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The Role of Distribution Infrastructure and Equipment in the Life-cycle Air Emissions of Liquid Transportation Fuels

By

Bret Michael Strogen

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering - Civil & Environmental Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in Charge:

Professor Arpad Horvath, Chair

Professor Robert Harley

Professor David Zilberman

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ABSTRACT

The Role of Distribution Infrastructure and Equipment in the Life-cycle Air Emissions of Liquid Transportation Fuels

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Production of fuel ethanol in the United States has increased ten-fold since 1993, largely as a result of government programs motivated by goals to improve domestic energy security, economic development, and environmental impacts. Over the next decade, the growth of and eventually the total production of second generation cellulosic biofuels is projected to exceed first generation (e.g., corn-based) biofuels, which will require continued expansion of infrastructure for producing and distributing ethanol and perhaps other biofuels. In addition to identifying potential differences in tailpipe emissions from vehicles operating with ethanol-blended or ethanol-free gasoline, environmental comparison of ethanol to petroleum fuels requires a comprehensive accounting of life-cycle environmental effects. Hundreds of published studies evaluate the life-cycle emissions from biofuels and petroleum, but the operation and maintenance of storage, handling, and distribution infrastructure and equipment for fuels and fuel feedstocks had not been adequately addressed. Little attention has been paid to estimating and minimizing emissions from these complex systems, presumably because they are believed to contribute a small fraction of total emissions for petroleum and first generation biofuels.

This research aims to quantify the environmental impacts associated with the major components of fuel distribution infrastructure, and the impacts that will be introduced by expanding the parallel infrastructure needed to accommodate more biofuels in our existing systems. First, the components used in handling, storing, and transporting feedstocks and fuels are physically characterized by typical operating throughput, utilization, and lifespan. US-specific life-cycle GHG emission and water withdrawal factors are developed for each major distribution chain activity by applying a hybrid life-cycle assessment methodology to the manufacturing, construction, maintenance and operation of each component. Emissions from activities at the end of life of equipment and infrastructure are not included, as these activities have previously been shown to contribute negligibly to life-cycle emissions. Life-cycle transportation mode GHG emission factors per tonne-kilometer (t-km) are presented for long distance pipelines (5-20 g CO_2-e/t-km), ocean tankers (5-17 g/t-km), fuel-carrying barges (31 g/t-km), fuel-carrying unit trains (25 g/t-km), tanker trucks (140-180 g/t-km), and bale-transporting flatbed trucks (200 g/t-km). Life-cycle emission factors are also presented per tonne of material throughput for several types of agricultural equipment (600-19,000 g

CO_2-e/t handled), fuel conversion facilities (9,000-98,000 g/t), fuel storage and dispensing facilities (2,000-12,000 g/t), and the portion of passenger vehicle operations dedicated to refueling errands (2,000-200,000 g/t). The emissions intensity ranges reported for specific transportation modes are largely due to the greater energy efficiency of larger vehicles and pipelines, and the emissions intensity ranges within stationary storage and handling equipment is often due to differences in utilization of capital equipment and/or material losses during storage and handling activities. Consistent with existing literature, the contribution of non-operation stages to life-cycle GHG emissions ranges from 20% to 40% for most of the components modeled. Criteria air pollutant (NO_x, $PM_{2.5}$, SO_x, VOC, CO) emission factors are also presented for the operation stage (e.g., tailpipe only) of each transportation mode.

In order to apply the new emission factors to policy-relevant scenarios, a projection is made for the fleet inventory of infrastructure components necessary to distribute 21 billion gallons of ethanol (the 2022 federal mandate for advanced biofuels under the Energy Independence and Security Act of 2007) derived entirely from Miscanthus grass, for comparison to the baseline petroleum system. Due to geographic, physical and chemical properties of biomass and alcohols, the distribution system for Miscanthus-based ethanol is more capital- and energy-intensive than petroleum per unit of fuel energy delivered. Assuming steady-state annual turnover, operation, and maintenance of infrastructure to supply the projected quantities of ethanol and petroleum fuels, ethanol is estimated to be approximately five times more GHG and water intensive than petroleum (i.e., GHG emissions of more than 17 g CO_2-e/MJ versus 3 g/MJ, and water withdrawals of 380 L/MJ vs. 77 L/MJ of consumed fuel, neglecting feedstock production and conversion). Embodied GHG emissions from manufacturing and maintaining infrastructure, equipment, and vehicles make up less than half of these emissions, at approximately 1 g CO_2-e/MJ of petroleum fuel and 8 g CO_2-e/MJ of ethanol. Although petroleum fuels are projected to supply twenty times the energy content of ethanol in 2022, the annual GHG and water withdrawal footprint of petroleum's liquid fuel infrastructure and distribution system is slightly less than four times that of ethanol (i.e., 110 vs. 30 million tonnes of CO_2-e and 2,500 vs. 640 billion liters of water). Opportunities to significantly reduce emissions include shifting transportation to more efficient modes, consuming products closer to producers, and converting biorefineries to produce fuel with higher energy density than ethanol. Minimizing fuel transportation distance is believed to be the most feasible and cost-effective opportunity to reduce emissions in the near term.

The transportation of biofuels away from producer regions poses environmental, health, and economic trade-offs that are herein evaluated using a simplified national distribution network model. In just the last ten years, ethanol transportation within the contiguous United States is estimated to have increased more than ten-fold in total t-km as ethanol has increasingly been transported away from Midwest producers due to air quality regulations pertaining to gasoline, renewable fuel mandates, and the 10% blending limit (i.e., the E10 blend wall). From 2004 to 2009, approximately 10 billion t-km of ethanol transportation are estimated to have taken place annually for reasons other than the E10 blend wall, leading to annual freight costs greater than $240 million and more than 300,000 tonnes of CO_2-e emissions and significant emissions of criteria air pollutants from the combustion of more than 90 million liters of diesel. Although emissions from distribution activities are small when normalized to each unit of fuel, they are large in scale.

Archetypal fuel distribution routes by rail and by truck are created to evaluate the significance of mode choice and route location on the severity of public health impacts from locomotive and truck emissions, by calculating the average $PM_{2.5}$ pollution intake fraction along each route. Exposure to pollution resulting from trucking is found to be approximately twice as harmful as rail (while trucking is five times more energy intensive). Transporting fuel from the Midwest to California would result in slightly lower human health impacts than transportation to New Jersey, even though California is more than 50% farther from the Midwest than most coastal Northeast states.

In summary, this dissertation integrated concepts from infrastructure management, climate and renewable fuel policy, fuel chemistry and combustion science, air pollution modeling, public health impact assessment, network optimization and geospatial analysis. In identifying and quantifying opportunities to minimize damage to the global climate and regional air quality from fuel distribution, results in this dissertation provide credence to the urgency of harmonizing policies and programs that address national and global energy and environmental goals. Under optimal future policy and economic conditions, infrastructure will be highly utilized and transportation minimized in order to reduce total economic, health, and environmental burdens associated with the entire supply and distribution chain for transportation fuels.

This work is dedicated to

My mother

Carol Ann Strogen

My father

Edward Michael Strogen, Jr.

and to

My brother

Kevin Edward Strogen

My sister

Kelly Ann Strogen

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ACRONYMS AND KEY TERMS

Organizations

API	American Petroleum Institute
AOPL	Association of Oil Pipelines
BTS	Bureau of Transportation Statistics (within US DOT)
BEA	(US) Bureau of Economic Analysis (within US Department of Commerce)
EBI	Energy Biosciences Institute
EIA	Energy Information Administration (within US DOE)
IISI	International Iron and Steel Institute (now World Steel Association, or "WorldSteel")
ISO	International Organization for Standardization
NETL	National Energy Technology Laboratory (within US DOE)
ORNL	Oak Ridge National Laboratory (within US DOE)
SETAC	Society of Environmental Toxicology and Chemistry
US ACE	US Army Corps of Engineers
US EPA	US Environmental Protection Agency
US DOE	US Department of Energy
US DOT	US Department of Transportation
US GAO	US Government Accountability Office

Models and Tools

APEEP	Air Pollution Emission Experiments and Policy (analysis model developed by researchers at Yale University)
GIFT	Geospatial Intermodal Freight Transportation (GIFT) (network model developed by researchers at Rochester Institute of Technology, University of Delaware, and University of California, Berkeley)
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (model developed at Argonne National Laboratory)
LEM	Lifecycle Emissions Model (created by Professor Mark Delucchi at the University of California, Davis)

Pollutants and Impact Categories

CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2-e	Carbon Dioxide Equivalent (common unit for reporting total global warming potential (GWP) of all GHG emissions from an activity)
ESAL	Equivalent Single Axle Load (used to estimate the burden of trucks on roads)
GHG	Greenhouse Gas
GWP	Global Warming Potential (often expressed in equivalents of CO_2 (CO_2-e), typically applied to a 100-year reference period)
HC	Hydrocarbons

LUC	Land Use Change
N_2O	Nitrous Oxide
NO_x	Nitrogen Oxides (including nitrogen dioxide (NO_2) and nitric oxide (NO))
O_3	Ozone
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter, diameter < 2.5 microns
PM_{10}	Particulate Matter, diameter < 10 microns
SO_x	Sulfur Oxides (primarily sulfur dioxide (SO_2))
SOC	Soil Organic Carbon
VOC	Volatile Organic Compound

Key Terms

AST	Aboveground storage tank, ranging from small household tanks to large storage tanks at terminals
BPCD	Barrels per calendar day (maximum average daily processing capacity of a refinery, after including non-productive time for maintenance, etc.)
BPD	Barrels per day (daily average crude input processing rate for a refinery)
E10	Ethanol–gasoline blends containing a maximum of 10% ethanol by volume.
E15	Ethanol–gasoline blends containing 10%-15% ethanol by volume.
E85	The highest blend of ethanol in gasoline permitted in US FFVs. Although the average annual composition of "E85" has previously been estimated to be only 78% (Hsu et al. 2010) or 80% (Jacobson 2007) ethanol, E85 is simplified as 85% ethanol and 15% gasoline in this study.
EISA	Energy Independence and Security Act (of 2007)
FFV	Flex-fuel vehicle (permitted in the United States to use gasoline blends containing up to 85% ethanol by volume).
GPD	Gallons per day (annual average)
kmDD	Kilometers of delivered distance
LCI	Life-cycle Inventory
LCA	Life-cycle Assessment
MGTM	Million gross ton-miles (see t-km)
MTBE	Methyl tert-butyl ether, a gasoline additive used to increase octane number and oxygen content.
RFS	Renewable Fuel Standard
t	Tonne (metric)
t-km	Tonne-kilometer, a common freight transportation metric implying one tonne of goods is moved one t-km. (Note: 1.5 t-km are approximately equivalent to 1 (short) ton-mile).
UST	Underground storage tank, typically connected to fuel dispensers
Utilization	Metric to express activity as a function of capacity (e.g., kmDD/v-km is between 0.0-1.0 for freight vehicles)
v-km	Vehicle-kilometer, a common transportation metric implying a vehicle, whether empty or full of cargo, travels one km. (Note: 1.61 km are approximately equivalent to 1 mile).

ACKNOWLEDGEMENTS

This dissertation is the most significant independent project that I have completed in my life, but it was built upon the findings of hundreds of researchers before me, was inspired by questions from professors and fellow students, was made more relevant through insights from industry experts, and was motivated by the support of friends and family.

I am deeply grateful to Professor Arpad Horvath for his support these last few years. Arpad's enthusiasm for applying intelligent and policy-relevant methodology in the field of life-cycle assessment (LCA) captured my interest as a master's student in his course, "Civil Systems and the Environment." After leaving Berkeley with a MS degree in 2004, I hoped to eventually return to pursue a PhD under his mentorship, as he embodies many of the characteristics that I value. He is a charismatic, kind, and thought-provoking teacher; he has published research articles on a variety of important infrastructure and environmental problems; and he is a very engaged leader in the academic community – managing the Engineering and Business for Sustainability (EBS) certificate program at UC Berkeley, volunteering as an Editor for several journals, and serving as the Chair of the International Society for Industrial Ecology (ISIE) 2011 Conference in Berkeley. Arpad welcomed me to participate in each of these activities, and also encouraged me to take on leadership roles in my civic and professional communities. As a PhD student, I served as Chair of the International House Resident Council, Co-chair of the Berkeley Energy & Resources Collaborative (BERC) annual Energy Symposium, and Board Member of the Udall Alumni Association (UAA). He also supported my interest in taking extra classes, attending conferences, and pursuing side-projects that advanced my personal career interests (e.g., serving as an advisor for the Energy Free Home Challenge). Arpad offered me a wealth of advice in filtering and prioritizing which items to pursue among my long lists of potentially interesting courses, research project ideas, conferences, and potential collaborations. He taught me to write and present my ideas and results more effectively, and helped me better understand how to navigate the administrative and political challenges inherent to academia. Arpad certainly enabled me to become a better researcher, but also to be a better student, writer, leader, and engaged citizen. I might never have pursued a doctorate without his encouragement, and the experience has been more enriching and challenging than I could ever have expected or hoped. Thanks to his trust and support, I grew as much personally and professionally as I did intellectually over the last few years, and feel incredibly fortunate to have had this opportunity.

I would also like to thank my committee members. Robert Harley, Professor of Environmental Engineering, is a professor I will seek to emulate if I ever return to academia. He is consistently willing to meet to discuss research ideas and challenges, has proven to be an excellent communicator as a course instructor and administrator of my oral exams, is extremely fair and reliable, forthright and supportive, and is admirably intelligent and passionate about energy and air quality research and policy. David Zilberman, Professor of Agricultural and Resource Economics, is also an inspiring professor with a contagious enthusiasm for sharing and discussing research that is creative and useful. His dedication to hosting "pizza and policy" discussions with students, orchestrating the annual Berkeley Bioenergy Conferences, and organizing workshops at the EBI to ensure our

scientists and engineers have a basic understanding of key economic concepts relevant to biofuels is commendable. Additionally, by publishing on economic topics ranging from OPEC's market power to GMO crops and efficient water supply, he has proven that intellectuals can contribute valuable insights about various types of industries and problems. By selecting both professors to serve on my committee, I had to ensure that my assumptions and choice of modeling scenarios were defensible in light of contemporary fuel and engine technologies, air quality problems, economic conditions, and policies related to biofuels and climate change. In hindsight, I could not have picked committee members that better matched my PhD goals and my general interest in exploring the interfaces of science, technology, and policy.

I would like to thank the EBI for funding me during my tenure as a PhD student, and for supporting such a diverse portfolio of research projects within a single research organization. The directors of the EBI, Chris Somerville, Paul Willems and Susan Jenkins in Berkeley, and Steve Long in Illinois, have created a model research community that supports cutting edge work in fields ranging from plant science to environmental economics, and I could not imagine having such a well-rounded, intellectually-stimulating experience as a PhD student elsewhere. I have benefited from countless opportunities to exchange information and ideas with other researchers, including weekly guest lectures from academic, government, and industry professionals from around the world, weekly research presentations from EBI graduate students, the annual EBI Retreats, and occasional workshops. Our monthly "EBI Café" birthday celebrations and occasional happy hours further created valuable opportunities to discuss interdisciplinary challenges and innovative developments associated with the evolving biofuels industries. Additionally, the staff members of the EBI have been incredibly supportive – whether I needed to reserve a room for meetings, print a poster for a conference, or obtain help debugging or upgrading my computers from Adam Cohen – allowing me to spend the vast majority of my time in the office actually performing research, writing, and editing. The EBI has proven to me that the private sector and academic institutions can form incredibly fruitful partnerships, generating valuable high-impact knowledge and offering students and other participating researchers a unique and powerful experience.

Within the EBI, I am grateful for the support and feedback from members of my research team: Professor Thomas E. McKone, Dr. Corinne Scown, Dr. Agnes Lobscheid, Dr. Umakant Mishra, Professor William W Nazaroff, and Ben Greenfield. I also appreciate the assistance I received in creating biomass-to-ethanol model scenarios and occasional fact-checking from other EBI researchers: Yogendra Shastri, Amit Gokhale, Caroline Taylor, Heather Youngs, and my officemate, Craig Dana. Other colleagues at UC Berkeley that provided valuable input related to editing, formatting, or creating graphics include Matthew Ritchie, Bradley Zamft, Samveg Saxena, Timothy Dallmann, Brian McDonald, Kimberly Lucas, Erik Brinsmead, Katherine Adamides, and Erin Condit-Bergren. I am also thankful to Richard Lechtenberg and Megan Williams for performing the invaluable favor of delivering my dissertation to my committee members when I was out of town.

I am grateful to the American-Scandinavian Foundation for granting me a fellowship to visit the Industrial Ecology faculty at KTH in Stockholm, Sweden and NTNU in Trondheim, Norway. I would like to thank Professor Björn Frostell for hosting me at KTH, Professor Anders Strømman for hosting me at NTNU, and Olaf Rimmen for giving me a full tour of STX Europe's ship building operations in Florø, Norway. My experiences in Scandinavia exposed me to different skills and

tools that are emphasized in performing LCA research abroad, and my time proved to be culturally educational as well.

I also appreciate the generous help of many experts within U.S. government agencies and private organizations that "sanity checked" several of my modeling assumptions pertaining to fuel and freight systems. Through friends, family, and professional networks within LinkedIn, I found experts willing to answer questions about topics including construction and operation of petroleum pipelines (Adrianne Cook and Wally Stasioski), international maritime operations (Jack Opet), dredging of inland waterways and sea ports (Jeff McKee, Ginny Pankow, and Aaron Ellis), inland barge transportation of liquid commodities (Chris Vecellio), the renewable identification number (RIN) system (Brian Shadle, Luiz Figer, and Clayton McMartin), retrofitting existing pipelines for biofuels (Chad Zamarin), international trade and transportation of ethanol from Brazil (Claudio Marquez), domestic grain and ethanol transportation (Brock Massin), and rotation of liquid commodities through storage tanks at shipping terminals (Marcos Vendramini). Government staff members at the U.S. Bureau of Economic Analysis (BEA), Department of Energy (DOE), Environmental Protection Agency (EPA), and Army Corps of Engineers (ACE) were also particularly helpful. While several of these conversations took less than an hour, each one spared me countless hours of background research, and generally increased the level of fun and relevance of my research.

I am beholden to my professors at the University of Delaware, Professors Steven Dentel, Daniel Cha, and Pei Chiu, for captivating and supporting my interests in environmental engineering, and providing me with my first opportunities to perform independent research as an undergraduate. I am also thankful to Professor David Jenkins, my research advisor while I was a master's student at UC Berkeley, who was also a very supportive and engaged mentor during and after completing my master's program. Common traits among the professors that positively influenced me throughout my student career include an unbiased curiosity for how the world works, dedication to performing important and relevant work, high degree of trust in my judgment and competence as a researcher, and ability to bring humor into almost every meeting.

Outside of research, I have been intellectually challenged and inspired by the incredible network and events hosted by BERC, by my friends in the Environmental Engineering program, in the Udall Alumni Association, and at the two residential communities that served as my home during my time as a graduate student – the International House and the Berkeley Student Cooperative's Hillegass Parker House. Lastly, I would like to thank YouTube and Pandora for enabling me to jam out during my writing and editing endeavors – whether I was in the mood for MTS or Eminem, Pachelbel or Tupac, nature sounds with steel drums, or techno-remixes of pop songs that I am embarrassed to name in writing.

1 INTRODUCTION AND MOTIVATION[1]

1.1 Petroleum Alternatives are Needed

Petroleum is an incredible energy carrying material. Once refined, petroleum products are extremely energy dense without requiring pressurization, relatively safe to store, and require inexpensive engines to convert it into useful energy. It has enabled drastic improvements to the quality of life of people in many countries, while its extraction, refining, and combustion have also caused extensive problems to human health, ecosystems, and our climate. For example, total greenhouse gas (GHG) emissions from the transportation sector have increased 20% from 1990 to 2008, from 1.5 to 1.8 billion tonnes of CO_2-e (US EPA 2010a), while consistently contributing approximately 30% to total US emissions. In the last century, humans have engineered methods to extract and convert various petroleum feedstocks into transportation fuels, in addition to a myriad of other useful materials from asphalt roads to plastic bottles. Inexpensive petroleum-fueled transportation services have catalyzed globalization, enabling people and products to move from virtually any city on earth to another, within hours or days, for an arguably under-valued price. Though not as extensively distributed as electricity, water, or natural gas, petroleum fuels can be purchased within miles of most communities in industrialized countries, where its consumption is intricately linked to the economic production and lifestyle of citizens. Despite the value it brings to human society, research and development of replacement(s) for petroleum are warranted, due to the following problems associated with current practices of extraction and consumption:

1) contribution of greenhouse gas emissions to global warming;
2) contribution of air and water pollution to local public health and environmental problems;
3) eventual exhaustion of petroleum as a natural resource;
4) contribution to net national trade imbalance, and specific dependence of transportation sector on supplies from high risk unstable countries;
5) minimal opportunity for domestic economic growth (especially in rural areas); and
6) financial support of nations with non-democratic leaders, instead of domestic organizations.

For these reasons, governments (and industrial groups) around the world have been incenting the research, development, and adoption of various propulsion technologies that are assumed to be safer and renewable, to enable the development of more "sustainable" transportation services.

1.2 Recent Expansion of Ethanol and Biodiesel Industries

For several decades, US federal policy makers have created incentives to decrease consumption of petroleum and increase domestic production of biofuels. Although scaling up biofuel (as well as pure electric and hybrid drive-train) vehicles remains among the most expensive means to reduce GHG emissions from the passenger transportation sector (McKinsey & Company 2009),

[1] Parts of this chapter were reproduced with permission from the American Society of Civil Engineers, after first being submitted for publication in the *Journal of Infrastructure Systems* in 2011 under the title, "Greenhouse Gas Emissions from the Construction, Manufacturing, Operation and Maintenance of US Distribution Infrastructure for Petroleum and Biofuels" (Strogen and Horvath 2012). This article was under review at the time this dissertation was submitted.

government subsidies for these technologies exist based on the assumption that they will spur 'learning by doing' improvements that would not occur fast enough through conventional research and development (and because alternatives to petroleum can help meet goals outside of GHG emissions reduction).

Over the last ten years, the biofuels ethanol and biodiesel have been incorporated into the transportation fuel sector at an incredible rate, serving as the most disruptive alternative vehicle fuel since petroleum overtook ethanol and vegetable oil nearly 100 years ago. Most notably, US ethanol production more than tripled to 9 billion gallons from 2003 to 2008 (Renewable Fuels Association 2009). Today's biofuels have been sold for prices competitive with petroleum, largely due to government mandates and subsidies. Almost all ethanol has been produced from corn, which is often considered a 'bridge' feedstock until more sustainable fuel feedstocks and fuel products can be economically made from feedstocks such as ligno-cellulosic biomass.

The federal Renewable Fuel Standard (RFS) under the Energy Independence and Security Act (EISA) of 2007 (Rahall [D-WV3] 2007) requires that the United States nearly triple its current biofuel production levels to 36 billion gallons per year by 2022; 21 billion gallons must qualify as "advanced" biofuel, meaning it must be created from a feedstock other than corn starch and must have a GHG footprint less than 50% that of conventional petroleum. The 2005 baseline carbon footprint for conventional gasoline used by the US EPA is 93 g CO_2-e/MJ (18 of which would be considered pre-combustion) (US EPA 2010d), though a slightly lower value of 91 was estimated by another source (US DOE NETL 2008). The maximum carbon footprint of fuels meeting the EISA RFS would therefore be 75 g/MJ for new corn-based ethanol (20% less than baseline gasoline), 47 g/MJ for advanced biofuels (50% less), and 37 g/MJ for cellulosic biofuels (60% less) (US EPA 2010e). California hopes to reduce emissions from the transportation sector by 80% by 2050, which would limit the entire carbon footprint of petroleum replacements to less than 19 g/MJ, unless vehicle efficiency and travel behavior improvements somehow outpace growth in demand for mobility (measured in passenger-kilometers, or p-km).

1.3 Problem Statement

To meet these policy targets, the United States (and other countries) will be expanding infrastructure capable of producing, storing, blending, transporting and dispensing ethanol derived from ligno-cellulosic feedstocks. It will be difficult to cost-effectively achieve such aggressive carbon reduction targets unless both the cost and carbon-intensity of many processes in the distribution chain of biofuels are drastically reduced. In order to quantify the environmental implications of these infrastructure challenges, an inventory of the emissions from operating and maintaining the existing and future liquid fuel infrastructure must be performed. To comprehensively and accurately estimate these emissions, a life-cycle assessment (LCA) approach to modeling infrastructure components will be used, and a network systems approach will be used to characterize actual and optimal transportation distances that may inform regional and national fuel policy makers.

1.3.1 Scaling up Biofuels will Result in Infrastructure and GHG Challenges

The cheap and energy-efficient distribution systems for conventional fuels such as coal and petroleum enable them to arrive to markets at a cheaper price and lower energy penalty than alternative fuels currently on the market. As has been pointed out by (Morrow 2006) and others, fossil energy systems have been operating and improving in cost efficiency for over a hundred years. In contrast, the infrastructure requirements for hydrogen, which is an otherwise efficient and pollution-free energy carrier at its point of use, have been regarded as an "insurmountable technical and economic barrier" (Ogden 1999).

Current liquid biofuels can be integrated into many parts of the existing petroleum-based infrastructure and engine, but differ from petroleum in their material compatibility, biodegradability, location of supply and demand centers, and intra-annual production patterns (discussed in Section 2.3). In the long term, petroleum-displacing fuels may resemble petroleum fuels even more so than ethanol and biodiesel, in order to utilize much of the existing distribution infrastructure and existing propulsion systems.

While the economic (and employment) merits of expanding upon or modifying the existing fuel infrastructure have been evaluated by the ethanol industry and state and federal government agencies, the embodied and operational environmental emissions associated with these decisions must also be comprehensively evaluated. Additionally, the resource demands and other environmental and health risks associated with building and maintaining the existing petroleum distribution systems must be characterized in order to contextualize the implications of large scale adoption of new fuels.

1.3.2 GHG Evaluation of Fuels Requires LCA

Unless environmental policy takes the form of a tax that is levied consistently across sectors and nations, thus imposing costs on final products that are proportional to cumulative supply chain environmental impacts, LCA enables analysts to assess the full environmental 'footprint' of a product (and to estimate the exposure of products to a potential future environmental policies, such as a carbon tax). Since the 1980s, industrial ecologists have been applying LCA frameworks (e.g., developed by ISO, SETAC) to transportation and fuel production activities, in order to quantify the full environmental cost that society is bearing as a result of consuming transportation services.

The growing government-driven push for commercializing alternative fuels in North America, Europe, Brazil, and elsewhere has inspired many LCA studies to assess whether new fuel products outperform petroleum products as intended, and if they may lead to other problems (e.g., by shifting or exacerbating impacts in other industries or locations). Many of these studies have fostered skepticism among the public and alternative energy researchers that any biomass-to-fuel program will be able to offer a net benefit over petroleum at a significant scale. In addition to evaluating the potential indirect and unintended impacts of policy options and purchasing decisions, LCA has been incorporated into fuel policies created by the US EPA and the state of California.

1.3.3 The Significance of Distribution to Fuel GHG Footprints will Increase

As many products and processes continue becoming more energy efficient and less polluting, and as fuels and other products are increasingly produced far from where they are consumed, the significance of accurately estimating embodied supply chain emissions is expected to grow. Specifically with regard to fuels, any change in local or national fuel formulation policies has the potential to increase the economic, energy, environmental emissions and health impacts of refining, blending, and distribution logistics, in addition to potentially requiring new infrastructure investments. Depending on the feedstock type, fuel type, infrastructure available and location of producers and consumers, the life-cycle emissions from biofuel distribution systems may be significantly greater or less than emissions from respective petroleum systems.

As the biofuels industry matures, agricultural yields and biomass-to-fuel conversion efficiency are expected to improve, though technologies used for handling, storing, and transporting fuel and fuel feedstocks are already mature and are not expected to experience similar efficiency improvements. Despite the foreseen challenge in efficiently transporting ligno-cellulosic feedstocks and fuels, E85 produced with second generation ethanol (e.g., derived from switchgrass, corn stover, or Miscanthus) after the year 2020 is expected to have a total life-cycle GHG footprint of at least 43% (Hsu et al. 2010) and up to 70% (Spatari et al. 2005) lower than that of conventional gasoline. As a result, contribution of life-cycle emissions from feedstock and fuel storage, handling and transportation are expected to increase in importance, and will be evaluated in depth throughout the remainder of this dissertation.

1.4 Organization, Goals and Contributions

The work summarized in this dissertation aims to fill several gaps in the LCA literature of freight activity and liquid transportation fuels. The main questions this dissertation seeks to answer are listed below.

1. If infrastructure and equipment are included in creating emission factors for feedstock and fuel handling and transportation modes, in addition to fuel production and combustion, how significant is the additive effect from expanding the scope to include these stages?
2. When comprehensive emission factors are applied to each activity throughout an entire distribution system for petroleum and biofuels, what is the significance of cumulatively accounting for equipment and infrastructure cycles in the life-cycle emissions of a fuel supply system? What are some of the most significant areas of sensitivity and uncertainty?
3. How could fuel policies be structured or implemented differently, so as to reduce total emissions from the distribution of feedstocks and fuels?

The remainder of this dissertation is organized into a discussion of background information, a review of relevant literature, an explanation of the methodology employed in the main projects, a summary of findings from each project, and a discussion and conclusion section with suggestions for future work. The following paragraphs provide the structure of this dissertation, highlighting the new contributions of each section to the literature on LCA and environmental assessment of fuels and freight transportation.

The *Background* section provides a brief overview of the role of freight movement in US GHG inventories, trends in freight activity over the last few decades, and the significance of petroleum fuels as a type of freight. Additionally, historic infrastructure construction and maintenance activity for each of the major transportation modes is presented. In order to put biofuels in a context that enables fair comparison to petroleum, the historic and future driving forces behind ethanol policies are discussed and critiqued from the perspective of someone aiming to minimize total freight activity.

The *Literature Review* section summarizes the publications related to LCA of freight transportation, transportation fuels, and fuel distribution systems (though literature was reviewed throughout each stage of this research). These examples from the literature served as primary influences on the methodology and objectives of this study. Through the literature review process, gaps were identified that led to research exercises and contributions discussed in the methodology, component characterization, and key project/scenario development sections of this dissertation.

As the *Methodology* section will confirm, the general methodology employed in generating life-cycle emission factors in this dissertation, an economic input-output analysis-based hybrid LCA approach (Suh et al. 2004), has been used by researchers in the past in evaluating passenger and freight transportation systems (e.g., (Chester 2008; Facanha 2006)). However, methodological contributions of this dissertation include the manner in which I accounted for utilization-induced deterioration of infrastructure, expanded fuel LCA analysis to include infrastructure and equipment life-cycles, estimated the economic and emissions costs of sub-optimal national fuel policies through distribution scenario optimization, estimated the relative human health impacts of alternative modes and routes, and expanded the scope to include relevant consumer behavior.

In the *Component Characterization* section, the energy intensity and tailpipe emissions from operating components in the fuel distribution system (and from producing the fuel consumed) are presented, as is customary for most fuel-cycle well-to-wheels (WTW) assessments. In addition, the "embodied" emissions associated with manufacturing, construction, maintenance, and replacement of material storage, handling and distribution infrastructure and equipment were included. Completely new life-cycle emission factors were created for agricultural equipment, storage and dispensing facilities, and transportation of liquid fuels by maritime pipeline modes, and updated emission factors were created for truck and rail by building upon the methodology of (Facanha and Horvath 2006). The life-cycle emission factors presented in this dissertation can easily be used in future case studies that involve storage, handling or transportation of fuel and fuel feedstocks.

The *US Distribution System Model* describes the first major application project within this dissertation, in which component models were compiled into a national system for distributing petroleum and another model for distributing Miscanthus and ethanol. The estimated inventory of the stock and annual turnover of components modeled for the year 2022. The new component-specific emission factors were integrated into both scenarios using the same methodology, and results present the contribution of infrastructure and equipment (i.e., capital assets) to the GHG footprint of consumed petroleum and biomass derived fuel. In order to characterize decision opportunities in the distribution chain as having significant or insignificant potential to reduce the total GHG footprint of a fuel, sensitivity analyses were also performed on several realistic scenarios for distributing feedstocks and fuels. These results will inform readers about the potential merits of encouraging (e.g., subsidizing) certain modes or practices of biomass or fuel transport, storage or handling, and encouraging the sourcing of materials locally or remotely.

The final project, *Evaluation of US Domestic Ethanol Trade*, consisted of modeling historic actual and hypothetical minimum necessary distribution of ethanol throughout the United States, by applying linear optimization to the distribution of ethanol via the national transportation network. This project was motivated in order to quantify "conventional wisdom" that much fuel is consumed and CO_2 emitted in vain by transporting ethanol from the Midwest to the coasts, when it could and would otherwise have been consumed closer to production sites. Essentially, this project served as a sensitivity analysis of scenarios governed by sub-national (e.g., state-level) distributed decision-making, in order to estimate the potential benefit of formulating policy goals on a more central (e.g., national or global) basis, which may be characterized by harmonization of metrics, methodologies, and application of tradable credits.

In the *Discussion* section, a summary of findings and results is presented, and a discussion of the key limitations and areas of uncertainty within each of the models used. The dissertation closes with suggestions for future work, which consists of expanding upon the scope of activities and metrics accounted for, or applying my models and results to questions of relevance to policy makers or life-cycle assessment practitioners in the fields of freight transportation, fuel supply, and civil infrastructure.

2 BACKGROUND INFORMATION[2]

Prior to evaluating the environmental impacts of the distribution system for petroleum and biofuels, it is important to understand the scale and modes of US freight distribution and the significance of petroleum as a freight commodity. Additionally, it is important to understand the evolution of and future motivations behind policies aimed at displacing petroleum with biofuels, and the technical challenges to distributing biomass-based feedstocks and biofuels as economically and environmentally efficient as petroleum.

As LCA requires consideration of capital assets as well as operation and maintenance activities, statistics summarizing the utilization and extent of infrastructure, total freight movement activity (in t-km), and annual investments in each of the major modes (i.e., truck, rail, maritime, pipeline) are presented. Economic input-output tables are often used by LCA practitioners, so a discussion of infrastructure construction and maintenance investments highlights some of the limitations that would be encountered by relying entirely on national industry accounts. The significance of petroleum as a freight commodity within the major freight transportation modes is then presented, in terms of extent of the infrastructure and total activity.

Differences between a biomass based fuel system and the existing petroleum system are also discussed, in order to distill the justifications and deterrents for government incentives that influence ethanol distribution. Motivations to reduce freight activity include the reduction of GHG emissions, air pollutant emissions that impact human health, consumption of imported petroleum fuels, and cost efficiency of meeting national demand for transportation fuels. Geographic, physical, and chemical properties of biofuels are discussed as challenges to distributing ethanol (and likely future biofuels) with the same efficiency as petroleum.

2.1 US Freight Distribution System

The primary transportation modes used for distributing freight in the United States include truck, maritime, rail, pipeline and airplane. Other than airplane, all of these modes play an important role in transporting petroleum feedstocks and finished products. Other than pipelines, which tend to transport one type or class of product, the infrastructure supporting each of these modes has multiple purposes, enabling transportation of multiple types of freight as well as passengers.

2.1.1 US Freight Infrastructure Extent by Mode

As can be seen in Figure 1, the extent of the infrastructure network for gas pipelines increased almost 50% since 1980, the mileage of railways and oil pipelines dropped more than 20%, and the

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[2] Some parts of this chapter were reproduced with permission from the American Society of Civil Engineers, after first being submitted for publication in the *Journal of Infrastructure Systems* in 2011 under the title, "Greenhouse Gas Emissions from the Construction, Manufacturing, Operation and Maintenance of US Distribution Infrastructure for Petroleum and Biofuels" (Strogen and Horvath 2012). This article was under review at the time this dissertation was submitted. Other parts of this chapter were reproduced with permission from the American Chemical Society, after publishing the article, "Fuel Miles and the Blend Wall: Costs and Emissions from Ethanol Distribution in the United States," in the journal, *Environmental Science & Technology,* in 2012 (Strogen et al. 2012).

total length of waterways and highways did not change significantly. As the following section will show, the slow growth or actual decline in the extent of freight infrastructure did not stem from decreased activity, but more likely occurred as freight logistics and infrastructure management practices increased the intensity of utilization (e.g., t-km per km) of infrastructure without yet leading to debilitating congestion problems.

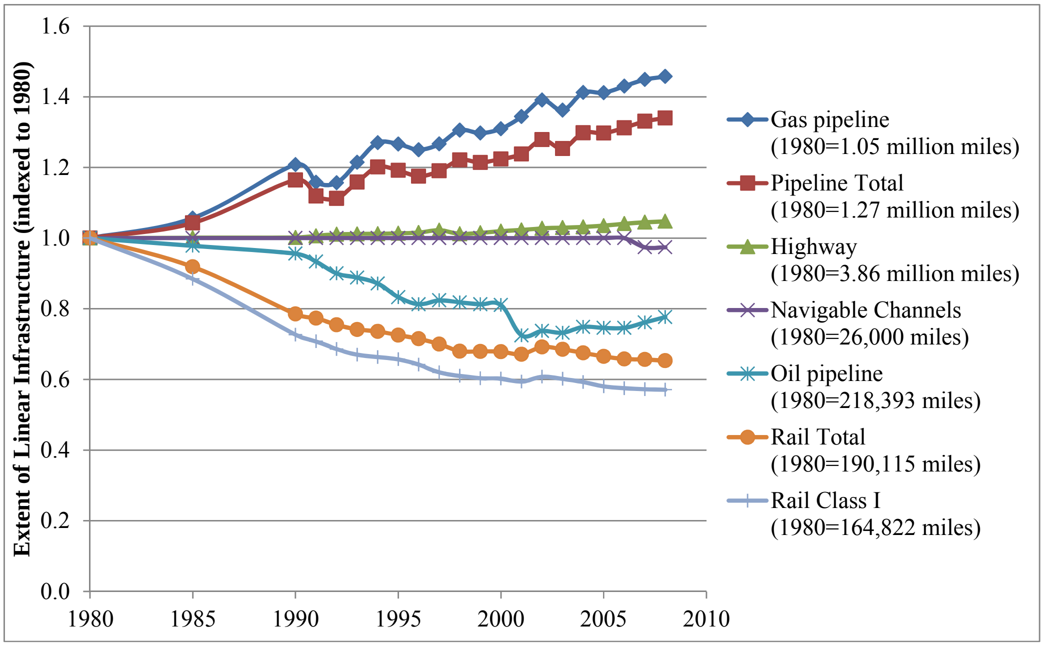


Figure 1. Extent of US Transportation Networks, 1980-2008 (data indexed from (US DOT BTS 2010))

2.1.2 US Freight Activity by Mode

Since 1980, overall demand has grown for transportation services (except for domestic waterway transportation) as can be seen in Figure 2.

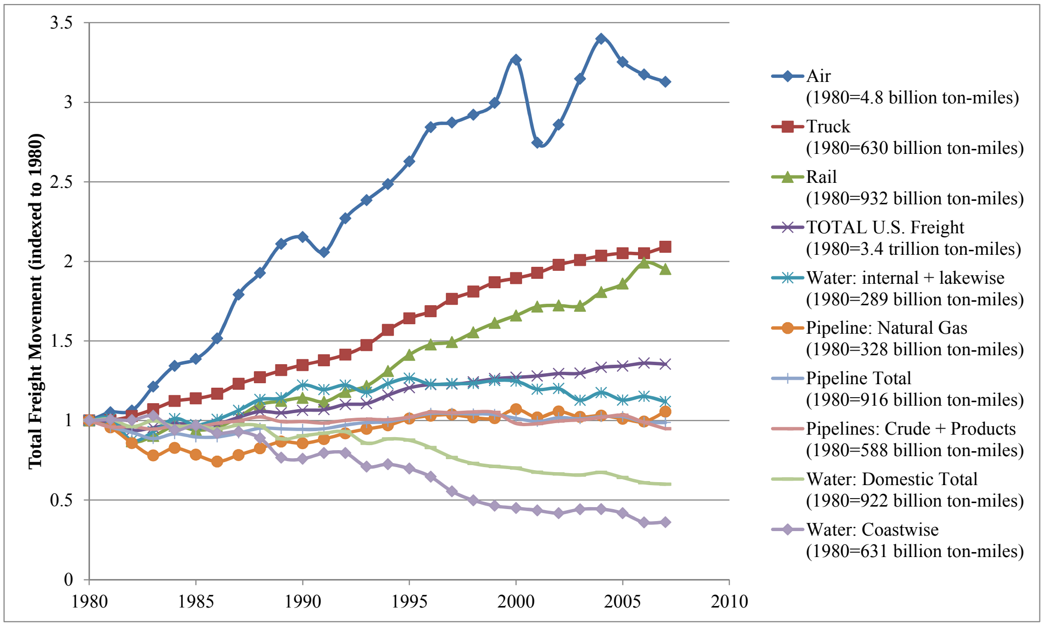


Figure 2. Freight Activity on US Transportation Networks, 1980-2008 (data indexed from (US DOT BTS 2010)).

2.1.3 US Investment and Operating Costs by Mode

In reviewing the costs of operating the four primary modes used for transporting petroleum (and other commodities), fuel typically makes up less than half of the total operating cost of shipping (e.g., 37% for trucking (ATRI 2008); 25% for rail (Pew Center 2010), 8-40% for deep sea and inland maritime (US ACE 2000a), 21-30% for pipelines (Masseron 1990; Miesner 2011; Rabinow 2004). However, the contribution of operating costs to total costs varies by mode, and non-operating activities also result in environmental emissions, though intuitively it may seem that the construction and maintenance of tanks, pipelines, railcars, and other components that last for decades will result in negligible emissions in comparison to the combustion of the fuels that they carry. Additionally, the ratio of variable to fixed costs for each mode varies tremendously; the trucking sector has the highest proportion of variable costs, while pipelines have the greatest proportion of fixed costs. Although few economic activities release as much air pollution as the (direct) consumption of energy per dollar spent, material expenses will result in environmental impacts that should also be taken into account. For these reasons, it was deemed inappropriate to performance an environmental comparison of modes only by their variable operational energy-intensive emissions, as is often done.

Figure 3 shows the contribution of intermediate inputs (energy, material inputs) and investments in fixed assets (structures, equipment, and software) to the total gross output of four major transportation sectors under consideration in this study during the years 1997-2009, with the average values from 2005-2009 presented in Figure 4. While energy inputs are the dominant non-administrative input for truck and water transportation, the contribution of material and fixed asset investments to total costs for pipe and rail transportation are much greater than energy expenditures. However, it remains unfair to compare modes by total sector energy and material expenditures, as the rail and pipeline sectors maintain their own infrastructure, whereas roads and waterways are primarily maintained by government agencies. As can be seen in Figure 5, state and federal governments invest most heavily in highway and waterway infrastructure, and recoup most but not all of expenditures through sector-specific tax revenue.

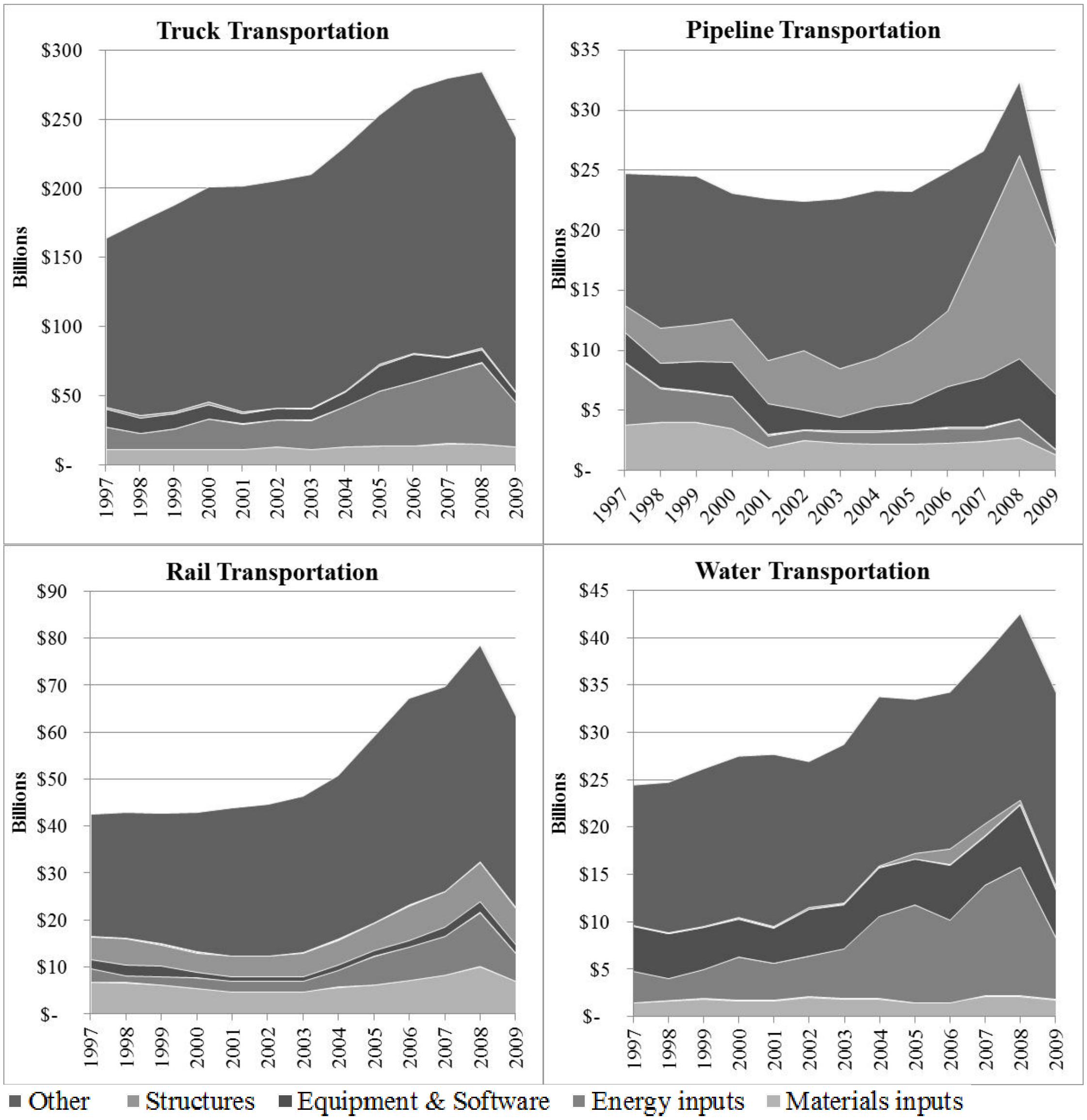
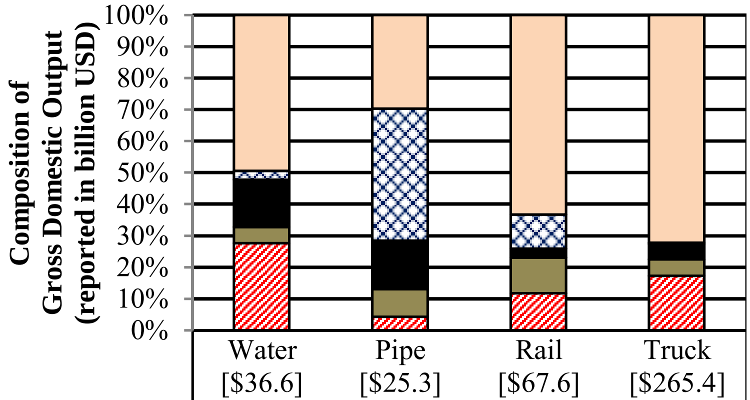


Figure 3. Intermediate Inputs (Energy and Materials), Fixed Asset Investments (Structures, Equipment, and Software), and Other[3] Contributions to Average Gross Domestic Output of Transportation Sectors, 1997-2009 (data adapted and reorganized from (US BEA 2011))

3 "Other" makes up the balance and consists of employee compensation, taxes less subsidies, surplus less private fixed asset investment, and purchased services



	Water [$36.6]	Pipe [$25.3]	Rail [$67.6]	Truck [$265.4]
Other	$18.1	$7.5	$42.8	$191.6
Structures	$1.0	$10.6	$7.3	$1.2
Equipment & Software	$5.5	$3.9	$1.9	$12.9
Materials inputs	$1.9	$2.2	$7.7	$14.0
Energy inputs	$10.1	$1.1	$7.9	$45.8

Figure 4. Average Annual Gross Domestic Output of US Transportation Sectors, 2005-2009.[4]

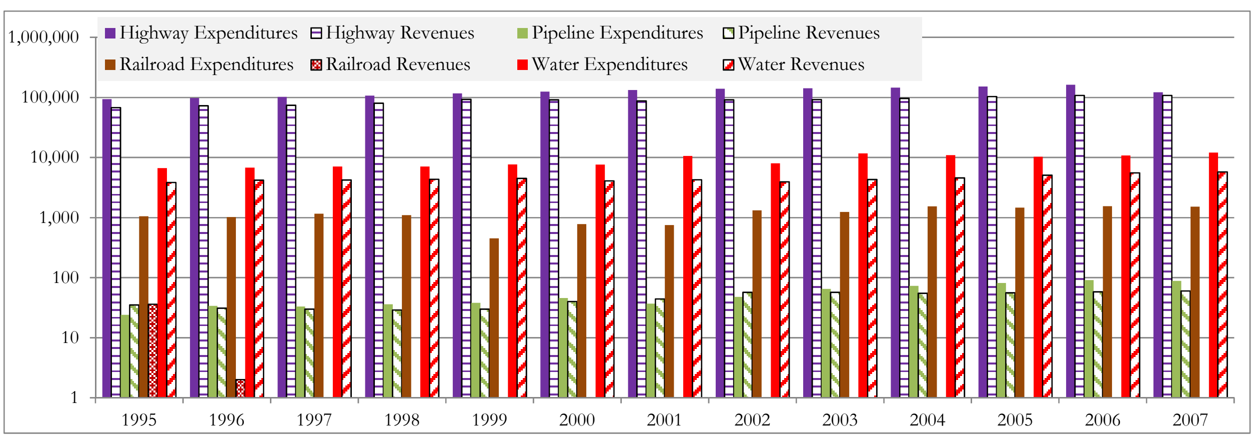


Figure 5. State and Federal Government Transportation Expenditures and Revenues (Current $ Millions) by Transportation Mode, 1995-2007 (data from (US DOT BTS 2010)).

2.2 US Petroleum Distribution System

Crude oil and petroleum products are the dominant commodity traded around the world (now more than 30% of total trade tonnage (UNCTAD 2010)), and make up more than 60% of inbound

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[4] Contributions to Gross Output are presented according to US BEA (2011) categories of Intermediate Inputs (Energy and Materials) and Fixed Asset Investments (Structures, Equipment and Software), and in this graph the balance of contributions to gross output (Employee Compensation, Taxes less Subsidies, Surplus less Private Fixed Asset Investment, and Purchased Services) are considered "Other". Total values are presented in brackets.

foreign freight tonnage entering the United States (US DOT MA et al. 2008).[5] Although the United States imports much more petroleum than any other country, net petroleum imports (crude and petroleum products) dropped below 50% of petroleum consumed in 2010 for the first time since 1997 (US EIA 2011c).

The extensive supply chain for importing, storing, refining and transporting petroleum products described in Figure 7 helps to ensure a continuous supply and adequate stock of fuel, supporting approximately one billion tonnes (~7 billion barrels) of crude petroleum per year throughout the US economy (US EIA 2008a). More than 80% of the volume of crude petroleum in the US ends up as transportation fuel, as can be seen in Figure 6. In this dissertation, the bulk of crude oil and petroleum product storage and distribution infrastructure is assumed to be dedicated to motor fuel and heating fuel purposes (and in some noted cases, exclusively motor fuel purposes).

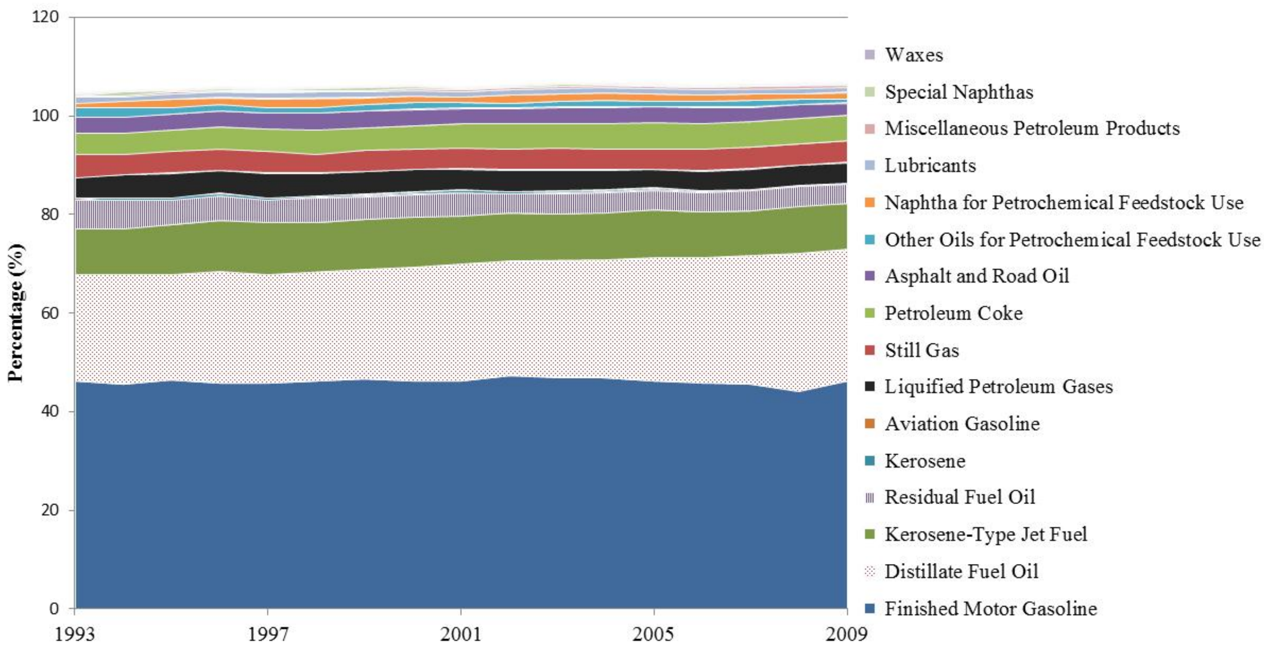

Figure 6. US Refinery Volumetric Yield, 1993-2009 (data from (US EIA 2011a))

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[5] In 2010, petroleum imports made up only 17% of the value of US imports, and petroleum exports made up 5.5% of US export value (US DOT BTS 2007)

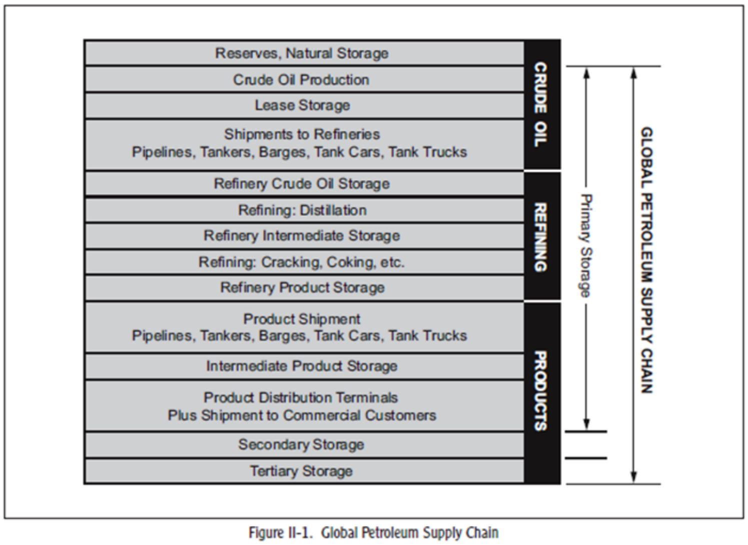

Figure 7. Global Petroleum Supply Chain (reproduced from (Shackouls et al. 2004))

2.2.1 US Petroleum Infrastructure Extent

In the US and most industrialized countries, enormous investments have been made to create and maintain efficient systems that distribute petroleum fuels from the oil well to the vehicle's fuel tank, though the quantity of many components of petroleum infrastructure has decreased over the last few decades. The number of operable refineries in the United States dropped from 301 to 148 from 1982 to 2010 (US EIA 2011a), and only 137 refineries were actually operating in 2010 (US EIA 2011a). Additionally, the number of petroleum (i.e., crude, liquid product, and highly volatile liquid) pipeline miles dropped from 214,000 (US DOT BTS 2010) in 1985 to 172,000 in 2009 (US DOT PHMSA 2011), and the number of public retail gas stations decreased from 190,000 in 1996 (US DOE AFDC 2011) to 159,000 in 2010 (Reid 2010). The only infrastructure components that seem to have increased in number are registered fuel terminals, which increased from 1,300 in 2000 to 1,350 in 2011 (US IRS 2011). The reduced extent of domestic petroleum infrastructure components was possible as foreign supplies grew to exceed domestic supplies, despite an increase in total petroleum consumption.

2.2.2 US Petroleum Freight Activity by Mode

Just as the extent of infrastructure has decreased in certain respects over the last few decades, domestic movement (t-km) of petroleum has decreased despite an increase in the amount of petroleum refined, transported, and sold throughout the United States. Figure 8 presents data on the historic distribution of petroleum and freight throughout the United States over the last three decades, and Figure 9 shows that petroleum has been significant as a domestically transported commodity. Most petroleum is transported by energy-efficient pipeline and maritime modes, the energy used to move petroleum by all modes is only approximately 3%[6] of all US transportation energy. Petroleum also makes up a significant portion of the freight transported by pipeline and maritime (at approximately 40% and 60% of t-km for each mode, respectively).

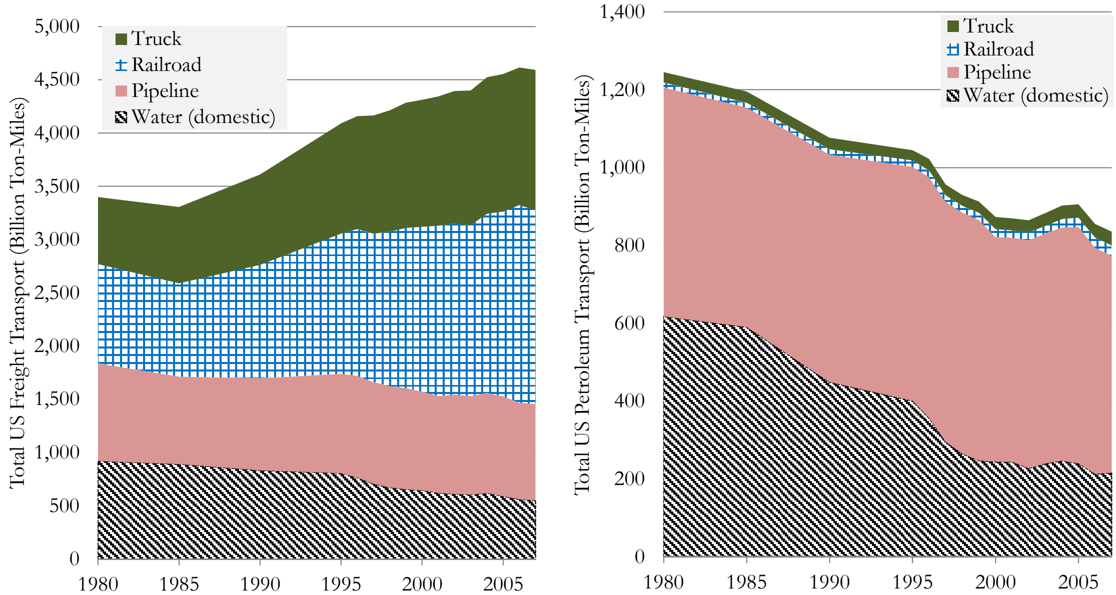

Figure 8. Total Freight (left) and Petroleum (right) Transportation in the United States, 1980-2007 (data from (US DOT BTS 2010))

From 1985 through 2010, the percent of foreign-sourced crude oil received at refineries has increased from 25% to 60% (US EIA 2010a), though the vast majority of petroleum products are still refined domestically. The increased reliance on crude imports has contributed to a reduction of more than 25% in total domestic petroleum movement (tonne-km) from 1985 to 2008 (AOPL 2011), which can be seen in Figure 8, despite a 20% increase in demand for petroleum products over the same time period (US EIA 2011a).

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[6] Moving petroleum by pipelines requires about 1% of all transportation energy (though petroleum pipelines currently consume more electricity than any other transportation mode, at approximately 0.2 quads) (adapted from (US DOT BTS 2000)) and moving petroleum by water makes up less than 2% of all transportation energy.

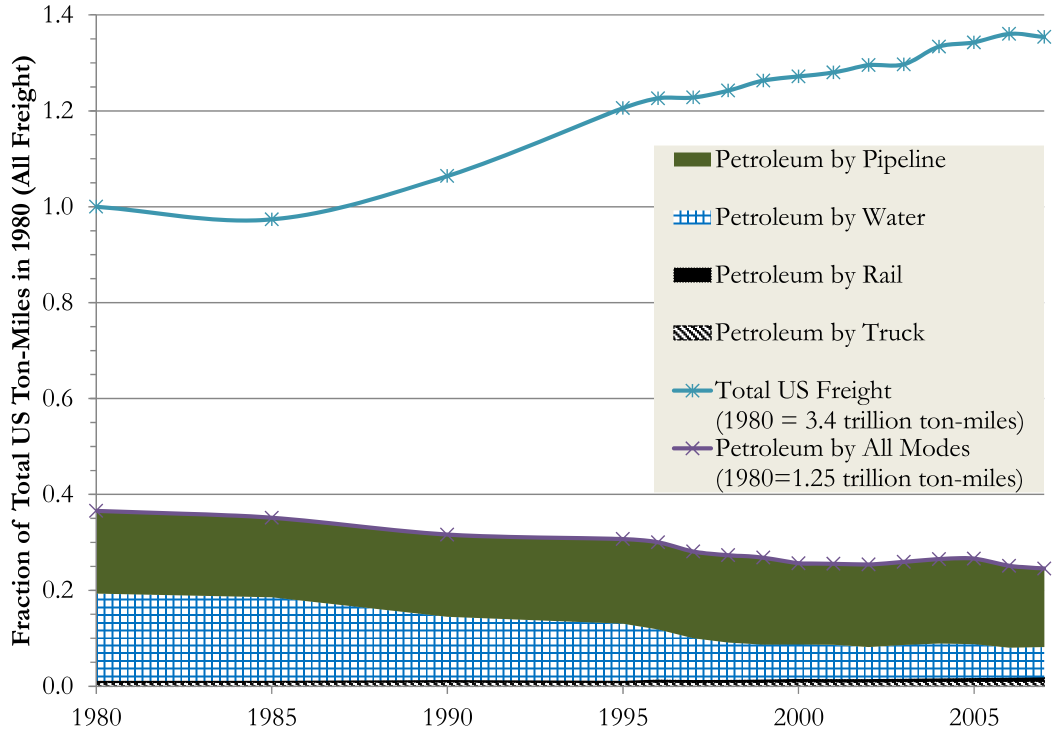

Figure 9. Contribution of Petroleum to Total US Freight Transportation Activity, 1980-2007 (data indexed from (US DOT BTS 2010)).

