IMPACTS OF THE OVERWEIGHT AND OBESE ON THE US FOOD SUPPLY AND TRANSPORTATION SYSTEMS

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ABSTRACT

Since the 1970s, the percentage of the US population that is overweight and obese has increased significantly, with nearly 70% of American adults now overweight or obese (National Center for Health Statistics, 2013). The American Medical Association officially recognized obesity as a disease (American Medical Association, 2013) that afflicts approximately one out of every three adults in the US (National Center for Health Statistics, 2013). While the health implications of being overweight or obese are well established, the environmental impacts have not received equal attention. In light of this inattention, this dissertation analyzes the effects of the overweight and obese population on energy use, water withdrawals, greenhouse gas (GHG) emissions, and fuel costs through the US food supply system and transportation system.

The first empirical chapter investigates the impacts of current US food consumption on energy use, water withdrawals, and GHG emissions. The purpose of this analysis is twofold: first, two top-down approaches are used to establish a range of life-cycle industrial energy use, water withdrawals, and GHG emissions in the US food supply system that are attributed to total food consumed by the US adult population. The two methods utilized are 1) economic input-output life-cycle assessment (EIO-LCA) and 2) process-based analysis. Second, the additional industrial energy use, water withdrawals, and GHG emissions required to support the extra Caloric intake of the US overweight and obese adult population are estimated. Extra Caloric intake estimates are developed using anthropometric data from the Centers for Disease Control (CDC) National Health and Nutrition Examination Survey. In 2012, 6.1-6.2 million TJ of cumulative energy use, 100-105 billion m^3 of water withdrawals, and 600 million metric tons (MMT) CO_2-eq were needed to provide food to the US adult population. Furthermore, 8-10% of total Caloric intake of adults

were extra Calories consumed from overeating for overweight and obese adults. Providing these additional Calories resulted in 440,000-610,000 TJ of energy use, 7-10 billion m^3 of water withdrawals, and 43-59 MMT CO_2-eq.

The second empirical chapter uses a bottom-up approach to measure the changes in energy use, water withdrawals, and GHG emissions associated with shifting from current US food consumption patterns to three dietary scenarios, which are based, in part, on the 2010 USDA *Dietary Guidelines* (US Department of Agriculture and US Department of Health and Human Services 2010). Amidst the current overweight and obesity epidemic in the US, the *Dietary Guidelines* provide food and beverage recommendations that are intended to help individuals achieve and maintain healthy weight. The three dietary scenarios examined include 1) reducing Caloric intake levels to achieve “normal” weight without shifting food mix, 2) switching current food mix to USDA recommended food patterns, without reducing Caloric intake, and 3) reducing Caloric intake levels and shifting current food mix to USDA recommended food patterns, which support healthy weight. This analysis finds that shifting from the current US diet to dietary Scenario 1, decreases energy use, water withdrawals, and GHG emissions by around 8.5%, while shifting to dietary Scenario 2 increases energy use by 48%, water withdrawals by 22%, and GHG emissions by 13%. Shifting to dietary Scenario 3, which accounts for both reduced Caloric intake and a shift to the USDA recommended food mix increases energy use by 39%, water withdrawals by 13%, and GHG emissions by 6%.

The third empirical chapter analyzes the transportation industry to determine the amount of additional fuel use, GHG emissions, and fuel costs that are attributed to excess passenger weight in light-duty vehicles, transit vehicles, and passenger aircraft in the US from 1970 to 2010. Using driving and passenger information in the US and historical anthropometric data, it is estimated that since 1970 over 205 billion additional liters of fuel were consumed to support the extra weight of the American population. This is equivalent to 1.1% of total fuel use for transportation systems in the United States. Also, excess passenger weight results in an extra 503 MMT CO_2-eq and \$103 billion of additional fuel cost over the last four decades. If overweight and obesity rates continue to increase at its current pace, cumulative excess fuel use could increase by 460 billion liters over the next 50 years, resulting in an extra 1.1 billion metric tons CO_2-eq and \$200 billion of additional fuel costs by the year 2060.

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1. INTRODUCTION

Since 1970, the percentage of the US population that is overweight and obese has increased significantly, with nearly 70% of American adults now overweight or obese (National Center for Health Statistics 2013). The excess weight that Americans are carrying has a number of documented effects, including increased rates of health problems (Dixon 2010), greater lifetime healthcare costs (Thompson et al. 2001), increased absenteeism at work (Frone 2008), and added burden on transportation systems (Jacobson and Mclay 2006). As such, the alarming rise of overweight Americans over the past 40 years has garnered much attention from policy makers, researchers, physicians, concerned citizens, and public health officials. In 2013, the American Medical Association officially recognized obesity as a disease (American Medical Association 2013) that afflicts approximately one out of every three adults in the US (National Center for Health Statistics 2013).

While most of the literature and media discourse surrounding overweight and obesity tends to focus exclusively on human health and healthcare costs, this study examines the overweight and obese population from an environmental and resource use perspective. In particular, this dissertation analyzes the food consumption patterns of the US population contributing to extra body weight, as well as the extra weight of passengers in various transport modes. These factors have implications for energy use, water withdrawals, and GHG emissions within the food supply and transportation systems of the US.

Research goals were set in three main areas: (1) investigating the impacts of current food consumption patterns on cumulative energy use, water withdrawals, and GHG emissions through the US food supply chain, (2) evaluating the impacts of shifting from the current US diet to the USDA dietary recommendations on cumulative energy use, water withdrawals, and GHG emissions through the US food supply chain, and (3) assessing the impacts of increasing passenger weight on fuel use, GHG emissions, and fuel costs within the US transportation system.

Research goal 1 is to investigate the impacts of current food consumption patterns on cumulative energy use, water withdrawals, and GHG emissions through the US food supply chain. The first objective of this research goal is to establish a range of life-cycle industrial energy use, water withdrawals, and GHG emissions in the US food supply system that are attributed to total food consumed by the US adult population using two top-down approaches: the economic input-output life cycle assessment (EIO-LCA) model and a process-based analysis. The second objective is to estimate the extra Calories consumed by the US overweight and obese adult population and then to quantify the additional energy use, water withdrawals, and GHG emissions associated with producing these additional Calories.

Research goal 2 is to evaluate the impacts that shifting from the current US diet to various dietary recommendations, has on cumulative energy use, water withdrawals, and GHG emissions through the US food supply chain. A bottom-up approach is used to assess the impacts of switching to three dietary scenarios, which are based, in part, on the 2010 USDA *Dietary Guidelines*. These scenarios include reducing Caloric intake levels to achieve "normal" weight without shifting food mix, shifting food mix to food patterns recommended by the USDA *Dietary Guidelines*, without reducing Caloric intake, and reducing Caloric intake levels and shifting food mix to meet USDA *Dietary Guidelines* in order to achieve and maintain healthy weight.

Research goal 3 is to assess the impacts of increasing passenger weight on fuel use, GHG emissions, and fuel costs within the US transportation system. In general, as weight in vehicles increases, fuel consumption also increases, which results in more greenhouse gas (GHG) emissions and greater spending on fuel. For this analysis, three modes of transportation are analyzed: light-duty vehicles, public transit, and commercial passenger aircraft. Furthermore, the trends of the extra passenger weight effects on fuel use, emissions, and costs are evaluated over 40 years, from 1970 to 2010.

As public health, food security, natural resource use, and environmental protection continue to be relevant issues in society, this thesis provides important contributions to the bodies of knowledge concerning these topics. Fortunately, there is substantial literature on policies that promote healthy lifestyles and support sustainable living (e.g. Story et al. (2008)). This dissertation contributes to this literature by further investigating the nuanced relationships between human and environmental health. In doing so, it demonstrates that while healthy living and environmental sustainability may be complementary, they are not always so.

The results found in this thesis have implications at multiple levels. At the individual level, dietary choices and consumer behavior have environmental ramifications. At the policy level, decision makers should be aware of the complex relationships between food consumption, health, body weight, and the environment in order to develop policies that help us move toward a healthier, more sustainable future.

2. Energy Use, Water Withdrawals, and Greenhouse Gas Emissions for Food Consumption in the US

2.1 Introduction

Since 1970, average per-capita Caloric intake has risen in the US, contributing to the nation's escalating overweight and obesity rates. Modern agriculture and technological advancements in the food supply sector have increased the availability of all food types, particularly meat products and inexpensive, Calorie-dense foods, which have promoted weight gain, intensified natural resource use, and been key culprits in a cycle of environmentally harmful practices. In 2012, roughly 9% of greenhouse gas (GHG) emissions in the US resulted from agricultural activities, including land use and land use change and forestry (LULUCF) (US Environmental Protection Agency 2014a). Agricultural production has also contributed to other types of environmental degradation such as increased use of pesticides, nutrient runoff, soil erosion, and groundwater depletion. As of 2000, global livestock production alone accounted for 14% of the world's anthropogenic GHG emissions (including LULUCF), 63% of reactive nitrogen mobilization, and 58% of directly used human-appropriated biomass (Pelletier and Tyedmers 2010). These impacts are projected to escalate over the next 50 years based on predicted increase in livestock production.

While food is a basic need, food consumption that exceeds our optimal Caloric intake may have negative implications for our health and for our environment. To begin this analysis, two top-down approaches are used to establish a range of life-cycle industrial energy use, water withdrawals, and GHG emissions in the US food supply system that are attributed to total food consumed by the US population. The two methods utilized are 1) economic input-output life cycle assessment (EIO-LCA) and 2) process-based analysis, both of which will be discussed in further detail in the following sections. Then the additional environmental impacts required to support the extra Caloric intake of the US overweight and obese adult population are estimated. For this analysis, extra Caloric intake refers to the additional food Calories eaten beyond those that are necessary to maintain a “normal” or healthy body weight; body weight categories (normal weight, overweight, obese, etc.) are established by the Centers for Disease Control (CDC).

2.1.1 Food Consumption

Prior estimates of environmental effects attributable to supplying food to the US population range from approximately, 8% to 15.7% of annual US energy use and 8% to 13% of annual US GHG emissions. Canning et al. (2010) used input-output material flow analysis to develop 2002 food-related industrial energy use, and then projected to 2007 based on total US energy consumption and food expenditures in 2007. Cuellar and Webber (2010) used a top-down approach, compiling energy use data from various sources for all stages (agriculture, processing, packaging, etc.) of the food supply system in 2002 and scaling up to 2007, assuming linear changes in food-related energy use based on total national energy consumption. With regard to food-related GHG emissions, Heller and Keoleian (2014) used a bottom-up approach, compiling emission impacts for each food type and applying to various food mix scenarios to develop GHG estimates for 2010. In contrast, Jones and Kammen (2011) estimated food-related GHG emissions in 2005 and Weber and Matthews (2008) in 1997 using EIO-LCA models.

While several studies have examined water withdrawals for different food types, no studies have been identified that evaluate the total water withdrawals (surface and groundwater) in the US food supply chain required to provide food to the US population. Hoekstra and Mekonnen (2012) calculated the water footprint of food consumption in various countries, including the US, from 1996-2005. However, their water footprint estimates refer only to water that is evaporated or is incorporated into a product, and exclude the volume of water that returns to the ground or surface water. Hence, the water footprint is usually smaller than the water withdrawal quantity for US food consumption, which is quantified in this study. Furthermore, this analysis implements two top-down approaches with the most recent data to develop a comprehensive, updated account of industrial energy use, water withdrawals, and GHG emissions for current US food consumption.

2.1.2 Diet

Numerous studies link overweight and obesity to health conditions (Dixon 2010), rising medical costs (Thompson et al. 1999, Thompson et al. 2001), and lowered work productivity levels (Frone 2008). Fewer studies assess the environmental impacts related to excess body weight in the US. Most of these studies concentrate on the effects of passenger weight on transportation systems fuel use, fuel costs, and GHG emissions (Jacobson and McLay 2006, Tom et al. 2014). Other analyses investigate the relationship between environmental and human health via diet. Tilman and Clark (2014), for example, find that current shifts in global diet toward higher consumption of Calorie-dense foods, such as refined sugars, refined fats, oils, and meats, have led to enhanced levels of diet-related non-communicable diseases, many of which are associated with obesity, as well as increased agricultural land use and clearing and increased global GHG emissions. They also estimate that if current dietary trends continue, food production emissions will increase 80% from 2009 to 2050. Conversely, adopting a healthier diet (Mediterranean, pescetarian, and vegetarian) would result in zero net increase in global food production emissions by 2050 (Tilman and Clark 2014).

Eshel and Martin (2006) estimate that mixed animal and plant-based diets result in nearly 1,500 kg CO_2-eq more than a plant-based diet incorporating the same number of Calories. Likewise, Weber and Matthews (2008) find that replacing less than one day's worth of red meat and dairy Calories per week with chicken, fish, eggs, or vegetables is more effective in reducing GHG emissions than buying all food that is locally produced for one week. Heller and Keoleian (2014) determine that an iso-Caloric shift from current consumption patterns to the U.S. Department of Agriculture recommended diet could increase diet-related GHG emissions by 12%. Furthermore, they find that decreasing Caloric intake in addition to shifting diets for a population engaged in moderate physical activity could decrease diet-related GHG emissions by 1%. And finally, Jalava et al. (2014) determine that at the global level, shifting to the World Health Organization recommended macronutrient intake and conforming to the average dietary Caloric requirement for each country, would reduce the global blue water footprint by 1% and the global green water footprint by 2%.

While diet and food choices are shown to play an important role in environmental and resource use impacts, the effects of extra Caloric intake alone on US food related industrial energy use, water withdrawals, and GHG emissions have not been strictly quantified. This analysis therefore, contributes to the existing literature by measuring the potential savings in industrial energy use, water withdrawals, and GHG emissions that would be achieved if Americans consumed the appropriate amount of Calories, not accounting for change in food mix. The next sections present the methods and data used followed by a summary of the results and a discussion of the results.

2.2 Methods and Data

The method utilized is comprised of two main parts. First, two top down approaches, implementing an EIO-LCA model and a process-based model, are used to estimate the cumulative industrial energy use, water withdrawals, and GHG emissions needed to supply food to the US population. Data for the EIO-LCA model is retrieved from the Bureau of Labor Statistics 2012 Consumer Expenditures Survey (Bureau of Labor Statistics 2013) while data for the process-based model is taken from various government sources and scientific literature, which are discussed in Section A-2 of Appendix A. The results of these two models provide upper and lower bound estimates for cumulative energy demand, water withdrawals, and GHG emissions attributed to US food consumption.

Second, the total Calories and extra Calories consumed per American adult are estimated using data from the CDC National Health and Nutrition Examination Survey (Centers for Disease Control 1a). The basic formulation for determining extra environmental impacts associated with extra Caloric intake then follows as:

$$Extra\ Impact = Total\ Food\ Consumption\ Impact\ \times \frac{Extra\ Caloric\ Intake}{Total\ Caloric\ Intake} \qquad (1)$$

Where *Extra Impacts* are the additional industrial energy use, water withdrawals, and GHG emissions associated with producing extra Calories consumed by American adults, age 19+. Children and teens are excluded from this analysis since the criteria for establishing weight categories and thus, Caloric intake differ from those of adults (Centers for Disease Control 1b, Centers for Disease Control 1c). Also, while food consumption patterns are likely to vary between normal weight, overweight, and obese adults, the top down approach used in this Chapter does not allow for estimation of different food mix effects on overall impacts. Furthermore, food losses across the food supply chain are included in the food consumption and environmental impact estimates. Although food losses do not contribute to being overweight or obese, they are considered a part of the environmental impacts of the food that is consumed.

2.2.1 Food Related Industrial Energy Use, Water Withdrawals, and GHG Emissions

Environmental and resource use impacts associated with supplying food for US consumption are estimated using 1) the EIO-LCA model and 2) a process-based analysis. The first approach utilizes the 2002 EIO-LCA model, which estimates life-cycle industrial energy use, water withdrawals, and GHG emissions associated with economic activity (Lave et al. 1995, Hendrickson et al. 2006, CMU GDI 2008, Weber et al. 2009). Food expenditure data for input into the EIO-LCA model is retrieved from the Bureau of Labor Statistics 2012 Consumer Expenditure Survey, which categorizes annual household spending by items purchased (cereal, beef, fresh vegetables, etc.) and by consumer demographics, including by age group (Bureau of Labor Statistics 2013). The listed food items for adults are mapped to corresponding economic input-output commodity groups to obtain commodity-level adult food expenditures in the US, which are then adjusted to the year 2002 using the Bureau of Economic Analysis price indices for gross output for each commodity group (Bureau of Economic Analysis 2014). Standard errors are also provided for expenditures for each food item, which are propagated throughout all calculations to estimate total uncertainty in the annual food costs for the American adult population. The annual commodity-level adjusted constant food purchases for adults in 2012 is approximately, \$479 $\pm$ \$8.78 billion, which results in around 77% of total US food-related life-cycle environmental impacts. The remaining impacts are attributed to food consumed by children and teens. Detailed food expenditure accounts are available in Section A-1 of Appendix A.

Although some food choice purchases are tied to commodities produced in other countries, this analysis excludes international effects. It is assumed that international food-related technologies yield similar environmental impacts to US technology. Also, while the EIO-LCA model is effective in scoping large quantities of products, it aggregates different goods into same economic sectors (Weber and Matthews 2008, Lave et al. 1995). Another drawback is the use of a 2002 model, the latest EIO-LCA model, to evaluate the environmental impacts for food consumption in 2012. Consequently, any food-related technological change over the last decade is unaccounted for in this model. Despite these limitations, the EIO-LCA method is advantageous in reducing "cutoff error" through the food supply system, which is a major shortcoming of the process-based model (Weber and Matthews 2008, Lave et al. 1995). "Cutoff error" is the difference between the impacts associated with a limited supply chain and those accompanying the entire supply chain (Lenzen 2000).

The second approach in this study, the process-based model, entails compiling and totaling separate industrial energy use, water withdrawal, and GHG emissions estimates for each phase of the US food supply system, including agriculture, processing and packaging, transportation, wholesale and retail, food services, and household preparation. This analysis excludes impacts associated with waste disposal methods as well as impacts due to land use and land use change and forestry. Furthermore, unlike the EIO-LCA model, the process-based model does not account for resource inputs needed to produce transportation modes used in the US food supply system.

To obtain food-related impacts for adult consumption only, 77% (determined using the EIO-LCA model) is applied to the process-based impacts.

Process activity estimates for each food stage are retrieved from various governmental data sources and scientific literature (Section A-2 of Appendix A), many of which include the environmental impacts associated with food exports and exclude those for food imports. Since different food products are associated with different environmental effects, the top-down approach used here cannot facilitate allocation of impact estimates to food exports and imports. This part of the analysis, therefore, excludes any international effects related to food consumption in the US. Despite this limitation, it is assumed that any environmental impacts pertaining to food imports and exports would be relatively small compared to the overall impacts attributed to US food consumption. In 2009, US food exports were roughly 3% greater than food imports (USDA Economic Research Service 1d, USDA Economic Research Service 1e). Another limitation of this model is the lack of uncertainty parameters for various food supply stages. For those phases for which uncertainty is provided, standard errors are developed and propagated throughout all calculations to estimate total uncertainty of environmental impacts associated with US food consumption. Uncertainty estimations are detailed in Section A-5 of Appendix A.

2.2.2 Extra Caloric Intake per Person

Extra Caloric intake per person is the amount of food Calories beyond which a person needs to maintain a healthy weight, given that the individual is overweight or obese. The daily Caloric intake for adults is a function of Resting Energy Expenditure (REE) and physical activity (Lieberman and Marks 2013). REE is the amount of energy in the form of food Calories that is required to support 24 hours of normal metabolic functions at rest, including heartbeat, breathing, and body temperature (Lieberman and Marks 2013). Numerous predictive equations for REE have been developed, with subsequent studies examining the validity of many of these equations. Eight of these equations, which were found to be more accurate in predicting REEs, were selected for use in this analysis (Weijs 2008). Table 2-1 displays relevant information for these eight REE predictive equations.

Table 2-1 Selected REE predictive equation studies

Authors	**Year**	**Parameters**	**RMSE[a] (Calories/day)**
Mifflin et al.	1990	Weight, Height, Age, Gender	136
Harris & Benedict	1919	Weight, Height, Age, Gender	148
Roza & Shizgal	1984	Weight, Height, Age, Gender	151
Schofield	1985	Weight, Age, Gender	156
Owen et al.	1986, 1987	Weight, Gender	174
Muller et al.	2004	Weight, Age, Gender	139
Henry	2005	Weight, Age, Gender	144
Livingston	2005	Weight, Age, Gender	139

[a]Note: RMSE is root mean squared prediction error. *Weijs, P. (2008) evaluated the accuracy of 29 REE predictive equations based on bias, RMSE, and percentage accurate prediction. Eight of these equations, which yielded higher accuracy scores, were selected for use in this study, and their corresponding RMSE values were used in the uncertainty analysis, which is provided in Section A-5 of Appendix A.*

Anthropometric parameters for the REE predictive equations along with physical activity data are retrieved from the CDC National Health and Nutrition Examination Survey, which interviews and examines thousands of respondents in the US each year (Centers for Disease Control 1a). Refer to Section A-3 of Appendix A for detailed methods used to calculate extra Caloric intake estimates.

Figure 2-1 displays extra daily Calories consumed per American adult and the percentage of Calories consumed that are extra Calories.

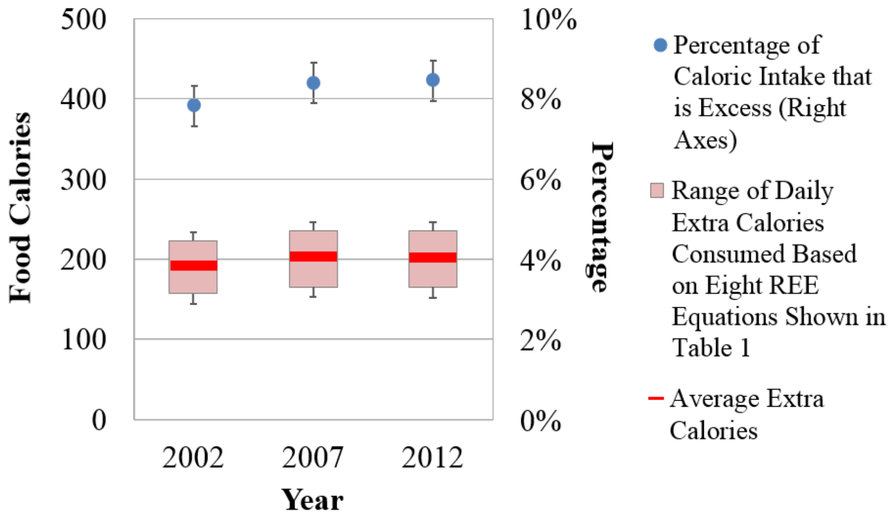


Figure 2-1 Extra Caloric intake per US adult. Whiskers represent the standard errors for estimated values. The boxplot whiskers are the uppermost and lowermost standard errors for the upper bound and lower bound estimates for the daily extra Calories consumed. See Table A-2 in Appendix A, for numerical results.

Between 2007 and 2012, average extra Caloric intake did not increase. During this time period, adults consumed, on average, between 170 (±7) and 240 (±6) extra Calories per day, representing roughly 7.5% (±0.2) to 10% (±0.2) of total Caloric intake. Uncertainty is estimated based on the root mean squared prediction errors (RMSE) for the REE equations, which are used as approximations for the standard errors of actual and recommended Caloric intake estimates for each NHANES survey respondent. Furthermore, it is assumed that the eight REE equations used in this analysis provide a wide range of values that account for the majority of uncertainty in the extra Caloric intake estimates. Refer to Appendix A for detailed results and for further discussion of the uncertainty associated with this step of the process.

2.3 Results

2.3.1 Food Related Industrial Energy Use, Water Withdrawals, and GHG Emissions

Figure 2-2 displays the cumulative energy use, water withdrawals, and GHG emissions through the food supply system that are needed to provide food to US adults.

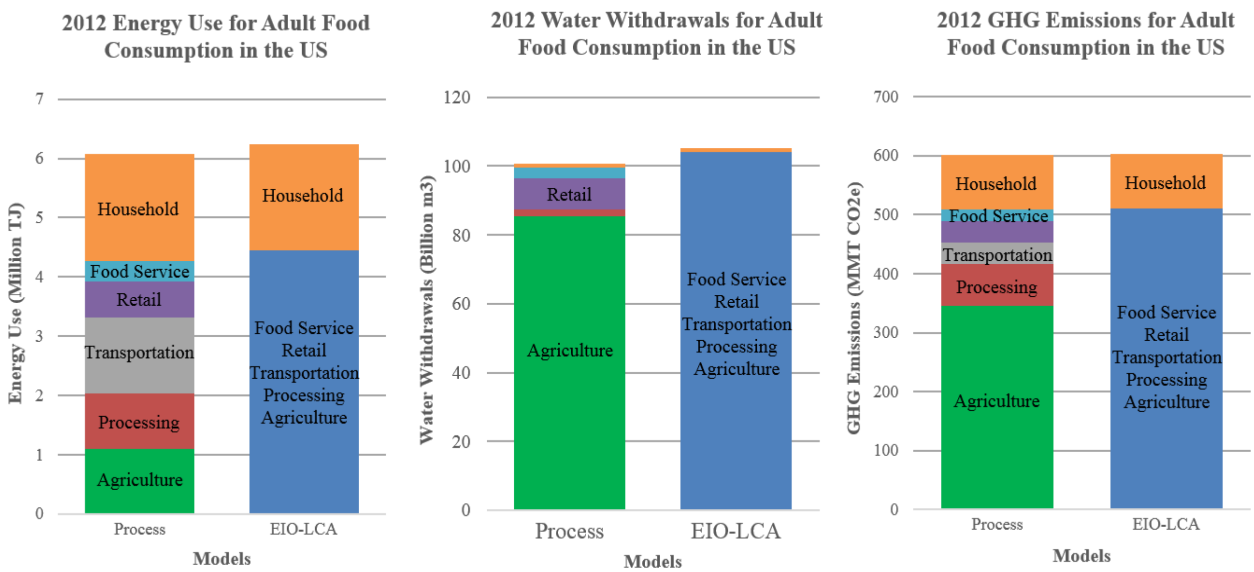


Figure 2-2 Total industrial energy use, water withdrawals, and GHG emissions. Environmental impacts are allocated to various food supply stages. Food losses are included in these estimates. Refer to Table A-3 in Appendix A, for numerical results and data sources used.

