle was calculated to be 366.4 gCO_{2e}/km while for bicycles it was 90.1 gCO_{2e}/km. This demonstrated that biking is more environmentally favorable. It can be stated, then that driving releases more CO_{2e} than biking and comparing the transportation habits of an average city to Davis does show a decrease of the CO_{2e} emissions within Davis. This decrease is credited to the large number of bike commuters within the city and lower number of those who commute by car.

References

[Bik] National biking and walking study: Case study no. 1. [Online; at http://safety.fhwa.dot.gov/ped_bike/docs/case1.pdf].

[2] (2007). Energy trends in selected manufacturing sectors: Opportunities and challenges for environmentally preferable energy outcomes. Online. [Online; accessed 3-March-2015 at http://www.epa.gov/sectors/pdf/energy/ch3-4.pdfandhttp://www.epa.gov/sectors/pdf/energy/ch2.pdf].

[3] (2009). American community survey bicycle commuting trends, 2000 to 2008. Online. [Online; accessed 25-January-2015 at http://www.advocacyadvance.org/docs/acs_commuting_trends.pdf].

[4] (2009). National household travel survey tables: Table designer. Online Database. [Online; accessed 28-Janurary-2015 at http://nhts.ornl.gov/tables09/Login.aspx?ReturnUrl=\%2ftables09\%2fae\%2fTableDesigner.aspx].

[5] (2011). Cycle more often 2 cool down the planet! quantifying co2 savings of cycling. Online. [Online; accessed 30-January-2015 at http://www.ecf.com/wp-content/uploads/ECF_CO2_WEB.pdf].

[6] (2012). Body measurements: Measured average height, weight, and waist circumference for adults ages 20 years and over. Online. [Online; accessed 5-March-2015 at http://www.cdc.gov/nchs/fastats/body-measurements.htm].

[7] (2012). Our cars are getting older, too: Average age now 10.8 years. Online. [Online; accessed 11-March-2015 at http://usatoday30.usatoday.com/money/autos/story/2012-01-17/cars-trucks-age-polk/52613102/1].

[8] (2012). U.s. life cycle inventory database. Online Database. [Online; accessed 28-Janurary-2015 at https://www.lcacommons.gov/nrel/search].

[9] (2013). American community survey: Fact finder data download. Online Database. [Online; accessed 3-February-2015 at http://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t].

[10] (2014a). 2013 annual report: Developing profitable growth for all. Company Website. [Online; accessed 23-February-2015 at http://corporate.ford.com/microsites/sustainability-report-2013-14/doc/sr13-annual-report-2013.pdf].

[11] (2014). By the numbers — uc davis. Online. [Online; accessed 15-Janurary-2015 at http://ucdavis.edu/about/facts/].

[12] (2014). Corolla 2015 ebrochure. Online. [Online; accessed 18-February-2015 at http://www.toyota.com/content/ebrochure/2015/corolla_ebrochure.pdf].

[13] (2014a). Food availability (per capita) data system: Summary findings. Online Database. [Online; accessed 4-March-2015 at http://ers.usda.gov/data-products/food-availability-\%28per-capita\%29-data-system/summary-findings.aspx].

[14] (2014b). Ford explorer specifications. Online. [Online; accessed 23-February-2015 at http://www.ford.com/suvs/explorer/specifications/capacities/].

[15] (2014). How much carbon dioxide is produced by burning gasoline and diesel fuel? Online. [Online; accessed 1-March-2015 at http://www.eia.gov/tools/faqs/faq.cfm?id=307\&t=11].

[16] (2014b). Lca commons: Data and community for life cycle assessment. Online Database. [Online; accessed 10-February-2015 at https://www.lcacommons.gov/discovery/].

[17] (2014). The needs life cycle inventory database. Online Database. [Online; accessed 15-February-2015 at https://nexus.openlca.org/database/NEEDS].

[18] (2014c). Sustainability report 2013/2014. Company Website. [Online; accessed 23-February-2015 at http://corporate.ford.com/microsites/sustainability-report-2013-14/doc/sr13.pdf].

[19] (2014a). Table 4-11m: Light duty vehicle, short wheel base and motorcycle fuel consumption and travel. Online Database. [Online; accessed 1-March-2015 at http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_11_m.html].

[20] (2014b). Table 4-12m: Light duty vehicle, long wheel base fuel consumption and travel. Online Database. [Online; accessed 1-March-2015 at http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_12_m.html].

[21] (2014c). Table 4-23: Average fuel efficiency of u.s. light duty vehicle. Online Database. [Online; accessed 28-Janurary-2015 at http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_23.html].

[22] (2015). Davis, california. Online. [Online; accessed 5-March-2015 at http://www.city-data.com/city/Davis-California.html].

[23] (2015a). Goodyear wrangler radial tire - 235/75r15 105s. Online. [Online; accessed 21-February-2015 at http://www.amazon.com/Goodyear-Wrangler-Radial-Tire-75R15/dp/B004QL66XO/ref=sr_1_1?ie=UTF8&qid=1424744533&sr=8-1&keywords=235\%2F75R15+105S].