Figure 10 and Figure 11 present the estimated average distance in which crude petroleum and petroleum products were transported in the United States, respectively, with data presented in Figure 19. The reduction in domestic petroleum transport activity can almost all be attributed to reduced crude transportation by water carriers (from an average of 800 km to less than 100 km) and pipeline (from an average of 600 km to less than 500 km) from 1985-2008. The driving forces behind this change include reduced coastal shipment (and production) of Alaskan petroleum (AOPL 2011), and increased costs to manufacture ships and barges domestically in accordance with Section 27 of the Merchant Marine Act of 1920 (aka the Jones Act) that are also double-hulled in accordance with Section 4115 of the Oil Pollution Act of 1990. At the same time, the amount of petroleum transported by rail doubled in total t-km, increasing from 1.3% of total petroleum t-km in 1985 to 3.2% in 2007 (AOPL 2011), and petroleum is making up an increasing share of total national rail traffic. One trade group reported that "shipments of crude oil and liquefied natural gas accounted for about 2% of all carloads in 2008, 3% in 2009, 7% in 2010, and about 11% so far in 2011" (US EIA 2011e).

In contrast to the decreased transport activity for crude oil, refined petroleum products were consistently transported on average 700-760 km (domestically) almost every year since 1985. However, the average product distance may have dropped as well, had it not been for increasing geographic and seasonal variation in fuel formulation specifications covering vapor pressure, sulfur content, renewable content, oxygenates and other additives. Within the petroleum gasoline market, several differentiated blending stocks and finished products exist (e.g., reformulated gasoline). The

US GAO summarized the logistics challenges associated with efficiently distributing specialty blends, as "conventional" gasoline made up less than 50% of the gasoline market share in 2004 (US GAO 2005).

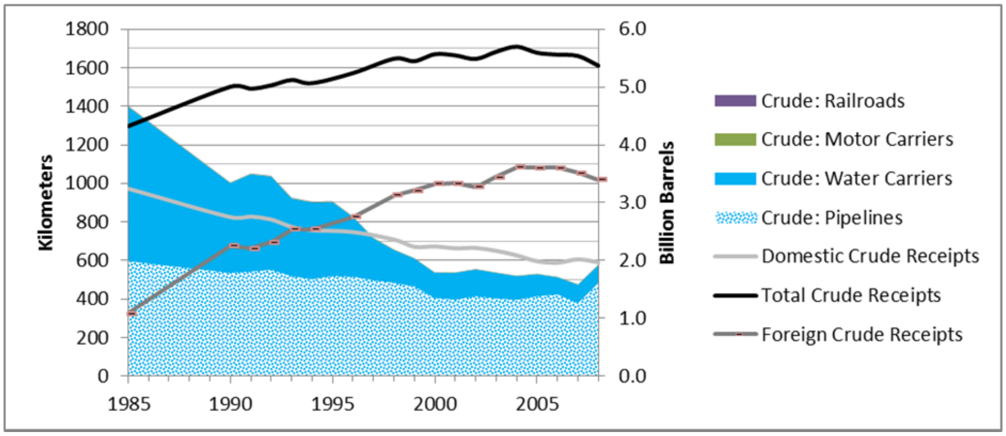

Figure 10. Total US Crude Input to Refineries and Average Distance Traveled,[7] 1985-2008

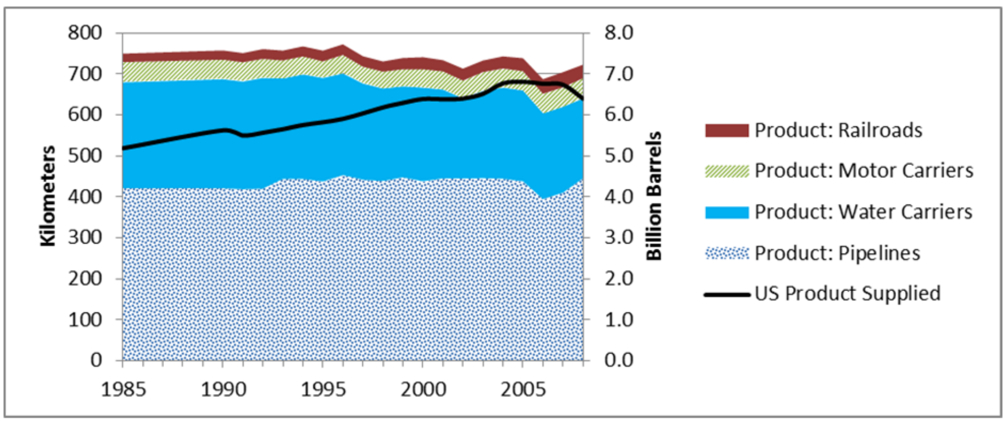

Figure 11. Total US Petroleum Product Supplied and Average Product Distance Traveled,[8] 1985-2008

[7] Distance estimated by dividing total crude oil t-km (AOPL 2011) by crude oil tonnage entering refineries (calculated by multiplying annual average crude density by crude oil receipts at US refineries (US EIA 2010a). All crude oil imported to and produced within the United States is assumed to end up at US refineries, as crude exports have not exceeded the equivalent of 1% of US refinery input since 1988 (US EIA 2010a).

[8] Distance estimated by dividing total petroleum product t-km (AOPL 2011) by petroleum product supplied in tonnage (calculated by multiplying total volume of product supplied (US EIA 2011a) by an average of 0.14 short tons per barrel (AOPL 2011). Product supplied includes imports, but excludes exports (neither of which were greater than 13% of Product Supplied from 1993-2008). Roughly 90% of exports leave the gulf coast, and are assumed to travel negligible distance within the United States. Note: The volumetric difference between Figure 10 and Figure 11can be explained by a) the Refinery Processing Gain, which averaged 6.3% (v/v) from 2000-2009, and b) that imports made up 16% (v/v) of total products supplied during the same years (US EIA 2011a).

2.3 Technical Considerations for Ethanol Fuel Policy

Prior to modeling the projected role of infrastructure in the life-cycle environmental footprint of a fuel, it is important to understand the historic background and influences on the distribution of petroleum and ethanol, as they are not entirely interchangeable.

2.3.1 History of US Ethanol Policy

Ethanol has been used in internal combustion engines for more than 100 years, and its most common use has shifted from initially serving as a stand-alone fuel, to serving as a valuable oxygenate and octane enhancing additive, and is currently serving as a bulk renewable blending agent for motor gasoline. Ethanol has been subsidized in the United by at least $0.40 per gallon since 1978, when it was first granted a waiver to allow blending up to 3.6% oxygen by mass (i.e., E10[9]) with gasoline, although other oxygenates (e.g., butanol) have been limited to 2.7% oxygen by mass, in order to be considered "substantially similar" to gasoline (Schulz et al. 2011).

The 1990 Clean Air Act (CAA) amendments required the use of reformulated gasoline (RFG) in certain areas starting in 1995, with the goal of reducing harmful emissions (primarily of VOCs, NO_x, and CO) from motor vehicles that cause ozone, commonly called smog (in addition to reducing emissions of toxic air pollutants such as benzene) (US EPA 2005, 2006b). The CAA amendments also required the use of oxygenates (primarily MTBE[10] and ethanol) in CO non-attainment areas during the winter, and year-round in ozone non-attainment areas. RFG was required to contain 2%-3.2% oxygen by mass, and in 1995 a new rule under the Clean Air Act (which was never implemented) would have required that 30% of the RFG-required oxygen content be derived from renewable feedstocks (US EPA 1994).

As an oxygenate, blending ethanol into gasoline led to comparable (ARB et al. 2000) or slightly less (Williams et al. 2003) local-level air quality benefits than would be found from blending MTBE. As the vehicle fleet modernized in the 1990s with the adoption of fuel injection systems, closed loop emissions control, and three way catalysts, emissions reductions from blending ethanol in gasoline became less and less significant (Hood and Farina 1995). Ethanol overtook MTBE as the most widely used fuel oxygenate and anti-knocking agent in the United States in 2003 at 2.0% (v/v) of motor gasoline (US EIA 2011a). When ethanol was used as a substitute for the oxygenate MTBE, which was primarily derived from natural gas, it had a greater impact on reducing natural gas demand than crude oil demand (Szklo et al. 2007).

In 1999, a Blue Ribbon panel commissioned by the US EPA recommended that Congress remove the oxygenate requirement under the RFG (US EPA 1999), primarily as they determined the costs associated with MTBE (the dominant oxygenate at the time) were not worth the benefit. Additionally, the US EPA continued to encourage Congress to replace the fuel oxygen requirement

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[9] Higher-level blends will follow the same nomenclature (e.g., E15, E85). Because butanol has not (yet) received the same waiver as ethanol, the butanol blend wall is 11.5% by volume (9.8% by energy, 2.7% oxygen by mass). If butanol is blended at 3.5% oxygen by mass, this will correspond with a Bu16 blend wall (16% by volume, 13.8% by energy).
[10] MTBE was the dominant fuel oxygenate until it was phased out of most states in the early 2000s due to groundwater contamination problems, when ethanol became the most commonly used fuel oxygenate.

with a "flexible, national renewable fuels program" (US EPA 2005). Additionally, this panel warned that increased inclusion of ethanol into gasoline could increase ozone precursor emissions, will require infrastructure enhancement to distribute fuel from the Midwest (where they anticipated the production center would continue to be), and voiced concerns that ethanol's biodegradability may delay the degradation (and therefore increase mobility) of benzene and other hydrocarbon contaminants from leaking tanks. In June of 2005, EPA denied requests made by the states of California, Connecticut and New York (which had been filed as early as 1999) for a waiver of the oxygen content requirement of the RFG program, as the states believed ethanol impaired their ability to meet air quality goals related to ozone. With a waiver, total volatile organic compounds (VOC) and nitrogen oxide (NO_x) emissions were likely to decrease while carbon monoxide (CO) emissions were likely to increase (US EPA 2005).

Shortly afterwards, Congress did remove the oxygen content requirement for RFG as part of the Energy Policy Act of 2005, which went into effect in 2006 (US EPA 2006a), and ensured that gasoline sold in the United States contained a minimum (average) quantity of renewable fuel through a Renewable Fuel Standard (RFS) (US EIA 2002). Ethanol is now the most consumed non-petroleum liquid transportation fuel in the United States, with net domestic production equivalent to 9.6% (v/v) of supplied motor gasoline in 2010 (US EIA 2011a), such that its consumption impacts the quantity and percentage of refining and distribution infrastructure that oil companies dedicate to gasoline.

2.3.2 Technical Considerations for Ethanol–Gasoline Blends in Vehicles

Complete combustion of fuels could theoretically occur under stoichiometric conditions (i.e., an air-to-fuel equivalence ratio of 1.0), such that all fuel carbon and hydrogen would be oxidized to CO_2 and H_2O without any excess oxygen leaving in the exhaust. In reality, for spark ignition internal combustion engines running on gasoline and ethanol–gasoline blends, fewer products of incomplete combustion (PIC) such as CO and hydrocarbons would be emitted under slightly fuel-lean conditions (i.e., air-to-fuel equivalence ratio slightly greater than one) (C. W. Wu et al. 2004), and optimum engine efficiency during cruising would also be found under slightly fuel lean conditions (MacLean and Lave 2003). Adding oxygenates to gasoline essentially introduces a partially oxidized fuel molecule (e.g., ethanol) to dilute the (reduced-form) gasoline fuel molecules entering engines. As a result, oxygenated gasoline could combust completely in combustion chambers that would contain too little oxygen to completely combust non-oxygenated gasoline (i.e., the engine would be operating under "fuel rich" conditions with non-oxygenated gasoline), thus reducing CO and other PICs.

Even under stoichiometric or slightly lean conditions, small amounts of carbon may exit the combustion chamber in incompletely oxidized form (e.g., CO or various hydrocarbons) and some nitrogen may exit in an oxidized form (e.g., NO), so catalytic converters have been adopted to enable most PICs to react to CO_2, H_2O, and N_2 prior to exiting the tailpipe. Excess air must be kept very slight as three-way catalytic converters operate best under an equivalence ratio between 0.98 and 1.02 (MacLean and Lave 2003); slightly more air could allow NO_x to form and escape catalytic destruction, and too much air would reduce the temperature of the combustion chamber (and in the catalytic converter) such that incomplete combustion of fuel would occur.

Although engines are designed to run fuel-rich when high power output is needed (e.g., during acceleration), modern engine controls ensure combustion conditions are nearly stoichiometric much more consistently than older carbureted engines. Modern vehicles also tend to run fuel rich during cold starts (before the catalytic converter is hot enough to effectively catalyze reactions), which leads to seasonal air quality problems in some areas, though less than 25% of the US population currently resides in "carbon monoxide maintenance areas" (US EPA 2011b). The number of regions mandating the blending of oxygenates into gasoline dropped from 39 (throughout 23 states) in 1992 to just eight regions (in six states), all of which mandate ethanol (between 1.8-3.5% oxygen) for 4-6 months during the winter (US EPA 2008).

In addition to air pollutant emissions, the introduction of oxygenates may also have desirable or undesirable impacts on vehicle fuel economy, octane, performance, or other air pollutant emissions of the gasoline fuel. The following sections summarize the main technical concerns that should be considered prior to incentivizing or mandating ethanol (or other fuel additives) to be blended in regions far from where they are produced.

2.3.2.1 Fuel Economy

Current literature suggests that no efficiency synergies should be expected from low-level blends of ethanol with gasoline. In a summary of the US DOE's latest studies on the combustion of ethanol–gasoline blends, automobiles running on intermediate ethanol blends exhibited a loss in fuel economy commensurate with the energy density of the fuel (i.e., an average reduction in fuel economy of 3.7 percent using E10, 5.3 percent using E15, and 7.7 percent using E20) (US GAO 2011).

While the Brazilian government has mandated a minimum ethanol content in gasoline, enabling vehicle manufacturers to design engines with a higher compression ratio that would be feasible for conventional gasoline (R. C. O. B. Delgado et al. 2007), vehicles in the United States are still designed to be functional with ethanol-free gasoline. However, preliminary studies have shown that even current US engines using Bu16 and E85 may experience higher first law efficiency than with gasoline alone (2.2% and 3.5%, respectively) (Schulz et al. 2011), though such results have yet to be replicated in a statistically significant manner. Other studies have shown energy-based fuel economy to peak at mid-level blends between E20 and E40 in conventional engines (Shockey et al. 2008; Turner et al. 2011).

Properly tuned engines have obtained energy efficiency performance at E30 that more than compensated for the fuel's decreased energy density (Szklo et al. 2007). Such tuned engines (i.e., variable compression ratio engines or Ricardo's Ethanol Boosted Direct Injection (EBDI) engines) can exploit ethanol's high octane and high heat of vaporization, and may enable vehicles to obtain higher thermal (first law) efficiency than is possible with spark-ignition vehicles currently on the market, and may even exceed the volumetric fuel efficiency (e.g., mpg) of conventional gasoline (Szklo et al. 2007). At blends of E85, energy-based fuel efficiency has been found to be up to 9% greater than gasoline alone, by making changes such as configuring an engine with a turbocharger (IEA ETSAP 2010).

2.3.2.2 Motor Vehicle Emission Models

2.3.2.2.1 GREET Model

The commonly used GREET model assumes that low-level ethanol–gasoline blends do not change emissions from vehicles manufactured in 2005 or later. In model years 1990, 1995, and 2000, the only pollutant affected by introducing low-level ethanol blends is carbon monoxide, for which a 20%, 20% and 10% emissions reduction is expected, respectively (US DOE ANL 2010). For flex-fuel vehicles operating on ethanol or butanol blends, evaporative VOC emissions were assumed to be 15% lower for FFVs manufactured from 1990 to 2020 (relative to the conventional vehicle baseline); exhaust emissions of VOCs, CO, PM, and CH4 were also lower for FFV model years prior to 2000, without any emissions expected to be higher than the baseline for any model year (US DOE ANL 2010). In summary, the GREET model assumes that the use of low-level blends in conventional vehicles, and high-level ethanol–gasoline blends in FFVs, has ether resulted in a net reduction in pollutant emissions or no change at all, for all model years considered.

In a modification of the GREET model more than ten years ago, life-cycle toxic emissions from ethanol–gasoline blends were estimated to provide overall emissions benefits (e.g., lower 1,3-butadiene emissions), but higher emissions of some pollutants such as acetaldehyde (Winebrake et al. 2001).

2.3.2.2.2 US EPA Models

The US EPA vehicle emissions model, MOVES, assumes that pre-Tier 2 (i.e., model year 2003 or earlier) gasoline vehicles essentially exhibit a positive linear relationship between ethanol blend level and emissions of benzene and VOCs, no difference in PM emissions, and a linearly decreasing CO emissions factor on a grams per mile basis up to 15% ethanol (with none of these factors making more than a 10% difference); additionally E15 was found to produce 60% more ethanol and acetaldehyde emissions than E10 (US EPA OTAQ 2011).

A comprehensive assessment of the impacts of E10 was performed for the Regulatory Impact Assessment of the first Renewable Fuel Standard (RFS1), and concluded that results from existing studies were too inconsistent to confidently predict that E10 would have an impact on exhaust VOC (HC) and NO_x emissions in Tier 1 (1996 to 2003) vehicles, relative to (E0) gasoline. Nevertheless, in the final rule analysis for RFS2, the EPA conservatively assumed that the following (conventional gasoline|reformulated gasoline) exhaust emissions changes would apply to both Tier 0 and Tier 1 vehicles by shifting from non-oxygenated gasoline to E10, but the EPA could not justify attributing the same results to Tier 2 vehicles (manufactured in 2004 or later) (p. 507 of (US EPA 2010d)).

- Reductions: VOC (7.4%|9.7%), CO (11-19%|36%), Benzene (24.9%|38.9)
- Increases: NO_x (7.7%|7.3%), Formaldehyde (6.7%|2.3%), Acetaldehyde (156.8%|173.7%)
- Mixed results: 1,3-Butadiene (13.2% reduction|6.1% increase)

2.3.2.2.3 US GAO Summary

A summary of federally sponsored emissions studies for intermediate ethanol blends can be found in (US GAO 2011). According to a 2009 DOE report for vehicle model years from 1999 to 2007, emissions were "largely unaffected by the ethanol content of the fuel," and EPA's more recent ruling on E15 suggests that emissions may increase for vehicles from model years prior to 2000 (US GAO 2011). While studies on E85 exhaust emissions have found highly variable results, "data indicates that E85 causes a slight increase in non-methane organic gases (NMOG) emissions, a slight decrease in NO_x and CO_2, and significant reductions in CO" relative to conventional Tier 2 certification gasoline (US EPA 2010d)).

2.3.2.3 Fuel Evaporative Emission Studies

Evaporative emissions from E10 are expected to be significantly higher than (E0) gasoline for both older vehicles (65%) and even more so (on a relative scale) for well-sealed newer vehicles (213%); this effect results primarily from increased fuel vapor permeation through tanks and hoses (due to lower molecular weight) and only slightly from greater volatilization losses (due to fuel volatility) (US EPA 2010d). In a recent study that deemed E15 to be as safe as E10 in terms of volatile emissions, "[n]o reliable evidence was presented that vapor components of evaporative emissions other than ethanol increased from E10 to E15", and the concentration of ethanol in the vapor phase above E10 and E15 was approximated to be in proportion to their volumetric concentration (i.e., 10% and 15%, respectively) (US EPA 2012). This approximation conservatively overestimates the concentration of ethanol in the vapor phase, as the liquid-phase activity coefficient of ethanol in gasoline decreases at higher blends (Harley et al. 2000). If ethanol is added to gasoline blendstock (without adjusting blendstock components based on the expected ethanol concentration), the total (Reid) vapor pressure of the mixture will reach a maximum around 4-5% ethanol by volume, and will actually decrease with further increases in ethanol concentration (French and Malone 2005). For this reason, mid-level blends (e.g., E30) are expected to result in fewer evaporative emissions than E10 or E20 (Szklo et al. 2007). E85 was found in a single study to result in 50% lower evaporative emissions than gasoline, though variability in these emissions were assumed to be too great to warrant different treatment from conventional gasoline in the RFS final rule analysis (US EPA 2010d).

2.3.2.4 Air Quality and Emissions Inventory Models

In addition to impacting vehicle tailpipe emissions, new fuels can impact airshed-scale pollution through system interactions with non-vehicle sources of emissions. From 1980 to 2009, the US saw an average of 80% reduction in CO concentration[11] at 187 monitoring sites (US EPA 2010b), though approximately 21 million Americans still live in areas considered "serious" CO maintenance areas (US EPA 2011b). As wintertime CO reductions of approximately 14% were found in 1997 in United States locations where "oxy fuels" were used (Whitten et al. 1997), it is likely that the use of oxygenates did play a role in reducing CO concentrations in urban areas. Although motor vehicle and fuel policies are typically designed to meet national ambient air quality standards (NAAQS), which relates to outdoor air, reduction in harmful emissions from stationary vehicles (e.g., in a garage) can also help to improve indoor air quality. In one modeling study, (oxygenated) reformulated gasoline was also suggested to have played a role in reducing accidental carbon

[11] 2nd annual maximum 8-hour value

monoxide poisonings from vehicle idling emissions (e.g., in garages) in the late 1990s (Marr et al. 1998), in addition to the wider use of catalytic converters and inspection programs.

Despite many historic accounts that ethanol and oxygenates have reduced emissions of carbon monoxide and therefore improved public health, it has long been known that ethanol–gasoline blends may result in elevated aldehyde and other pollutant emissions (Niven 2005; US EPA 1999). This concern has inspired cautionary papers suggesting that more lives may be lost than improved by increasing the use of ethanol in gasoline fuel (e.g., (Jacobson 2007)). Other recent modeling efforts found that blends of 10% ethanol with gasoline (i.e., E10) have the potential to lower many emissions from the entire urban vehicle fleet (e.g., NO_x, hydrocarbons, and some air toxics), though at the expense of higher acetaldehyde emissions in locations such as Mexico City (García et al. 2010).

The US EPA performed a comprehensive modeling effort to understand air quality impacts throughout the nation as a result of production, distribution, and consumption (combustion) of ethanol for blending with gasoline in order to meet the Energy Independence and Security Act (EISA) of 2007. Although significant uncertainty should be expected due to limited data availability, their models predict that meeting the large increases in ethanol use will have a negligible impact on air toxic emissions (other than ethanol), an increase in ozone concentrations over much of the United States by up to 1 part per billion (ppb), but a decrease in ozone concentrations in a few highly populated areas largely due to increased NO_x emissions (Cook et al. 2011) (which actually has a negative impact on ozone concentration in VOC-limited airsheds).

2.3.2.5 Empirical Vehicle Emission Studies

Empirical tests over the last two decades have either found that ethanol addition has little or no influence on the emissions profile from gasoline engines, or it results in a decrease in certain pollutant emissions that are accompanied by an increase in other pollutants. The uncertainty around this issue motivated the exploration of whether GHG emissions could have been reduced, if ethanol blending was presumed to result in a negligible net benefit to air quality.

In the past, CO and HC emissions were successfully reduced when ethanol was added to gasoline used in carbureted engines with open loop emissions controls; however, smaller emissions reductions were found in models considered "modern" in the early 1990s, which tended to have fuel injection systems, closed loop emissions control, and three way catalysts (enabling consistent stoichiometric combustion) (Hood and Farina 1995). At this time, no consistent impact on NO_x emissions, evaporative emissions, or vehicle drivability was found at low ambient temperatures, but benzene and butadiene emissions decreased while aldehyde emissions increased (Hood and Farina 1995). During these years, the "modern petrol engine" would typically operate under fuel-rich conditions that produce emissions rich in carbon monoxide; several studies during this period indicated that oxygenates would reduce regulated pollutants such as CO, NO_x and hydrocarbons, but would increase aldehyde emissions which may exacerbate ozone levels in cities with smog problems (Perry and Gee 1994).

According to the 2009 DOE report for Project V1, regulated tailpipe emissions from 16 automobiles (including model years ranging from 1999 to 2007) remained largely unaffected by the ethanol content of the fuel, though emissions of ethanol and acetaldehyde were found to increase with increased ethanol addition (US GAO 2011). A recent study by ASTM found no statistically significant differences in emissions between E10, E20, E85, and Bu16 (including aldehyde emissions), though the concern was raised that long-term use of ethanol blends may degrade catalysts because ethanol–gasoline blends tend to combust hotter than Tier 2 (ethanol-free) gasoline (Schulz et al. 2011). Another recent study on the effects of using E85 instead of gasoline in FFVs found that NO_x, CO, NMHC, and formaldehyde all decrease by 10% or more, whereas acetaldehyde emissions increased by a factor of 20, though results varied widely (Yanowitz and McCormick 2009).

In a study of test vehicles manufactured between 1994 to 2006, which were certified to either federal Tier 1 (model year 1994 to 2003), National Low Emission Vehicle (NLEV), or Tier 2 (model years 2004 and later) exhaust emission standards, found that increasing the ethanol concentration will increase NO_x emissions (e.g., 20% higher for E20), decrease THC emissions (e.g., 15% lower for E20), and decrease CO (e.g., 30% lower for E20) (Sierra Research (for CRC) 2009). Qualitatively similar results were recently reported by the Oak Ridge National Laboratory, after studying the durability of vehicles manufactured between 2000 and 2009 operating with blends of 0% to 20% ethanol with certification gasoline. Although vehicles using ethanol blends were not found to age differently (in terms of emissions profiles), the following fleet-wide changes in tailpipe emissions and fuel economy were reported.

- "Median CO emissions decreased by 0.03 to 0.14 g/mile.
- Median nonmethane hydrocarbon emissions decreased by 0.002 to 0.008 g/mile.
- Median NOX emissions increased by 0.001 to 0.004 g/mile.
- Median ethanol emissions increased by 2.3 to 4.6 mg/mile.
- Median acetaldehyde and formaldehyde emissions increased slightly (by less than 1 mg/mile).
- Nonmethane organic gas and methane emissions were largely unchanged.
- Fuel economy was decreased by about 3% to 7%, consistent with the energy density of the test fuel." (B. H. West et al. 2012)

After a study was performed to determine if E15 leads to a different emissions profile than E10 from a 2011 Toyota Camry, it was determined that "no additional Tier 1 literature search and no Tier 2 health effects testing are merited for E15. First, evaporative and combustion emissions of E15 are highly similar to E10 emissions: no new species were consistently identified in E15 compared to E10, an approved fuel. Second, the existing database demonstrates that the evaporative and exhaust emissions for E15 are *reasonably comparable* (per 40 CFR 79.52(b)) to those already addressed by the Section 211(b) Research Group …" (Fanick 2011).

2.3.3 Infrastructure Challenges for Ethanol

The types of infrastructure capable of distributing ethanol (and other liquid biofuels) are similar to petroleum products, especially in comparison to alternative fuels such as hydrogen and electricity, and much existing petroleum infrastructure can be converted to handle ethanol and/or ethanol–gasoline blends. Parallel infrastructure dedicated to ethanol has been rapidly expanding over the last decade, as the number of ethanol production facilities more than quadrupled since 1999, from 50 plants to more than 200 in 2011 (RFA 2011), and production capacity increased almost 80-fold from 175 million gallons in 1980 to 13.2 billion gallons (315 million barrels) in 2010 (RFA 2011). Ethanol infrastructure has been almost entirely dedicated to domestic supply (predominantly in the Midwest), as ethanol imports peaked in 2006 at only 13% of US consumption, and dropped to less than 1% in 2010 (US EIA 2011a) as the United States became a net exporter in 2011.

In 2011, the United States will have enough production capacity to potentially a) fulfill the quota for all 15 billion gallons of first generation biofuels under EISA 2007, and b) saturate the national gasoline market at the current E10 blend wall. Figure 12 shows that the country as a whole essentially "hit" the blend wall this past summer, 2011. The E10 blend wall has been referred to as "the biggest issue facing the U.S. ethanol industry today." In order to reduce the costs and perceived market risk facing private enterprises capable of expanding the domestic ethanol market via mid- or high-level blends, the federal government and many states are subsidizing private development of downstream ethanol infrastructure (e.g., fuel dispenser tax credits, FFV subsidy via CAFE credits to automakers) in addition to continued subsidization of biofuel production and blending (e.g., 45-cent volumetric ethanol excise tax credit (VEETC) and blending mandates).

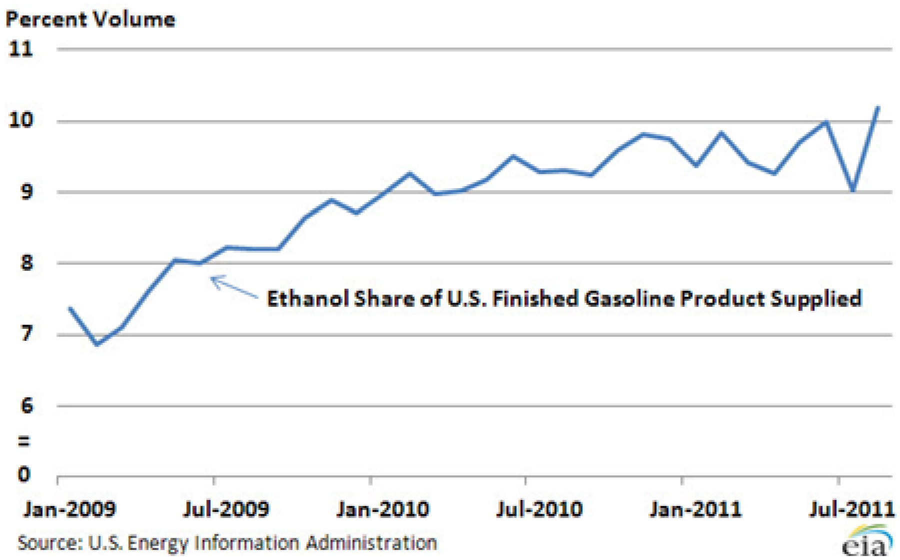

Figure 12. Ethanol Share of US Motor Gasoline, 2009-2011 (reproduced from (US EIA 2011f))

The concerns associated with expanding ethanol production and the resulting increased burden of freight networks is not new. A report published almost ten years ago by the EIA stated the following:

> "Increasing the use of ethanol to 5 BGY by 2012 more than doubles the current level of ethanol production and could place a considerable burden on the current transportation infrastructure. . . Pipeline and truck shipment is not addressed in this report because it is not currently considered a cost-effective method of transport due to special handling requirements. . . Although most logistical issues should be overcome with proper planning, there are concerns regarding capital costs for expanding the current infrastructure, congestion, spatial constraints at terminal facilities, and availability of equipment." (US EIA 2002).

Although new products typically cannot be distributed as efficiently as incumbent products, there are several technical, economic, and environmental challenges to scaling up the production and distribution of biomass-based ethanol that are unlikely to disappear in the near future. Two lists A and B, both of which are explained in detail later in this section, were created in order to synthesize the biomass feedstock, biofuel molecules and fuel market characteristics that render a biofuels system at a disadvantage relative to petroleum.

List A summarizes the physical and chemical properties of ethanol (and butanol) that render them more or less desirable than gasoline for distribution, which is explained in further detail later in this section.

List A

1. Energy density
2. Hygroscopicity
3. Corrosivity
4. Solvent and surfactant properties
5. Biodegradability
6. Volatility

List B summarizes the energy efficiency and environmental challenges that result from the greater capital intensity and market challenges for biomass-to-fuel systems relative to petroleum, and is explained in more detail later in this section.

List B

1. Crude oil is extracted almost continuously; biomass is harvested seasonally
2. Crude oil can be stored for years; biomass and ethanol have a short "shelf life"
3. Petroleum refineries typically have a liquid fuel production capacity more than twenty times that of biorefineries; construction of cellulosic biorefineries is currently several times more expensive per unit of capacity
4. Petroleum refineries have access to efficient distribution infrastructure; biorefineries are remote from infrastructure and customers
5. The US gasoline market is (nearly) saturated at the E10 blend wall
6. Retail stations everywhere sell petroleum fuels; stations struggle to justify offering mid- and high-level biofuel blends
7. High-level ethanol blends are only available to a small fraction of gasoline consumers

2.3.3.1 List A: Concerns related to properties of alcohol fuels

2.3.3.1.1 Energy density

Ethanol (at 21.4 MJ/L LHV) is 65%-71% as energy dense as most oxygenate-free gasoline by volume (E. Christensen et al. 2011), and approximately 62% as energy dense by mass. As a result, 150% as much ethanol must be delivered to customers to meet the same quantity of energy demand that would otherwise be met with gasoline, as the fuel economy for various ethanol–gasoline blends tends to be commensurate with the energy content of the fuel (US GAO 2011). 1- and 2-butanol (at

26.9 and 26.7 MJ/L LHV) have 82%-89% (v/v) (E. Christensen et al. 2011) of the energy density of gasoline (roughly 76% by mass), so this problem will be less severe if butanol becomes economically viable.

2.3.3.1.2 Hygroscopicity

Water will quickly mix into ethanol–gasoline fuels upon contact, degrading fuel quality and potentially leading to ethanol–gasoline phase separation (Szklo et al. 2007). Phase separation has occurred at 0.4% water in E10 fuel blends, but not until 2.5-5.5% water for Bu16 blends (Ryan et al. 2011).

2.3.3.1.3 Corrosivity

Internal corrosion of materials (in pipes, tanks, gaskets in fuel lines, etc.) may occur when using ethanol–gasoline blends, especially if water is present (Zamarin 2007), though a recent study found no signs of corrosion on unstressed metal samples with ethanol blends (Kass et al. 2011).

Stress corrosion cracking (SCC) of steel from ethanol–gasoline blends has been found in the United States, especially when dissolved oxygen or chlorides are present (Beavers and Sridhar 2007). No SCC problems were found in neat butanol or with gasoline blends containing 12.5% or 50% butanol (Ryan et al. 2011).

2.3.3.1.4 Solvent and surfactant properties

Ethanol can dissolve and mobilize gums, inhibitors, and other contaminants in contact with fuel (Zamarin 2007). Ethanol blends have caused elastomeric swelling and degradation problems with (standard) sealants (Kass et al. 2011), but iso-butanol blends were found to cause less elastomeric material degradation than gasoline alone (Ryan et al. 2011).

2.3.3.1.5 Biodegradability

Plumes of ethanol from leaks and spills pose little risk to water supplies and degrade quickly (Fernandez and Keller 2000), though ethanol may increase the mobility of other hydrocarbons if dissolved oxygen is depleted (US EPA 1999). Neither ethanol nor butanol is expected to (alone) cause drinking water contamination problems comparable to MTBE, as both are readily degradable and have a much higher odor and taste threshold than MTBE (Butamax Advanced Biofuels et al. 2010).

2.3.3.1.6 Volatility

Use of low-level ethanol–gasoline blends have long been known to have greater fuel vapor losses than gasoline, and ethanol has a higher ozone forming potential than would be found with gasoline alone (US EPA 1999). In addition to the loss of fuel vapors through tank breathing and filling losses, permeation of ethanol through fuel lines and tanks is a significant source of vapor losses (because ethanol's molecular weight is lower than most molecules found in gasoline) (US EPA 2010d).

Even though environmental agencies have increased the maximum allowable vapor pressure for ethanol–gasoline blends, the volatility concern has put pressure on refiners and blenders to reformulate gasoline to reduce evaporative losses from finished products; this concern is also a challenge for evaporative emissions capturing devices (e.g., carbon canisters), which were found to be less effective for ethanol than gasoline (Martini et al. 2007). Butanol has a much lower volatility than ethanol, and therefore is less of a concern for volatilization emissions; however, blending butanol with low vapor pressure gasoline in cold climates may lead to start up and drivability problems (E. Christensen et al. 2011).

2.3.3.2 List B: Concerns related to infrastructure, scale, seasonality, geography and fuel markets

2.3.3.2.1 Crude oil is extracted almost continuously; biomass is harvested seasonally

The annual coefficient of variation for monthly crude oil production has only exceeded 5% twice since 2000 (adapted from (US EIA 2011a)), and the seasonal factor for motor gasoline demand remained within the range 0.93-1.05 from 2000-2006 (Morris 2007). Miscanthus, however, is expected to be harvested for only four months out of the year (including inactive harvest days due to inclement weather) (Shastri et al. 2010), so most equipment will be sitting idle for more than two-thirds of the year. For comparison, natural gas is produced at near full capacity year-round, but monthly consumption doubles in the winter time (NPC 2007).

Although a four month harvest season enables higher equipment utilization than is possible for food-based biofuel crops (e.g., 2 weeks for corn), biomass handling equipment will still be utilized fewer hours per year than oil industry equipment; additionally, unlike with energy-dense petroleum feedstock, much of the energy used for handling biomass is essentially used for moving water, air and oxygen. Initiating harvesting earlier in the autumn (i.e., before senescence and in-field drying take place) will result in greater energy recovery, reduced storage costs, and may improve equipment utilization, at the expense of handling more water weight and removing nutrients that would otherwise be returned to the roots and soil (which may compromise growth in subsequent years) (Shastri et al. 2010). Harvesting in the spring increases the risk of losing biomass to weathering and biodegradation. Cooperative ownership of feedstock handling, transporting equipment and storage facilities may increase access to, and utilization of, the best equipment and practices.

2.3.3.2.2 Crude oil can be stored for years; biomass and ethanol have a short "shelf life"

Crude oil can and has been stored for decades in tanks and salt caverns (as part of the US Strategic Petroleum Reserve (SPR)). Neither petroleum products such as gasoline and diesel, nor biofuels such as ethanol (or butanol or biodiesel) are recommended to be stored for longer than a year. However, biomass cannot be stored as securely as crude petroleum. The agricultural sector operates with the risk that crops may be totally lost to pests or bad weather, which is unlikely to happen to crude oil unless a catastrophic accident occurs. However, unlike agriculture, the oil industry invests heavily in exploration and development of wells that may never produce; it is unclear if the risk of not achieving expected feedstock production levels (e.g., return on investment) will remain higher for petroleum or biomass.

2.3.3.2.3 Petroleum refineries typically have a liquid fuel production capacity more than twenty times that of biorefineries; construction of cellulosic biorefineries is currently several times more expensive per unit of capacity

The median petroleum refinery receives 81 thousand barrels per day (US EIA 2011a); assuming 46% of the volume of petroleum product leaving refineries is gasoline, the median refinery produces 71 trillion btu of gasoline per year. In contrast, the median ethanol biorefinery constructed by 2011 only has the capacity to produce 56 million gallons per year (RFA 2011), 3.65 thousand barrels per day, or 4.8 trillion btu per year (i.e., 7% of the gasoline output from the median petroleum refinery).

The highest cost estimate found in the literature for a complete petroleum refinery was $25,000 per BPD ($1.60 per annual gallon) (Handwerk and Gary 2001), though petroleum refineries have recently been constructed outside the United States for as little as $10,000 per BPD. In contrast, the 2006-2030 average capital investment required for production, conversion and distribution of corn-based ethanol was estimated to be just over $2 per annual gallon of capacity (T. West et al. 2009), whereas refining costs alone for cellulosic ethanol have been estimated at $6 per annual gallon of capacity (Randle 2010), and the latest NREL biochemical pathway model for ligno-cellulosic ethanol production suggests that biorefineries will cost approximately $7 per annual gallon of production (Humbird et al. 2011).

Assuming the fraction of capital costs dedicated to equipment and materials is relatively consistent across different scales of construction projects, the construction of biorefineries is likely to remain more energy and material intensive than petroleum per unit energy output for many years, as long as the high cost of feedstock transportation prohibits construction of biorefineries at a scale comparable to petroleum refineries.

2.3.3.2.4 Petroleum refineries have access to efficient distribution infrastructure; biorefineries are remote from infrastructure and customers

Pipelines throughout the supply chain for petroleum products have been estimated to add only $0.0066/L to the price of gasoline (AOPL 2011), and shipping crude from as far as the Persian Gulf or distillate from Europe to the US costs less than $0.02/L in 2009 (PetroStrategies, Inc. 2011). The overall cost of transporting petroleum fuels from refineries to fueling stations was estimated at $0.008-$0.013/L (US GAO 2007), whereas NREL estimates the typical overall cost of transporting ethanol from production plants to fueling stations to ranges from $0.034-$0.048/L – a factor of four greater.

More than 92% of US ethanol is produced in the Midwest (PADD 2), where less than 30% of US finished gasoline is consumed (US EIA 2011a). Efficient fuel distribution infrastructure components (e.g., pipelines, terminals, rail spurs) are not available close to many biofuel producers, and of more than 1,350 fuel terminals in the United States (US IRS 2011), only a few dozen can receive ethanol by rail or barge ("Energy Supply Logistics" 2011). Although butanol is often regarded as chemically similar enough to gasoline to make it safe to ship via petroleum pipeline, and is therefore referred to as a "drop-in" fuel, it is also expected to be produced at retrofitted existing ethanol facilities (e.g., (Ryan et al. 2011)) which are predominantly in the Midwest. As a result, opportunities to transport butanol (or eventually "biogasoline") by pipeline to petroleum blending terminals will be very limited in the near term.

As a result, it is much more energy intensive and costly to move feedstocks and biofuel than the petroleum counterparts, though state and federal policies have historically incentivized the dispersed consumption of ethanol. Additionally, the cost of constructing new infrastructure adds to these costs. Assuming infrastructure is well utilized, the required investment in tanks, local rail spurs, retail stations, etc. was expected to add just under $0.01 per ethanol gallon for E10, but $0.05-$0.07 for E85 in 2002 (Reynolds 2002a).

In 2010, a DOE report to Congress projected the ethanol demand in the northeastern US that would be needed to justify construction of a dedicated 1,700-mile 25-inch diameter ethanol pipeline from the Midwest to the Northeast with an economic lifespan of 40 years (US DOE 2010); assuming construction costs exceed $3.75 billion (without subsidies), the pipeline can only compete along this route with current intermodal transport ($0.05/L) if demand exceeds 4.1 billion gallons in the northeast, which will not happen unless blends greater than E10 become widespread (US DOE 2010). As a result, truck and rail are expected to continue dominating the transportation of ethanol. Both modes tend to be more expensive, energy intensive, and polluting than the ocean tankers and pipelines that dominate transportation of petroleum. As importantly, emissions along highways and railways are likely to pose a greater risk to human health than emissions from ocean tankers and the power plants that provide electricity for pipeline pumps, as most emissions from tankers and power plants take place remote from human populations.

2.3.3.2.5 The US gasoline market is (nearly) saturated at the E10 blend wall

The United States already has the capacity to produce enough ethanol to exceed 10% (v/v) of consumed motor gasoline, and from 2010-2011 began exporting more ethanol than is imported. If all existing ethanol production facilities were converted to produce butanol, approximately 60% more biofuel (by energy) could be absorbed into the gasoline market without requiring the blend wall policy to change for several more years. Butanol is currently permitted to be blended up to 11.5% (v/v) with gasoline (Schulz et al. 2011; US DOE AFDC 2009), allowing it to be considered "substantially similar" to certification fuel (without a Clean Air Act waiver).

2.3.3.2.6 Retail stations everywhere sell petroleum fuels; stations struggle to justify offering mid- and high-level biofuel blends

Despite the recent EPA waiver to allow fuel retailers to sell E15 to vehicles manufactured after 2001 (US EPA 2011a), few retailers are expected to sell blends greater than E10 in the near future. In fact, of the 160,000 fuel retail stations in the United States (Reid 2010), fewer than 3,000 sell blends greater than E10 (US DOE AFDC 2011). Retailers will not dedicate a "spare" tank to E15, nor will they purchase adjustable fuel dispensers to accompany an ethanol-only tank, without sufficient financial incentives. The gross margin to fuel retailers was only $0.12 (and net margin $0.06) on a per-gallon basis in 2010 (Reid 2010). If a similar margin would be expected for ethanol, and a 4,000 gallon ethanol tank and dispenser costs $100,000 to install (Protec Fuel 2010), a retailer may not invest in a new ethanol tank unless they are certain the tank will be filled more than 400 times in its lifespan.

Even if there is no need for retail stations to install a new fuel tank for ethanol, one industry group estimated that it could cost almost $10 billion to enable all US convenience store retail stations to sell E15, as current dispensers (valued at $20,000 each, averaging four per store) are not, and cannot be, approved by Underwriter's Laboratory (UL) to sell blends higher than E10 without product liability reform (NACS 2011b). Limiting the liability of marketers selling blends higher than E10 has made it to the list of top 2011 legislative priorities for the Society of Independent Gasoline Marketers of America (SIGMA). The US GAO also mentioned that the OSHA requirement for all dispensing equipment to be certified to handle the specific product will be a challenge, as UL "does not recertify equipment that has already been certified to an existing UL standard", nor does it "retroactively certify manufactured or installed equipment to new safety standards" (US GAO 2011). Additionally, some components of existing E10-certified dispensers were found to have problems when using higher blends (US GAO 2011), so retroactive certification may not be technically appropriate even if bureaucratic challenges are removed.

Approximately 25% of light-duty vehicles were manufactured prior to 2001 and are not permitted by US EPA to use E15, and the owner's manuals for at least ten large vehicle manufactures do not permit blends greater than E10 in cars manufactured as recently as 2010 (Kelly 2011). Without an unprecedented rapid turnover of older vehicles, legal reform for fuel dispensers, and warranty changes from vehicle manufacturers, it is unlikely that E15 will soon be sold as the default motor gasoline at retail stations that are unable to offer E10.

2.3.3.2.7 High-level ethanol blends are only available to a small fraction of gasoline consumers

The United States contains fewer than 10 million FFVs (US DOE AFDC 2011) (of more than 250 million registered vehicles (US DOT BTS 2010)), and FFVs have not made more than 10% penetration in any single county (Moriarty et al. 2009). Only 2,475 E85 stations could be found throughout the country in 2010 (E85 Vehicles 2011), for a US average of approximately 3,500 FFVs per E85 station. This ratio varies from less than 400 in South Dakota and Minnesota (where state subsidies are strong) to more than 76,000 in Massachusetts (Protec Fuel 2010). If the $100-$200 manufacturing premium on flex-fuel vehicles (Anderson and Sallee 2009) is allocated to each E85 dispenser in a state, the investment[12] attributed to manufacturing FFVs in Midwestern states is comparable to the investment in constructing each E85 fuel tank and dispenser (i.e., $100,000), whereas up to $15 million has been invested in FFVs for each E85 dispenser in Massachusetts. In contrast, the average ratio of vehicles to conventional retail stations is closer to 1,600 for the 256 million registered highway vehicles in 2008 (US DOT BTS 2010) with access to 160,000 conventional retail stations in 2010 (Reid 2010).

The lower energy density of E85 in comparison to gasoline requires E85 consumers to purchase fuel more frequently. E85 consumers may also drive out of the way a slightly farther distance than gasoline consumers to purchase E85, due to the lower spatial density of E85 merchant retail stations and potentially greater fuel loyalty to ethanol. As a result, the amount of fuel consumed in E85 purchasing errands may be significantly more than is consumed in gasoline refueling errands (leading to slightly higher GHG and air pollutant emissions), as discussed in the Appendix Section 10.2.5.

[12] Note: this "investment" is partially subsidized by the corporate average fleet economy (CAFE) credit that auto-makers earn for each FFV (Anderson and Sallee 2009).

2.4 US Ethanol Distribution Models

Many existing models and statistics address how ethanol has and will move around the country. Prior to applying existing estimates regarding distances and mode choice, or creating new distribution network models, a summary of existing models and data on ethanol distribution around the United States was completed.

2.4.1 US Ethanol Mode Split

According to a 2006 survey of corn ethanol plant owners performed by the Renewable Fuels Association and analyzed by Argonne National Laboratory, 25-26.3% of ethanol is shipped by truck, 66-73.7% is shipped by rail, and up to 9% of ethanol from wet mills is shipped by barge (M. Wu 2008). In the 2007 commodity flow survey (CFS),[13] ethanol (UN 1170) was shipped 44% by truck (for 11% of total tonne-km), 43% by rail (for 63% of total tonne-km), and 13% by a combination of truck and rail (for 26% of total tonne-km), but statistics on water and pipeline transport were not reported because they did not meet publication standards (US Census Bureau 2010). The commonly used GREET model estimates that 40% of ethanol is expected to be moved by barge, with rail and truck making up the remaining 40% and 20%, respectively (US DOE ANL 2010).

More recent estimates from the DOE suggest that ethanol is transported predominantly by rail and truck (66% and 29%), with barge transport accounting for 5% of shipment volumes (US DOE 2010; US GAO 2011). In summarizing the ethanol distribution projections modeled by Oak Ridge National Lab, the EPA created several scenarios for ethanol distribution in 2022. In each of the scenarios, the average mode share by t-km consisted of 1-2% long-haul truck, 90-91% rail, 7-8% barge, and 1% local truck (though the percent of shipments handled by each mode was estimated at 7-9% long-haul truck, 32-42% rail, 5-7% barge, and 44-56% short-haul truck) (US EPA 2010d).

2.4.2 US Ethanol Transportation Distances

Of the 19.4 million tonnes of ethanol produced in the United States in 2006, the US Commodity Flow Survey (CFS) only captured shipments of ethanol (classified as UN 1170) totaling 5.3 million tonnes and 7.1 billion t-km (US Census Bureau 2010), for a tonne-weighted average of 1,338 km travelled for each unit of ethanol (though the average shipment length was only 555 km, implying an average of 2.4 legs between origin and destination). According to a CFS expert at the US DOT, the majority of ethanol may not have been captured in the CFS because most agriculture is out of scope, and ethanol may take on a different commodity code after being denatured; it is unclear if the data captured by the CFS has a bias towards certain lengths or modes of ethanol shipment.

In a hypothetical 19 billion liter (5 billion gallon) ethanol scenario, in which existing corn facility locations were presumed to accept switchgrass as a feedstock, employing the cheapest combination of truck and rail in order to satisfy an E5 target in 271 of the 273 metropolitan statistical areas

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[13] According to the CFS description of tonnage (as reported), "for freight shipments to distribution centers for subsequent redistribution, the tonnage is counted each time the goods are transported in the production and consumption cycles" (US Census Bureau 2010), so tonnes are not "conserved" in the physical sense in this metric and may be double-counted.

(MSAs), the average ethanol transportation distance from biorefinery to retail station was estimated to be 1100 km (Morrow et al. 2006). In a more recent optimization paper projecting corn and cellulosic ethanol distribution in 2022 (with significant penetration of FFVs), ethanol was only projected to be transported 430 km or less in each scenario (Wakeley et al. 2009).

After assuming that biomass feedstock is transported on average 64 km (40 miles) from to biorefinery, the GREET model estimated an average distance in between these two optimization efforts, at 875 km on average between rail, barge, and truck transport (US DOE ANL 2010). In 2010, the US EPA created models for ethanol distribution and consumption in 2022 (as part of the impact analysis for the Renewable Fuel Standard), in which the average tonne of ethanol was assumed to be transported between 850-1,650 km in the various scenarios considered (US EPA 2010d).

3 REVIEW OF FREIGHT AND FUEL LCA LITERATURE

In 2008, fossil fuel combustion from transportation made up 30% of US CO_2 emissions, and 26% of all GHG emissions (US EPA 2010a), and a large portion of air pollutant emissions as well. The EPA estimates that freight transportation makes up 29% of all transportation GHG emissions, though freight growth has contributed to 47% of the increase in transportation emissions since 1990 (US EPA OTAQ 2010). These numbers are underestimated because life-cycle emissions associated with fuel production are not internalized, but are categorized separately as industrial activity. Additionally, pipeline transport was omitted from EPA's inventory of freight GHG emissions, even though pipelines moved 558 billion ton-miles of petroleum crude and products in 2007 (AOPL 2011), which was equivalent to 15% of the BTS CFS's reported total of 3,491 billion ton-miles of freight in 2007. In 2001, liquid petroleum pipelines (40 million barrels per day, or 4 trillion barrel-miles) represented about 17% of all freight transported in the United States, yet the cost of doing so amounted to only 2% of the nation's freight bill (Pharris and Kolpa 2008). Although government statistical databases need boundaries for classifying emissions and freight activities, these examples highlight that petroleum is more significant as a freight commodity and as a source of GHG emissions than could be immediately determined by reviewing US statistical reports.

Due to the lack of easily available and comprehensive emissions reports on specific products and services, a significant body of literature supporting my research has been developing over the last few decades to quantify the life-cycle energy and environmental impacts from transportation services and fuels. Studies on freight and passenger transportation often are motivated by goals to reduce transportation costs and emissions by improving upon a) logistics of existing modes (e.g., congestion reduction, utilization improvement), b) by shifting goods and passengers to a different mode (e.g., from truck to rail or water transport), or c) by improving technology (e.g., more fuel efficient or cleaner-burning engines). Additionally, life-cycle emissions fossil and alternative fuels for transportation have also been researched for decades, though emphasis is typically placed on feedstock production and conversion to fuel products.

The following subsections summarize the key publications and models related to life-cycle emissions estimation for freight transportation modes and alternative fuels, and this section closes with a summary of gaps identified that influenced research priorities throughout this dissertation.

3.1 LCA Background

While the number of "life-cycle" studies is increasing each year, many published reports are restricted in scope; results are often limited to the inventory phase (without carrying out an impact assessment), or else global warming potential (GWP) is the only impact evaluated with the assumption that GHGs are the only contributor. These two issues are addressed in the LCA Requirements and Guidelines document, ISO 14044:2006(E).

> "An LCI study alone shall not be used for comparisons intended to be used in comparative assertions intended to be disclosed to the public. . . . It should be recognized that there is no scientific basis for reducing LCA results to a single overall score, or number." (ISO 2006)

Traditionally, the most common form of LCA used in evaluating fuels and other products is considered attributional LCA (ALCA), and entails accounting for all activities related to raw material collection, conversion, distribution, and consumption. Over the past few years, many ALCA studies of biofuels have enabled much of the public to become aware that ethanol produced from corn is fossil energy intensive, polluting to the water and air, and may also lead to depletion of soil organic carbon (SOC) on previously uncultivated land. Such conclusions have been typically been made without accounting for construction and operation of distribution infrastructure.

A problem that has emerged in regulating and evaluating biofuel environmental impacts has been that many impacts occur in sectors and regions outside the physical scope of the study, typically due to the economic response in one sector to disruptions in the scale of activities within another sector. Such findings would not be captured in an ALCA, but are often addressed in consequential LCA (CLCA) studies which aim to account for the consequences of a decision, typically by performing "system expansion" and focusing on marginal production activities (Ekvall and B. P. Weidema 2004). Many CLCAs have suggested that the indirect macroeconomic impacts of biofuels contribute towards deforestation (via "indirect land use change," or ILUC), increased costs of agricultural land, and increased costs of food commodities, which adversely impact the environment and the purchasing power of many impoverished people around the world. While the value of these insights into market-mediated effects has been significant, the impacts of fuel distribution infrastructure construction and operation has been as overlooked in CLCA studies as with ALCA studies.

3.2 Life-cycle Fuel Studies

As has been mentioned before, the cost and energy inputs required to store and distribute feedstocks and finished fuel products often represent a small fraction of the total supply chain "footprint," and are therefore often simplified and approximated. The following subsections summarize how feedstock and fuel distribution have been estimated in previous large-scale efforts to quantify supply chain emissions of transportation fuels.

3.2.1 NETL

A comprehensive report on petroleum fuels showed that pre-combustion (i.e., "well-to-tank" (WTT)) activities, including extraction, refining and distribution, contributed on average 20%, 19%, and 16% towards the life-cycle (i.e., "well-to-wheels" (WTW)) GHG footprint of gasoline, diesel and jet fuel in the year 2005; however, this percentage can range from approximately 10% to 30% (11.8 to 37.5 kg CO_2-e/MMBTU LHV) (US DOE NETL 2008), and total WTT emissions can vary by a factor of two. Of total life-cycle GHG emissions, the contribution of storage and transportation activities rarely exceeds 3% for petroleum fuels (US DOE NETL 2008). While this report was extremely thorough, it did not include infrastructure, as "[a]ll operations are considered pre-existing; therefore, no construction related emissions are included within the scope of this study" (US DOE NETL 2008).

3.2.2 GREET

The most commonly used tool for assessing the greenhouse gas and air pollutant footprint of various transportation fuels is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, which was first published in 1996. As can be seen in Figure 13, GREET clearly specifies the boundaries of analysis in both the "Fuel Cycle" Series 1 (currently 1.8) and "Vehicle Cycle" Series 2 (currently 2.7) of the model. The term "cycle" is used to emphasize that neither model serves as a full "life-cycle" model, but do serve as cumulative calculators of operation stage emissions throughout the production and/or use cycle. Although Series 2 captures the life-cycle emissions of consumer vehicles, and Series 1 includes some embodied emissions from farm equipment and feedstock storage facilities, neither model captures the embodied emissions from construction of infrastructure and manufacturing of equipment that support the production and distribution of conventional or alternative fuels.

Many of the feedstock and fuel transportation assumptions in the original GREET model were based on a paper published in 2000 (D. He and M. Q. Wang 2000). In order to more accurately account for transportation of fuels (specifically within the maritime industry), many of the original energy intensity and emission factor values from GREET were updated in creating the TEAMS model (Winebrake et al. 2007a). Although a new version of TEAMS has not been released, transportation energy and emissions values have been updated in the latest GREET model version.

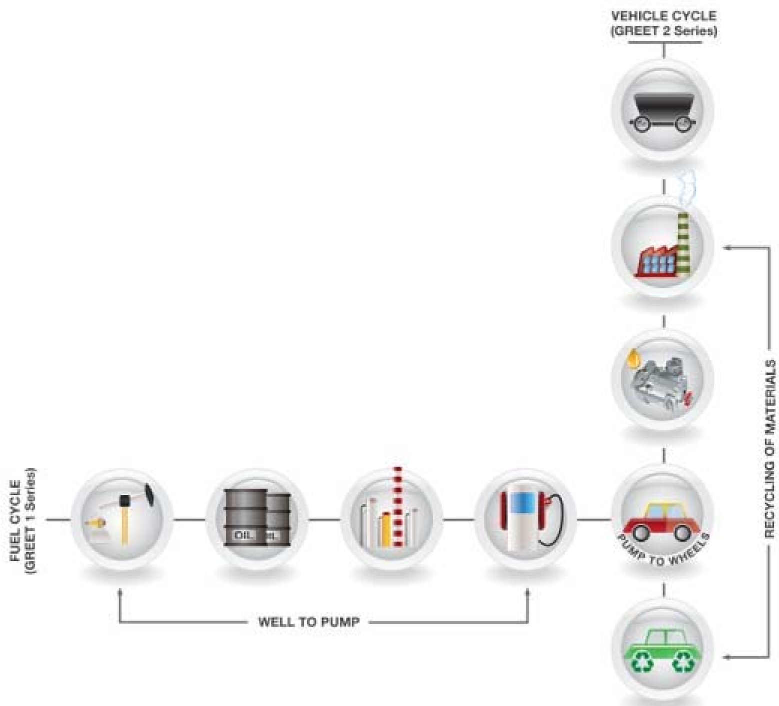

Figure 13. Scope of the GREET Model (reproduced from (US DOE ANL 2010))

It should be noted that many of the modal energy intensity values in GREET (and TEAMS) rely on national average statistics (e.g., rail and pipeline), though significant variation in energy and emissions intensity exists within these modes. Additionally, in creating emission factors (typically normalized to fuel energy content), GREET uses maximum allowable policy values, instead of data from actual experiments. Fuel-based emission factors estimated from in-use monitoring of mobile sources often exceed results obtained from US EPA models (e.g., MOVES, Mobile6, NONROAD) and national emissions inventory (NEI), while EPA has also overestimated other emissions (e.g., off-road NO_x and $PM_{2.5}$) (Dallmann and Harley 2010). More representative emissions estimates for fuel transportation could be obtained by applying fuel-based emission factors to transportation modes specific to carrying liquid fuels.

3.2.3 LEM

The Lifecycle Emissions Model (LEM) developed at UC Davis "estimates energy use, criteria pollutant emissions, and CO_2-equivalent greenhouse-gas emissions from a variety of transportation and energy lifecycles." (Delucchi 2003). LEM also captures the dispensing (pumping) of liquid fuels, transport and shipment of fuels to end users, operation of bulk-service facilities, and a country-by-country accounting of feedstock transportation (e.g., from wellhead to refinery). Additionally, it includes "the manufacture and transport of raw and finished materials used in the construction of highways, railways, etc., as well as energy use and emissions associated with the construction of the transportation infrastructure," though currently "represented crudely" (Delucchi 2003).

In its closing discussion, the caveat is made that LEM "includes emissions associated with materials manufacture and assembly for vehicles, trains, and ships, [but] it does not include emissions associated with materials used for large construction projects such as power plants and refineries. Although generally these emissions are small compared to the emissions from fuel production and use (especially end use), they might add nontrivially to some fuel cycle totals" (Delucchi 2003).

Although the write-up of the LEM model acknowledges most of the activities of interest to my research, its analytical emphasis is focused on operation stage emissions, as the assumptions and data for infrastructure were very limited in the extensive (more than 400 page) model write-up.

3.3 Evaluation of Freight Modes

3.3.1 Freight Transportation as Embodied Energy in Products

Because the energy intensity of commodity transportation varies due to material properties and characteristic shipping distance, Vanek and Morlok created an insightful model using data from 1993 US input-output tables and the commodity flow survey (CFS). They estimated that freight transportation can make up a substantial portion of a product's life-cycle energy footprint – equivalent to 70% of the production energy for apparel or lumber/wood products, but only 7% for pulp/paper (Vanek and Morlok 2000). When accounting for the embodied energy of biomass received at the biorefinery gate, farm-to-biorefinery transportation can make up 3-5% for corn and oil seeds and 7-26% for ligno-cellulosic feedstocks ((Richard 2010), citing other studies), which is much higher than the 3% or less estimated for US petroleum (US DOE NETL 2008).

3.3.2 Life-cycle Comparison of Modes[1]

Few existing studies account for infrastructure assets in comparing externalities from freight distribution modes (e.g., (Facanha and Horvath 2007; Forkenbrock 2001; Frischknecht et al. 2007; Kruse et al. 2009; Spielmann and Scholz 2005)). While some mode-specific studies account for the vehicle-cycle of shipping fleets (Gratsos et al. 2009; Lindstad et al. 2011), most studies only address fuel use and associated emission impacts (van Essen et al. 2003; Kristensen 2002; Psaraftis and Kontovas 2009; Vanek and Morlok 1998; Winebrake et al. 2008).

In 2005, comprehensive life-cycle emission factors (in units of pollutant emissions per mass-distance) for road, rail and barge transport of freight were created for Europe (Spielmann and Scholz 2005), and in 2006 life-cycle emission factors were first developed for road, rail and air transport of freight in the United States (Facanha and Horvath 2006). Both studies account for infrastructure construction, vehicle manufacturing, operation, maintenance and disposal into the transport stage of a product (amortizing environmental releases over each ton or ton-mile of transported product). Results of both studies showed that vehicle manufacturing and infrastructure construction can contribute significantly to the life-cycle emissions of GHGs and pollutants such as PM, VOCs, and NO_x.

While very insightful, the Facanha and Spielmann studies were designed to evaluate freight goods, and a similarly thorough study for liquid fuels has not yet been conducted. Pipeline and ocean transport of goods, which are responsible for most of the mass-weighted distance traveled by petroleum, has not yet been scrutinized in this framework. As petroleum requires specialized equipment, and its infrastructure is often utilized year-round for several decades, the profile of environmental impacts attributed to fuel distribution will differ substantially from average freight. In an older study of truck and rail transport of various commodities in 1993, the transport of petroleum by truck was shown to be 80% as energy intensive as trucking the average commodity (2092 kJ/t-km), and transporting petroleum by rail was found to be 117% as energy intensive as the average commodity (284 kJ/t-km) (Vanek and Morlok 1998).

Additionally, infrastructure-related emissions were typically amortized into the functional unit of freight shipment (i.e., ton-miles or tonne-km) in both studies, which requires an assumption that infrastructure will be utilized as intensely and for as long as was typical in the past. This attributive approach to LCA implies that each marginal shipment causes wear on the infrastructure, which is not necessarily true. Additionally, it does not best equip a decision-maker to choose between distribution pathways which a) require a completely new system of infrastructure to be built (with considerations for risk of obsolescence), and/or b) require negligible utilization-induced maintenance (e.g., waterways) for each marginal shipment, which may be increased with more intelligent logistics.