In 2012, total energy use and GHG emissions for all sectors in the US were 100.3 million TJ and 6,526 MMT CO_2-eq, respectively (US Environmental Protection Agency 2014a, US Energy Information Administration 1c). The latest US Geological Survey estimated that in 2010, 490.5 billion m^3 of water was consumed for all purposes in the US (US Geological Survey 2014). This suggests that the environmental impacts attributed to providing food for American adults represents, on average, 6% of energy use, 21% of water withdrawals, and 9% of GHG emissions for all sectors in the US.

The cumulative energy demand estimates for providing food to US adults range from around 6.1-6.2 million TJ. Cuellar and Webber (2010) and Canning et al. (2010) also used top-down approaches to determine cumulative energy use in the US food supply system as 8.4 million TJ in 2004 and 13.5 million TJ in 2007, respectively. These values amount to roughly 6.5 and 10 million TJ for adult consumption only. The estimates found here are therefore, 6% lower than that of Cuellar and Webber and 38% lower than that of Canning et al.

Hoekstra and Mekonnen (2012) calculated that from 1996 to 2005, the total water footprint of the average American consumer was 2,842 m^3 per year. Using a bottom-up approach, they also found that roughly 85% of this amount was attributed to food consumption. Furthermore, they determined that the blue water footprint (ground and surface water) accounted for roughly 8% of the total US water footprint. Based on these percentages, the blue water footprint for providing food to the US adult population during the period 1996 to 2005, was approximately 53 billion m^3 of water per year. In this analysis, the water withdrawal values of 100 and 105 billion m^3 in 2012 are nearly twice as large as the blue water footprint amount estimated by Hoekstra and Mekonnen.

Additionally, Weber and Matthews (2008) determined that food consumption accounted for 8.1 t CO_2-eq/household-yr. Based on their value, GHG emissions are approximately 740 MMT CO_2-eq for adult food consumption in 2012. Meanwhile Heller and Keoleian (2014), using a bottom-up approach, estimated annual GHG emissions associated with total food consumption as 573 MMT CO_2-eq, which would amount to roughly 440 MMT CO_2-eq for the adult population in 2012. The GHG emissions estimate found here of 600 MMT CO_2-eq is 19% lower than that of Weber and Matthews, who also use a top-down approach, and 36% higher than that of Heller and Keoleian.

2.3.2 Extra Food-Related Environmental Impacts Attributed to Extra Caloric Intake

Figure 2-3 shows the extra environmental and resource use impacts in the food supply system needed to provide the additional Calories consumed by overweight and obese adults in the US. In 2012, extra Caloric intake of the adult population comprised, on average, 8.9% of the total Caloric intake of adults. This means that, on average, 8.9% of the total impacts of adult food consumption in the US were attributed to supporting the extra Caloric intake of the overweight and obese adult population. In 2012 the extra impacts represented approximately 0.5% of total energy use, 2% of total water withdrawals, and 0.8% of total GHG emissions for all sectors in the US.

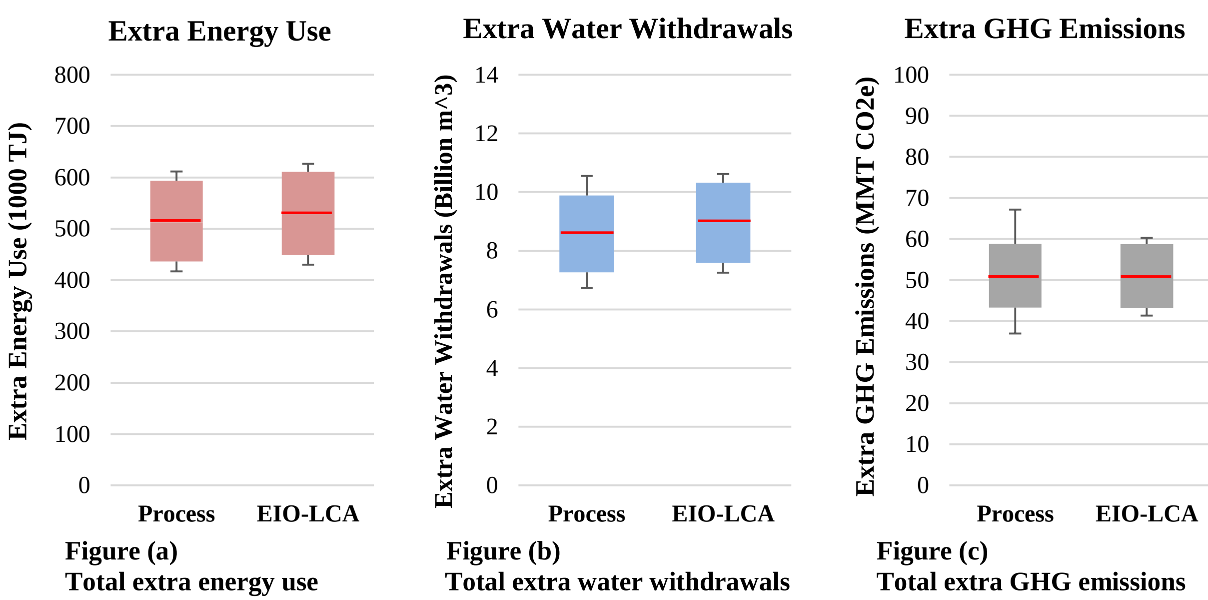


Figure 2-3 Extra Industrial Energy Use, Water Withdrawals, and GHG Emissions. Figures (a)-(c) display the extra energy use, water withdrawals, and GHG emissions required to support the extra Calories consumed by the US adult population. The boxes represent the range of impacts estimated from the range of extra Caloric intake values (see Figure 2-1), which were calculated using eight REE equations (see Table 2-1). Results are presented for both the process-based model and the EIO-LCA model. The red lines represent the mean impact values. The whiskers represent the topmost and lowermost standard error bars corresponding to the upper bound and lower bound extra impact estimates.

The spread of values in Figure 2-3 corresponds to the range of estimates for extra Caloric intake per adult, which are discussed in Section 2.2.2. Numerical values for the extra impact results are provided in Tables A-4 and A-5 of Appendix A. On average, 8.9% of total food consumption impacts in 2012 are attributable to extra Caloric intake of US adults. This means that the added industrial energy and water inputs needed to produce extra food Calories for overweight and obese Americans are enough to supply food to 8.9% of the US adult population for an entire year. This represents nearly 20 million healthy weight adults, which is roughly equivalent to the population of New York State.

2.4 Discussion

From this analysis it is estimated that in 2012, providing food to the US adult population results in 6.1-6.2 million TJ of cumulative energy use, 100-105 billion m^3 of water withdrawals, and 600 MMT CO_2-eq GHG emissions. These results are subject to significant uncertainty; an uncertainty analysis was implemented and is provided in Section A-5 of Appendix A. A sensitivity analysis was also performed for the process-based model to gain insight as to which parameters were most critical. Table 2-2 addresses model sensitivity to 10% changes in the process-based model input parameters. Comparing the sensitivity of changes in the food consumption impacts from the various food supply phases, Table 2-2 shows that a 10% adjustment in household energy use produces the greatest change in energy use results while food services energy use changes have the least impact. For water withdrawal and GHG emissions estimates, 10% changes in agricultural impacts yield the highest change in impact results while adjustments in household and food service impacts result in the least amount of change.

Table 2-2 Sensitivity of impact estimates to changes in process-based model input parameters

Model Parameters[a]	Sensitivity Results: Extra Energy Use (% Change)	Extra Water Withdrawals (% Change)	Extra GHG Emissions (% Change)
Total Impacts[b]	10	10	10
Agricultural[c]	2.3	8.5	5.7
Processing/Packaging[c]	2.0	0.2	1.2
Transportation[c]	2.1	0.0	0.6
Wholesale/Retail[c]	1.3	0.9	0.6
Food Services[c]	0.7	0.3	0.3
Household[c]	3.7	0.1	1.5

[a] Model parameters are individually changed by 10% to determine the effects on the impact results.
[b] Total impacts refer to total food-related cumulative energy demand, water withdrawals, and GHG emissions required to produce food consumed by the US adult population (including impacts associated with food losses).
[c] Impacts refer to cumulative energy demand, water withdrawals, and GHG emissions associated with individual food production stages that are required to produce food consumed by the US adult population (including impacts associated with food losses)

Additionally, it is determine that 8.9% of total food-related environmental impacts in the US are attributed to providing extra Calories consumed from overeating. To demonstrate the relevance of these results, they are compared to impacts from other consumer choices. 1) The extra industrial energy use estimates are roughly equivalent to the annual energy use savings that would be achieved by replacing traditional incandescent lightbulbs with energy-saving incandescents in all US residential and commercial buildings or switching 45% of all traditional incandescents to compact fluorescent lamps (CFLs) or light emitting diodes (LEDs) (US Department of Energy 2014, US Energy Information Administration 1a). 2) The extra water withdrawal estimates are 35% greater than the annual water use savings of replacing all toilets, faucets, and showerheads in US households with water efficient fixtures and nearly three times greater than annual water use savings that could be achieved from installing water efficient appliances (washing machines, dishwashers, etc.) in all residential buildings in the US (US Environmental Protection Agency 2014b). 3) Finally, the GHG emissions estimates are equivalent to the GHG emissions of nearly

12 million passenger vehicles annually based on the estimated GHG emissions of 4.4 MMT CO_2-eq light-duty vehicle^{-1} year^{-1} (Davis and Diegel 2014).

The implications of these results suggest that the impacts associated with extra Caloric intake are comparable to those attributed to many other consumer choices. Also, while individual American citizens have less ability to affect policies that seek to lower costs for eco-friendly consumer products, Americans can adopt consumption behaviors that promote food-related environmental sustainability, particularly in terms of our food purchases.

That being said, the quality of our diet is as important as the quantity of Calories we consume with regard to human and environmental health outcomes. While it is feasible to achieve normal weight by reducing Calories without shifting diet mix (Freedman et al. 2001), it is beneficial from a human health perspective to consider both factors. From an environmental standpoint, it is also important to consider both the source of our Calories and the amount of Calories we consume. Heller and Keoleian (2014), for example, found that adopting the recommended US Department of Agriculture (USDA) Dietary guidelines, in terms of food mix, without reducing Caloric intake increased diet-related GHG emissions by 12% and that changing both diet and reducing Calories only decreased emissions by 1%.

Due to the top-down method utilized in this Chapter, a lower level analysis of individual foods, and therefore, consideration of shifts in dietary food mix, is not possible. It is acknowledged that this is one of the major drawbacks of this section. In response to this limitation, a bottom-up approach, which enables assessments of the environmental impacts associated with individual food types, is implemented in the next Chapter of this manuscript. This approach allows for further investigation of the impacts of dietary changes, in terms of both quality and quantity, on cumulative energy use, water withdrawals, and GHG emissions in the food supply system.

While savings in industrial energy use, water withdrawals, and GHG emissions from the food supply system could be achieved if US adults consumed the requisite Caloric intake for maintaining normal weight, a number of other compounding factors also affect overall food-related impacts, including population size, food mix, food cost, technology, and industrial processes within the food supply chain. At the individual level we have less ability to affect some of these factors, particularly technology and food supply chain processes. However, we can adjust our ecological footprint through our purchasing decisions and lifestyle choices, which may also impact the overweight and obesity rates in the US and the accompanying health risks associated with extra body weight.

3. ENERGY USE, WATER WITHDRAWALS, AND GREENHOUSE GAS EMISSIONS FOR CURRENT FOOD CONSUMPTION PATTERNS AND DIETARY RECOMMENDATIONS IN THE US

3.1 Introduction

In 2010, the US Department of Agriculture (USDA) published their most recent *Dietary Guidelines for Americans*, which help individuals choose healthy eating patterns (USDA and US Department of Health and Human Services 2010). Amidst the current overweight and obesity epidemic in the US, the *Dietary Guidelines* provide food and beverage recommendations that are intended to help individuals achieve and maintain healthy weight. While the previous chapter used two top-down approaches to examine the impact of Caloric consumption on energy use, water withdrawals, and GHG emissions in the food supply system, this chapter implements a bottom-up approach to examine the changes in energy use, water withdrawals, and GHG emissions resulting from shifts in both food mix and Caloric consumption. Furthermore, while Heller and Keoleian (2014) evaluated the GHG emissions impact of adopting the USDA recommended diet, this analysis is the first to examine the multiple effects that shifting to the USDA dietary recommendations has on energy use, water withdrawals, and GHG emissions.

Heller and Keoleian (2014) determined that shifting from our current average diet to the USDA recommended diet (for a population engaged in moderate physical activity) could reduce GHG emissions within the food supply chain by 1%. However, they also find that shifting food mix alone, without accounting for decreased Caloric intake could increase diet-related GHG emissions by 12%. While this study also examines the impact on emissions of shifting to the USDA dietary recommendations, this analysis assumes different Caloric intake levels and includes only adults.

Further explanation is provided in subsequent sections. In another study similar to this analysis, Meier and Christen (2012) determine that, in Germany, switching from current dietary patterns to the German Nutrition Society dietary recommendations could reduce energy use by 7%, blue water use by 26%, GHG emissions by 11%, and land use by 15%.

Additionally, a number of studies investigate the impacts of various other diets on the environment. Tilman and Clark (2014), for example, find that current global dietary shifts toward Calorie-dense foods have not only led to enhanced levels of obesity and diet-related non-communicable diseases around the world, but have also increased agricultural land use and clearing and increased global GHG emissions. They also estimate that by the year 2050 food production emissions will increase 80% if current dietary trends continue. Conversely, large scale shifts toward Mediterranean, pescetarian, and vegetarian diets could potentially reduce global agricultural emissions and land clearing by 2050. Eshel and Martin (2006) determine that an omnivorous diet produces approximately 1,500 kg CO_2-eq more than a vegetarian diet incorporating the same number of Calories. Likewise, Weber and Matthews (2008) find that replacing less than one day's worth of red meat and dairy Calories per week with chicken, fish, eggs, or vegetables is more effective in reducing GHG emissions than buying all food that is locally produced for one week.

This study contributes to the existing literature by providing further insight and analysis to the environmental costs that various dietary choices have on the food supply system in the US. To the best of my knowledge, this analysis is the first to measure the changes in energy use, water withdrawals, and GHG emissions associated with shifting from current consumption patterns to three dietary scenarios, which are based, in part, on the 2010 USDA *Dietary Guidelines*. The three dietary scenarios include 1) reducing Caloric intake levels to achieve "normal" weight without shifting food mix, 2) shifting food mix to food patterns recommended by the USDA *Dietary Guidelines*, without reducing Caloric intake, and 3) reducing Caloric intake levels and shifting food mix to meet USDA *Dietary Guidelines* in order to achieve and maintain healthy weight.

This analysis uses a bottom-up approach based on a meta-analysis of existing academic literature and scientific reports to quantify the cumulative energy use, water withdrawals, and GHG emissions throughout the food supply chain associated with the three aforementioned dietary scenarios. The next sections present the methods and data used followed by a summary of the results and a discussion of the results.

3.2 Methods and Data

The method used is comprised of three main parts: population size, Calories consumed (including food losses) per person, and the life-cycle energy use, water withdrawals, and GHG emissions associated with each Calorie. For this study, Caloric consumption refers to the sum of Calories eaten (or the Caloric intake) plus Calories lost through retail-level and consumer-level food losses, which is discussed further below.

The basic formulation for this analysis then follows as:

$$Impact_{(A,R)} = \sum_{i}^{n} Adult\ Population * \left(\frac{Calories}{Person}\right)_{i_{(A,R)}} * \left(\frac{Impact}{Calorie}\right)_{i_{(A,R)}} \qquad (1)$$

Where *Impact* represents food-related energy use, water withdrawals, and GHG emissions associated with actual (*A*) and recommended (*R*) Calories consumed within each food group, *I*, by American adults, age 19+. Children and teens are excluded from this analysis since the criteria for establishing weight categories and thus, Caloric intake, differ from those of adults (Centers for

Disease Control 1b, Centers for Disease Control 1c). Population data is retrieved from the US Census Bureau, which categorizes individuals by demographics, including by age group (US Census Bureau 2013). In 2010 the US adult population was roughly 230 million people.

3.2.1 Calories per Person

The 2010 *Dietary Guidelines* for Americans categorizes the average daily intake (per 2,000 Calories) in the US from 2007 to 2010 by food group and by age group (USDA and US Department of Health and Human Services 2010). Furthermore, the *Dietary Guidelines* provide a benchmark food density chart, which displays recommended daily intake of each food group for a range of daily Caloric intake needs. Caloric intake estimates were developed in the previous chapter (Section 2.2.2) of this report and were based on average physical activity levels and Resting Energy Expenditure (REE) values. Resting energy expenditure is the amount of food Calories an individual's body requires for normal metabolic functions at rest over a 24-hour period (Lieberman and Marks 2013). Anthropometric data as well as physical activity levels were retrieved from the Centers for Disease Control (CDC) National Health and Nutrition Examination Survey, for input into select REE predictive equations.

In Chapter 2, the average Caloric intake per US adult is determined to be, on average, 2,350 Calories per day, which is approximately, 210 Calories more than what is required to maintain "normal" or healthy weight given the physical activity level of the average American adult. According to the USDA Economic Research Service (ERS) Loss-Adjusted Food Availability (LAFA) data series, Americans eat, on average, 2,534 Calories daily (USDA Economic Research Service 1b). The USDA, however, states that despite the current obesity epidemic, this Calorie amount is high and unrealistic (Buzby et al. 2014). Therefore, the actual and recommended Caloric intake levels that were developed here, are used in this analysis. Caloric intake estimates are detailed in Tables A-6 and A-7 in Appendix B.

Additionally, food losses are incorporated at the retail and consumer levels into this analysis. Although food losses do not contribute to unhealthy eating, they contribute to the overall environmental impacts associated with purchased food, which is directly related to food that is eaten. Food loss estimates based on the LAFA data series (USDA Economic Research Service 1b), are retrieved from a USDA report by Buzby et al. (2014), which provides a best estimate of the percentage of Calories within each food group that are lost at the retail and consumer levels in 2010. Based on these percentages, it is determined that in 2010, American adults consumed, on average, around 3,570 Calories daily, with around 34% of the total Calories attributed to retail and consumer-level food losses. It is important to note that while efforts are underway to improve food loss estimates, the USDA Economic Research Service (ERS) still considers their food loss data to be preliminary, particularly at the retail and consumer levels. However, to our knowledge, this information is the best that is available at this time. Refer to Table A-8 in Appendix B, for detailed estimates of food losses and total food consumed in the US in 2010.

Figure 3-1 displays the daily shifts in Caloric consumption of each food group from the current US diet to three dietary scenarios. The first scenario accounts for a reduction in Caloric intake needed to achieve "normal" weight, but maintains our current food mix. The second and third scenarios follow the *Dietary Guidelines* for recommended food mix. But the second scenario does not account for a reduction in Caloric intake, while the third scenario does. The average current

Caloric consumption per American adult is around 3,570 Calories. Average recommended Caloric consumption values are estimated as 3,250 Calories for scenario 1, 3,510 Calories for scenario 2, and 3,210 Calories for scenario 3. Although the first and third scenarios account for the same reduction in Caloric intake, Caloric consumption estimates differ due to different food mixes, which yield separate food loss values.

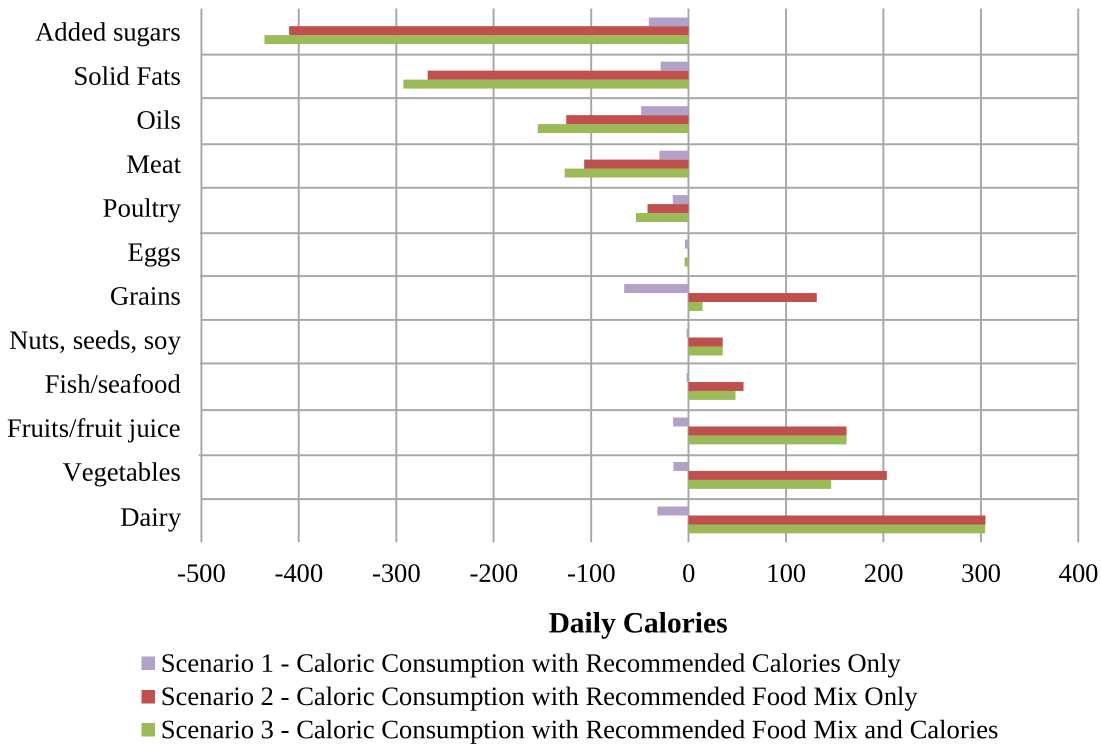


Figure 3-1 Shifts in average daily Caloric consumption per adult from the current US diet to three dietary scenarios. Positive values represent an increase in Caloric consumption from our current diet to a recommended diet, while negative values represent a decrease in Caloric consumption from our current diet to a recommended diet.

3.2.2 Environmental Impact per Calorie

Following Heller and Keoleian (2014), a meta-analysis was conducted, of data published in a variety of government reports and scientific literature to determine ranges of life-cycle energy use and water withdrawals per Calorie consumed of each food type. In addition, GHG emissions data from Heller and Keoleian were incorporated. The food-related environmental impact estimates were drawn from life-cycle assessment studies conducted in advanced industrialized countries. Various climates, transport modes and distances, food-related technology, and production methods are reflected among the data compiled. Therefore, the impact intensity estimates found for each food type are averaged and used in this analysis. Furthermore, the minimum and maximum environmental impact estimates found in the literature are listed to provide impact intensity ranges for each food type. Refer to Section B-2 of Appendix B for detailed results of the meta-analysis of environmental impact factors for 100 plus food types.

Figure 3-2 displays index scores for average energy use, water withdrawals, and GHG emissions through the food supply system required to produce and consume one Calorie of each food group. Fish and seafood have the highest energy use index value, while vegetables and meat yield the highest index scores for water withdrawals and GHG emissions, respectively. The energy intensity of fishing activity is the main contributor toward the high energy use for fish and seafood (Foster et al. 2006). Meanwhile vegetables have the highest water withdrawal index score because 1) vegetables have, in general, low-Calorie density compared to other food types and 2) a large portion of our vegetables are grown in California, which has a naturally dry climate, thereby requiring large volumes of irrigation. Red meat attains the highest index score for GHG emissions, mainly due to methane emissions from enteric fermentation and nitrous oxide from excreted nitrogen as well as from fertilizers used to produce animal feed (United Nations Environment Programme 2012). Conversely, the grains food group as well as nuts, seeds, and soy have the lowest energy index scores, with grains also having the lowest GHG emissions index value. Meanwhile, fish and seafood rank lowest for water withdrawals.