[24] (2015). Google maps. Online. [Online; accessed 15-February-2015 at https://www.google.com/maps/@38.5442756,-121.737572,15z].

[25] (2015b). Ppr industries 304741095gtn replacement glass windshield for 1997-06 jeep wrangler tj. Online. [Online; accessed 23-February-2015 at http://www.amazon.com/PPR-Industries-304741095GTN-Replacement-Windshield/dp/B002Y3545M/ref=sr_1_1?s=automotive\&ie=UTF8\&qid=1424761590\&sr=1-1\&keywords=windshield+replacement\#productDetails].

[26] (2015). Precision tig 225 tig welder. Online. [Online; accessed 2-March-2015 at http://www.lincolnelectric.com/en-us/Equipment/Pages/product.aspx?product=K2533-2\%28LincolnElectric\%29].

[27] (2015). Wolframalpha. Website. [Online; accessed 23-February-2015 at http://www.wolframalpha.com].

[28] Adams, W. C. (1967). Influence of age, sex, and body weight on the energy expenditure of bicycle riding. *Journal of Applied Physiology*, 22(3):539–545.

[29] Austen, K. (2012). Examining the lifecycle of a bike - and its green credentials. Online. [Online; accessed 24-Febuary-2015 at http://www.theguardian.com/environment/bike-blog/2012/mar/15/lifecycle-carbon-footprint-bike-blog].

[30] Berners-Lee, M. (2010). Whats the carbon footprint of cycling a mile? *The Guardian*. "[Online; accessed 2-March-2015 at http://www.theguardian.com/environment/2010/jun/08/carbon-footprint-cycling]".

[31] Bock, J. (2015). Email Interview.

[32] Dave, S. (2010). *Life cycle assessment of transportation options for commuters*. PhD thesis, Master thesis. Massachusetts Institute of Technology (MIT), United States.

[33] Eshel, G. and Martin, P. A. (2006). Diet, energy, and global warming. *Earth interactions*, 10(9):1–17.

[34] Frankenfield, D., Roth-Yousey, L., Compher, C., Group, E. A. W., et al. (2005). Comparison of predictive equations for resting metabolic rate in healthy nonobese and obese adults: a systematic review. *Journal of the American Dietetic Association*, 105(5):775–789.

[35] Hendriksen, I. and van Gijlswijk, R. (2010). Fietsen is groen, gezond en voordelig. *Leiden: TNO*.

[36] Johnson, R., Kodama, A., and Willensky, R. (2014). The complete impact of bicycle use: Analyzing the environmental impact and initiative of the bicycle industry.

[37] Kim, B. and Neff, R. (2009). Measurement and communication of greenhouse gas emissions from us food consumption via carbon calculators. *Ecological Economics*, 69(1):186–196.

[38] MacLean, H. L. and Lave, L. B. (1998). Peer reviewed: A life-cycle model of an automobile. *Environmental Science & Technology*, 32(13):322A–330A.

[39] Maness, M. (2012). Bicycle ownership in the united states: Empirical analysis of regional differences. In *Proceedings of Transportation Research Board Annual Conference*.

[40] McGuckin, N. (2012). Walking and biking in california: Analysis of the ca-nhts. Technical report.

[41] Nelson, A. C. and Allen, D. (1997). If you build them, commuters will use them: association between bicycle facilities and bicycle commuting. *Transportation Research Record: Journal of the Transportation Research Board*, 1578(1):79–83.

[42] Pimentel, D., Williamson, S., Alexander, C. E., Gonzalez-Pagan, O., Kontak, C., and Mulkey, S. E. (2008). Reducing energy inputs in the us food system. *Human Ecology*, 36(4):459–471.

[43] Popovich, N. (2014). Results of the 2013-14 campus travel survey. Technical report.

[44] Reynolds, Conor CO, M. A. H. K. T. P. A. C. and Winters, M. (2009). The impact of transportation infrastructure on bicycling injuries and crashes: A review of the literature. *Environmental Health*. [Online; at `http://www.biomedcentral.com/content/pdf/1476-069X-8-47.pdf`].

[45] Rydh, C. J. and Sandén, B. A. (2005). Energy analysis of batteries in photovoltaic systems. part i: Performance and energy requirements. *Energy Conversion and Management*, 46(11):1957–1979.

[46] Samaras, C. and Meisterling, K. (2008). Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy. *Environmental science & technology*, 42(9):3170–3176.

[47] Santos, A., McGuckin, N., Nakamoto, H. Y., Gray, D., and Liss, S. (2011). Summary of travel trends: 2009 national household travel survey. Technical report.

[48] Ungureanu, C., Das, S., and Jawahir, I. (2007). Life-cycle cost analysis: aluminum versus steel in passenger cars. In *TMS Meeting, Aluminum Alloys for Transportation, Packaging, Aerospace and Other Applications, Florida, USA*, pages 11–24.

[49] Weber, C. L. and Matthews, H. S. (2008). Food-miles and the relative climate impacts of food choices in the united states. *Environmental science & technology*, 42(10):3508–3513.