It is also important to note that modes cannot be adequately compared by emission factor alone. Even when one available mode appears to be competitive with the less efficient mode for a particular route (after factoring in actual case-specific path length, grade changes, predicted congestion, etc.), the amount of potential mode-shifting is often limited by practical constraints (e.g., cost, transit time, reliability, and risk of loss and damage (ICF International 2009)), or financial barriers (including utilization risk) to constructing new infrastructure on a particular route. For example, in a recent corridor study of the I-81 in Virginia looking out to the year 2035, a feasible diversion of only 5-10% of truck traffic to the rail system was estimated in the high case (VDOT and US DOT FHWA 2005)

3.4 Life-cycle Inventory Databases

3.4.1 EIO-LCA

In the US and a few other countries, economic input-output matrices have been tied to sector level environmental emissions and releases in the EIO-LCA tool, which enables users to estimate the average emissions that result from a specified level of economic activity within a sector. It is relatively easy to find national average prices for commodities and services, and average trade and transportation data for various commodities. Statistical databases (e.g., the US Census and BTS Commodity Flow Survey) enable researchers to find average input values for models, without adequately representing variability in costs, materials and resource intensity for each activity.

While most biofuel LCA papers use GREET emission factors for supply chain activities, some have estimated transportation emission factors by inputting freight rates into the EIO-LCA tool (e.g., (Wakeley et al. 2009). While EIO-LCA offers a comprehensive inclusion of all supply chain emissions (including infrastructure) associated with shipping products by different modes, sector-level activity is overly aggregated and does not include subsidized investments in maintenance and infrastructure improvements.

3.4.2 Ecoinvent

Ecoinvent, which is a commercial for-purchase life-cycle database published by the Swiss Centre for Life Cycle Inventories. This is the most commonly used commercial life-cycle data inventory, and contains comprehensive modules that include the construction, manufacturing, operation and maintenance of most major components of fuel and other freight storage, handling and freight supply chains, including the five modes of fuel transportation that are addressed in this dissertation (truck, rail, barge, ship, and pipeline). Both direct emissions (i.e., from operations) and supply chain emissions (i.e., vehicle production, maintenance and disposal; infrastructure construction, maintenance and disposal; fuel extraction and production) are allocated based on the aggregate average service (e.g., tonne-kilometers) in a given region (typically Europe or a single country) and utilization of equipment.

While Ecoinvent publishes data in a format that is very simple for users to incorporate into models with commercial software such as SimaPro, many process output values resulted from limited case studies (or national statistics) that may be inappropriately applied by practitioners. As a result, the degree of resolution (and perceived representativeness) for the different modes varies tremendously: Sources of data published in Ecoinvent are of varying age, geographic specificity, and equipment representativeness, rarely were generated using US data, and are not freely available to the public. Whenever possible, differences between the emissions estimates reported in this dissertation and those reported by Ecoinvent are discussed in Section 10.2.

3.5 Gaps Addressed in this Dissertation

Gaps identified in the freight and fuel LCA literature primarily relate to shortcomings in transportation sector emissions inventories, emission factors for liquid fuel transportation modes, and fuel life-cycle emissions values. The most well recognized LCA modeling studies on liquid fuels are limited to energy intensive "fuel-cycle" activities throughout the entire supply chain (i.e., extraction/cultivation and harvesting, refining/conversion, transportation, and end-use). It has not yet been substantiated if the construction, operation and maintenance of infrastructure, such as terminals, pipelines, and retail stations, could be significant contributors to the life-cycle environmental footprint of biofuels, petroleum or other alternative fuels. These infrastructure related activities are typically overlooked or only given cursory treatment due to prioritization of fuel-cycle activities, as these stages do tend to dominate the life-cycle costs and environmental emissions of fuels and most other products.

In addition to taking for granted the infrastructure needed for handling and distributing fuels, researchers also often accept rules of thumb distances and modes for transporting fuels. Even in the few cases in which transportation distances are modeled on a case-study or national basis, little evaluation has been done on whether policy influences on the distribution system are optimal.

Specific details from existing literature are most useful if presented in the context of new contributions. For this reason, previously published assumptions and data values will be found throughout this dissertation, when results were built upon the foundation of previous literature or if results warranted comparison to existing modeling results.

4 RESEARCH METHODOLOGY

The first and most time-intensive project of this dissertation consisted of the creation of life-cycle emission factors for various components and activities in the fuel supply chain. When appropriate, the methods employed in the main modeling projects were explained within its own sub-chapter. In order to apply these new emission factors in a manner useful to policy, hypothetical but realistic scenarios were developed in which components were assembled in series or parallel as part of a distribution system for petroleum and biofuels. An inventory of components and their associated emissions was created on a national scale. Lastly, linear optimization was employed in order to estimate the role of various fuel policies in influencing the distance, and therefore cost and air emissions, associated with distributing fuel from production centers to consumers.

While very different types of modeling and analysis were required for each of these projects, a common general framework was used to view each problem with a life-cycle perspective, although a complete life-cycle assessment was not completed at any point in this dissertation. Recommended guidelines for conducting LCA were incorporated into each of the main modeling efforts.

4.1 Goal and Scope

The first step in performing a life-cycle assessment of a product (or service) is the selection of the goal and scope of the system for analysis. For the initial project that entailed characterizing components, the goal of the system was limited to the main functional units of the component being considered. When components were assembled in creating a distribution infrastructure system model, the goal of the system was defined by the functional unit of the (fuel) product delivered to customers.

4.2 Life-cycle Inventory of Environmental Metrics

Once the system has been defined, a life-cycle inventory (LCI) analysis is conducted to quantify the inputs and outputs across the supply chains and life stages of a product, as shown in Figure 14. In this dissertation, the inputs and outputs included in each project varied due to data availability, computational capabilities and relevance to the type of impact being evaluated.

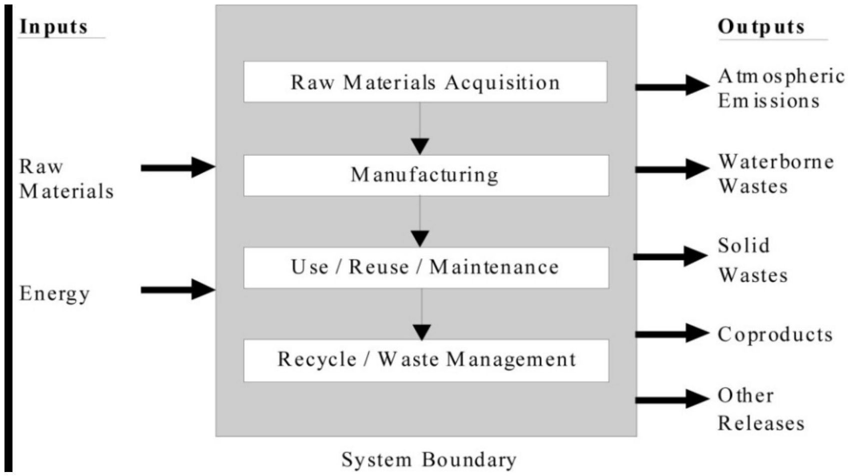

Figure 14. Standard Life-cycle Inventory Diagram (reproduced from (US EPA 1993))

4.2.1 Life-cycle Metrics

GHG emissions reduction goals for the transportation sector are likely to be the most significant environmental policy driver influencing the fate of the biofuels industry. As a result, GHG emissions are the primary environmental metric used in characterizing each activity within fuel distribution systems in a life-cycle framework (i.e., incorporating the infrastructure cycle and fuel cycle). GHG emissions are typically dominated by CO_2 from fossil fuels (CO_2-f) for activities considered in this study, and will be expressed in terms of mass of CO_2-equivalent (CO_2-e)

The EIO-LCA model for 2002 also reports supply chain water withdrawals for materials, equipment, and services, and other literature presents water withdrawals from fuel and electricity production. Because water withdrawals could easily be accounted for in the same manner as GHG emissions, life-cycle water withdrawals were tracked (but not always reported) and normalized to the functional unit of each component (e.g., tonnes handled or t-km). Figure 15 presents the general scope and approach to modeling each activity.

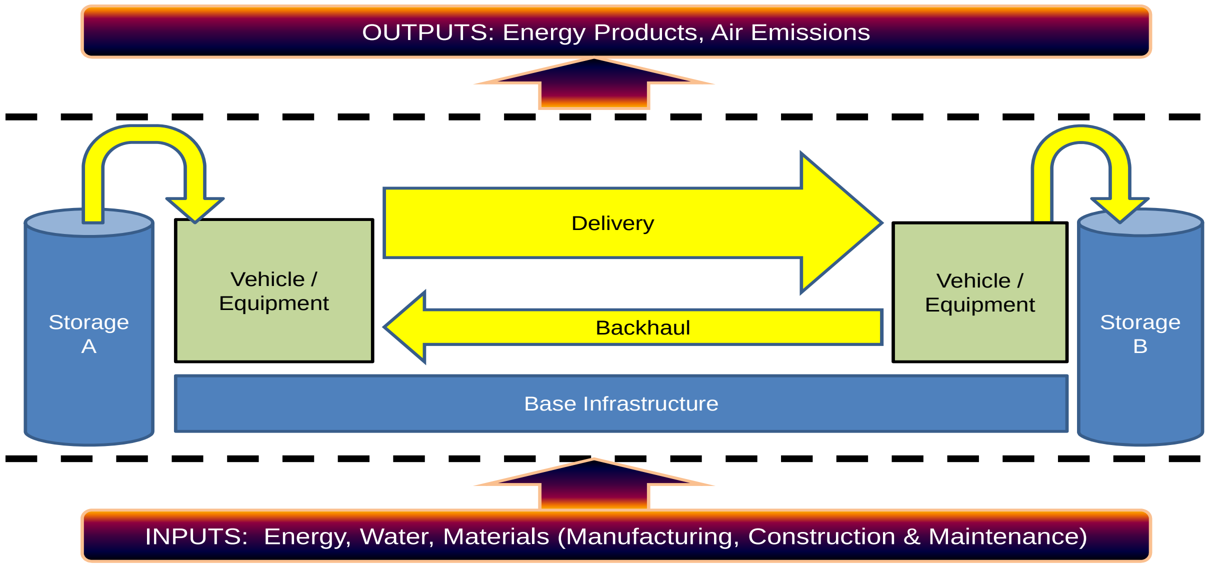

Figure 15. Schematic of Approach and Metrics Employed in this Study.[14]

4.2.2 Operation-only Metrics

Due to the high geographic sensitivity and lack of representative (geographical and process-specific) data, criteria air pollutants will not be reported for manufacturing, construction, and refining processes. Several operation-only criteria air pollutants were inventoried and normalized to the operation-only CO_2 emissions of each component used in handling or transporting feedstocks and fuels, and are described in Table 1.

[14] Yellow = operation activity, Blue = infrastructure, Green = vehicle or equipment, Red = energy, water, and material inputs and outputs from system operation and maintenance

Pollutant	Description
Sulfur Oxides (SO_x)	SO_x is typically emitted as a product from the combustion of fuels containing sulfur. Marine fuel (and to a smaller extent off-road diesel) tends to have the most sulfur of the petroleum fuels. Within electricity fuels, the sulfur content of coal can be quite high, but is typically very low in natural gas. SOx is considered a respiratory irritant and precursor to acid deposition.
Nitrogen Oxides (NO_x)	NO_x is most commonly formed as "thermal NO_x," which results from the reaction of (atmospheric) oxygen and nitrogen in combustion chambers at high temperature (e.g., >1,700K). NO_x is typically emitted as NO and oxidized to NO_2 in the atmosphere. NO_x can react with VOCs in sunlight to form ground-level ozone (O_3), which is a respiratory irritant. NO_x may also contribute to the formation of secondary $PM_{2.5}$, and can contribute to acid rain and eutrophication of water bodies after deposition.
Fine Particulate Matter ($PM_{2.5}$)	$PM_{2.5}$ is defined as particulate matter with an aerodynamic diameter less than 2.5 microns. It can be in liquid or solid form, and results from either primary emissions (e.g., tailpipe emissions of incomplete combustion byproducts such as soot) or secondary formation in the atmosphere (e.g., condensation of the oxidation products of VOCs, NO_x, and SO_x). Within the broader category of PM with an aerodynamic diameter less than 10 microns (i.e., PM_{10}), $PM_{2.5}$ makes up the vast majority of particles from diesel exhaust (e.g., 97% or more) which is the main source of PM considered in this study. Additionally, $PM_{2.5}$ is a significantly greater health concern than larger particles as a respiratory irritant and as a vector to introduce contaminants into the bloodstream, due to its ability to penetrate deep into the lungs.
Volatile Organic Compounds (VOCs)	VOC is the broad term that includes potentially benign volatile hydrocarbons as well as hazardous air pollutants (e.g., benzene), which are typically emitted through incomplete combustion or volatilization of fuels or solvents. Many emissions inventories report total hydrocarbon emissions (HC), which are a large subset of VOCs. VOCs can react with NO_x in sunlight to form ground level ozone (O_3), and may also contribute to the formation of secondary $PM_{2.5}$.
Carbon Monoxide (CO)	CO is a product of incomplete combustion of carbon-containing fuels. CO is most often dangerous as a local-level pollutant (e.g., in households or urban neighborhoods), as CO exposure reduces the oxygen carrying capacity of hemoglobin in red blood cells.

Table 1. Criteria Air Pollutants Included in the Creation of (Tailpipe) Emission Factors.

4.2.3 Metrics not Included

It is important to note that many other metrics for evaluating fuels exist, but were not covered in this study. For example, impacts on biodiversity or water quality, risk of environmental accidents or human injury, emissions of toxic materials, and noise and light pollution are regarded as externalities that are typically not priced into the cost of products and services. However, much like with criteria air pollutants, the severity of these impacts depends highly on the location of activity. As the location is unknown for most activities in the supply chain of the component systems modeled, these activities were considered out of scope.

4.3 Impact Assessment

A complete LCA will qualify the impacts of each product or activity, by applying characterization factors (e.g., intake fraction and toxicity) to the indicators quantified in the inventory (e.g., grams of pollutant).

For the two metrics accounted for and reported in a life-cycle framework, GHG emissions and water withdrawals, two important distinctions should be made.

1. GHG emissions are directly proportional to impact (i.e., global warming potential over a given time interval), whereas the impact of water withdrawals will depend on regional rainfall and access to groundwater and should not be regarded as an impact on their own. As water withdrawals do not necessarily imply long-term removal or reduction in quality of water from the water body source (Scown et al. 2011), water "consumption" (long-term removal from its source) would more closely approximate impact assessment.
2. Additionally, life-cycle GHG emissions from infrastructure and equipment typically contribute less than 30% of total GHG emissions from fuel systems, so sensitivity to changes or errors in supply chain activities is not very significant. In contrast, 100% of water withdrawals occur from supply chain activities, as the operation stage when fuel or energy services are consumed is not associated with water withdrawals.

For the operation-only metrics considered in this study, criteria air pollutant emissions, the location of emissions is extremely important in assessing impacts. While some authors have proposed the use of "archetypal" environmental for categorizing locations based on emissions height, population density, meteorology, etc. (Humbert et al. 2011), this simplification is only helpful if the location of emissions is actually known. The human health impacts from a given quantity of mobile source emissions can range by four orders of magnitude depending on location (Lobscheid et al. 2010), and the actual routes that are used for transporting fuel and feedstocks have not been comprehensively documented. As a result, archetypal routes were used to estimate the significance of route and mode choice on the air emissions impacts.

4.4 Improvement Analysis

The final stage of an LCA entails the interpretation of results into conclusions and recommendations (ISO 2006), for which a comparison to reference case (e.g., "business as usual") is often compared to alternative scenarios, in order to compare the trade-offs from using one product or service over another. An improvement analysis for the national distribution systems entailed performing sensitivity analysis on a few single decisions in Section 6.5. Improvement analysis was also the main focus of the national optimization project presented in Section 7, in which the sensitivity of the entire national distribution system was estimated for alternative policy implementation strategies.

5 EQUIPMENT AND INFRASTRUCTURE COMPONENT CHARACTERIZATION[15]

This section presents a characterization of feedstock and fuel handling, storage and distribution components in terms of functional unit(s), operating performance and life-span activity, and activity-based life-cycle GHG emissions and water withdrawal factors. Additionally, cost factors and air pollutant emission factors are presented for the operation of key equipment and transportation vehicles.

An attributional life-cycle methodology was employed (instead of consequential), in order to understand the baseline emissions inventory on a steady-state basis (i.e., assuming activities are identical year-after-year) without attempting to project marginal consequential impacts. More specifically, a tiered hybrid analysis approach was used (Suh et al. 2004), in which detailed physical data were used as inputs to model energy production and consumption processes, and economic data were used to characterize manufacturing, construction and maintenance activities. The sections below briefly summarize key methodological details. More details on assumptions and data sources for each component can be found in the Appendix.

5.1 Boundary

The activities modeled were limited to fuel and fuel feedstock handling, storage, and transportation. Feedstock production and fuel product conversion activities were ignored. The boundary of fuel distribution chain activities modeled extends from the location of conditioned feedstock to the point where fuel consumers return to their regular route after refueling, as can be seen in Figure 16, which could be referred to as an inventory of "well-to-route" activities. Although the boundary of the fuel distribution system considered in previous transportation fuel LCA studies extends only to the retail station pump, the consumer errand to refuel vehicles is unique to transportation fuels and should be included; though some deployment models for electric vehicles (EVs) incorporate public battery charging or battery switching stations, many involve charger stations where people live or work.

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[15] Some parts of this chapter were reproduced with permission from the American Society of Civil Engineers, after first being submitted for publication in the *Journal of Infrastructure Systems* in 2011 under the title, "Greenhouse Gas Emissions from the Construction, Manufacturing, Operation and Maintenance of US Distribution Infrastructure for Petroleum and Biofuels" (Strogen and Horvath 2012). This article was under review at the time this dissertation was submitted. Other parts of this chapter were reproduced with permission from the American Chemical Society, after publishing the article, "Fuel Miles and the Blend Wall: Costs and Emissions from Ethanol Distribution in the United States," in the journal, *Environmental Science & Technology,* in 2012 (Strogen et al. 2012).

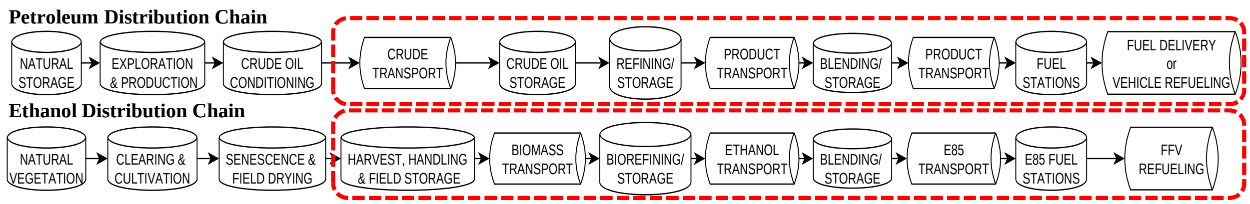

Figure 16. Simplified Schematic of Feedstock and Fuel Distribution Chains for Petroleum Fuels and Miscanthus-derived Ethanol.[16]

5.2 Functional Units

Activity-specific emission factors are presented using the functional unit of t-km for transportation modes, and tonne of throughput for storage and material handling activities. However, the functional units and demand factors for inputs throughout each supply chain are not all mass-based, as some components may be constrained by volume, time, or other units. Additionally, some activities may be considered to have multiple functional units[17] (e.g., tanks enable storage of stock reserves, blending, and dispensing of fuels, and highways serve multiple freight and non-freight activities). Additionally, although the mass density varies between liquid fuels (e.g., residual oil is 30% more dense than gasoline), and even by region and season, the capacity or payload of all components are assumed to be mass-based.

Although the functional units and demand factors for inputs within a system vary, and impacts may vary drastically depending on whether average annual utilization or actual variable utilization are used for an isolated component's activity, all activity-specific emissions will be presented per t-km for transportation modes, and per tonne of throughput for storage and material handling activities. Secondary activities that are more proportional to trip number than trip length (e.g., vehicle dispatching, idling, load transferring, material losses) were allocated to nodes in the distribution chain instead of distance traveled. It should also be noted that other functional units such as land area or vehicle-km travelled may also be worth considering (e.g., if a technology or efficiency difference would be found when using alternative fuels) (Cherubini and Strømman 2011)).

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[16] The functional unit is one tonne of throughput for upright cylinders and one t-km for sideways-facing cylinders; dashed red boxes delineate the study boundary.

[17] The key functional unit offered by an oil tanker is a tonne-km of goods transported, which is strongly correlated with a ship's size, travel time and fuel consumption. However, ocean tankers rely on port infrastructure, for which maintenance and operation efforts are carried out according to the quantity and type of goods (e.g., cargo-transferring equipment) or according to age and weather (e.g., dredging) – all of which are agnostic to the distance cargo has traveled. While it may seem irrelevant to include maintenance that is a function of weather and aging, this infrastructure would not be maintained without a certain level of demand for freight handling. Additionally, most deep draft (e.g., 52 feet) dredging projects were initiated to support large oil tankers, although ships for many types of cargo currently require deep draft ports. This example highlights why, as much as was feasible, the model was not constructed to be entirely deterministic according to the primary functional units of the key component.

5.3 Scope of Component Models

The environmental life-cycle modeling scope for component systems includes emissions from four generalized stages: component operation (direct), fuel production (precombustion), equipment and vehicle manufacturing and maintenance, and infrastructure construction and maintenance. In this model, "maintenance" encompasses activities beyond manufacturing and construction, such as repair, cleaning, (non-energy) material inputs, and infrastructure "renewal" (which is sometimes accounted for as a capital investment). The energy and CO_2-e intensities of all life-cycle stages were informed by literature from the years 2002 to 2010 specific to the United States, and a more detailed explanation of the four life-cycle stages follows.

5.3.1 Operation (Direct or Tailpipe)

All of the equipment used to handle, store, and transport feedstocks and fuel products typically operate with petroleum fuels or electricity as their energy source(s). Activity-based energy intensity values were estimated from existing literature or engineering estimates. Because the functional unit for transportation modes is the t-km, emissions from activities not attributed to physically transporting materials (e.g., vehicle dispatching, idling, load transferring, material losses, fugitive emissions) were accounted for at delivery point storage nodes. The quantity of energy consumed and/or lost during each operation activity was coupled with the emissions intensity of the energy carriers (e.g., electricity, feedstock, or fuel product), in order to estimate emissions from operations. Diesel and residual oil are the primary fuels consumed in the equipment included in this study, so there was assumed to be a negligible amount of GHGs emitted during combustion other than CO_2, as is consistent with previous studies (APTA 2009).

5.3.2 Energy Production (Precombustion)

The quantity of energy consumed and lost in handling, storing or transporting the feedstock or fuel of concern was also coupled with emission factors associated with supplying petroleum fuels such as diesel and residual oil, biomass feedstocks, or electricity to the point of use or loss.

5.3.3 Equipment/Vehicles (Manufacturing and Maintenance) and Infrastructure (Construction and Maintenance)

Supply chain life-cycle emissions specific to equipment, vehicles, and infrastructure were estimated using an approach similar to the reference (Joshi 1999), considered an input-output-based hybrid analysis (Suh et al. 2004). First, capital and maintenance expenditures were converted to 2002 US producer prices and disaggregated into more homogenously defined commodities or industrial sectors defined by the BEA. Direct (foreground) expenditures outside of material and energy intensive sectors (e.g., taxes, labor, and services) were not included. Presumably, these expenses result in supply chain emissions per dollar comparable to the "ideal" minimum baseline of a service-based economy, and/or total emissions from all service sectors would be unresponsive to demand changes from activities considered in this study.

Next, sector-specific costs were multiplied by their emission factor as reported by the economic input-output analysis-based life-cycle assessment (EIO-LCA) tool (CMU GDI 2010), which is a "cradle-to-gate" commodity-by-industry model for the 428 main sectors of the 2002 U.S. economy

(Weber, D. Matthews, et al. 2010). A cost-weighted sum of the emission factors from all contributing sectors was then calculated and normalized to the component's functional unit. Unfortunately, we were unable to find representative bills of materials and records on utilization, maintenance, lifespan, and performance for many components. In these cases, statistics from the US government, industry reports, or rules of thumb from technical experts informed the estimation of these parameters.

End of life of infrastructure and equipment was omitted because railways, ports, waterways, roads, and pipelines are rarely decommissioned (rather than reconstructed), and the environmental impacts from deconstructing and recycling of materials were found to result in less than 0.1% of most life-cycle pollutant emissions in a prior study (Facanha 2006). Additionally, exporting of old vehicles and ships to be used and/or recycled in developing countries can result in highly variable, but potentially significant, environmental and human health burdens that are beyond the scope of this paper. Other considerations omitted include potential emission-intensity changes from economy-wide efficiency improvements since 2002, offshoring of equipment and materials manufacturing, and importing or exporting of products.

5.3.3.1 EIO-LCA EMISSIONS MODELING METHODOLOGY

A common approach was used to characterize the infrastructure and equipment components (tanks, trucks, etc.) that support the storage and distribution of liquid fuels in the United States. After listing the supply chain sectors and associated expenditures involved in supporting the maintenance and replacement of each component over its lifespan, the emissions associated with purchases in each sector were estimated and then totaled for the typical life-span for each component. Lastly, these "infrastructure cycle" emissions were normalized to the functional unit of each component, for easy addition to existing or updated "fuel cycle" emission factors.

5.3.3.1.1 Quantifying and Categorizing Expenditures

Infrastructure and equipment expenditures were disaggregated into more well-defined homogenous industrial sectors (e.g., paint and coating manufacturing). Expenditures were estimated in 2002 dollars, and emissions were determined by entering producer prices into the appropriate sector of the economic input-output analysis-based life-cycle assessment (EIO-LCA) tool (CMU GDI 2010), which was developed as a "cradle-to-gate" commodity by industry model for the 428 main sectors of the 2002 U.S. economy (Weber, D. Matthews, et al. 2010). This step is presented as Equation 1, and the process of estimating the total (infrastructure-cycle) emissions in the life-cycle of a single component is represented in Equation 2.

Activities outside of material and energy flows were ignored (e.g., taxes, labor expenses, services), although emissions from insurance and registration have been previously estimated to contribute more than 2% to total GHG emissions for freight trucking (Lenzen 2000). These service sector activities were neglected in order to facilitate comparison between modes, without penalizing modes that may have high administrative (but low material and energy) requirements. Most service sector activities are presumed to result in emissions per dollar comparable to the "ideal" minimal baseline of a service-based economy and/or total service sector emissions would be unresponsive to demand changes from activities considered in this study. Because the emissions intensity of each sector varies, a good faith effort was made to disaggregate expenditures into several specific sectors, so as to more accurately represent the activity being modeled.

To help ensure that all fixed asset (capital stock) investment and variable (operation and maintenance) expenditure activities and associated emissions were captured, nationwide economic data from the US Bureau of Economic Analysis (BEA) was considered to aid the quantification and categorization of material inputs to four reasonably well-defined transportation mode sectors: truck, rail, water and pipeline. Unfortunately, economic input-output sectors do not exist independently for several activities that are crucial for fuel production and distribution (e.g., constructing refineries, ports and pipelines), as they are aggregated into sectors defined by the US Department of Commerce with significant heterogeneity with regard to financial costs and/or environmental burdens per unit of production. Nonetheless, the carbon intensity of most activities that are economically significant and relevant to this study lie between 400 and 1,600 tonnes CO_2-e/$MM in 2002, so errors associated with poor or overly aggregated assignment of activities to a sector should not drastically compromise the results.

5.3.3.1.2 Purchase-specific Infrastructure and Equipment Emissions ($\mathbf{E_x}$)

$$E_x = \sum_{s=0}^{s=428} P_s^y * (1+r)^{2002-y} * EIOEF_s^{2002}$$

Equation 1. Purchase-specific Emissions (tonnes) or Water Withdrawals (L), Estimated by Summing Life-cycle Purchase-related Emissions from the Specified Life-cycle Stage (using data from 2002 EIO-LCA)

$x = purchase\ stage\ (maximum\ of\ 4\ purchase\ stages\ defined\ per\ component)$

- Purchase stages are categorized as A) vehicle/equipment purchase, B) vehicle/equipment maintenance, C) infrastructure construction, or D) infrastructure maintenance.

$s = economic\ sector\ number\ (428\ economic\ sectors\ existed\ in\ 2002)$

- Most stages were represented by expenditures in less than 6 unique sectors.
- For example, the stage "vehicle maintenance" may include the purchase of tires, paint, etc.

$P_s^y = producer\ purchase\ price\ in\ calendar\ year\ \text{"y"}\ paid\ tosector\ \text{"}s\text{"}\ (\$MM)$

- For expenses less straightforward and deterministic than the purchase of a truck or ship, such as buildings and communication systems, prices were estimated by multiplying average annual industry-wide expenses by the fraction of national functional units (e.g., t-km) provided by a single component throughout its typical lifespan.

$$EIOEF_s^{2002} = 2002\ EIOLCA\ emission\ factor\ for\ sector\ "s"\ (t\ CO_2e\ or\ t\ H_2O\ per\ \$MM)$$

$$r = inflation\ rate$$

- When estimating the price of equipment in 2002 US dollars (for the use of the EIO-LCA tool), an inflation rate of 3% was applied to the cost of goods documented in other years. While more accurate prices could be estimated using industry-specific producer price indices, the results are assumed to be more sensitive to other factors than warrants exact dollar estimation.
- Note: other cost indices such as the chemical engineering plant cost index (CEPCI) were applied to some activities.

5.3.3.1.3 Life-cycle Infrastructure and Equipment Component Emissions ($\mathbf{IE_m}$)

$$IE_m = \sum_{x=A}^{x=D} E_x$$

Equation 2. Total Infrastructure and Equipment Emissions over One Lifespan of a Single Component (e.g., tonnes per truck lifespan)

$m = mode\ or\ component\ type$ (e.g., short-haul truck, underground storage tank)

- These emissions include construction and maintenance throughout a typical lifespan of the component (i.e., and would occur even if the components were directly operated with perfectly "clean" fuel or electricity).

5.3.3.1.4 Deterioration Mechanisms for Infrastructure and Equipment

As much as possible, physically meaningful drivers behind infrastructure or equipment deterioration, obsolescence and replacement were incorporated into the model, as functional units are often not the direct (proportional) demand factor for infrastructure or equipment deterioration and replacement. For example, roads must be repaved largely as a function of the axle loading from freight trucks (which is not a linear function of tonnes transported), and tractors are replaced after operating for a certain number of hours (which is not a linear function of dry weight biomass handled). In these cases, an expression was derived for the marginal increase in emissions-generating activity resulting from a marginal increase in functional unit activity. An example expression that translates emissions from overlaying (repairing) a kilometer of road into emissions from each t-km of freight movement by a specific type of truck is represented in Equation 3, where the demand factor (DF) for road overlaying is the "equivalent single axle load" (ESAL).

$$\frac{\partial E}{\partial t\text{−}km} = \frac{\partial E}{\partial overlay\text{−}km} * \frac{\partial overlay\text{−}km}{\partial ESAL\text{−}km} * \frac{ESAL}{truck} * \frac{truck}{payload(tonnes)}.$$

Equation 3. Relationship between the Functional Unit of Trucks (t-km) and the Demand Factor for Road Deterioration (ESALs), Used to Create an Expression for Marginal Road Repair Related Emissions (E) per t-km (adapted from (Sathaye et al. 2010)).

When maintenance and renewal activities are required for, but do not directly result from, freight activity (e.g., maintaining shipping channel depth), tax systems designed for funding maintenance activities (and not simply generating revenue) provided useful information. For example, fuel taxes for the Inland Waterway Trust (maintenance) Fund were created in order to fairly match the funds needed to support barge shipments, and fuel energy intensity is well correlated with t-km shipped by barge (as the energy intensity of barges per t-km is relatively consistent). Alternatively, instead of a fuel tax to support port infrastructure, port tax schemes are based on product value, dock time, and/or TEUs; all of these units are correlated to tonnage transferred by a given ship, so the emissions from port infrastructure were allocated to tanker ships based on tonnage instead of t-km.

Previously established (or easily regressed) relationships between infrastructure utilization and maintenance investments were not available for all activities, so in most cases fixed asset infrastructure and maintenance expenses were presumed to be proportional to steady-state[18] system utilization (assumed to follow design values).

5.3.3.1.5 Functional Unit-Based Emission Factor Contribution (EF_m^{IE})

Infrastructure and equipment emissions were then normalized (i.e., expressed in proportion) to the functional unit of service that a component delivers throughout a single life-cycle (i.e., before it is expected to require replacement). This is the simplest way to allocate emissions for components such as non-vehicle assets (e.g., buildings, tanks) which do not require maintenance or replacement as a function of utilization. In these cases, the demand factor (DF) in Equation 4 would be considered equivalent to a life-cycle functional unit (LCFU). Equation 4 illustrates how emissions from infrastructure and equipment were normalized to the functional units of the particular component (e.g., g CO_2 per tonne of material handled).

$$EF_m^{IE} = \frac{IE_m}{DF_m} * \frac{DF_m}{LCFU_m}$$

Equation 4. Contribution of Infrastructure and Equipment Emissions over a Component Lifespan (IE), Normalized to a Functional Unit Activity-based Emission Factor (EF)

$$DF = \text{Demand Factor driving deterioration and repair of component}$$

$$LCFU = \text{Functional units delivered during one component lifespan}$$

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[18] Conditions are regarded as "steady-state" when annual activity is constant year after year, resulting in identical annual demands for energy, maintenance, renewal, and replacement of manufactured and constructed components.

5.4 Component Modeling Inputs

5.4.1 Modeling Scope and Input Data Sources

The scope of relevant life-cycle stage activities considered and demand factor units for each of these activities are described in Table 2 through Table 9. In these tables, it is important to note that "maintenance" is generalized to include repair, cleaning, and (non-energy) material inputs, in addition to "renewal" activities (which are sometimes accounted for as a capital investment) for existing but aging infrastructure components. More details on assumptions and data sources can be found by following the page number in parentheses after the unit processes listed.

Transport Mode (land)		**Truck**	
Reference Flow ("r(p)")		*t-km*	
		Demand factor ("d")	*Unit Process(es) ("p")*
Operation (Direct/ Tailpipe)	Energy Consumption Intensity	t-km	Diesel Combustion (p. 175)
Fuel/ Energy Production	Energy Production Intensity	MJ of fuel consumed	Diesel Production (p. 169)
Vehicle/ Equipment	Manufacturing	v-km	Truck, Trailer (p. 176)
	Maintenance Materials	v-km	Tires, vehicle parts, vehicle maintenance (p. 177)
Infrastructure	Core Infrastructure Construction	-	
	Core Infrastructure Maintenance & Renewal	Equivalent Single Axle Load (ESAL)	Asphalt overlay (p. 181)
	Supporting Infrastructure Construction	-	
	Supporting Infrastructure Maintenance & Renewal	-	

Table 2. Scope of Work – Transport[19] by Truck (using the four life-cycle stages employed by (Facanha and Horvath 2006), and terminology from (Spielmann and Scholz 2005)).

[19] Transportation vehicles are assumed to be dedicated to one type of fuel delivery (so vessel washing is rarely necessary), and are assumed to deliver a full load to a single customer, returning empty along the same route to their supplier (i.e., utilization is 50%).

Transport Mode (land)		**Unit Train**	
Reference Flow ("r(p)")		*t-km*	
		Demand factor ("d")	*Unit Process(es) ("p")*
Operation (Direct/ Tailpipe)	Energy Consumption Intensity	t-km	Diesel Combustion (p. 182)
Fuel/ Energy Production	Energy Production Intensity	MJ of fuel consumed	Diesel Production (p. 169)
Vehicle/ Equipment	Manufacturing	Years	Locomotive, Rail Cars (p. 183)
	Maintenance Materials	Years	Parts replacement, cleaning, lubrication, inspection (p. 183)
Infrastructure	Core Infrastructure Construction	-	
	Core Infrastructure Maintenance & Renewal	t-km	Railway track repair & renewal (p. 185)
	Supporting Infrastructure Construction	-	
	Supporting Infrastructure Maintenance & Renewal	t-km (US Ave)	Communication & electrical systems, materials & paints, service trucks, supporting equipment (p. 185)

Table 3. Scope of Work – Transport[19] by Unit Train (using the four life-cycle stages employed by (Facanha and Horvath 2006), and terminology from (Spielmann and Scholz 2005)).

Transport Mode (water)		**Inland Tow**	
Reference Flow ("r(p)")		*t-km*	
		Demand factor ("d")	*Unit Process(es) ("p")*
Operation (Direct/ Tailpipe)	Energy Consumption Intensity	t-km	Diesel Combustion (p. 188)
Fuel/ Energy Production	Energy Production Intensity	MJ of fuel consumed	Diesel Production (p. 169)
Vehicle/ Equipment	Manufacturing	Years	Tugboat, Barges (p. 189)
	Maintenance Materials	Years	Lubricating oils, drydocking (repair to hull, coatings, electrical & engine equipment) (p. 190)
Infrastructure	Core Infrastructure Construction	-	-
	Core Infrastructure Maintenance & Renewal	t-km (after allocating US waterway maintenance activities by tonnage[20]: inland vs. coastal)	Dredging, lock and dam repair and upgrades (p. 195, 195)
	Supporting Infrastructure Construction	-	-
	Supporting Infrastructure Maintenance & Renewal	t-km (US Ave)	Structures & buildings, communication & electrical systems, machinery & equipment (p. 191)

Table 4. Scope of Work – Transport[19] by Inland Tow (using the four life-cycle stages employed by (Facanha and Horvath 2006), and terminology from (Spielmann and Scholz 2005)).

[20] Dredging and infrastructure allocated evenly to tonnage regardless of freight type. However, only port facilities specific to liquid bulk commodities were considered, as the equipment for handling bulk liquids is substantially less expensive per tonne handled than for containers and other types of freight.

Transport Mode (water)		**Ocean Tanker**	
Reference Flow ("r(p)")		*t-km*	
		Demand factor ("d")	*Unit Process(es) ("p")*
Operation (Direct/ Tailpipe)	Energy Consumption Intensity	t-km	Residual Oil Combustion (p. 197)
Fuel/ Energy Production	Energy Production Intensity	MJ of fuel consumed	Residual Oil Production (p. 169)
Vehicle/ Equipment	Manufacturing	Years	Ocean Going Vessel (p. 198)
	Maintenance Materials	Years	Lubricating oils, drydocking (repair to hull, coatings, electrical & engine equipment) (p. 199)
Infrastructure	Core Infrastructure Construction		
	Core Infrastructure Maintenance & Renewal	tonnes[20]	Dredging, breakwater, jetty and port structural repair and upgrades (p. 204)
	Supporting Infrastructure Construction		
	Supporting Infrastructure Maintenance & Renewal	tonnes (US Ave)	Structures & buildings, communication, electrical & security systems, supporting equipment (p. 201)

Table 5. Scope of Work – Transport[19] by Ocean Tanker (using the four life-cycle stages employed by (Facanha and Horvath 2006), and terminology from (Spielmann and Scholz 2005)).

		Pipelines	
Reference Flow ("r(p)")		*t-km*	
		Demand factor ("d")	*Unit Process(es) ("p")*
Operation (Direct/ Tailpipe)	Energy Consumption Intensity	t-km	Electricity Consumed (p. 209)
Fuel/ Energy Production	Energy Production Intensity	MJ and location of fuel consumed	Electricity Generated (p. 172)
Vehicle/ Equipment	Manufacturing	-	-
	Maintenance Materials	-	-
Infrastructure	Core Infrastructure Construction	km and diameter	Steel pipeline and pump station manufacturing and installation (p. 220)
	Core Infrastructure Maintenance & Renewal	t-km (US Ave)	Replacement and maintenance of pipes and pump stations (p. 221)
	Supporting Infrastructure Construction		
	Supporting Infrastructure Maintenance & Renewal	t-km (US Ave)	Breakout tanks and tools maintenance and parts replacement (p. 222)

Table 6. Scope of Work – Transport by Fuel Pipelines (using the four life-cycle stages employed by (Facanha and Horvath 2006), and terminology from (Spielmann and Scholz 2005)).

		Storage Tanks[21]	
Reference Flow ("r(p)")			
		Demand factor ("d")	*Unit Process(es) ("p")*
Operation (Direct/ Tailpipe)	Energy Consumption Intensity	tonnes; years	Vehicle Fuel Combustion (handling & idling), Handling losses; Exterior lighting (p. 239, 240, 241, 244, 249)
Fuel/ Energy Production	Energy Production Intensity	MJ of fuel consumed	Diesel & Electricity Production (p. 169, 172)
Vehicle/ Equipment	Manufacturing	Modification to vehicles to enable fuel consumption (i.e., E85 only)	Additional components for FFVs (NA for conventional vehicles) (p. 245)
	Maintenance Materials	-	
Infrastructure	Core Infrastructure Construction	Tank type and storage capacity (gallons or tonnes)	Steel tank, piping, valves, and pumps, controls, concrete or asphalt, foundation and/or liner (p. 240, 242, 245, 246, 247, 249)
	Core Infrastructure Maintenance & Renewal	Years	Replacement of steel tank, piping, valves, and pumps, controls, concrete, foundation (p. 240, 242, 245, 246, 247, 249)
	Supporting Infrastructure Construction	Years	Buildings, communication equipment, canopy and lighting (p. 240, 242, 245, 246, 247, 249)
	Supporting Infrastructure Maintenance & Renewal	-	

Table 7. Scope of Work – Storage Tanks (using the four life-cycle stages employed by (Facanha and Horvath 2006), and terminology from (Spielmann and Scholz 2005)).

[21] Fuel storage tanks are assumed to require a negligible amount of electrical energy to pump fuel in and out of tanks. However, a non-negligible amount of energy is assumed to be expended in delivery vehicle idling, auxiliary engine use, and facility operation (which includes fuel energy content losses and electricity for lighting). For example, it was simply assumed that one ten-thousandth (0.0001) of the energy content of a load is expended between the stationary combustion activities of the delivery vehicle (e.g., truck, train, or ship idling) and terminal-side pumping equipment. This assumption would correspond to 2.5-kg (~0.8 gallons) of diesel consumed while idling for every 25-tonne truckload delivered. A similar value would be estimated for tanker ships, using the assumption that at-port auxiliary fuel consumption of 0.08 to 0.17 tonnes/hour, which corresponds with 13 to 8% of the at-sea hourly fuel consumption rate for small to large ships (US ACE 2000b), enabling a ship to pump 1,000 or more tonnes/hour. For fuel service stations, electricity used to light the dispensing area was also included. From a public health perspective, it is also important to note that ships are estimated to burn approximately 6% of their fuel "in-port" (Entec UK Limited 2002), while locomotives burn approximately 7% of fuel in switching operations (as opposed to line-haul operations) (US EPA 2009a).

Biomass Handling and Storage Systems		Farm Storage		Farm Equipment	
Reference Flow ("r(p)")		*tonnes*		*tonnes*	
		Demand factor ("d")	*Unit Process(es) ("p")*	*Demand factor ("d")*	*Unit Process(es) ("p")*
Operation (Direct/ Tailpipe)	Energy Consumption Intensity	tonnes	Storage Losses (p. 257)	tonnes	Material handling losses, Diesel Combustion (p. 253, 254, 256)
Fuel/ Energy Production	Energy Production Intensity	MJ of fuel consumed	Diesel Production (p. 169)	MJ of fuel consumed	Diesel Production (p. 169)
Vehicle/ Equipment	Manufacturing	-		Operating Hours	Tractor + Mower, Tractor + Baler, Stinger (Bale Transporter), Telescopic Bale Loader (p. 253, 254, 255, 256)
	Maintenance Materials	-		Operating Hours	Equipment Maintenance and Repair (p. 253, 254, 255, 256)
Infrastructure	Core Infrastructure Construction	Storage Capacity (tonnes biomass)	Asphalt pad, plastic tarp manufacturing (p. 257)	-	
	Core Infrastructure Maintenance & Renewal	Years	Replacement of asphalt pad, plastic tarp manufacturing (p. 257)	-	
	Supporting Infrastructure Construction	-		-	
	Supporting Infrastructure Maintenance & Renewal	-		-	

Table 8. Scope of Work – Farm Storage and Biomass Handling Equipment (using the four life-cycle stages employed by (Facanha and Horvath 2006), and terminology from (Spielmann and Scholz 2005)).

Conversion and Refueling Systems		**Petroleum and Biorefineries**		**Motor Vehicle**	
Reference Flow ("r(p)")		*tonnes*		*tonnes*	
		Demand factor ("d")	*Unit Process(es) ("p")*	*Demand factor ("d")*	*Unit Process(es) ("p")*
Operation (Direct/ Tailpipe)	Energy Consumption Intensity	-		Distance and frequency of "errands" to service stations	Gasoline or E85 combustion (p. 260)
Fuel/ Energy Production	Energy Production Intensity	-		MJ of fuel consumed	Gasoline or E85 Production (p. 169)
Vehicle/ Equipment	Manufacturing	-			
	Maintenance Materials	-		-	
Infrastructure	Core Infrastructure Construction	Refining Capacity (BPD)	Process & electrical equipment, structures, vessels, piping, etc. (p. 230, 233)	-	
	Core Infrastructure Maintenance & Renewal	tonnes (US Ave Maintenance Spending per tonne)	Process & electrical equipment, structures, vessels, piping, etc. (p. 230, 233)	-	
	Supporting Infrastructure Construction	tonnes (US Ave Maintenance Spending per tonne)	Buildings, communication equipment, etc. (p. 230, 233)	-	
	Supporting Infrastructure Maintenance & Renewal	tonnes (US Ave Maintenance Spending per tonne)	Buildings, communication equipment, etc. (p. 230, 233)	-	

Table 9. Scope of Work – Fuel Conversion and Refueling (using the four life-cycle stages employed by (Facanha and Horvath 2006), and terminology from (Spielmann and Scholz 2005)).

5.4.2 Component Performance Characterization

Table 10, Table 11, Table 12, Table 13, and Table 14 present the quantitative assumptions used in modeling each of the major components of feedstock and fuel handling, storage and distribution, with the manufacturing or construction scaling units (which do not necessarily coincide with the size of a typical component). Assumptions, data sources, and discussion of alternative data sources and approaches to modeling these activities are described in Section 10.1, and can be found by following the page number in parentheses after the corresponding unit processes listed in Table 2 through Table 9.

		Biomass Handling Equipment				**Fuel Conversion Facilities**	
		Bale Loader	*Stinger, Bale-transport*	*Mower, with Tractor*	*Baler, with Tractor*	*Refinery, Petroleum*	*Biorefinery, Ligno-cellulosic*
Scaling Unit		1 bale loader	1 stinger	1 mower	1 baler	1,000 BPD (crude in)	1,000 BPD (ethanol out)
Lifespan	Years	10	10	10	10	50	30
Service Life	Operating Hours per Lifespan	5,000	5,000	2,000	1,500	382,000	287,000
Throughput Capacity	Tonnes per Hour	124	260	44.2	13.2	6.1	5.2
Utilization	Annual Throughput per Capacity	-	-	-	-	0.87	0.90
Lifetime Throughput	Tonnes per Life	620,000	1,300,000	88,400	19,800	2,325,035	1,233,705
Mass Conserved	Fraction	0.95	0.995	0.95	0.95	NA	0.236
Energy Intensity	kJ/t	5,871	8,120	34,094	137,162	NA	NA
Fuel Type		Diesel	Diesel	Diesel	Diesel	NA	NA

Table 10. Characterization of Harvesting and Conversion Systems.[22]

[22] NA = not applicable to the scope of this study.

		Bale Storage, Tarp + Asphalt Pad	*AST, Mid-size Product*	*AST, Large Product*	*AST, Small*	*UST, Service*	*AST, Commercial*	*AST, Large Crude*	*UST, E85*
Scaling Unit		1 m²	1 million gal capacity	1 million gal capacity	1 thousand gal capacity	1 thousand gal capacity	1 thousand gal capacity	1 million gal	1 thousand gal capacity
Lifespan	Years	10	25	25	25	25	25	25	25
Throughput Capacity	Tonnes of Holding Capacity per Scaling Unit	0.4	3,051	3,051	3	3.1	3.1	3,318	3
Utilization	Annual Fill-Empty Cycles	1.5	6	2.6	6	6	6	1.6	10
Lifetime Throughput	Tonnes per Life	6	457,666	198,322	446	458	458	132,723	744
Mass Conserved	Fraction	0.85	0.9994	0.9991	0.99997	0.9991	0.9991	0.9972	0.9991
Energy Intensity	kJ/t	-	4,330	4,330	4,330	16,388	4,330	4,330	10,085
Fuel Type			Diesel, Electricity	Diesel	Diesel	Diesel, Electricity	Diesel, Electricity	Diesel	Diesel, Electricity

Table 11. Characterization of Storage Systems.

		Transportation Modes (onshore pipelines)			Transportation Modes (land)			
		Pipe, Ethanol (25")	*Pipe, Crude (US ave)*	*Pipe, Product (US ave)*	*Train, 100-unit*	*Truck, Long-Haul Tanker*	*Truck, Short-Haul Tanker*	*Truck, Short-haul Flatbed*
Scaling Unit		1 km	1 km	1 km	1 unit train	1 truck	1 truck	1 truck
Typical Operation	km per Year	10.9 million	5.4 million	2.4 million	240,750	90,400	90,400	17,280
Lifespan	Years	40	50	50	20	5	5	12
Service Life	v-km per Life	-	-	-	4.8 million	464,000	464,000	200,000
Capacity	Tonnes (DWT) Payload	249.2	105.5	61.2	10,000	24.3	24.3	24.3
Utilization	t-km/ (v-)km	1	1	1	0.5	0.5	0.5	0.5
Lifetime Performance	t-km per Life	436 million	270 million	118 million	24.1 billion	5.6 million	5.6 million	2.4 million
Mass Conserved	Fraction	1	1	1	1	1	1	0.995
Approximate Empty Mass**	Tonnes	306	125	83	4,400	15	15	15
Energy Intensity	kJ/t-km	37	65	71	268	1,217	1,537	1,780
Fuel Type		Electricity	Electricity	Electricity	Diesel	Diesel	Diesel	Diesel

Table 12. Characterization of Transportation Modes (land).

		Transportation Modes (water)			
		Tanker, Crude (128kDWT)	*Tanker, Product (37kDWT)*	*Tanker, Ethanol (25kDWT)*	*Inland Tow, 2-barge (6kDWT)*
Scaling Unit		1 tanker ship	1 tanker ship	1 tanker ship	1 inland tow
Typical Operation	km per Year	101,440	101,440	101,440	50,000
Lifespan	Years	30	30	30	30
Service Life	v-km per Life	3,043,200	3,043,200	3,043,200	1,500,000
Capacity	Tonnes (DWT) Payload	128,000.00	37,000.00	25,000.00	6,000.00
Utilization	t-km/ (v-)km	0.5	0.5	0.5	0.5
Lifetime Performance	t-km per Life	194,764,800,000	56,299,200,000	38,040,000,000	4,500,000,000
Typical Lifetime Throughput	Tonnes per Life	23,409,231	6,766,731	4,572,115	-
Mass Conserved	Fraction	1.0	1.0	1.0	1.0
Energy Intensity	kJ/t-km	51	128	171	320
Fuel Type		Residual Oil	Residual Oil	Residual Oil	Diesel

Table 13. Characterization of Transportation Modes (water).

	Units	Vehicle Refueling Errands	
		Vehicle, Flex-fuel (refueling operation related to E85 consumption only)	*Vehicle, Non-FFV (refueling operation only)*
		1 vehicle	1 vehicle
Lifespan	Years	10	10
Service Life	Gal per Life	3,650	6,667
Capacity	Tonnes (DWT) Payload	0.044	0.042
Utilization	t-km/ (v-)km	0.5	0.5
Lifetime Performance	t-km per Life	11.1	20.2
Lifetime Throughput	Tonnes per Life	11.1	20.2
Mass Conserved	Fraction	1	1
Energy Intensity	kJ/t-km	270,313	270,313
Fuel Type		E85	Gasoline

Table 14. Characterization of Vehicle Refueling Errands.

5.5 Results: Component Emission Factors

5.5.1 Life-cycle GHG Emission Factors

The estimated carbon intensity of each component modeled in this study is shown in Figure 17, with supporting data for these graphs in Table 15 (and percent contribution of each stage shown in Table 16). The composition of transportation mode emission factors match reasonably well with existing life-cycle emission factor studies (Facanha and Horvath 2006; Spielmann and Scholz 2005), as non-operation stages typically contribute 20-30% to the GHG emissions of each transportation mode considered. In particular, the contribution from "upstream" activities to the life-cycle GHG emission factor is less than 25% for rail and water transport modes, but more than 30% for trucking (which would be the most carbon-intensive mode even if only tailpipe emissions were considered). As expected, infrastructure is the most significant relative contributor to pipeline emission factors, contributing 25-30% of total GHG emissions, with electricity production making up the remainder.

The 20-30% rule of thumb also held for most agricultural equipment, though the role of manufacturing was more significant for balers due to their shorter lifespan (operating hours) and slower biomass throughput (tonnes per hour) than any other piece of equipment considered. In contrast, infrastructure made up more than half of life-cycle emissions for several storage tanks, with emissions from loading, unloading and evaporative losses making up the majority of the rest. For small underground storage tanks (USTs) at retail stations, electricity used for canopy lighting can result in emissions comparable to tank construction and vehicle refueling errands.

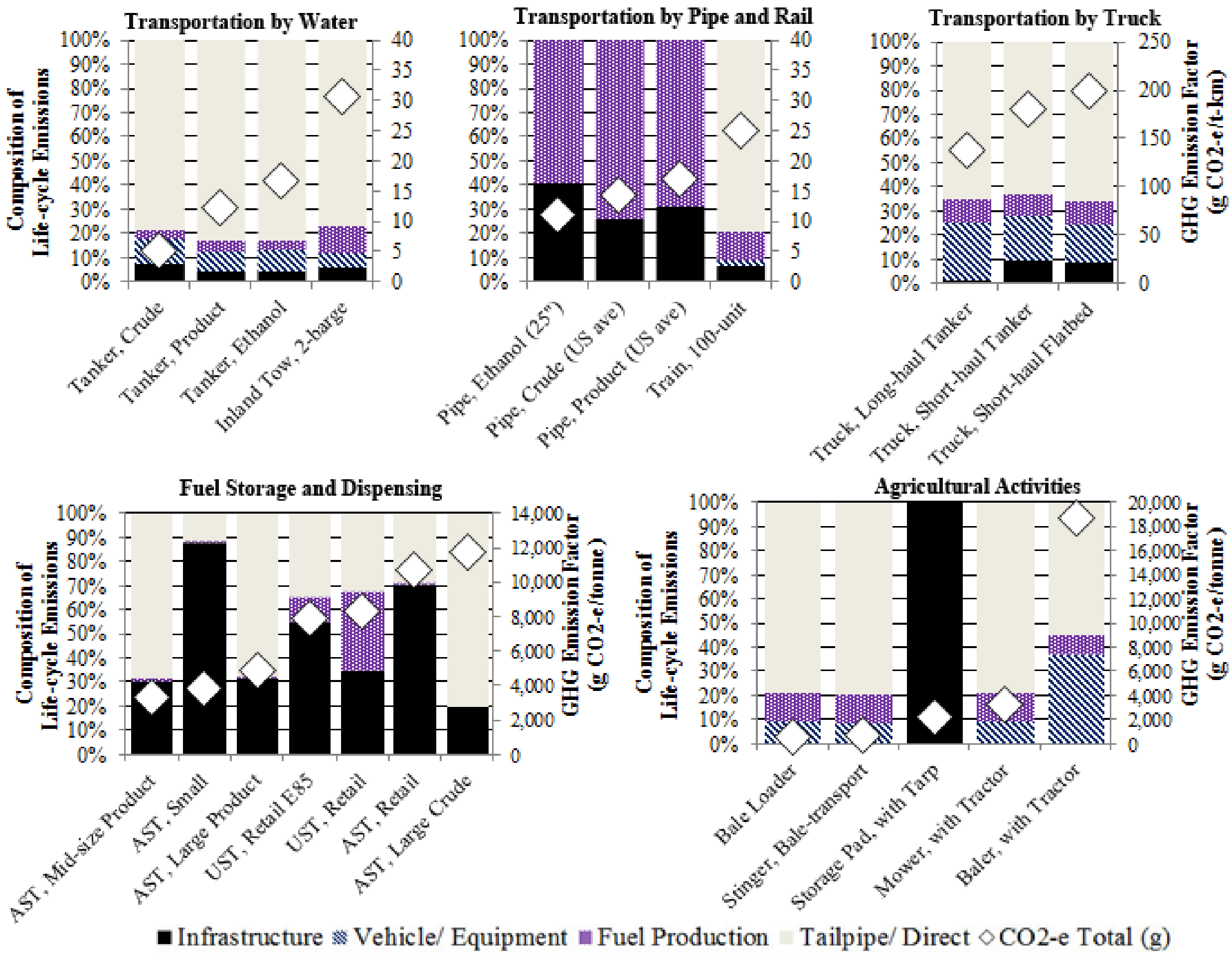

Figure 17. Life-cycle GHG Emission Factors for Components Considered.[23]

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[23] The left y-axis corresponds with the stacked percent contributions of each life-cycle stage to total GHG emissions. The right y-axis corresponds with life-cycle GHG emission factors per t-km delivered (top three) and per tonne of throughput (bottom two).

	Functional Unit	Infrastructure	Vehicle/ Equipment	Fuel Production	Tailpipe	Total
Biomass Handling Equipment		g CO_2-e	g CO_2-e	g CO_2-e	g CO_2-e	g CO_2-e
Bale Loader	t	-	57	64	435	556
Stinger, Bale-transport	t	-	72	89	602	763
Mower, with Tractor	t	-	332	374	2,527	3,233
Baler, with Tractor	t	-	7,099	1,503	10,166	18,768
Fuel Conversion Facilities (Infrastructure Only)						
Refinery, Petroleum	t	8,701	-	-	-	8,701
Biorefinery	t	98,259	-	-	-	98,259
Storage and Dispensing Units						
Bale Storage, Tarp + Asphalt Pad	t	2,263	-	-	-	2,263
AST, Mid-size Product	t	1,007	-	47	2,223	3,277
AST, Large Product	t	1,580	-	47	3,289	4,917
AST, Small	t	3,347	-	47	3,015	6,409
UST, Service	t	2,960	-	2,683	2,694	8,336
AST, Commercial	t	7,610	-	47	3,015	10,672
AST, Large Crude	t	2,361	-	47	9,307	11,716
UST, E85	t	4,405	-	825	2,694	7,924
Transportation Modes (land)						
Pipe, Ethanol (25")	t-km	4	-	7	-	11
Pipe, Crude (US ave)	t-km	4	-	11	-	14
Pipe, Product (US ave)	t-km	5	-	12	-	17
Train, 100-unit	t-km	2	0.5	3	20	25
Truck, Long-Haul Tanker	t-km	2	33	13	90	138
Truck, Short-Haul Tanker	t-km	18	33	17	114	181
Truck, Short-haul Flatbed	t-km	18	30	20	132	199
Vehicle (refueling errand only)	t-km	-	-	2,977	19,687	22,663
Transportation Modes (water)						
Tanker, Crude (128 kDWT)	t-km	0.4	0.6	0.2	4.1	5.2
Tanker, Product (37 kDWT)	t-km	0.5	1	0.5	10.4	12.4
Tanker, Ethanol (25 kDWT)	t-km	0.6	1.5	0.7	13.8	16.6
Inland Tow, 2-barge	t-km	1.7	1.9	3.5	23.7	30.7

Table 15. Composition of Component-specific Emission Factors (used in Figure 17).

	Functional Unit	Infrastructure	Vehicle/ Equipment	Fuel Production	Tailpipe
Biomass Handling Equipment					
Bale Loader	t	0%	10%	12%	78%
Stinger, Bale-transport	t	0%	9%	12%	79%
Mower, with Tractor	t	0%	10%	12%	78%
Baler, with Tractor	t	0%	38%	8%	54%
Fuel Conversion Facilities (Infrastructure Only)					
Refinery, Petroleum	t	100%	0%	0%	0%
Biorefinery	t	100%	0%	0%	0%
Storage and Dispensing Units					
Bale Storage, Tarp + Asphalt Pad	t	100%	0%	0%	0%
AST, Mid-size Product	t	31%	0%	1%	68%
AST, Large Product	t	32%	0%	1%	67%
AST, Small	t	52%	0%	1%	47%
UST, Service	t	36%	0%	32%	32%
AST, Commercial	t	71%	0%	0%	28%
AST, Large Crude	t	20%	0%	0%	79%
UST, E85	t	56%	0%	10%	34%
Transportation Modes (land)					
Pipe, Ethanol (25")	t-km	36%	0%	64%	0%
Pipe, Crude (US ave)	t-km	29%	0%	79%	0%
Pipe, Product (US ave)	t-km	29%	0%	71%	0%
Train, 100-unit	t-km	8%	2%	12%	80%
Truck, Long-Haul Tanker	t-km	1%	24%	9%	65%
Truck, Short-Haul Tanker	t-km	10%	18%	9%	63%
Truck, Short-haul Flatbed	t-km	9%	15%	10%	66%
Vehicle (refueling errand only)	t-km	0%	0%	13%	87%
Transportation Modes (water)					
Tanker, Crude (128 kDWT)	t-km	8%	12%	4%	79%
Tanker, Product (37 kDWT)	t-km	4%	8%	4%	84%
Tanker, Ethanol (25 kDWT)	t-km	4%	9%	4%	83%
Inland Tow, 2-barge	t-km	6%	6%	11%	77%

Table 16. Relative Composition of Component-specific Emission Factors.

Note: A conversion table in the footnote[24] was created to translate supply chain emission factors into the equivalent units based on mass, volume, energy, and vehicle travel distance, as some readers may be more familiar with functional units other than the megajoule (MJ).

5.5.2 Air Pollutant Emission Factors

In addition to GHG emissions (and water withdrawal) intensity, key transportation modes were also characterized by air pollutant emissions intensity and cost intensity. In the previous section of this dissertation, a review of energy intensity values found in the literature (and existing models) was presented for each mode, which is the major driver of pollutant emissions variability between modes (in addition to fuel type and engine technology). In this section, a review of air pollutant emission factors found in the literature is provided. Emission factors for freight transport have been reported in various reports assuming countless different functional units (e.g., per vehicle-mile, per ton-mile, per bhph, per MMBTU of fuel, per gallon of fuel), but the most consistent manner for reporting emission factors is on a mass basis.

In order to understand the variation in emission factors that are reported in the literature, the values presented by all sources were converted into units of "gram-pollutant/gram-CO_2" either by using the actual article's reporting of CO_2 emissions, or by using the typical carbon content of the fuel (and in a few cases, assumptions about the vehicle's fuel efficiency) to estimate this ratio if CO_2 is not reported alongside criteria air pollutants (as is the case in some of EPA's reports). The sections below list the energy and carbon intensity of each transportation mode, and provide the range of values found in literature sources. After addressing each of the transportation modes, a summary of recommended values can be found in Table 22 and Table 23. The last subsection summarizes the emission factors applicable to agricultural (biomass handling) equipment, using the same format as was used for transportation modes.

5.5.2.1 TRUCK

Long-haul fuel delivery trucks are assumed to require 1217 kJ/t-km of diesel (Appendix 10.2.1.1), and diesel has a carbon intensity of 0.074 g-CO2/kJ. A review of truck emission factors can be found in Table 17. The costs of shipping ethanol by truck were estimated to be \$0.15/t-km (Morrow et al. 2006), which is slightly more expensive than the \$0.137/t-km cost of shipping

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[24] Conversion Table for Supply Chain Emission Factors (i.e., for a hypothetical supply chain activity that emits 10 kg of a pollutant for every tonne of fuel product handled):

	kg/tonne	**g/L**	**g/gal**	**g/MJ**	**g/km driven by motor vehicle (at 10.6 km/L-eqv, or 9.43 L-eqv/100 km)**	**g/mile driven by motor vehicle (at 25 mpg-eqv)**
Gasoline	10	7.4	28	0.21	0.70	1.1
Iso-butanol	10	8.2	31	0.30	0.91	1.5
E85	10	7.9	30	0.34	1.03	1.7
Ethanol	10	7.8	30	0.37	1.11	1.8

biomass by truck (Kang et al. 2010). Highway distance was used as the basis of analysis, but roads have been estimated to be 1.23 more circuitous than Euclidian distance (Wakeley et al. 2009).