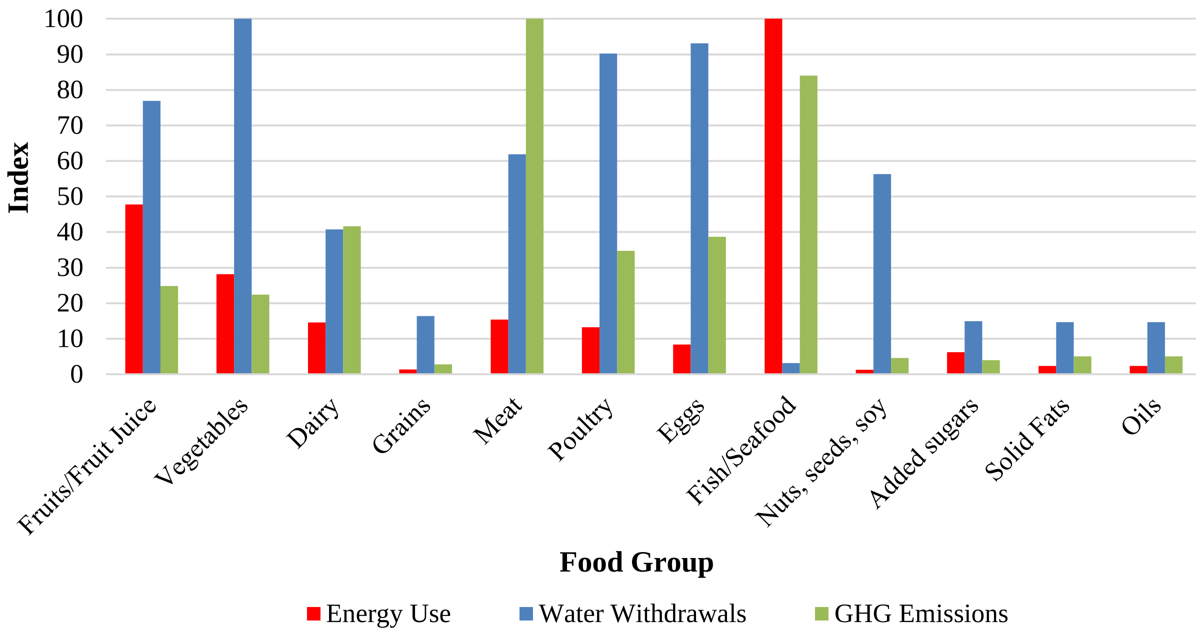
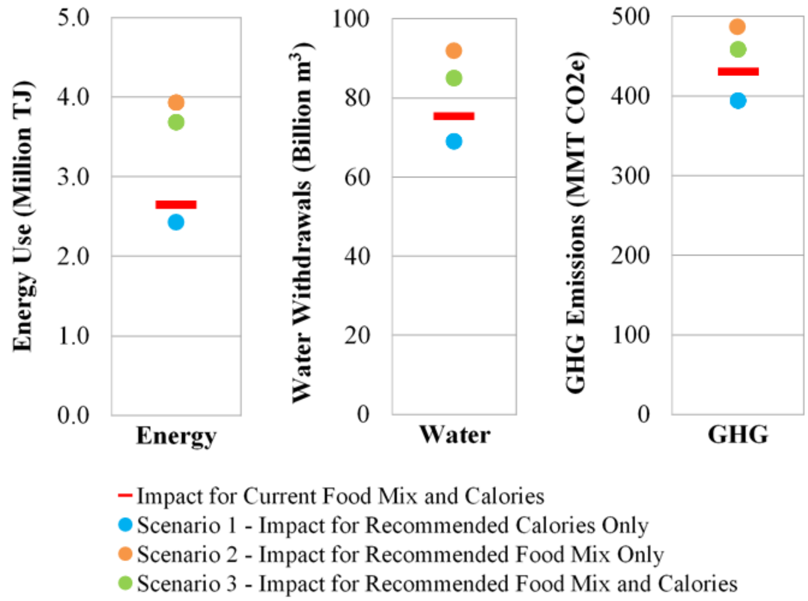


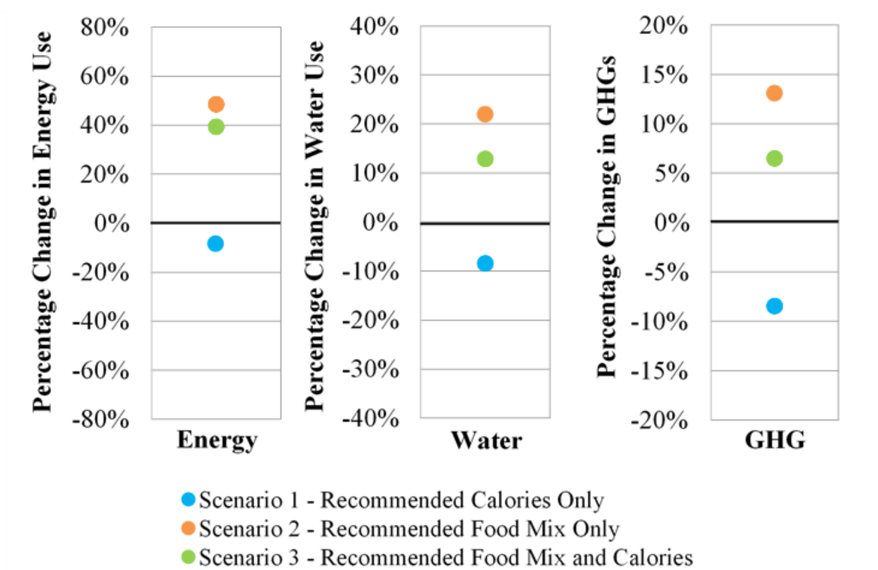
Figure 3-2 Indices of average energy use, water withdrawals, and GHG emissions per Calorie of food for each food group. An index score of 100 represents the highest environmental impact per Calorie. Scores were developed based on the weighted averages of impact per Calorie estimates found for comparable food types within each food group. Refer to Section 1.2 of the Supplementary Online Information for impact factors for all 100 plus food types used in this analysis.

3.3 Results

Figure 3-3(a) displays the average annual energy use, water withdrawals, and GHG emissions associated with the current average diet of American adults and with the three dietary scenarios, which are based, in part, on the USDA *Dietary Guidelines*. It is important to note that all values include consumer and retail-level food losses. As shown in Figure 3-3(b), a shift to a diet with the recommended Caloric intake only, reduces energy use, water withdrawals, and GHG emissions by around 9%, while a shift to a diet with the recommended food mix only, increases energy use by 48%, water withdrawals by 22%, and GHG emissions by 13%. Shifting to the recommended dietary scenario that accounts for both reduced Caloric intake and a shift to the USDA recommended food mix increases energy use by 39%, water withdrawals by 13%, and GHG emissions by 6%.



a.) Total annual energy use, water withdrawals, and GHG emissions



b.) Percentage change in energy use, water withdrawals, and GHG emissions

Figure 3-3 Energy use, water withdrawals, and GHG emissions through the food supply chain. Graph a. displays the average annual energy use, water withdrawals, and GHG emissions required to support the current diet of the US adult population as well as the three recommended dietary scenarios. The red lines represent the food-related impacts associated with our current diet while the dots correspond to the annual impacts associated with the three dietary scenarios. Graph b. represents the shifts in energy use, water withdrawals, and GHG emissions from our current diet to the three recommended diets.

It is perhaps especially surprising that cumulative energy use, water withdrawals, and GHG emissions all increase under Scenario 3, which, in addition to a shift in food mix, also accounts for an 9% reduction in Caloric consumption. Despite this Calorie reduction, cumulative energy use increases by nearly 40% due to USDA recommendations for higher consumption of seafood, fruits, and vegetables (Figure 3-1). Among all food groups, these foods represent the greatest cumulative energy use per Calorie (Figure 3-2). Furthermore, although the USDA recommended diet requires substantial decreases in sugars, fats, and oils, these foods require significantly less cumulative energy use per Calorie.

Water withdrawals also increase significantly under dietary Scenario 3 mainly due to increased quantities of fruits and vegetables, which require relatively high amounts of irrigation per Calorie. Although poultry and eggs are the second and third most water-intensive foods per Calorie as shown in Figure 3-2, the recommended reduction of these two foods is small relative to the considerable increase in fruits and vegetables, demonstrated in Figure 3-1. Furthermore, despite significant decreases in Caloric consumption of sugars, fats, and oils, these foods require relatively low water withdrawals per Calorie.

Lastly, GHG emissions increase despite reduction of Calories and a shift to the USDA recommended food mix, which lowers red meat consumption. Although meat products have the highest emissions per Calorie, overall GHG emissions increase due to increased Caloric intake of dairy, seafood, fruits, and vegetables, which collectively offset emission reductions resulting from decreased meat consumption as well as reduced sugars, fats, and oils, which again, have relatively low emissions per Calorie. While the recommended reduction of Calories is mainly attributable to lower consumption of sugars, fats, and oils, these food products have very low impacts and are therefore, insufficient in reducing overall environmental impacts associated with shifts toward the USDA *Dietary Guidelines*.

3.4 Discussion

In light of the obesity epidemic in America, there have been recent efforts to promote healthy eating habits through reducing Caloric intake and encouraging healthier dietary choices. This movement has led to the emergence of a body of scholarship investigating the relationships between food consumption and environmental sustainability. The present study advances the debate further by utilizing a more nuanced measure of food consumption to demonstrate that healthy dietary changes can have negative implications for environmental sustainability, thus illustrating an example of tension between public health and environmental sustainability. In addition, this study's results demonstrate how the environmental benefits of reduced meat consumption may be offset by increased consumption of other relatively high impact foods, thereby challenging the notion that reducing meat consumption automatically reduces the environmental impacts of one's diet. As the results found in this analysis show, food consumption behaviors are more complex, and the outcomes more nuanced.

While it is feasible to achieve normal weight by reducing Calories without shifting food mix (Freedman et al. 2001), it is beneficial from a human health perspective to consider both factors. As shown here, from an environmental standpoint, it is also important to consider both the source of our Calories and the amount of Calories we consume. As this study demonstrates, reducing Calories alone to achieve normal weight, could reduce energy use, water withdrawals, and GHG emissions for adults by as much as 9%, assuming that food supply follows reduced demand. However, when considering both Caloric reduction and a dietary shift to the USDA recommended food mix, energy use increases 39%, water withdrawals increase 13%, and GHG emissions increase 6%. These results represent an increase of roughly 1% of the total national annual energy budget, 2% of total US water withdrawals, and 0.5% of total US GHG emissions for all sectors. These findings provide reasons for decision makers to consider both the nutritional value and environmental implications of food choices when developing dietary recommendations.

As noted above, there is a robust and ever growing literature on this subject. Heller and Keoleian's results for GHG emissions associated with shifts to dietary recommendations differ from the estimates found here. Heller and Keoleian (2014) find that shifting food mix without reducing Calories yields a 12% increase in diet-related GHG emissions, while accounting for both food mix and Calorie reduction leads to a 1% decrease in emissions. Their results differ from the estimates found here, in part because their findings are based on Caloric intake estimates, whereas the results found in this analysis are based on Caloric consumption estimates, which include retail and consumer-level food losses. Food-losses are included in the estimates because they contribute to the overall environmental impacts associated with food choices. Furthermore, Heller and Keoleian assume a reduction in Calories from current Caloric intake (based on the LAFA data series) to recommended Caloric intake (for the average American, including children, assuming moderate physical activity) that is more than twice the reduction estimates implemented in this study. It is therefore, determined that shifting to the USDA recommended food mix alone yields a 13% increase in food-related GHG emissions for American adults, while shifting food mix and reducing Calories results in a 6% increase in GHG emissions.

Meier and Christen's findings for decreased energy use, blue water use or water withdrawals, and GHG emissions associated with an iso-Caloric shift to the German Nutrition Society official food-based dietary recommendations are significantly different from the increased impact estimates found here resulting from an iso-Caloric shift to the USDA *Dietary Guidelines*. This is largely due to contrasting shifts from current to recommended diets. For example, Meier and Christen's study accounts for larger reductions in meat, poultry and egg consumption and smaller increases in vegetable and dairy products. Their analysis also accounts for reduced fruit consumption, whereas the USDA recommends that the portion of the US current Caloric intake attributable to fruit intake be increased by nearly 85%. Furthermore, contrary to our dietary recommendations, the German Nutrition Society suggests a slight increase in fats and oils, and a larger increase in grain consumption. These foods, however, have relatively low impacts per Calorie compared to other foods, such as fruits, vegetables, meat, poultry, and eggs. Hence, the interplay between consumption patterns and dietary recommendations of different nations, and the environmental impacts associated with different foods explain the differences between the results found here and those of Meier and Christen (2012).

Environmental impact data for each food type evaluated in this study was collected from various environmental life-cycle assessment (LCA) studies, many of which were conducted in other developed countries. A major limitation of this study, thus, stems from this meta-analysis approach. For instance, differences in geography, climate, and culture may warrant different food production methods and resource requirements. Also, system boundaries and allocation methods differ among LCAs (Heller and Keoleian 2014). Therefore, minimum and maximum environmental intensities for each food type are reported in Section B-2 of Appendix B to demonstrate the potential range of results. An uncertainty analysis, however, was not conducted for this study due to insufficient statistical uncertainty information for model parameters. More extensive analyses of US-based LCAs for food products are also needed to better substantiate the findings of this analysis.

Additionally, the 100+ food types accounted for in this study are based on those listed in the LAFA data series. These foods, however, represent raw or semi-processed agricultural goods as opposed to final retail products (Heller and Keoleian 2014). Consequently, cumulative energy use, water withdrawals, and GHG emissions may be omitted from part of the processing phase of the food supply system for certain food types, thereby leading to underestimated results, which are discussed further in Chapter 5. Current literature, however, lacks LCA data for the wide array of food products purchased and consumed in the US. Despite this limitation, I feel that, given the available data, this analysis is the most comprehensive yet in this area.

This study sheds light on the trade-offs between human and environmental health within the context of dietary choices. Shifting from current consumption patterns to USDA dietary recommendations corresponds to an increase in diet-related energy use, water withdrawals, and GHG emissions among American adults. This perhaps counterintuitive outcome reveals the complex relationship between diet and the environment. While the results found here are not intended to dissuade healthy eating, they do draw attention to the need for cooperative efforts between policymakers, health officials, and consumers to establish dietary recommendations that meet both health and environmental objectives.

4. ENERGY USE, WATER WITHDRAWALS, AND GREENHOUSE GAS EMISSIONS FOR CURRENT FOOD CONSUMPTION PATTERNS AND DIETARY RECOMMENDATIONS IN THE US

4.1 Introduction

The effects of overweight and obesity are associated with increased social, economic, and environmental costs and may also be counteracting the efforts of industries and policymakers to move towards a more energy efficient and sustainable future. For example, most automobile manufacturers are developing strategies to reduce vehicular weight in order to achieve higher fuel efficiency ratings. However, the extra weight of overweight and obese passengers may be curtailing these efforts. In general, as weight in vehicles increases, fuel consumption also increases, which results in more greenhouse gas (GHG) emissions and greater spending on fuel.

This study builds upon existing literature to evaluate the impacts of increasing passenger weight on fuel use, GHG emissions, and fuel costs for three modes of transportation: light-duty vehicles, public transit, and commercial passenger aircraft. Furthermore, this study examines the trends of these impacts over 40 years, from 1970 to 2010, and performs an uncertainty analysis of the data and results.

Several studies evaluate the impacts of increasing passenger weight on various modes of transportation. Dannenberg et al. (2004) evaluate the impact of the average American weight gain from 1990 to 2000 on jet fuel consumption and associated fuel costs for passenger airliners in the year 2000. Jacobson and McLay (2006) develop a mathematical model to quantify the additional fuel consumed by noncommercial light-duty vehicles in the US that is attributable to excess passenger weight. They calculate that in 2003, between 272 and 938 million gallons (1.0 to 3.6 billion liters) of fuel were consumed because of increasing passenger weight in light-duty vehicles.

Contrary to the Jacobson and McLay (2006) model, which assumes constant values for vehicle-kilometers traveled, annual fuel consumption, and other critical parameters between 1960 and 2002, this analysis develops a more inclusive model that accounts for changes in all input variables over time. Furthermore, the Dannenberg et al. (2004) and Jacobson and McLay (2006) studies develop excess weight estimations based on average body weights of American adults, which accounts for the underweight and healthy weight portion of the population, thereby, offsetting the extra weight of the overweight and obese populations and reducing the estimated impacts attributable to excess weight. This analysis, however, excludes the underweight and healthy weight portion of the population in order to determine the amount of fuel use, GHG emissions, and fuel cost savings that would be achieved if individuals were not overweight or obese. This approach yields excess weight impacts that are roughly two times higher than if the average body weights were used for this analysis. And lastly, unlike most other studies, which examine one mode of transportation for one year, and in some instances, only evaluates one type of impact, this study investigates the GHG emissions and economic impacts of increased fuel use for light-duty vehicles, transit systems, and passenger aircraft over four decades. An uncertainty assessment of input variables and impacts is also established.

Finally, many studies explore the wide-ranging health and environmental impacts of transportation. In particular, growing evidence indicates that overweight and obesity are linked to a lack of infrastructure for active mobility (Frank et al. 2006). Active transport modes such as walking, cycling, and accessing public transit have many health benefits, which include reduced risk of obesity, cardiovascular disease, cancer, and type 2 diabetes, as well as increased life expectancy (Genter et al. 2008). Active transport also benefits individuals and society through reduced air pollution, noise pollution, and congestion associated with decreased automobile travel. Air pollution in the form of GHG emissions contribute to global climate change, which plays a significant role in human health. Warmer temperatures can lead to more extreme heat waves, which cause heat-related illnesses, such as heat exhaustion or heat stroke. Global climate change also contributes to extreme weather events, such as floods, droughts, and windstorms, which pose direct threats to human life and can also contribute to the spread of diseases (Costello et al. 2009). Automobiles also increase fine particulate matter, which is known to exacerbate asthma and bronchitis (Grabow et al. 2012). Additionally, vehicle noise pollution has been linked to health issues such as stress related illnesses, high blood pressure, hearing loss, and sleep disruption (US Environmental Protection Agency 2012a). The health and environmental impacts of vehicle air pollution, noise pollution, and climate change are later compared to the results found in this study.

This Chapter is organized into four main sections. The first section summarizes the data collected for the analysis. The second section describes the models used to determine impacts of increasing passenger weight on different transportation systems. The third section provides results of the models and uncertainty associated with the data and results. And the last section performs a critical analysis and discussion of the results.

4.2 Data

Data for this study is collected or estimated for light-duty vehicles, public transit, and passenger aircraft from 1970 to 2010, and includes vehicle, passenger, anthropometric, greenhouse gas (GHG) emissions, and economic data. These variables are then incorporated into the excess weight, fuel consumption, GHG emissions, and economic models for this analysis. When information for a particular year is not available, estimates are developed using linear interpolation from the surrounding years. Refer to Section C-1 in Appendix C for detailed analysis of all data used in this study.

Light-duty vehicles include passenger cars and light-duty trucks, which include pick-up trucks, SUVs, and vans. Public transit consists of commuter rail, light rail, and heavy rail (also known, in the US, as metro, subway, or rapid rail) systems, as well as public buses. Taxis are not included in transit. For passenger aircraft, information is collected and used for common carrier, domestic services. Table 4-1 lists vehicle data used and sources.

Table 4-1 Vehicle data and sources used

Number of Registered Vehicles for:	**Source**
Light-Duty Vehicles	US DOT, FHWA, Highway Statistics Series, 1970-2010
Transit Vehicles	Dickens et al., APTA, Fact Book, 2012
Passenger Aircraft	US DOT, BTS, National Transportation Statistics, 1970-2010
Annual Vehicle-Kilometers for:	**Source**
Light-Duty Vehicles	US DOT, FHWA, Highway Statistics Series, 1970-2010
Transit Vehicles	Dickens et al., APTA, Fact Book, 2012
Passenger Aircraft	US DOT, BTS, TranStats, 1970-2010
Annual Passenger-Kilometers for:	**Source**
Light-Duty Vehicles	US DOT, FHWA, Highway Statistics Series, 1970-2010

Transit Vehicles	Dickens et al., APTA, Fact Book, 2012
Passenger Aircraft	US DOT, BTS, TranStats, 1970-2010
Occupancy Load for:	**Calculation**
All Vehicles	Passenger-Kilometers Divided by Vehicle-Kilometers
Annual Fuel/Energy Use for all:	**Source**
Transit Vehicles	APTA, Fact Book, 2012
Passenger Aircraft	US DOT, BTS, TranStats, 1977-2010
Ratio of Change in Fuel Use to Change in Weight for:	**Source**
Light-Duty Vehicles	Heavenrich, US EPA, 1975-2010
Commuter Rail Vehicles	New York MTA, Smart Fleets Task Force Report, 2009
Light Rail Vehicles	Los Angeles MTA, Sustainable Rail Plan, 2013
Heavy Rail Vehicles	New York MTA, Smart Fleets Task Force Report, 2009
Transit Buses	Newland, University of Michigan HSRI, 1980
Passenger Aircraft	Lee et al., Historical and Future Trends in Aircraft Performance, Cost, and Emissions. Annual Review of Energy and Environment, 2001
Vehicle Kilometers Traveled Given Vehicle Age for:	**Source**
Light-Duty Vehicles	US DOT, NHTS, 1983, 1990, 2001, 2009

Notes: US DOT, United States Department of Transportation
FHWA, Federal Highway Administration
BTS, Bureau of Transportation Statistics
APTA, American Public Transportation Association
US EPA, United States Environmental Protection Agency
MTA, Metropolitan Transportation Authority
HSRI, Highway Safety Research Institute
NHTS, National Household Travel Survey

Passenger data is based on demographic and passenger statistics from various government sources and is listed with sources in Table 4-2.

Table 4-2 Passenger data and sources used

Kilometers Traveled per Male Driver and per Female Driver for:	Source
Light-Duty Vehicles	US DOT, FHWA, National Household Travel Survey
Number of Licensed Drivers for:	**Source**
Light-Duty Vehicles	US DOT, FHWA, Highway Statistics Series, 1970-2010
Adult Population Size of:	
Males and Females in the US	US Census Bureau, 1970-2010
Proportion of:	**Source**
Males and Females in the US	US Census Bureau, 1970-2010
Proportion of People who are Age:	**Source**
20+ Years	US Census Bureau, 1970-2010
Notes: US DOT, United States Department of Transportation FHWA, Federal Highway Administration	

Anthropometric data is retrieved from the National Center for Health Statistics and includes the percentages of male and female adults who are overweight or obese and mean weight and height data for different age groups in the US. The Body Mass Index (BMI) method, which is detailed in Section 4.3.1a, is used to determine the healthy or "normal" weight of individuals within specific age groups. This information is then used to estimate the average excess weight of passengers.

Greenhouse gas emissions data is retrieved from the Environmental Protection Agency (EPA) and the American Public Transportation Association (APTA), and includes only tailpipe emissions (Table 4-3). Greenhouse gases included in this study are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Hydrofluorocarbons (HFC) are omitted from this analysis because they are not emitted via combustion of fuels, but rather from vehicle air-conditioning leaks and end-of-life disposal (US Environmental Protection Agency 2008c, US Environmental Protection Agency 2008e), which are beyond the scope of this project.

Table 4-3 GHG emissions data and sources used

Annual GHG Emissions for:	Source
Transit Buses[a]	US EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011
Passenger Rail[a]	US EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011
Passenger Aircraft[a]	US EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011
GHG Emissions in Grams per Fuel Used or per Vehicle-Kilometers Traveled for:	**Source**
Light-Duty Vehicles[b]	US EPA, Direct Emissions from Mobile Combustion Sources, 1984-2005

Note: US EPA, United States Environmental Protection Agency
[a] For years prior to 1990, annual GHG emissions are estimated based on 1990 data. Refer to Section 4.3.3.
[b] For years prior to 1984 and after 2005, GHG emissions per unit are assumed to be consistent with those from 1984 and 2005, respectively.

Lastly, economic data include fuel or energy costs for each mode of transportation (Table 4-4).

Table 4-4 Economic data and sources used

Cost per Liter of:	Source
Gasoline (Petrol)	US EIA, 1970-2010
Jet Fuel	US EIA, 1970-2010
Costs for Energy (Electricity, Diesel, etc.) used in:	**Source**
Transit Vehicles	US EIA, 1970-2010

Note: US EIA, United States Energy Information Administration
APTA, American Public Transportation Association

4.3 Models

This section describes four models that are used to determine the impact of excess passenger weight on fuel use for light-duty vehicles, transit systems, and passenger aircraft in the US from 1970 to 2010. The first model builds upon the Jacobson and McLay (2006) model, which determines total occupant weight, to estimate excess occupant weight in vehicles. This process is discussed in more detail in Section 4.3.1. The second model computes additional fuel use attributed to excess occupant weight for each mode of transportation. And the last two models estimate GHG emissions and energy costs associated with this additional fuel use. For this analysis, the terms “excess occupant weight” and “excess passenger weight” are used interchangeably.

4.3.1 Excess Weight Model

Obesity patterns in the US vary with race, gender, income, and geography. However, the intent of this project is to establish a general estimate for the country as a whole. Identifying transportation statistics for each race, socioeconomic class, and geographical region is beyond the scope of this study.

4.3.1a Maximum “Normal” Weight

According to the National Institute of Health, “the terms ‘overweight’ and ‘obesity’ refer to body weight that’s greater than what is considered healthy for a certain height” (National Institute of Health 2012). A person’s weight and height is used to calculate Body Mass Index (BMI), which determines an adult’s weight category (e.g., normal, overweight, obese) as shown in Table A-10 of Appendix C. These criteria differ from those used to interpret BMI for children and teens (Centers for Disease Control 1b).

In this study, excess weight refers to additional weight beyond the healthy or maximum “normal” weight (BMI $\geq$ 25.0). Since weight categories are much more difficult to establish for children and teens, it is assumed that people age 0-19 years old are not carrying excess weight. Therefore, only excess weight of adults, age 20+ years old is included in this study. Maximum normal weights are calculated for adults using Equation (1) provided by the Centers for Disease Control and Prevention (Centers for Disease Control 1c).

$$E[MNW_G] = BMI * \ (H_G)^2 \tag{1}$$

where $E[MNW_G]$ represents maximum normal weight in kilograms, given gender, subscript G represents gender, *BMI* is 25, which corresponds to the overweight threshold, and H_G represents height in meters, given gender. Note that although the equation is nonlinear, any impact on maximum normal weight outcomes using weighted averages for mean heights is minimal.

4.3.1b Average Excess Weight per Overweight/Obese Individual

Average excess body weight is determined separately for male and female adults who are overweight or obese. These weight estimates are developed from 1970 to 2010 using Equations (2) through (4). First, the total weights of all male and all female adults in the US, $E[TW_G]$, are given by

$$E[TW_G] = W_G * Population_G \tag{2}$$

where W_G is the average weight of an adult and $Population_G$ is the adult population size.