	Pollutant Emissions Factor ($g/g-CO_2$)	**Source**
CO_2	1	
NO_x	0.001-**0.011***[25]	Adapted from (US DOE ANL 2010), (Ecoinvent 2010), and on-road fuel-based emissions estimates (Dallmann and Harley 2010)*****
$PM_{2.5}$	0.00004-**0.00033***	Adapted from (US DOE ANL 2010), (Ecoinvent 2010), and on-road fuel-based emissions estimates (Dallmann and Harley 2010)*****
VOC	0.00011-0.00126 **(0.00035)***	Adapted from (US DOE ANL 2010)*****, (Ecoinvent 2010)
CO	0.0012-**0.0063***	Adapted from (US DOE ANL 2010), (Ecoinvent 2010), and review of remote-sensing data (Bishop and Stedman 2008)*****
SO_x	0.00011-**0.00012***	Adapted from (Ecoinvent 2010), (US DOE ANL 2010)*****

Table 17. Air Pollutant Emission Factors for Trucks.

5.5.2.2 RAIL

Locomotives used for a unit train of fuel tank-cars are assumed to require 268 kJ/t-km of diesel (adapted from (Facanha 2006), which has a carbon emissions intensity of 0.074 $g-CO_2/kJ$. Train emission factors can be found in Table 18. The costs of shipping ethanol have been estimated as high as $0.05/t-km by rail (with a relative fixed cost of $20.6/t) (Morrow et al. 2006), though more recent estimates of ethanol shipping costs showed marginal costs to range from $0.009/t-km to $0.021/t-km in 2008 dollars (Hughes 2011), with the higher estimate consistent with the Association of American Railroads (AAR) industry average of $0.019/t-km (AAR 2008). As fixed shipping costs were not included in this analysis, a conservative average price of $0.020/t-km was chosen. Railways are assumed to have a circuity factor of 1.2 over highways, as the difference in travel distance by both modes was 1.23 and 1.16 for two routes considered (using *ArcGIS*), and has previously been reported to be 1.23 greater than highways (Wakeley et al. 2009).

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[25] Bold text with an asterisk (*) indicates the recommended value and the asterisk is also placed on the corresponding reference(s) when more than one value is presented. On-road measurements (e.g., Dallmann and Harley) were given preference over regulatory standards (e.g., US DOE ANL))

	Pollutant Emissions Factor (g/g-CO_2)	Source
CO_2	1	
NO_x	0.014-0.024 (**0.021)***	Adapted from (US DOE ANL 2010), 2005 ethanol transporting trains (US EPA 2010d)*, 2012 line-haul locomotives (US EPA 2009a), 2012 large switchyard locomotives (US EPA 2009a), and in-use fuel-based emissions estimates (Dallmann and Harley 2010)*****
$PM_{2.5}$	0.0004-**0.0006***	Adapted from 2012 line-haul locomotives (US EPA 2009a), 2005 ethanol transporting trains (US EPA 2010d)*, 2006 to 2012 large switchyard locomotives (US EPA 2009a), and in-use fuel-based emissions estimates (Dallmann and Harley 2010)*****
VOC	0.0007-0.0017 **(0.0011)***	Adapted from (US DOE ANL 2010)**,** 2006 to 2012 line-haul locomotives (US EPA 2009a), 2005 ethanol transporting trains (US EPA 2010d)*, 2012 large switchyard locomotives (US EPA 2009a), (Ecoinvent 2010)
CO	0.0026-**0.0027***	Adapted from (US DOE ANL 2010), 2005 ethanol transporting trains (US EPA 2010d)*
SO_x	**0.00012*-**0.0014	Adapted from (US DOE ANL 2010)*, (Ecoinvent 2010)

Table 18. Air Pollutant Emission Factors for Locomotives.

5.5.2.3 INLAND TOW

Tugboats used to pull tank barges are assumed to require 320 kJ/t-km of diesel (Winebrake et al. 2007b), which has a carbon intensity of 0.074 g-CO_2/kJ. Inland tow emission factors can be found in Table 19. Barges burning residual oil would have had significantly higher SO_x emissions than shown in this table. The average cost of shipping freight by barge was $0.012/t-km in 2004 (US DOT BTS 2010). Inland waterways were assumed to be 1.3-1.38 more circuitous than rail (Nicollet Island Coalition 2010a), which implies a circuity factor greater of 1.5-1.8 greater than highways.

	Pollutant Emissions Factor ($g/g\text{-}CO_2$)	Source
CO_2	1	
NO_x	0.013-0.022 **(0.016)***	Adapted from (US DOE ANL 2010), NONROAD 2006 (US EPA 2009b), 2005 ethanol transporting barges (US EPA 2010d)*, (Dallmann and Harley 2010)
$PM_{2.5}$	0.0002-**0.0007***	Adapted from (US DOE ANL 2010), (Ecoinvent 2010), 2005 ethanol transporting barges (US EPA 2010d)*, (Dallmann and Harley 2010)*
VOC	0.00029-0.00061 **(0.00034)***	Adapted from (US DOE ANL 2010), (Ecoinvent 2010), NONROAD 2006 (US EPA 2009b), 2005 ethanol transporting barges (US EPA 2010d)*
CO	0.0010-**0.0030***	Adapted from (Ecoinvent 2010), (US DOE ANL 2010)**,** NONROAD 2006 (US EPA 2009b), 2005 ethanol transporting barges (US EPA 2010d)*
SO_x	0.00010-0.0035 **(0.00012)***	Adapted from (Ecoinvent 2010), (US DOE ANL 2010)*

Table 19. Air Pollutant Emission Factors for Inland Tow Tugboats.

5.5.2.4 OCEAN TANKERS

Ocean tankers are assumed to require 51, 128, and 171 kJ/t-km of bunker fuel or residual oil (though a small percentage operate with diesel and natural gas) to transport liquid products in tankers that can hold 128, 37, and 25 thousand DWT of bulk liquid fuel products, respectively (adapted from (Psaraftis and Kontovas 2009)), which has a carbon intensity of 0.081 $g\text{-}CO_2/kJ$. Ocean tanker emission factors can be found in Table 20. The costs of shipping liquid fuel by ocean tanker can vary from $0.0008/t-km (e.g., large tankers of crude from the Middle East to Houston) to $0.0065/t-km (e.g., small tankers of distillate products from the Caribbean to New York) (adapted from (PetroStrategies, Inc. 2011)).

	Pollutant Emissions Factor (g/g-CO_2)	Source
CO_2	1	
NO_x	0.008-0.033 **(0.026)***	Adapted from (Ecoinvent 2010), (Murphy et al. 2009), (US DOE ANL 2010), (US EPA OTA 2009), (Kristensen 2006), 2005 ethanol transporting ships (US EPA 2010d)*
$PM_{2.5}$	0.0004-.0038 **(0.0019)***	Adapted from (Ecoinvent 2010), (Murphy et al. 2009), (US DOE ANL 2010), (US EPA OTA 2009), (Kristensen 2006), 2005 ethanol transporting ships (US EPA 2010d)*
VOC	0.0006-0.0012 **(0.00093)***	Adapted from (US DOE ANL 2010)*, (US EPA OTA 2009), (Ecoinvent 2010), (Kristensen 2006), 2005 ethanol transporting ships (US EPA 2010d)*
CO	0.0005-0.0051 **(0.0021)***	Adapted from (Murphy et al. 2009), (US DOE ANL 2010)*, (Ecoinvent 2010), (US EPA OTA 2009), (Kristensen 2006), 2005 ethanol transporting ships (US EPA 2010d)*
SO_x	0.013-0.021 **(0.019)***	Adapted from (US DOE ANL 2010)*, (Murphy et al. 2009), (US EPA OTA 2009), (Kristensen 2006), (Ecoinvent 2010)

Table 20. Air Pollutant Emission Factors for Ocean Tankers.

5.5.2.5 PIPELINES

Pipelines operating at full capacity for liquid fuels such as gasoline, crude oil, or ethanol require from 40-70 kJ(electricity)/t-km for large diameter (40") pipelines to 100-120 kJ(electricity)/t-km for smaller diameter (10") pipelines (adapted from (Hooker 1981) and confirmed through Colebrook equation iteration), and approximately 95% of oil pipelines operate with electricity. The greenhouse gas and air pollutant emissions intensity of electricity generation in each NERC region (as defined by the US EPA) are presented in Table 21.

Air pollution resulting from pipeline operation is not attributed to the actual location of pipelines, as more than 75% of crude and product pipelines were powered by electricity in 1978 (Hooker 1981) and 95% are currently powered by electricity according to recent conversations with oil and pipeline experts. As a result, a simplification was made that 100% of pipelines are operated with grid baseload electricity. The fraction of fuel handled by pipelines that is lost as fugitive volatile organic compound (VOC) emissions was assumed to be similar to other modes of transportation, and were assumed to take place at storage or blending tanks.

The average cost of shipping oil by pipeline was $0.009/t-km in 2004 (US DOT BTS 2010), though this cost is expected to vary drastically by location and pipeline diameter; for example, long distance transport of gasoline (e.g., 2,400 km from Houston to New York) through large diameter pipelines has been reported to cost as little as $0.004/t-km (Rabinow 2004), but transport of ethanol through the proposed 25" Midwest-to-Northeast pipeline was estimated to require a tariff of up to $0.034/t-km (US DOE 2010).

NERC Region Name	NERC Acronym	*CO_2-e (g/kJ of electricity)*	NO_x (g/g-CO_2-e)	SO_x (g/g-CO_2-e)	CH_4 (g/g-CO_2-e)	N_2O (g/g-CO_2-e)
Alaska Systems Coordinating Council	ASCC	*0.143*	0.0033	0.001	0.023	0.006
Florida Reliability Coordinating Council	FRCC	*0.154*	0.0016	0.0026	0.034	0.012
Hawaiian Islands Coordinating Council	HICC	*0.194*	0.0031	0.0051	0.067	0.014
Midwest Reliability Organization	MRO	*0.222*	0.0018	0.0032	0.017	0.017
Northeast Power Coordinating Council	NPCC	*0.099*	0.0010	0.0030	0.064	0.015
Reliability First Corporation	RFC	*0.180*	0.0016	0.0058	0.016	0.017
SERC Reliability Corporation (Southeast)	SERC	*0.172*	0.0013	0.0040	0.016	0.016
Southwest Power Pool	SPP	*0.212*	0.0015	0.0024	0.014	0.015
Texas Regional Entity	TRE	*0.158*	0.0006	0.0020	0.014	0.011
Western Electricity Coordinating Council	WECC	*0.128*	0.0015	0.0011	0.021	0.014
United States Average	U.S.	*0.164*	0.0014	0.0037	0.019	0.015

Table 21. Electricity Generation Air Pollutant Emission Factors for the Year 2007 (adapted from eGRID model v1.0 (US EPA 2010g)).

5.5.2.6 SUMMARY OF OPERATION-STAGE AIR POLLUTANT EMISSION FACTORS FOR TRANSPORTATION MODES

A summary of the values recommended for use in this study, as indicated in the previous sections characterizing each mode, can be found in Table 22 and Table 23.

	Truck (diesel)	Train (diesel)	Inland Tow (diesel)	Small Ocean Tanker (residual oil)
Typical circuity factor over highway distance	1.0	1.2	1.6 (if available)	Case-specific
Estimated or adapted from:	Basis for analysis	Average of two major corridors using *ArcGIS*	(Nicollet Island Coalition 2010a)	
Cost (ignoring circuity)	0.15	0.020	0.012	0.0065
Cost estimates from:	(Morrow et al. 2006)	(Hughes 2011)	(US DOT BTS 2010)	(PetroStrategies, Inc. 2011)
g CO_2-e (life-cycle)	138	26	31	16.7
Life-cycle CO_2-e/direct CO_2 multiplier from:	Appendices 10.2.1.1 and 10.2.1.2	Appendices 10.2.1.3 and 10.2.1.410.2	Appendices 10.2.1.5 and 10.2.1.6	Appendices 10.2.1.7 and 10.2.1.8
g CO_2 (direct)	90.1	19.8	23.7	13.9
Energy intensity estimated or adapted from:	(adapted from (Facanha 2006)	(adapted from (Facanha 2006)	(Winebrake et al. 2007b)	(Psaraftis and Kontovas 2009)
Fuel carbon intensity from:	(US DOE ANL 2010)	(US DOE ANL 2010)	(US DOE ANL 2010)	(US DOE ANL 2010)
g NO_x (direct)	0.991	0.416	0.379	0.36
NO_x:CO_2 (direct) ratio estimated from:	(Dallmann and Harley 2010)	(Dallmann and Harley 2010; US EPA 2010d)	(US EPA 2010d)	(US EPA 2010d)
g $PM_{2.5}$ (direct)	0.03	0.012	0.017	0.026
$PM_{2.5}$:CO_2 (direct) ratio estimated from:	(Dallmann and Harley 2010)	(Dallmann and Harley 2010; US EPA 2010d)	(Dallmann and Harley 2010; US EPA 2010d)	(US EPA 2010d)
g SO_x (direct)	0.011	0.002	0.003	0.263
SO_x:CO_2 (direct) ratio estimated from:	(US DOE ANL 2010)	(US DOE ANL 2010)	(US DOE ANL 2010)	(US DOE ANL 2010)
g VOC (direct)	0.032	0.022	0.008	.013
VOC:CO_2 (direct) ratio estimated from:	(US DOE ANL 2010)	(US DOE ANL 2010)	(US DOE ANL 2010)	(US DOE ANL 2010; US EPA 2010d)
g CO (direct)	0.567	0.054	0.071	0.029
CO:CO_2 (direct) ratio estimated from:	(Bishop and Stedman 2008)	(US EPA 2010d)	(US EPA 2010d)	(US DOE ANL 2010; US EPA 2010d)

Table 22. Estimated Costs and Recommended Emission Factors for CO_2 and Air Pollutants, Resulting from 1 Metric Ton-Kilometer of Fuel Transportation in the United States (representative for years 2004 to 2008).

	Oil Pipeline-10" (MRO electricity)	Oil Pipeline-40" (NPCC electricity)	Ethanol Pipeline-25" (NPCC electricity)
Typical circuity factor over highway distance	Case-specific	Case-specific	Case-specific
Estimated or adapted from:			
Cost:	0.020	0.004	0.034[26]
Cost estimates from:	US ave oil pipeline cost (US DOT BTS 2010), x 2.2	(Rabinow 2004)	(US DOE 2010)
g CO_2-e (life-cycle)	35	5	6.8
Life-cycle CO_2-e/direct CO_2 multiplier from:	Appendix 10.2.1.9	Appendix 10.2.1.9	Appendix 10.2.1.9
g CO_2 (direct)	26.6	4	3.7
Energy intensity estimated or adapted from:	(Hooker 1981) and Appendix 10.2.1.9	(Hooker 1981) and Appendix 10.2.1.9	(Hooker 1981) and Appendix 10.2.1.9
Fuel carbon intensity from:	(US EPA 2010g)	(US EPA 2010g)	(US EPA 2010g)
g NO_x (direct)	0.048	0.004	0.004
NO_x:CO_2 (direct) ratio estimated from:	(US EPA 2010g)	(US EPA 2010g)	(US EPA 2010g)
g $PM_{2.5}$ (direct)			
$PM_{2.5}$:CO_2 (direct) ratio estimated from:			
g SO_x (direct)	0.085	0.012	0.011
SO_x:CO_2 (direct) ratio estimated from:	(US EPA 2010g)	(US EPA 2010g)	(US EPA 2010g)
g VOC (direct)			
VOC:CO_2 (direct) ratio estimated from:			
g CO (direct)			
CO:CO_2 (direct) ratio estimated from:			

Table 23. Estimated Costs and Recommended Emission Factors for CO_2 and Air Pollutants, Resulting from 1 Metric Ton-Kilometer of Domestic Fuel Pipeline Transportation in the United States (representative for years 2004 to 2007).

5.5.2.7 AGRICULTURAL EQUIPMENT

All agricultural equipment is assumed to operate using diesel, which has a carbon intensity of 0.074 g CO_2/kJ, and emission factors are assumed to relate to the horsepower of engines. Air pollutant emissions are presented as a fraction of CO_2 emissions, as CO_2 emissions are essentially constant in

[26] Cost estimated in 2010, when competing intermodal ethanol transport averaged only $0.19/gallon ($0.023/t-km assuming 1700 miles) (US DOE 2010).

proportional to the carbon (and energy) content of the fuel. Agricultural equipment emission factors can be found in Table 24.

	Pollutant Emissions Factor for Tractors (US DOE ANL 2010) (g/g-CO2)	Pollutant Emissions Factor for 100 hp Agricultural Equipment NONROAD 2006 (US EPA 2009b) (g/g-CO2)	Pollutant Emissions Factor for 175 hp Agricultural Equipment NONROAD 2006 (US EPA 2009b) (g/g-CO2)
CO_2	1	**1**	**1**
NO_x	0.009	**0.011**	**0.012**
$PM_{2.5}$	0.0007	**0.0017**	**0.0014**
VOC	0.0009	**0.0015**	**0.0017**
CO	0.0046	**0.0088**	**0.0062**
SO_x	**0.00012**		

Table 24. Air Pollutant Emission Factors for Agricultural Equipment (bold = recommended value).

6 US DISTRIBUTION SYSTEM MODEL[27]

This section applies the performance, lifespan, and emission factor characteristics of each component evaluated in Section 5 to create an inventory of system components necessary to distribute petroleum and biofuels from feedstock origin to product destination. Environmental impacts incorporated into these models include GHG emissions and water withdrawal volumes resulting from the use of materials and energy products in the infrastructure and equipment used in handling, storing, transporting and dispensing liquid fuel feedstocks and products to customers (i.e., processes other than chemical conversion). This was performed by incorporating the GHG and water factors from Section 5 into the national distribution models for petroleum-based fuels and biomass-based fuels. Although total water withdrawals is not a meaningful environmental impact by itself, this first attempt to present total water withdrawals by life-cycle stage for fuels (including infrastructure and equipment) may enable readers to gauge whether infrastructure, vehicles, refining, or equipment operation are likely to play a significant role in total life-cycle water impacts.

An estimate of total annual and total embodied GHG emission and water withdrawals of the national distribution system for both fuels is presented. To estimate the contribution of distribution chain activities to the life-cycle GHG and water footprint of fuel consumed, cumulative emissions from infrastructure and equipment maintenance and replacement were normalized to the energy content of consumed fuel. This approach was designed to be consistent with an attributional life-cycle methodology (instead of consequential), in order to understand the baseline emissions inventory on a steady-state basis (i.e., assuming all activities are identical year-after-year), without attempting to project marginal consequential impacts.

6.1 Functional Unit

Although the functional unit of most of the components modeled in Section 5 was either tonnes or t-km, the overarching functional unit for the entire petroleum and biofuel systems is the energy content (in MJ) delivered to motor vehicles. Previous LCA studies have normalized emissions to gallons of fuel or kilometers traveled by a typical car, but the choice of the MJ is consistent with the EPA's criteria for RFS-qualifying fuels and the European Parliament's directive on the promotion of the use of energy form renewable sources (European Parliament, Council 2009).

6.2 Distribution System Component Fleet Model

The next step in creating an energy and emissions inventory for the supporting infrastructure of fuels is to create an inventory of components and activity levels for each stage. In order to create a national distribution system model for both petroleum and biofuels, the following steps were taken.

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[27] Much of the material in this chapter was reproduced with permission from the American Society of Civil Engineers, after first being submitted for publication in the *Journal of Infrastructure Systems* in 2011 under the title, "Greenhouse Gas Emissions from the Construction, Manufacturing, Operation and Maintenance of US Distribution Infrastructure for Petroleum and Biofuels" (Strogen and Horvath 2012). This article was under review at the time this dissertation was submitted.

1) A literature survey was performed to understand and quantify the services (functions) provided by each infrastructure component throughout the existing US petroleum distribution system, and the projected scale up in infrastructure services needed to support a Miscanthus-based US ethanol distribution system.
2) The fleet (or inventory) of infrastructure components and sub-components (e.g., tires for trucks) needed to supply each of these services was estimated based on the expected annual and lifespan performance (i.e., throughput of functional unit services) of each component, using one of two approaches:
    a. When possible, the fleet size of infrastructure components that are currently in service were quantified using existing publications (e.g., government or industry reports), and the typical in-field utilization for each component was then back-calculated.
        i. This approach was used for pipelines, storage tanks and service stations, because these facilities serve purposes in addition to distribution (e.g., catastrophe insurance, security and consumer services).
    b. Alternatively, apply the default design values (or rules of thumb) of typical annual and lifespan performance for each component from Section 5 as the expected utilization of each component.
        i. This approach was used for estimating the fleet of harvesting equipment and transportation vehicles.

6.3 Structure of National Distribution System Models

6.3.1 Scope and Boundary of Distribution Systems

The distribution system model for both types of fuel, described in detail below, extends from the original location of (conditioned) feedstock until the point where fuel consumers have returned to their regular route after refueling, which could be referred to as an inventory of "well-to-route" activities in the United States. This boundary expansion should enable fair comparison to vehicles that may not require refueling errands (e.g., electric vehicles).

6.3.1.1 Petroleum System

2008 is considered the base case year, when approximately 5.4 billion barrels of crude oil (approximately 32.4 EJ) were received at refineries within the United States (US EIA 2010a), and 6.4 billion barrels (approximately 32.9 EJ) of petroleum products were supplied throughout the country (US EIA 2011a).

Total crude supply in the United States is not expected to decrease more than 6% by 2022, even under low economic growth or low renewable cost projections (US EIA 2011b).

a) The first activity accounted for in the petroleum scenario was the movement of crude oil after extraction and initial conditioning (e.g., upgrading, desalting, water removal). Activities and infrastructure related to exploration and production were ignored (though information on these activities can be found in (US DOE NETL 2008)).
b) All crude oil distribution infrastructure is assumed to exist to support liquid fuels (e.g., gasoline, diesel, jet fuel, fuel oil), which make up more than 80% (v/v) of the products leaving refineries

(US EIA 2011a) and more than 85% of the market value of products leaving refineries (M. Q. Wang et al. 2004).

c) The distribution of other inputs (e.g., water, hydrogen, carbon dioxide, catalysts) and outputs (e.g., gas and solid products, waste products) that are critical to producing and refining petroleum were also ignored, as was the refining process itself, though assessment of full environmental impacts and profitability of the system would need to account for these activities.
d) Transportation activities for all imported and domestically produced crude and petroleum products were included, but transportation distances were not considered for crude oil exports (which are equivalent to less than 1% of US refining capacity) nor for petroleum product exports (more than 90% of which are shipped from the Gulf Coast, where much refining occurs).
    - Note: Petroleum exports have been equivalent to less than 13% of product supplied volume in any year since 1983 (US EIA 2011a).

6.3.1.2 Ethanol System

Biomass production in 2022 is assumed sufficient to produce 21 billion gallons (1.7 EJ) of advanced (ligno-cellulosic) biofuel, to meet the mandated volumes prescribed by the EISA of 2007. During the time in which this research was performed (2008-2011), the crop Miscanthus was regarded by many researchers at the EBI to hold the most promise as a high-yield, low-risk, feedstock for biofuels in the United States. Ethanol produced from biomass such as Miscanthus grass is therefore expected to be the dominant alternative transportation fuel to gasoline within the United States for at least the next decade.

a) The first activity accounted for in the Miscanthus to ethanol scenario was the harvesting of Miscanthus after senescence (i.e., field drying and conditioning). Activities related to farm establishment, planting, and crop maintenance were ignored.
b) All equipment used in the harvesting, handling, storing, transporting, and refining of Miscanthus grass was included in this analysis (presuming that conditions found in Illinois, used to determine parameters in the BioFeed model, do not differ wildly from conditions that would be found in other Miscanthus producing regions of the US). The degree to which these activities were allocated to ethanol fuel is discussed in the Sensitivity Analysis section of the paper. Figure 18 shows how mass and energy are conserved or converted at each stage from field to biorefinery.
c) The production and distribution of other inputs (e.g., water, enzymes, yeasts, chemicals, natural gas) and outputs (e.g., biogas, electricity, animal feed, waste products) resulting from biorefining were also ignored, though the full environmental impacts and profitability of the system would need to account for these activities.
d) In the "base case," only domestically produced Miscanthus ethanol was considered, so international imports and exports were ignored.
    - Note: imported ethanol made up less than 2% of US ethanol consumed from 2009-2010, and the US became a net exporter of ethanol in early 2011.

e) 100% of growth in ethanol demand is expected to require increased utilization of higher level blends such as E85 (i.e., the highest blend of ethanol in gasoline permitted in US FFVs). Although the average volumetric ethanol composition of "E85" has previously been estimated to be only 78% (Hsu et al. 2010) or 80% (Jacobson 2007), E85 is simplified as 85% ethanol and 15% gasoline in this study.

f) The biomass and ethanol production levels were selected in order to hypothetically supply enough advanced biofuel in 2022 to meet the mandated volumes prescribed by the EISA of 2007, which would require approximately 388 million (dry) tonnes of Miscanthus (at peak biomass in the field) in order to produce 21 billion gallons (1.7 EJ, 63 million tonnes) of ligno-cellulosic ethanol each year.

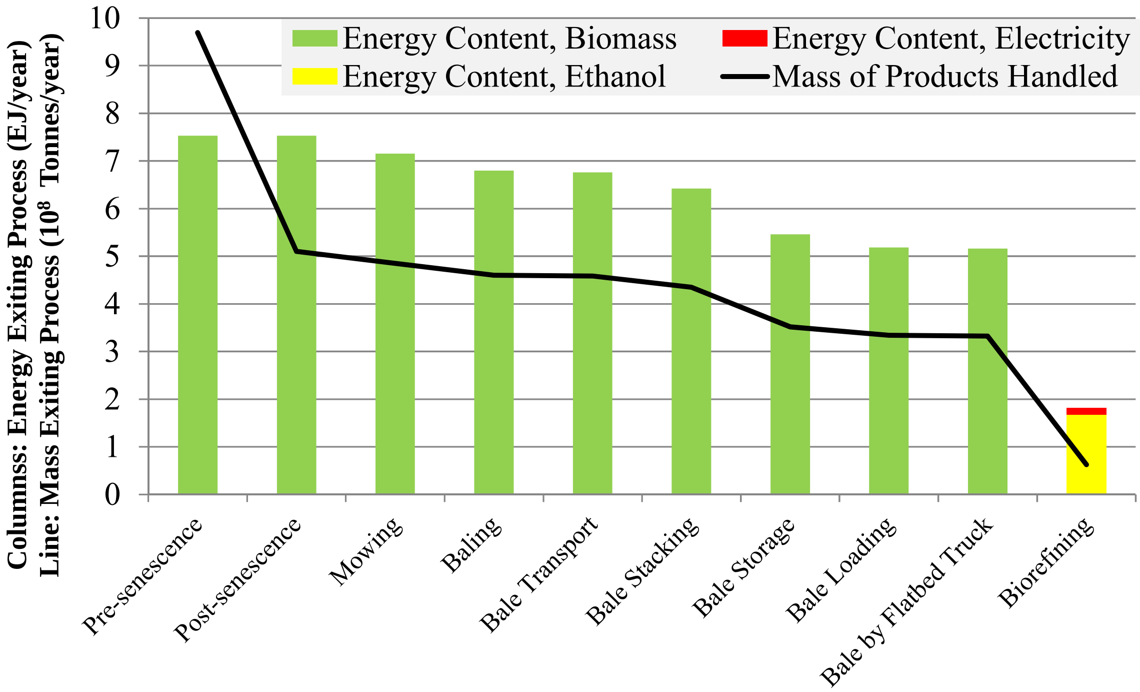


Figure 18. Fate of Miscanthus Mass and Energy by Stage from Field to Biorefinery

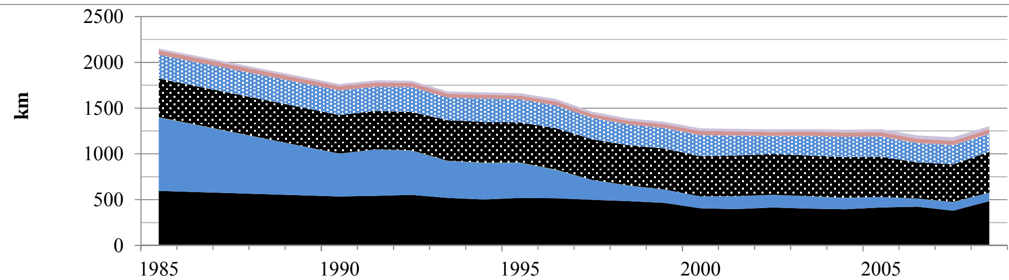
6.3.2 Component Inventory and Transportation Distance Estimates

A simplified distribution system was created for both petroleum fuels and Miscanthus-based ethanol, which was primarily a function of how much fuel is supplied to consumers, where and by what mode feedstock and fuels were transported, and how materials are stored between producer and consumer. A model was then created for the national-level production and consumption of both types of fuel, in order to estimate the fleet of equipment, vehicles, and infrastructure necessary to distribute feedstocks and products at each stage of the supply chain.

6.3.2.1 Petroleum Transportation Baseline

Crude oil is assumed to be stored once prior to transportation to the refining (conversion) facility. After conversion, products are assumed to be held initially in large storage tanks, then transported to a mid-size tank at a blending or holding terminal, prior to being trucked to the final dispensing tank (which is most commonly an underground storage tank at a service station).

In 2008, the aggregate average mode split by t-km for petroleum consisted of approximately 71% pipeline, 22% water, 4% truck, and 3% rail (AOPL 2011), and crude oil typically moved 580 km while products moved 720 km. The exact values used in the model can be found in Figure 19 for year 2008.



	1985	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Product: Railroads	21	22	22	24	24	25	26	26	26	25	27	30	28	29	28	30	32	36	37	33
Product: Motor Carriers	49	48	47	46	44	44	41	45	41	41	42	45	44	44	46	47	47	47	47	50
Product: Water Carriers	259	266	263	270	246	255	253	248	235	226	222	229	217	196	213	222	222	210	210	195
Product: Pipelines	421	421	419	420	444	444	437	453	442	439	447	438	445	444	445	444	438	394	410	445
Crude: Railroads	1.5	1.1	1.3	1.3	1.4	1.2	1.2	1.2	0.7	0.7	0.7	0.6	0.6	0.7	0.7	0.7	0.6	0.6	0.6	1.0
Crude: Motor Carriers	3.2	2.4	2.6	2.7	2.8	2.6	2.6	2.6	2.5	2.3	2.0	1.7	1.6	1.7	1.8	1.7	2.0	2.0	2.3	2.5
Crude: Water Carriers	802	466	505	484	403	400	383	309	217	171	145	130	140	139	133	124	115	90	95	93
Crude: Pipelines	597	536	543	552	519	502	520	516	498	484	465	406	396	415	403	396	415	423	379	484

Figure 19. Average Distance Traveled by Crude Oil and Petroleum Products,[28] 1985-2008 (estimated using data from (AOPL 2011; US DOT BTS 2010; US EIA 2010a, 2011a)).

6.3.2.2 Biomass and Biofuels Transportation Baseline

Biomass feedstock is assumed to be stored once in bale form[29] prior to transportation (84 km by flatbed truck (Kang et al. 2010)) to the biorefinery. After conversion, ethanol is assumed to be held initially in large storage tanks, then transported to a mid-size tank at a blending or holding terminal, prior to being trucked to the final dispensing tank (which is assumed to be a underground E85 storage tank at a service station). The baseline ethanol transportation scenario from biorefinery to fuel blending terminal is described in Table 25 using the CFS and other references[30] as a guide. As

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[28] Shaded areas represent the same information presented in the shaded areas in Figure 10 and Figure 11

[29] Although it is possible that biomass will be densified through pelletization or some other means (which is common if biomass will be directly combusted for electricity production) prior to transportation to biorefineries, the prevailing assumption is that biomass destined for biochemical conversion to ethanol will be transported to biorefinery facilities by truck.

[30] A summary of the recent history of and projections for ethanol distribution according to several publications, in terms of mode split and total distance traveled, can be found in the Background section of this dissertation.

ethanol production and consumption in the United States has more than doubled since 2007 (when CFS statistics were gathered), several states already produce more ethanol than can be consumed in-state as E10. In the baseline ethanol transportation scenario, ethanol is estimated to travel just over 1,400 km (830 miles) from biorefinery to service station, on average, which is double the typical distance petroleum products are transported from refinery to retail station. The distance to "unsaturated" markets may decrease if the blend wall eventually exceeds E10 or if more high-level blends (e.g., E85) are consumed near producers.

Ethanol is currently, and will continue to be, transported primarily by truck and rail, and both modes are typically more expensive and energy intensive than transport by pipeline, which distributes the majority of petroleum t-km in the United States. Ethanol can and has been distributed by pipelines in Brazil and to a small extent in the United States, but the economic infeasibility of constructing new large ethanol pipelines (US DOE 2010), in addition to geographic and fuel chemistry concerns, are among the challenges restricting the likelihood that biofuels will be significantly distributed by pipeline.

Mode	Mass weighted average distance (km)	% of total t-km	Distance if handled by this mode (km)	Approximate % of tonnes handled
Truck (biorefinery to terminal)	190	13%	342 [31]	56%
Rail	1,080	77%	1,973 [31]	55%
Barge	70	5%	973 [32]	7%
Truck (terminal to station)	69	5%	69 [32]	100%
Total	1,409	100%	NA	NA

Table 25. Baseline Typical Ethanol Transportation Scenario in the United States.

6.4 Results

6.4.1 National Component and Emissions Inventory

Table 26 and Table 27 list the fleet stock and annual turnover of components necessary to distribute petroleum and Miscanthus-based ethanol, respectively. These tables also present the GHG emissions and water withdrawals associated with a) the total embodied manufacturing, construction and maintenance of the fleet stock (e.g., resulting from a commitment to replace the entire infrastructure), and b) the annual operation, maintenance, and expected turnover of components for both fuel systems.

[31] Adapted from ethanol summary in (US Census Bureau 2010).

[32] Adapted from gasoline and aviation fuel summary in (US Census Bureau 2009).

Data from Table 26 and Table 27 were used to estimate the annual GHG and water intensity from both fuel distribution systems under steady-state conditions, which are presented from left to write in order of sequential or parallel activities in Figure 20 and Figure 21 (petroleum supply chain GHG and water intensity) and Figure 22 and Figure 23 Miscanthus-based ethanol supply chain GHG and water intensity). While most of the mass and energy content of petroleum fuels is conserved after being extracted and conditioned, biomass undergoes significant water and mass losses at each stage until reaching the biorefinery, as illustrated in Figure 18.

Component Unit	Capacity of One Unit (as modeled)	Fleet Inventory	Annual Turnover	Embodied Emissions and Withdrawals (if fleet were rebuilt)		Annual Emissions and Withdrawals (from turnover, operation and maintenance)	
		(Number of Units)	(Units per Year)	CO_2-e (10^6 t)	H_2O (10^9 L)	CO_2-e (10^6 t)	H_2O (10^9 L)
Tanker, Crude	128 kDWT	860	29	121	8,800	29	470
Pipe, Crude (1 km)	105 t	89,000	1,800	30	840	6.9	460
Truck, Long-Haul Tanker	24.3 t	2,300	440	0.37	21	0.34	5.6
Train, Unit (100-car)	10^4 t	0.85	0.04	0.01	0.5	0.03	0.3
Inland Tow (2-barge)	6 kDWT	620	20	5.8	340	2.8	26
AST, Large Crude	10^6 gal	140,000	5,600	44	1,800	8.7	70
Refinery, Petroleum	10^3 bpcd	16,000	320	200	13,000	6.5	430
AST, Large Product	10^6 gal	100,000	4,100	32	1,300	4	52
Tanker, Product	37 kDWT	383	13	29	2,100	8.9	97
Pipe, Product (1 km)	61 t	185,000	3,700	32	950	7.4	480
Truck, Short-Haul Tanker	24.3 t	44,000	8,600	7.2	410	8.8	140
Train, Unit (100-car)	10^4 t	27	1.4	0.26	16	0.81	8
Inland Tow (2-barge)	6 kDWT	1,300	42	12	700	5.9	55
AST, Mid-size Product	10^6 gal	12,000	480	5.5	220	0.72	9.1
AST, Commercial	10^3 gal	10 million	410,000	36	1,500	2	61
UST, Service	10^3 gal	16 million	660,000	22	1,000	2.5	110
AST, Small	10^3 gal	5.9 million	240,000	8.8	420	0.4	17
Vehicle, Conventional (non-FFV)	15 gal	260 million	26 million	NA	NA	11	49
Sum				580	34,000	110	2,500

Table 26. Crude Oil to Petroleum Products: Estimated Infrastructure and Equipment Fleet Inventory, Annual Component Turnover, Total Embodied GHG Emissions and Water Withdrawals, and Total Annual GHG Emissions and Water Withdrawals. (Total product supplied: 269 billion gallons, 32.9 EJ, 811 million tonnes).

Component Unit	Capacity of One Unit (as modeled)	Fleet Inventory	Annual Turnover	Embodied Emissions and Withdrawals (if fleet were rebuilt)		Annual Emissions and Withdrawals (from turnover, operation and maintenance)	
		(Number of Units)	(Units per Year)	CO_2-e (10^6 t)	H_2O (10^9 L)	CO_2-e (10^6 t)	H_2O (10^9 L)
Mower, with Tractor	44 t/hr	55,000	5,500	1.0	48	1.6	14
Baler, with Tractor	13.2 t/hr	230,000	23,000	25	1,200	8.6	200
Stinger, Bale-transport	260 t/hr	3,500	350	0.25	12	0.35	2.8
Bale Stacker	124 t/hr	7,000	700	0.25	12	0.24	1.9
Bale Storage, Tarp + Asphalt Pad (m^2)	0.4 t	590 million	59 million	8.0	300	0.80	30.3
Bale Loader	124 t/hr	5,400	540	0.19	9.3	0.18	1.5
Truck, Short-haul Flatbed	24.3 t	130,000	11,000	8.6	470	5.6	76
Biorefinery	10^3 bpcd	1,500	51	74	2,800	6.2	230
AST, Large Product	10^6 gal	7,900	320	2.5	99	0.31	4
Truck, Long-Haul Tanker	24.3 t	11,000	2,100	1.8	99	1.7	27
Train, Unit (100-car)	10^4 t	56	2.8	0.54	33	1.7	17
Inland Tow (2-barge)	6 kDWT	29	1	0.28	16	0.13	1.3
AST, Mid-size Product	10^6 gal	3,400	137	1.6	63	0.21	2.6
Truck, Short-Haul Tanker	24.3 t	3,900	767	0.64	36	0.78	12
UST, E85	10^3 gal	1.05 million	42,000	25	1,300	0.50	17
Vehicle, Flex-fuel	15 gal	58 million	5.8 million		NA	1.4	6.3
Sum				**150**	**6,500**	**30**	**640**

Table 27. Miscanthus to Ethanol: Estimated Infrastructure and Equipment Fleet Inventory, Annual Component Turnover, Total Embodied GHG Emissions and Water Withdrawals, and Total Annual GHG Emissions and Water Withdrawals. (Total ethanol supplied: 21 billion gallons, 1.7 EJ, 63 million tonnes).

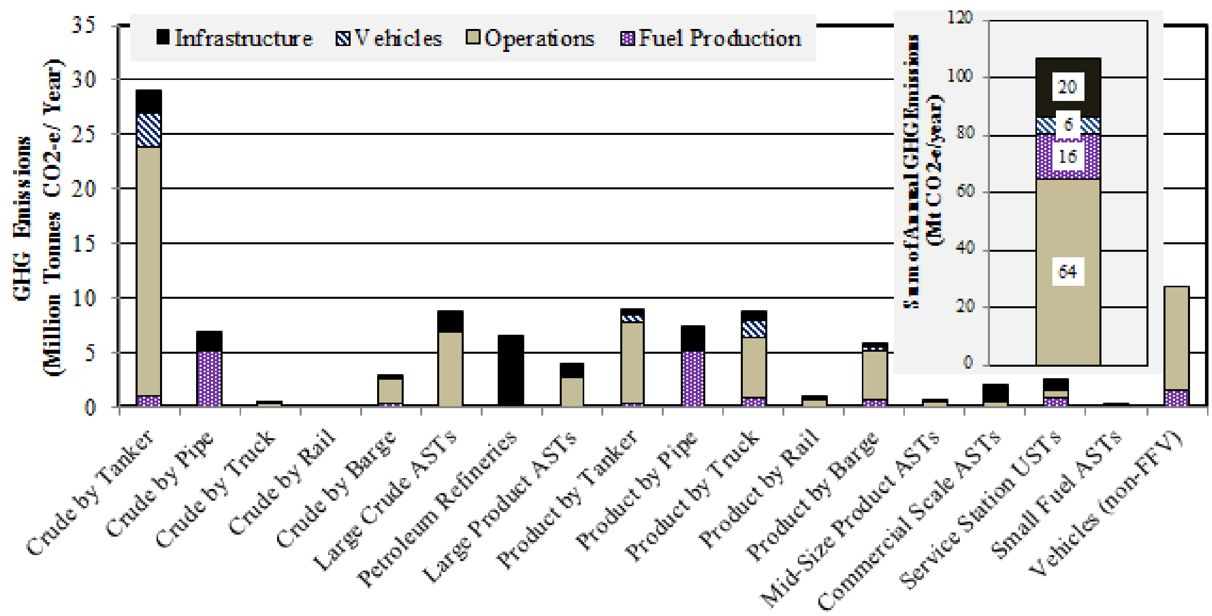

Figure 20. Annual Steady-state GHG Emissions by Stage for Crude Oil to Petroleum Products Scenario[33] (left to right).

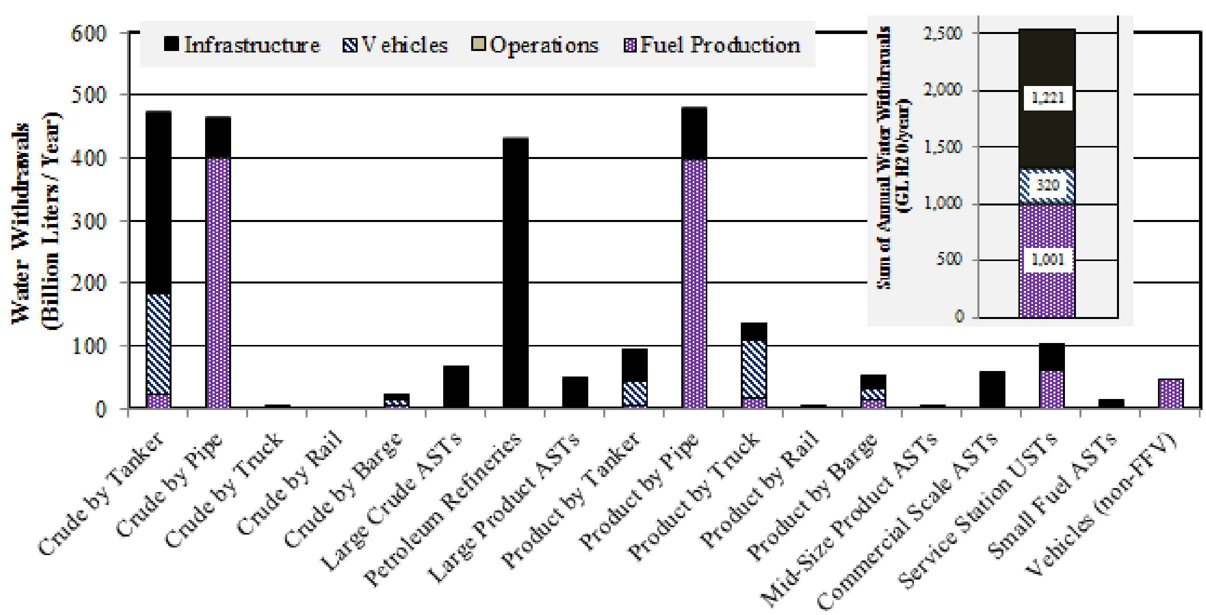

Figure 21. Annual Steady-state Water Withdrawals by Stage for Crude Oil to Petroleum Products Scenario[34] (left to right).

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[33] Columns sum to the corresponding value in the second right-most column of Table 26.

[34] Columns sum to the corresponding value in the right-most column of Table 26.

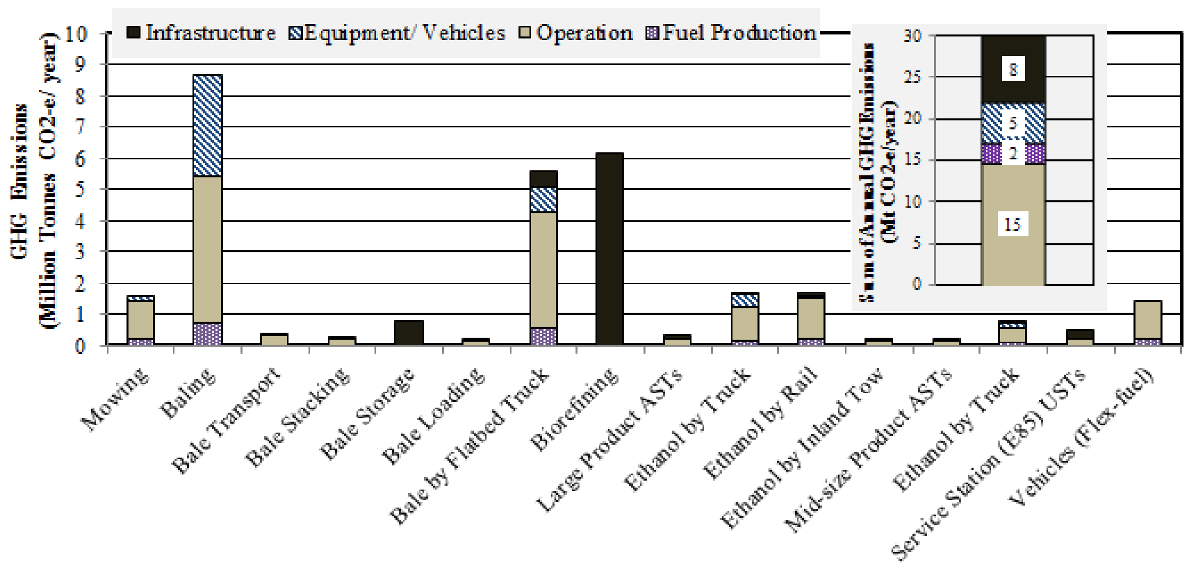

Figure 22. Annual Steady-state GHG Emissions by Stage for Miscanthus to Ethanol Scenario[35] (left to right).

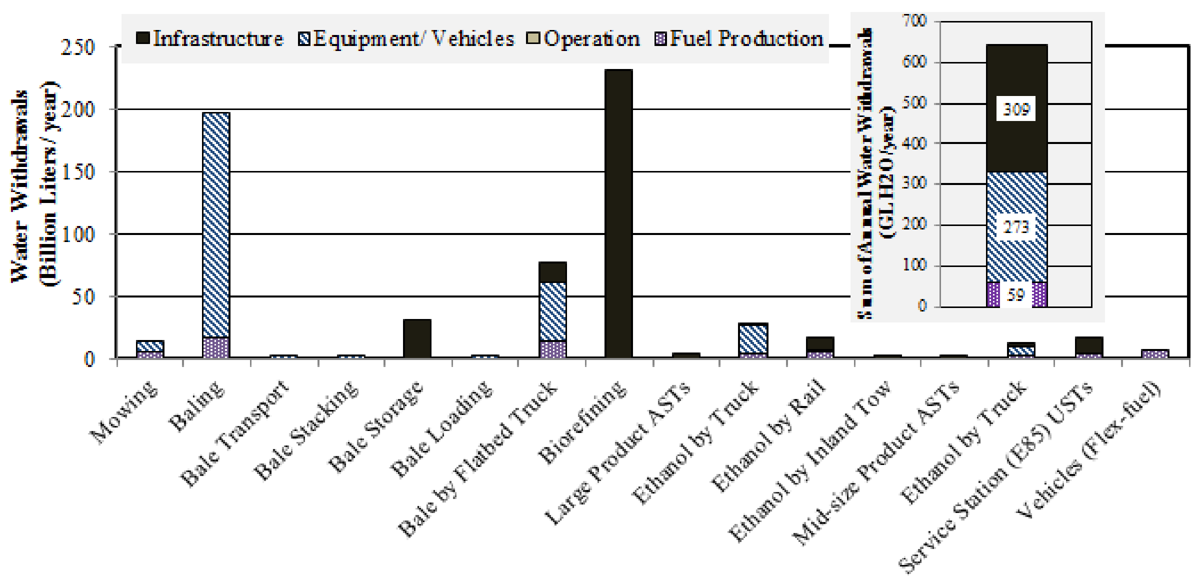

Figure 23. Annual Steady-state Water Withdrawals by Stage for Miscanthus to Ethanol Scenario[36] (left to right).

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[35] Columns sum to the corresponding value in the second right-most column of Table 27.
[36] Columns sum to the corresponding value in the right-most column of Table 27.

6.4.2 Contribution of Infrastructure and Equipment to the Fuel GHG Footprint

In order to put results from Figure 20 and Figure 22 into units more familiar to environmental policy analysts, total system emissions were divided by the energy content of delivered products, to estimate the average contribution of infrastructure and distribution systems to the life-cycle carbon footprint of both types of fuel products, which can be found in Figure 24. Only one allocation scheme for petroleum product was considered (G1), as total system emissions are smaller for petroleum than ethanol on a relative and absolute scale. Ethanol is expected to make up 92.5% of the energy output and 95% of the market value of energy products leaving a ligno-cellulosic biorefinery, while electricity makes up the balance of output (assuming $2.15 per gallon of ethanol and $0.06 per kWh) (Humbird et al. 2011). Figure 24 presents several alternative approaches to allocating emissions between ethanol and electricity (E1-E4), and also shows the maximum likely GHG offset that ethanol may receive if the export of electricity to the grid displaces demand for regional baseload electricity (O1, O2).

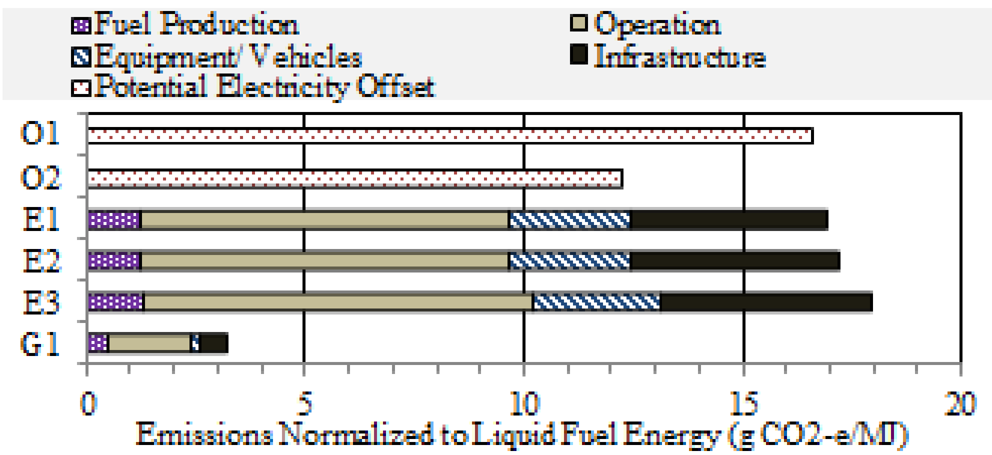

Figure 24. Contribution of Distribution System Emissions and Potential Electricity Offsets to the Life-cycle GHG Footprint of Gasoline and Miscanthus-based Ethanol.[37]

6.4.3 Summary

All petroleum infrastructure and distribution activities result in just over 100 million tonnes of CO_2-e emissions each year (equivalent to less than 5% of all petroleum combustion emissions). When

[37] Energy-normalized system emissions for gasoline [G1] were allocated by MJ. Options for allocating GHG emissions to ethanol from feedstock collection, biorefinery construction and maintenance, and post-biorefinery fuel distribution activities include: [E1] allocation of feedstock and biorefinery by MJ, and 100% of post-biorefinery to ethanol; [E2] allocation of feedstock by MJ, and 100% of biorefinery and post-biorefinery to ethanol; [E3] allocation of 100% of feedstock, biorefinery, and post-biorefinery to ethanol. Biorefinery electricity exports may reduce net emissions allocated to ethanol by [O1] offsetting Midwest (MRO) baseload electricity (222 g CO_2-e/MJ electricity), or [O2] offsetting US average baseload electricity (164 g CO_2-e/MJ). Baseload electricity emissions were estimated from US EPA (2010d).

normalized to the energy content of supplied fuel, importing crude oil by tanker is the highest emitting activity, contributing 0.9 g CO_2-e/MJ towards the total of 3.2 g CO_2-e/MJ. The sum of (previously overlooked) embodied emissions from equipment, vehicles and infrastructure components total 25% of emissions (0.8 g CO_2-e/MJ). Additionally, typical (1 km) refueling errands were estimated to contribute more than 10% (0.34 g CO_2-e/MJ) to the total footprint, so emissions reductions from improving consumer refueling habits may be comparable to improvements from major infrastructure and logistics optimization. If all distribution components were replaced, the emissions from construction and manufacturing would amount to less than four months' worth of emissions from all US petroleum combustion.

All miscanthus-based ethanol infrastructure and distribution activities result in approximately 30 million tonnes of CO_2-e emissions each year. The energy-normalized life-cycle GHG emissions from the Miscanthus-ethanol distribution system are five times greater than petroleum, totaling between 17 and 18 g CO_2-e/MJ of supplied ethanol. Activities resulting in the greatest emissions include mowing (0.9 g CO_2-e/MJ), baling (5.1 g CO_2-e/MJ), bale transporting (3.3 g CO_2-e/MJ), biorefinery construction and maintenance (3.7 g CO_2-e/MJ), and ethanol distribution by truck (1.0 g CO_2-e/MJ) and rail (1.0 g CO_2-e/MJ). Embodied emissions make up 43% of life-cycle emissions (up to 7.8 g CO_2-e/MJ), 29% of which take place pre-biorefinery, 50% from biorefineries, and 21% post-biorefineries.

Minimization of water withdrawals is not a common policy priority for alternative fuels, and the quality of water withdrawal data (and the meaningfulness of these data as indicators of environmental impact) is lower than GHG data. However, it is worth noting that the biofuel distribution system was estimated to be approximately five times more water withdrawal-intensive than the petroleum system (i.e., 380 L/MJ vs. 77 L/MJ).

As Figure 24 shows, if distribution-related emissions are allocated between electricity and ethanol, it makes little difference at which stage and by which metric (e.g., energy content or market value), as ethanol is the dominant output economically and energetically. However, if demand for conventional baseload electricity declines due to biorefinery electricity production, carbon reduction credits could offset more than 70% of the emissions accounted for in this study (similar to the findings of reference (Scown et al. 2012)). It would not be reasonable to credit ethanol with such emissions savings if biomass-based electricity supply reduces demand for other "clean" electricity options (e.g., wind and solar) due to policy or economic forces (e.g., Renewable Portfolio Standards as discussed by (Lemoine et al. 2010)).

6.5 Sensitivity Analysis

In order to determine if emissions from distribution activities are significant and flexible relative to other decision points in fuel production and consumption systems, a few options were evaluated to determine which changes may yield the greatest emissions reductions.

6.5.1 Feedstock Transportation from Field to Biorefinery

Due to the low mass density, high moisture and high molecular oxygen content of biomass (whether loose or baled), it is common to hear that biorefineries may not be profitable if feedstock is transported much more than 50 miles (80 km). For the same reasons, the contribution of feedstock transportation to the total carbon footprint of the biofuel production system is significant and sensitive to transportation distance. Assuming that biomass bales will be transported a minimum of 20 km, and a maximum of 193 km (Kang et al. 2010), Figure 25 shows that the GHG emissions from biomass transportation to biorefineries are expected to range from 1-7 g CO_2-e per MJ of ethanol supplied. While biomass densification would reduce per-mile biomass transportation costs and emissions, it may be more expensive for biorefineries to process dense (e.g., baled) biomass than loose biomass; alternatively, harvesting and transporting moist (green) biomass would increase transportation costs, but could reduce (direct) biomass energy losses (Shastri et al. 2010).

6.5.2 Biofuel Transportation from Biorefinery to Blending Terminal

Several different ethanol supply scenarios were considered (and described in Table 28), in order to assess the significance of the mode, distance, and alternative biofuel types on the distribution footprint for a biofuel. The emissions attributed to each distribution scenario are presented in Figure 25. Transporting ethanol by 25" diameter pipeline from the Midwest to the Northeast United States would serve as a very low-carbon long-distance transportation option, though such a pipeline was proposed and found to be economically unviable, even if operated for 40 years (US DOE 2010). As may be expected, the lowest feasible carbon footprint contribution from the biorefinery-to-terminal stage (0.7-1.1 g CO_2-e/MJ) would result from consumption within the region of production. This result aligns well with the average emissions estimated (0.8 g CO_2/MJ) in an ethanol distribution optimization study (Wakeley et al. 2009). In the GREET model, ethanol is assumed to travel 875 km on average from biorefinery to terminal (20% of trips by truck, 40% by barge, 40% by rail), and trucked 48 km to fueling stations, resulting in slightly higher emissions of 1.4 g CO2-e/MJ. If the emission factors in Figure 17 are applied to GREET's default distances, the result would coincidentally be identical. However, GREET did not account for vehicle and infrastructure emissions (0.2 g/MJ), and our modal energy intensities per t-km (from) are 12% higher for rail, 9% lower for long-distance truck, 15% higher for short-distance truck, and 31% lower for barge compared to GREET. Assuming it will remain difficult to find "unsaturated" ethanol markets due to blend wall constraints and limited demand for high-level blends near producers, the default total biorefinery-to-station distance in this paper (Table 25) is 50% greater than GREET's default, and results in 2.2 g CO_2-e/MJ.

Although the United States became a net ethanol exporter in 2011 and Brazil has been importing an increasing amount of ethanol, trade of ethanol between the two largest global ethanol producing and consuming countries is likely to be advantageous for economic and/or security goals at times in the future. Although the shipping distance between Brazil and the United States is more than four times the surface transportation distance between the US Midwest and California, the CO_2-e emissions from an ethanol tanker would be less than twice the emissions of a Midwest-to-CA train (and less than half the emissions from a truck). If ethanol were shipped in crude tankers (i.e., larger than 100,000 DWT), emissions from this trip would actually be less than the emissions from Midwest-to-CA rail transport. This result is consistent with the finding that domestically sourced goods tend to have lower life-cycle emissions than imported goods (assuming identical production emissions), only if international suppliers are more than six-times farther away than domestic suppliers (Hawkins and Dente 2010).

Lastly, if conversion facilities produce fuels such as iso-butanol or biogasoline, emissions from product transportation would be 26% or 38% lower, respectively, due to their energy density advantage over ethanol. In fact, emissions reductions may be greater in the long-term, if opportunities to "drop in" butanol or bio-gasoline to existing petroleum pipelines and tanks become available.

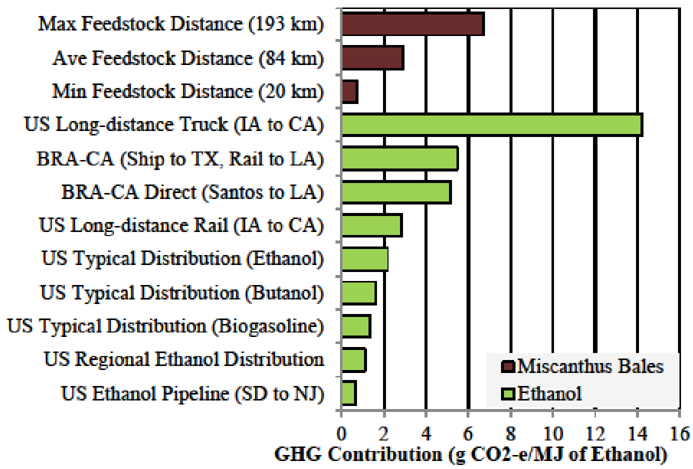

Figure 25. Contribution of Biomass Feedstock and Biofuel Product Transportation to the GHG Footprint of Ethanol for a Range of Possible Distances. (100% of emissions are assumed to be allocated to ethanol).

	Pipeline	Tanker	Truck	Rail	Barge	Total
	(km)	(km)	(km)	(km)	(km)	(km)
US Pipeline (South Dakota to Philadelphia)	1,700					1,700
US Regional Consumption			100	520		620
US Typical Distribution (Bio-gasoline)			190	1,080	70	1,340
US Typical Distribution (Butanol)			190	1,080	70	1,340
US Typical Distribution (Ethanol)			190	1,080	70	1,340
US Long-distance Rail (Iowa to California)				2,729		2,729
Brazil-California Direct (Santos to Long Beach)[38]		13,555				13,555
Brazil-US Typical (Santos to Houston; Houston to Long Beach or Philadelphia)		10,100		1,600		11,700
US Long-distance Trucking (Iowa to California)			2,729			2,729

Table 28. Biorefinery (or International Port) to Blending Terminal Transportation Scenarios (used in Figure 25).

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[38] The same result would be expected if ethanol were transported from Mozambique to either Amsterdam or Puerto Rico, or from Panama to Japan.

6.5.3 Motor Vehicle Refueling Errand

Although the boundary of most transportation fuel LCA studies stop at the retail station pump, it is also important to assess the significance of the final decision in the distribution chain for fuels made by consumers. The service station errand is unique to transportation fuels, as future scenarios for electric vehicles (EVs) typically involve charger stations where people live or work (except for EV deployment models that incorporate battery switching stations, e.g., (Better Place 2011)). While much of the fuel distribution system is supported by professional analysts and computer programs that work to optimize the efficiency of distribution logistics, most consumers do not choose to purchase gasoline based entirely on the least cost path to an operating retail station. In one survey, 79% of consumers list brand or price as the most important factor when deciding where to buy gasoline, whereas only 19% list the location of the station (NACS 2011a). Additionally, more than 25% of consumers stated that they would drive 10 minutes out of the way to save $0.03/gallon on fuel. It was therefore deemed reasonable to assume that the typical consumer drives 1 km out of their way, "worst case" consumers drive 10 km (6.2 miles), and "best case" consumers drive less than a city block to the closest fuel pump. Figure 26 shows that the energy-normalized emissions from a 10 km errand to purchase 10 gallons of fuel (6-9 g CO_2-e/MJ) would be greater than the emissions from importing fuel 10,000 km by sea (e.g., from Brazil).

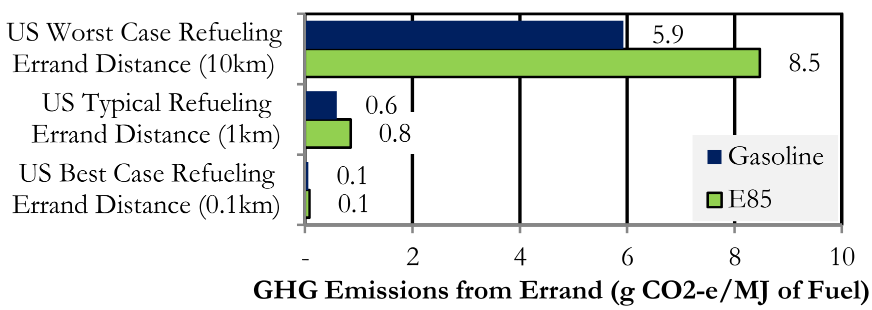


Figure 26. Contribution of Motor Vehicle Refueling Errand Distance to GHG Footprint of Purchased Fuel (assuming vehicles operate with conventional gasoline prior to refueling).

6.6 Discussion

The amount of energy supplied to the United States by all petroleum products is approximately 20 times more than Miscanthus-based ethanol is proposed to provide in 2022. Yet, the annual and total embodied GHG emissions and water withdrawals from petroleum infrastructure and distribution are only four times greater than the corresponding emissions from the Miscanthus-to-ethanol system. The higher emissions-intensity of the ethanol distribution system result from the relatively high capital and operating energy intensity (and expenses) for handling and distributing each unit of energy. However, the greater efficiency of the petroleum distribution system is not enough to render the life-cycle GHG footprint of petroleum products comparable to that of ligno-cellulosic biofuels. Extraction and refining operations for petroleum contribute on average 11-18 g/MJ for residual oil, diesel, kerosene and gasoline (NETL 2008; US DOE ANL 2010), and vehicle tailpipe emissions of fossil carbon range from 72.8 g/MJ for gasoline to 80.6 g/MJ for residual oil (US DOE ANL 2010)).

7 EVALUATION OF US DOMESTIC ETHANOL TRADE[39]

As was mentioned in the *Introduction*, current policy drivers supporting ethanol production and consumption in the United States revolve around national goals to 1) reduce global greenhouse gas emissions, 2) encourage domestic economic growth (especially in rural areas), and 3) reduce dependence of the US transportation sector on many oil exporting countries. The ideal policies to achieve these goals would incentivize the cheapest and least energy intensive national scenario for distributing ethanol from producers to consumers, as "[t]he promotion of renewable fuels must not undermine the quest for energy efficiency" (Szklo et al. 2007). In comparison to a scenario in which ethanol is consumed locally near producers, geographically dispersed consumption would result in greater total distribution costs and emissions, as every km that ethanol is transported adds to the cost of retail ethanol, and freight transportation modes rely heavily on imported and carbon-intensive petroleum diesel. Although the distribution of ethanol is commonly estimated to contribute much less than 5% to the total cost and life-cycle greenhouse gas (GHG) footprint of ethanol (i.e., less than \$0.005/MJ (Morrow et al. 2006; Wakeley et al. 2009) and less than 1 g CO_2-e/MJ (Spatari et al. 2005; Wakeley et al. 2009)), improvements to this stage would be significant as US ethanol production has exceeded one trillion MJ annually since 2010 (RFA 2011). However, ethanol consumption in non-producer regions has been encouraged by federal, state and local government mandates and subsidies, in addition to non-governmental commitments by private organizations that operate vehicle fleets.

A combination of political, economic, and infrastructure constraints have resulted in geographically dispersed consumption of low-level ethanol–gasoline blends throughout the United States. Federal and state policies have influenced where ethanol is produced and consumed for decades. From 1980 through 2007, many states offered production subsidies that made ethanol plants more viable in locations that may otherwise have been cost-prohibitively far from feedstocks and/or consumers (Cotti and Skidmore 2010). From 1984 through 1993, state-level ethanol consumption subsidies (ranging from zero to over \$0.40/gallon) and regional oxygenate requirements led to dispersed demand and high transportation costs for ethanol (Rask 1998). Although the oxygen content requirement for reformulated gasoline was removed at the end of 2005 with the passage of the Energy Policy Act (US EPA 2006a), dispersed consumption of ethanol continued to be encouraged by federal policy through this act's renewable fuel standard (RFS1) by creating renewable volumetric obligations (RVO) for fuel blenders, which were later updated in the Energy Independence and Security Act (EISA) of 2007 (R. Schnepf and B. Yacobucci 2010). Independent of subsidies and mandates, ethanol increasingly needed to be transported away from Midwest producers over the last decade to avoid exceeding the "blend wall." (The blend wall is the maximum limit of ethanol that can be blended into common gasoline for use in the existing fleet of motor vehicles. For the last four decades, the US blend wall has been E10 – i.e., 10% ethanol by volume, 7% ethanol by energy, and 3.5% oxygen by mass).

[39] Much of the material in this chapter was included in an article, "Fuel Miles and the Blend Wall: Costs and Emissions from Ethanol Distribution in the United States," which was published in the journal, *Environmental Science & Technology*, in 2012 (Strogen et al. 2012); the publisher, the American Chemical Society, permits authors to reproduce material for incorporation into academic theses.

Assuming that fuel economy is purely a function of fuel energy content, frugal consumers seek to minimize travel costs per kilometer by purchasing fuel at the lowest cost per MJ (such that ethanol would be priced at 67% of gasoline's per-gallon price). However, consumers were rarely able to express this preference, as ethanol–gasoline blends are rarely labeled by ethanol content and/or sold side-by-side with ethanol-free gasoline. For comparison, fuel blenders seek to minimize input costs for finished gasoline. As consumers could not discount gasoline commensurate with its ethanol content at blends below E10, blenders near producers were found to discretionally "splash" more ethanol into gasoline than was required when ethanol was cheaper than gasoline on a volumetric (but not necessarily energetic) basis (Walls et al. 2011). So long as ethanol is more expensive than gasoline per gallon, which has been true for most of the last few decades, fuel blenders' interests aligned with consumers' interests and ethanol would be found at the minimum percentage required by law. It should be noted that some consumers under-discount ethanol for a variety of reasons, such that they are paying a higher price per MJ from ethanol than gasoline. Evidence of under-discounting has been found in Brazil (Salvo and Huse 2011), Iowa (Gallagher 2007), Minnesota (Anderson 2010), and for various ethanol–gasoline blends throughout the United States (E85Prices.com 2012), though few consumers are willing to purchase ethanol at the same per-gallon price as gasoline.

The final stage of a comprehensive life-cycle assessment consists of interpretation and improvement analysis, where opportunities are identified to reduce environmental impacts. Given the circumstances just described, and details on technical considerations for using ethanol presented in the following section, reducing incentives for "unnecessary" transportation of (ethanol) fuel is expected to be the easiest manner of reducing emissions from the ethanol distribution system. While other LCA studies have addressed the systems-related consequences of demand for resources such as land or commodities, this project aims to explain the policy influences on ethanol distribution, in order to assess the consequences of different policy scenarios on demand for transportation services and associated environmental impacts. This section then presents modeling estimates of total historic and minimum necessary annual interstate ethanol trade in the United States (7.3.1) and tonne-kilometers (t-km) of domestic ethanol transportation (7.3.2) over the last decade. Additionally, the difference in cost, fuel consumed, air pollutants emitted and resulting health costs between the two distribution scenarios is estimated (7.3.3). In order to make results relevant to decision makers at a centralized (e.g., federal) level or local (e.g., state) level, a marginal sensitivity analysis was performed to understand the significance and potential rebound effect of single decisions makers (e.g., states) on total nation-wide distribution system activity (7.3.4).

7.1 Potential Justifications for Transporting Ethanol Away from Producers

We completed a literature review to assess whether policy-makers (and consumers) far from producers should differentiate low-level ethanol–gasoline blends from ethanol-free gasoline by characteristics other than energy density and life-cycle GHG emissions. Ethanol–gasoline blends, primarily those below 15% ethanol v/v, were evaluated in terms of engine performance, regional economic, and regional environmental considerations. Engine performance metrics include fuel economy, octane number (decreased risk of knocking), flame propagation and power output (related to acceleration potential), and engine reliability and longevity. Regional considerations include proximity to low-cost distribution infrastructure (e.g., pipelines or waterways) that may enable ethanol to be less expensive relative to gasoline far from producers, or air quality conditions that enable ethanol to offer greater public health benefits relative to gasoline (as was the case when gasoline in certain regions was initially required to contain oxygenates under the 1990 Clean Air Act Amendments). The literature reviewed did not conclusively show that low-level blends offered engine performance, economic or air quality benefits that justified transporting ethanol away from producers after the year 2000. Although variations in regional fuel requirements have led to distribution challenges for gasoline (US GAO 2005) which is predominantly distributed by low-cost energy-efficient pipelines, excessive distribution of ethanol by less efficient modes (truck, rail and barge) could have more severe economic and environmental implications for the country. The following subsections summarize the characteristics of ethanol that could (hypothetically) be used to justify the transport of ethanol from producer regions (e.g., the Midwest) to consumers in non-producer regions (e.g., the coasts).

7.1.1 Engine Performance Impacts

Engine performance metrics include characteristics such as fuel economy, octane number (decreased risk of knocking), flame propagation and power output (related to acceleration potential), and expected engine life. If performance is undesirable at very low level blends, a minimum threshold for ethanol blending (e.g., E5) may help prevent problems, so geographically "patchy" ethanol consumption may be justified. As one example, water contamination of the fuel has a higher potential to cause phase separation in low level blends (e.g., E3) than higher level blends (e.g., E20); this risk has been more of a concern in Brazil (where hydrated ethanol has been used) than in the United States (where neat ethanol is used) (Szklo et al. 2007).

Alternatively, if performance improves with the addition of ethanol up to an optimal ethanol blend, but decreases at higher ethanol concentration, dispersed consumption would be justified. This phenomenon has been found for mid-level blends in conventional engines (Turner et al. 2011), and properly tuned engines obtained energy efficiency gains that more than compensated for decreased energy density around E30 (Szklo et al. 2007), but local performance maximums have not been found at blends below E10. Even at blends of E85, energy-based fuel efficiency has been found to be up to 9% greater than gasoline alone, by making changes such as configuring an engine with a turbocharger (IEA ETSAP 2010). If mid- or high-level ethanol gasoline blends are found to combust more efficiently than common gasoline (on an energy basis), it would be advisable consume more ethanol in FFVs and less ethanol in the form of low-level blends.

7.1.2 Regional Technical Considerations

If regionally heterogeneous infrastructure (e.g., pipelines or waterways that only serve a few markets) enable the relative cost difference between ethanol and gasoline to favor ethanol in distant markets more so than in markets near producers, long-distance ethanol transportation could be justified. As ethanol has been shipped almost entirely by rail and truck, and both modes are available throughout the country, it is unlikely that infrastructure availability justified a significant percent of domestic ethanol transportation. Alternatively, if ethanol-induced changes to air quality in non-producer regions (e.g., coastal cities) result in more public health benefits than would be expected from consumption of ethanol close to producers, long-distance ethanol transportation could be justified. This is the premise behind historic oxygenate mandates, though ethanol has been known to exacerbate certain air quality problems for more than ten years, and EPA models suggest that increased ethanol usage will continue presenting air quality trade-offs (see 2.3.2).

7.1.3 Regional Policy and Economic Considerations

If a lack of well-known, trusted, effective political or economic mechanisms (e.g., a carbon tax, carbon market or tradable domestic or renewable energy credits) render it difficult for nationally or globally minded decision makers (e.g., state policy makers, companies, or consumers) to exert demand towards accomplishing these goals, physical distribution of ethanol could be justified. The RFS1 established a system allowing fuel blenders to meet their obligations without physically blending biofuels by trading credits known as renewable identification numbers (RIN) (R. Schnepf and B. Yacobucci 2010). Much like renewable energy credits (REC) were created for tracking and trading units of renewable electricity (without attempting to track the electrons), RINs could save costs and emissions associated with supplying biofuels to remote consumers. Corn ethanol RINs were only valued at fractions of a penny (per gallon) when first implemented in 2007 (Heinsohn et al. 2009), peaked at over $0.17 in 2009 (US DOE OPIA 2011), dropped below $0.01 in 2010, and returned to $0.03-$0.04 in 2011 (McPhail et al. 2011), and their value has historically been correlated with the price spread between ethanol and gasoline blendstock (US DOE OPIA 2011). Because the current study does not extend beyond 2009, the RIN program did not exist for most of the years evaluated. However, if used effectively, RINs may reduce ethanol transportation costs up to 50% (or $400 million in 2011) (Figer 2011) by allowing non-producers to demand and "consume" ethanol without physically importing it. Such economic mechanisms may not be fully utilized if policy makers or consumers are willing to pay a higher premium to directly purchase ethanol in non-producer regions (e.g., the coasts) than in producer regions (e.g., the Midwest), whether or not the product is seen or noticed by consumers.

7.2 Method of Modeling US Ethanol Trade

Modeling exercises were performed to determine when, and to what degree, the blend wall served as a significant influence on distribution of ethanol in the United States in recent years. In order to build a simple but informative model, several assumptions were made and are described below. Data sources and algorithms for defining variables used in this analysis can be found in Appendix 10.3.1. A description of how the national trade network was constructed is then presented, and is followed by an explanation of the approach used in optimizing ethanol distribution and estimating impacts associated with alternative distribution scenarios.

7.2.1 Modeling Assumptions

7.2.1.1 Ethanol is considered perfectly substitutable with conventional gasoline on an energy basis in terms of fuel economy, performance, and emissions up to the E10 blend wall.

Consistent with most existing literature discussed in Section 2.3.2, the fuel economy and air emissions of vehicles operating with gasoline containing various ethanol blends was assumed to be commensurate with the energy content of the fuel. The perfect substitutability assumption (up to E10) has also been used in recent economic studies on ethanol and gasoline market dynamics (Lapan and Moschini 2012). However, as discussed in Section 2.3.2, recent engine tests have shown that there may be a non-linear relationship between the energy content of ethanol–gasoline blends and the energy-based fuel economy of vehicles.

If ethanol's value as a performance-enhancing additive (e.g., octane) is greater than its value as a bulk replacement for gasoline, it would be optimal for fuel blenders around the country to purchase ethanol instead of fossil fuel derived fuel additives (e.g., aromatics, olefins, or highly branched paraffins (Wallington et al. 2006)). Additionally, if ethanol–gasoline blends result in less harmful air emissions than would be found with conventional (ethanol-free) gasoline in certain regions (as was historically common for densely populated CO non-attainment areas), it would also be optimal to transport ethanol to these regions. As discussed in Section 2.3.2, we have not found convincing evidence that ethanol currently offers unique performance or emissions advantages (after accounting for increased volatile losses due to the increased vapor pressure of ethanol blends), but recognize that these assumptions may be controversial.

Ethanol is still regarded by many as a valuable fuel additive due to its contribution of octane, oxygen, and its impact on fuel emissions. In the past, ethanol or other additives were necessary to fill the "octane deficit" of refinery gasoline (Gallagher et al. 2003). Ethanol has been more expensive than gasoline on an energy-basis for all but a few brief periods throughout the current study period (Walls et al. 2011), and we assume it has also been more expensive than competing additives produced from conventional feedstocks. Nevertheless, economic analyses performed in the last six years have assumed that the oxygen content of ethanol warrants up to $0.25 premium per gallon over gasoline blendstock (Hurt et al. 2006), despite the removal of the oxygenate requirement in reformulated gasoline. Ethanol's value is expected to decline up to 25% once its value as an additive is overshadowed by its role as a bulk gasoline substitute, and E10 may define the upper limit of the market segment in which ethanol is price competitive with gasoline on a volumetric basis (Gallagher 2007).

7.2.1.2 Demand for ethanol and gasoline were considered fixed at the national level, so transportation costs and emissions should be calculated and allocated using a national network model instead of isolated producer-consumer exchanges.

Until renewable fuels are produced with a GHG footprint much less than half that of petroleum, the fuel transportation stage from producer to blending terminal will contribute relatively little to the total carbon footprint of the fuel, and is typically calculated on a case-specific basis or by assuming a typical national distance (applying per t-km factors such as those presented in Section 5.5). This same approach is often used to estimate inputs for activities related to farming (e.g., off-road diesel, water and chemicals) and biorefining (e.g., electricity, heating). By using this simple approach, opportunities to reduce transportation emissions have been "off the radar" of most analysts, which is why analyzing these emissions on a national network level is useful. Over the last few years, the "consequential" impacts of biofuel demand on activities in other sectors (e.g., agricultural commodity price increases, land use change) have been modeled and found to be of significant concern. As has been assumed for commodities and available land, in this study we assume transportation services are substitutable but constrained.

7.2.1.3 Ethanol has been consumed almost exclusively (more than 99%) in the form of gasoline blends containing less than or equal to 10% ethanol by volume.

In 2011, the EPA approved the use of E15 in motor vehicles made in 2001 or later (US EPA 2011a), but more than 99% of ethanol continues to be consumed as a low-level (10% or less) blend with common motor gasoline. Retail fueling stations that offer E85 have been growing rapidly over the last few years (increasing tenfold since 2004, from 200 to more than 2,100 in 2010 (US DOE AFDC 2010a)), but still make up less than 2% of all stations in the US (US DOE AFDC 2010b). Although light duty consumption of E85 more than doubled from 1.22 to 2.63 trillion BTU from 2008 to 2010, it still made up less than 0.3% of ethanol sold in the US (US EIA 2011b). As a result, this assumption could reasonably apply to similar models through year 2011.

7.2.1.4 If policies governing ethanol supply were formulated to minimize total national costs and GHG emissions, and implemented with perfect efficiency, fuel suppliers would minimize ethanol transportation.

Although subsidies and mandates for ethanol are not as variable from state to state as they were in the 1980s, several states still subsidize ethanol (through production subsidizes, infrastructure subsidies, and fuel blending mandates), and the implementation of the RFS requires each fuel supplier to meet a certain biofuel blend. Although the renewable identification number (RIN) trading program was created to eliminate the need for physical transportation and consumption of ethanol, the cost for fuel suppliers to learn and participate in the RIN program may have prevented it from being fully utilized during its initial years.

Some advocates for environmental and economic causes often express a desire for consumers to purchase goods that were produced locally, though the environmental and economic merit of these claims have not been well substantiated for fuels. In contrast to food products, for which transportation from producer to final consumer makes up only 9%-50% of total supply chain t-km (Weber and H. S. Matthews 2008), biofuel feedstocks (e.g., corn and grasses) are typically sourced locally (under 100 km) because of their low density, low value, and low degree of quality differentiation. However, ethanol is often transported more than 1,000 km to consumers. Although byproducts from corn biorefineries known as dried distillers grains with solubles (DDGS) make up 1/3 of the output of biorefineries, they are predominantly used to supply animal feed markets that are not directly impacted by regional fuel policies.

7.2.1.5 Gasoline marketers near ethanol producers have had the infrastructure to absorb ethanol–gasoline blends up to the E10 blend wall, and the E10 blend wall was the only significant constraint to increasing local ethanol consumption through (at least) 2009.

E10-compatible infrastructure, including storage, blending and dispensing equipment, was assumed to (potentially) exist in states close to ethanol producers such that more ethanol could have been consumed locally. Evidence of this assertion was found in the period from 1999 to 2008, during which time the price of ethanol ranged from 0.75 – 2.5 times the price of gasoline per gallon; wholesale fuel terminals were found to discretionarily blend (aka "splash") more ethanol into gasoline than was legally required when ethanol was cheaper than gasoline on a volumetric basis, though terminal operators did not necessarily use blending proportions that would be optimal for engine or environmental performance (Walls et al. 2011). Even if infrastructure was historically limiting (around the Midwest), it could be argued for the sake of reducing national-level costs and greenhouse gas emissions, the infrastructure investments that took place in coastal states could have more appropriately been directed closer to ethanol producers.

7.2.1.6 Storage costs have a negligible impact on optimizing domestic ethanol distribution.

Although resolving trade activity on a monthly basis may be appropriate for hemisphere-to-hemisphere trade (in which both parties could reduce seasonal storage inventory costs), it was not deemed worthwhile to resolve state-to-state trade beyond annual statistics, as the seasonality of harvesting corn and other ethanol feedstock crops is assumed to be relatively similar throughout the country. It is also worth noting that the embodied greenhouse gas emissions from constructing and maintaining storage infrastructure is very small in comparison to other life-cycle stages, assuming the tanks are utilized several times (see Appendix 10.2.3).

7.2.1.7 Consumers were considered homogeneous across all states and indifferent to fuel type (after adjusting for energy content).

Although performance of ethanol-gasoline blends in conventional vehicles is similar when normalized to energy, some consumers are willing to pay a premium for ethanol (i.e., by under-discounting it per unit energy). Under-discounting is evident in the pricing of mid-level and high-level ethanol blends throughout the United States (E85Prices.com 2012), though there is not an obvious correlation between region and the local price spread between ethanol-gasoline blends and conventional gasoline. Consumers have been found to under-discount ethanol-gasoline blends on an energy basis in Iowa (Gallagher 2007), where E10 has been sold side-by-side with ethanol-free gasoline at retail stations. Under-discounting (based on energy content) has also been found in Brazil (to a greater extent in sugar producing regions) (Salvo and Huse 2011), and in Minnesota where consumers were found to be very heterogeneous with regard to the premium or discount they will pay for ethanol (Anderson 2010), likely due to varying priorities and perceptions about the impact of ethanol on fuel economy, concerns about adverse engine impacts, and its role in achieving social, economic or environmental objectives. Presumably, consumers are also heterogeneous in their belief that ethanol would or would not be consumed if they chose not to purchase it (i.e., their perceived market power under a mandate). If a fraction of consumers around the country are willing to pay a high premium for ethanol, we would expect fuel suppliers to saturate these premium markets (if the premium exceeds transportation costs) before lowering prices to saturate local markets with E10 (to minimize transportation costs). Alternatively, if consumers' willingness to pay for ethanol is highest near ethanol producers, or if consumers are completely homogeneous, frugal, and indifferent to fuel type (as we are assuming), fuel suppliers would maximize profits by concentrating consumption of ethanol in the Midwest (in the absence of other market forces).

7.2.2 Construction of US Trade Network

The *OD Cost Matrix* tool within *ArcGIS* was employed to create a 48x48 trade distance matrix between each of the 48 contiguous US states (instead of PADD regions, which are more often and easily used for modeling fuel trade flows). A map of major roads of the United States (Kambly and Ertep 2000a) was used as the constraining network, and the centroid point of each state was arbitrarily chosen to function as a large fuel trading terminal. All ethanol consumed within the state of production, or imported from another country, was assumed to travel 100 km. Below are two limitations that result from such simplification of the model.

- Although most ethanol moves by Class I rail lines, the highway network is more extensive throughout the country. The use of highway distance, instead of railway or intermodal distance, is assumed to present a conservatively low estimate of actual travel distance between state centroids.
- In reality there are hundreds of biofuel production facilities and thousands of fuel terminals around the country. However, optimizing such a resolved system would not necessarily produce results that are more reflective of reality than the state-by-state optimized model.

Table 70, Table 71, Table 72, and Table 73 present the estimated distances between states, which are identified by their 2-letter state postal code and an arbitrary numeric identifier.

7.2.3 Trade Network Optimization

A convex linear optimization model was then constructed in Microsoft Excel, in order to estimate state-to-state ethanol trade flows within the contiguous United States, for each year from 2000 to 2009. For more details on how data was found and manipulated for this analysis, see Appendix 10.3.1. In each modeling exercise, a globally optimal solution was found.

- MATRIX VARIABLES
  - d_{ij}= Distance between origin (i) and destination (j) state.
  - t_{ij} = Ethanol quantity traded from origin (i) to destination (j) state
  - N = Number of states in the contiguous United States
- CONSTRAINTS
  - Trade between any two states is greater than or equal to zero
    - $t_{ij} \geq 0$
  - All ethanol traded from one state (either to other states or "traded" and consumed within its state of production) is equal to the historic reported production quantity, Eth_Prod_BB-BTU.
    - $\sum_j^N t_{kj}$ = Total ethanol production of a state (k), true for all states
  - State ethanol consumption:
    - If ACTUAL CASE:

$\sum_i^N t_{ik}$ = Reported historic ethanol consumption in state (k), Eth_Cons_Total_BB-BTU (or ENCTCB), true for all states

- If NECESSARY CASE:

  $\sum_i^N t_{ik} \leq$ Maximum potential consumption in state (k) at E10 blend wall, E10_MaxEth_BB-BTU, true for all states

  $\sum_i^N \sum_j^N t_{ij} =$ Total actual historic ethanol consumption in all 48 states

- OBJECTIVE FUNCTIONS
  - Minimize ethanol transportation activity required to satisfy the production and consumption volumes (tonnes) specified for each state.
    - ACTUAL CASE (Equation 5): 49 origin states, 49 destination states, resulting in 2,401 variable values.
      - A fictional 49th state referred to as "US" was created to account for net imports or exports, which were assumed to enter or exit out of the Gulf of Mexico via Texas. The impact of this simplification on overall trade estimation is expected to be minimal, as domestic production made up at least 95% of consumption in every year except 2006, when imports accounted for 11% of consumption.

Minimize $\sum_i^N \sum_j^N t_{ij} d_{ij} \qquad i, j = 1 \ldots 49$

Equation 5. Objective Function for Optimization of Actual National Ethanol Distribution Scenario

- NECESSARY CASE (Equation 6): 48 origin states, 48 destination states, resulting in 2,304 variable values
  - International imports and exports were ignored, as the assumed optimal scenario (for reducing greenhouse gas emissions) would be for countries to consume all ethanol that they produce until market demand or technical limits prevent further consumption (neither of which has happened in major ethanol exporting countries). Nevertheless, for a more intuitive comparison to the actual case, such that both scenarios consist of identical national ethanol volumes, all imports are assumed to travel 100 km within the United States.

Minimize $\sum_i^N \sum_j^N t_{ij} d_{ij} \qquad i, j = 1 \ldots 48$

Equation 6. Objective Function for Optimization of Necessary National Ethanol Distribution Scenario

7.2.4 Location-based Health Impact Assessment

Reliable characterization of human health externalities from air pollution must incorporate the location of emissions, as health impacts can vary by orders of magnitude depending on the proximity of pollution and emissions (McKone et al. 2011). For this reason, four archetypal trade routes were created from the Midwest: a west-bound route (Sioux Falls, SD to Long Beach, CA) and an east-bound route (Des Moines, Iowa to Newark, NJ), by following the shortest route along either the railroad network (Kambly and Ertep 2000b) or road network (Kambly and Ertep 2000a) of the United States. To assess human health impacts, the "intake fraction," or the fraction of the emitted air pollutants that are inhaled, was estimated for tailpipe emissions along each of these four routes. As fine particulate matter ($PM_{2.5}$) dominates the life-cycle disease burden of transportation fuels (McKone et al. 2011), the intake fraction analysis included $PM_{2.5}$ derived from primary $PM_{2.5}$ emissions and from secondary $PM_{2.5}$ (resulting from NO_x, SO_2, and VOC emissions). First, the mean intake fraction values for each US county were obtained from APEEP modeling results (National Research Council 2010), and then imported into *ArcGIS* and converted to raster format. The mean value along each of the four routes was estimated using the *Spatial Analyst (Zonal Statistics)* tool within *ArcGIS*. The intake fraction for each of the pollutants considered is visually presented in raster map format in Figure 27, Figure 28, Figure 29, Figure 30, and Figure 31, with a summary of extracted values for each route presented in Table 29 and Table 30.

Mode	Pollutant	COUNT	MIN	MAX	RANGE	MEAN	STD	SUM	STD/ MEAN	MAX/ MIN
Rail	NH_3	2327	0.10	29.86	29.76	2.24	5.17	5211	2.31	305.5
Rail	NO_x	2327	0.03	0.60	0.57	0.10	0.07	225	0.73	19.7
Rail	$PM_{2.5}$	2327	0.31	12.97	12.67	1.68	1.83	3914	1.09	42.5
Rail	SO_2	2327	0.12	2.55	2.44	0.55	0.33	1284	0.60	22.2
Rail	VOC	2327	0.03	1.18	1.15	0.15	0.17	356	1.09	42.5
Road	NH_3	2003	0.10	29.86	29.76	2.03	5.45	4062	2.69	305.5
Road	NO_x	2003	0.03	0.60	0.57	0.10	0.08	195	0.78	19.7
Road	$PM_{2.5}$	2003	0.31	12.97	12.67	1.52	1.87	3036	1.24	42.5
Road	SO_2	2003	0.12	2.55	2.44	0.51	0.33	1018	0.65	22.2
Road	VOC	2003	0.03	1.18	1.15	0.14	0.17	276	1.24	42.5

Table 29. Intake Fraction (mg $PM_{2.5}$/kg of Emitted Pollutant) for East-bound (Des Moines, IA to Newark, NJ) Routes.

Mode	Pollutant	COUNT	MIN	MAX	RANGE	MEAN	STD	SUM	STD/ MEAN	MAX/ MIN
Rail	NH_3	3897	0.04	20.17	20.13	0.95	3.08	3716	3.23	482.5
Rail	NO_x	3897	0.02	0.30	0.28	0.06	0.05	227	0.80	15.0
Rail	$PM_{2.5}$	3897	0.12	17.12	17.01	0.77	2.52	2996	3.28	147.8
Rail	SO_2	3897	0.07	10.90	10.83	0.39	1.61	1501	4.18	146.2
Rail	VOC	3897	0.01	1.56	1.55	0.07	0.23	272	3.28	147.8
Road	NH_3	3161	0.04	20.17	20.13	0.85	3.09	2692	3.63	509.8
Road	NO_x	3161	0.02	0.09	0.07	0.04	0.02	141	0.44	4.5
Road	$PM_{2.5}$	3161	0.10	17.12	17.03	0.72	2.61	2289	3.60	172.6
Road	SO_2	3161	0.08	10.90	10.82	0.42	1.66	1335	3.92	136.3
Road	VOC	3161	0.01	1.56	1.55	0.07	0.24	208	3.60	172.6

Table 30. Intake Fraction (mg $PM_{2.5}$/kg of Emitted Pollutant) for West-bound (Sioux Falls, SD to Long Beach, CA) Routes.

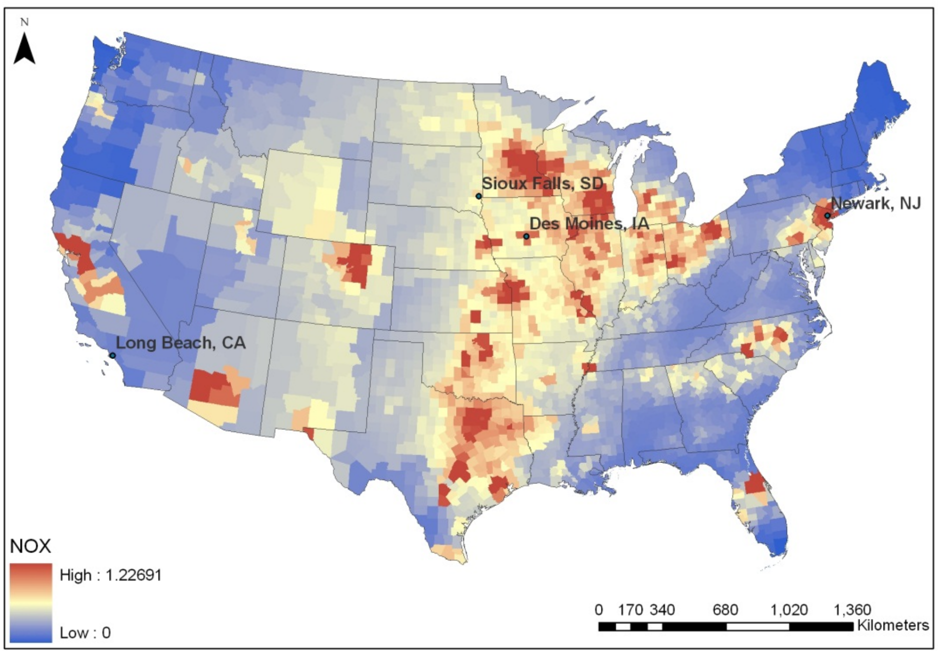


Figure 27. US Intake Fraction (mg/kg) Map for Nitrogen Oxides (NO_x) (data from (National Research Council 2010)).

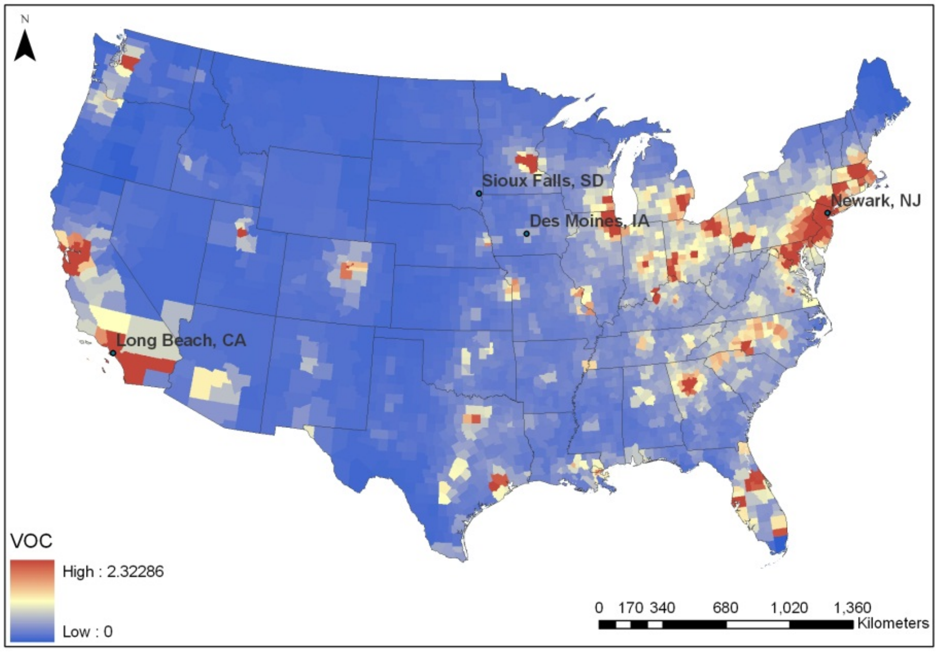


Figure 28. US Intake Fraction (mg/kg) Map for Volatile Organic Compounds (VOC) (data from (National Research Council 2010)).

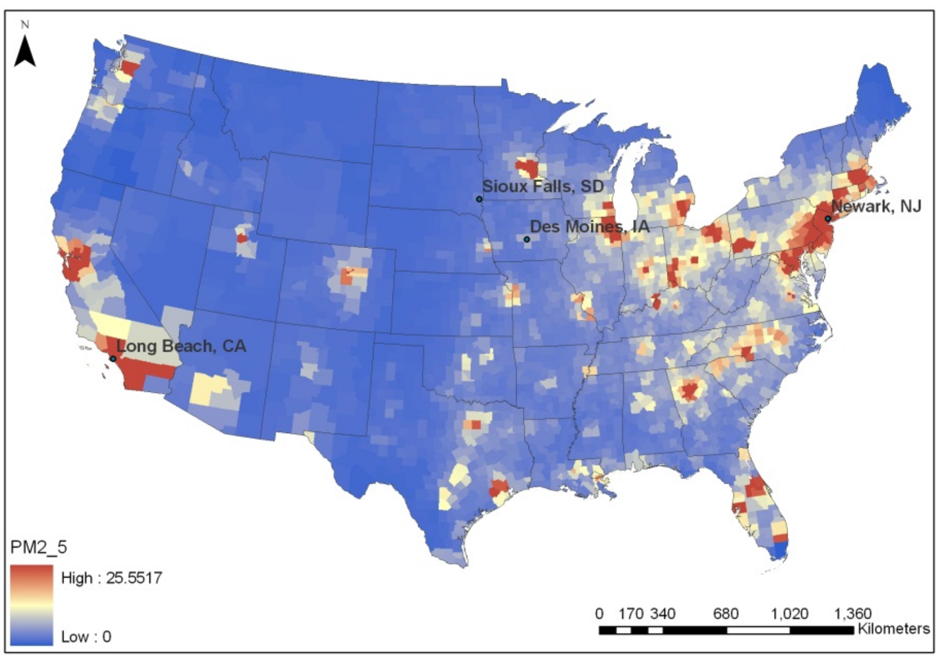


Figure 29. US Intake Fraction (mg/kg) Map for Fine Particulate Matter ($PM_{2.5}$) (data from (National Research Council 2010)).

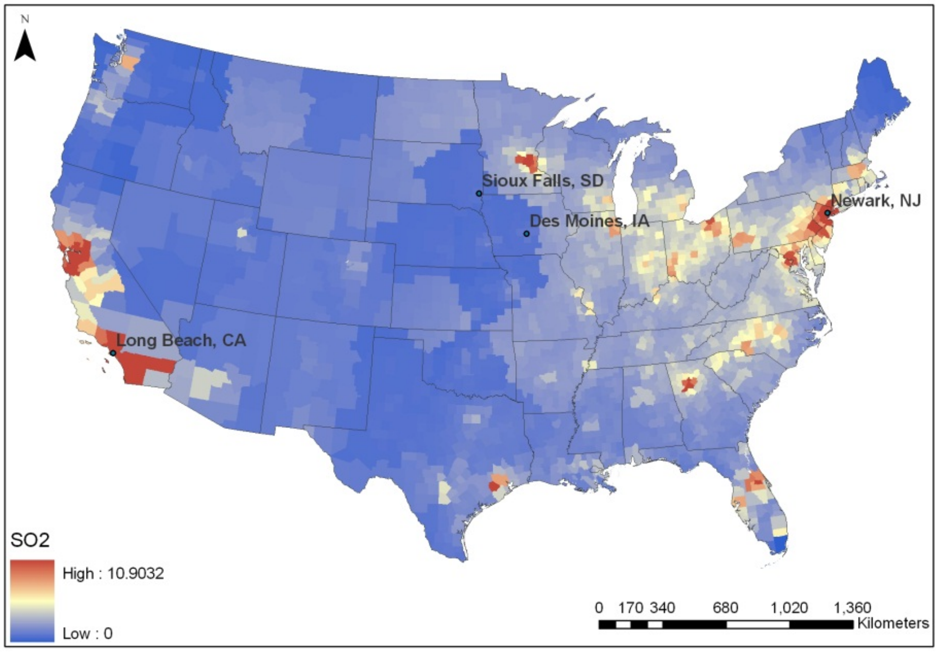


Figure 30. US Intake Fraction (mg/kg) Map for Sulfur Dioxide (SO_2) (data from (National Research Council 2010)).

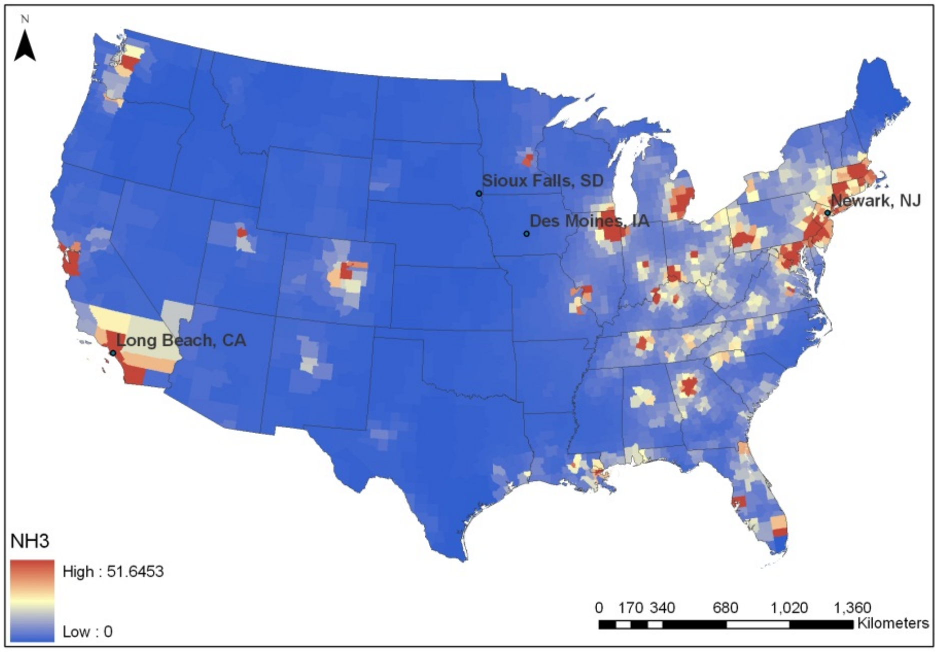


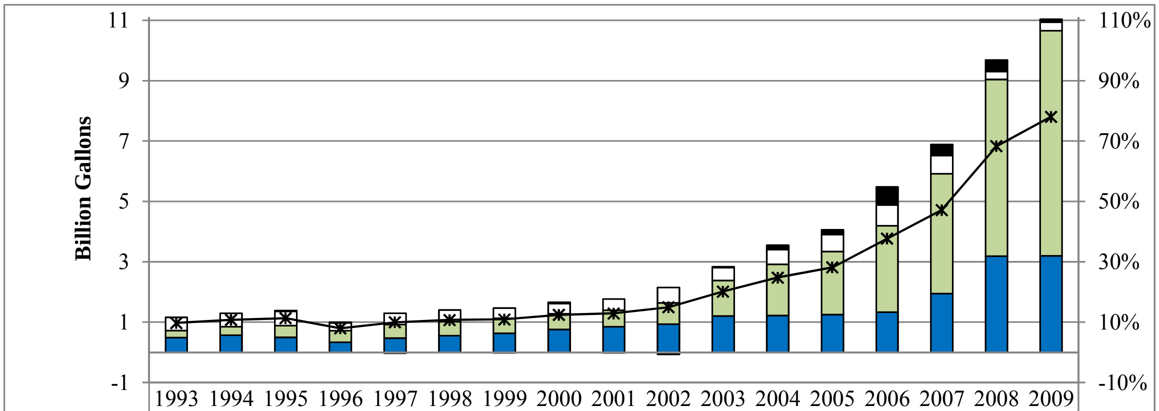
Figure 31. US Intake Fraction (mg/kg) Map for Ammonia (NH_3) (data from (National Research Council 2010)).

7.3 Case Studies within the Contiguous United States

The detailed methodology and results from several national scenarios and case studies were evaluated and are summarized below.

7.3.1 Ethanol Consumption and Net Interstate Trade, 1993-2009

The maximum quantity of ethanol that could have feasibly been consumed in each state in a given year was estimated by assuming that motor gasoline would be blended to the maximum permissible limit of 10% (v/v) ethanol (7% by energy content). Annual state-specific statistics on ethanol production, ethanol consumption, and motor gasoline consumption from the State Energy Database System (US EIA 2011d) were used to estimate the annual net quantity of ethanol consumed in the United States that fell into the following four pathways, presented in Figure 32. From Figure 32, it is clear that domestic production made up at least 95% of consumption in every year except 2006, when we estimate that imports accounted for approximately 11% of the 465 trillion BTUs (US EIA 2011d) (18 million tonnes) of ethanol consumed. The amount of ethanol estimated to have been consumed in the state of production averaged around 30% since 2004, which is not surprising as less than 30% of US finished gasoline is consumed in the Midwest (PADD 2) region (US EIA 2011a), where most ethanol is produced. However, the percent of interstate trades considered "necessary" due to the blend wall increased from less than 60% of total tonnage in 2000 to more than 96% of total tonnage in 2009, and the number of states that produced more ethanol than they could feasibly consume (without exceeding the E10 blend wall) grew from two to nine in this period. The method used here to characterize ethanol pathways based on tonnage was used in estimating a more useful freight metric based on total tonne-kilometers, as presented in Section 7.3.2.



	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
IX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.1	0.2	0.6	0.4	0.4	0.1
UT	0.4	0.4	0.5	0.3	0.4	0.4	0.3	0.3	0.4	0.5	0.4	0.5	0.6	0.7	0.6	0.3	0.3
NT	0.2	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.7	1.2	1.7	2.1	2.9	4.0	5.9	7.5
LC	0.5	0.6	0.5	0.3	0.5	0.5	0.6	0.8	0.8	0.9	1.2	1.2	1.2	1.3	1.9	3.2	3.2
%E10	10%	11%	11%	8%	10%	11%	11%	12%	13%	15%	20%	25%	28%	38%	47%	68%	78%

Figure 32. Trade Categories[40] of Ethanol Consumed in the United States, 1993-2009.

7.3.2 Net Domestic Ethanol Trade Activity, 2000-2009

In order to estimate the costs and environmental implications of ethanol trade, the distance traveled must be estimated. In 2007, the US Commodity Flow Survey (CFS) tracked less than 6 million metric tons of ethanol shipments (US Census Bureau 2010), though US consumption had exceeded 20 million tons. To create a more comprehensive model of ethanol trade for multiple years, a simple network model of interstate ethanol trade within the United States was created. The *Origin-Destination (OD) Cost Matrix* tool within *ArcGIS* was employed using major roads of the United States (Kambly and Ertep 2000a) as the constraining network between the centroid points of each state (treated as large fuel trading terminals), and assuming that ethanol not traded between states traveled 100 km. A linear optimization model was then constructed to estimate the optimal state-to-state ethanol trade flows within the contiguous United States for each year from 2000 to 2009. The modeling approach was applied under two hypothetical domestic distribution algorithms as described below, in order to compare status quo transportation conditions to conditions that minimize transportation costs and emissions.

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[40] The legend consists of [IX] (black, top): imported into (+), or exported from (-), the United States; [UT] (white, second from top): "unnecessary" trade between states motivated by factors other than the blend wall; [NT] (light green, third from top): "necessary" trade between states to avoid exceeding the E10 blend wall; [LC] (dark blue, bottom): local consumption within state of production. [%E10] (line): US average gasoline market share of E10. (Note: The mass of one billion gallons is three million metric tons).

7.3.2.1 Scenario A: "Actual" net trade

i. Historic annual production of ethanol (US EIA 2011d) was used for each of the 48 contiguous states.
ii. Historic annual consumption of ethanol (US EIA 2011d) was used to determine the net tonnage of ethanol imported to or exported from each of the 48 contiguous states.
iii. International import and export of ethanol was estimated as the difference between total annual consumption and production, and was assumed to take place through the Gulf of Mexico via Texas.
iv. Trade volumes between states (i.e., between each of 2,401 origin-destination pairs) were simultaneously calculated so that the resulting trade routes resulted in the fewest t-km of ethanol transportation.

7.3.2.2 Scenario N: "Necessary" net trade

i. Historic annual production of ethanol (US EIA 2011d) was used for each of the 48 contiguous states.
ii. Producer states were assumed to consume ethanol until their gasoline reached E10, after which point ethanol would be exported to the next-closest unsaturated state.
iii. To meaningfully compare the "actual" scenario to the "necessary" scenario, net imports were also included (though none of the major ethanol producing regions of the world had saturated their own ethanol–gasoline blend wall through 2009).
iv. Hypothetical consumption of ethanol by state, and trade volumes between states (i.e., between each of 2,304 origin-destination pairs), were simultaneously calculated so the locations of consumption resulted in trade routes with the fewest t-km of ethanol transportation. (Implications for increasing or decreasing gasoline t-km were not estimated).

The modeled "actual" and "necessary" net exports, net imports, and net trade flows between states are presented for the years 2000-2002 in Figure 33, years 2003-2005 in Figure 34, and years 2006-2008 in Figure 35. In these maps, states are shaded according to the actual average market share of ethanol in motor gasoline for the given year. If the "necessary" distribution and consumption scenarios had occurred, shading would have been concentrated in the Midwest, and only producer states with an average ethanol content in their gasoline of 10% (and therefore shaded black) should be net exporters (indicated by a white dot) or have trade routes passing through them. In contrast to this optimal expectation, several Midwestern states exported ethanol despite blending much less than 8% ethanol in their gasoline on average. A more concise depiction of "actual" ethanol trade flows for the years 2000-2009 is presented in Figure 36.

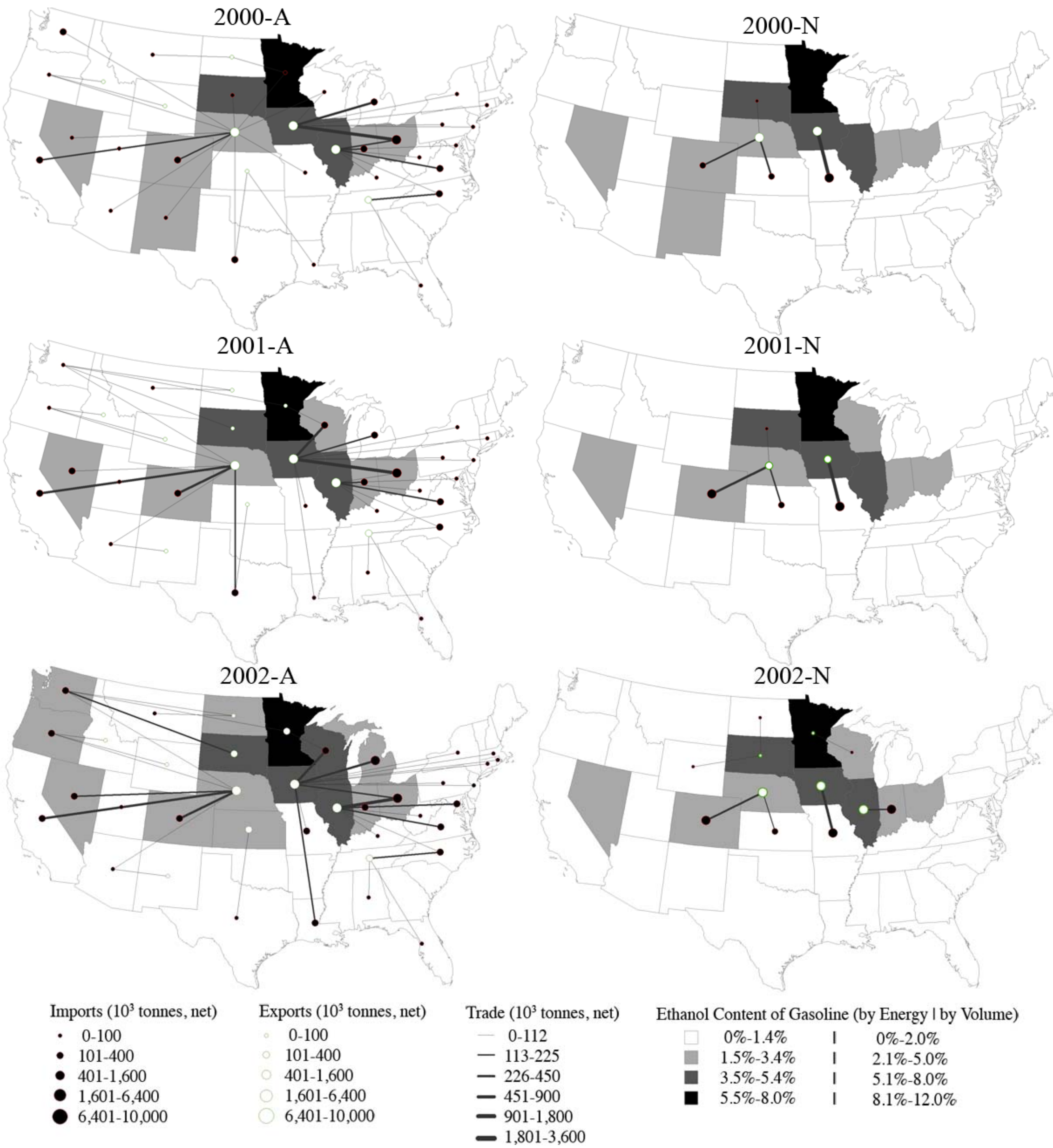

Figure 33. U.S. Ethanol Market Share and Modeled Actual (A) and Necessary (N) Net Trade, 2000-2003

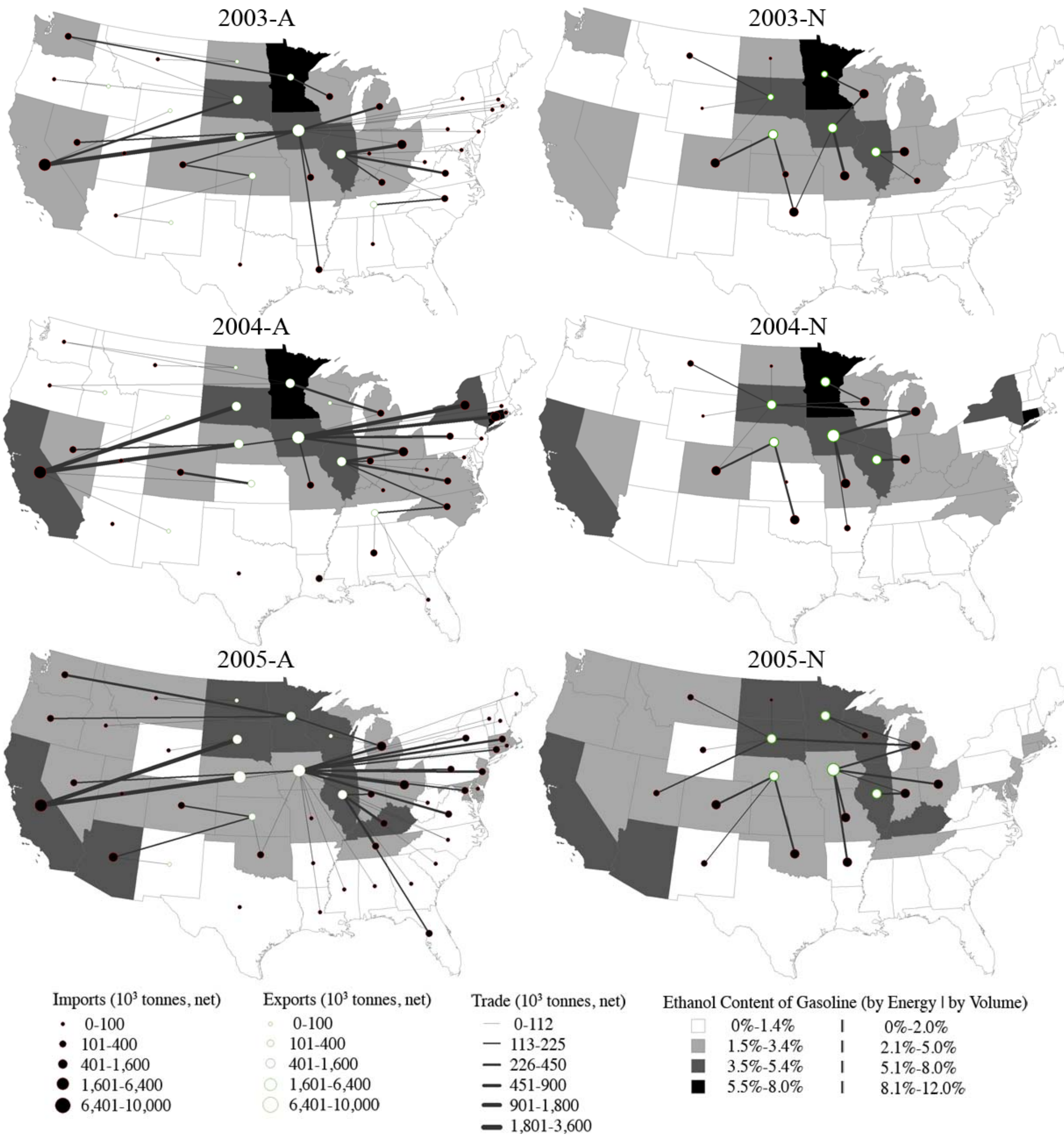

Figure 34. U.S. Ethanol Market Share and Modeled Actual (A) and Necessary (N) Net Trade, 2003-2006

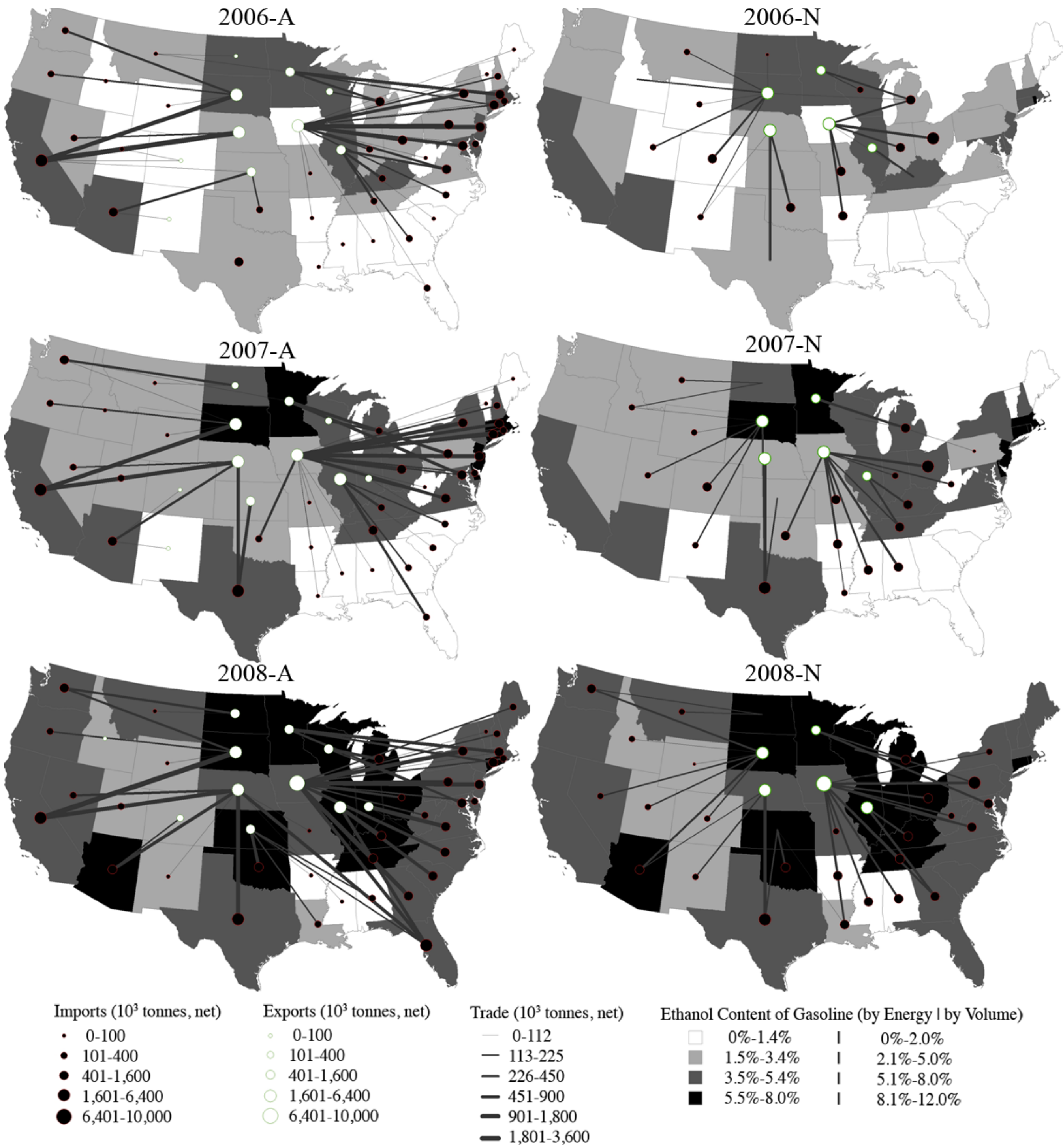

Figure 35. U.S. Ethanol Market Share and Modeled Actual (A) and Necessary (N) Net Trade, 2006-2008

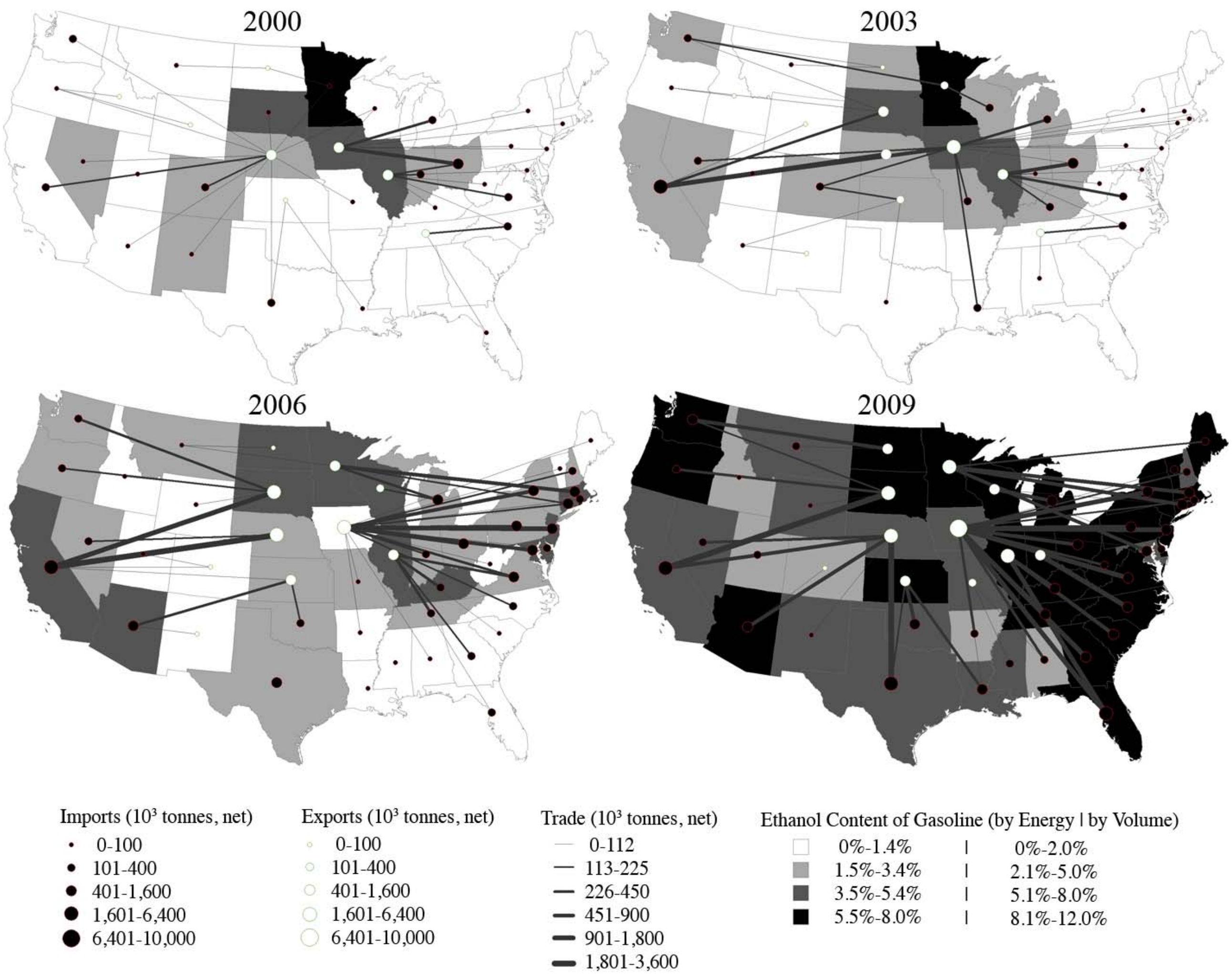

Figure 36. Summary U.S. Ethanol Market Share and Modeled Net Actual Trade, 2000-2009.

A statistical summary of the national total t-km and average distance of ethanol transport in each year from 2000 to 2009 (including those displayed in Figure 36) is presented in Figure 37. As annual ethanol production increased by a factor of 2.5 from 2000 to 2005, the average transport distance nearly doubled in both the "actual" and "necessary" scenarios, to 1,190 and 470 km, respectively. Although ethanol exported from producer states traveled on average more than 1,500 km every year since 2003, the national average ethanol transport distance has been around 1,100 km since 2004 because we assumed that ethanol consumed in producer (or international importing) states traveled only 100 km.

The blend wall could be used to justify less than 40% of total annual t-km until 2006, when "necessary" transportation made up 10 of the 21 billion "actual" t-km, and eventually contributed to more than 80% of the 42 billion t-km in 2009. The average difference between "actual" and "necessary" state trade was relatively constant from 2004 to 2009, averaging around 10 (i.e., 9.6 with a range of 7.9-11.4) billion t-km/year. In reality, ethanol may have been transported more than these estimates indicate due to temporal and regional variability in demand (which is sensitive to relative market prices), and because only annual net imports and exports were considered (so if a state exported as much ethanol as it imported during a given year, net trade activity would be counted as zero).