Next, anthropometric data from the CDC National Health and Nutrition Examination Survey (Centers for Disease Control 1a) is examined to determine the proportion of the total adult population weight attributed to the overweight/obese males and females, $E[OW_G]$. These percentages are then used to estimate the collective weight of all overweight and obese adults, $E[TWO_G]$, as follows:

$$E[TWO_G] = E[TW_G] * E[OW_G] \tag{3}$$

The average excess weight per overweight/obese adult in the US, $E[EW_G]$, is then given by

$$E[EW_G] = \frac{E[TWO_G] - P(O_G) * Population_G * E[MNW_G]}{P(O_G) * Population_G} \tag{4}$$

where $P(O_G)$ represents the percentage of adults who are overweight or obese.

4.3.1c Excess Occupant Weight in Light-Duty Vehicles

For light-duty vehicles, average excess weight is estimated separately for drivers and for non-driving passengers. Excess occupant weight is the sum of excess driver weight and excess non-driving passenger weight. It is assumed that the average driver weight is the same for both passenger cars and light-duty trucks. First, the average excess weight of the driver is established for each year from 1970 to 2010 using Equations (5) through (7).

$$P(A_{20+}\ I\ G_D) = \frac{LD_{G,A=20+}}{\sum_A LD_{G,A}} \tag{5}$$

where $P(A_{20+}\ I\ G_D)$ is the probability that a driver is age 20+, given gender, the subscript D represents driver, and $LD_{G,A}$ is the number of licensed drivers, given gender and age group.

$$P(G_D) = \frac{E[VMT\ I\ G] \sum_A LD_{G,A}}{(E[VMT\ I\ M] \sum_A LD_{M,A} + E[VMT\ I\ F] \sum_A LD_{F,A})} \tag{6}$$

where $P(G_D)$ is the proportion of vehicle kilometers driven, given gender, and $E[VMT\ I\ G]$ represents the number of vehicle kilometers driven, given gender.

$$E[EW_D] = \sum_{A_D,G_D} E[EW_D\ I\ A_{20+} \cap G_D]\, P(A_{20+}\ I\ G_D)\, P(G_D)\, P(O_G) \tag{7}$$

where $E\ [EW_D]$ is the average excess weight of a driver and $E\ [EW_D\ I\ A_{20+} \cap G_D]$ is the excess weight of an adult in the US, given age and gender. Equations (5) and (6) are taken directly from the Jacobson and McLay (2006) model while Equation (7) has been modified to incorporate excess weight computations from Section 4.3.1b and the percentages of overweight and obese adults in the US.

Next, the average excess weight of non-driving passengers in light-duty vehicles, $E[EW_{ND}]$, is determined for each year from 1970 to 2010 using Equation (8), which has also been modified from the Jacobson and McLay (2006) model in a similar manner to that of Equation (7). Furthermore, it is assumed that each light-duty vehicle has one driver, and that for any given year, the non-driving passengers reflect the age and gender composition of the general population in the US for that particular year. The average excess weight of non-driving passengers, $E[EW_{ND}]$, is estimated as

$$\begin{aligned} E[EW_{ND}] &= \sum_{A_{ND},G_{ND}} E[EW_{ND}\ I\ A_{ND} \cap G_{ND}]\, P(A_{ND}\ I\ G_{ND})\, P(G_{ND})\, P(O_G) \\ &= \sum_{A,G} E[EW\ I\ A \cap G]\, P(A)\, P(G)\, P(O_G) \end{aligned} \tag{8}$$

where the subscript ND represents non-driving passenger, $E[EW_{ND}\ I\ A_{ND} \cap G_{ND}]$ is the average excess weight of an adult in the US, given age and gender, $P(A)$ is the proportion of the US population, given age, and $P(G)$ is the proportion of the US population, given gender. Since the non-driving passengers reflect the age and gender demographics of the Unites States population, $E\ [EW_{ND}\ I\ A_{ND} \cap G_{ND}] = E\ [EW\ I\ A \cap G]$.

Total extra weight of all occupants, including the driver, in a light-duty vehicle, $E[EW_V]$, is given by

$$E[EW_V] = E[EW_D] + ((E[N_V] - 1) * E[EW_{ND}]) \tag{9}$$

where subscript V represents the type of light-duty vehicle and N_V is the occupancy load within a vehicle. Average excess occupant weight for light-duty vehicles is estimated for each year from 1970 to 2010 (see Table A-11 of Appendix C). Note that since the excess weight of children and teens are unaccounted for in this analysis, excess occupant weight per light-duty vehicle is underestimated.

4.3.1d Excess Occupant Weight in Transit Systems and Aircraft

While passenger demographics are likely to impact passenger weight in public transportation systems and passenger aircraft, estimating the demographic effects on overall fuel use is outside the scope of this analysis. For the purposes of this study, passenger demographics in transit systems and in commercial passenger aircraft are assumed to resemble those of the general population of the US. Consequently, the average excess weight of a passenger in a transit vehicle and in an aircraft are assumed to be the same as those for a non-driving passenger in a light-duty vehicle.

Total excess occupant weights in transit vehicles and passenger aircraft are estimated using Equation (9) in Section 4.3.1c, where, in this case, subscript V represents commuter rail, light rail, heavy rail, or passenger aircraft. Average excess occupant weights for transit systems and passenger aircraft are estimated for each year from 1970 to 2010 (see Table A-11 of Appendix C). Note that since the excess weight of children and teens are unaccounted for in this analysis, excess occupant weight per transit vehicle and passenger aircraft is underestimated.

4.3.2 Fuel Use Model

Additional annual fuel/energy use attributed to excess passenger weight in light-duty vehicles, transit buses, light rail vehicles, and passenger aircraft, $E[EF_{V1}]$, is estimated as

$$E[EF_{V1}] = VMT_{V1} * R_{V1} * E[EW_{V1}] \tag{10}$$

where *V1* represents vehicle type, VMT_{V1} represents annual vehicle kilometers traveled, and R_{V1} is the average ratio of change in fuel use (liters) or energy use (kWh) per distance traveled to change in weight. The variable, R_{V1}, measures fuel efficiency given weight change, and therefore, represents technological change and vehicle development for each year. This parameter is discussed in more detail in Section 4.5. Note that for this analysis, it is assumed that the overweight and obese drive vehicles with an average fuel economy equivalent to the country as a whole.

Additional annual energy use due to excess passenger weight in commuter rail and heavy rail vehicles, $E[EF_{V2}]$, is given by

$$E[EF_{V2}] = RV_{V2} * AR_{V2} * E[EW_{V2}] \tag{11}$$

where subscript *V2* represents vehicle type, RV_{V2} represents the number of vehicles used per year, and AR_{V2} is the average annual energy consumption (kWh) per kilogram of weight. The Oak Ridge National Laboratory provides the conversion factor, 9.7 kWh/liter of gasoline, which is used to convert excess energy use for transit rail (commuter, heavy, and light rail) vehicles to equivalent gasoline use to enable comparison with other transportation results.

4.3.3 GHG Emissions Model

For light-duty vehicles, the EPA reports greenhouse gas emissions for CO_2 in grams per liter of fuel consumed and for CH_4 and N_2O in grams per vehicle-kilometer traveled from 1984 to 2005 (US Environmental Protection Agency 2008e). This data is used to develop separate estimates for

CO_2, CH_4, and N_2O emissions for light-duty vehicles from 1970 to 2010. For years prior to 1984 and after 2005, GHG emissions in grams per unit are assumed to be consistent with those in 1984 and 2005. Extra CO_2 emissions due to excess occupant weight in light-duty vehicles, $E[EGHG_{V-CO2}]$, from 1970 to 2010 are given by

$$E[EGHG_{V-CO2}] = E[EF_V] * GHG_{V-CO2} \tag{12}$$

where GHG_{V-CO2} represents CO_2 emissions in grams per liter of fuel consumed.

CH_4 and N_2O emissions have 100-year global warming potentials (GWP) of 21 and 310, respectively. Over a 100-year time period, CH_4 and N_2O emissions trap 21 and 310 times more heat in the atmosphere than the same amount (by mass) of CO_2 emissions (Environmental Protection Agency 2013b). Extra CH_4 and N_2O emissions due to excess occupant weight in light-duty vehicles, $E[EGHG_{V-CH4/N2O}]$, from 1970 to 2010 are estimated as

$$E\left[EGHG_{V-CH4/N2O}\right] = E[EF_V] * GHG_{V-CH4/N2O} * GWP_{CH4/N2O} * FE_V \tag{13}$$

where $GHG_{V-CH4/N2O}$ is CH_4 or N_2O emissions in grams per vehicle-kilometer traveled and FE_V is the fuel economy for passenger cars and light-duty trucks. The sum of these estimates yield total excess GHG emissions attributed to excess weight for light-duty vehicles for each year from 1970 to 2010.

The EPA reports annual greenhouse gas emissions, including CO_2, CH_4, and N_2O, for transit systems and passenger aircraft from 1990 to 2010 in the US. This study assumes that GHG emissions are directly proportional to fuel use. Therefore, GHG emissions associated with excess passenger weight are given as

$$E[EGHG_V] = E[EF_V]/TF_V * AGHG_V \tag{14}$$

where E[GHG_V] is extra GHG emissions due to excess occupant weight, subscript V represents vehicle type (transit vehicle or passenger aircraft), TF_V is the annual fuel/energy use, and $AGHG_V$ represents annual greenhouse gas emissions. Annual GHG emissions are not reported prior to 1990. Therefore, annual emissions from 1970 to 1989 are estimated for transit systems and passenger aircraft by multiplying annual vehicle kilometers for each year by the ratio of annual GHG emissions to vehicle kilometers traveled for the year 1990.

4.3.4 Economic Model

Costs associated with additional fuel use in light-duty vehicles, buses, and aircraft are computed based on fuel prices reported by the US Energy Information Administration (EIA). Extra fuel costs due to excess occupant weight within these transportation modes, $E[EC_{V1}]$, are given by

$$E[EC_{V1}] = E[EF_{V1}] * C_{V1} \tag{15}$$

where C_{V1} is the cost of one liter of gasoline for light-duty vehicles and one liter of jet fuel for aircraft. Additional fuel cost attributed to excess occupant weight in transit rail vehicles, $E[EC_{V2}]$, is estimated as

$$E[EC_{V2}] = E[EF_{V2}]/TF_{V2} * TEC_{V2} \tag{16}$$

where TEC_{V2} is the total annual energy cost for transit vehicles. Energy prices are reported by the US EIA. All costs are adjusted for inflation to the year 2012.

4.4 Results

Between 1970 and 2010, the average overweight/obese American male and female gained approximately, 5 kilograms and 6 kilograms, respectively. In 2010 the American population collectively carries 3.6 billion kilograms of excess weight, which is equivalent to the weight of 50 million additional healthy weight individuals. This excess passenger weight has resulted in greater fuel use, GHG emissions, and fuel costs over the past four decades. Table 4-5 summarizes the results of this study. Fuel use is reported in equivalent gasoline consumption for light-duty vehicles and transit vehicles. Jet fuel consumption is given for passenger aircraft. Refer to Tables A-12, A-13, and A-14 of Appendix C for all results.

Table 4-5 Annual fuel use, GHG emissions, and fuel costs due to excess passenger weight

	Year	Light-Duty Vehicles	Transit Vehicles	Passenger Aircraft
Fuel Use (million liters)				
Per Year:	1970	1,130	2.85	604
	1980	1,390	3.29	959
	1990	2,990	5.00	2,320
	2000	3,870	7.21	3,940
	2010	3,810	8.64	3,840
Cumulative from 1970 to 2010		110,000	213	95,200
GHG Emissions (1,000 metric tonnes CO2e)				
Per Year:	1970	3,010	9.3	1,260
	1980	3,760	8.9	2,030
	1990	8,170	13.4	5,940
	2000	10,300	20.9	9,940
	2010	9,930	37.1	10,300
Cumulative from 1970 to 2010		265,000	654	238,000
Fuel/Energy Cost (million $) Costs adjusted to 2012				
Per Year:	1970	684	1.45	218
	1980	1,250	2.59	611
	1990	1,690	2.63	824
	2000	2,130	3.48	1,246
	2010	3,010	7.69	2,350
Cumulative from 1970 to 2010		66,400	129	37,000

From 1970 to 2010, cumulative fuel use, GHG emissions, and fuel costs attributable to excess passenger weight are approximately, 205 billion liters, 503 million metric tonnes CO_2e, and \$103 billion. Light-duty vehicles have the highest cumulative impacts, while transit vehicles yield the lowest. Cumulative excess fuel use and GHG emissions for light-duty vehicles are slightly more than for aircraft and roughly 520 and 450 times more, respectively than for transit vehicles. Furthermore, jet fuel for aircraft cost less per liter of fuel than gasoline for light-duty vehicles, thereby resulting in lower overall fuel costs relative to the amounts of fuel consumed by aircraft.

Figure 4-1 displays annual excess fuel-use trends for all transportation modes. Although transit vehicles experience a significant increase in excess fuel consumption, this fuel use is very small relative to fuel use for other transportation systems. This is because total vehicle kilometers, passenger kilometers, annual energy use for transit systems, and the ratio of change in energy use to change in average weight per transit vehicle is smaller than for other vehicles. Refer to Figure 4-2 for annual excess fuel-use for transit vehicles only.

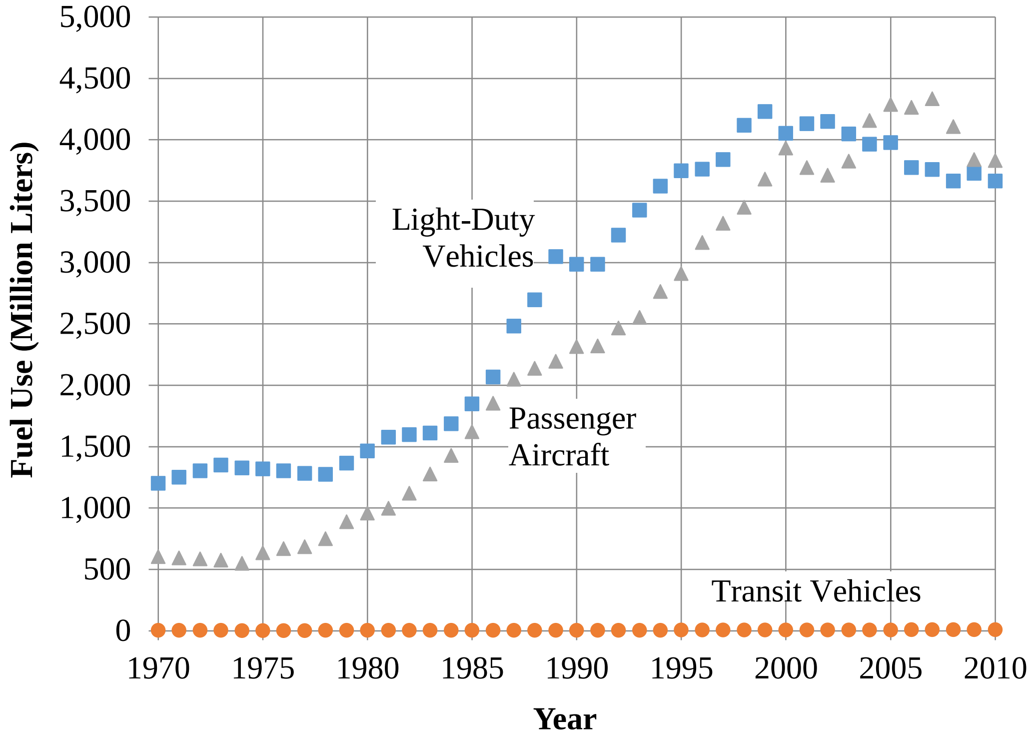


Figure 4-1 Annual fuel use due to excess passenger weight

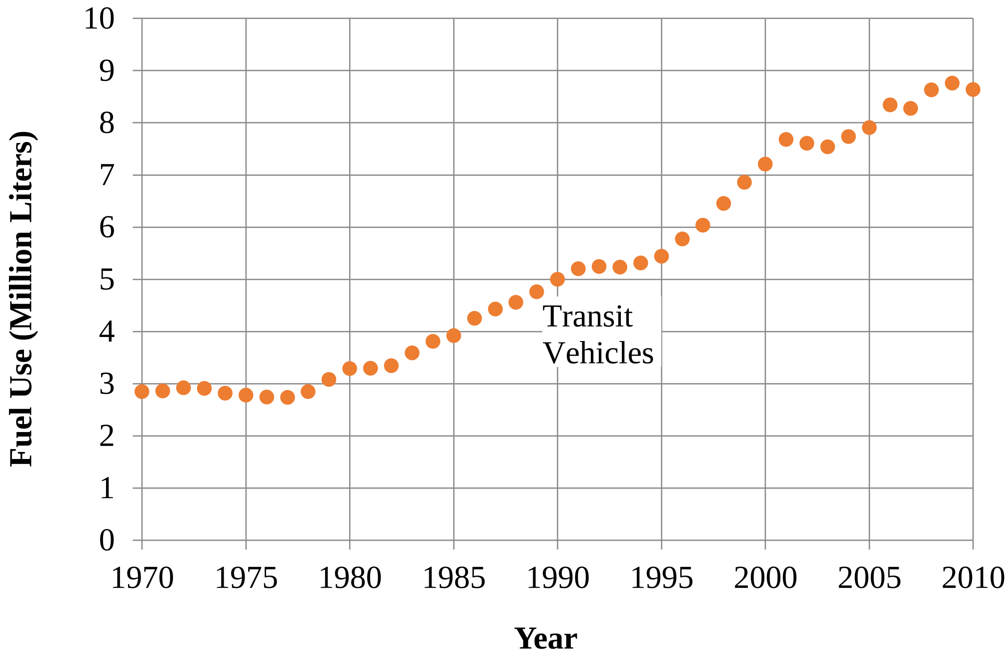


Figure 4-2 Annual fuel use for transit vehicles due to excess passenger weight

Over four decades excess fuel consumption for light-duty vehicles, passenger aircraft, and transit systems increases by roughly 240%, 530%, and 200%, respectively. Hence, total excess fuel use attributable to excess occupant weight in all vehicles increases by around 340%.

After 2007, with the onset of the economic recession, the number of vehicles, vehicle-kilometers traveled, and passenger-kilometers traveled declines for both light-duty vehicles and aircraft, which offsets increasing passenger weight. Consequently, total excess fuel consumption for light-duty vehicles and passenger aircraft decreases overall from 2007 to 2010. Conversely, the total impacts of increasing passenger weight in transit systems are compounded by an increased number of transit vehicles, vehicle-kilometers traveled, and passenger-kilometers traveled, which results in increasing total excess fuel consumption attributable to excess passenger weight for transit systems. In 2010, annual excess fuel use for all modes of transportation due to increased passenger weight is estimated to be approximately, 7.6 billion liters, which comprises nearly 1.4% of total transportation fuel use for that year. In relative terms, the amount of excess fuel used to carry excess passenger weight is small compared to the total fuel use. However, in absolute terms, 1.4% or 7.6 billion liters, is a substantial amount of fuel that is worth further attention.

Figures 4-3 and 4-4 display annual excess GHG emissions and additional fuel cost trends.

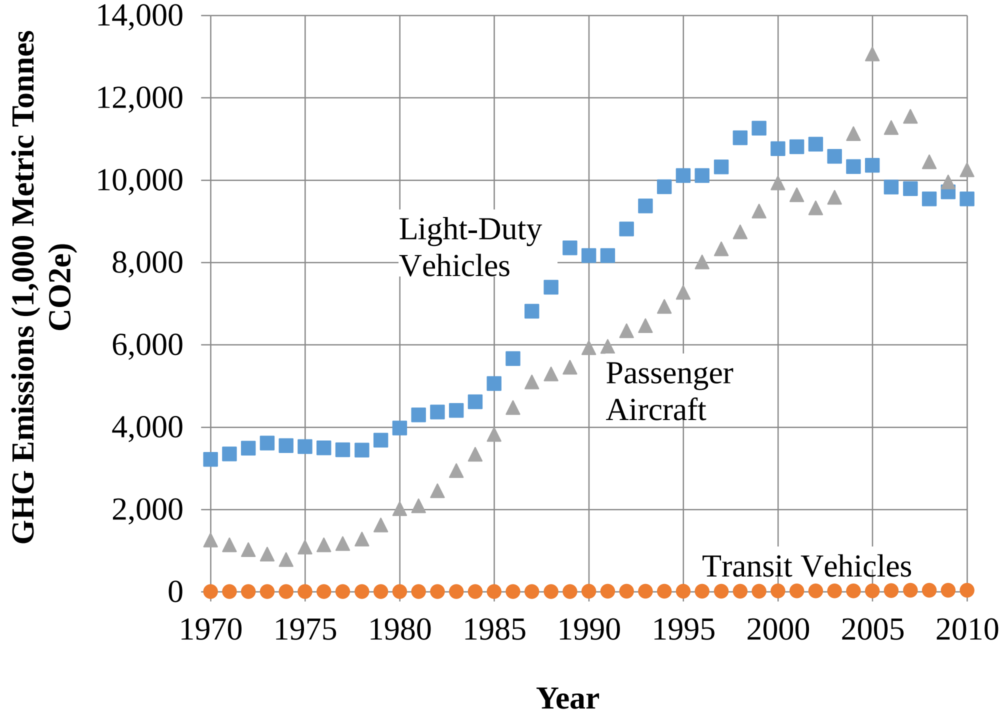


Figure 4-3 Annual GHG emissions due to excess passenger weight

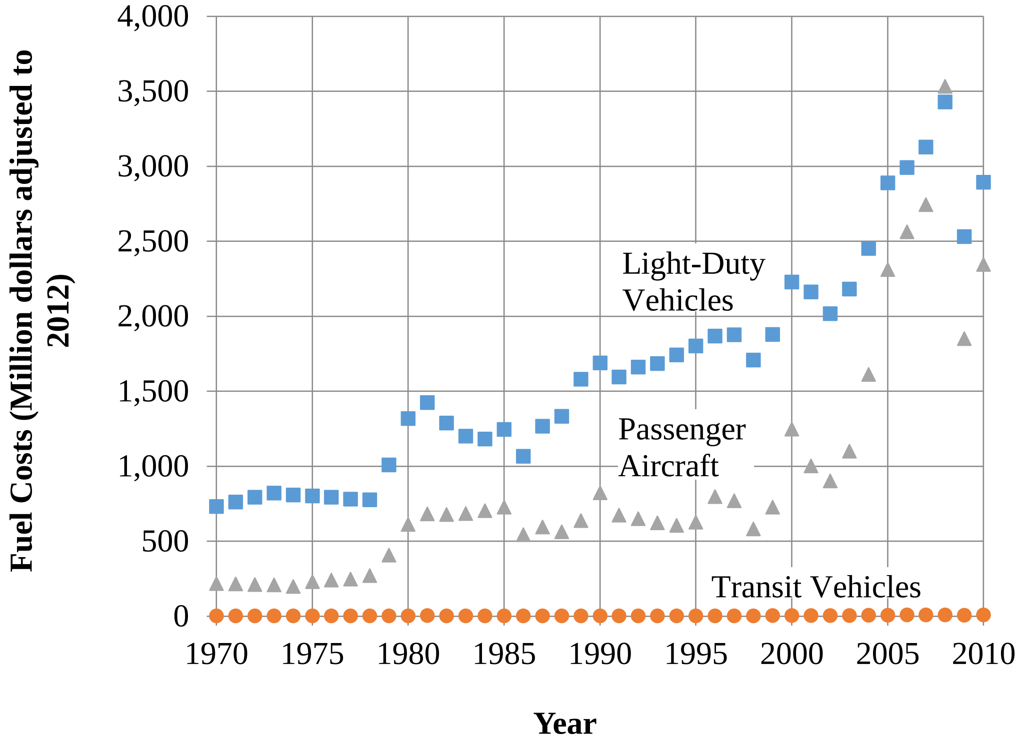


Figure 4-4 Annual fuel costs from excess passenger weight

Excess GHG emissions follow the same trends as those for excess fuel consumption. Extra fuel costs deviate slightly from the fuel use and GHG emissions trends shown in Figures 4-1 and 4-3 because of fuel price fluctuations over the past four decades. In particular, in 2009 and 2010, fuel prices drop considerably, which significantly impacts excess fuel costs for all modes of transportation.

4.5 Uncertainty Analysis

An uncertainty analysis of the results is performed by investigating the uncertainty of variables used in the models. Variables for which values can be counted or directly measured are likely to have low uncertainty. These parameters include the number of registered vehicles, annual fuel use, fuel and energy prices, number of licensed individuals, the percentage of men and women in the US, and the proportion of people within different age groups in the US. A sensitivity analysis is also developed using Monte Carlo simulation to determine which uncertainties are likely to have the greatest impact on the results. The sensitivity analysis reveals the key variables to be the ratio of change in fuel use per distance traveled to change in weight, annual passenger kilometers traveled, and average excess weight per overweight/obese individual. Adjusting the fuel use-to-weight ratio, passenger kilometers, and excess weight variables by ±10% produces roughly ±10%, ±9%, and ±10% change, respectively, in total excess fuel use over 40 years. The uncertainty parameters for these variables are used to generate uncertainty intervals for the results.