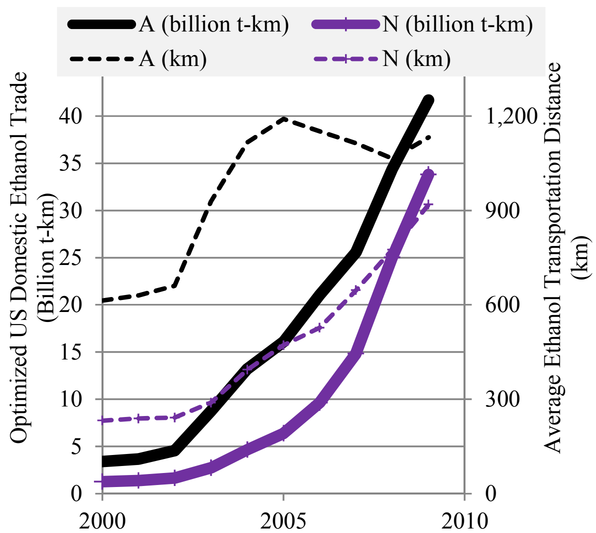

Figure 37. Historic US Ethanol Trade Volume and Distance under Modeled Conditions,[41] 2000-2009.

Year	Actual [A] (km)	Necessary [N] (km)	Actual [A] (billion t-km)	Necessary [N] (billion t-km)
2000	614	232	3.4	1.3
2001	630	239	3.7	1.4
2002	660	242	4.6	1.7
2003	928	289	8.7	2.7
2004	1,116	394	13.2	4.7
2005	1,191	472	16.1	6.4
2006	1,151	527	21.0	9.6
2007	1,114	647	25.6	14.8
2008	1,065	775	34.4	25.0
2009	1,133	919	41.7	33.8

Table 31. Historic US Ethanol Trade Volume and Distance under Modeled Conditions,[42] 2000-2009.

[41] [N] = "Necessary" Trade Scenario due to E10 Blend Wall, and [A] = "Actual" Trade Scenario. Supporting data can be found in Table 31.

7.3.3 Ethanol Distribution: Costs, Air Pollutant Emissions, and Health Impacts

In sources ranging from the US CFS to reports issued by the US DOE and surveys of ethanol plant operators (US Census Bureau 2010; US DOE 2010; M. Wu 2008), ethanol was reported to be transported primarily by rail (66%-90% of all t-km), with a smaller amount moved by truck (13%-29%) and barge (5%-9%). Each of these modes, small ocean tankers, and two currently unavailable modes – a 10" pipeline in the Midwest and a 25" pipeline in the Northeast – were evaluated to provide a wide range of costs and air emission factors representative of the years 2004 to 2008. The fuel, cost, and emissions intensities of each mode, as summarized in Section 5.5.2.6, were applied to 10 billion t-km, and results are presented in Table 32. This quantity corresponds to the "unnecessary" domestic ethanol transportation that took place annually from 2004 to 2009. Additionally, net ethanol imports from 2004 to 2008 averaged 1 million metric tons, and would have resulted in 10 billion t-km annually by ocean tanker if transported from Santos, Brazil to Houston, Texas. This quantity is also approximately half of the average annual ethanol that could be transported from the proposed 25" Midwest-to-Northeast pipeline that was evaluated by the US Department of Energy (US DOE 2010).

		Truck	Train (c=1.2)	Barge (c=1.6)	Pipeline* (10", MRO)	Pipeline* (25", NPCC)	Small Ocean Tanker
Fuel	10^6 Liters	334 (D)	88 (D)	141 (D)	-	-	51 (RO)
Electricity	GWhr	-	-	-	333	111	-
Transport Cost	$Million	1,500	240	192	Variable	340	65
CO_2-e (life-cycle)	10^3 metric tons	1,381	312	491	345	58	167
CO_2 (direct)	10^3 metric tons	901	238	379	266	37	139
NO_x (direct)	metric tons	9,906	4,998	6,062	480	37	3,601
$PM_{2.5}$ (direct)	metric tons	297	143	265	NA	NA	263
SO_x (direct)	metric tons	108	29	45	852	110	2,632
VOC (direct)	metric tons	315	262	129	-	-	129
CO (direct)	metric tons	5,674	643	1,137	-	-	291

Table 32. Estimated Cost, Energy Consumption, Life-cycle GHG Emissions, and Direct Air Pollutant Emissions from Transporting 10 Billion t-km of Eethanol.[43]

The mode(s) used for transporting ethanol farther than "necessary" was most likely rail and potentially barge, with trucking unlikely to contribute more than 20% of t-km. Consequently, $240–$520 million in annual domestic distribution costs and 300,000–500,000 metric tons of CO_2-e emissions (from at least 90 million liters of diesel) could have been avoided if ethanol was only

[42] [N] = "Necessary" Trade Scenario due to E10 Blend Wall; [A] = "Actual" Trade Scenario.

[43] MRO = Midwest Reliability Organization electrical grid region (US EPA 2010g); NPCC = Northeast Power Coordinating Council electrical grid region (US EPA 2010g); NA = Not available; D = diesel; RO = residual oil; c = circuity factor over highway distance (applied to 10 billion t-km if applicable, so results more realistically reflect differences between modal options); *Illustrative (not currently available in the United States).

distributed as much as "necessary" from 2004 to 2009. If imports were also considered unnecessary, an additional \$65 million in costs and 167,000 metric tons of CO_2-e could have been avoided annually from 2004 to 2008. These cost estimates agree relatively well with a recent model of domestic ethanol distribution, which projected that renewable identification number (RIN) trading may reduce ethanol transportation costs by 50% (or \$400 million) in 2011 (Figer 2011) by allowing non-producers to demand ethanol without physically consuming it.

By applying the "likeliest" external costs of air pollutants in 2008 dollars (\$7/metric ton CO_2, \$0.08/kg CO, \$14.6/kg NO_x, \$124/kg $PM_{2.5}$, \$21.4/kg SO_x, and \$0.90/kg VOC) according to (Kusiima and Powers 2010), without employing geospatial modeling, the external costs for transporting 10 billion t-km of ethanol domestically by each mode would have been approximately \$194 million for trucking (13% beyond private freight costs), \$126 million for barge (66%), \$94 million for rail (39%), and at least \$28 million for small-diameter pipeline. Although the proposed 25" Midwest-to-Northeast ethanol pipeline would be less polluting than other modes, smaller pipelines (e.g., 10") may not have a GHG or cost advantage over rail and barge (but may still offer a relative public health advantage due to the height of electricity generators' exhaust stacks).

7.3.3.1 Pollution Impacts Estimated by Route and Mode

The mode-specific energy intensity and emission factors reported in Section 5.5.2.6 were then applied to the average intake fraction for each of the routes shown in Figure 38 (as explained in Section 7.2.4) to estimate the intake mass of $PM_{2.5}$ for each t-km of fuel transported as presented in Table 33. Locomotives emit significantly more primary $PM_{2.5}$ and NO_x than trucks per unit of fuel, and these two pollutants are responsible for more than 90% of $PM_{2.5}$ intake along each route. As a result, the $PM_{2.5}$ health burden from rail shipment is 50% that of trucking along the east-bound route and 61% along the west-bound route, though shipping ethanol by truck is up to five times more fuel-intensive than rail (depending on geography and circuity). Additionally, shipping goods along the west-bound route, while 67% farther by rail and 58% farther by truck than the respective east-bound routes, actually results in an intake mass of $PM_{2.5}$ that is 8% less if comparing rail routes, and 25% less if comparing road routes; the difference can be attributed to the lower population density along the west-bound routes.

These results highlight the potential error if pollution damage is assumed to be proportional only to pollutant mass. If these two routes comprise the upper and lower bounds of national average human exposure to air pollution from ethanol transportation, and rail made up at least 80% of t-km, total human intake of $PM_{2.5}$ resulting from 10 billion t-km of "unnecessary" domestic ethanol trade was between 440 and 910 grams of $PM_{2.5}$ each year. It is worth acknowledging that more or less emissions would also have taken place from distributing and consuming gasoline in producer and consumer states. However, this concern was not addressed because a) emissions from gasoline distribution were likely small, as coastal states refine much of their own gasoline in-state and transportation distances would be short and b) most gasoline is traded via large-diameter efficient pipelines. As a result of the simplifications used in this analysis, total emissions and impacts from ethanol transportation were likely underestimated. Alternatively, had the "necessary" scenario been created using an algorithm that minimized human exposure to pollution instead of t-km, more trade would have been directed westward leading to greater total t-km, costs, and emission of GHG and other air pollutants.

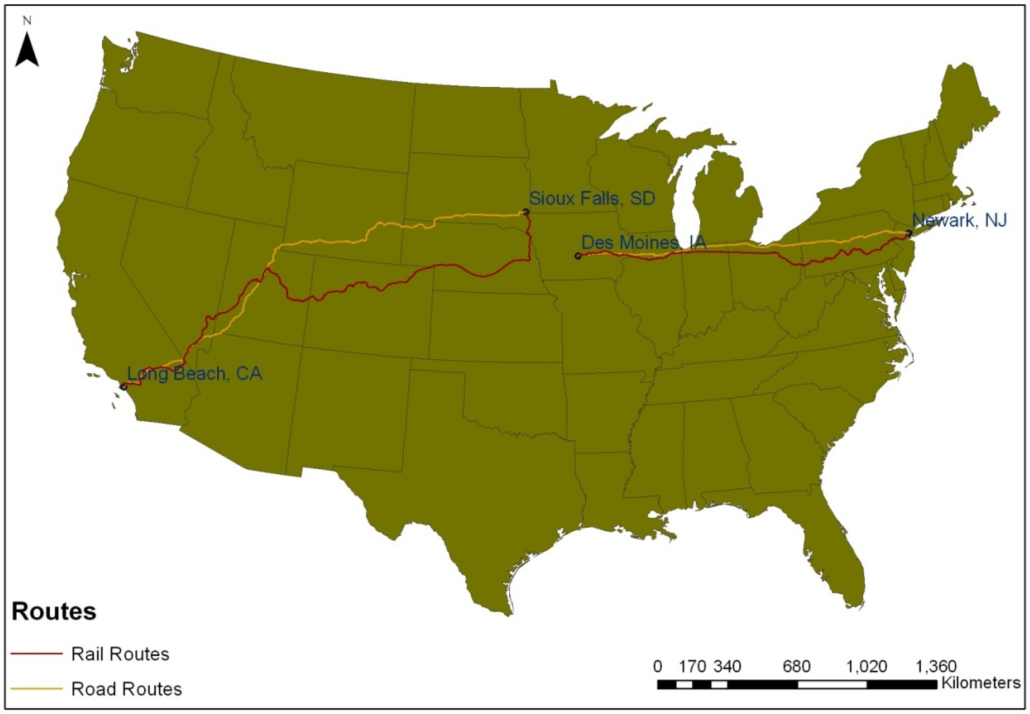

Figure 38. East-bound and West-bound Ethanol Trade Routes by Road and Rail

Pollutant	**Pollutant Emission Factor (g/t-km)**		**Average $PM_{2.5}$ Intake Fraction (mg $PM_{2.5}$/ kg pollutant)**				**$PM_{2.5}$ Intake Mass Factor (g $PM_{2.5}$/ 10^6 t-km)**			
			East-bound		*West-bound*		*East-bound)*		*West-bound*	
	Rail	*Truck*	*Rail*	*Truck*	*Rail*	*Truck*	*Rail*	*Truck*	*Rail*	*Truck*
NO_x	0.416	0.991	0.10	0.10	0.06	0.04	0.040	0.097	0.024	0.044
$PM_{2.5}$ (primary)	0.012	0.030	1.68	1.52	0.77	0.72	0.020	0.045	0.009	0.022
SO_2	0.002	0.011	0.55	0.51	0.39	0.42	0.001	0.005	0.001	0.005
VOC	0.022	0.032	0.15	0.14	0.07	0.07	0.003	0.004	0.002	0.002
Total							0.065 (0.075)[44]	0.151	0.036 (0.044)[44]	0.072

Table 33. Emission Factors and Pollutant Intake Estimates for East-Bound and West-Bound Truck and Rail Routes.

[44] The value in parentheses indicates the total intake mass factor after correcting for rail circuity over highway distance along the East-bound (1.16) and West-bound (1.23) routes.

7.3.4 Marginal Analysis of Individual State-level Decisions

The life-cycle greenhouse gas footprint of fuels has been incorporated into fuel policy on the federal level (e.g., the Renewable Fuel Standards (RFS) resulting from the Energy Independence and Security Act (EISA) of 2007) and on the state level (e.g., California's Low-Carbon Fuel Standard (LCFS)). With state-level policies or product certification programs that govern commodities, it is important to assess whether some potential buyers are indifferent to (or do not face) the premium of the certification program. If so, it becomes challenging to accurately model and attribute supply chain activity emissions (e.g., distribution) to the supplier or consumer of the product. This issue has been discussed at length with "green" electricity, which is even more fungible than ethanol and gasoline, but the distribution system for electricity is completely networked so resistive loss between origin and destination is automatically minimized.

Assuming that production volume is fixed, it is important to consider whether demand from a remote customer draws a product like ethanol further than the alternative customer would. Additionally, it is important to understand whether a ban or tariff on imports from a potential customer located near producers could have unintended impacts on total emissions from the system.

In order to ascertain the significance of state-level decisions on nation-wide emissions, four hypothetical scenarios (below) are presented for the years 2000, 2006 and 2009. During this time period, ethanol consumption increased almost 7-fold and the blend wall became a significant constraint on minimizing the distance that ethanol could be transported between producers and their closest available market. Modeling results for each of the scenarios is presented in Table 34.

a) Scenario N (US Optimal Distribution Scenario)
In this scenario, ethanol is distributed in a way that minimizes transportation distance, without exceeding 10% (v/v) ethanol in gasoline in any state.

b) Scenario N, perturbed by the (isolated) introduction of actual CA net demand
California has been one of the largest markets for ethanol, and is also one of the most distant states from the Midwest (within the 48 contiguous states), so ethanol transportation to California has resulted in more t-km than ethanol transportation to any other state. However, California would consume very little ethanol in Scenario N and has produced very little of its own ethanol.

c) Scenario N, perturbed by the (isolated) introduction of actual NJ net demand
New Jersey produced a negligible amount of ethanol from 2000 to 2009, but ethanol transportation to New Jersey resulted in the second most t-km (after California) in a few years. New Jersey is also a central and reasonably representative destination within the Mid-Atlantic/Northeast region, where a number of high demand states exist (e.g., NY, PA, and CT). New Jersey would consume very little ethanol in Scenario N and has produced a negligible amount of its own ethanol.

d) **Scenario N, perturbed by an isolated (fictional) blend wall increase to E15 in IA**
Iowa has been the top fuel ethanol producing state since 2004, but consumes only 1.2% of US gasoline. This scenario would have been feasible if E85 made up more than 6% of gasoline sales by volume (or 4% by vehicle-kilometers traveled). As recently as 2008, FFVs made up less than 5% of Iowa vehicles (Moriarty et al. 2009), and E85 stations were still not ubiquitous. Although not legally possible at the time, a lower E85 market share would have been needed if owners of

vehicles manufactured in or after 2001 (which were approved to use E15 in 2011 (US EPA 2011a)) had access to and chose to purchase E15 (which is not yet commonly unavailable.

[a] Scenario N (US Optimal Distribution Scenario)	Units	2000	2006	2009
US total ethanol demand	Mt	5.5	18.3	36.8
US total ethanol freight transportation	Mt-km	1,268	9,436	33,771
US average ethanol transport distance	km	230	516	918
US maximum ethanol transport distance of all state-to-state trades	km	697	1,476	2,055
[b] Scenario N, perturbed by the isolated introduction of actual CA net demand				
CA demand under [a] (i.e., in-state production only)	Mt	0.02	0.13	0.16
CA actual demand	Mt	0.22	3.15	3.31
CA average transport distance from origin	km	1,972	2,287	2,371
CA total ethanol freight transportation entering state	Mt-km	439	7,204	7,838
US system increase from [a] to [b]	Mt-km	326	3,565	1,881
Proportion of t-km entering CA that are considered additional to total national t-km	%	74%	49%	24%
[c] Scenario N, perturbed by the isolated introduction of actual NJ net demand				
NJ demand under [a]	Mt	0	0	1.13
NJ actual demand	Mt	0.03	1.05	1.31
NJ average transport distance from origin	km	990	1,717	1,531
NJ total ethanol freight transportation entering state	Mt-km	31	1,796	2,002
US system increase from [a] to [c]	Mt-km	27	731	2
Proportion of t-km entering NJ that are considered additional to total national t-km	%	88%	41%	0.1%
[d] Scenario N, perturbed by an isolated (fictional) blend wall increase to E15 in IA				
IA actual demand (for reference)	Mt	0.31	0.11	0.32
IA demand under [a]	Mt	0.53	0.58	0.57
IA demand under E15 blend wall	Mt	0.79	0.87	0.85
Average avoided transport distance for additional ethanol consumed in IA (i.e., distance to alternative next-closest unsaturated markets)	km	410	940	1,630
US system decrease from [a] to [d]	Mt-km	108	274	463
US system decrease from [a] to [d] in average transport distance and total t-km	%	8.6%	2.9%	1.4%

Table 34. Summary of State-level Impacts on US Ethanol Distribution System.

In 2000, most of the ethanol producing states had not yet saturated their own ethanol markets, so the national average distance from producers to consumers was less than 300 km (and maximum distance of any state-to-state trade was 700 km). As a result, most of the t-km associated with ethanol transportation to California (74%) and New Jersey (88%) should be considered marginally additional to the total national t-km for ethanol. Assuming that ethanol consumed within Iowa traveled 100 km, the next-closest market was 500 km away, leading to a savings of 400 km

($0.03/gal) for each additional unit of ethanol that could be consumed in Iowa under an E15 blend wall.

By 2009, the ethanol markets within producer states and several neighboring states would have been saturated at E10. As a result, the average ethanol transportation distance would have been greater than 900 km (and maximum trade distance greater than 2,000 km). Only 24% of the t-km associated with ethanol transported to California would have been considered marginally additional. Whether New Jersey decided to import slightly more or less ethanol would have had a negligible impact on total national t-km for ethanol, as alternative unsaturated ethanol markets were also more than 1,500 km from producers on average. Increasing ethanol consumption in Iowa would have prevented the need to transport ethanol more than 1,600 km to the next-closest unsaturated state, resulting in marginal transportation savings exceeding $0.12/gal ($0.002/MJ) and 2.5 g CO_2-e/MJ in 2009; total savings would have exceeded $11 million and 14,000 metric tons CO_2-e in comparison to the E10 scenario, and would nearly double if compared to the actual reference case.

The marginal impacts from introducing new supply or demand sources has been discussed at length in environmental and economic literature on electricity (Ekvall and B. P. Weidema 2004; Frischknecht and Stucki 2010; Kammen and Pacca 2004; Lidicker et al. 2010; Lund et al. 2010; Weber, Jaramillo, et al. 2010). As electricity distribution losses are minimized by grid operators and not directly controlled by consumer decisions, certified renewable electricity is purchased in the form of non-tangible renewable energy credits (RECs) to avoid the need for a separate grid to carry renewable electricity. For fungible liquid fuel commodities, it is easy to calculate emissions from a truck or train carrying product from producer to consumer, but difficult to estimate and allocate marginal or avoidable emissions. This national modeling exercise showed that the estimation of additional (or avoided) transportation emissions from supplying specific states with ethanol depended heavily on the alternative next-closest fuel markets available to producers.

In addition to being difficult to allocate marginal emissions from activities such as ethanol transportation, it was recently found to be unconstitutional for a single state to discriminate against ethanol assigned with emissions considered outside the control of producers, as required by California's Low Carbon Fuel Standard (LCFS) (*Rocky Mountain Farmers Union v. Goldstene, CV-F-09-2234* 2011); the factors considered "off-limits" are often critical to GHG LCA results, such as distance to consumers, biorefinery access to water (Scown et al. 2011), and industrial practices specific to the region (Cicas et al. 2007). If the LCFS is eventually implemented, leakage and shuffling have been discussed as key challenges to minimizing its potential futility (Yeh and Sperling 2010), whereby commerce activity external to the certification program (e.g., ethanol sales to GHG-indifferent consumers) may continue unaffected.

7.3.4.1 Global Implications

Lessons from this modeling exercise may be applicable to contemporary issues in the global liquid fuel markets. As many nations aim to reduce GHG emissions from their transportation sector (in conjunction with economic and security goals), it is important to ensure such efforts lead to a reduction in total global emissions. For example, it is plausible that global GHG emissions could be reduced by encouraging current biofuel exporters (e.g., Brazil) to consume more of their own fuels domestically, if they have the vehicles, infrastructure and capacity to absorb more biofuels into their transportation fuel market (which has been true in Brazil). In another example, if the United States, or specific states within the United States, implement a ban, tax, or tariff specifically on Canadian petroleum (e.g., due to the high energy, carbon, or water intensity of oil sands), oil sands production may continue at the same rate if demand from international customers is inelastic (unresponsive) to the cost of transporting oil sands petroleum overseas (which is typically a small component of petroleum costs). As a result, oil transportation related emissions may simply increase if Canadian oil is transported farther, and the United States sources more of its fuel from overseas.

7.4 Outlook

US ethanol consumption from 2000 to 2009 was primarily motivated by goals related to GHG emissions, fuel security, and economic development. When compared to conventional gasoline, ethanol blends have not been shown to offer local-level benefits such as improving air quality, but fuel policies have favored the dilution of ethanol into gasoline markets far from producer states instead of blending ethanol (up to the blend wall) near producers. As a result, ethanol was often transported farther than the blend wall would justify, leading to excessive costs and air pollutant emissions. Hypothetically, much of this "unnecessary" transportation could have been avoided if the RIN program been in place. For states far from producers, the transportation component value of RINs has exceeded \$0.12 (and would save more than 200 g CO_2-e) per gallon since 2009, which could partially subsidize E15 or E85 in Iowa. One economist forecasted that ethanol's price could drop 25% when used in blends greater than E10 (Gallagher 2007), so extra subsidization of ethanol used in mid- and high-level blends will be needed.

In 2011, the US gasoline mix became saturated with E10 (US EIA 2011f), so opportunities for more ethanol to be consumed close to producers as E10 are virtually non-existent. Over the next decade, most vehicles manufactured prior to 2001 will be removed from the fleet, so more gasoline retailers can sell E15 as the default gasoline. As a result, the blend wall for the mass gasoline market could approach E15 if infrastructure and legal barriers (US DOE OPIA 2011; US GAO 2011) are overcome. Unfortunately, an E15 blend wall would only postpone current problems by a few years, unless FFVs in and near producer states also start consuming a significant fraction of ethanol in high-level blends. As E85 makes up less than 0.3% of ethanol sold in the US and is not expected to reach 1% of national gasoline sales until 2018 (US EIA 2012), the commercialization of biofuels with higher blending limits than ethanol will become increasingly valuable.

Depending on where growth in ethanol production and consumption occur, the average ethanol transportation distance is projected to range from 700-1,700 km in 2020 under a national blend wall of E20 (Scown et al. 2012) or 800-1,600 km in 2022 for scenarios considered by US EPA (US EPA 2010d). Despite such a large potential increase in ethanol volume and average transportation distance, government agencies projected that the increase in ethanol distribution activity will not increase total traffic on freight networks by more than 3% over the next decade (US GAO 2011). As a result, the costs and emissions discussed in this paper are not significant at the scale of the entire transportation sector (or even biofuels alone). However, as demands for transportation fuels and freight services continue rising around the world, any transportation of goods that is not adding value to individual consumers, the general public, or the environment should be minimized.

8 DISCUSSION[45]

This dissertation began with a summary of the relevant history and description of petroleum, biofuel and freight distribution systems in the United States in Section 2, with a literature review of the main studies addressing the life-cycle environmental performance of each of these systems presented in Section 3. After outlining the general methodology employed throughout this dissertation in Section 4, the main components and activities involved in storing, handling and distributing petroleum and biofuel feedstocks and finished products were identified and characterized in terms of lifespan performance and activity-based emission factors in Section 5. Next, a physical characterization and simplified fleet model of the major components involved in nationally distributing petroleum and biofuels and their respective feedstocks was presented in Section 6, and system-wide emissions were normalized to each unit of consumed fuel (as would be customary to determine if the fuel meets policy targets). Section 7 consisted of several case studies designed to illuminate the economic and air emissions costs from the status quo national distribution of ethanol, in contrast to policies that would have resulted in more nationally and globally optimal distribution scenarios. This section summarizes areas of uncertainty and methodological limitations to consider when interpreting results, the main findings presented throughout this dissertation, most significant contributions to the research literature, and closes with suggestions for future research opportunities.

8.1 Limitations due to Uncertainty and Variability

Life-cycle assessment is plagued by uncertainty due to the reliance of practitioners on hundreds of data points and assumptions, most of which are embedded in the published work of others. Results presented in cases throughout this dissertation, and the range of results found in sensitivity analyses, were calculated based upon dozens of assumptions – some of which were simple engineering estimates or industry rules of thumb. Interpretation of results is complicated, as the differences in GHG emissions between different feasible production practices and operating circumstances are significant. In addition to the known variability in the emissions intensity of various practices, a great deal of uncertainty remains in estimating the life-cycle emissions intensity of different activities.

The policy implications of variability and uncertainty with regard to GHG emissions from transportation fuels is significant, as recent studies have found that the uncertainty in GHG footprint estimates for petroleum and biofuels may be greater than the difference in GHG footprint between the two fuels (Mullins et al. 2011; Venkatesh et al. 2010), and the presumed difference between fuels is often the justification for policies that favor biofuels. Variability that is understood and quantifiable may result from different agricultural practices or biorefinery operating practices, some of which can be controlled by farmers and biorefinery operators (e.g., whether to irrigate, which fuel to use in boilers). If the GHG footprints of biofuels are calculated at the facility-level,

[45] Some parts of this chapter were reproduced with permission from the American Society of Civil Engineers, after first being submitted for publication in the *Journal of Infrastructure Systems* in 2011 under the title, "Greenhouse Gas Emissions from the Construction, Manufacturing, Operation and Maintenance of US Distribution Infrastructure for Petroleum and Biofuels" (Strogen and Horvath 2012). This article was under review at the time this dissertation was submitted. Other parts of this chapter were reproduced with permission from the American Chemical Society, after publishing the article, "Fuel Miles and the Blend Wall: Costs and Emissions from Ethanol Distribution in the United States," in the journal, *Environmental Science & Technology,* in 2012 (Strogen et al. 2012).

they could vary by up to 42% within a single state among corn-based biorefineries (Boies et al. 2011). Additionally, the single decision for a biorefinery to shift from natural gas to coal could result in an ethanol GHG footprint that was significantly less than gasoline to actually exceed the GHG footprint of gasoline (Rajagopal and Zilberman 2008).

In prior discussions of uncertainty in LCA, uncertainty has been divided into (1) parameter uncertainty, (2) model uncertainty, and (3) uncertainty due to choices, which can each be further divided into environmental and product system uncertainty (Huijbregts 1998). Variability, on the other hand, has been categorized into (1) spatial variability, (2) temporal variability, and (3) variability between objects and sources (Huijbregts 1998). However, the variability or even range in environmental impact severity from a given activity is often unknown for different regions, time periods, practices that consume resources or emit pollutants, and relationships that characterize the impact of emissions on sensitive human or ecological populations. As a result, limitations in detailed data over different time periods, geographic and economic sector boundaries, and limited methodological abilities to accurately incorporate scaling, averaging, and substitution issues have also been included in discussions of uncertainty in previous energy infrastructure LCA studies (Pacca 2003).

The subsections below describe and discuss the forms of uncertainty pervasive throughout the models and results in this dissertation in a qualitative manner, as a simple range of high and low data values was often not available. The types of uncertainty have been organized into three main categories: parametric data uncertainty, scenario uncertainty, and model choice uncertainty. In order to summarize many of the limitations related to data and model uncertainty for each component, Section 8.2 presents a data quality assessment table that is used to evaluate the quality of input data quality and reliability of modeling outputs for each of the components.

8.1.1 Parametric Data Uncertainty

Parametric data uncertainty results from limitations and uncertainty in the data available as inputs for modeling efforts presented in this dissertation. Although data such as the density of steel or carbon content of fuels are known to two or three significant digits, there is a significant amount of uncertainty associated with the majority of data inputs used throughout this dissertation. When available, empirical physical data was used to characterize processes such as fuel production, fuel combustion, and utilization-induced deterioration of materials used in equipment and infrastructure. However, a large percent of data inputs ultimately were taken from the EIO-LCA tool, which was treated as a database for many modeling inputs described in this dissertation. Although supply chain activities are more completely included in input-output databases than process-based databases (Lenzen 2000), the EIO-LCA tool's shortcoming include the averaging of national values and over-aggregation of some industrial sectors with dissimilar practices among sub-sectors. As a result, EIO-LCA uncertainty will be included in the discussion of parametric uncertainty, which results from limited incorporation of geographic, temporal, and geo-temporal variability.

8.1.1.1 Geographic Variability

Industrial sector emission factors were extracted from EIO-LCA, based on average US practices in 2002, though manufacturing practices and inputs vary by location. Additionally, international activities may be more or less efficient than the modern US practices incorporated into this analysis, and much of the equipment modeled in this study is already manufactured abroad (e.g., ships and tires). The energy (and likely water) intensity of industrial practices overseas may deserve as much attention as US-specific practices, as the United States continues shifting away from energy-intensive industrial activities while the global average carbon intensity per unit of economic activity has been increasingly greater than the US average (from 1994-2006, based on market exchange comparison) (US EIA 2008b).

Independent of manufacturing and construction practices, the operation and maintenance of the systems modeled in this dissertation will vary by region within the United States due to differences in terrain, weather, available existing infrastructure, and available fuel and electricity sources. However, no consideration was given to geographic variability of activities modeled using EIO-LCA, although limited regionalized EIO-LCA inventories have been created (e.g., (Cicas 2005)). The only data input source that accounted for regional heterogeneity was the air pollutant emissions intensity of electricity production, which was resolved to the North American Electric Reliability Corporation (NERC) regions.

8.1.1.2 Temporal Variability

Almost all of the US-based data employed in this dissertation was published between the years 2000 and 2010. Industrial sector emission factors were typically taken directly from the 2002 EIO-LCA tool, so emissions estimates were made assuming that little change has occurred in technological efficiency and/or fuel or material inputs over the last decade. This assumption is reasonable for "mature" industries such as manufacturing and construction, which are not believed to have experienced major energy efficiency improvements in the last decade[46] and are not expected to undergo drastic improvements over the next decade.

However, activity-based energy intensity values were specific to within a few years of the modeled year (including the future scenario in Section 6), though the efficiency of agricultural, biorefining, and combustion processes in the emerging ligno-cellulosic biofuels industry may experience significant improvements as research and infrastructure investments take place in the future. Fuel-based air pollutant emission factors were also based on the closest year for which data was available.

The same inflation rate was applied to expenditure records regardless of the year, though the actual inflation rate varied between sectors and from year to year. Overall, the US economy's carbon intensity has been decreasing in tonnes of CO_2-e per million chained (2005) dollars of GDP, from 602 t/$MM in 2002 to 529 t/$MM in 2008 (US EIA 2010c), which is approximately a 2.1% annual drop. However, it is unclear whether this drop resulted primarily from industrial efficiency improvements, a shift in total expenditures from energy-intensive goods to energy-efficient services, or from continued offshoring of industrial activities.

[46] Although it is unclear if US construction industries experienced energy efficiency improvements commensurate with the economy-wide average, an evaluation of Chinese construction product-chain sectors from 2002-2007 found a slower energy intensity reduction rate than was found for the entire economy (Chang et al. 2011).

8.1.1.3 Geo-temporal Variability

The previous two sections made clear that significant uncertainly results from incomplete treatment of variability over time and across geographies. Additionally, in Section 7, state-to-state ethanol transportation was modeled using the simplification that net exporting and importing of ethanol for each state could be used to model total trade activity between states. However, inter-annual variability in total fuel supply, demand, and the differential in price between ethanol and gasoline may vary independently from region to region, and may have resulted in greater interstate transport than was estimated in the model. Unfortunately, data was only available at an annual resolution, so the model essentially presents a lower-bound estimate of optimal annual ethanol transportation.

8.1.2 Scenario Uncertainty

The previous section on parametric data uncertainty pertains mainly to the accuracy of component characterization (i.e., the creation of activity-based emission factors). However, the most policy-relevant results from this dissertation relate to insights from case study scenario modeling. This section will address the key areas of uncertainty related to these new modeling efforts, which are divided into political and economic uncertainty, technological uncertainty, and source and receptor uncertainty.

8.1.2.1 Political and Economic Uncertainty

The driving forces behind the emergence of the modern biofuels industry have been a function of public policy. As second generation biofuels are not expected to be cost-competitive with petroleum for many years, national or global demand will probably not meet policy targets without continued government intervention, though economic conditions and technological developments may reduce the need for, or influence of, fuel-based policies. As much of this dissertation was motivated to inform future energy and infrastructure policy makers, this subsection will address key areas of political and economic uncertainty.

The 2022 scale-up scenarios presented in Section 6 were formulated to align with EISA policy targets, though the US government has not yet met the original EISA targets for cellulosic biofuel production for any year to date. Government infrastructure construction subsidies, biofuel blending subsidies, and biofuel demand-based mandates increase the likelihood that private capital will be invested into equipment and infrastructure that are needed to most efficiently distribute biofuels, though the future portfolio and implementation of such policy interventions remains uncertain. Whether vehicle and infrastructure policies favor low-blend biofuel consumption (e.g., E10 or E15) or high-level blends (e.g., E85) may significantly impact the average distance biofuels are transported from producers.

Independent of public policy, changes to global oil markets and total demand for transportation fuels could strongly influence the economic viability of biofuels, and regional-level economic conditions will influence whether, where, and how many biorefineries will be sited, and. The geographic location and density of biorefineries has implications for feedstock and biofuel distribution, as locating biorefineries in locations with a low density of feedstock would increase feedstock transportation distance; similarly, a high density of biorefineries in remote areas would quickly lead to saturation of local markets near producers (e.g., at E10 or E15), making it necessary to transport fuel longer distances.

8.1.2.2 Technological Uncertainty

Although Miscanthus was assumed to be the dominant biomass crop for second generation biofuels, presumably ethanol, advances in and adoption of new technologies may enable other crops (e.g., agave, energy cane, poplar trees), other fuel molecules (e.g., butanol, bio-gasoline), or other engine types (e.g., fuel cell, homogeneous charge compression ignition) to render many aspects of this dissertation's 2022 scenario inaccurate. Additionally, research on currently available vehicle engines may differentiate ethanol–gasoline blends from ethanol-free gasoline on the grounds of combustion efficiency or air pollutant intensity, and these results may impact how policy makers or consumers influence the distance that biofuels will be transported from producers to consumers.

8.1.2.3 Source and Receptor Location Uncertainty

The geospatial analysis (presented in Section 7) of distribution activities did not address the actual locations of facilities for producing, blending, storing, and dispensing feedstocks and fuels. It is uncertain whether efforts to improve the resolution and real world representativeness of models would have significantly altered the relative advantage of certain distribution modes or routes over the alternative presented. In reality, the availability of infrastructure and distribution modes is limited, which may significantly impact how and where materials are handled and transported. For example, if actual transportation routes go through areas with more elevation change than the national average, more fuel will be consumed in transit. Additionally, if actual transportation routes go through areas with different population density and meteorological conditions than the routes modeled in this dissertation, the corresponding human intake of pollution may differ substantially.

8.1.3 Limitations and Uncertainty from Model Choices

Limitations in available data restricted the scope, metrics, and computational flexibility of component and distribution system models. Additionally, restrictions in available time and resources required that simplifications be made that limit the resolution, comprehensiveness and representativeness of the models, case studies, and impact assessment results. As a result, models may not be applicable to answering research questions not posed in this dissertation. Consideration of more complex models, additional metrics, or alternative case scenarios may be necessary to make well-informed decisions. The following subsections describe the types of limitations and uncertainty associated with methodological and model choices that should be considered when interpreting results presented in this dissertation.

8.1.3.1 Functional Unit Limitations

As discussed in the structure of component modeling within Section 5, the functional unit or activity that defines the performance or utility of a component does not always dictate demand for inputs such as infrastructure repair, energy intensity, or component replacement. Additionally, the shortcoming in available input reference data (discussed previously) over space and time resulted in models that failed to address much heterogeneity and variability, a problem previously referred to as "geographic and temporal masking" (Chester 2008). Instead of reporting results by several functional units (e.g., vehicle km, ton-km, and vehicle lifespan (Chester 2008)), the driving forces for each input (i.e., operation, fuel production, equipment, and infrastructure) are explained carefully in Appendix 10.1.

8.1.3.2 Simplification of Demand Factors

In modeling components and distribution systems, a balance was reached between having a very flexible, comprehensive, and accurate model, versus an efficient, understandable, and usable model. Results were presented in a fashion that implies a linear relationship between all components, though many of the relationships embedded in the analysis are nonlinear. For example, the relationship between truck weight and pavement deterioration (i.e., demand for road maintenance) is fourth order (Sathaye et al. 2010), and the relationship between the velocity and energy intensity of transportation modes will often vary from second order (e.g., pipelines (Masseron 1990)) to third order (e.g., ships (Lindstad et al. 2011)). Additionally, the energy required for agricultural equipment to handle biomass will depend on moisture, grass or stalk diameter, and other variables in addition to mass. If equipment is utilized differently in practice than is assumed in the model, then the implications for total emissions may be significant. Since most components and systems are reduced to a single functional unit at some point in the modeling efforts, the complexity of reality is not accurately reflected within the mechanisms in the model (even if the outputs match real world performance).

8.1.3.3 Data and Model Boundary Omissions

Although this study more comprehensively accounts for the components necessary to store, handle and distribute fuel and fuel feedstocks than existing petroleum and biofuel LCA studies, it remains incomplete. The boundaries of analysis of data sources for modeling inputs limit the accuracy and completeness of results. In addition to problems with EIO-LCA mentioned in the previous sections related to data age and sector aggregation, EIO-LCA is also not completely comprehensive. Section 5 outlined some of the shortcomings of US economic tables used to create EIO-LCA tables, such as inconsistent accounting for infrastructure maintenance. The US government invests heavily in maintaining inland waterways, and collects only half of this investment back through waterway fuel taxes. Unfortunately, government-funded maintenance activities are not accounted for in the "water transportation" sector explicitly, but these activities are categorized as general government taxes and subsidies (which has a much lower average material and energy intensity than maintenance-specific activities). In comparison, pipeline transportation receives a negligible amount of government subsidization, so construction and maintenance activities are thoroughly included in economic tables. These insights on transportation sector accounting only occurred after noticing that conflicting information had been published on the environmental advantages of rail in comparison to barge by different advocacy groups. It is unclear if comprehensive accounting of government (material and energy) inputs into all sectors would have significantly impacted other results in this dissertation.

Another boundary-related problem pertains to the choice of boundary in modeling efforts. This project initially sought to model emissions solely from liquid fuel distribution, but expanded to include feedstock harvesting and distribution, and the construction and replacement of petroleum refineries, biorefineries, and storage tanks. In order to perform a comprehensively fair comparison between fuels, infrastructure required to produce feedstock (e.g., oil rigs, agricultural planting equipment) would have been included. Although the boundary cut-off at feedstock handling was applied consistently to both fuels, it is uncertain whether a comparison that included emissions before feedstock handling would yield the same result, as "exploration and development" (E&D) expenditures are expected to remain significant[47] for the petroleum industry. If one is concerned with minimizing emissions from liquid fuels infrastructure, infrastructure investment forecasts could be used to justify the prioritization of E&D construction project evaluation. Petroleum distribution and refining infrastructure, which were included in this dissertation, are equivalent to only a quarter of the scale of all investments into E&D. If the boundary of analysis were expanded to include activities prior to feedstock handling for petroleum, E&D would probably increase the total embodied emissions for petroleum several-fold. However, emissions from clearing land and establishing biomass farms may also be significant.

As mentioned throughout this dissertation, the national scenario models did not account for the entire "cradle to grave" life-cycle of petroleum and biofuels, with feedstock-to-fuel conversion being the most obvious life-cycle stage omitted from this analysis. Activities deemed insignificant through preliminary calculations (e.g., soil carbon oxidation during excavation or dredging, storage tank inspection and washing, lighting of fuel terminals, shipping and disposing of end-of-life equipment and infrastructure) would have increased total emissions for both fuels to varying degrees. Lastly, when optimizing the distribution of ethanol from state-to-state in Section 7, results would be more comprehensive if consideration was given for how changing ethanol demand by region would have an opposite impact on regional petroleum gasoline demand; another step further would be to account for indirect impacts on the international trade of petroleum and biofuels.

8.1.3.4 Environmental Metrics

About 90% of existing bioenergy LCA studies reviewed in one study account for GHG emissions (Cherubini and Strømman 2011). Although minimizing GHG emissions is an important global goal (and the main metric considered in this study), decision-makers must also consider local, regional and indirect global impacts related to air pollution and human health, release of toxic substances, land use, biodiversity and ecosystem connectivity, water resources, noise and light pollution, workplace injuries, traffic and environmental accidents, employment and other considerations. Most life-cycle studies on the impacts of bioenergy on human and ecosystem toxicity (i.e., non-GHG impacts) have concluded that bioenergy systems lead to increased impacts when compared to fossil fuel reference systems (Cherubini and Strømman 2011). If Miscanthus-based ethanol is distributed as projected, the contribution of infrastructure and distribution to non-GHG environmental and health impacts will also likely be worse than petroleum by most environmental metrics, though it is unclear if this difference is significant in terms of all life-cycle impacts.

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[47] In comparison to electric power, gas and coal, the fraction of anticipated global infrastructure investments from 2007-2030 by the oil industry that are dedicated to distribution are the smallest (at 4%), whereas the bulk of oil infrastructure investments are expected to take place in E&D (80%) and refining (16%) (OECD/IEA 2008).

8.2 Assessment and Significance of Data Quality

The sources of uncertainty in the data and models described in this dissertation are numerous; it would be impossible to quickly garner an understanding of what components and processes were modeled with excellent data and modeling approaches, and which ones were estimated using poor data and rudimentary assumptions. In order to present a snapshot summary of data quality issues associated with each type of component model, a data quality evaluation system was used in order to draw attention to results that are associated with a high or low degree of confidence. Existing literature on addressing uncertainty in LCA was used to guide the creation of the data quality pedigree matrix presented in Table 35, which consists of previously defined data quality evaluation categories with definitions revised to be appropriate for this project, and a few new categories were included to address data quality questions most relevant to this research.

The categories and scoring system presented in Table 35 were used to create a data quality scorecard for each of the nine major types of components modeled in this dissertation. Immediately following the data quality scorecard for each component, an additional table incorporates results from Sections 5 and 6 to indicate the significance of each life-cycle stage to the component's GHG emission factor. Additionally, this table presents the significance of the component's GHG emissions with respect to the entire petroleum fuels and miscanthus-based ethanol systems: first as a percentage of emissions from all components that fell into the particular life-cycle category, and second as a percentage of emissions from all distribution components at all life-cycle stages.

By reviewing the two tables simultaneously, the reader can more easily identify which results can be interpreted with confidence and which areas warrant further research, depending on the specific research question. For example, data quality associated with fuel and electricity production was consistently found to be better than data quality for other life-cycle stages. If trying to improve the accuracy of emission factors for agricultural equipment and transportation vehicles, little improvement in accuracy would be expected from focusing efforts on this stage. However, this stage deserves careful attention in the modeling of pipeline transportation, as electricity production accounts for the majority of life-cycle emissions from pipeline transportation, and the GHG intensity of electricity varies significantly by region. With respect to the entire infrastructure and distribution system for petroleum, pipelines contribute only 4% of emissions while refineries were estimated to contribute 6% of emissions. Refinery construction and maintenance emissions are also not understood as well, so further research into materials and construction practices for refineries should be a higher priority than improving upon pipeline models.

	A	B	C	D
Independence of Data Supplier	Verified data (well-documented public or independent source)	Independent source, with non-verified sources from industry	Non-verified industry source	Non-verified information from industry expert
Data Acquisition	Measured data for specific processes	Calculated based on verified models	Qualified expert estimate	Nonqualified estimate (e.g., rule of thumb)
Data Representativeness and Scope Completeness	Sufficient and comprehensive samples from specific processes under relevant conditions	Adequate sample size, but scope is partially incomplete or lacks specificity to the system being analyzed	Data scope is incomplete and data lack specificity to the system being analyzed	Unknown or incomplete data (shorter time periods and/or fewer sites)
Model Representativeness	Model relationships and allocation are based on well-understood mechanisms	Model relationships and allocation are based on well-defined industry statistics	Model relationships and allocation are based on general industry planning guidelines	Model relationships and allocation are based on limited case studies or industry expert
Temporal Correlation of Resource Input Intensity	Less than 5 years of differences to year of analysis	Less than 10 years of differences to year of analysis	Less than 15 years of differences to year of analysis	Age unknown, or > 15 years of differences to year of analysis
Temporal Correlation of Air Pollution Intensity	Less than 5 years of differences to year of analysis	Less than 10 years of differences to year of analysis	Less than 15 years of differences to year of analysis	Age unknown, or > 15 years of differences to year of analysis
Geographical Correlation of Resource Input Intensity	Data collected from statistics appropriate for area of study	Data collected from limited areas likely to be typical for area of study	Data collected from an area much larger or smaller than area of study	Data from an unknown area or with very different conditions
Geographical Correlation of Air Pollution Intensity and Impacts	Data collected from statistics appropriate for area of study	Data collected from limited areas, but likely to be typical for area of study	Data collected are from an area much larger or smaller than area of study	Data from an unknown area or with very different conditions
Further Technological Correlation[48]	Data from same processes, materials , and conditions	Data from same processes, but not specific to materials under analysis	Data from similar or overly generalized processes or materials	Data from similar system, but unclear similarity in driving mechanisms
Potential for Variability Score[49]	Small variability (High/Low <1.3)	Moderate variability (High/Low <3)	Significant variability (High/Low <10)	Extreme variability (High/Low >10)

Table 35. Data Quality Assessment (influenced by (Huijbregts 1998; Huijbregts et al. 2001; Junnila and Horvath 2003; Spielmann et al. 2005)).

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[48] Further technological correlation relates to accurately estimating energy intensity of activities; modeling the actual average component capacity (e.g., payload), utilization, and transportation distance (if applicable); and the driving mechanisms for deterioration and replacement.

[49] This is a metric for variability, not uncertainty, and is intended to show the importance of choosing the right model or equation.

	Infrastructure	Equipment	Fuel Production	Operations/ Direct
Independence of Data Supplier	-	A	A	A
Data Acquisition	-	B	B	B
Data Representativeness and Scope Completeness	-	B	A	A
Model Representativeness	-	B	A	A
Temporal Correlation of Resource Input Intensity	-	D	C	C
Temporal Correlation of Air Pollution Intensity	-	-	-	A
Geographical Correlation of Resource Input Intensity	-	B	A	A
Geographical Correlation of Air Pollution Intensity and Impacts	-	-	-	-
Further Technological Correlation	-	A	A	A
Potential for Variability Score	-	B	A	B

Table 36. Agricultural Equipment Data Quality Assessment.

	Infrastructure	Equipment	Fuel Production	Operations/ Direct
Contribution to Component's Emission Factor	-	9% - 38%	8% - 12%	54% - 79%
Petroleum: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	-	-	-	-
Petroleum: Contribution to Total Distribution System GHG Emissions	-	-	-	-
Ethanol: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	-	71%	43%	43%
Ethanol: Contribution to Total Distribution System GHG Emissions	-	12%	3%	21%

Table 37. Agricultural Equipment: Significance of Life-cycle Stages to Component and National System Emissions Models.

	Infrastructure	Vehicle	Fuel Production	Operations/ Direct
Independence of Data Supplier	A	A	A	A
Data Acquisition	B	B	B	B
Data Representativeness and Scope Completeness	B	A	A	A
Model Representativeness	B	B	A	A
Temporal Correlation of Resource Input Intensity	D	D	C	C
Temporal Correlation of Air Pollution Intensity	-	-	-	A
Geographical Correlation of Resource Input Intensity	A	A	A	A
Geographical Correlation of Air Pollution Intensity and Impacts	-	-	-	B
Further Technological Correlation	B	A	A	A
Potential for Variability Score	D	B	A	B

Table 38. Truck Transportation Data Quality Assessment.

	Infrastructure	Vehicle	Fuel Production	Operations/ Direct
Contribution to Component's Emission Factor	1% - 10%	15% - 25%	9% - 10%	63% - 66%
Petroleum: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	4%	28%	5%	9%
Petroleum: Contribution to Total Distribution System GHG Emissions	1%	2%	1%	5%
Ethanol: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	7%	28%	35%	35%
Ethanol: Contribution to Total Distribution System GHG Emissions	2%	5%	3%	17%

Table 39. Truck Transportation: Significance of Life-cycle Stages to Component and National System Emissions Models.

	Infrastructure	Vehicle	Fuel Production	Operations/ Direct
Independence of Data Supplier	A	A	A	A
Data Acquisition	B	B	B	B
Data Representativeness and Scope Completeness	B	A	A	A
Model Representativeness	B	B	A	A
Temporal Correlation of Resource Input Intensity	D	D	C	C
Temporal Correlation of Air Pollution Intensity	-	-	-	A
Geographical Correlation of Resource Input Intensity	A	A	A	A
Geographical Correlation of Air Pollution Intensity and Impacts	-	-	-	B
Further Technological Correlation	B	A	A	A
Potential for Variability Score	B	B	A	B

Table 40. Rail Transportation Data Quality Assessment.

	Infrastructure	Vehicle	Fuel Production	Operations/ Direct
Contribution to Component's Emission Factor	8%	2%	12%	80%
Petroleum: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	-	-	1%	1%
Petroleum: Contribution to Total Distribution System GHG Emissions	-	-	-	1%
Ethanol: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	1%	1%	9%	9%
Ethanol: Contribution to Total Distribution System GHG Emissions	-	-	1%	4%

Table 41. Rail Transportation: Significance of Life-cycle Stages to Component and National System Emissions Models.

	Infrastructure	Vehicle	Fuel Production	Operations/ Direct
Independence of Data Supplier	A	A	A	A
Data Acquisition	B	B	B	B
Data Representativeness and Scope Completeness	C	A	A	A
Model Representativeness	C	B	A	A
Temporal Correlation of Resource Input Intensity	D	D	C	C
Temporal Correlation of Air Pollution Intensity	-	-	-	A
Geographical Correlation of Resource Input Intensity	A	A	A	A
Geographical Correlation of Air Pollution Intensity and Impacts	-	-	-	B
Further Technological Correlation	C	B	A	A
Potential for Variability Score	D	B	A	B

Table 42. Inland Tow Transportation Data Quality Assessment.

	Infrastructure	Vehicle	Fuel Production	Operations/ Direct
Contribution to Component's Emission Factor	6%	6%	11%	77%
Petroleum: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	2%	9%	6%	10%
Petroleum: Contribution to Total Distribution System GHG Emissions	-	-	1%	6%
Ethanol: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	-	-	1%	1%
Ethanol: Contribution to Total Distribution System GHG Emissions	-	-	-	-

Table 43. Inland Tow Transportation: Significance of Life-cycle Stages to Component and National System Emissions Models.

	Infrastructure	Vehicle	Fuel Production	Operations/ Direct
Independence of Data Supplier	A	A	A	A
Data Acquisition	B	B	B	B
Data Representativeness and Scope Completeness	C	A	A	A
Model Representativeness	C	B	A	A
Temporal Correlation of Resource Input Intensity	D	D	C	C
Temporal Correlation of Air Pollution Intensity	-	-	-	A
Geographical Correlation of Resource Input Intensity	A	C	B	A
Geographical Correlation of Air Pollution Intensity and Impacts	-	-	-	B
Further Technological Correlation	C	B	A	A
Potential for Variability Score	D	B	A	B

Table 44. Ocean Tanker Transportation Data Quality Assessment.

	Infrastructure	Vehicle	Fuel Production	Operations/ Direct
Contribution to Component's Emission Factor	4% - 8%	8% - 12%	4%	79% - 84%
Petroleum: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	12%	63%	9%	47%
Petroleum: Contribution to Total Distribution System GHG Emissions	2%	4%	1%	28%
Ethanol: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	-	-	-	-
Ethanol: Contribution to Total Distribution System GHG Emissions	-	-	-	-

Table 45. Ocean Tanker Transportation: Significance of Life-cycle Stages to Component and National System Emissions Models.

	Infrastructure	Equipment/ Vehicle	Electricity Production	Operations/ Direct
Independence of Data Supplier	A	-	A	A
Data Acquisition	B	-	B	B
Data Representativeness and Scope Completeness	B	-	A	A
Model Representativeness	C	-	A	A
Temporal Correlation of Resource Input Intensity	D	-	C	C
Temporal Correlation of Air Pollution Intensity	-	-	A	-
Geographical Correlation of Resource Input Intensity	A	-	A	A
Geographical Correlation of Air Pollution Intensity and Impacts	-	-	B	-
Further Technological Correlation	A	-	A	A
Potential for Variability Score	D	-	B	C

Table 46. Pipeline Transportation Data Quality Assessment.

	Infrastructure	Equipment/ Vehicle	Electricity Production	Operations/ Direct
Contribution to Component's Emission Factor	29% - 36%	-	64% - 79%	-
Petroleum: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	20%	-	64%	-
Petroleum: Contribution to Total Distribution System GHG Emissions	4%	-	10%	-
Ethanol: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	-	-	-	-
Ethanol: Contribution to Total Distribution System GHG Emissions	-	-	-	-

Table 47. Pipeline Transportation: Significance of Life-cycle Stages to Component and National System Emissions Models.

	Infrastructure	Equipment/ Vehicle	Fuel Production	Operations/ Direct
Independence of Data Supplier	A	-	-	A
Data Acquisition	B	-	-	B
Data Representativeness and Scope Completeness	B	-	-	B
Model Representativeness	B	-	-	B
Temporal Correlation of Resource Input Intensity	D	-	-	B
Temporal Correlation of Air Pollution Intensity	-	-	-	-
Geographical Correlation of Resource Input Intensity	A	-	-	A
Geographical Correlation of Air Pollution Intensity and Impacts	-	-	-	-
Further Technological Correlation	B	-	-	B
Potential for Variability Score	B	-	-	A

Table 48. Petroleum Refineries and Biorefineries Data Quality Assessment.

	Infrastructure	Equipment/ Vehicle	Fuel Production	Operations/ Direct
Contribution to Component's Emission Factor	100%	-	-	-
Petroleum: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	32%	-	-	-
Petroleum: Contribution to Total Distribution System GHG Emissions	6%	-	-	-
Ethanol: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	76%	-	-	-
Ethanol: Contribution to Total Distribution System GHG Emissions	20%	-	-	-

Table 49. Petroleum Refineries and Biorefineries: Significance of Life-cycle Stages to Component and National System Emissions Models.

	Infrastructure	Equipment/ Vehicle	Fuel Production	Operations/ Direct
Independence of Data Supplier	A	-	A	C
Data Acquisition	C	-	B	C
Data Representativeness and Scope Completeness	B	-	A	B
Model Representativeness	C	-	A	C
Temporal Correlation of Resource Input Intensity	D	-	C	C
Temporal Correlation of Air Pollution Intensity	-	-	-	-
Geographical Correlation of Resource Input Intensity	A	-	A	A
Geographical Correlation of Air Pollution Intensity and Impacts	-	-	-	-
Further Technological Correlation	B	-	A	B
Potential for Variability Score	D	-	A	C

Table 50. Storage Tanks Data Quality Assessment.

	Infrastructure	Equipment/ Vehicle	Fuel Production	Operations/ Direct
Contribution to Component's Emission Factor	20% - 71%	-	0% - 32%	28% - 79%
Petroleum: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	6%	-	-	4%
Petroleum: Contribution to Total Distribution System GHG Emissions	6%	-	1%	11%
Ethanol: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	5%	-	3%	3%
Ethanol: Contribution to Total Distribution System GHG Emissions	1%	-	-	2%

Table 51. Storage Tanks: Significance of Life-cycle Stages to Component and National System Emissions Models.

	Infrastructure	Equipment/ Vehicle	Fuel Production	Operations/ Direct
Independence of Data Supplier	-	-	A	A
Data Acquisition	-	-	B	B
Data Representativeness and Scope Completeness	-	-	A	A
Model Representativeness	-	-	A	A
Temporal Correlation of Resource Input Intensity	-	-	C	B
Temporal Correlation of Air Pollution Intensity	-	-	-	A
Geographical Correlation of Resource Input Intensity	-	-	A	A
Geographical Correlation of Air Pollution Intensity and Impacts	-	-	-	-
Further Technological Correlation	-	-	A	A
Potential for Variability Score	-	-	A	C

Table 52. Vehicle Errand Data Quality Assessment.

	Infrastructure	Equipment/ Vehicle	Fuel Production	Operations/ Direct
Contribution to Component's Emission Factor	-	-	13%	87%
Petroleum: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	-	-	9%	15%
Petroleum: Contribution to Total Distribution System GHG Emissions	-	-	1%	9%
Ethanol: Contribution to Total Distribution System GHG Emissions from this Life-cycle Category	-	-	8%	8%
Ethanol: Contribution to Total Distribution System GHG Emissions	-	-	1%	4%

Table 53. Vehicle Errands: Significance of Life-cycle Stages to Component and National System Emissions Models.

8.3 Summary of Findings

In constructing models of infrastructure components and national scenarios for distributing transportation fuels, this dissertation sought to quantify the contribution of distribution activities and infrastructure operation and maintenance to the life-cycle emissions footprint of petroleum fuels and biofuels. The contribution from "upstream" (i.e., non-operation stage) activities to the life-cycle GHG emission factor ranged from less than 25% for rail and water transport modes, to more than 30% for trucking, 40% for biomass balers, and 60% for retail station and smaller storage tanks. As shown in Table 36 through Table 52 (even numbers), uncertainty and limited treatment of variability in the component models are concentrated in the embodied emissions from infrastructure, equipment and vehicles, though operating stage emissions dominate life-cycle emissions for material handling and transportation modes, as shown in Table 37 through Table 53 (odd numbers). For this reason, addressing limitations associated with "upstream" activities is unlikely to change the relative importance or comparative advantages of different modes in terms of total GHG emissions. However, emissions from storage node and conversation facility components (described in detail in Appendices 10.2.2 and 10.2.3) are dominated by manufacturing, construction and maintenance activities, and the operating conditions are also considered highly variable and less well understood than transportation modes. The degree of uncertainty in the emissions results for these components is therefore significant, so results should not be referenced with a high degree of confidence.

Infrastructure and distribution activities are projected to contribute just over 3 g CO_2-e/MJ to the life-cycle GHG footprint of petroleum fuels, but approximately five times that (17 to 18 g CO_2-e/MJ) to the life-cycle GHG footprint of Miscanthus-based ethanol. Emissions from the operation stage (i.e., direct or tailpipe emissions) make up the majority of modeled emissions for both fuels, totaling approximately 2 g CO_2-e/MJ for petroleum and 10 g CO_2-e/MJ for miscanthus-based ethanol, with embodied emissions from infrastructure, equipment, and vehicles making up the balance. As the total life-cycle GHG footprint of second generation ethanol is required and expected to be less than half that of petroleum fuels, the percent contribution of distribution and infrastructure to the biofuel's total GHG footprint will be more than five times greater than petroleum. The infrastructure and distribution related emissions for biofuels are greater than those of petroleum because biofuels are: projected to continue being distributed by less energy (and cost) efficient modes than those used for petroleum distribution (i.e., truck and rail vs. pipeline and ocean tanker); are distributed comparable or farther distances than petroleum due to demand for Midwest-produced ethanol on the coasts; are more equipment-intensive due to the lower utilization of agricultural equipment and infrastructure; and because ethanol and its feedstocks are significantly less energy dense per unit mass and volume than petroleum fuels. In addition to data quality and component model limitations, there is significant uncertainty in how distribution scenarios were constructed for both fuels. The degree and implications of this uncertainty are much more significant for biofuels, as the petroleum distribution system is well established, well understood, and more efficient than that of ligno-cellulosic biofuels. Biomass feedstock and biofuel product transportation contribute approximately one-third of total emissions, so improved knowledge about future geographic, technological, political and economic influences on transportation distances could change the total GHG footprint of these biofuels by more than 10%.

In evaluating the historic distribution of ethanol within the contiguous United States, it was determined that approximately 10 billion t-km of ethanol transportation could have been avoided each year from 2004-2009 if ethanol had been consumed close to producers until local gasoline markets became saturated at the E10 blend wall . This "unnecessary" transportation of ethanol resulted in more than $240 million in freight costs, 300,000 tonnes of CO_2-e emissions, and thousands of tonnes of criteria air pollutant emissions that adversely impact human health and the environment. The national network model was built using many simplifications due to a lack of data on actual trade and transportation activity. Results were generated assuming the shortest possible routes between producer states and their actual or nearest-feasible consumer states, using annual net production and consumption volumes to estimate total trade and transportation activity, so costs and emissions may have been greatly underestimated. Additionally, geo-temporal variability associated with fuel prices, freight costs, and delivery speed would also influence the choice of mode and route of ethanol transportation. These sources of uncertainty affect results from the national network model, as well as the estimation of $PM_{2.5}$ intake fractions for the archetypal routes and modes described in Section 7. In evaluating the westbound and eastbound fuel delivery routes by truck and rail from the Midwest, the estimated pollution intake values differed enough to make relative comparison more meaningful than if alternatives were compared only by total mass of emissions. While transport of ethanol by rail is only one-fifth as energy intensive as truck, locomotives emit more pollution per unit of fuel than trucks, so ethanol shipped by rail results in more than 50% as much harm to human health as trucks. Additionally, transportation from the Midwest to the West Coast, despite being more than 50% longer and fuel-intensive than routes to the East Coast, would result in slightly less harm to human health.

8.4 Policy Implications

Although the contribution of infrastructure and distribution to the carbon footprint of currently available petroleum fuels is small, ambitious carbon-reduction goals will require many currently overlooked activities to be worth optimizing in future fuel systems. The contribution of supply chain (embodied) emissions will become more significant if the carbon intensity of producing gasoline replacements decreases over time, while the provision of infrastructure, equipment, and vehicles remain carbon intensive. For example, if biofuels are distributed as projected in this dissertation, it will be extremely difficult to supply a biofuel to consumers with a GHG footprint 80% less than petroleum-based gasoline, a potential future policy goal, even if feedstock production and conversion processes become extremely efficient. Results from Section 7 suggest that reducing GHG and air pollutant emissions impacts of ethanol distribution could be accomplished through encouraging local consumption; however, many other technically feasible and cost effective opportunities may exist to reduce emissions, and possibly at a greater scale, throughout the production, distribution, and consumption stages of petroleum or biofuels.

Results presented in this dissertation underscore the need for LCA studies to include capital goods such as infrastructure and equipment, and to accurately represent the handling and transportation of feedstocks and finished products, in order to identify opportunities to minimize total system emissions. Additionally, although life-cycle emissions from distribution systems are often assumed to have little influence on demand for commodities such as freight goods (Facanha and Horvath 2006) or publicly supplied water (Stokes and Horvath 2009), regional demand for alternative fuels is often motivated by the estimated life-cycle greenhouse gas footprint of the fuel product at the point of consumption. Mandates for biofuels have historically been disconnected at the national and state level, leading to inefficient distribution of biofuel products (as quantified in Section 7). In order to effectively reduce total global greenhouse gas emissions, greater harmonization or centralization of policies at national or international scales will be required in response to the improving understanding of international economic and agricultural system relationships. As a result, fuel suppliers will be incentivized to make decisions that minimize the carbon intensity of the entire global transportation sector, instead of certifying or otherwise differentiating the carbon-intensity of fuels on a case-by-case basis.