Excess weight estimates are a function of anthropometric data such as average body weight and average height as well as the percentage of individuals that are overweight/obese. The National Center for Health Statistics provides standard errors for average heights and weights of adults in the US (Ogden et al. 2004, Mcdowell et al. 2008, and Fryar et al. 2012b) and for the proportion of the population that is overweight and obese (National Center for Health Statistics 2013, Fryar et al. 2012a). Average heights range from 0.25 to 1.3 centimeters while average weights range from 0.36 to 1.34 kilograms. Roughly every 5 years, The National Household Travel Survey (NHTS) gives standard errors for daily kilometers traveled, by gender, and for annual passenger kilometers. These statistics are summarized in the 2001 and 2009 NHTS summary reports (Hu and Reuscher 2004, Santos and McGuckin et al. 2011). The EPA reports the ratios of change in fuel use per distance traveled to change in weight for light-duty vehicles based on the model year vehicles. The NHTS provides the number of vehicle kilometers traveled given vehicle ages of the US fleet for a given year. This data is then used to determine the mean and standard errors for the fuel use-to-weight ratios for the entire fleet for each year. Refer to Figure 4-5 for the combined uncertainty of the excess fuel use results attributed to excess passenger weight. The uncertainty intervals for annual excess fuel use range from roughly ± 6% in 2010 to ± 10% in 1970.

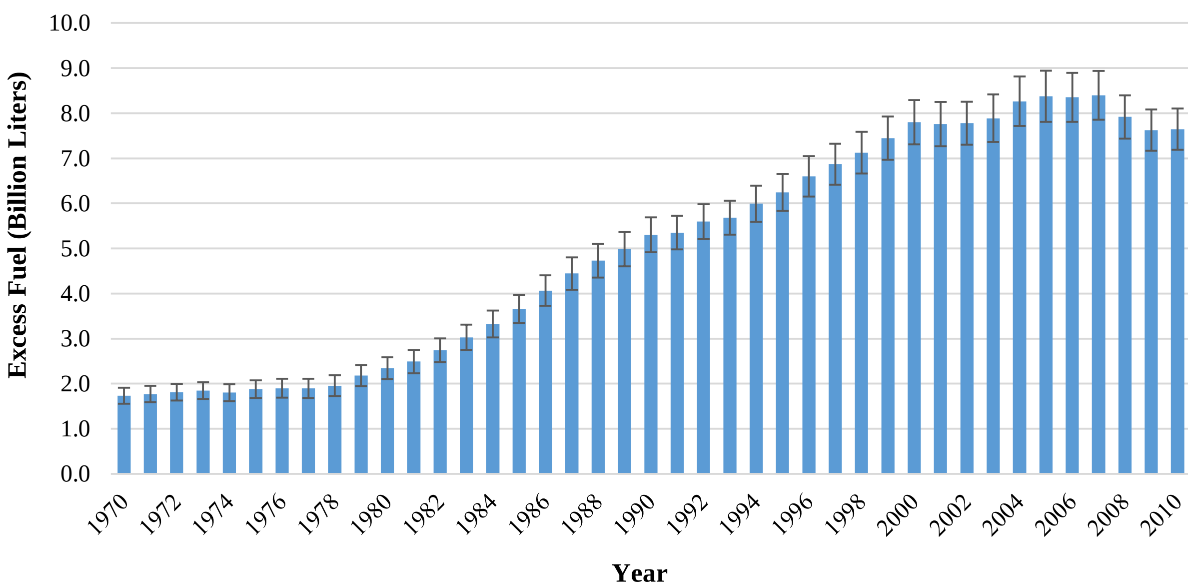


Figure 4-5 Annual extra fuel use attributed to excess passenger weight for all transportation systems. Whiskers represent standard error bars.

This study contains several difficult to quantify uncertainties, which have been analyzed to determine the potential impacts on the excess fuel use results. One uncertainty is ignoring the number of unregistered light-duty vehicles that are operated in the US, due to insufficient national data. The California Department of Insurance, however, determined that between 1988 and 1999, the percentage of on-the-road unregistered vehicles in California ranged from 8.5% to 11.7% (Hunstad, 1999). Though it cannot be assumed that these statistics are nationally representative, they do provide a general idea of the potential increase in total fuel use that could result from including unregistered vehicles in the analysis. Adding 8.5% to 11.7% light-duty vehicles to U.S. roads would increase extra fuel use due to excess passenger weight for all transportation systems by roughly 1.4% to 2.0%.

Additionally, cross-border refueling and illegal use of diesel fuel for light-duty vehicles have been excluded from this study, due to insufficient data. Marion and Muehlegger (2008), however, found that following the implementation of federal regulations in 1993 that were designed to prevent illegal use of untaxed diesel fuel in the U.S., diesel fuel sales rose 26 percent. Since diesel cars and trucks only represent a little more than 2% of all light-duty vehicles in the US though (Environmental Protection Agency 2008d), increasing diesel fuel use by 26% for each year from 1970 to 1993 would increase additional fuel use due to excess passenger weight for all transportation systems by less than 0.50%.

Another uncertainty is in the exclusion of HFC emissions, which represent approximately, 3.3 percent of U.S. transportation end-use GHG emissions, by global warming impact (US Department of Transportation 2010). The majority of HFC emissions occur through vehicle air-conditioning servicing and repair and vehicle disposal while a smaller amount of HFCs are emitted through air-conditioning leaks (Environmental Protection Agency, 2008c). While air temperature has been linked to factors, such as appetite and human energy expenditure, which affect weight gain, it is difficult to quantify the effects of excess weight on vehicle air-conditioning systems. Also, while HFC emissions are greater than CH_4 (0.1%) and N_2O (1.5%) emissions, they are relatively small compared to CO_2 emissions (95.1%) and within the wider context of total transportation GHG emissions (US Department of Transportation 2010).

In addition, this study does not account for differences between light-duty vehicle, transit, and airline passengers. Although Frank et al. (2004) find that "the odds of obesity decline by 4.8% for each additional kilometer walked" and "increase by 6% for each additional hour spent in a car per day," there are other demographic factors, not included in this study, that are also linked to excess weight, such as income level and race/ethnicity, which could counteract the effects of travel-related physical activity on overweight and obesity rates. For example, in the US whites have the greatest access to light-duty vehicles while blacks have the highest use of public transit (Neff and Pham 2007, Transportation Research Board 2009) as well as obesity rates that are 51% higher than whites (Centers for Disease Control 2009). Fuel use impacts resulting from racial disparities could very well offset those from using more active transportation modes. Identifying differences in demographic profiles (including physical activity level) among transportation modes and estimating their total effects on excess passenger weight, however, is beyond the scope of this study.

Lastly, uncertainty lies in the assumption that the overweight and obese exhibit similar vehicle purchasing behaviors as the rest of the population. Li et al. (2011) find evidence that overweight and obesity rates may be linked to a decrease in fuel economy of new light-duty vehicles purchased. They observe that for every 10% increase in overweight and obesity rates in the US, fuel-efficiency for new vehicles purchased decreases by roughly 2.5%. Their study, however, does not specifically conclude that it is the overweight and obese portion of the population that buys larger and less fuel-efficient vehicles. While it may seem reasonable that heavier people buy larger vehicles for comfort, there are a number of factors that drive vehicle purchasing decisions, such as income and social status. Hence, it is assumed that the overweight and obese drive vehicles with an average fuel economy equivalent to the country as a whole. Even when assuming the worst case scenario in which only the overweight and obese buy less fuel-efficient vehicles, additional fuel use due to excess passenger weight for all transportation systems would increase by less than 0.10% due, in part, to the small percentage of new vehicles that are purchased each year.

Cumulative uncertainty or measurement error in the aforementioned parameters, which also includes excess weight, vehicle-miles traveled, and the fuel use-to-weight ratio, could yield total excess fuel use from 1970 to 2010 that is 10% higher, or nearly 21 billion liters more than the current cumulative excess fuel-use estimate of 205 billion liters. Subsequently, the percentage of total transportation fuel use attributable to carrying excess passenger weight in the U.S. over the last four decades would increase from 1.1% to 1.2%. In relative terms, this change is small compared to the total fuel use. However, in absolute terms, the potential for an additional 10% excess fuel use, or 21 billion liters, is a significant amount of excess fuel use resulting from uncertainty in the contributing factors.

Finally, it is worthwhile to note that since this study estimates the impacts associated with the excess weight of the overweight and obese populations only, the underweight and normal weight populations are excluded from the excess weight calculations. Exclusion of these portions of the population yield excess weight estimates that are roughly twice as high. Consequently, fuel-use, GHG emissions, and fuel cost impacts attributed to excess weight are also doubled. This approach, however, should not be viewed as an uncertainty in the data; rather it is an alternative method for estimating excess weight.

4.6 Discussion

The results of this study indicate that among all transportation modes, for the majority of years, light-duty vehicles, in total, experience the greatest fuel-use, environmental, and economic impacts from excess passenger weight Although from 2004 to 2010, excess passenger weight results in greater total excess fuel use and GHG emissions for passenger aircraft. The effects of weight gain on fuel use, GHG emissions, and fuel costs involve multiple additional factors that can mitigate or compound the net impact (e.g., the number of vehicles, annual vehicle-kilometers traveled, etc.). Figure 4-6 demonstrates how these variables have changed per light-duty vehicle since 1970.

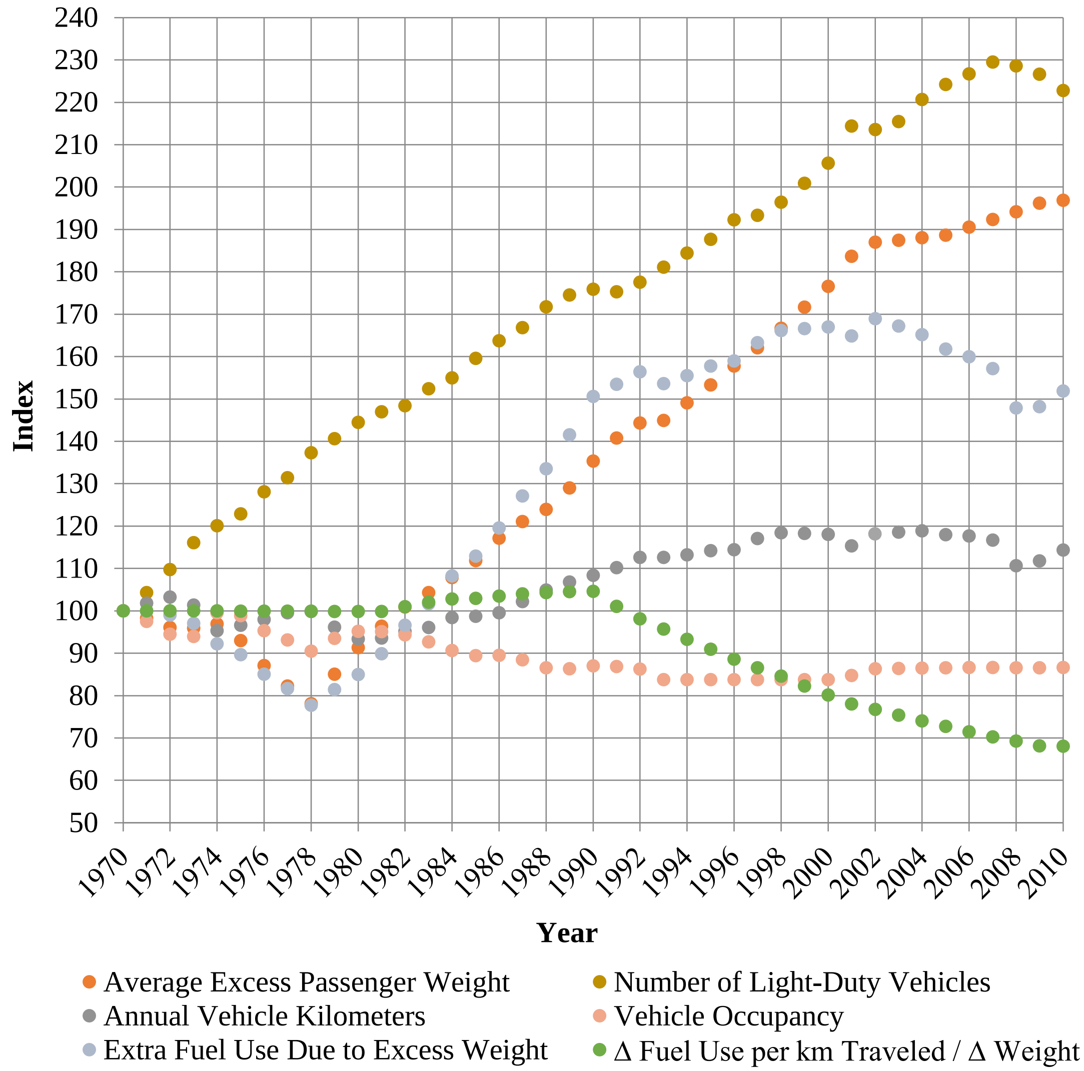


Figure 4-6 Index of factors contributing to excess fuel consumption per light-duty vehicle (1970-2010)

Although vehicle occupancy per light-duty vehicle has either decreased or remained fairly constant over the last 40 years, excess occupant weight per vehicle has nearly doubled. The number of light-duty vehicles and average annual kilometers traveled per vehicle also increased by around 120% and 15%, respectively, while the average vehicle occupancy and ratio of change in fuel use per kilometer traveled to change in weight per light-duty vehicle decreased by nearly 15% and 40%, respectively, over the last 40 years. The impacts associated with the average adult weight gain, increased number of light-duty vehicles, and increased vehicle-kilometers offset those from reduced vehicle occupancy and fuel use to weight ratio; thus, resulting in higher rates of total excess fuel consumption overall. These outcomes also apply to extra fuel use for transit vehicles and passenger aircraft.

The results of this study can be compared to those found by other researchers. For example, Jacobson and McLay (2006) determine that the total annual amount of excess fuel consumed in the U.S. due to increasing passenger weight in light-duty vehicles ranges from 1.0 to 3.6 billion liters. Whereas this analysis estimates that 4.1 billion liters of total excess fuel are consumed in 2003 due to excess passenger weight in light-duty vehicles. Unlike the Jacobson and McLay (2006) model, this study accounts for changes in all input variables (e.g. vehicle-kilometers traveled, annual fuel consumption, etc.) over time and yields higher excess weight estimates, thereby contributing to higher impact results. For passenger aircraft, Dannenberg, Burton, and Jackson (2004) determine that in 2000, based on an average per adult weight gain of approximately, 4.5 kilograms since 1990, an additional 1.3 billion liters of jet fuel are consumed, in total, to carry excess passenger weight. This analysis, however, estimates that an extra 3.9 billion liters of jet fuel are consumed due to excess passenger weight in 2000, which is based on a per adult excess weight estimate of approximately, 9.1 kilograms. In addition to using a different approach for estimating excess weight, which have been discussed in previous sections, this study also includes non-revenue passenger-miles for the flight crew and assumes a lower average fuel economy for passenger aircraft which leads to significantly higher results.

Comparisons can also be made between excess transportation fuel costs attributed to excess passenger weight and other obesity-related costs. For instance, in 1998 and 2006, annual medical expenditures for an obese person are $1,221 and $1,524 (in 2012 dollars) greater, respectively, than those for a healthy weight individual (Finkelstein et al. 2009). Whereas, for those same years, an overweight/obese person incurs $17 and $40 (in 2012 dollars) more in annual transportation fuel costs than a healthy weight individual. Additionally, Ricci and Chee (2005) determine that, based on data collected from 2001 to 2003, annual nationwide productivity losses due to obesity-related absenteeism amount to $3.83 billion (in 2002 dollars). These costs are roughly 1.6 times more than extra annual fuel costs due to excess passenger weight, which, in 2002, is $2.3 billion (in 2002 dollars). Ricci and Chee (2005) do not find a significant difference in productivity losses between overweight and healthy weight individuals.

Schreyer et al. (2004) estimate the environmental and health costs of passenger transportation air pollution and noise pollution in Europe to be roughly $0.01 and $0.004, respectively per passenger kilometer. They also determine that the external costs of transportation related climate change range from $0.003 to $0.02 per passenger kilometer. These costs are higher than the additional fuel costs attributed to excess passenger weight, which is approximately, $0.001 per passenger kilometer. Although geographical differences may impact air and noise pollution levels and effects on climate change, this comparison provides a general idea of the order of magnitude of excess fuel costs due to excess passenger weight relative to the environmental and health costs attributed to air pollution, noise pollution, and climate change associated with passenger transportation systems.

Finally, it is worthwhile to note that while excess passenger weight per light-duty vehicle has increased by 8.6 kilograms since 1970, the average passenger car weight decreased by roughly 230 kilograms and the average light-duty truck increased by 320 kilograms, resulting in a weighted average of approximately, 7.3-kilogram increase per light-duty vehicle in the last 40 years. Therefore, the fuel use, GHG emissions, and fuel cost impacts of excess passenger weight on light-duty vehicles are greater than those resulting from increased vehicle weight. If overweight and obesity rates continue to increase at its current pace and given projected population growth of the US, cumulative excess transportation-related fuel use could increase by 87 billion liters in the next 10 years or 460 billion liters over the next 50 years. This amounts to 210 million metric tonnes of CO_2e and $38 billion by year 2020 and 1.1 billion metric tonnes of CO_2e and $200 billion by the year 2060.

5. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Summary

This dissertation developed a comprehensive analysis of the resource-use, environmental, and economic impacts of overweight and obesity on the food supply and transportation industries in the US. The first research goal was to quantify the life-cycle energy use, water withdrawals, and GHG emissions within the food supply chain attributable to producing total food consumed by the US adult population (Chapter 2). The EIO-LCA model and the process-based model were used to develop a range of estimates. Additionally, a linear model was implemented to determine the additional energy use, water withdrawals, and GHG emissions required to supply the extra Calories consumed by the US overweight and obese population. Caloric intake estimates were developed using anthropometric data from the Centers for Disease Control (CDC) National Health and Nutrition Examination Survey. It was determined that on average, 6% of energy use, 21% of water withdrawals, and 9% of GHG emissions for all sectors in the US were used to provide food for current adult consumption in the US. Furthermore, 8-10% of these environmental and resource use impacts within the food supply system were attributed to extra Calories consumed by overweight and obese American adults.

The second research goal was to examine the effects of both the quantity and quality of Calories consumed by US adults, on life-cycle energy use water withdrawals, and GHG emissions through the food supply system (Chapter 3). Unlike Chapter 2, which used two top-down approaches, Chapter 3 used a bottom-up approach, allowing for the inclusion of dietary mix in the overall analysis. As such, the second research goal assessed the impacts of shifting to three dietary scenarios, which were based, in part, on the 2010 USDA *Dietary Guidelines*. It was determined that shifting from the current US diet to a diet with the recommended Caloric intake only, reduces energy use, water withdrawals, and GHG emissions by around 9%, while a shift to a diet with the recommended food mix only, increases energy use by 48%, water withdrawals by 22%, and GHG emissions by 13%. Finally, shifting to the recommended dietary scenario that accounts for both reduced Caloric intake and a shift to the USDA recommended food mix increases energy use by 39%, water withdrawals by 13%, and GHG emissions by 6%.

The third research goal was to analyze the transportation industry to determine the amount of additional fuel use, GHG emissions, and fuel costs that are attributed to extra passenger weight in light-duty vehicles, transit vehicles, and passenger aircraft in the US from 1970 to 2010. It was determined that roughly 1.1% of total fuel use for transportation systems in the US was consumed to support the extra weight of the American population. This extra fuel use resulted in an additional 503 MMT of CO_2-eq and $103 billion of extra fuel cost over the last four decades.

5.2 Discussion

Different methods were used to achieve research goal 1 (Chapter 2) and research goal 2 (Chapter 3). Chapter 2 implemented two top-down approaches: The EIO-LCA model, which treated all food expenditures as the boundary of analysis, and the process-based model, which summed impacts associated with each stage of the food supply system. Conversely, in response to the limitations of using top-down approaches in Chapter 2, a bottom-up method was implemented in Chapter 3, in which the environmental impacts of each food type were assessed individually. Using these two approaches led to separate outcomes, which are shown in Table 5.1.

Table 5.1 Research Goal 1 and Research Goal 2 Results

Impact	Scenario	Research Goal 1 Results	Research Goal 2 Results
Energy Use (Million TJ)	Total Current Food Consumption for Adult Population	6.0 - 6.2	2.6
	Reduce Caloric Intake	5.5 – 5.7	2.4
	Shift to USDA Recommended Dietary Mix	--	3.9
	Reduce Caloric Intake and Shift to USDA Recommended Dietary Mix	--	3.7
Water Withdrawals (Billion m^3)	Total Current Food Consumption for Adult Population	100 - 105	75
	Reduce Caloric Intake	92 - 96	69
	Shift to USDA Recommended Dietary Mix	--	92
	Reduce Caloric Intake and Shift to USDA Recommended Dietary Mix	--	85
GHG Emissions (MMT CO2e)	Total Current Food Consumption for Adult Population	600	430
	Reduce Caloric Intake	550	390
	Shift to USDA Recommended Dietary Mix	--	490
	Reduce Caloric Intake and Shift to USDA Recommended Dietary Mix	--	460

Research goal 2 yielded significantly lower cumulative energy use, water withdrawals, and GHG emissions estimates attributable to total food provided for adult consumption in the US. As previously discussed, the 100+ food types accounted for in achieving research goal 2 were based on those listed in the LAFA data series, some of which represented raw or semi-processed agricultural goods as opposed to final retail products (Heller and Keoleian 2014). Therefore, cumulative energy use, water withdrawals, and GHG emissions may have been omitted from various phases of the food supply system for certain food types, thereby leading to underestimated results. Current literature, however, lacks LCA data for the vast array of food products purchased and consumed in the US. Further work is, therefore, needed to develop and incorporate LCAs of final retail food products into this analysis. Based on the results displayed in Table 5.1 above though, it is reasonable to assume that including final processed foods in the analysis for Research Goal 2 would lead to more than twice as much energy use and nearly 50% more water withdrawals and GHG emissions through the food supply chain to provide food for adult consumption in the US.

The results of research goal 1 are likely more accurate estimates of cumulative energy use, water withdrawals, and GHG emissions attributable to total food provided for US adult consumption. This is due to the nature of the top-down approach utilized and the subsequent availability of requisite data, which accounts for all stages of the food supply system (except for waste disposal). The top-down approach, however, is not without its limitations, the most significant of which is the exclusion of analyses of the environmental impacts associated with individual foods. Hence, the effects of shifting food mix cannot be examined using this method. Whereas, the bottom-up approach that was used to meet research goal 2, was built upon the environmental impacts and quantity consumed of individual foods, thereby facilitating analysis of environmental effects attributed to shifting food mix in addition to reducing Caloric consumption.

To better understand the relevance of the results, comparisons are made between the results found in each chapter. This comparison demonstrates that reducing Caloric consumption to achieve "normal" weight, has nearly twice as much impact on energy use and roughly 2.5 times as much impact on emissions within the food supply system than through the transportation system. Specifically, in achieving the first research goal, it was determined that, on average, 500,000 TJ of additional energy were needed to provide the extra Calories consumed by the US overweight and obese adult population, not accounting for changes in food mix. This energy use resulted in additional GHG emissions of 50 MMT CO_2-eq. For the third research goal, the extra transportation-related fuel use required to carry the excess passenger weight of the US adult population amounted to approximately, 257,000 TJ. The accompanying GHG emissions were around 20 MMT CO_2-eq.

In comparing the results from research goal 2 to those from research goal 3, it was determined that reducing Caloric consumption in addition to shifting food mix to the USDA dietary recommendations resulted in increased cumulative energy use that offset the energy use savings achieved by reducing passenger weight within the transportation system, by a factor of two. Likewise, reducing Caloric consumption and shifting food mix increased GHG emissions through the food supply chain, which more than offset the reduction in emissions achieved by reducing passenger weight in the transportation system.

In order to differentiate the signal from the noise, uncertainty analysis has been conducted in two of the three empirical chapters. In Chapter 2 (corresponding to Research Goal 1) and in Chapter 4 (corresponding to Research Goal 3), standard errors have been identified and highlighted in key charts, in order to clarify the range of possible outcomes. No such uncertainty analysis has been undertaken in Chapter 3, due to data limitations. In light of this lack of uncertainty analysis, there remains some imprecision in the results, yet the findings are large enough relative to the baseline that we can at least have confidence that there are meaningful impacts and that the direction of these impacts are consistent with predictions.

5.3 Conclusion

This dissertation has made an important contribution to the literature on health and the environment, while providing new insights for public health officials. In doing so, it has demonstrated the nuanced relationships between excess population weight and environmental sustainability. Extra Caloric intake places heavier burdens on the food supply system and extra passenger weight places heavier burdens on transportation systems.

These findings are not without nuances. In substantive terms, overweight and obesity have different effects on different sectors, as is illustrated by this dissertation's findings on the food supply system and transportation systems. In empirical terms, the contrasting findings in Chapters 2 and 3 demonstrate that the choice of methods utilized and the availability of data affect the results. In future research, investigators must take into account the strengths and weaknesses of various methodologies, as they select appropriate empirical strategies for their research.

Each of the empirical chapters have their own conclusions and implications. Chapter 2 demonstrates that the resources required to support current adult food consumption patterns in the US comprise a relatively significant portion of the total energy use, water withdrawals, and GHG emissions for all sectors in the US. Furthermore, this chapter provides an updated account of the resource use and environmental impact intensities for each stage of the food supply system. Thus, understanding where in the food supply chain, the greatest resources are being used may enable policy makers and industry leaders to make informed decisions that improve energy and water use efficiencies and reduce emissions. The results of this chapter also reveal the extent to which we are over-consuming Calories in the US, and the subsequent effects on cumulative energy use, water withdrawals, and GHG emissions through the food supply chain. Hence, this analysis provides general information for consumers and public health officials regarding the relationship between Caloric intake and the environment.