8.5 Contributions to Knowledge

This dissertation builds off of previous literature and presents the most comprehensive inventory of components and activities that occur between feedstock handling and fuel consumption for both petroleum fuels and miscanthus grass-based biofuels. The physical characterization of feedstock and fuel handling and transportation activities is considered more complete and representative in terms of energy, material and water input intensity, and in terms of life-cycle GHG and tailpipe criteria air pollutant emissions, for the United States during the time periods under analysis. Methodological contributions include the development of new hybrid life-cycle models to account for embodied infrastructure and equipment emissions, improved modeling of infrastructure cycles using physically representative models, accounting for product losses in fuel distribution systems, and policy insights from case study and scenario optimization modeling. Results may contribute towards informing public policy or industry certification standards on the environmental impacts from fuels. The following sections summarize the key contributions of this dissertation, as differentiated from existing publicly available research literature.

8.5.1 Life-cycle Emission Factors of Distribution Components

Although life-cycle emission factors had previously been created for several of the components modeled in this study, new emission factors were generated using almost entirely US-based publicly available data from 2000 or more recently. In addition to creating completely new life-cycle emission factors for agricultural and storage activities, this study employed a more comprehensive allocation of infrastructure emissions to freight transportation than was possible in the past, due to recent developments in allocating infrastructure deterioration and maintenance to freight transportation. This is the first known study to create US-based emission factors for maritime and pipeline transportation, though application of emission factors should be limited to liquid fuels. Literature contributions that result from improved modeling of transportation modes are categorized as being more geographically representative, temporally representative, or physically representative than could be found in existing literature. The main contributions attributed to the specific life-cycle stage for each type of component are summarized in Table 54.

GR Geographically Representative: Model input data consist of US-specific publicly available data, with transparent assumptions and calculations (i.e., not using commercial databases such as EcoInvent).

PR Physically Representative: Emissions-inducing activities are modeled and allocated according to technically (or economically) defensible mechanisms that are specific to the component design, size or payload, and type of material handled.

TR Temporally Representative: Model input data and assumptions are based on information published more recently than was incorporated into existing studies in the literature on life-cycle emissions for biomass or petroleum handling, storage and transportation.

\- Not applicable in this study.[50]

	Infrastructure Cycle	Equipment Cycle	Fuel or Electricity Production	Operation
Agricultural Equipment	-	GR	TR	GR
Truck	PR, TR	TR	TR	TR
Rail	PR, TR	TR	TR	TR
Inland Waterway	GR, PR, TR	GR, PR, TR	TR	PR, TR
Ocean Tanker	GR, PR, TR	GR, PR, TR	TR	PR, TR
Pipeline	GR	-	TR, GR	PR
Biorefineries and Petroleum Refineries	GR	-	-	TR
Storage Tanks	GR	-	-	PR, TR
Vehicles (re-fueling only)	-	-	TR	PR

Table 54. Summary of New Contributions to Fuel Distribution Life-cycle Emissions Modeling.

Although the emission factors reported in this dissertation are simplified to functional units of t-km of goods transported or tonnes handled, the model structure for each component was designed in order to reflect the most significant influence on the maintenance and replacement of infrastructure and equipment components. For some components (e.g., storage tanks), age is a more significant driver of replacement than utilization, whereas allocation of infrastructure maintenance emissions to truck and rail transport modes incorporated recent studies on marginal damage per t-km specific to the commodity and vehicle configuration. This approach differs from simply dividing emissions from all known national maintenance activities by the total quantity of functional units delivered by

[50] Equipment cycles were grouped with the infrastructure cycle for pipelines, biorefineries, petroleum refineries, and fuel dispensers. In the case of petroleum refineries and biorefineries, modeling of "operation" is limited to the mass conversion efficiency of feedstock to fuel and electrical energy; no consideration was given to other energy and material inputs or the fate of waste products.

each mode, as has been done by LCA practitioners using hybrid approaches and/or commercial software, though this approach was used when the driving mechanism(s) was unknown or age-based. Assuming technology efficiency and infrastructure utilization do not change drastically, the emission factors presented in this dissertation could be applied to other situations outside of those presented here.

8.5.2 Physical Inventory of Fuel Distribution System Components

As was mentioned earlier, the initial motivation in performing this study was to include the embodied emissions from infrastructure and equipment in the life-cycle environmental "footprint" of liquid transportation fuels. These activities are overlooked in many fuel studies that are referred to as LCAs, but more accurately could be described as fuel-cycle well-to-wheels (WTW) assessments. While some biofuel and petroleum LCA studies have accounted for (or acknowledged) the embodied emissions of limited aspects of infrastructure and equipment, the tools and reports most commonly referenced by policy makers (e.g., (US DOE ANL 2010; US DOE NETL 2008; US EPA 2010e)) do not consistently account for these embodied emissions. This is the first known study to include emissions estimates for maintenance and replacement of many liquid fuel storage, handling and transportation components in the life-cycle "footprint" of fuels.

The data employed in this dissertation are publicly available (and free to most university researchers), bringing greater transparency to results than would be possible using commercial databases (e.g., (Ecoinvent 2010)) that have been employed in many biofuel LCA studies. Additionally, much of the data found in commercial databases are limited to a certain region (e.g., Europe) and more than ten years old. Almost all data employed in my analysis were specific to the United States and published within the last decade.

After reviewing much of the academic and industry literature on fuel systems, a few additional areas to expand the boundary and scope of this analysis became evident. Instead of terminating the study boundary at the point of fuel sale, the scope of this study included the construction and operation of fueling stations, and also included the errand required by vehicle owners to fill their tank. This expansion was deemed necessary due to the energy density difference between ethanol and gasoline (which leads to more frequent refueling errands), and because future vehicles that run on electricity or other fuels may not require refueling stations to be constructed, operated (e.g., which includes lighting at night), and visited every few days by vehicle operators.

8.5.3 Optimization of Freight Networks

Optimization of freight transportation networks is a very well established field, and is commonly performed by industry and government analysts. Typically, the objective is to minimize the time and cost of distributing goods or forecasting congestion in highly utilized corridors. More recently, models have been created that enable freight logistics to be optimized to meet environmental criteria related to GHG emissions and energy efficiency (Winebrake et al. 2008), though such models are not publicly available. Several biofuel environmental assessment studies incorporate optimization into the placement of biorefineries (Kocoloski et al. 2011) or routing of ethanol from producers to consumers (Figer 2011; Morrow et al. 2006; Wakeley et al. 2009) based on historic or expected supply and demand volumes. However, this is the first known study to interrogate the justification of geographically heterogeneous fuel policies that induce ethanol transportation away from producer regions.

In order to draw attention to how policy has influenced the distance and modes by which ethanol (or other commodities) are distributed when it cannot be differentiated by consumers on a performance basis, it was necessary to create alternative distribution scenarios that are economically and environmentally preferable. In creating alternative historic scenarios that are technically defensible, it was important to consider the fungibility of ethanol with conventional gasoline, saturation of fuel markets close to producers, and evaluate political-economic tools that may or should enable system-wide emissions to achieve a minimum. Through these exercises, new insight is provided on the significance of market saturation (in this case, the 10% ethanol blend wall) near producers on the necessary minimum transportation distance for relatively fungible products. This approach to modeling alternative distribution scenarios could be useful in creating alternative distribution scenarios for other commodities as well, so long as a significant fraction of the commodity could technically be consumed close to producers.

8.5.4 Impact Assessment of Alternative Transportation Routes

Most studies that report air pollutant emissions from freight transportation mention that tailpipe exhaust pollution can lead to adverse human health impacts. Many authors acknowledge that the health damages from emissions are strongly dependent on the proximity of emissions to human populations, but nevertheless report an inventory of emissions without regard for where emissions actually take place (e.g., (Chester 2008; Facanha 2006)) because it is either impossible or analytically burdensome to account for the location of all air emissions from transportation activities (which are more dispersed than point sources such as power plants). Other authors account for the estimated human health burden from transportation emissions by extrapolating results from published air quality models (as discussed by (H. S. Matthews et al. 2001)), and apply an average or range of characterization factors to new project-specific transportation emissions without having performed case-specific geographic analysis (e.g., by simplifying air quality impacts into either urban or rural categories, as is done by (US DOE ANL 2010)).

Recently, more sophisticated national biofuel models have been published that estimate the human health burden based on the estimated location of exhaust emissions from agricultural and transportation equipment (e.g., (Cook et al. 2011; Hill et al. 2009)). Although a national spatial model of biomass production and distribution was not created in this dissertation, air emissions along hypothetical but possible alternative trade routes were evaluated using spatial software (*ArcGIS*) in order to highlight how human health impacts are much more sensitive to the location of emissions than the amount of pollutants emitted, and how health impacts will vary with the location of transportation routes.

8.6 Recommendations for Future Work

Throughout the process of reviewing existing literature and performing analysis for the projects described in this dissertation, many new challenges were identified as unaddressed or poorly addressed in the literature on environmental impacts from freight (in particular, liquid fuels) distribution systems. As much as possible, these challenges informed the models and scenarios developed in this dissertation, but unfortunately not all worthwhile questions could be answered.

Some of these gaps were discussed in the previous section as limitations in the scope, boundary, metrics, and modeling methodology incorporated into this research, and this section outlines options for extending or improving upon the tools and scenarios in this dissertation. Additionally, a few new projects related to life-cycle environmental data analyses are proposed.

8.6.1 Expand Modeling of Component and Distribution Systems

This dissertation presented new life-cycle emissions models specific to major components in the distribution system for biofuels and petroleum fuels under typical operating conditions. In the future, it may be useful to expand the flexibility of component and system models, in order to more accurately reflect conditions in proposed or actual case studies. For example, instead of creating emission factors for each mode operating at the national average utilization with average maintenance requirements and lifespan, it would be insightful to present the range of emissions corresponding with different sizes of each mode (especially the diameter of pipelines), different maintenance requirements (especially for waterways), and different lifespans.

Additionally, it may also be worthwhile to expand the system boundaries to incorporate other components involved in liquid transportation fuel systems (such as biomass crop establishment or petroleum exploration equipment) and to evaluate environmental metrics in addition to air emissions and water withdrawals. The same framework adopted in this dissertation could also be applied to products other than fuels, such as waste products or other materials that are handled differently than common bulk commodities (for which transportation and handling emissions can be approximated using freight emission factors that have been published in existing literature).

The availability of geographic information system (GIS) data and analytical tools enabled the models in this dissertation to incorporate real world geospatial data into scenarios. However, national distribution networks were optimized using simple transportation distance between state centroids. Results would be most relevant if intermodal routes could be considered (when available), and routing could be optimized (and trade-offs evaluated) based on multiple objectives, and international distribution could also be considered. The recently developed Geospatial Intermodal Freight Transport (GIFT) model (Winebrake et al. 2008) offers this type of optimization based on GHG emissions, delivery time, and costs, though only on a case by case basis for origin-destination pairs. A valuable synergy of the research presented in this dissertation with the GIFT model would be to enable analysts to perform nationwide network optimization using existing GIFT criteria (i.e., cost, GHG emissions, delivery time), and specifying the locations of existing or potentially available facilities and transportation infrastructure. Additionally, it would be valuable to enable optimization of distribution routing decisions using health burden as another criteria (following the methodology described in Section 7).

8.6.2 Evaluate Distribution System Changes and Alternatives

In addition to improving the comprehensiveness and accuracy of modeling distribution components, there are countless interesting questions that could be answered by performing different types of life-cycle systems analysis. For this reason, it is worthwhile to explore various approaches for comparing alternative technologies (e.g., transportation modes), products (e.g., transportation fuels), new infrastructure projects (e.g., ports or pipelines), or changes to operations or consumer behavior. The approach to evaluating alternatives has a strong influence on the policy relevance of the estimated environmental impact results, in terms of understanding trade-offs and setting priorities when resources are limited.

This dissertation characterizes the baseline scenarios and most common modes for storing and handling liquid fuels, though valuable insights could be generated by evaluating alternative policy strategies for expanding ethanol consumption and commercializing second (and potentially third) generation biofuels. Contemporary challenges in optimizing US biofuel policy relate to whether demand should be increased by raising the low-level blend wall for common gasoline (e.g., from E10 to E15 or E20), by investing in (concentrated) retail station infrastructure and FFVs to enable consumption of mid- and high-level blends, and by constructing ethanol pipelines that could outcompete the currently-available modes (e.g., truck, rail and barge) in terms of environmental and economic performance in the long term. Policy-relevant scenario optimization results would highlight opportunities to reduce GHG emissions for little to no cost, using a transparent range of assumptions about expected utilization, policy timeframe, and potentially elevated risks to infrastructure or vehicles from using alternative fuels.

As this dissertation primarily served to address the GHG and other air emissions from national provision of conventional and alternative transportation fuels, additional practical and tangible insights could be gained by using alternative modeling approaches to case studies. The following subsections describe four approaches to using the types of models and results presented in this dissertation, with suggested example projects for future case studies.

8.6.2.1 Steady-state Alternative Comparison

A straightforward approach for presenting life-cycle emissions for infrastructure case studies is to evaluate several options for meeting a fixed level of demand over a specified time period, assuming infrastructure is routinely maintained and occasionally replaced. This approach has been useful in evaluating alternative options for meeting electricity demand (Bergerson and Lave 2005; Pacca and Horvath 2002) and transoceanic transportation demand (Lindstad et al. 2011) over several decades. The "steady-state" assumption was built into the component and national systems models described in Sections 5 and 6, though all transportation and storage infrastructure was assumed to already be in place in the year of analysis (but maintained and replaced routinely).

For case studies in locations that lack existing transportation infrastructure, an analysis that includes construction of infrastructure in the first year of a study may conclude that emissions from a truck, train, water, or pipeline based fuel transportation systems rank differently than this dissertation may seem to suggest. Additionally, valuable insights could also be gained by performing steady-state analysis for specific cases in the United States, as was recently performed to compare truck and rail routes for transporting different commodities along different freight corridors (ICF International 2009). This approach would enable analysts identify opportunities when one mode may outcompete another mode, based on regionally-specific mode configuration and size, utilization, energy-intensity, or maintenance and replacement requirements.

In addition to comparing modes, this approach could be used to compare alternative operating strategies. For example, pipeline operators may consider saving money by pumping oil faster at night when electricity rates are lower, instead of piping at a constant velocity. This decision would present trade-off implications for energy efficiency as well as the emissions factor of the electricity grid (which would be different at night than during peak hours of the day).

8.6.2.2 Project Payback Analysis

While useful for modeling mature technologies in reliable markets, the steady-state approach does not typically do a good job of addressing possible changes in technology, market demand, or premature failure or obsolescence of infrastructure. The simplest way to address these concerns is to estimate the environmental "payback" or "breakeven" period for new technologies or infrastructure projects that would compete with existing systems. As environmental externalities are sometimes disproportionate to financial costs, a simple "environmental return on investment" calculation can produce results that are counterintuitive and insightful; for example, constructing a large efficient infrastructure system may be financially infeasible over a 30-year time period, but may outperform alternative existing systems in terms of environmental performance in only a few years, thus calming concerns that the environmental investment would not be repaid. Results can help the government and private investors prioritize infrastructure opportunities that most effectively reduce environmental impacts, especially if evaluated in conjunction with more comprehensive environmental and health impact assessments, and the expected risk of a rapid change in technology or market conditions. Project payback analysis allows for a better understanding of the sensitivity and range of environmental metrics of total life-cycle damage (e.g., pollutant intake) and success (e.g., cost of saved carbon) to variables such as expected project lifespan and utilization.

A common concern with expanding the biofuels industry is that infrastructure utilization will need to increase,[51] as global demand for biomass has been projected to result in transport volumes that exceed that of current energy and agricultural commodities combined (Richard 2010). The amount of transportation congestion and maintenance problems that should be expected has been debated,[52] but this concern is nonetheless driving research into biomass and biofuel transportation infrastructure. Additionally, the growing development of unconventional fossil fuel resources is also driving interest in petroleum pipelines and other infrastructure projects. The following proposed infrastructure projects could serve as valuable case studies for project payback analysis.

- The Pacific Gateway Terminal is a proposed port development project in Whatcom County, Washington. This port would require little dredging to accommodate deep-draft vessels, and is already connected to existing rail lines, meaning that US exports such as coal may travel

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[51] If all 36 billion gallons (108 million tonnes) of ethanol consumed in the year 2022 are shipped 1,000 km by truck and 1,000 km by rail in the United States, the contribution of all liquid transportation fuels to highway and rail freight traffic would increase 1.8-fold and 2.4-fold, but would still contribute less than 5% to the total t-km of either mode (assuming total freight activity does not decrease). In a more realistic future case in which 22 billion gallons of ethanol are distributed in 2022, the railways most affected by ethanol transportation out of the Midwest would only see a 2.5% increase in traffic (US GAO 2011).

[52] EPA officials do not believe freight-rail capacity will be a limiting factor in successfully implementing RFS requirements, though GAO and others acknowledge that highway, rail and port congestion may continue driving up costs (US GAO 2011). However, even if the scale up of ethanol only increases freight traffic by a few percent, the significance of this marginal increase may exacerbate maintenance challenges if not incorporated into planning, as the United States is already often criticized for underinvesting in transportation infrastructure (ASCE 2009; The Economist 2008, 2011).

less distance by land to get to the port, and would be transported overseas by larger, more efficient vessels than are currently accessible.

- The Keystone XL Pipeline project is a large-diameter pipeline that was proposed to bring (oil sand) petroleum from Alberta to US refineries. Although this pipeline would cross through a variety of ecological habitats, it would almost certainly allow the oil to be transported in a more energy-efficient manner than existing rail and water modes (on a per t-km basis). Additionally, this pipeline may also enable existing refineries in the Gulf to increase utilization rates, whereas the absence of this pipeline may drive the expansion or new construction of refineries closer to Alberta.
- Poet and Magellan had proposed a large-diameter ethanol pipeline (approximated in Section 5) to transport ethanol from the Midwest to the Northeast region of the United States. Although determined to be cost-prohibitive, this pipeline would offer a much more energy-efficient option than is currently, and is expected to be, available along this corridor. Other ethanol pipelines that may be worth evaluating are also being proposed and developed in Brazil.
- Other smaller-scale projects that could be evaluated include deciding whether, where, and how large to install feedstock densification facilities, refining or ethanol dewatering facilities, and installing a single large terminal or numerous small satellite terminal locations.

8.6.2.3 Marginal Infrastructure Deterioration

A shortcoming of most steady-state and payback period type LCA studies is that infrastructure maintenance and replacement is often not approximated using physical deterioration models. Gaining a better understanding of how marginal impacts differ from average impacts has been a goal of many LCA practitioners (e.g., (Chester 2008)) for years. Additionally, life-cycle impacts from capital projects should be compared with operational improvements in the form of case studies (as suggested by (Facanha 2006)), instead of assuming status quo operation practices will persist. As discussed through much of this dissertation, a comprehensive evaluation of life-cycle costs and environmental emissions for different modes requires an accounting of operational activities (e.g., intermediate inputs of energy and materials) as well as construction and maintenance activities (e.g., fixed asset investments in infrastructure and equipment).

Figure 39 and Figure 40 show that the average expenditures in each of these categories for rail and truck transportation have remained relatively constant at different levels of freight activity over the last decade, after normalizing to t-km of freight activity and converting expenditures into constant 2005 US dollars. Unfortunately, such nationally aggregated data does not enable analysts to understand the driving forces for each of these expenditures, and the relatively consistent annual increase in freight activity makes it difficult to determine whether expenditure trends are more correlated with time than with utilization. If detailed data was available on a regional or case study level, statistical analysts could better categorize inputs and investments as 1) directly related to marginal use (e.g., fuel use, engine and motor maintenance); 2) fixed and uncorrelated with marginal use, but necessary to enable continued use (e.g., waterway dredging); or 3) driven by multiple variables such as age, weather and also utilization (e.g., railroad track maintenance). Inputs considered marginal would have a slope of zero if Figure 39 or Figure 40 were created for a specific case study, and inputs considered fixed would have a negative slope. A combination of cumulative prior utilization (related to "wear and tear") and projected future utilization would drive decisions to invest in fixed assets, so a combination of lagging and leading variables may be needed to accurately model infrastructure investment decisions (e.g., dredging waterways, improving security controls).

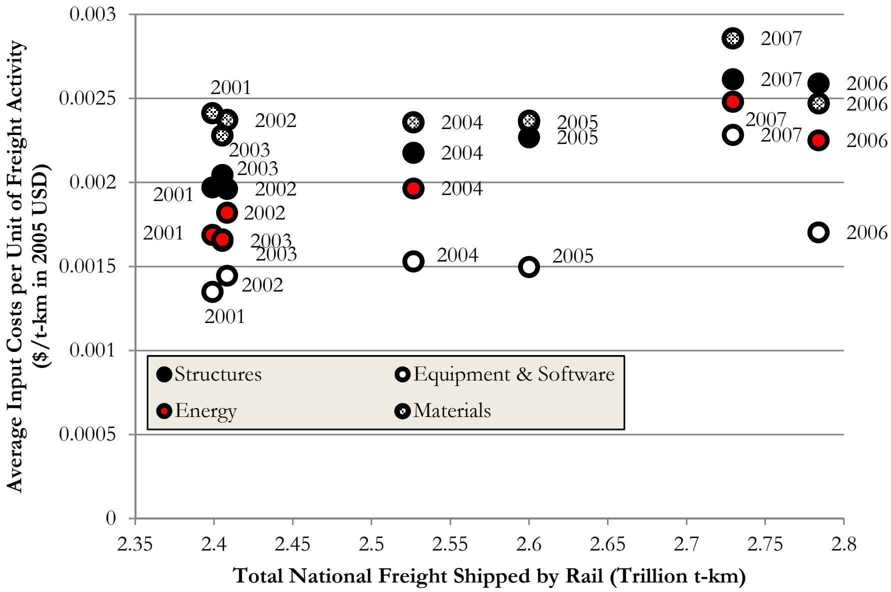

Figure 39. Energy and Material Inputs Normalized to Freight Activity for Rail Transportation (estimated using freight activity data from (US DOT BTS 2010), intermediate expenditures and chain-type price indexes (using interactive GDP-by-Industry tables), and fixed asset expenditures (Tables 3.7E and 2.7S) and price indexes (Tables 5.4.4U and 5.5.4U) from (US BEA 2011)).

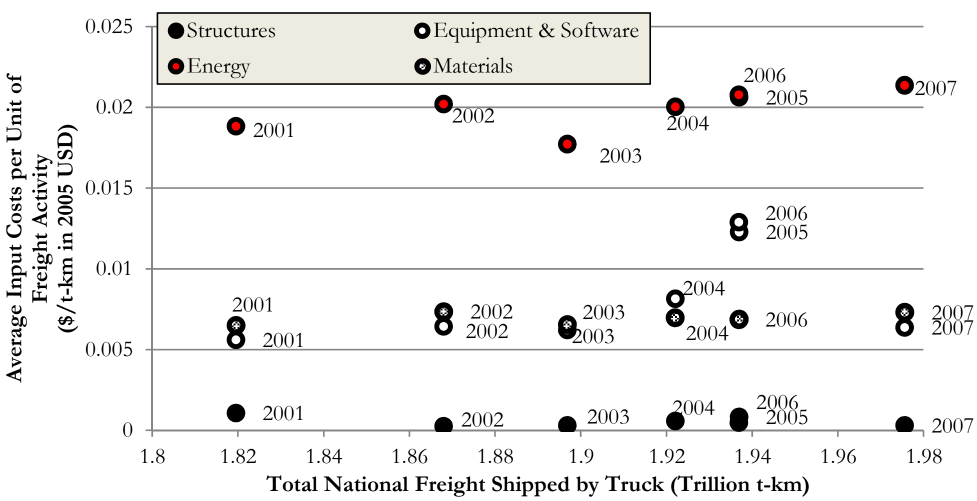

Figure 40. Energy and Material Inputs Normalized to Freight Activity for Truck Transportation (estimated using freight activity data from (US DOT BTS 2010), intermediate expenditures and chain-type price indexes (using interactive GDP-by-Industry tables), and fixed asset expenditures (Tables 3.7E and 2.7S) and price indexes (Tables 5.4.4U and 5.5.4U) from (US BEA 2011)).

8.6.2.4 Simple Network Analysis

Although interesting and important to quantify environmental emissions from infrastructure, and to understand the drivers behind infrastructure construction and maintenance, operation stage emissions still typically dominate life-cycle emissions. For this reason, it is also important to accurately model how far and by what mode materials would be transported under different infrastructure or economic scenarios. For example, port and pipeline projects would not only improve the efficiency with which products would move between a single customer and single producer, but they could impact how commodities are routed throughout the entire country.

A "rebound" effect in demand for transportation services may occur by introducing new infrastructure or other changes, even if total product demand remains unchanged. For example, building new transportation infrastructure could allow shippers to transport a product to limited distant markets for a lower cost than would be needed to transport it to local markets by truck. Network analysis, as performed in Section 7, may offer new insights on the project examples proposed earlier. Additionally, the network model from Section 7 could be made more comprehensive by including gasoline distribution, as ethanol is assumed to displace demand for gasoline (on an energy basis).

Another direction research could take is to include international trans-oceanic trade of ethanol (and gasoline) in distribution optimization models. Because Brazil does not have a blend wall problem similar to the United States, Brazil should not be exporting ethanol if minimizing GHG emissions was the primary objective; additionally, it would make more sense for the United States to import gasoline from Brazil than ethanol (as a tanker of gasoline could transport approximately 1.5 times as much energy than gasoline, assuming equal volume or mass). The GHG and other emissions implications of these decisions could be quantified using network analysis. Furthermore, to quantify missed opportunities to minimize GHG emissions over the last decade, and to estimate the implied value of carbon and non-carbon goals attributed to fuel mandates and tariffs, a network analysis of alternative policy scenarios could be performed using time-series prices of ethanol and gasoline in Brazil and the United States.

8.6.2.5 Network Analysis with Market Effects

While a simple network analysis treats demand for transportation services as flexible but demand for product as fixed, a more complex model that includes economic modeling could address the ability of projects (e.g., infrastructure construction, technology adoption, improved operating practices, consumer education) to enable demand for products to change on a local and/or aggregate level. This form of analysis would improve the ability of decision-makers to choose projects and locations that enable the greatest cost or emissions savings per unit of product sold.

This approach may help determine the optimal way to continue increasing ethanol production in the United States, now that the common gasoline market has been saturated at the E10 blend wall. Below are several options that may be worth evaluating.

- The United States could continue to increase ethanol exports to other countries (including Brazil). Trade analysis would be needed to determine if US exports are increasing or decreasing global demand for international ethanol transportation services (i.e., t-km).

- A consumer education campaign could be launched to increase the fraction of high-level ethanol blends purchased by flex-fuel vehicle (FFV) owners, in conjunction with improved promotion of retail stations that sell blends above E10.

- Evaluate whether flex-fuel fuel dispensers should be installed in a) the Midwest (where population density may be low), or b) 1,000-2,000 km away from producers in the Midwest where retail stations may (eventually) have access to a much higher density of FFV owners. In this case, ethanol transportation emissions would be lower in (a), but emissions from station construction, maintenance, and consumer refueling errands would be lower in (b).

- Pacific Gateway Terminal. Cost savings enough to induce more or less a) coal development in the United States, b) coal consumption globally, and c) potential to save emission that would otherwise take place from coal exports being shipped to other ports (closer or further) which may have access to smaller less fuel-efficient ships that transport coal to Asia.

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10 APPENDICES

10.1 Characterizing Energy Inputs

The following sections present the assumptions and data sources used in creating life-cycle emission factors for producing and delivering fuel and electricity inputs for components modeled in this study.

10.1.1 Petroleum (Crude and Products)

10.1.1.1 CRUDE OIL EXTRACTION – CO_2-e

Only average values were used in this project for the purpose of putting infrastructure emissions in perspective. Although not used independently in this study, the values attributed to gasoline, diesel and kerosene were 6.9, 6.3, and 6.4 g CO_2-e/MJ (Table L-2 of (US DOE NETL 2008)). The composite mix of extraction emission for crude oil refined in the US was found to be approximately 39 kg CO_2-e/bbl of crude, or 7.6 g CO_2-e/MJ (assuming 35MJ/L), though the range varied from 14-128 kg CO_2-e/bbl of crude (Table 2-3 of (US DOE NETL 2008)). Table 5-1 of GREET 1.8d shows a US average of 7.1g CO_2-e/MJ of crude oil refined in 2010, and a California-specific result was found to be 7.5g CO_2-e/MJ of crude (CARB 2009).

10.1.1.2 PETROLEUM REFINING – CO_2-e

Emissions from US refining operations were reported by volume of product in Table 4-54 of (US DOE NETL 2008), based on the unit operations necessary to produce each product. By multiplying the estimated emissions per product by the volume fraction of each product exiting a refinery, the average emission factor of 45.84 kg CO_2-e/bbl of total product output was determined, or 8.9 g CO_2-e/MJ of product (assuming an average finished petroleum product density of 32.4 MJ/L, or 5,145 MJ/bbl, which I estimated from 2010 EIA).

US REFINING	SOURCE	Gasoline	Diesel	Kerosene	Residual Oil	Coke	Light Ends	Heavy Ends	SUM
Volumetric Attribution Factor (f_V)	Table 4-54 of (US DOE NETL 2008)	0.45	0.23	0.09	0.04	0.05	0.1	0.04	1
CO_2-e (kg/bbl_product)	Table 4-54 of (US DOE NETL 2008)	47.7	52.6	31.6	36.9	43.9	29.9	69.4	
CO_2-e Contribution (kg CO_2-e/ bbl_total_output)		21.47	12.10	2.84	1.48	2.20	2.99	2.78	45.8

Table 55. GHG Emissions from Petroleum Refining (data from (US DOE NETL 2008)).

10.1.1.3 PETROLEUM PRODUCT TOTAL "PRECOMBUSTION" – CO_2-e

In order to account for pre-combustion emissions for the fuels used in the storage, handling, and transportation of fuels and fuel feedstocks, the Well-to-Tank emissions were taken directly from (US

DOE NETL 2008) for diesel and gasoline, and this emission factor was interpolated for residual oil (for which no value was clearly reported) by subtracting the difference in refining emissions from diesel.

Fuel	Precombustion Total g CO_2-e/ MJ	Source	Precombustion Total (Extraction + Refining) g CO_2-e/ MJ	Source
Diesel (conventional)	17.4	(US DOE NETL 2008)	18.1 (7.1+11.0)	Table 5-1 of (US DOE ANL 2010)
Gasoline (conventional)	18.6	(US DOE NETL 2008)	18.1 (7.1+11.0)	Table 5-1 of (US DOE ANL 2010)
Residual Oil (conventional)	15.0	Interpreted from (US DOE NETL 2008)	11.0 (7.1+3.9)	Table 5-1 of (US DOE ANL 2010)
Kerosene (conventional)	14.4	(US DOE NETL 2008)		

Table 56. Total Pre-combustion CO_2-e data for Common Liquid Petroleum Fuels (data from (US DOE NETL 2008) and (US DOE ANL 2010)).

10.1.1.4 LIQUID FUEL TOTAL "PRECOMBUSTION" – WATER WITHDRAWALS

The average water withdrawals from the extraction of conventional crude oil were back-calculated from (Scown et al. 2011), which were created for gasoline. Water use was allocated to gasoline its market value, which is 1.2 times the average value of a MJ of products sold from a refinery (Scown 2011). Allocation to MJ of crude oil and other products was performed using the same approach.

	Market-based allocation adjustment factor per MJ	Feedstock Extraction/ Production	Refining	Total (including transport)
		L/ MJ_fuel	L/ MJ_fuel	L/ MJ_fuel
Conventional Oil to Gasoline (Scown et al. 2011)		0.111	0.251	0.374
Oil Sands to Gasoline (Scown et al. 2011)		0.167	0.236	0.418
Crude Oil	1	0.093	0.209	0.312
Oil Sands	1	0.139	0.196	0.349
Products - US Average	1	0.093	0.209	0.312
Diesel - Conventional	0.87	0.081	0.182	0.271
RO - Conventional	0.31	0.029	0.065	0.097
Gasoline - Conventional	1.2	0.111	0.251	0.374
Corn-derived Ethanol		6.19	.96	7.15
Ligno-cellulosic Ethanol			0.363 (without allocation to electricity) (Humbird et al. 2011)	0.363 (without allocation to electricity) (Humbird et al. 2011)

Table 57. Life-cycle Water Withdraw Factors of Fuel Production.

10.1.1.5 PETROLEUM PRODUCT COMBUSTION (TAILPIPE) – CO_2

Greenhouse gas emissions resulting from the combustion of fuels are almost exclusively made up of carbon dioxide. Carbon dioxide emission factors were calculated using the carbon and energy content of the fuel, and can be found in Table 58. In this table, no consideration was given for whether the fuel carbon was considered fossil or plant-based, though only CO_2 emissions from petroleum-based were included in the analysis.

Fuel	Emission Factor (g CO_2/ MJ)	Fuel	Emission Factor (g CO_2/ MJ)
Crude Oil	73.3	E10	72.7
Bunker Fuel	80.6	E85	71.4
Residual Oil	80.6	Ethanol	71.0
Diesel	74.1	Natural Gas	56.1
Gasoline	72.8		

Table 58. Carbon Dioxide Intensity of Fuel Combustion (data adapted from (US DOE ANL 2010)).

10.1.1.6 PETROLEUM PRODUCT COMBUSTION (TAILPIPE) – WATER EMISSIONS

The combustion of any hydrocarbon fuel will result in the production of water (typically 20-40 grams per MJ), which is less than 10% of the amount of water withdrawn for the purposes of producing conventional petroleum fuels. Because this water is not typically returned to freshwater bodies (and would not be considered clean), combustion water emissions were not credited towards the water withdrawals required for fuel production (Scown 2011).

10.1.2 Electricity

10.1.2.1 PURPOSE/ BACKGROUND

Electricity is a direct input for only a few activities described in this model, including pipeline pumps and exterior lighting for service stations.

10.1.2.2 SPECIFICATIONS

For all electricity-consuming activities in this study, electricity is assumed to come from baseload power sources (e.g., coal and nuclear). Non-baseload power is more expensive and often more carbon intensive than baseload power, unless baseload power is high in coal and low in nuclear, for example (as is the case in the TRE and SPP regions).

10.1.2.3 OPERATIONAL CONSIDERATIONS

The average water withdrawals from the production of electricity by NERC region and the national average were taken directly from (Scown et al. 2011), and greenhouse gas emissions per MJ of electricity were taken from the US EPA's eGRID model v1.0 for the year 2007. Both sets of data are presented in Table 59.

Electricity NERC Region	***GHG Intensity (g CO_2-e/kJ of electricity)***	***Water Intensity (g H_2O withdrawn/kJ of electricity)***
	eGRID model v1.0 for year 2007 (US EPA 2010g)	(Scown et al. 2011)
E_ASCC	*0.143*	-10.063
E_FRCC	*0.154*	-7.729
E_HICC	*0.194*	-10.159
E_ MRO	*0.222*	-18.109
E_NPCC	*0.099*	-12.315
E_RFC	*0.180*	-13.787
E_SERC	*0.172*	-16.438
E_ SPP	*0.212*	-10.869
E_TRE	*0.158*	-17.353
E_WECC	*0.128*	-4.958
E_US_ave	*0.164*	-12.903

Table 59. Electricity Generation Carbon and Water Intensity (Scown 2011; US EPA 2010g).

10.2 Characterizing Equipment and Infrastructure Components

The following sections present the methods, assumptions, and data sources that were used in creating life-cycle emission factors for each of the components included in this study

10.2.1 Transportation Modes and Associated Infrastructure

10.2.1.1 TRUCKS

10.2.1.1.1 PURPOSE/ BACKGROUND

Long-haul tanker trucks are used for the transportation of fuel ethanol, whereas petroleum products are typically distributed long distances by existing pipelines and waterways.

Short-haul tanker trucks are used for the transportation of both petroleum products and fuel ethanol, and most commonly are used to transport fuel from a terminal directly to a service station or customer.

Although the function of trucks may realistically change with truck age (e.g., long-haul trucks become less reliable with age, and will be reassigned to short hauls), this nuance is not accounted for in the model. Tanker trucks are assumed to be manufactured and utilized identically, whether dedicated to long or short hauls trips.

Flatbed trucks are used for the transportation of biomass feedstock (i.e., bales of Miscanthus in this model) from farms to biorefineries or other collection points.

10.2.1.1.2 SPECIFICATIONS

Some tanker trucks will carry upwards of 10,000 gallons (more than 30 tonnes), but the typical tanker truck is assumed to carry 24.3 tonnes of liquid fuel.

F-40 Flatbed Trailers are assumed to have a maximum payload of 27.3 tonnes, or 34 bales (Shastri et al. 2010), but are assumed in this model to have a typical load of 24.3 tonnes.

Equipment mass was not used as an input for modeling efforts, but can be used to put emissions into context. All trucks are assumed to have 18 wheels and an empty weight of 15 tonnes (adapted from (Sathaye et al. 2010)).

10.2.1.1.3 OPERATIONAL CONSIDERATIONS

All trucks are assumed to be line-haul trucks dedicated to a certain commodity and route, in which they deliver a full payload and return empty. The assumed annual activity does not influence the replacement cycle of trucks, but will impact estimates of the size of the truck fleet for certain activities. Activities such as trailer assembly, drayage and cleaning were assumed to be insignificant in this analysis.

Long-haul (diesel) tanker trucks: 90,400 v-km/year, as defined by "For-Hire Transportation" for 2002 (US DOT FHWA 2006a), though many long-haul truck drivers average more than 160,000 km per year.

Short-haul (diesel) tanker trucks: 90,400 v-km/year, as defined by "For-Hire Transportation" for 2002 (US DOT FHWA 2006a)

> Note: The American Petroleum Institute (API) estimated that the US has 35,000 trucks dedicated to the delivery of crude and petroleum products (API 2006), and AOPL estimated that trucks delivered 51 billion t-km of crude and products in the same year (AOPL 2011). Assuming the average truck has a capacity of 24.3 tonnes and is utilized 50%, this implies that each truck drives 120,000 km per year and delivers approximately 1.5 million t-km each year.

Flatbed (diesel) trucks: 17,280 v-km/year under the category of "Agriculture, Forestry, Fishing, or Hunting" (US DOT FHWA 2006a)

The costs of shipping ethanol by truck were estimated to be $0.15/t-km (Morrow et al. 2006), and $0.137/t-km for trucking of biomass (Kang et al. 2010).

10.2.1.1.4 OPERATIONAL ENERGY INTENSITY

Long-haul tanker trucks: 1,217 kJ/t-km

- The energy intensity of long-haul trucking was estimated by inputting tanker truck parameters into a model developed by (Facanha 2006) (which incorporates idling, backhaul).
- Note: This value is in between the maximum (2014 kJ/t-km) and minimum (1068 kJ/t-km) values for tanker trucks reported by (ICF International 2009), less than the value reported in GREET 1.8c (US DOE ANL 2010) for crude, gasoline and coal (1480 kJ/t-km), and less than the US economy-wide trucking average value in 1993 for petroleum and coal products (1675 kJ/t-km) (Vanek and Morlok 1998).

Short-haul tanker trucks: 1,537 kJ/t-km

- To estimate the energy intensity of short-haul tanker trucks, a coefficient was applied to long-haul trucking based on the fuel cost ratio of long haul (>100 miles) to short-haul (<100 mile) petroleum shipments ($0.168 per mile/$0.133 per mile), as reported by (US DOT BTS 2003)).

Flatbed trucks: 1,780 kJ/t-km (Bonilla and Whittaker 2009)

- The energy intensity of Miscanthus bale transport on flatbed trucks was taken from an existing study on bale transport.
- Bale-transporting trucks are therefore estimated to be more energy intensive than corn stover transportation (1541 kJ/t-km) as reported in GREET 1.8c (US DOE ANL 2010), but

less energy intensive than the US economy-wide trucking average value in 1993 for farm products (2141 kJ/t-km) or wood products (2439 kJ/t-km) (Vanek and Morlok 1998).

10.2.1.1.5 TURNOVER

TANKER TRUCKS

The life of a truck is assumed to be 464,000 vehicle kilometers (v-km) traveled (Facanha 2006), leading to a 5.1 year lifetime during which 5.6 million t-km of freight is delivered.

- Note: The service life is estimated to be as high as 540,000 km in other life-cycle assessments of freight trucks (e.g., in Europe (Spielmann and Scholz 2005)).

FLATBED TRUCKS

The life of a truck is assumed to be 200,000 vehicle kilometers (v-km) traveled (just under half of the life of long-haul trucks), leading to an 11.6 year lifetime during which 2.43 million t-km of biomass feedstock is delivered.

10.2.1.1.6 ECONOMIC CHARACTERIZATION – MANUFACTURING

TANKER TRUCKS

Truck

- Cost: $68,000 in 1988 dollars, as estimated by the US DOT FHWA for 3-axle 115K tractors (Fancher and Campbell 1995)
- Sector: Heavy Duty Truck Manufacturing (Facanha 2006)

Tank Trailer

- 1.67 Trailers/ Truck Life (trailers assumed to last 278,400 km/life) (Facanha 2006)
- Cost: $48,000 in 1988 dollars, as estimated by the US DOT FHWA for a 42' tank trailer (Fancher and Campbell 1995)
- Sector: Truck Trailer Manufacturing (Facanha 2006)

FLATBED TRUCKS

Truck

- Cost: : $67,591 in 2009 (Shastri et al. 2010)
- Sector: Heavy Duty Truck Manufacturing (Facanha 2006)

Trailer

- 1 F-40 Trailer/ Truck Life

- Cost: $43,081 in 2009 (Shastri et al. 2010)
  - Other estimates:
  - $48,000 in 1988 dollars, as estimated by the US DOT FHWA for a 42' tank trailer (Fancher and Campbell 1995)
- Sector: Truck Trailer Manufacturing (Facanha 2006)

10.2.1.1.7 ECONOMIC CHARACTERIZATION – MAINTENANCE

Truck supply/operational costs were estimated by filtering data from the 2003 Motor Carrier Operators Annual Report (US DOT BTS 2003). Specifically, entries were included if the primary commodity was listed as "PETR" (Liquid Petroleum or Chemical Products), and entries were discarded if they contained a zero value under column 302C (Total Miles Highway), 305C (Total Shipments Carried), or 307C (Total Ton-Miles – Intercity). Data was further segregated into long-haul (>100 miles, 63% of total PETR trucking miles) and short-haul (<100 miles, 37% of total PETR trucking). The same process was followed for flatbed trucks, but selecting only entries for "AGR" or "FOR" (Agriculture and Forestry) instead of "PETR."

Tires

- Long-haul Cost: $0.031/truck-mile (>100 miles)
- Short-haul Cost: $0.013/truck-mile (<100 miles)
- Flatbed Cost: $0.027/truck-mile
  - Note: it was expected that long-haul trucks spend more on tires, as these vehicles spend more time at high speeds (which results in higher tire temperatures).
  - Other prior estimates:
  - $0.03/truck-mile (ATRI 2008)
  - $0.035/mile in 1988 for 39-ton GVW tank and flatbed trucks (Fancher and Campbell 1995)
  - $0.035/truck-mile in 2003 (Barnes and Langworthy 2004)
  - $0.05/truck-mile ($3,000/12 tires for 60,000 miles) (Facanha 2006)
- Sector: Tire Manufacturing (Facanha 2006)

Vehicle Parts

- Long-haul Cost: $0.041/truck-mile (>100 miles)
- Short-haul Cost: $0.016 (<100 miles)
- Flatbed Cost: $0.034/truck-mile
- Sector: Motor vehicle parts manufacturing

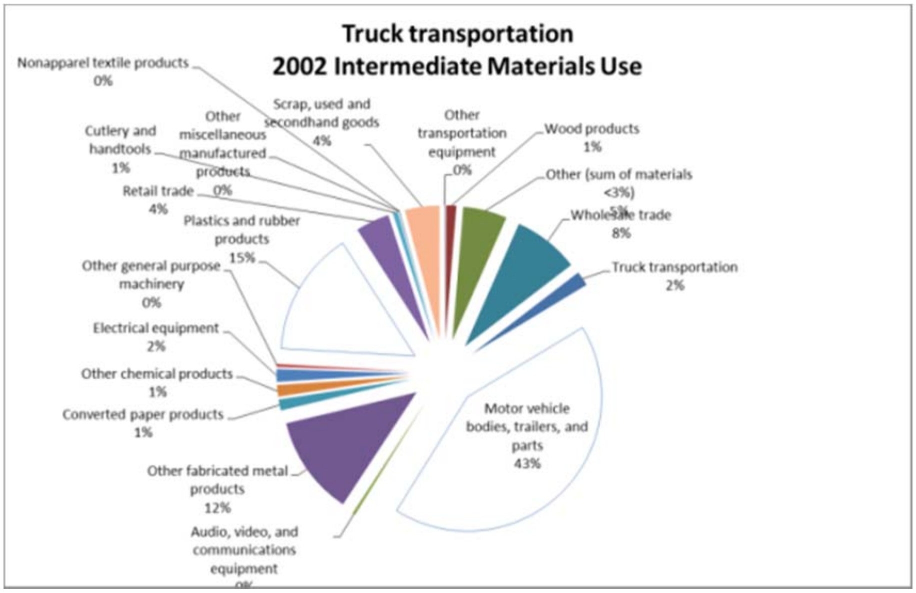
Maintenance

- Long-haul Cost: $0.072/truck-mile ($0.038 outside maintenance, $0.034 other operating supplies and expenses for vehicles, terminals, shops)

- Short-haul Cost: $0.164/truck-mile ($0.143 outside maintenance, $0.021 other operating supplies and expenses for vehicles, terminals, shops)
- Flatbed Cost: $0.061/truck-mile (($0.033 outside maintenance, $0.028 other operating supplies and expenses for vehicles, terminals, shops))
    - Other prior estimates:
    - $0.105/truck-mile in 2003 (Barnes and Langworthy 2004)
    - $0.092/truck-mile in 2003 (ATRI 2008)
    - $0.109/mile in 1988 for 39-ton GVW tank and flatbed truck "repair" (Fancher and Campbell 1995)
- Sector: Automotive repair and maintenance, except car washes(Facanha 2006)

10.2.1.1.8 OTHER APPROACHES

If trucking costs were not so well documented, and if material inputs and non-vehicle asset investments (see Figure 41) were significant (as they are for rail and pipeline transportation), BEA statistics could be used to inform estimates for maintenance material flows.

a) 

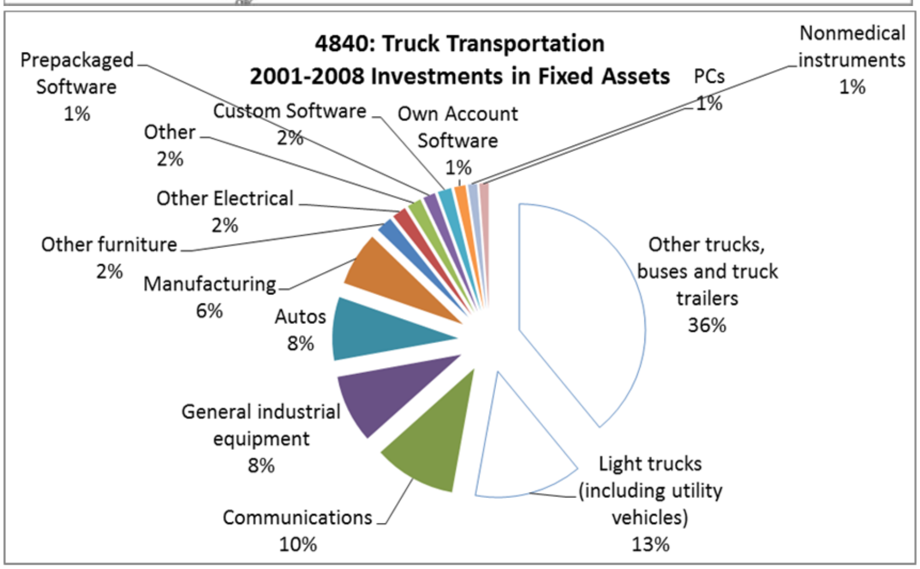
b) 

Figure 41. US Truck Transportation Sector (a) Intermediate Inputs, and (b) Fixed Asset Investments (data adapted from (US BEA 2011))

10.2.1.1.9 DISCUSSION

The CO_2-e emissions estimated in this analysis are significantly higher than those estimated in the Ecoinvent model. Ecoinvent reports shows that CO_2-f emissions from manufacturing 16, 28, and 40 tonne lorries equate to approximately 1:1 of the payload of the unit, and 0.5:1 for lifetime maintenance emissions (17.4, 24.9, and 24.2 for the unit; and 10.1, 13.3, and 19.1 for maintenance) (Ecoinvent 2010). In contrast, the lifetime non-operational emissions estimated in this study for 24.3-tonne long-haul tankers, short-haul tankers, and flatbed trucks were much higher, with manufacturing resulting in approximately 7 tonnes of CO_2-e per tonne of payload for tanker trucks and 3 tonnes for flatbed trucks, and life-cycle non-operational emissions adding up to 8, 12, and 5 tonnes of CO_2-e per tonne of payload capacity (13, 19, and 8 tonnes per tonne of empty truck).

10.2.1.2 ROAD INFRASTRUCTURE

10.2.1.2.1 PURPOSE/ BACKGROUND

Highways and local main roads make up the "base infrastructure" for trucking fuel and fuel feedstocks from one node to another (e.g., farms, refineries, terminals, and retail stations). Pavement maintenance makes up 25-30% of total O&M for road systems, and almost all of these costs should be attributed to goods movement (as pavement maintenance is a function of the 4th power of the axle load); remaining costs are fixed costs (e.g., bridges, lights, etc.), and could be allocated to passenger travel (PIANC 2005).

10.2.1.2.2 SPECIFICATIONS

Although highways may be made of concrete or asphalt, maintenance activities often entail application of a new layer of hot-mixed asphalt (HMA) to highways and major roads. The functional unit driving deterioration, and thus repaving, of roads is an equivalent single axle load (ESAL); this unit was chosen because the damage trucks induce on the roadways is approximately proportional to the 4^{th} power of the mass over each axle (Sathaye et al. 2010).

10.2.1.2.3 OPERATIONAL CONSIDERATIONS

Long-haul trucks are driven primarily on major highways, which are assumed to have a strong resistance to load-driven deterioration similar to California's I-80 (as modeled by (Sathaye et al. 2010)), enabling them to withstand 12.48 million ESALs per hot-mixed-asphalt (HMA) overlay.

Short-haul and flatbed trucks are assumed to operate primarily on local major roads (but not interstate highways), which are assumed to have a resistance to load-driven deterioration similar to California's SR-13 (as modeled by (Sathaye et al. 2010)), enabling them to withstand 1.3 million ESALs per hot-mixed-asphalt (HMA) overlay.

10.2.1.2.4 TURNOVER

24.3-tonne trucks are estimated to burden the road with an average of 1.8 ESALs per v-km (3.6 ESALs per km of delivered distance, or kmDD), by applying a 50% utilization rate to Equation 7.

$$Number\ of\ ESALs = 3.3 * km(loaded) + 0.29 * km(empty)$$

Equation 7. ESAL Estimation Equation for 24.3-tonne Trucks (adapted from (Sathaye et al. 2010))

The number of overlays required per truck life was estimated to be 0.067 lane-km-overlay/truck-life for long-haul, and 0.64 for short-haul, and 0.277 for flatbed trucks.

10.2.1.2.5 OTHER APPROACHES

Facanha, Spielmann, and others have allocated impacts to freight trucks according to total t-km of freight activity, after estimating the total share of highway maintenance burden that falls on the trucking industry as a whole. This approach neglects differences between heavy and light trucks (which can be a function of commodity density), and differences in utilization rates (which may range from 40-75% depending on the industry). Heavier trucks (e.g., fuel delivery trucks) will place a greater burden on roads than empty or lightly-loaded trucks.

FHWA's Cost Allocation Study estimated that a five-axle combination truck with a gross vehicle weight of 80,000 pounds operating on urban interstate highways causes almost $0.41 in pavement damage per vehicle mile traveled (VMT) (though this cost falls to less than $0.13 per VMT on rural interstates), and costs can be significantly higher for overloaded trucks exceeding 80,000 pounds (US DOT FHWA 2000). According to my estimates, pavement damage costs are approximately $0.036/mile for highway and $0.36/mile for main roads in 2002.

10.2.1.2.6 ECONOMIC CHARACTERIZATION – ONE HMA OVERLAY

It costs $1.25 million to mill and resurface a 4-lane road (ARTBA 2009), which translates to $195,000/lane-km. Assuming 1,000 tonnes/lane-km per overlay (adapted from (Willoughby et al. 2004)) at $65/ton asphalt in 2009, one third of overlay costs ($65K) are attributed to asphalt purchases.

Hot-mixed Asphalt (HMA) materials/lane-km-overlay

- Cost: $65,000
  - Note: asphalt alone contributes 88 tonnes CO_2-e/lane-km.
- Sector: Asphalt paving mixture and block manufacturing

HMA Overlay Application

- Cost: The remaining $130,000/lane-km-overlay costs are assumed to go towards equipment, material transportation, etc.
- Sector: Nonresidential maintenance and repair (although not a well-defined sector, the incorporation of this sector enables the total overlay emissions estimate to be 162 tonnes/lane-km, which closely resembles the 175tonnes CO_2-e/lane-km, as estimated by Sathaye using the PaLATE model (Horvath et al. 2004)).

10.2.1.2.7 DISCUSSION

When empty, trucks weigh approximately 15 tonnes. The life-cycle non-operation stage CO_2-e emissions are about 10 times the mass of trucks. Pavement overlay air emissions are just over half of vehicle manufacturing and maintenance emissions for short-haul tanker and flatbed trucks, but are much less significant for long-haul trucks. For example, the impact on pavement deterioration is similar for a 50 km local delivery as it would be for a 500 km long-haul delivery.

10.2.1.3 UNIT TRAINS

10.2.1.3.1 PURPOSE/ BACKGROUND

Trains are a major mode of transporting fuel ethanol in the United States, but a small amount of petroleum is also moved by rail. A negligible amount of biomass feedstock is assumed to be transported by train.

Unit trains are considered in this study to be the only form of rail transport for liquid fuels. Shorter trains are also used for fuel transport, and are slightly more expensive and less fuel efficient than unit trains (e.g., $0.15 vs. $0.167 to transport a gallon (J. Farrell 2007)). Differences in fuel consumption per t-km and life-cycle impacts are assumed to be small, and are not considered in this study.

10.2.1.3.2 SPECIFICATIONS

A typical Unit Train is assumed to haul 100 tank cars, each holding 100 tonnes (or approximately 30,000 gallons of fuel), for a total of 10,000 tonnes. 7.1 locomotives (on average) are needed to pull 100 tank cars (calculated using a tool developed by (Facanha 2006)), which is rounded to 7 locomotives (after a few online forum posts by rail transportation experts suggested that fewer locomotives would be necessary).

Equipment mass was not used as an input for modeling efforts, but can be used to put emissions into context. Locomotives are assumed to weigh 200 tonnes (GE Transportation 2011), and each railcar weighs 30 tonnes (World Trade Press 2008), for a total unit train mass of approximately 4,400 tonnes.

10.2.1.3.3 OPERATIONAL CONSIDERATIONS

Trains are expected to travel 240,750 v-km/year (Ottmann 2010), which would hypothetically correspond with a train operating 50% of the year at 55 km/hr.

The costs of shipping ethanol were estimated to be $0.05/t-km by rail (fixed cost $20.6/t) (Morrow et al. 2006).

10.2.1.3.4 OPERATIONAL ENERGY INTENSITY

Unit Train with 7 (diesel-powered) locomotives and 100 tank-cars: 268 kj/t-km

- The energy intensity of shipping liquid fuels by train was estimated by inputting unit train parameters into a round-trip energy model developed by (Facanha 2006).
- Note: This value is slightly greater than the US average freight rail intensity of 220-250 kJ/t-km for most years since 2000 (which has been used in the GREET model and in (D. He and M. Q. Wang 2000), but lower than the US average in 1993 and 1998 (280 kJ/t-km and 313 kJ/t-km, respectively) (S. C. Davis et al. 2010). However, this value was slightly less than the value reported for rail tank cars in 2009 (381 kJ/t-km) for rail shipments along competitive corridors with trucks (ICF International 2009), the US average rail energy intensity for

petroleum and coal products (331 kJ/t-km) in 1993 (Vanek and Morlok 1998), and the oil-specific rail energy intensity (470 kJ/t-km)reported by Rose in 1979. It should be noted that energy efficiency has been improving over time, so the current estimate was expected to be lower than the values reported before the year 2000.

As with other line-haul freight modes, a significant portion of the energy expended by freight rail is attributed to non-haul purposes. According to one source, more than 30% is used for empty backhaul, about 4% is reported lost or spilled each year, about 4% is consumed in idling, and 10% is used by yard locomotives assembling and switching cars (Kruse et al. 2009). Within my modeling efforts, backhaul energy is included in t-km energy intensity, but non-transport losses and energy expenditures are captured to some degree at storage tank nodes (though in a manner that is generalized for all freight delivery modes).

10.2.1.3.5 TURNOVER

Under typical utilization, the lifespan of locomotives are expected to be 20 years (GE Transportation 2011), though Facanha assumed 22 years. Rail tank cars are also assumed to last 20 years ((Facanha 2006) citing Armstrong, 1990). As a result, unit trains are assumed to travel 4.8 million km before being replaced (half of the 9.6 million km assumed for trains in ecoinvent), delivering 24 billion t-km of freight during its lifetime.

10.2.1.3.6 ECONOMIC CHARACTERIZATION – MANUFACTURING

Locomotive

- Cost: $2,000,000 per unit in 2009 (Kruse et al. 2009) (same cost assumption as (Facanha 2006))
- Sector: Railroad rolling stock manufacturing (Facanha 2006)

Railroad Tank Car

- Cost: $60,000 in 2000 (Reynolds 2002b)
- Sector: Railroad rolling stock manufacturing (Facanha 2006)

According to these assumptions, vehicle manufacturing costs would correspond with a life-cycle cost contribution of $1,173/MGTM.

10.2.1.3.7 ECONOMIC CHARACTERIZATION – MAINTENANCE

Total annual locomotive and railcar maintenance was estimated to be $1,150 per car in 1997 (Facanha 2006). For a lifespan of 20 years, this equates to an annual repair factor of approximately 14% of initial purchase price (directed towards material-intensive maintenance activities).

Locomotive Maintenance

- Annual Cost: 55% of total unit train maintenance costs
- Sector: Railroad rolling stock manufacturing (Facanha 2006)

Railroad Tank Car Maintenance

- Annual Cost: 39% of total unit train maintenance costs
- Sector: Railroad rolling stock manufacturing (Facanha 2006)

Inspection, Lubrication and Annual Servicing

- Annual Cost: 5% of total unit train maintenance costs
- Sector: Petroleum lubricating oil and grease manufacturing (Facanha 2006)

Rail Car Cleaning

- Annual Cost: 1% of total maintenance costs
- Sector: Car washes

10.2.1.3.8 DISCUSSION

The scope of activities included in this study is the same as the Ecoinvent module on United States freight rail locomotives. However, the US rail freight module was created by applying the 2000 European system with 100% diesel fuel (Ecoinvent 2010). While the Ecoinvent module suggests approximately 1.7 tonnes of fossil CO_2 emissions are emitted from regional train manufacturing, I estimate approximately 2.2 tonnes of CO_2-e per tonne of unit train (1.0 tonnes per tonne of payload).

10.2.1.4 RAIL INFRASTRUCTURE

10.2.1.4.1 PURPOSE/ BACKGROUND

Class I (freight) railways enable goods to move by rail throughout the country. Unit trains are assumed to operate primarily on Class I railways, which supported an average of 1.5 trillion ton-miles of total freight movement each year in the United States from 1993-2003 (US DOT BTS 2010). Total rail mileage in the United States has declined steadily from 207,000 to 94,000 miles from 1960 to 2008 (US DOT BTS 2010), so infrastructure investments are assumed to be geared towards maintenance and renewal, as opposed to new construction.

10.2.1.4.2 SPECIFICATIONS

Railways are assumed to be relatively homogeneous, with similar construction (e.g., ballast, wooden ties, and steel rails) and maintenance and renewal requirements that are driven by rail utilization.

Although this analysis was US-specific, the scope and allocation of freight rail infrastructure was following a similar approach to that used in the 2000 Ecoinvent module on freight rail, described below.

> *For rail infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on the gross tonne kilometre performance in Europe.*

Expenditures due to operation of the rail infrastructure, as well as land use have been allocated based on the yearly train kilometre performance in Europe. (Ecoinvent 2010).

10.2.1.4.3 OPERATIONAL CONSIDERATIONS

The energy requirements and emissions resulting from operation of railway infrastructure were presumed to be negligible in comparison to train operation and railway maintenance.

10.2.1.4.4 TURNOVER

Traffic-induced wear on railways is assumed to be proportional to the tonnage of goods passing over the railway (i.e., ton-miles or t-km of freight, consistent with the methodology of (Facanha 2006; Grimes and Barkan 2006)). More sophisticated deterioration and maintenance models are currently being developed to include factors such as train speed, total number of cars, track type, etc. (e.g., see (Tolliver and Benson 2011)).

10.2.1.4.5 ECONOMIC CHARACTERIZATION

A combination of items included in the BEA's intermediate inputs tables (minus locomotives and railcars) and fixed asset investment reports were used to characterize the various types of purchases made towards maintaining the base infrastructure for railways; Figure 42 and Figure 43 show the composition of these expenses, excluding expenses that contribute less than 2% to the total. $5 billion was reported as spent on material items for rail transportation in 2002, when total gross output was $44.7 billion. Additionally, an average of $7.5 billion was invested annually in fixed assets within the rail transportation industry from 2001-2008.

If all costs accounted for in the BEA tables were attributed to freight rail (see Figure 42 and Figure 43), a higher maintenance budget would have been estimated. So as to be consistent with prior literature, the infrastructure maintenance cost was assumed to be $2,507/MGTM ($1,718/million t-km) (Grimes and Barkan 2006), and most of these costs were assumed to consist of material expenses. For simplicity of presentation and to conservatively reduce the chance that emissions were overestimated, only activities making up 2% or more of material costs were included (i.e., 81% of the $2,507).