Chapter 3 establishes the importance of considering the source of Calories consumed, in addition to the quantity of Calories consumed, when assessing diet-related implications for energy use, water withdrawals, and GHG emissions through the food supply system. While numerous studies have examined the environmental effects of various diets around the world, this analysis is the first to determine the impacts that shifting from the current US diet to USDA dietary recommendations has on energy use, water withdrawals, and GHG emissions. The results found in Chapter 3 reveal the potential trade-offs between a more nutritious diet and environmental sustainability. These findings indicate that health initiatives and environmental agendas are not always aligned, and therefore, public health officials should be cognizant of these diverging interests as they continue to develop dietary guidelines in the future.

As Chapter 4 demonstrates, excess weight places heavier burdens on transportation systems, which can offset improvements in fuel efficiency, resulting in excess fuel use, GHG emissions, and fuel costs. If overweight and obesity rates continue to rise, the adverse consequences on transportation systems will continue to escalate. Fortunately, there is ever-growing literature on policies that promote healthier lifestyles and support active transportation modes. This study contributes to that literature, and may be particularly important to policymakers who are promoting healthy lifestyles because it demonstrates that excessive weight incurs individual and societal costs by discouraging sustainable living through reduced fuel efficiency, in addition to having negative health impacts for individuals. Policies that encourage people to live a healthy lifestyle not only help people individually, but may also promote sustainable energy resource use through reduced transportation-related fuel consumption.

5.4 Future Work

Using several methodologies, this thesis provided a comprehensive analysis of the impacts of overweight and obesity on energy use, water withdrawals, GHG emissions, fuel use, and fuel costs within the US food supply system and transportation systems. However, a number of limitations emerged through the research process. In particular, in the absence of LCA studies for the immense selection of final retail food products, individual foods listed in the USDA LAFA data set (many of which were raw or semi-processed agricultural products) were used to assess the implications of dietary shifts in Chapter 3. Consequently, energy use, water withdrawals, and emissions from various stages of the food supply system were excluded. Future research is needed to expand the LCA database of final food products sold and purchased by US consumers. Incorporating more retail-level food products into the analysis would expand the system boundaries in Chapter 3, thus, providing a more exhaustive analysis of the impacts associated with dietary shifts. Addressing this issue would also reconcile the discrepancies between the results from Chapter 2 and those from Chapter 3.

Future research might include expanding this study to include the extra weight of children and teens. The prevalence of childhood obesity has become a serious problem in the US, with roughly 17% of children and adolescents currently obese (Centers for Disease Control, 1d). Furthermore, since children and teens comprise roughly a quarter of the US population, rising overweight and obesity rates among this portion of the population will intensify the results of this dissertation.

Additionally, it would be worthwhile to examine the impact of extra body weight on mortality rates and the consequential environmental effects. While there is controversy over whether being overweight increases or decreases one's lifespan, most studies reveal that being obese reduces life expectancy. Moderate obesity may shorten life expectancy by two to four years (Prospective Studies Collaboration 2009), while extreme obesity may reduce one's lifespan by up to 14 years (Kitahara et al. 2014). Fewer resources and environmental effects would accompany a shorter lifespan. However, future work is needed to quantify these reduced impacts and to assess the degree to which these effects would offset the results found in this dissertation.

Future contributions to this field may also include developing forecast models to assess future diet-related energy use, water withdrawal, and GHG emissions impacts under various scenarios of food consumption patterns and to further examine excess transportation-related fuel use under various scenarios of passenger weight change. Preliminary analyses of future projections have been conducted. However, a more extensive analysis is warranted. Both overweight and obesity rates of children, teens, and adults are expected to increase, which will continue to be of concern as the nation deals with limited oil supplies, water shortages, global warming, and increasing fuel costs.

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APPENDIX A ENERGY USE, WATER WITHDRAWALS, AND GHG EMISSIONS FOR FOOD CONSUMPTION IN THE US, SUPPLEMENTARY INFORMATION

A-1 Food Expenditure Accounts for Input into the EIO-LCA Model

Table A-1 US food expenditure accounts for 2012[a]

	Age Under 25[b]	Age 25-34[b]	Age 35-44[b]	Age 45-54[b]	Age 55-64[b]	Age 65 and over[b]
Total consumer units (in thousands)	8,159	20,112	21,598	24,624	22,770	27,154
Average number in consumer unit:						
Persons	2.0	2.8	3.4	2.7	2.1	1.7
Children under 18	0.4	1.1	1.4	0.6	0.2	0.1

				Mean Annual Food Expenditures per Consumer Unit						
Food categories	Food subcategories	Commodity Description[c]	Food Group	Age Under 25	Age 25-34	Age 35-44	Age 45-54	Age 55-64	Age 65 and over	2012 Adult Food Consumption Expenditures (million $ adjusted to 2002)[d]
Cereal and Cereal Products	Flour	Flour milling and malt manufacturing	Grain Products	6.15	9.95	9.82	11.47	10.01	7.03	443
Cereal and Cereal Products	Prepared flour mixes	Cookie, cracker and pasta manufacturing	Grain Products	9.40	13.60	18.61	21.09	16.27	13.69	1,126
Cereal and Cereal Products	Ready-to-eat and cooked cereals	Breakfast cereal manufacturing	Grain Products	75.05	99.18	116.50	115.79	82.67	70.50	6,999
Cereal and Cereal Products	Rice	Grain farming	Grain Products	25.33	27.06	31.53	33.08	17.86	14.72	807
Cereal and Cereal Products	Pasta, cornmeal and other cereal	Cookie, cracker and pasta manufacturing	Grain Products	27.23	37.07	46.21	46.48	32.02	27.68	2,519
Bakery Products	Bread	Bread and bakery product manufacturing	Grain Products	58.75	96.38	118.44	122.10	113.57	92.87	7,014
Bakery Products	Crackers and cookies	Cookie, cracker and pasta manufacturing	Grain Products	57.89	80.63	96.49	101.82	89.01	81.34	6,126

Bakery Products	Frozen and refrigerated bakery products	Bread and bakery product manufacturing	Grain Products	19.96	30.63	38.74	30.74	26.60	21.91	1,867
Bakery Products	Other bakery products	Bread and bakery product manufacturing	Grain Products	74.78	117.11	155.43	150.48	139.47	129.54	8,984
Meats, poultry, fish, and eggs	Beef	Beef cattle ranching and farming, including feedlots and dual-purpose ranching and farming	Meat	160.04	192.35	263.80	287.50	241.22	173.59	12,362
Meats, poultry, fish, and eggs	Pork	Animal (except poultry) slaughtering, rendering, and processing	Meat	109.61	144.98	197.85	195.25	174.76	138.45	9,529
Meats, poultry, fish, and eggs	Other meats	Animal (except poultry) slaughtering, rendering, and processing	Meat	76.85	111.04	147.52	143.67	120.84	105.26	6,999
Meats, poultry, fish, and eggs	Poultry	Poultry processing	Poultry	114.39	163.37	179.62	207.36	159.41	109.30	10,639
Meats, poultry, fish, and eggs	Fish and seafood	Seafood product preparation and packaging	Fish and Seafood	72.99	93.19	149.60	153.72	137.76	112.06	8,276
Eggs	Eggs	Poultry and egg production	Eggs	38.69	50.47	60.46	59.86	53.10	47.29	2,963
Dairy products	Fresh milk and cream	Dairy cattle and milk production	Fluid Milk	99.91	149.59	189.92	181.64	142.12	119.22	9,691
Dairy products	Other dairy products	Fluid milk and butter manufacturing	Other Dairy Products	151.58	244.27	307.14	316.31	290.90	222.88	18,155
Fruits and Vegetables	Fresh fruits	Fruit farming	Fresh Fruit	162.19	236.97	296.71	308.31	257.81	241.70	13,359
Fruits and Vegetables	Fresh vegetables	Vegetable and melon farming	Fresh Vegetables	128.49	208.36	243.26	269.33	234.43	209.90	21,745
Fruits and Vegetables	Processed fruits – frozen fruits and fruit juices	Frozen food manufacturing	Processed Fruits and Vegetables	7.31	11.19	13.18	18.44	11.12	11.22	922
Fruits and Vegetables	Processed fruits – canned fruits	Fruit and vegetable canning, pickling, and drying	Processed Fruits and Vegetables	10.34	19.21	22.41	24.12	18.78	20.54	1,427
Fruits and Vegetables	Processed fruits – dried fruit	Fruit and vegetable canning, pickling, and drying	Processed Fruits and Vegetables	3.29	10.52	7.53	8.52	8.86	10.08	618

Fruits and Vegetables	Processed fruits – fresh fruit jiuce	Fruit farming	Processed Fruits and Vegetables	10.35	14.40	21.68	21.28	17.69	13.01	863
Fruits and Vegetables	Processed fruits – canned and bottled fruit juice	Fruit and vegetable canning, pickling, and drying	Processed Fruits and Vegetables	45.51	56.60	59.27	62.55	54.46	46.33	3,818
Fruits and Vegetables	Processed vegetables – frozen vegetables	Frozen food manufacturing	Processed Fruits and Vegetables	18.91	39.02	43.03	44.50	37.42	31.25	2,696
Fruits and Vegetables	Processed vegetables – canned and dried vegetables and juices	Fruit and vegetable canning, pickling, and drying	Processed Fruits and Vegetables	70.07	87.11	100.70	114.87	92.37	75.45	6,429
Sugar and other sweets	Candy and chewing gum	Non-chocolate confectionery manufacturing	Added Sugar and Sweeteners	49.30	82.87	101.13	98.40	96.90	75.76	5,537
Sugar and other sweets	Sugar	Sugarcane and sugar beet farming	Added Sugar and Sweeteners	21.22	23.80	30.30	26.51	23.60	19.66	1,170
Sugar and other sweets	Artificial sweeteners	Flavoring syrup and concentrate manufacturing	Added Sugar and Sweeteners	2.30	2.84	4.35	4.32	8.34	5.48	430
Sugar and other sweets	Jams, preserves, other sweets	Fruit and vegetable canning, pickling, and drying	Added Sugar and Sweeteners	17.82	25.39	34.55	33.52	30.72	28.02	2,079
Fats and Oils	Margarine	Fats and oils refining and blending	Added Fats and Oils	7.40	6.40	9.96	8.38	8.60	10.43	399
Fats and Oils	Fats and oils	Fats and oils refining and blending	Added Fats and Oils	31.44	32.70	45.27	44.33	33.40	30.46	1,626
Fats and Oils	Salad dressings	Seasoning and dressing manufacturing	Added Fats and Oils	19.27	26.81	32.90	36.28	34.81	29.69	2,321
Fats and Oils	Nondairy cream and imitation milk	Fluid milk and butter manufacturing	Added Fats and Oils	12.06	15.84	19.98	24.73	19.43	15.25	1,268
Fats and Oils	Peanut butter	Snack food manufacturing	Added Fats and Oils	11.37	16.10	24.97	23.62	16.98	14.65	1,194
Miscellaneous Foods	Frozen prepared foods	Frozen food manufacturing	Other	99.04	146.52	138.18	165.10	124.00	96.66	9,353

Miscellaneous Foods	Canned and packaged soups	Fruit and vegetable canning, pickling, and drying	Other	29.63	38.40	47.59	56.21	45.27	48.29	3,283
Miscellaneous Foods	Potato chips, nuts, and other snacks	Snack food manufacturing	Other	95.16	146.31	183.86	193.60	156.69	114.77	9,886
Miscellaneous Foods	Salt, spices, other seasonings	Seasoning and dressing manufacturing	Other	27.05	36.62	44.68	48.40	38.58	30.28	2,814
Miscellaneous Foods	Olives, pickles, relishes	Fruit and vegetable canning, pickling, and drying	Other	9.32	13.70	17.73	20.84	21.12	16.53	1,245
Miscellaneous Foods	Sauces and gravies	Seasoning and dressing manufacturing	Other	35.37	59.78	72.31	75.54	60.60	44.19	4,353
Miscellaneous Foods	Baking needs and miscellaneous products	All other chemical product and preparation manufacturing	Other	12.80	26.34	26.79	31.29	23.97	21.15	1,710
Miscellaneous Foods	Prepared salads	All other food manufacturing	Other	15.95	30.86	37.07	41.07	38.02	34.82	2,583
Miscellaneous Foods	Prepared desserts	All other food manufacturing	Other	11.74	12.17	14.90	14.98	14.14	15.74	1,056
Miscellaneous Foods	Baby food	Fruit and vegetable canning, pickling, and drying	Other	21.05	65.77	36.66	18.70	8.37	5.07	1,504
Miscellaneous Foods	Miscellaneous prepared foods	All other food manufacturing	Other	82.31	152.41	163.54	163.81	170.26	118.64	10,716
Miscellaneous Foods	Food prepared by consumer unit on out-of-town trips	Food services and drinking places	Other	8.36	39.51	47.04	66.42	64.15	46.95	3,687
Nonalcoholic beverages	Cola	Soft drink and ice manufacturing	Other	54.04	66.93	81.25	90.86	81.56	60.41	5,161
Nonalcoholic beverages	Other carbonated drinks	Soft drink and ice manufacturing	Other	58.21	63.63	80.67	80.30	66.81	40.53	4,416
Nonalcoholic beverages	Coffee	Coffee and tea manufacturing	Other	45.53	63.79	78.12	106.55	99.16	94.86	5,181
Nonalcoholic beverages	Tea	Coffee and tea manufacturing	Other	19.86	28.98	32.82	35.48	33.73	25.20	1,763
Nonalcoholic beverages	Nonalcoholic beer	Breweries	Other	0	0	0	.66	1.04	.49	36

Nonalcoholic beverages	Other nonalcooholic beverages and ice	Soft drink and ice manufacturing	Other	52.6	53.92	78.07	67.98	46.3	38.89	3,776
Food away from home	Meals at restaurants, carry outs and other	Food services and drinking places	Total	1,673.58	2,437.65	2,719.26	2,580.66	2,196.90	1,524.26	156,281
Food away from home	Board (including at school)	Food services and drinking places	Total	20.30	4.63	25.21	105.09	92.66	3.26	3,378
Food away from home	Catered affairs	Food services and drinking places	Total	20.68	54.78	33.60	79.12	130.43	21.17	4,470
Food away from home	Food on out-of-town trips	Food services and drinking places	Total	83.51	220.41	243.65	316.16	334.87	228.58	18,800
Food away from home	School lunches	Food services and drinking places	Total	7.79	53.23	150.03	102.64	18.70	3.04	3,768
Food away from home	Meals as pay	Food services and drinking places	Total	77.53	62.41	38.50	26.00	14.60	5.12	2,010
Alcoholic Beverages at Home	Beer and ale	Breweries	Other	118.71	155.10	120.78	125.06	113.35	58.39	8,091
Alcoholic Beverages at Home	Whiskey	Distilleries	Other	7.57	7.20	10.38	7.15	23.23	17.94	1,294
Alcoholic Beverages at Home	Wine	Wineries	Other	49.09	74.60	117.96	95.71	133.99	108.98	8,751
Alcoholic Beverages at Home	Other alcoholic beverages	Breweries	Other	23.73	15.61	22.49	20.51	29.06	18.69	1,630
Alcoholic Beverages Away from Home	Away from home	Food services and drinking places	Total	154.68	311.73	229.71	206.00	193.78	111.11	13,850
									Total	477,247

[a] Annual food expenditure data is retrieved from the Bureau of Labor Statistics Consumer Expenditure Survey (CES) (Bureau of Labor Statistics 2013), which collects expenditure data for US households (consumer units).
[b] Age category refers to the age of the reference person surveyed from each consumer unit.
[c] Food subcategories are mapped to commodity groups that best represent the food category.
[d] 2012 adult food consumption expenditures are calculated as $AE_F = \sum \left(\frac{No.People - No.Children\ under\ 18}{No.People}\right)_{A,F} * Expenditures_{A,F} * Number\ of\ Consumer\ Units_{A,F} * Price\ Index\ Factor_F / 1{,}000{,}000$, where AE_F represents annual adult food expenditures for given food category, F, the *No.People* is the number of people in consumer unit, A (categorized by age of reference person), and the $Price\ Index\ Factor_F$ is based on price indices data for gross output for each commodity group provided by the Bureau of Economic Analysis (Bureau of Economic Analysis 2014). Although this study excludes children under 19, for the purposes of this step of the analysis, the CES data for children under 18 is used as an approximation.

A-2 Process-Based Model

A-2.1 Industrial Energy Use Estimation Methods and Data Sources

Agriculture

In 2011, total agricultural energy use is roughly 1.6 million TJ (Beckman et al. 2013) while the latest energy use estimate for aquaculture is 87,000 TJ (Cuellar and Webber 2010). Agricultural energy use includes on-farm use of fuels and electricity as well as the embodied energy in farm inputs, including fertilizer and chemicals (Beckman et al. 2013). In 2012 around 28% of farmland acres is allocated to corn production, while cotton and tobacco crops comprise over 3% of farmland (National Corn Growers Association 2013). Also, 31% of corn (in bushels) is used to produce bioethanol (National Corn Growers Association 2013). Based on these percentages, a rough estimate for total agricultural energy use (including for livestock and aquaculture) that is attributed to US food production is obtained. Although different crops as well as similar crops grown for different purposes may require different energy inputs, differentiating these energy intensities is beyond the scope of this study. Also, since total energy consumed in 2011 and 2012 for all sectors in the US differs by only 2%, it is assumed that energy use in the agriculture phase is the same in 2011 and 2012.

Processing/Packaging

In 2012 delivered energy consumption and associated electricity losses is approximately, 1.2 million TJ for food manufacturing (US Energy Information Adminstration 2015b). This value is projected based on energy estimates from the Energy Information Administration Manufacturing Energy Consumption Survey (MECS) of 2010, which also provide relative standard errors (US

Energy Information Administration 2013). Standard errors are calculated by dividing the relative standard errors by 100 and then multiplying by the corresponding energy use value.

Transportation

Approximately, 21% of total food-related industrial energy use is attributed to the transportation stage of the food supply system (Cuellar and Webber 2010). The amount of industrial energy use required to transport food within the food supply chain is then determined by applying this percentage to the total energy use estimates.

Wholesale and Retail

Industrial energy use per square foot of food wholesale and retail buildings is estimated based on the 2003 Commercial Buildings Energy Consumption Survey (CBECS), which is the most recent CBECS (US Energy Information Administration 2006). This value is then multiplied by the corresponding square footage of all food wholesale and retail buildings in the US in 2012, which is retrieved from the 2012 CBECS preliminary results (US Energy Information Administration 2015a). Relative standard errors are also provided for the square footage and building energy intensity values, which enable us to calculate standard errors for total food-related wholesale and retail energy use.

Food Services

Industrial energy use per square foot of food service buildings is estimated based on the 2003 Commercial Buildings Energy Consumption Survey (CBECS), which is the most recent CBECS (US Energy Information Administration 2006). This value is then multiplied by the corresponding square footage of all food service buildings in the US in 2012, which is retrieved from the 2012 CBECS preliminary results (US Energy Information Administration 2015a). Relative standard errors are also provided for the square footage and building energy intensity values, which enable us to calculate standard errors for total food service building energy use.

Household

Food-related household energy use data is retrieved from the US Energy Information Administration Annual Energy Outlook 2015, and includes both delivered energy consumption and associated electricity losses for household refrigeration (1.2 million TJ), cooking (590,000 TJ), freezers (250,000 TJ), and dishwashers (310,000 TJ) in 2012 (US Energy Information Administration 2015c).

A-2.2 Water Withdrawal Estimation Methods and Data Sources

Agriculture

Agricultural water withdrawal estimates are retrieved from the 2012 USDA Census of Agriculture, Farm and Ranch Irrigation Survey (USDA National Agricultural Statistics Service 2014) while livestock and aquaculture water withdrawal values are taken from the latest US Geological Survey (US Geological Survey 2014). In 2012 around 28% of farmland acres is allocated to corn production, while 31% of corn (in bushels) is used to produce bioethanol (National Corn Growers Association 2013). These percentages are used to approximate the amount of irrigation required to grow crops for fuel production. This estimate in addition to water withdrawals required to irrigate tobacco and cotton crops (USDA National Agricultural Statistics Service 2014) are then subtracted from total agricultural water withdrawals to estimate water withdrawals attributed to

US food production. Although crops grown for different purposes may require different water inputs, differentiating these water intensities is beyond the scope of this study. Also, while errors are not provided for livestock and aquaculture estimates, relative standard errors are given for food crops and feed crops (USDA National Agricultural Statistics Service 2014), which are used to estimate standard errors for total food-related agricultural water withdrawals in 2012.

Processing and Packaging

Approximately, 8.6 gallons of water are used in the manufacturing industry per unit output of food, where unit of output is measured in tons for food products and in gallons for beverages (Ellis et al. 2001). The USDA food-availability data (USDA Economic Research Service 1a) is then used to determine the mass and/or volume of food consumed by US adults in 2012. It is acknowledged that this data does not correspond to the Caloric intake estimates directly; however, it is assumed that the USDA dataset provides suitable approximations for US food quantities. Therefore, the industry-wide water use average is applied to the food quantity estimates to obtain total water withdrawals for processing and packaging food consumed by American adults in 2012.

Transportation

Water withdrawals are not estimated for the transportation phase. Supply chain transportation-related water withdrawals are assumed to be included in the estimates for other food production stages.

Wholesale and Retail

Water withdrawals per food store is taken from a report by the American Water Works Association (2000), which provides water withdrawal data for commercial buildings. This number is then multiplied by the number of wholesale and retail establishments in the US in 2012, which is retrieved from the 2012 CBECS preliminary results (US Energy Information Administration 2015a). Relative standard errors are provided for the number of wholesale and retail establishments in the US.

Food Services

Water withdrawals per restaurant is taken from a report by the American Water Works Association (2000), which provides data for commercial buildings. This number is then multiplied by the number of food service establishments in the US in 2012, which is retrieved from the 2012 CBECS preliminary results (US Energy Information Administration 2015a). Relative standard errors are provided for the number of food service establishments in the US.

Household

Total water withdrawals per household in the US is roughly 1.5 m^3 per day (US Environmental Protection Agency 2008b). This translates to around 43 billion m^3 of residential water use in 2012 (US Census Bureau 2013). Given that roughly 7% of household water use is for indoor use (US Environmental Protection Agency 2008b) and that 5% of this amount is for use in the kitchen (US Environmental Protection Agency 2004a), total food-related water withdrawals for the household phase in 2012 is estimated.

A-2.3 GHG Emissions Estimation Methods and Data Sources

<u>Agriculture</u>

In 2012, the total agricultural GHG emissions is 526 million metric tons (MMT) of CO_2-eq (US Environmental Protection Agency 2014a). This estimate is calculated in accordance with methodologies recommended by the Intergovernmental Panel on Climate Change (IPCC). Uncertainty parameters are also given for total agricultural GHG emissions. Furthermore, in 2012 around 28% of farmland acres is allocated to corn production, while cotton and tobacco crops comprise over 3% of farmland (National Corn Growers Association 2013). Also, 31% of corn (in bushels) is used to produce bioethanol (National Corn Growers Association 2013). Based on these percentages, a rough estimate for total agricultural GHG emissions that is attributed to US food production is obtained. Although different crops as well as similar crops grown for different purposes may produce different GHGs, differentiating these emissions intensities is beyond the scope of this study.

<u>Processing and Packaging</u>

In 2012 GHG emissions for food manufacturing are 93 MMT CO_2-eq (US Energy Information Administration 2015c).

<u>Transportation</u>

Approximately, 6% of total food-related GHG emissions is attributed to the transportation stage of the food supply system (Wakeland et al. 2012). The amount of emissions associated with food transport within the food supply chain is then determined by applying this percentage to the total GHG emissions estimates.

Wholesale and Retail

GHG emissions for food wholesale and retail stores are estimated by first determining the percentage of total commercial sector energy use (US Energy Information Administration 1d) that is used for food wholesale and retail establishments in 2012. This percentage is then applied to the total commercial sector GHG emissions (US Environmental Protection Agency 2014a) to determine GHG emissions for all food wholesale and retail stores in 2012. Standard errors for wholesale and retail building energy use, which are previously estimated in Section 1.2.1 – Wholesale and Retail, and for commercial building use, which are provided by the US EIA (US Energy Information Administration 1d) are propagated through the calculations to determine standard errors for food wholesale and retail GHG emissions.

Food Services

GHG emissions for restaurants are estimated by first determining the percentage of total commercial sector energy use (US Energy Information Administration 1d) that is used for food service establishments in 2012. This percentage is then applied to the total commercial sector GHG emissions (US Environmental Protection Agency 2014a) to determine GHG emissions for all food service establishments in 2012. Standard errors for food service building energy use, which are previously estimated in Section 1.2.1 – Food Services, and for commercial building use, which are provided by the US EIA (US Energy Information Administration 1d) are propagated through the calculations to determine standard errors for food service GHG emissions.

Household

Food-related household energy use data is retrieved from the US Energy Information Administration Annual Energy Outlook 2015, and includes GHG emissions associated with household refrigeration (60 MMT CO_2-eq), cooking (30 MMT CO_2-eq), freezers (13 MMT CO_2-eq), and dishwashers (16 MMT CO_2-eq) in 2012 (US Energy Information Administration 2015c).

A-3 Methods for Estimating Extra Daily Caloric Intake

Anthropometric parameters for the Resting Energy Expenditure (REE) predictive equations along with physical activity data are retrieved from the CDC National Health and Nutrition Examination Survey, which interviews and examines thousands of respondents in the US each year (Centers for Disease Control 1a). Requisite anthropometric data for each adult respondent is input into the eight REE equations to calculate a range of predicted REEs for each respondent. Additionally, Metabolic Equivalent of Task (MET) scores, which provide energy expenditures for given physical activities at a designated intensity, are used to determine the Caloric cost of each activity in which individuals participate (Gerrior et al. 2006). The sum of these scores are then used to estimate total physical activity levels (PALs) (sedentary: $1.0 \le PAL < 1.4$, low active: $1.4 \le PAL < 1.6$, active: $1.6 \le PAL < 1.9$, or very active: $1.9 \le PAL < 2.5$) for each respondent. The corresponding physical activity factors for each level are 1.0, 1.12, 1.27, and 1.54 for men and 1.0, 1.14, 1.27, and 1.45 for women, respectively (Gerrior et al. 2006). The products of REEs and physical activity factors yield a range of daily Caloric intake, or Total Energy Expenditure (TEE), for each respondent. A basic formulation for daily per-capita TEE in the US then follows as:

$$TEE = \frac{\sum_{i=1}^{m} REE_i \times \ Physical\ Activity\ Factor_i \times Weight\ Factor_i}{n} \quad (1)$$

Where *m* represents the number of adults surveyed, *n* represents the number of adults in the US (US Census Bureau 2013) and $Weight\ Factor_i$ is the number of people in the US that survey participant, *I*, represents. The weight factor parameters are specified by the CDC and applied to this analysis to ensure adequate representation of Caloric intake estimates for the US population.

Daily recommended Caloric intake is estimated in a similar manner. However, for REE in equation 2, actual weight is replaced with maximum healthy or "normal" weight (MNW), which is estimated as:

$$MNW_i = BMI \times (H_i)^2 \tag{2}$$

Where *BMI* is set to 25, the overweight threshold, and *H* is height in meters (Centers for Disease Control 1c).

The difference between TEE and recommended TEE is the amount of extra Calories an individual consumes. Extra Caloric intake is estimated for each overweight and obese respondent. This study does not account for the deprivation of Calories by underweight individuals or for normal weight examinees whose weights fall below their estimated maximum normal weight values. Underweight and normal weight individuals, however, are included in the total adult population estimates.

Table A-2 Caloric intake estimates per US adult[a]

2012	Average Daily Caloric Intake	Extra Daily Caloric Intake	Standard Error[c]	% of Calories that are Extra	Standard Error
Mifflin et al. (1990)	2,280	180	5.2	7.9%	0.23%
Harris & Benedict (1919)	2,340	220	5.7	9.4%	0.24%
Roza & Shizgal (1984)	2,420	210	5.7	8.7%	0.24%
Livingston (2005)	2,250	170	5.2	7.6%	0.23%
Muller et al. (2004)	2,390	210	5.2	8.8%	0.22%
Schofield (1985)	2,410	200	5.9	8.3%	0.25%
Henry (2005)	2,380	240	5.4	10%	0.23%
Owen et al. (1986, 1987)	2,270	170	6.6	7.5%	0.29%
Average[b]	2,350	210	6.2	8.9%	0.26%

[a] Caloric intake estimates include Calories associated with food losses.
[b] Average estimates are the mean of the values estimated from the eight REE equations.
[c] The methods used to estimate standard errors are described in Section 3, the Uncertainty Analysis section.

A-4 Results

Table A-3 Total Food Related Impacts for the US Adult Population and Data Sources[a]

Energy Use (1,000 TJ)

Stage	EIO-LCA	Process-Based	Year(s)	Source
Agriculture	4,400 ± 88	1,100	2002/2011/ 2012	*Cuellar and Webber 2010, Beckman et al. 2013, National Corn Growers 2013*
Processing/Packaging		930 ± 28	2012	*US EIA 2013, US EIA 2015b*
Transportation		1,300	2012	*Cuellar and Webber 2010*
Wholesale and Retail		620 ± 98	2012	*US EIA 2006, US EIA 2015a*
Food Services		340 ± 62	2012	*US EIA 2006, US EIA 2015a*
Household[b]	1,800	1,800	2012	*US EIA 2015c*
Total	6,200 ± 88	6,100 ± 120		

Water withdrawals (billion m^3)[c]

Stage	EIO-LCA	Process-Based	Year(s)	Source
Agriculture	104 ± 2.3	85 ± 1.5	2010-2013	*National Corn Growers 2013, USDA NASS 2014, USGS 2014*
Processing/Packaging		2.2	2001	*Ellis et al. 2001, USDA ERS 1a*
Transportation		0.0	--	--
Wholesale and Retail		8.9 ± 4.2	2012	*US EIA 2015a, AWWA 2000*
Food Services		3.1 ± 2.0	2012	*US EIA 2015a, AWWA 2000*
Household[b]	1.2	1.2	2012	*US Census Bureau 2013, US EPA 2008b, US EPA 2004a*
Total	105 ± 2.3	100 ± 4.9		

GHG Emissions (MMT CO_2-eq)

Stage	EIO-LCA	Process-Based	Year(s)	Source
Agriculture	510 ± 10	340 ± 64	2012	*US EPA 2014a, Beckman 2013, National Corn Growers 2013*
Processing/Packaging		72	2012	*US EIA 2015c*
Transportation		36	2012	*Wakeland et al. 2012*
Wholesale and Retail		36 ± 6	2012	*US EPA 2014a, US EIA 2006, US EIA 2015a, US EIA 1d*
Food Services		20 ± 4	2012	*US EPA 2014a, US EIA 2006, US EIA 2015a, US EIA 1d*
Household[b]	92	92	2012	*US EIA 2015c*
Total	600 ± 10	600 ± 64		

[a] All values include food losses through the food supply chain. See Section A-2 of Appendix A for methods used to obtain the process-based estimates.
[b] Household impacts for the EIO-LCA model are taken from the process-based model.
[c] Water withdrawal estimates include all ground and surface water withdrawals.
Note: *Years* and *sources* correspond to the process-based estimates only.

Table A-4 Total Extra Food Related Impacts for the US Adult Population (EIO-LCA Model)

2012	Extra Energy Use (1000 TJ)	Standard Error	Extra Water Withdrawals (Billion m^3)	Standard Error	Extra GHG Emissions (MMT CO_2-eq)	Standard Error
Mifflin et al. (1990)	511	15.0	8.6	0.28	49.1	1.5
Harris & Benedict (1919)	583	16.2	9.8	0.30	56.1	1.6
Roza & Shizgal (1984)	547	15.8	9.2	0.29	52.6	1.6
Livingston (2005)	488	15.3	8.2	0.28	46.9	1.5
Muller et al. (2004)	547	14.7	9.2	0.27	52.6	1.5
Schofield (1985)	527	16.2	8.9	0.30	50.7	1.6
Henry (2005)	611	15.6	10.3	0.29	58.8	1.6
Owen et al. (1986, 1987)	449	18.7	7.6	0.33	43.2	1.8
Average	458	26.2	7.7	0.45	44.0	2.5

Table A-5 Total Extra Food Related Impacts for the US Adult Population (Process-Based Model)

2012	Extra Energy Use (1000 TJ)	Standard Error	Extra Water Withdrawals (Billion m^3)	Standard Error	Extra GHG Emissions (MMT CO_2-eq)	Standard Error
Mifflin et al. (1990)	496	16.7	8.3	0.57	49.2	7.0
Harris & Benedict (1919)	566	18.3	9.4	0.64	56.2	8.0
Roza & Shizgal (1984)	532	17.6	8.9	0.60	52.7	7.5
Livingston (2005)	474	16.7	7.9	0.55	47.0	6.7
Muller et al. (2004)	532	16.7	8.9	0.60	52.7	7.5
Schofield (1985)	512	17.9	8.5	0.59	50.8	7.2
Henry (2005)	593	18.0	9.9	0.66	58.8	8.3
Owen et al. (1986, 1987)	436	19.6	7.3	0.54	43.3	6.3
Average	445	26.4	7.4	0.62	44.1	6.6

A-5 Uncertainty Analysis

The results of this analysis are subject to the uncertainty of the model input parameters, which include the total number of Calories and the extra Calories consumed by adults and the environmental and resource use impacts associated with producing food consumed by adults. In determining the uncertainty for the number of Calories consumed per adult, RMSE for the REE equations are used as approximations for the standard errors of Caloric intake estimates for each NHANES survey respondent. The uncertainty for the actual and recommended number of Calories consumed is therefore, described by the following relationship:

$$U_{Calories,R} = \sqrt{\sum_{i=1}^{m}\left(\frac{Weight\ Factor_i}{n}\right)^2 * (RMSE_R)^2}$$

Where $U_{Calories,R}$ is the total uncertainty for the actual and recommended Caloric intake per adult based on REE equation, *R*, *m* represents the number of adults surveyed in the NHANES, $Weight\ Factor_i$ is the number of people in the US that survey participant, *I*, represents, *n* is the number of adults in the US, and $RMSE_R$ is the root mean squared error for REE equation, *R*. Based on the laws of error propagation, the uncertainty for extra Caloric intake per adult is thus, $U_{Extra,R} = U_{Calories,R} * 2$. The RMSE for the REE equations result in standard errors that are $\pm$3-6% of extra Caloric intake per adult. Any additional uncertainty in the extra Caloric intake estimates are assumed to be accounted for through the application of eight REE equations, which yield upper and lower bound estimates that are 16% above and 18% below the average extra Caloric intake values.

The food consumption impacts were estimated using two methods: economic input-output environmental life-cycle assessment and process activity analysis. There are a number of assumptions and uncertainties within the EIO-LCA model. The model, for instance, assumes a linear model and assigns domestic impacts to international production of goods (CMU GDI 2008, Lenzen 2000). Also, while the EIO-LCA model is effective as a scoping method for evaluating large groups of items, aggregation of goods within economic sectors produces uncertainty in the results (Weber and Matthews 2008). Further explanation of assumptions and uncertainties in the EIO-LCA model are provided by the Carnegie Mellon University Green Design Institute EIO-LCA website and handbook (CMU GDI 2008, Hendrickson et al. 2006). Uncertainty bounds within the EIO-LCA model are not readily available, and are therefore, unaccounted for in this study. The consumer expenditures survey, however, provides standard errors for expenditure data, which when applied to the EIO-LCA model establishes some measure of uncertainty for the EIO-LCA impacts. Standard errors are estimated as roughly ± 3% for this phase.

Roughly half of the data sources used in the process activity analysis provide error estimates for individual impacts from each food supply stage. Those phases for which errors are unavailable are assumed to have zero uncertainty. Refer to Section A-2 of Appendix A for detailed accounts of these methods. Once errors are established for individual steps of the food system, total uncertainty is found by propagating these error values throughout all calculations. Hence, the following relationship is used to estimate total uncertainty for each impact: $U_{Impact,I} = \sqrt{\sum(u_{iI})^2}$, where $U_{Impact,I}$ is the uncertainty for total food consumption impacts, u_{iI} is the uncertainty for individual impact, *I*, attributed to each stage in the food supply system, and *I* is the impact category (energy use, water withdrawals, GHG emissions). Standard errors were estimated as ±5% for energy use, ±7% for water withdrawals, and ±15% for GHG emissions attributed to food provided for adult consumption in 2012.

The error values for each model input parameter are propagated through all remaining calculations to estimate total uncertainty for the extra impacts attributed to producing additional Calories for the US adult population. Uncertainty bounds for each input variable and for the results are shown in previous sections of this analysis.

APPENDIX B ENERGY USE, WATER WITHDRAWALS, AND GHG EMISSIONS FOR CURRENT FOOD CONSUMPTION PATTERNS AND DIETARY RECOMMENDATIONS IN THE US, SUPPLEMENTARY INFORMATION

B-1 Calorie Estimates

Table A-6 Current and recommended Caloric intake estimates per US adult[a]

	Current Caloric Intake	Recommended Caloric Intake	Extra Caloric Intake	Percentage Extra
Mifflin et al. (1990)	2,280	2,100	180	7.9%
Harris & Benedict (1919)	2,340	2,120	220	9.4%
Roza & Shizgal (1984)	2,420	2,210	210	8.7%
Livingston (2005)	2,250	2,080	170	7.6%
Muller et al. (2004)	2,390	2,180	210	8.8%
Schofield (1985)	2,410	2,210	200	8.3%
Henry (2005)	2,380	2,140	240	10%
Owen et al. (1986, 1987)	2,270	2,100	170	7.5%
Average[b]	2,350	2,140	210	8.9%

[a] Caloric intake estimates exclude Calories associated with food losses at the retail and consumer levels.
[b] Average estimates are the mean of the values estimated from the eight REE equations.

Table A-7 Daily Caloric Intake of Individual Foods per US Adult[a]

Food Group	Current Caloric Intake[b]	USDA Recommended Food Mix @ 2,000 Calories[c]	USDA Recommended Food Mix @ 2,200 Calories[c]	USDA Recommended Food Mix @ 2,400 Calories[c]	Caloric Intake (Dietary Scenario 1)[d]	Caloric Intake (Dietary Scenario 2)[e]	Caloric Intake (Dietary Scenario 3)[f]
Fruits/Fruit Juice	112	210	210	210	102	210	210
Vegetables	126	195	234	234	114	263	222
Dairy	258	465	465	465	235	465	465
Grains	540	487	568	649	492	629	543
Protein	473	370	401	435	431	425	392
Meat	256	153	167	176	233	178	163
Poultry	151	100	110	116	137	117	107
Eggs	32	27	30	31	29	32	29
Fish/Seafood	14	39	44	49	13	47	42
Nuts, seeds, soy	22	51	51	63	20	51	51
Added sugars	289	15	31	65	263	42	26
Solid Fats	206	15	31	65	187	42	26
Oils	351	243	261	279	319	275	256
Total	2,350	2,000	2,200	2,400	2,140	2,350	2,140

[a] Caloric intake estimates exclude Calories associated with food losses at the retail and consumer levels.
[b] Current Caloric intake for individual foods are estimated based on the Centers for Disease Control most recent *National Health and Nutrition Examination Survey (NHANES),* which presents average daily intake of food (per 2000 calories) by food group and demographic characteristics (Centers for Disease Control 1a, USDA Economic Research Service 1c).
[c] Recommended food mix is based on the *Benchmark Food Density* chart found in the USDA *Dietary Guidelines for Americans, 2010*, which presents recommended daily intake of individual foods at various Caloric intake levels (USDA and US Department of Health and Human Services 2010).
[d] Dietary Scenario 1 accounts for a reduction in Caloric intake only, without shifting the current US diet to the USDA recommended food mix.
[e] Dietary Scenario 2 accounts for a shift to the USDA recommended food mix only, without reducing total Caloric intake.
[f] Dietary Scenario 3 accounts for both a reduction in Caloric intake and a shift to the USDA recommended food mix.

Table A-8 Food Losses and Daily Caloric Consumption per US Adult[a]

Food Group	Retail Level Food Losses (Percentage)[b]	Consumer Level Food Losses (Percentage)[b]	Total Retail and Consumer Level Food Losses (Percentage)[b]	Current Caloric Consumption[c]	Caloric Consumption (Dietary Scenario 1)[d]	Caloric Consumption (Dietary Scenario 2)[e]	Caloric Consumption (Dietary Scenario 3)[f]
Fruits/Fruit Juice	11%	28%	40%	187	170	349	349
Processed Fruits	6%	15%	21%				
Vegetables	11%	21%	32%	185	169	388	331
Processed Vegetables	6%	15%	21%				
Fluid Milk	12%	20%	32%	379	345	684	684
Other Dairy Products	8%	20%	29%				
Grains	12%	19%	31%	783	713	914	797
Protein	--	--	--	639	582	581	537
Meat	5%	23%	28%	355	323	248	228
Poultry	4%	17%	21%	191	174	148	137
Eggs	7%	21%	28%	45	41	44	41
Fish/Seafood	8%	32%	40%	23	21	79	71
Nuts, seeds, soy	6%	11%	17%	26	24	61	61
Added sugars	11%	29%	40%	481	438	71	46
Solid Fats	19%	20%	39%	338	308	70	45
Oils	19%	20%	39%	576	525	451	421
Total	--	--	--	3,570	3,250	3,510	3,210

[a] Caloric consumption estimates include Calories associated with food losses at the retail and consumer levels.

[b] Source of food loss estimates: *USDA Economic Research Service 1b; Buzby et al. 2014*

[c] Current Caloric consumption estimates are obtained by applying the food loss percentages at the retail and consumer levels to the current Caloric intake estimates shown in Table A-7 above.

[d] Dietary Scenario 1 accounts for a reduction in Caloric intake only, without shifting the current US diet to the USDA recommended food mix. Food losses at the retail and consumer levels are applied to the Caloric intake estimates for dietary Scenario 1 to obtain Caloric consumption values.

[e] Dietary Scenario 2 accounts for a shift to the USDA recommended food mix only, without reducing total Caloric intake. Food losses at the retail and consumer levels are applied to the Caloric intake estimates for dietary Scenario 2 to obtain Caloric consumption values.

[f] Dietary Scenario 3 accounts for both a reduction in Caloric intake and a shift to the USDA recommended food mix. Food losses at the retail and consumer levels are applied to the Caloric intake estimates for dietary Scenario 3 to obtain Caloric consumption values.

B-2 Meta-Analysis of Environmental Intensities for Foods

The information presented in Table 4 is drawn from published life-cycle assessment (LCA) studies for food products evaluated in this study. The minimum and maximum values shown represent the minimum and maximum impact factors found in the literature. The average estimates are the averages of all intensity values obtained for each food type. Some sources provide multiple estimates for the same food type. In these instances, estimates originating from the same source are averaged, and presented as a single estimate, which are then averaged together with values obtained from other sources. In the case where only one source is found for a particular food product, estimates within the same source are used to represent the minimum and maximum values listed below. Additionally, proxies are used for food types for which data is unavailable. Proxies are displayed under the column, “Number of Sources.” This column also provides the number of studies contributing to the impact factor estimates for each food type. These sources are listed in the References section of this Supplementary Information.

The greenhouse gas (GHG) emissions estimates are not shown here. However, this study uses the GHG emissions factors from the Heller and Keoleian (2014) study. The GHG estimates are provided in their online Supporting Information.

Table A-9 Cumulative Energy Use and Water Withdrawal Factors for 100+ Food Types

Food Type	Energy Use MJ/kCal Average	Energy Use MJ/kCal min	Energy Use MJ/kCal max	Number of Sources	Water Withdrawals liters/kCal Average	Water Withdrawals liters/kCal min	Water Withdrawals liters/kCal max	Number of Sources
Grain products	**1.2E-03**	**8.5E-04**	**1.5E-03**		**1.1E-01**	**9.9E-02**	**1.3E-01**	
total wheat flours	9.0E-04	6.9E-04	1.1E-03	2	9.2E-02	8.7E-02	1.0E-01	3
rice	2.3E-03	1.9E-03	2.7E-03	1	3.6E-01	2.6E-01	4.4E-01	3
rye flour	1.5E-03	1.5E-03	1.5E-03	1	1.4E-01	1.1E-01	1.7E-01	2
corn products	1.5E-03	1.0E-03	2.1E-03	All grains	6.6E-02	6.4E-02	6.8E-02	2
barley products	6.2E-04	5.7E-04	6.8E-04	2	1.2E-01	9.9E-02	1.5E-01	2
oat products	3.1E-03	6.7E-04	4.6E-03	1	2.0E-01	1.3E-01	2.8E-01	2
Fresh fruit	**4.1E-02**	**2.1E-02**	**6.1E-02**		**5.4E-01**	**4.9E-01**	**6.0E-01**	
citrus	1.9E-02	1.6E-02	2.2E-02	1	3.0E-01	2.6E-01	3.5E-01	2
apples	1.2E-02	1.1E-02	1.3E-02	2	5.5E-01	5.2E-01	5.7E-01	2
apricots	1.6E-03	1.1E-03	2.2E-03	Cherries	1.5E-01	1.5E-01	1.5E-01	1
avocados	1.7E-02	1.6E-02	1.8E-02	All Fresh Fruit	5.0E-01	5.0E-01	5.0E-01	1
bananas	1.3E-02	1.3E-02	1.3E-02	1	1.8E-01	4.3E-02	4.4E-01	3
blueberries	1.6E-02	1.6E-02	1.6E-02	1	9.2E-01	9.2E-01	9.2E-01	1
cantaloupe	8.0E-02	7.6E-02	8.6E-02	All Fresh Fruit	3.0E-01	3.0E-01	3.0E-01	Watermelon
cherries	1.3E-02	9.1E-03	1.7E-02	1	1.8E+00	1.8E+00	1.8E+00	1
cranberries	2.3E-02	1.6E-02	3.3E-02	Berries	4.3E-01	4.3E-01	4.3E-01	1
grapes	1.3E-02	1.1E-02	1.4E-02	1	4.1E-01	3.8E-01	4.3E-01	2
honeydew	7.5E-02	7.1E-02	8.1E-02	All Fresh Fruit	2.8E-01	2.8E-01	2.8E-01	Watermelon
kiwi	1.9E-01	1.9E-01	1.9E-01	1 Tropical	9.7E-01	9.7E-01	9.7E-01	1
mangoes	1.8E-01	1.8E-01	1.8E-01	1 Tropical	3.4E+00	1.8E+00	5.0E+00	2
papaya	3.0E-01	3.0E-01	3.0E-01	1 Tropical	3.0E-01	3.0E-01	3.0E-01	1
peaches	1.7E-02	1.2E-02	2.3E-02	Cherries	9.8E-01	9.8E-01	9.8E-01	1
pears	1.1E-02	9.7E-03	1.2E-02	Apples	4.0E-01	4.0E-01	4.0E-01	1
pineapples	6.2E-03	5.4E-03	7.0E-03	1	5.3E-02	7.3E-03	8.7E-02	3
plums	1.5E-02	1.1E-02	2.1E-02	Cherries	1.3E+00	1.3E+00	1.3E+00	1

raspberries	1.5E-02	1.4E-02	1.7E-02	2	7.5E-01	7.5E-01	7.5E-01	1
strawberries	4.4E-02	1.9E-02	8.8E-02	1	2.6E-01	2.6E-01	2.6E-01	1
watermelon	9.0E-02	8.5E-02	9.7E-02	All Fresh Fruit	4.9E-01	4.9E-01	4.9E-01	1
Processed fruit	**--**	--	--	--	--	--	--	--
canned fruit	3.4E-02	3.4E-02	3.4E-02	1	1.6E+00	1.6E+00	1.6E+00	1
frozen fruit	1.0E-02	6.6E-03	1.4E-02	1	1.7E-01	1.7E-01	1.7E-01	1
dried fruit	1.9E-02	1.3E-02	2.7E-02	1	5.4E-01	5.4E-01	5.4E-01	1
fruit juices	6.5E-02	1.8E-02	1.1E-01	2	5.0E-01	5.0E-01	5.0E-01	1
Fresh vegetables	**2.4E-02**	**1.5E-02**	**4.0E-02**		**7.0E-01**	**6.4E-01**	**7.5E-01**	
artichokes	1.8E-02	1.1E-02	3.2E-02	All Fresh Veg	1.3E+00	1.3E+00	1.3E+00	1
asparagus	4.2E-02	2.5E-02	7.4E-02	All Fresh Veg	8.7E+00	8.7E+00	8.7E+00	1
bell peppers	4.2E-02	2.5E-02	7.4E-02	All Fresh Veg	7.7E-01	7.7E-01	7.7E-01	1
broccoli	1.3E-02	1.1E-02	1.5E-02	Cabbage	4.8E-01	4.8E-01	4.8E-01	1
115ilomet sprouts	1.0E-02	8.6E-03	1.2E-02	Cabbage	3.8E-01	3.8E-01	3.8E-01	1
cabbage	1.9E-02	1.6E-02	2.2E-02	1	7.6E-01	7.6E-01	7.6E-01	1
carrots	7.7E-03	7.1E-03	8.2E-03	2	1.5E-01	1.5E-01	1.5E-01	1
cauliflower	1.8E-02	1.5E-02	2.0E-02	Cabbage	6.6E-01	6.6E-01	6.6E-01	1
celery	6.1E-02	3.7E-02	1.1E-01	All Fresh Veg	4.3E-01	4.3E-01	4.3E-01	1
collards	1.4E-02	1.2E-02	1.7E-02	Cabbage	5.8E-01	5.8E-01	5.8E-01	Cabbage
sweet corn	9.9E-03	6.0E-03	1.7E-02	All Fresh Veg	3.9E-01	3.9E-01	3.9E-01	1
cucumbers	7.2E-02	4.3E-02	1.3E-01	All Fresh Veg	2.0E+00	2.0E+00	2.0E+00	1
eggplant	3.5E-02	2.1E-02	6.1E-02	All Fresh Veg	5.8E-01	5.8E-01	5.8E-01	1
escarole & endive	5.3E-02	3.2E-02	9.3E-02	All Fresh Veg	5.2E-01	5.2E-01	5.2E-01	Lettuce
garlic	2.9E-03	1.3E-03	6.6E-03	Roots	1.8E-01	1.8E-01	1.8E-01	1
kale	8.7E-03	7.3E-03	1.0E-02	Cabbage	3.5E-01	3.5E-01	3.5E-01	Cabbage
head lettuce	6.7E-02	4.0E-02	1.2E-01	All Fresh Veg	6.5E-01	6.5E-01	6.5E-01	1
romaine & leaf lettuce	5.0E-02	3.0E-02	8.8E-02	All Fresh Veg	4.9E-01	4.9E-01	4.9E-01	1
lima beans	7.3E-03	4.4E-03	9.8E-03	Legumes	3.8E-01	3.8E-01	3.8E-01	Snap Beans
mushrooms	3.9E-02	2.3E-02	6.8E-02	All Fresh Veg	3.2E-01	3.2E-01	3.2E-01	All Fresh Veg
mustard greens	1.6E-02	1.4E-02	1.9E-02	Cabbage	6.7E-01	6.7E-01	6.7E-01	Cabbage
okra	2.7E-02	1.6E-02	4.8E-02	All Fresh Veg	1.4E+00	1.4E+00	1.4E+00	1
onions	1.0E-02	4.5E-03	2.3E-02	Roots	2.5E-01	2.5E-01	2.5E-01	2

potatoes	7.1E-03	2.0E-03	1.9E-02	5	4.8E-01	4.7E-01	5.0E-01	2
pumpkin	3.3E-02	2.0E-02	5.7E-02	All Fresh Veg	4.0E-01	4.0E-01	4.0E-01	1
radishes	2.7E-02	1.2E-02	6.0E-02	Roots	1.0E+00	1.0E+00	1.0E+00	Broccoli
snap beans	2.7E-02	1.6E-02	3.6E-02	Legumes	9.3E-01	9.3E-01	9.3E-01	1
spinach	3.6E-02	2.2E-02	6.3E-02	All Fresh Veg	5.3E-01	5.3E-01	5.3E-01	1
squash	5.3E-02	3.2E-02	9.3E-02	All Fresh Veg	6.5E-01	6.5E-01	6.5E-01	1
sweet potatoes	4.2E-03	1.2E-03	1.1E-02	Potatoes	5.5E-01	5.2E-01	5.8E-01	2
tomatoes	3.8E-01	2.0E-01	7.3E-01	4	4.9E-01	3.8E-01	5.5E-01	4
turnip greens	1.3E-02	1.1E-02	1.6E-02	Cabbage	1.8E-01	1.8E-01	1.8E-01	1
Processed vegetables	--	--	--	--	--	--	--	--
Canned	4.0E-02	3.3E-02	4.7E-02	2	5.0E-01	3.8E-01	6.2E-01	2
frozen	2.2E-02	1.4E-02	2.9E-02	1	5.3E-01	5.3E-01	5.3E-01	1
processed and dehydrated	5.7E-03	4.0E-03	9.0E-03	4	1.3E-01	1.3E-01	1.3E-01	2
Legumes	6.2E-03	3.8E-03	8.4E-03	1	4.4E+00	3.9E+00	4.9E+00	2
Fluid milk	**1.2E-02**	**1.1E-02**	**1.3E-02**	4	**2.9E-01**	**2.9E-01**	**2.9E-01**	2
Other dairy products	**1.3E-02**	**1.1E-02**	**1.7E-02**		**2.7E-01**	**2.7E-01**	**2.7E-01**	
Yogurt	2.5E-02	1.9E-02	3.1E-02	2	1.5E+00	1.5E+00	1.5E+00	1
cheese	1.3E-02	1.1E-02	1.8E-02	3	2.1E-01	2.1E-01	2.1E-01	1
cottage cheese	5.9E-02	4.8E-02	8.0E-02	Cheese	9.5E-01	9.5E-01	9.5E-01	Cheese
ice cream	4.9E-03	2.6E-03	7.2E-03	2	1.1E-01	1.1E-01	1.1E-01	Cream
other frozen dairy	2.1E+00	1.1E+00	3.1E+00	Ice Cream	2.0E+02	2.0E+02	2.0E+02	Cream
evaporated condensed milk	2.0E-02	2.0E-02	2.0E-02	Cream	1.6E-01	1.6E-01	1.6E-01	Milk
dry milk products	1.6E-02	1.6E-02	1.6E-02	1	1.9E-01	1.9E-01	1.9E-01	1
half and half	3.1E-02	3.1E-02	3.1E-02	Cream	3.7E-01	3.7E-01	3.7E-01	Cream
eggnog	3.1E-02	3.1E-02	3.1E-02	Cream	3.7E-01	3.7E-01	3.7E-01	Cream
cream	8.8E-03	8.8E-03	8.8E-03	1	1.1E-01	1.1E-01	1.1E-01	1
sour cream	9.0E-03	6.8E-03	1.1E-02	Yogurt	5.6E-01	5.6E-01	5.6E-01	Yogurt
cream cheese	1.7E-02	1.4E-02	2.2E-02	Cheese	2.7E-01	2.7E-01	2.7E-01	Cheese
Meat	**1.3E-02**	**8.1E-03**	**1.6E-02**		**4.3E-01**	**4.1E-01**	**4.5E-01**	
beef	1.4E-02	9.2E-03	1.7E-02	4	4.1E-01	4.1E-01	4.1E-01	2
veal	1.9E-02	1.2E-02	2.3E-02	Beef	2.0E+00	2.0E+00	2.0E+00	Other

pork	1.1E-02	6.3E-03	1.4E-02	4	4.4E-01	3.7E-01	5.2E-01	2
lamb	1.2E-02	1.2E-02	1.2E-02	3	8.0E-01	1.5E+00	1.2E-01	2
Poultry	**1.1E-02**	**8.6E-03**	**1.3E-02**	5	**6.3E-01**	**9.7E-01**	**1.0E+00**	3
Fish and Seafood	**8.5E-02**	**8.1E-02**	**8.9E-02**		**2.2E-02**	**2.2E-02**	**2.2E-02**	1
fresh and frozen fish	4.4E-02	4.3E-02	4.6E-02	2	--	--	--	--
fresh and frozen shellfish	2.5E-01	2.5E-01	2.5E-01	1	--	--	--	--
canned fish and shellfish	2.6E-02	1.6E-02	3.6E-02	1	--	--	--	--
cured fish	3.8E-02	3.8E-02	3.8E-02	Canned Fish	--	--	--	--
Eggs	**7.1E-03**	**1.8E-03**	**1.3E-02**	2	**6.5E-01**	**1.0E+00**	**1.1E+00**	2
Nuts	**1.1E-03**	**9.2E-04**	**1.2E-03**	1	**3.9E-01**	**3.3E-01**	**4.5E-01**	
peanuts	--	--	--	--	9.9E-02	9.4E-02	1.0E-01	2
total tree nuts	--	--	--	--	1.0E+00	8.6E-01	1.2E+00	2
coconuts	--	--	--	--	2.0E-03	2.0E-03	2.0E-03	1
Added sugar and sweeteners	**5.3E-03**	**3.4E-04**	**1.2E-02**		**1.0E-01**	**6.8E-02**	**1.4E-01**	
cane and beet sugar	2.6E-03	2.6E-03	2.6E-03	1	5.6E-02	5.5E-02	5.7E-02	2
honey and syrup	9.1E-04	3.4E-04	1.5E-03	1	5.5E-02	5.5E-02	5.5E-02	Molasses
corn sweeteners	4.7E-03	4.7E-03	4.7E-03	1	1.7E-01	8.5E-02	2.5E-01	Sweeteners
Added fats and oils	**2.0E-03**	**9.6E-04**	**2.9E-03**		**1.0E-01**	**9.5E-02**	**1.1E-01**	
butter	4.8E-03	4.1E-03	5.6E-03	3	1.1E-01	1.1E-01	1.1E-01	2
margarine	3.6E-03	3.1E-03	4.1E-03	2	1.7E-01	1.5E-01	1.8E-01	Cooking oils
lard and beef tallow	3.9E-03	3.3E-03	4.4E-03	Butter	9.0E-02	9.0E-02	9.0E-02	1
shortening	1.7E-03	6.0E-04	2.7E-03	Cooking Oils	1.0E-01	9.2E-02	1.1E-01	Cooking oils
salad and cooking oils	1.7E-03	6.0E-04	2.7E-03	2	1.0E-01	9.2E-02	1.1E-01	2
other added fats and oils	2.7E-03	1.9E-03	3.3E-03	All Fats & Oils	1.0E-01	9.2E-02	1.1E-01	Cooking oils

Sources: *Almeida et al. 2014, Andersson et al. 1998, Beccali et al. 2009, Bengtsson, and Seddon 2013, Berlin, J. 2002, Blanke and Burdick 2005, Braschkat et al. 2003, Brodt et al. 2013, Broekema and Kramer 2014, Carlsson-Kanyama, A. 1998, Carlsson-Kanyama et al. 2003, Cederberg, C. 2003, Chapagain and Hoekstra 2004, Chapagain and Hoekstra 2011, Chapagain and Orr 2009, Foster et al. 2006, Girgenti et al. 2013, Girgenti et al. 2014, Ingwersen, W. 2012, Kendall, A. 2012, Leinonen et al. 2012, Mattsson and Wallen 2003, Mekonnen and Hoekstra 2010, Mekonnen and Hoekstra 2011a, Mekonnen and Hoekstra 2011b, Mekonnen and Hoekstra 2012, Nilsson et al. 2010, Pelletier et al. 2010, Pelletier et al. 2013, Prudencio da Silva et al. 2014, Ridoutt et al. 2010, Sikirica, N. 2011, Williams et al. 2006.*

APPENDIX C EXCESS PASSENGER WEIGHT IMPACTS ON US TRANSPORTATION SYSTEMS FUEL USE (1970-2010), SUPPLEMENTARY INFORMATION

C-1 Data

C-1.1 Vehicle Data

Light Duty-Vehicles

Light-duty vehicle data is gathered separately for passenger cars I and for light-duty trucks (T) for each year from 1970 through 2010. Light-duty trucks include pick-up trucks, SUVs, and vans, while cars include all other light-duty vehicles. Vehicle data for this study consists of 10 variables, the first eight of which are obtained from the US Federal Highway Administration Highway Statistics Series (US DOT Federal Highway Administration 1a). These parameters include the number of registered vehicles (RV_C and RV_T), annual vehicle kilometers for all vehicles (VMT_C and VMT_T), and annual passenger kilometers within all vehicles (PMT_C and PMT_T) in the US. Where annual passenger kilometers data is not provided by the FHWA, values are estimated using linear interpolation between known values. Average occupancy loads (N_C and N_T) are then determined for each year by dividing the annual passenger kilometers by the annual vehicle kilometers traveled.

The last two variables, R_C and R_T, denote the impact of weight on fuel consumption per vehicle, which is shown to exhibit a linear relationship (US Transportation Research Board 2002, Heavenrich 2005). These parameters represent the ratio of the change in fuel use per distance traveled to the change in weight. The average impact of weight on fuel consumption for each model year vehicle is available from the US Environmental Protection Agency from year 1975 to the present (Heavenrich, 2006). It is assumed that for prior years, these values are consistent with those from 1975. The National Household Travel Survey (NHTS) provides annual vehicle kilometers traveled per model year vehicle within the light-duty fleet for select years between 1970 and 2010 (US DOT Federal Highway Administration 2009). This information along with EPA data is then used to develop a weighted average for the parameters, R_C and R_T, which is applicable to the entire fleet. Where annual VMT data is not provided for model year vehicles, values are estimated using linear interpolation between known values.

Public Transit

Public transit vehicle data is gathered separately for commuter rail (CR), light rail (LR), heavy rail (HR), and public transit bus (TB) systems for each year from 1970 through 2010. Vehicle data for this study consists of 23 variables, 19 of which are obtained from the American Public Transportation Association Public Transportation Factbook (Dickens et al. 2012). These parameters include the number of transit vehicles (RV_{CR}, RV_{LR}, RV_{HR}, and RV_{TB}), annual vehicle kilometers for all transit vehicles (VMT_{CR}, VMT_{LR}, VMT_{HR}, and VMT_{TB}), annual passenger kilometers within all transit vehicles (PMT_{CR}, PMT_{LR}, PMT_{HR} and PMT_{TB}), and annual energy use by transit vehicles (TF_{CR}, TF_{LR}, *and* TF_{HR}) in the US. Transit energy includes electric power, diesel fuel, and non-diesel fuel for transit passenger vehicles only; cargo rail is excluded from this study. Average occupancy loads (N_{CR}, N_{LR}, N_{HR} and N_{TB}) are estimated for each year by dividing the annual passenger kilometers by the annual vehicle kilometers for each transit system. For some of the earlier years in which vehicle data is unavailable, the earliest reported values for each variable are used.

The last four variables, AR_{CR}, AR_{HR}, R_{LR}, and R_{TB}, represent the ratio of change in weight to change in energy consumption per transit vehicle. Estimates for AR_{CR} and AR_{HR} values are developed from a study conducted by the New York Metropolitan Transportation Authority that evaluates the potential energy savings of vehicle weight reductions for the New York City Transit rail fleet, which is mainly comprised of commuter and heavy rail systems (The Blue Ribbon Commission on Sustainability and the Metropolitan Transportation Authority 2009). It is assumed that results from the MTA study are applicable to all commuter rail and heavy rail vehicles within the US. Moreover, it is assumed that AR_{CR} and AR_{HR} values are constant from 1970 to 2010 since the majority of changes within the railroad industry occurred prior to 1970 (Johnson 1972). R_{LR} is the ratio of change in fuel use in liters per kilometer to the change in weight in kilograms for light rail vehicles. Estimates for R_{LR} values are based on a sustainable rail study conducted by the Los Angeles County Metropolitan Transportation Authority, which examines the impact of weight on energy use for vehicles operating along the Gold Line, a light rail system in Los Angeles (ICF International and LTK Engineering 2013). It is assumed that results from the LA MTA study are applicable to all light rail systems in the US, and that R_{LR} values are constant from 1970 to 2010.

Lastly, R_{TB} represents the linear slope defined by the ratio of change in fuel use in liters per kilometer to the change in weight in kilograms for public transit buses. This data is available from a study by Leonard Newland at the Highway Safety Research Institute at the University of Michigan (Newland 1980). Due to limited data for most years, it is assumed that R_{TB} values are consistent from 1970 to 2010.

Passenger Aircraft

Aircraft data is gathered for passenger aircraft (AC) that provides domestic services each year from 1970 to 2010. In this study, vehicle aircraft data consists of six variables: number of aircraft (RV_{AC}), annual vehicle kilometers traveled for all aircraft (VMT_{AC}), annual passenger kilometers traveled within all aircraft (PMT_{AC}), average occupancy load (N_{AC}), annual fuel use for all aircraft (TF_{AC}), and the impact of weight on fuel consumption in an aircraft (R_{AC}). The number of aircraft used for domestic services (RV_{AC}) is available from the US National Transportation Statistics (US DOT Bureau of Transportation Statistics 1a). The impact of weight on energy use for aircraft, or R_{AC}, is estimated by Lee et al. (2001), and represents the average amount of energy required to transport one passenger one kilometer by air. It is assumed that one passenger weighs 90 kg.

All other variables are retrieved from the US Bureau of Transportation Statistics, TranStats website (US DOT Bureau of Transportation Statistics 1b). Annual passenger kilometers traveled (PMT_{AC}) includes both revenue and non-revenue passenger (flight and cabin crew) kilometers traveled within the US. Average passenger load per aircraft is estimated for each year by dividing the passenger kilometers by the vehicle kilometers. This study estimates higher passenger loads than what is reported by BTS because this analysis accounts for non-revenue passengers, while BTS does not. The final variable, annual fuel use, denoted by TF_{AC}, includes only jet fuel for domestic services. Where data is unavailable, linear interpolation is applied to generate estimates for missing values.

C-1.2 Passenger Data

Passenger data is classified by gender and by age, where M represents male, F represents female, and A represents adults, aged 20+ years. Passenger data for this study consists of 9 variables, which were obtained for each year from 1970 to 2010. The first two passenger variables are available from the National Household Travel Survey, and are only applicable to the analysis of light-duty vehicles (Hu 2004, Santos 2011). These include kilometers traveled per male driver per day (*E[VMT I M]*) and kilometers traveled per female driver per day (*E[VMT I F]*). The next set of passenger variables are available from the US Federal Highway Administration Highway Statistics Series and includes the number of licensed individuals in the US, given gender and age (US DOT Federal Highway Administration 1a). These parameters are denoted as $LD_{M,A=20+\ years}$, and $LD_{F,A=20+\ years}$, and are also only applicable to the analysis of light-duty vehicles.

The last five variables are based on the US Census data, and include the following: the adult population size ($Population_M$ and $Population_F$), proportion of people in the US who are male and who are female (*P(M)* and *P(F)*), and the proportion of people in the US, aged 20+ years ($P(A_{20+\ years})$) (US Census Bureau 2013). These variables are used to analyze passenger weight for all three modes of transportation.

C-1.3 Anthropometric Data

Anthropometric data consists of average weights and average heights for people in the US, as well as the percentages of adult males and females who have BMIs above 25. These individuals are considered to be overweight or obese. $P(O_G)$ represents the percentage of adults who are overweight or obese, given gender, and this data is retrieved from the National Center for Health

Statistics (National Center for Health Statistics 2013). Average weight data consists of 2 variables, which are estimated for adult males and adult females who are age 20 and older (W_G). The National Center for Health Statistics (NCHS) has reported the average weight of people in the US for several time periods since 1960 (Fryar et al. 2012b, Mcdowell et al. 2008, Ogden et al. 2004). For this analysis, the NCHS weights are applied to the middle year of each time period, and linear interpolation is used to estimate average weights for all intermittent years. Population data is then retrieved from the US Census to develop weighted averages for each group from 1970 to 2010. Prior to 1988, the NCHS did not report weights for people age 75 years and older; therefore, weights for this age group are estimated based on 1988 weight change patterns.

Average height data consists of 2 variables, which are estimated for adult females and for adult males who are age 20 and older (H_G). The NCHS reports average heights of different age groups in the US for several time periods since 1960. For this analysis, the NCHS heights are applied to the middle year of each time period for each age group, and linear interpolation is used to estimate average heights for all intermittent years. Population data is then retrieved from the US Census to develop weighted averages for adult heights from 1970 to 2010. Mean heights are needed to calculate healthy weights for individuals, which are then used to estimate excess passenger weight. This process is explained in Section 4.3.1 of Chapter 4 of this manuscript.

C-1.4 GHG Emissions Data

Greenhouse gas (GHG) emissions data is collected separately for each mode of transportation and consists of 8 variables, which are provided by the US Environmental Protection Agency. For this analysis, greenhouse gas emissions include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The EPA reports annual GHG emissions for transit buses ($AGHG_{TB}$) and aircraft ($AGHG_{AC}$) from 1990 to 2010 (US Environmental Protection Agency 2013a). For light-duty vehicles, the EPA reports greenhouse gas emissions in grams per liter of fuel used and grams per vehicle-kilometer traveled from 1984 to 2005 (US Environmental Protection Agency 2008e). These are represented by the variables, $GHG_{Car\text{-}CO2}$, $GHG_{Truck\text{-}CO2}$, $GHG_{Car\text{-}CH4}$, $GHG_{Truck\text{-}CH4}$, $GHG_{Car\text{-}N2O}$, and $GHG_{Truck\text{-}N2O}$. For years in which data is unavailable, the earliest reported values are applied.

The EPA reports annual GHG emissions for passenger and cargo locomotives combined from 1990 to 2010 (US Environmental Protection Agency 2013a). Annual GHG emissions for passenger rail are estimated separately based on the percentage of total locomotive energy used for passenger rail systems included in this analysis. Total transit-related GHG emissions are then comprised of emissions from both passenger rail and public transit buses.

Annual GHG emissions are not reported for transit systems or aircraft prior to 1990. It is assumed, however, that GHG emissions per vehicle kilometer traveled did not change significantly between 1970 and 1990 for transit systems and aircraft. Therefore, GHG emissions for these years are estimated by multiplying the ratio of GHG emissions to vehicle kilometers traveled in 1990 by the vehicle kilometers traveled for each year prior to 1990.

C-1.5 Economic Data

Economic data consists of 3 variables: gasoline retail cost per liter (C_G), jet fuel price per liter (C_{JF}), and total annual energy cost for all transit vehicles (TEC_{TV}). Gasoline and jet fuel costs are reported by the US Energy Information Administration from 1970 to 2010 (US Energy Information Administration 1b). Energy use, by energy type, for transit systems is retrieved from the American Public Transportation Association (Dickens et al. 2012). Economic data for energy used in transit systems is reported by the US Energy Information Administration from 1970 to 2010 (US Energy Information Administration 1b). For years in which data is unreported, linear interpolation is used to develop estimates for missing values. All costs are adjusted for inflation to the year 2012.

C-2 CDC Body Weight Classifications

Table A-10 Adult weight classification by BMI [a]

Category	BMI Range
Underweight	Below 18.5
Normal Weight	18.5 – below 25.0
Overweight	25.0 – below 30.0
Obese	30.0 and Above

[a] CDC 2011, *About BMI for adults: Table view, Interpretation of BMI for adults*

C-3 Results

Table A-11 Excess passenger weight (kg) per vehicle

Year	Light-Duty Vehicles	Transit Vehicles	Passenger Aircraft
1970	9	138	429
1971	9	141	468
1972	9	149	515
1973	9	144	574
1974	9	136	628
1975	8	128	622
1976	8	123	644
1977	7	121	644
1978	7	126	703
1979	8	135	760
1980	8	140	757
1981	9	140	812
1982	9	142	897
1983	9	151	959
1984	10	151	967
1985	10	156	1,050
1986	10	157	1,080
1987	11	161	1,140
1988	11	164	1,180
1989	12	173	1,230
1990	12	179	1,240
1991	13	183	1,300
1992	13	182	1,360
1993	13	179	1,370
1994	13	182	1,430
1995	14	185	1,450
1996	14	191	1,540
1997	15	197	1,600
1998	15	214	1,650
1999	15	219	1,690
2000	16	227	1,730
2001	16	235	1,720
2002	17	230	1,710
2003	17	226	1,650
2004	17	225	1,690
2005	17	227	1,740
2006	17	238	1,800

2007	17	259	1,850
2008	17	262	1,880
2009	18	269	1,960
2010	18	259	2,000

Table A-12 Fuel use due to excess passenger weight (million liters)

Year	Light-Duty Vehicles	Transit Vehicles	Passenger Aircraft
1970	1,130	2.85	604
1971	1,170	2.86	594
1972	1,220	2.92	585
1973	1,270	2.91	576
1974	1,250	2.82	550
1975	1,240	2.78	635
1976	1,230	2.75	669
1977	1,210	2.74	686
1978	1,200	2.85	751
1979	1,290	3.08	890
1980	1,380	3.29	958
1981	1,490	3.30	998
1982	1,610	3.35	1,120
1983	1,740	3.59	1,280
1984	1,890	3.81	1,430
1985	2,030	3.93	1,620
1986	2,200	4.25	1,850
1987	2,380	4.43	2,050
1988	2,580	4.56	2,140
1989	2,780	4.76	2,200
1990	2,980	5.00	2,320
1991	3,030	5.21	2,320
1992	3,120	5.25	2,470
1993	3,130	5.24	2,550
1994	3,230	5.32	2,770
1995	3,330	5.45	2,910
1996	3,440	5.78	3,160
1997	3,550	6.04	3,320
1998	3,670	6.46	3,450
1999	3,760	6.86	3,680
2000	3,860	7.21	3,930
2001	3,980	7.68	3,770
2002	4,060	7.61	3,710

2003	4,050	7.55	3,830
2004	4,100	7.74	4,160
2005	4,080	7.91	4,290
2006	4,080	8.35	4,260
2007	4,060	8.28	4,330
2008	3,800	8.63	4,110
2009	3,780	8.77	3,840
2010	3,810	8.64	3,830

Table A-13 GHG emissions due to excess passenger weight (1,000 metric tonnes CO2e)

Year	Light-Duty Vehicles	Transit Vehicles	Passenger Aircraft
1970	3,010	9.58	1,260
1971	3,140	9.43	1,140
1972	3,270	9.53	1,030
1973	3,390	9.58	920
1974	3,330	7.57	787
1975	3,320	7.61	1,090
1976	3,290	6.66	1,140
1977	3,250	6.40	1,180
1978	3,240	7.04	1,290
1979	3,470	6.85	1,630
1980	3,750	8.86	2,020
1981	4,050	8.87	2,090
1982	4,410	9.18	2,460
1983	4,760	9.57	2,950
1984	5,160	9.07	3,350
1985	5,550	9.62	3,830
1986	6,040	10.9	4,480
1987	6,540	11.7	5,100
1988	7,080	12.0	5,300
1989	7,610	12.5	5,460
1990	8,160	13.4	5,930
1991	8,290	13.2	5,960
1992	8,550	13.4	6,340
1993	8,570	13.6	6,470
1994	8,770	14.8	6,930
1995	9,000	15.1	7,280
1996	9,250	16.7	8,020
1997	9,550	17.3	8,340
1998	9,840	18.6	8,750

1999	10,000	20.6	9,250
2000	10,300	20.9	9,930
2001	10,400	22.0	9,650
2002	10,600	21.0	9,330
2003	10,600	21.0	9,580
2004	10,700	23.9	11,100
2005	10,600	26.9	13,100
2006	10,600	28.7	11,300
2007	10,600	38.2	11,600
2008	9,910	37.9	10,500
2009	9,850	37.5	9,960
2010	9,920	37.1	10,300

Table A-14 Fuel costs due to excess passenger weight - adjusted to 2012 (million $)

Year	Light-Duty Vehicles	Transit Vehicles	Passenger Aircraft
1970	684	1.51	218
1971	712	1.45	214
1972	743	1.46	211
1973	770	1.44	207
1974	757	1.68	198
1975	753	1.67	229
1976	744	1.61	241
1977	733	1.60	247
1978	729	1.61	270
1979	949	2.02	407
1980	1,240	2.59	611
1981	1,340	2.72	682
1982	1,300	2.56	679
1983	1,300	2.46	683
1984	1,320	2.51	703
1985	1,370	2.50	727
1986	1,130	2.14	543
1987	1,220	2.25	594
1988	1,270	2.23	563
1989	1,440	2.38	636
1990	1,680	2.63	823
1991	1,620	2.57	673
1992	1,610	2.50	650
1993	1,540	2.43	622
1994	1,550	2.36	604

1995	1,600	2.35	626
1996	1,710	2.61	797
1997	1,730	2.64	769
1998	1,520	2.48	581
1999	1,670	2.76	727
2000	2,120	3.48	1,250
2001	2,080	3.54	1,000
2002	1,970	3.31	902
2003	2,180	3.66	1,100
2004	2,530	4.88	1,610
2005	2,960	6.08	2,310
2006	3,230	7.10	2,560
2007	3,380	7.37	2,740
2008	3,560	9.10	3,530
2009	2,570	6.61	1,850
2010	3,010	7.69	2,350