Wood

- Cost: 20% of maintenance expenses
- Sector: Sawmills and wood preservation (Facanha 2006)

Steel

- Cost: 15.4% of maintenance expenses (consisting of 8.4% foundry products + 4.2% primary ferrous metal products + 2.8% other fabricated metal products)
- Sector: Iron and steel mills (Facanha 2006)

Other material products

- Cost: 10% (2.5% nonmetallic mineral mining and quarrying, 2.3% petroleum and coal products, 2.2% nonmetallic mineral products, 1.2% paints and coatings and adhesives, 0.9% basic chemicals and 0.9% other chemical products)
- Sector: Paint and coating manufacturing

Communication and Electrical Systems

- Cost: 6.6% of maintenance expenses (consisting of 3.1% A/V and communications equipment, 2.7% other electrical equipment and components, 0.6% electrical equipment, and 0.2% electrical lighting equipment)
- Sector: Electricity and signal testing instruments (Facanha 2006)

Service truck activity and materials transportation

- Cost: 3.9% truck transportation
- Sector: Truck transportation

Machinery and other vehicles

- Cost: 6% (4% vehicle bodies, trailers and parts, 2% metalworking machinery)
- Sector: Other industrial machinery manufacturing

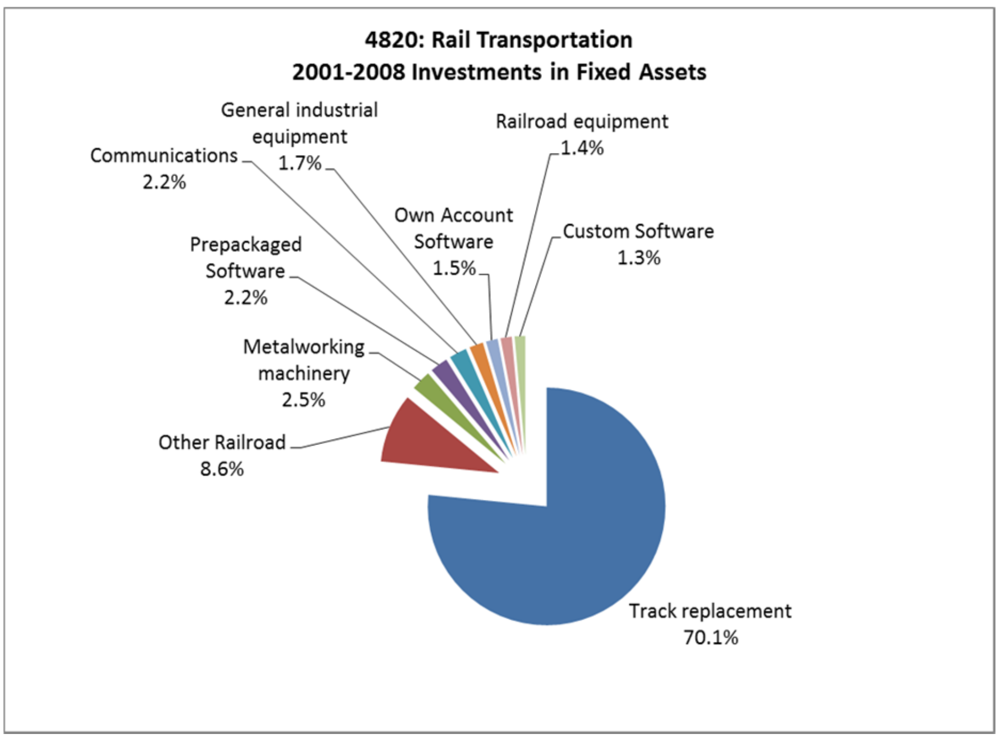


Figure 42. Private Fixed Asset Investment in Rail Transportation (average $7.5 billion per year, data adapted from (US BEA 2011))

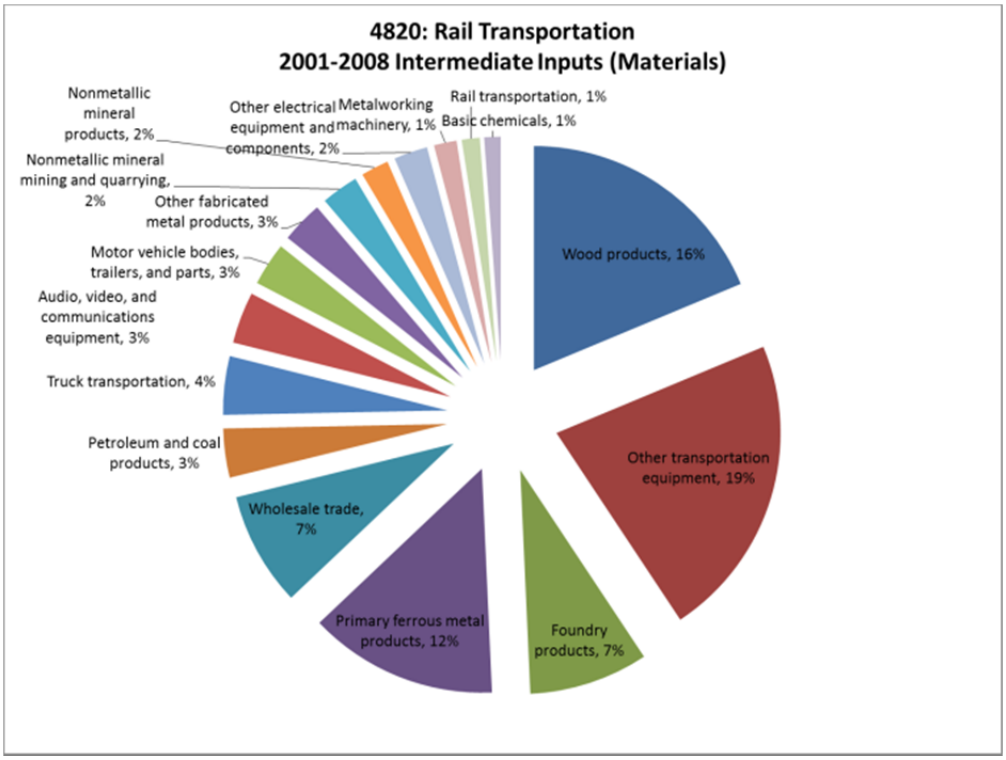


Figure 43. Intermediate Materials Inputs in Rail Transportation (average $7.0 billion per year, data adapted from (US BEA 2011))

10.2.1.4.5.1 ALTERNATIVE APPROACHES

Using the approach of Facanha, it would be found that "Repairs and Maintenance" to *ways and structures* cost $6.4 billion in 2004 (US DOT STB 2011); physically-significant maintenance expenses (e.g., roadways, power systems, building maintenance) made up only $1.8 billion of these expenses, while leases, insurance, depreciation, etc. made up the majority of expenses. Using BTS and STB data from 2001 and 2004, these physically-significant expenses totaled $1,013/MGTM in 2001 (Facanha's last year of analysis) and $1,068/MGTM in 2004. By employing statistics from BNSF (assumed to be a representative company), Facanha estimated that 28.5% of physically-significant expenses would be directed towards actual material purchases such as asphalt and steel (i.e., only 8% of total repair and maintenance expenses, or $198/MGTM in 2001). For the $198/MGTM in 2001 directed towards the purchases specified by Facanha, updated numbers using 2002 EIO-LCA would yield an average of 1225 tonnes of total CO_2-e (761 tonnes of fossil CO_2) per $million spent on materials, but an overall average repair and maintenance emission factor of only 98 tonnes of total CO_2-e (61 tonnes of fossil CO_2) per $million spent on maintenance and repair. This suggests a maintenance carbon intensity less than or equal to that from economic sectors such as "funds, trusts and other financial vehicles," "business support services," "insurance agencies, brokerages, and related," or "accounting and bookkeeping services." Although my analysis has also omitted many service and administrative activities, it is believed to more comprehensively and accurately capture maintenance activities.

10.2.1.4.6 DISCUSSION

Loaded railcars can hold roughly four times their empty mass, whereas a truck can only hold twice its own weight). When empty, a Unit Train weighs ~4,000 tonnes (7x200-tonne locomotives and 100x25-tonne cars), and life-cycle non-operation stage CO_2-e emissions are roughly 11.5 times the mass of an empty train (5 times its payload capacity), which is five times emissions from initial manufacturing alone, but less than 20% of total life-cycle emissions. When a similar analysis was performed for passenger rail (including urban subways), "[t]he construction and operation of rail mode infrastructure results in total energy requirements about twice that of operational" (Chester and Horvath 2009).

10.2.1.5 INLAND BARGE

10.2.1.5.1 PURPOSE/ BACKGROUND

Inland barge is a common and inexpensive mode for transporting bulk commodities including both petroleum and ethanol fuels. Although water transportation is available to fewer locations than rail or highway, and transportation speed is slow (e.g., 5 mph), barges are used to transport an enormous quantity of commodities for a very cheap price.

10.2.1.5.2 SPECIFICATIONS

The average size of petroleum barges is 3,000 tonnes (US ACE 2010a), and many barges are being constructed for petroleum carrying up to 30,000 barrels (4,400 tonnes) (AWO 2002). A discussion with a professional liquid barge fleet manager (Vecellio 2011) led to the assumption that a typical "tow" would consist of a 2,000 hp towboat (aka "pushboat") in conjunction with two 3,000 tonne barges. This was believed to be more representative than the 15-barge tow consisting of a single 5,600 hp tugboat with 15x1500-tonne barges (22,500 tonne capacity), as was assumed in a prior paper on fuel distribution by (D. He and M. Q. Wang 2000).

Equipment mass was not used as an input for modeling efforts, but can be used to put emissions into context. The tugboat is assumed to weigh 500 tonnes, and barges typically weigh 20% of payload, for a total mass of approximately 1,700 tonnes.

10.2.1.5.3 OPERATIONAL CONSIDERATIONS

Inland tows are assumed to travel at a speed of 5mph for 80% of the year, and in dock the remaining 20% of the year, so a typical tow will travel approximately 50,000 km/yr.

The average cost of shipping freight by barge was $0.012/t-km in 2004 (US DOT BTS 2010).

10.2.1.5.4 OPERATIONAL ENERGY INTENSITY

Inland tow with one (diesel-powered) tugboat and 2 barges: 320 kj/t-km (Winebrake et al. 2007b)

- The round-trip energy intensity of shipping liquid fuels by barge was taken from the TEAMS model (252 BTU/ton-mile from origin to destination and 192 BTU/ton-mile backhaul

(Winebrake et al. 2007b)), which was developed specifically to estimate fuel-cycle energy intensity and emissions for liquid fuels.

- Note: This value is greater than the US average freight barge intensity for most (but not all) of the last two decades (which had been used in the earlier GREET models and by (D. He and M. Q. Wang 2000), but lower than the 2006 US average of 411 kJ/t-km (S. C. Davis et al. 2010), lower than the average water transportation energy intensity of 480 kJ/t-km estimated for 1978 (Hooker 1981),and significantly lower than the value used in the latest GREET model (511 kJ/t-km) (US DOE ANL 2010).
- Many publications tout that barges are significantly more energy efficient than rail at transporting freight, though this is not assumed to be the case for bulk liquid transport.

10.2.1.5.5 TURNOVER

Under an assumed lifespan of 30 years (USDA AMS 2010), the typical barge and tugboat will travel 1.5 billion v-km (though assumptions as low as 860,000 km have been stated by Ecoinvent (2009)). As a result, an inland tow is expected to haul 4.5 billion t-km through the course of its life.

10.2.1.5.6 ECONOMIC CHARACTERIZATION – MANUFACTURING

2,000-hp Tugboat

- Cost: $2.3 million in 1998 (interpolated from (US ACE 2000a))
    - Note: A rule of thumb reported by US ACE through much of the early 2000's has been that towboats typically cost around $1,000/hp.
    - Other sources:
    - $2,200,000 for 2,000 hp tug in 2011 (Vecellio 2011) (double-checked via (Maritime Sales, Inc. 2011))
    - Note: The asking prices for used tugboats in January 2003 ranged from $271/BHP for tugs under 3,000BHP, $385/BHP for the 3-4,000BHP range and $502/BHP for 4-5,000BHP tugs (Marcon International, Inc. 2009).
- Sector: Ship building and repairing

3,000-tonne Barge

- Cost: $1.4 million per barge in 1998 (interpolated from (US ACE 2000a))
    - Other sources:
    - $1.12 million in 2002, if scaled from estimate of $1.4 million for 30,000 barrel barges ($48.3/bbl)) (AWO 2002)
    - $2,100,000 in 2011 (Vecellio 2011) (double-checked via (Maritime Sales, Inc. 2011))
    - $13.80/bbl in 2003 for used 20-30,000 bbl tank barges (Marcon International, Inc. 2003)
    - The price range for double hulled oil barges with coils ranged from $457/DWT for 3325 barges to $515/DWT for 1425 ton-barges.
- Sector: Ship building and repairing

10.2.1.5.7 ECONOMIC CHARACTERIZATION – VESSEL MAINTENANCE

Repair, Maintenance, and Supply costs are expressed below as a fraction of initial purchase price.

Tugboat Maintenance and Repair

- Cost: 176% of purchase cost (interpolated from (US ACE 2000a), assuming 30 year useful life.
    - Note: This varies between 130% and 440%, for towboats as large as 3,400 hp or as small as 400 hp.
- Sector: Ship building and repairing

Tugboat Supplies

- Cost: 66% of purchase cost (interpolated from (US ACE 2000a), assuming 30 year useful life.
    - Note: Cost of supplies varies from 49% to 166% of purchase cost, for towboats as large as 3,400 hp or as small as 400 hp.
- Sector: Petroleum lubricating oil and grease manufacturing

Barge Maintenance and Repair

- Cost: 56% of purchase cost (interpolated from (US ACE 2000a), assuming 30 year useful life.
    - This cost is between 55-56% for al barges listed.
- Sector: Ship building and repairing

Barge Supplies

- Cost: 1.7% of purchase cost (interpolated from (US ACE 2000a), assuming 30 year useful life.
    - This cost is 1.6-2.2% for all barges listed.
- Sector: Paint and coating manufacturing

With such small differences in the purchase and operating costs for tugboats and barges on a per-DWT basis, it was deemed unnecessary to compare different tow arrangements.

10.2.1.5.7.1 ALTERNATIVE APPROACHES

Without discounting, the life-cycle cost of tugboat and barge manufacturing and maintenance is estimated to be $0.0031/t-km ($0.0046/ton-mile), whereas the average freight revenue is $0.012/t-km ($0.017/ton-mile). A summary of intermediate inputs from the BEA is presented in Figure 44, but was not deemed to be useful (as it is unclear whether these costs are representative for inland water transportation), and material inputs are almost negligible in comparison to energy inputs

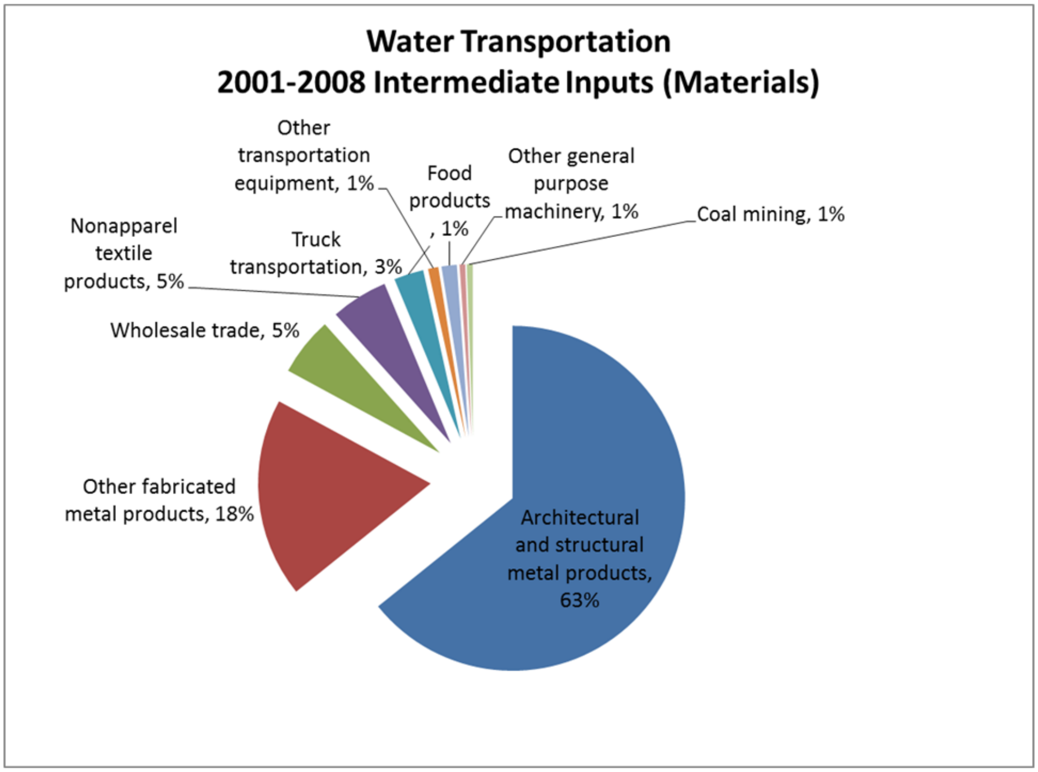


Figure 44. Intermediate Material Inputs for Water Transportation (average $1.9 billion per year, data adapted from (US BEA 2011)).

10.2.1.5.8 ECONOMIC CHARACTERIZATION – NON-VESSEL ASSETS

In addition to the fleet of waterborne vessels, the maritime freight industry requires a significant amount of other supporting infrastructure. In fact, vessels made up only 50-60% of fixed asset value for the water transportation industry from 2002-2006 (US DOT MA et al. 2008), which does not include publicly owned and maintained infrastructure.

A breakdown of water transportation material expenses greater than or equal to 1% of total material expenses for the water transportation sector can be seen in Figure 45. An annual average of $5.6 billion was invested in assets for the water transportation sector from 2001-2008 ($5.2 billion in 2002, which was equivalent to about 12% of total fixed asset value, or 8% of gross output).

The most surprising finding is that more money is invested in communications equipment than ships and boats, which may partially be explained by the life expectancy of equipment; ships last three decades on average, whereas the life expectancy of electronics and communications equipment for transportation management systems is often 10 or 20 years or less (Vick and Sumner 2002) (as could be inferred by the increased significance of ships and boats on a total asset stock basis, as shown in Figure 46). Most of the communications equipment costs accounted for by BEA are assumed to be dedicated to passenger cruise ships and more sophisticated freight ships (e.g., military and container ships). After showing this graph to a manager of a passenger expedition ship manager, the significance of communication expenses seemed reasonable; in contrast, after discussing this finding with a retired maritime shipping professional, he was unable to explain how communications costs could be so significant. However, instead of ignoring these costs, a conservative estimate was made, and scaled to the initial purchase cost (asset value).

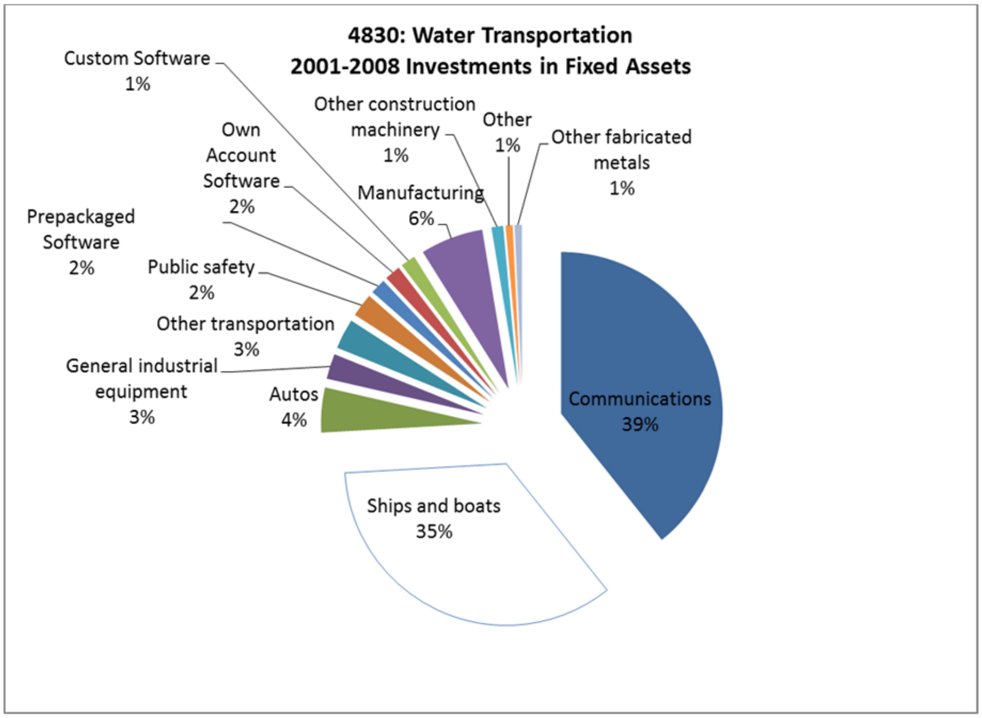


Figure 45. Fixed Asset Investments for the Water Transportation Sector (US BEA 2011)

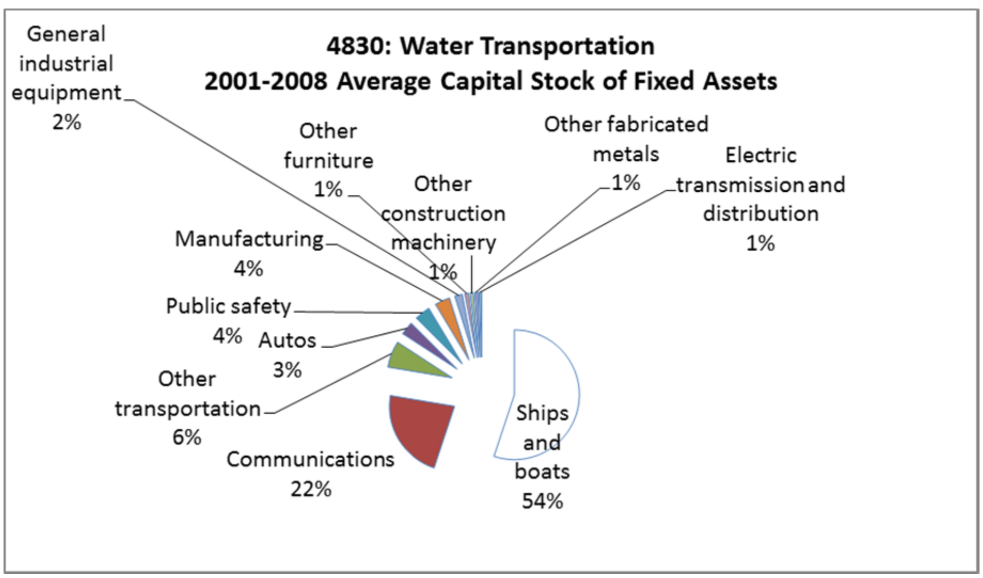


Figure 46. Average Total Capital Stocks of the Water Transportation Sector (US BEA 2011)

Communications assets (internet, email, phone, fax, postal, wireless, satellite, etc.)

- Cost: 20% of initial investment in (not life-cycle) tug and barges

  - Note: If directly interpreting the BEA statistics, this value would be greater than 100%.
- Sector: Broadcast and wireless communications equipment

Supporting vehicles, equipment, and machinery assets

- Cost: 30% of initial (not life-cycle) investment in tug and barges
  - Note: 50% would be estimated by dividing (4+3+3+6+1+1)/ 35)
- Sector: Other industrial machinery manufacturing

Software

- Cost: 14% of initial investment in tug and barges (5/35)
- Sector: Other computer related services, including facilities management

Note: By including this admittedly uncertain data in my model, infrastructure's contribution to the life-cycle emissions only increase from 3-6% to around or just over 10%.

10.2.1.5.9 DISCUSSION

A tow weighs roughly 1,700 tonnes. Initial manufacturing emissions alone are estimated to be 1.6 times the payload of the tugboat and barges (5.6 times its empty weight). In contrast, Ecoinvent reports that embodied emissions will be less than the payload of inland water vehicles (i.e., a 1200-t barge will have a 779-t CO_2-f footprint, and a barge tanker has a 935 tonne CO_2-f footprint).

10.2.1.6 INLAND WATERWAY INFRASTRUCTURE

10.2.1.6.1 PURPOSE/ BACKGROUND

The total length of navigable waterways in the United States is typically reported to be 25-26,000 miles (40-42,000 km), and consists of 238 locks at 192 locations, and 3,700 marine terminals (US DOT MA 2011).

The most uncertain and potentially significant consideration in the life-cycle emissions for inland maritime shipping is the maintenance of waterways. All US inland waterway infrastructure maintenance activities are assumed to be dedicated to domestic commerce, and emissions from these activities are allocated to freight by t-km. Inland and Great Lakes waterways enabled on average 460 billion t-km of freight movement in the United States from 2005-2009 (US ACE 2009).

In addition to maintaining a fleet of waterborne vessels and other fixed assets, a significant investment is made each year into the operation, maintenance, and renewal of waterway infrastructure. The vast majority of expenses for maintaining inland waterways (for commerce) is performed by the US ACE (McKee 2011), and includes dredging, lock operation and maintenance (for 241 locks at 196 different sites, excluding the St. Lawrence Seaway), and lock rehabilitation (major upgrading of a few locks each year). A small amount of waterway maintenance is performed by waterway facility owners.

In terms of long term planning, the entire life-cycle emissions from inland shipment should be considered. The high (subsidized) costs of maintaining waterways has driven several interest groups to petition against using federal funding for barge shipment, in favor of using rail shipment which is argued to be quicker, more reliable (e.g., in cold or inclement weather), and less or comparably energy intensive (when comparing direct operating energy consumption) (IATP 2002; Nicollet Island Coalition 2010a). For more information on various aspects of the economics and sustainability of inland waterways, see Working Group publications from the International Navigation Association (PIANC 2005), or the latest report to Congress on the America's Marine Highway.

10.2.1.6.2 SPECIFICATIONS

Dredging

The United States Army Corps of Engineers (US ACE) dredged an annual average of 256 million cubic yards (CY) per year from 1990-2009, for an average cost of $2.57/CY from 2000-2004, in 2000 dollars) (US ACE 2010c). Dredging activities were allocated 11% to inland waterways, and 89% to coastal ports (Lambert 2007), and then allocated by tonne-kilometers within inland waterways.

Lock Maintenance and Rehabilitation

Although under-budgeted according to the ASCE's Infrastructure Report Card, the US ACE spends $180 million to upgrade locks each year (ASCE 2009) from the Inland Waterway Trust Fund. This fund is replenished half by a $0.20/gallon fuel tax, and half by a government matching program. (Note: expenses over $14 million are considered major rehabilitation (McKee 2011)). Although the operation and maintenance budget was three times greater than the $191 million requested for construction projects in 2011 (Loew 2010), operation and maintenance costs (to my knowledge) are not recouped through taxes to freight users, and are not allocated to freight users in this analysis (though much of the labor, lighting and utilities, and other O&M costs could reasonably be attributed to freight barges).

At 511 kJ/t-km for liquid fuel distribution (US DOE ANL 2010) (which is significantly higher than the national average of 300-400 kJ/t-km over the last decade (US DOT BTS 2010)), a barge tow will deliver 270 t-km per gallon of diesel. At $0.20/gallon[53] for the Inland Waterway Tax (IRS No. 64), the tow will be paying $1,082/MGTM ($741/million t-km) in taxes; this tax is more than matched by the federal government, so the estimated infrastructure spending would be at least $2,164/MGTM ($1,483/million t-km). Instead of determining the exact costs associated with lock and dam construction and repair, costs were assumed to be 50% labor, 10% equipment use, 20% concrete, and 20% steel.

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[53] In light of a National Academy of Sciences report that 92% of waterway maintenance costs are paid by taxpayers, some sources argue that the tax should be increased from 20 to 52.5 cents to fund O&M in addition to infrastructure maintenance (Nicollet Island Coalition 2010b).

10.2.1.6.3 OPERATIONAL CONSIDERATIONS

The US Army Corps of Engineers annual budget for operating and maintaining waterways is typically three times as high as the capital improvement budget (e.g., \$600 million vs. \$200 million). However, operation of waterways is not explicitly included in this analysis. Additionally, emissions from sediment volatilization and/or oxidation are not included, as much sediment is made up of clay and other recalcitrant materials.

10.2.1.6.4 TURNOVER

An important note to make is that barge's induce minimal marginal damage on the waterway infrastructure per shipment. Additionally, the length of inland waterways has remained nearly unchanged for decades, so all capital and maintenance investments are driven by maintaining or improving the functionality of waterways, but not expanding them. Unlike highway maintenance, which is primarily driven by pavement wear from freight trucks, waterway dredging and other maintenance activities are primarily driven by weather, corrosion, and age. So, these numbers should be treated as average steady-state system emissions, and should not be treated as marginal impacts for specific shipments. In economic and environmental studies comparing barge to rail and/or truck transportation, total system costs are usually ignored (other than other than highway damage costs, which are included in a few comparative studies (Hanson Professional Services, Inc. 2007; Kruse et al. 2009)).

10.2.1.6.5 ECONOMIC CHARACTERIZATION – DREDGING

Dredging

- Cost: \$155/million t-km (\$225/MGTM)
- Sector: Sand, gravel, clay, and refractory mining (1,290 g CO_2-e/\$)
  - Note: A recent study found that the fuel intensity of dredging was 10-13 L of diesel/m^3 dredged for large projects, which results in 35 kg CO_2-e/m^3 (using the NETL life-cycle carbon factor of 95g CO_2-e/MMBTU).
  - For the smallest dredging project with the furthest transport distance, the average carbon intensity was found to be 47-150 kg CO_2/m^3, at a cost of \$30-\$70/m^3. If this cost was entered into 2002 EIO-LCA, the average carbon intensity (at 1,290 g CO_2-e/\$) would come out to 23-76 kg CO_2-e/m^3, suggesting that this sector is half as carbon-intensive as the actual dredging industry.

For simplicity of presentation, only activities making up 2% or more of material costs were included (i.e., 81% of all material costs), and wholesale trade was ignored due to its relatively low carbon and water footprint (relative to truck.

10.2.1.6.6 ECONOMIC CHARACTERIZATION – LOCK AND DAM REHABILITATION

Total Government Maintenance Expenses: \$1,483/million t-km (50% of which is assumed to be labor, and 50% materials)

Steel for sheet piling, concrete reinforcement for locks and other structural steel

- Cost: 20% of construction expenses
- Sector: Plate work and fabricated structural product manufacturing

Concrete for dams, lock construction, etc.

- Cost: 20% of construction expenses
- Sector: Ready mix concrete manufacturing

Installation equipment (excluding dredging)

- Cost: 10% of construction expenses
- Sector: Other nonresidential structures

10.2.1.6.7 DISCUSSION

When including US average waterway maintenance activities, the total embodied (non-operation stage) CO_2-e emissions of inland tows are 9.3 times the mass of the empty vehicle, but only 2.6 times its payload capacity.

In the Ecoinvent model, the only waterway infrastructure activities included were valid through 2000 and based on data from one port in the Netherlands and a typical German canal (Ecoinvent 2010). The results presented in this study include an average for all US waterways, neglecting heterogeneity in infrastructure maintenance for waterway systems, which are summarized below.

- Waterway O&M costs range from 0.08-11.85 cents per total system ton-mile for various waterways (Portiss 2002). In a case study specific to Alabama (Hanson Professional Services, Inc. 2007), the maintenance costs could be interpreted (using the typical freight throughput scenario) to suggest maintenance costs at 0.2c/t-mi (0.14c/t-km), which is just less than the costs assumed in this study.
    - From 2000-2004, total costs for shipping freight by barge were estimated at 1.7-1.8c/ton-mile (~1.2c/t-km) (US DOT BTS 2010), meaning waterway maintenance costs are sometimes much more expensive than the average operating cost for inland tows. However, energy costs (which are typically the only emissions modeled) have only made up 5-10% of total intermediate input costs (tripling from 2002 to 2006) (US DOT MA et al. 2008).
- In 2004, new work dredging cost almost $8/CY, whereas maintenance dredging cost just under $3/CY (Lambert 2007), though dredging can cost up to $100/CY if sediment is contaminated (McKee 2011). In 2010, average US dredging costs also soared to $8.63 in 2000 dollars) (US ACE 2010c).

10.2.1.7 OCEAN TANKERS

10.2.1.7.1 PURPOSE/ BACKGROUND

Ocean tankers are crucial for the distribution of conventional petroleum fuels, carrying fuels more than 12 trillion ton-miles of freight around the world (of 30 trillion ton miles in total) in 2006 (UNCTAD 2007), which is more than 10 times the distance moved by all modes for petroleum transportation within the United States (835 billion ton-miles) (AOPL 2011). Additionally, ocean tankers are increasingly being used to transport ethanol and other biofuels.

In 2009, global seaborne trade of crude oil and products made up 35% of global trade (2.7 billion tonnes of 7.8) (UNCTAD 2010), and in 2010, oil tankers made up the same fraction (35%) of the total global fleet of shipping capacity (450 million DWT). At 690 million tonnes (only 70 of which is exported) of oil traded at US ports (half of total tonnage traded at US ports, but only 34% of vessel calls) (US DOT MA et al. 2008), the United States accounts for 26% of world oil trade.

10.2.1.7.2 SPECIFICATIONS

In 2006, the US average product and crude tanker sizes were 37,000 DWT and 128,000 DWT, respectively, and the overall average tanker ship held 70,000 DWT (US DOT MA et al. 2008). According to a professional ethanol trader, ethanol is typically shipped in chemical tankers around 25,000 DWT, and most ethanol is traded through Houston. While not modeled in this study, tanker vessels are also used for domestic transportation and lightering of crude and products, and are assumed to be constructed and operated similar to ocean going vessels (but operated with shorter travel routes).

10.2.1.7.3 OPERATIONAL CONSIDERATIONS

Performance metrics for tankers (e.g., tonnes unloaded or t-km) are often expressed in terms of the ship's deadweight tonnage (DWT) capacity. In 2006 (and consistent with the adjacent years), tankers transported 31,700 ton-miles/DWT (UNCTAD 2007). Tankers also unloaded approximately 6.1 tons/DWT in 2006, meaning the average trip was 5,200 nautical miles (8,340 km). Neglecting conditions of high wind and waves, ship design speed is usually 90-95% of maximum speed, though reducing operating speeds has high potential for reducing emissions (due to the third power relationship between energy intensity and velocity), at the expense of reducing delivery time and potentially requiring more ships to be constructed and operated in the fleet (Lindstad et al. 2011). Additionally, bulk vessels are commonly assumed to utilize deadweight 100% one-way and 0% on the return, for an average utilization rate of 50% (Lindstad et al. 2011).

10.2.1.7.4 OPERATIONAL ENERGY INTENSITY

Large crude tanker (using residual oil), 128,000 DWT: 51 kj/t-km (Psaraftis and Kontovas 2009)

- The round-trip energy intensity of shipping crude oil by large tanker was taken from the estimate for the world fleet of crude carriers in the 120,000-200,000 DWT (Suezmax) size class (Psaraftis and Kontovas 2008); the majority of oil transported worldwide was actually carried by ships larger and smaller than this class, but this should serve as an appropriate average value.

- Note: This value is much greater than the default estimate of 30 kJ/t-km assumed for 1 million DWT crude tankers in the GREET model (US DOE ANL 2010).

Product tanker (using residual oil), 37,000 DWT: 128 kj/t-km (Psaraftis and Kontovas 2009)

- The round-trip energy intensity of shipping petroleum products by tanker was taken from the estimate for the world fleet of product carriers in the 10,000-60,000 DWT (Handysize) class (Psaraftis and Kontovas 2008);
- Note: This value is much greater than the default estimate of 44 kJ/t-km assumed for 150,000 DWT crude tankers in the GREET model (US DOE ANL 2010), or 48 kJ/t-km assumed for 120,000 DWT tankers in the TEAMS model (Winebrake et al. 2007b).

Ethanol/chemical tanker (using residual oil), 25,000 DWT: 171 kj/t-km (Psaraftis and Kontovas 2009)

- The round-trip energy intensity of shipping ethanol by tanker was interpolated from the world fleet energy intensity estimates for product carriers (Handysize) class (Psaraftis and Kontovas 2008).

As ships spend a lot of time around and at ports, it is important to recognize that a fraction of fuel is burned at port in addition to emissions from at-sea transportation; commonly estimates range from 3.2% (Gratsos et al. 2009) to 6.2% (Entec UK Limited 2002) of total fuel consumption by ships.

10.2.1.7.5 TURNOVER

A negligible amount of the world's current tanker fleet was manufactured prior to 1980, and the percent of the world's tanker fleet considered "idle" has remained less than 4% since 2004 (UNCTAD 2010), so a tanker lifespan of 30 years was assumed. By applying average performance numbers from 2006, the average DWT of tanker capacity will deliver 183 tonnes (1.5 million t-km), and will travel just over 3 million v-km during its life time.

10.2.1.7.6 ECONOMIC CHARACTERIZATION –MANUFACTURING

The ocean-going vessel (ship) construction industry is very global business, and prices (as well as workmanship and sophistication) vary greatly between countries. In a prior study which estimated ship construction emissions using EIO-LCA, construction costs in the US were assumed to be twice the global average, yielding an emission factor of 4.5kg CO_2-e per kg of ship for a Panamax bulk vessel (which was assumed to cost $50 million and hold 72,000 of DWT, or $694/DWT) (Lindstad et al. 2011).

Further research into construction prices as reported by the US Army Corps of Engineers shows that US flagged vessels cost 2.5 times the foreign flag average for tanker ships of all sizes. Ship construction in the United States has declined substantially over the last few decades, and ship costs reported by the UN confirm that prices of non-US built ships drive the average global market prices (as can be seen in Figure 47). While it may seem counterintuitive to assume new and used ships cost the same, UN statistics on newbuild and secondhand ships also had very similar costs per DWT. The UN and US ACE report prices of secondhand ships (with a typical age of 5 and 7 years, respectively), which are believed to fluctuate less than new construction costs year-to-year.

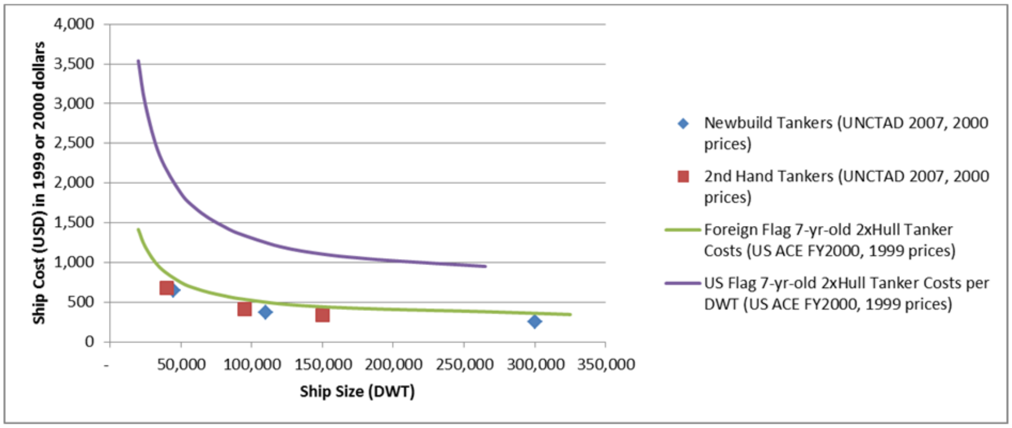

Figure 47. New and Secondhand Tanker Construction Prices (data adapted from (UNCTAD 2007; US ACE 2000b)).

Initial construction

- Cost: \$3,000/DWT for chemical tanker (25,000 DWT), \$2,100 for 37,000 product tanker, and \$1,200/DWT for 128,000 crude tankers (in 1999 dollars, interpolated from (US ACE 2000b))
    - Note: Construction costs were estimated to be 2.5 times higher for US-flagged tankers than foreign-flagged tankers (interpolated from (US ACE 2000b)).
- Sector: Ship building and repairing

10.2.1.7.7 ECONOMIC CHARACTERIZATION – VESSEL MAINTENANCE

In order to generate more accurate and comprehensive emission factors, it was necessary to include both the initial construction and the maintenance of ships over the course of their lifetime (assumed to be 30 years); these costs are estimated to add 20-35% to the initial purchase price without discounting future expenses as would be done for computing net present value (which would introduce an underestimation error of maintenance activities).

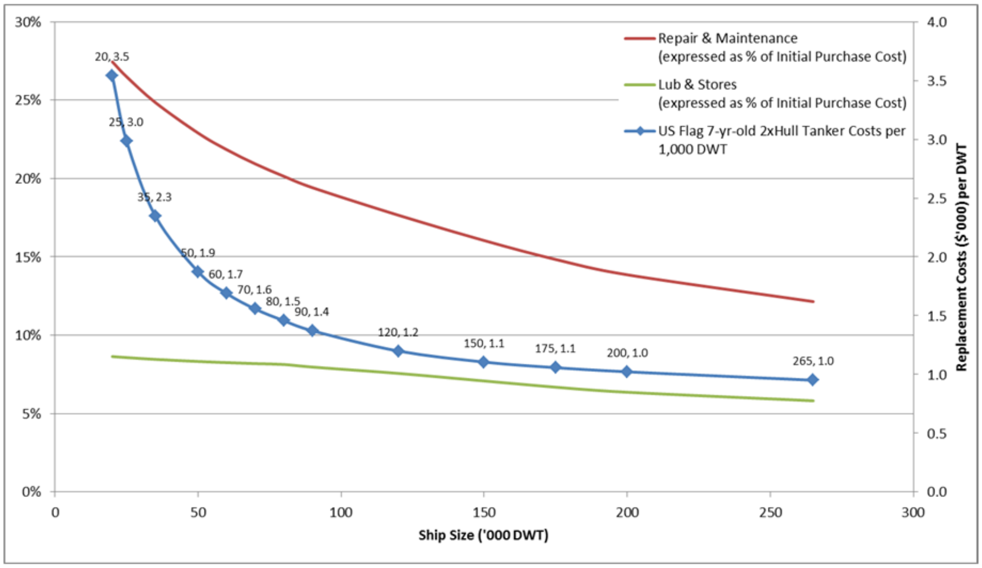

Figure 48. Life-cycle Costs for Repair and Maintenance, Lubrication and Stores, for US-flagged Double-hulled Tanker Vessels over a 30-year Lifespan, in 1999 Dollars (data adapted from (US ACE 2000b)).

In a more detailed summary of life-cycle costs for roll-on roll-off (RORO) ships, material-intensive costs are estimated to add more than 50% to the NPV beyond the initial purchase price (in NPV), though maintenance expenses are expected to be higher for RORO ships due to their high level of sophistication (Stenwall 2008).

Repair and Maintenance (e.g., dry docking for hull repair, repainting, engine and electrical equipment)

- Cost: 26.5% for 25,000 DWT; 23.9% for 37,000 DWT; and 17.5% for 128,000 DWT (interpolated from (US ACE 2000b))
  - Note: Repair and maintenance costs were estimated to be 2.27 times higher for US-flagged tankers than foreign-flagged tankers (interpolated from (US ACE 2000b)).
- Sector: Ship building and repairing

Lubrication and storage supplies (expressed as a fraction of purchase price)

- Cost: 8.6% for 25,000 DWT; 8.4% for 37,000 DWT; and 7.5% for 128,000 DWT (interpolated from (US ACE 2000b))
  - Note: These costs were reported to be identical for US and foreign flagged vessels (US ACE 2000b).
- Sector: Petroleum lubricating oil and grease manufacturing

10.2.1.7.8 ECONOMIC CHARACTERIZATION – NON-VESSEL ASSETS

Assumptions about the relationship between non-vessel asset investments and vessel investments were assumed to be the same for ocean going vessels as for inland vessels.

10.2.1.7.9 DISCUSSION

For a typical oil tanker (larger than 60,000 DWT), a ship's displacement is 1.14-1.19 of the cargo weight (estimated by (Pacific LA Marine Terminal LLC n.d.)), and tanks for fuel oil, diesel, and water typically make up 2-4% of total storage volume on the ship (interpreted from (Brodosplit-Brodogradilištu d.o.o. 2008). After speaking with engineers at STX Floro (Rimmen and Hauge 2009) and at the Aker Shipyard in Philadelphia, it is clear that smaller ships have a higher steel:payload (DWT) mass ratio (with a steel:DWT ratio of 11:40 in Norway and 9:46 in Philadelphia, as two examples).

The lightweight (LWT) is therefore assumed to be approximately 5,000 tonnes for 25,000 DWT chemical tankers (20% of DWT), 7,400 tonnes for 37,000 DWT product tankers (20% of DWT), and 16,000 tonnes (12.5% of DWT) for crude tankers. By applying results from EIO-LCA for ship manufacturing, a carbon intensity of 9 tonnes CO_2-e per tonne of (empty) ship was estimated for crude tankers, 10 tonnes for product tankers, and 15 tonnes for smaller ethanol tankers (for a carbon intensity of 1-3 tonnes CO_2-e per tonne of payload capacity). The 2005 emission factor for steel plate for ships and vessels was 1.11 kg CO_2/kg steel (WorldSteel 2010), so steel production does not seem to be the dominant source of emissions, though steel is a dominant cost for large ships. For smaller specialty tankers, total shipbuilding costs typically comprise 60-70% materials (70% of which is stainless steel), 5-10% design, and the remainder made up of tasks such as assembly, welding, and painting (which may require 260-390 tonnes of diesel per ship) (Rimmen and Hauge 2009).

Consistent with my other modules, my results for ships were about an order of magnitude greater than estimates from Ecoinvent. Ecoinvent reports that 30,644 tonnes of CO_2-f are emitted in producing a 100,000 DWT transoceanic tanker and 10,300 tonnes for a 51,500 DWT transoceanic freight ship (with an additional 166 tonnes for maintenance on freight ships), which suggests that vehicle manufacturing and maintenance are 1-2 times the mass of the ship. This result can only partially be explained by the fact that the Ecoinvent emission factors for manufacturing steel range from only 0.26-0.54 kg CO_2-f/kg of steel, which is lower than the WSI emission factor. Below are some of the assumptions made in the Ecoinvent module, which were not explicitly covered in my model.

1. Energy consumption in manufacturing two models of ships was estimated at 50% of the total energy from material inputs; the energy sources were assumed to be 10% electricity and 90% heavy fuel oil.
2. Freight container ships were assumed to undergo 6 paint jobs per 25-year life.
3. Lubricating oil inputs were grouped into fuel consumption, instead of being treated separately.

In another study to determine if thicker and longer-lasting steel hulls lead to reduced energy use and air emissions from Handymax and Panamax bulk carriers, Gratsos performed a hypothetical study of alternative ships over a 60-year service period (with the thicker hulled ships lasting 30 years instead of 20 years). While he believed non-operational emissions had been underestimated in the past, adding 5-6% beyond operational emissions (Gratsos et al. 2009), my results show that ship manufacturing and maintenance contributes closer to the equivalent of 10% (and the next section shows infrastructure adds another 5%) of operational emission to life-cycle emissions for the tanker ships considered.

10.2.1.8 PORT INFRASTRUCTURE

10.2.1.8.1 PURPOSE/ BACKGROUND

In addition to maintaining a fleet of waterborne vessels and other fixed assets, a significant investment is made each year into the operation, maintenance, and renewal of coastal waterway infrastructure. The United States has 185 coastal ports and about 3,200 berths (including some inland waterways) that can accommodate deep-draft ships (which handle 99.4% of foreign trade by volume) (AAPA 2008a). US coastal port infrastructure maintenance activities are assumed to be dedicated to trade of goods, and emissions from these activities are allocated by trade tonnage.

10.2.1.8.2 SPECIFICATIONS

Expenses for maintaining coastal ports include dredging, infrastructure maintenance and improvement, and security upgrades are included here. Given the large size and deep draft of petroleum tankers, but relatively simple unloading and offloading systems, it is unlikely that the infrastructure assets and maintenance needs will be as significant as the needs for a container ship, RORO, or other ship. Expenses for tanks are not included in this section, as they are addressed in the sections on aboveground storage tanks (ASTs).

10.2.1.8.3 OPERATIONAL CONSIDERATIONS

Although ports consist of offices, and require constant service from utilities (e.g., lighting), these activities are presumed to be insignificant in comparison to the energy and emissions from loading and offloading of fuels.

10.2.1.8.4 TURNOVER

Dredging

The United States Army Corps of Engineers (US ACE) dredged an annual average of 256 million cubic yards (CY) per year from 1990-2009, for an average cost of $2.57/CY from 2000-2004, in 2000 dollars) (US ACE 2010c). US ACE dredging activities were allocated 11% to inland waterways, and 89% to coastal ports (Lambert 2007), for a total of 228 million CY of coastal dredging. The American Association of Port Authorities (AAPA) reported that 400 million CY are typically dredged each year, so approximately 144 million CY are assumed to be dredged from berths and private terminals (AAPA 2008a), for a total of $956 million spent annually on coastal (deep draft) dredging between the public and private sector. At 633.4 million tonnes of petroleum products traded internationally through US ports (US ACE 2010b), petroleum makes up approximately half of the tonnage of goods traded through US ports, so $478 million is assumed to be spent on 633 million tonnes of petroleum traded, or $0.76 per tonne. This estimate assumes that dredging for cruise ships is negligible, and that tonnage is a reasonable metric for allocating dredging expenses (which is discussed in the methodology summary).

Port Security Investments

Ports are expected to annually invest roughly $500 million in security requirements over the next ten years (though budgeting has not yet been finalized[54]) (AAPA 2008a), averaging $50 million per year. This is consistent with 2006 spending of $47.7 million (US DOT MA 2009). It would not be reasonable to allocate these expenses by tonnage independent of cargo type, so wharfage security fees specific to liquid bulk handled by pipeline at Corpus Christi were used; this fee has been $0.06/barrel since 2008 (AAPA 2008b), or approximately $0.45/tonne. This fee is assumed to be split between security equipment and infrastructure (33%) and security services (67%).

Coastal Port Infrastructure Maintenance

The US ACE spends approximately $750 million/year to operate and maintain breakwater and jetty structures (McKee 2011). If dividing by the total average tonnage of foreign trade, this works out to $0.53/tonne traded in coastal infrastructure maintenance

Port Facility Upgrades

Consistent with the last five years ($1.8B/yr.), and the projections for the next five years ($2.1B/yr.) (AAPA 2008a), US ports are assumed to consistently invest $2B/year (of private money) into "capital projects to enhance their facilities." If dividing by the average tonnage, this works out to $1.42/tonne traded in port upgrades. However, liquid bulk ports were expected to spend only $287 million from 2007-2011 (US DOT MA 2009) ($57.4 million per year). Assuming petroleum products are the dominant liquid bulk commodity, this investment could be divided by 2009 foreign imports and exports of petroleum products (633.4 million tonnes (US ACE 2010b)), to estimate $0.09 per tonne traded. This result may seem low given the US average port expenditures by tonne, but liquid bulk port facilities were projected to only make up 2.6% of facility capital expenditures from 2007-2011 (whereas specialized and general cargo alone made up roughly half of expenses), despite making up roughly half of all foreign imports and exports (by tonnage). It could therefore be estimated that the facility capital expense intensity for petroleum is only approximately 5% of the average commodity, per tonne traded at ports.

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[54] The U.S. Coast Guard in 2003 projected that port facilities would need $5.4 billion to pay for security requirements over the next 10 years. Since 9/11/01, America's seaports have invested hundreds of millions of dollars into facility security enhancements while the federal government has provided ports approximately $1.5 billion for security funding. For fiscal 2008, Congress and the Administration approved $400 million in appropriations for the Department of Homeland Security's Port Security Grant program, although the Administration did an about-face and requested only $210 million for fiscal 2009.

For more information on various aspects of the sustainability of ports, see for example, the final report of the Port Innovation Workshop in 2007 (Rocky Mountain Institute 2007).

10.2.1.8.5 ECONOMIC CHARACTERIZATION

Dredging

- Cost: $0.42/tonne traded
- Sector: Sand, gravel, clay, and refractory mining (1,290 g CO_2-f/$)

Port Security Investments

- Cost: $0.15/tonne traded
- Sector: 33% (educated guess) Broadcast and wireless communications equipment (252 g CO_2f/$)
- Sector: 67% (educated guess) Investigation and security services

Port Infrastructure Maintenance Specific to Liquid Commodities (e.g., Petroleum)

- Cost: $0.62/tonne traded ($0.53 in public water-side infrastructure spending, and $0.09 in bulk liquid port facility upgrades), half of which is assumed to be labor.
- Sector: 20% (educated guess) Plate work and fabricated structural product manufacturing
- Sector: 20% (educated guess) Ready-mix concrete manufacturing
- Sector: 10% (educated guess) Other nonresidential structures

10.2.1.8.6 DISCUSSION

After including ship and waterway maintenance in the life-cycle emissions of ships, the life-cycle (non-operational) carbon intensity was estimated to be 1.4, 2.3, and 3.3 tonnes CO_2-e per tonne of payload capacity for crude, product and ethanol tankers (or 11, 12, and 16 tonnes CO_2-e per tonne of ship).

10.2.1.9 PIPELINES

10.2.1.9.1 PURPOSE/ BACKGROUND

Petroleum pipelines make up the vast majority of hazardous liquid pipelines in the United States. Pipelines are used for the transportation of crude petroleum from the point of extraction to storage tanks prior to entering a refinery. Additionally, pipelines are used to transport refined petroleum products to product terminals, where they are typically then trucked to retail stations and end-users. As can be seen in Figure 49, the mileage of US crude pipelines (as tracked by the Department of Transportation) has been decreasing over the last few decades, while the mileage of product pipelines has remained relatively constant since 1980; however, it should be noted that reporting requirements have changed[55] over time.

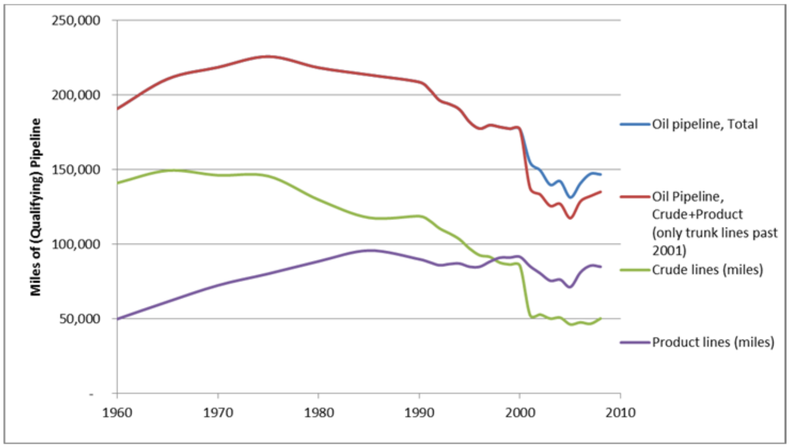

Figure 49. Mileage of US Oil Pipelines, 1960-2008 (data adapted from Table 1-10 in (US DOT BTS 2010)).

Although the US Federal Energy Regulatory Commission (FERC) regulates most oil pipelines, and many inventories of pipelines cite FERC annual reports (of Form 6 data), pipelines that are not carrying a certain volume of product from state to state are not regulated (e.g., many gathering lines), and therefore not tracked. The Department of Transportation (DOT) Pipeline and Hazardous Material Safety Administration (PHMSA) (which acts through the Office of Pipeline Safety (OPS)) tracks more of the "universe" of pipelines for health and safety concerns, and therefore the inventory of pipelines from PHMSA is typically 10% greater than the FERC inventory in length. However, pipeline movements not captured in FERC Form 6 were estimated to contribute only 0.2% of total t-km (US DOT FHWA 2006b).

10.2.1.9.2 SPECIFICATIONS

The PHMSA 2009 annual report will guide the majority of physical characterization exercises for pipelines used to transport crude oil, highly volatile liquids (HVL), and petroleum products. Other sources will be used to translate this inventory into costs, embodied environmental emissions, and energy intensity.

Pipelines constructed prior to World War II tend to have higher maintenance costs due to lack of modern corrosion prevention controls (according to one industry expert), though more than 96% of crude pipeline kilometers are currently protected by both coating and cathodic protection (and 99%

[55] Mileages of oil pipeline for years 1960-2000 include regulated and unregulated trunk and gathering crude lines, as well as refined oil trunk lines. After 1975, data include 5,000-6,200 miles of underground storage pipeline. Before 1990, data include field line mileage. Beginning in 2001, data include information for FERC-regulated oil pipeline companies only. For years 2001 and after, total miles of pipeline include both trunk and gathering lines, whereas the individual components, namely, crude and product lines, include the mileages of trunk lines only. Thus, detailed pipe values do not sum to the total for this period. (US DOT BTS 2010)

of HVL and 98% of product pipelines have both forms of protection) (US DOT PHMSA 2011). All modern pipelines are assumed to have both a coating and cathodic protection.

The clearing of plants, trees, and excavation will result in a release (oxidation) of soil and standing biomass carbon. However, these emissions are not expected to be significant contributors to the life-cycle carbon balance of pipelines, as the right of way for pipelines is expected to be returned to its initial condition (e.g., farmland or field) shortly after the pipeline is installed) (Stasioski 2010).

10.2.1.9.2.1 PIPELINE DIAMETER DISTRIBUTION

The US inventory of steel petroleum pipelines can be found in Figure 50 (and data found in Table 60). Approximately 10% of crude pipeline kilometers are offshore, but a negligible amount of HVL and product pipelines are located offshore. Offshore pipelines are grouped with onshore pipelines for this analysis, without considering differences in materials or construction practices.

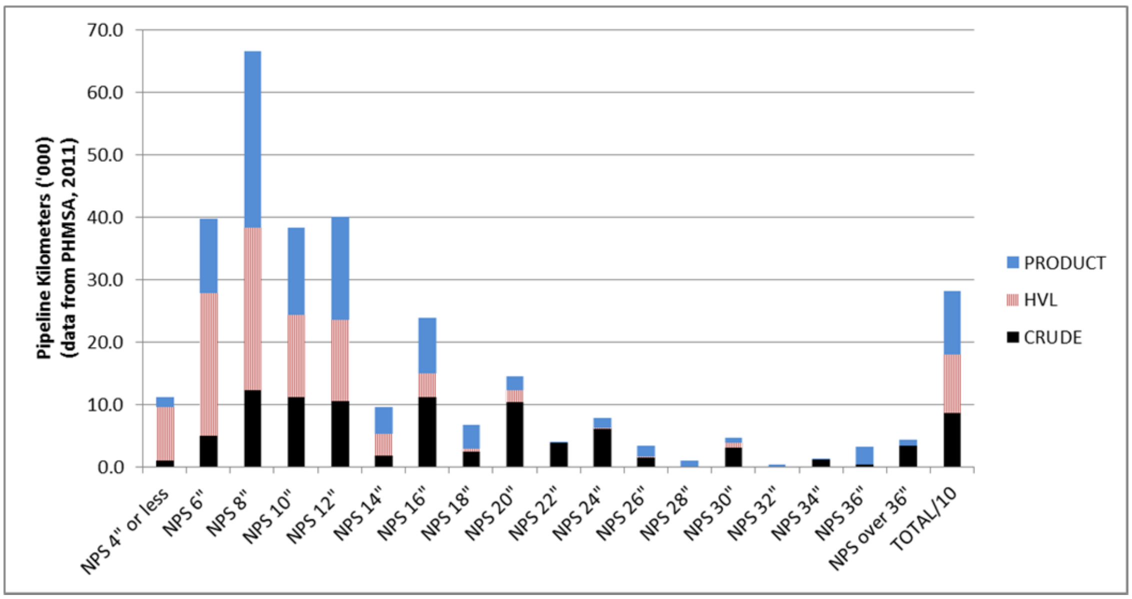

Figure 50. US Pipeline Inventory[56] in Kilometers by Diameter, 2009 (data adapted from (US DOT PHMSA 2011)).

[56] Supporting data can be found in Table 60.

Nominal Pipe Size	CRUDE	HVL	PRODUCT	SUM
NPS 4" or less	1.2	8.5	1.6	11.3
NPS 6"	5.1	22.8	12	39.9
NPS 8"	12.5	26	28.2	66.7
NPS 10"	11.3	13.2	14	38.5
NPS 12"	10.7	12.9	16.6	40.2
NPS 14"	2	3.4	4.3	9.7
NPS 16"	11.3	3.7	9	24
NPS 18"	2.6	0.4	3.9	6.9
NPS 20"	10.5	1.9	2.2	14.6
NPS 22"	3.9	0	0	4
NPS 24"	6.3	0.1	1.7	8
NPS 26"	1.6	0.1	1.7	3.5
NPS 28"	0.2	0	0.9	1.1
NPS 30"	3.2	0.8	0.8	4.8
NPS 32"	0	0	0.5	0.5
NPS 34"	1.3	0	0	1.3
NPS 36"	0.5	0	2.9	3.4
NPS over 36"	3.5	0	1	4.5
TOTAL/10	8.8	9.4	10.1	28.3

Table 60. US Pipeline Inventory in Kilometers by Diameter, 2009 (data from (US DOT PHMSA 2011) and presented visually in Figure 50).

10.2.1.9.2.2 PUMP STATIONS AND BREAKOUT TANKS

In order for pipelines to function, pump stations and breakout tanks are necessary to push liquid through the pipelines, and to enable pipeline sections to be temporarily emptied for maintenance work. According to a report prepared for the US DOE, "[p]ipeline pump stations are located every 30 to 60 miles along a pipeline and are variously equipped with breakout tanks, pumps, shut-off valves, pipeline leak detection equipment, fuel storage tanks and additional storage capacity to contain oil in the event of a pipeline upset." (i.e., 3,333-5,000 pump stations) (ARI, Inc. 2006). More recent data shows that the United States has about 3,500 breakout tanks for crude, HVL and product pipelines (US DOT PHMSA 2011), which suggests that one tank can be found on average every 80 km (50 miles) of pipe. The total storage capacity of breakout tanks within the 4 given size classes is summarized in Figure 51. As total petroleum storage in the United States was estimated to be more than 200 billion gallons, the amount potentially stored in breakout tanks would make up less than 5% of the total if entirely full.

Unfortunately, the total number and horsepower of pump stations is not available in the PHMSA data set, so economic data was the only means used for estimating emissions from the construction of pump stations and breakout tanks. In an email exchange with a pipeline expert, emissions from manufacturing and constructing pump stations were expected to be extremely small in comparison to emissions from pipeline production.

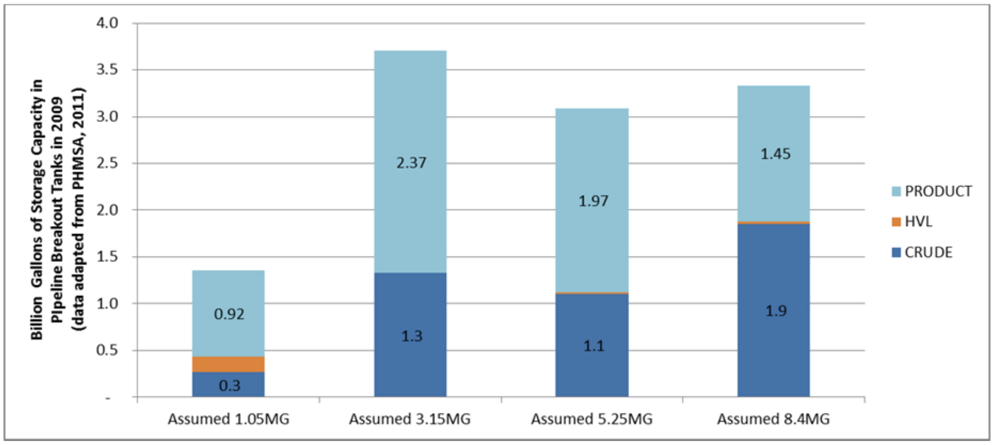

Figure 51. Storage Capacity of Pipeline Breakout Tanks by Assumed Tank Volume, 2009 (data adapted from (US DOT PHMSA 2011)).

	<50,000 bbl	50,001-100,000 bbl	100,001-150,000 bbl	>150,000 bbl	Total
Crude	252	421	211	221	1105
HVL	161	1	2	3	168
Product	878	753	375	173	2179
SUM	1291	1175	588	397	3452

Table 61. Number of Breakout Tanks by Number and Size Range Dedicated to a Single Petroleum-based Commodity (data adapted from the field "BT1" of (US DOT PHMSA 2011)).

10.2.1.9.3 OPERATIONAL CONSIDERATIONS

Unlike many line-haul freight transport vehicles that are almost entirely dedicated to a single product, pipelines are often used for transporting different liquid petroleum products. The interface between two different products may be identified by the aid of radioactive tracers, color dyes, or spacers (e.g., solid pigs or liquid separators such as water, kerosene or gasoline) (Kraus 1998). The contaminated mixed fuel at the interface (i.e., "transmix") may be downgraded or diluted and sold, or may be returned to a refinery for reprocessing (fractionation). It was impossible to estimate a "typical" mass or cost of materials impacted at the interface, though one pipeline expert suggested that transmix makes up a small fraction of one percent of total fuel transported through pipelines, so it was ignored in this analysis.

Pipeline companies invest a large amount of money in inspection and maintenance (IM) programs. In 2009, approximately 28% of the total US kilometers of pipelines were inspected; for each 100 km inspected, approximately 18 incidents were repaired or mitigated (US DOT PHMSA 2011). In order to reduce the likelihood of such problems, pipelines are routinely (often daily) monitored by aerial surveillance or by truck, in addition to remote monitoring from control centers. Inspection and monitoring were not considered to be energetically significant; if a large truck drove up and down the access road every day, the diesel fuel consumed by the truck would be negligible compared to the energy needed to move fluid weighing hundreds or thousands of times the mass of the truck through the pipeline each day.

Although total crude oil production in the U.S. declined by about 28 percent between 1990 and 2007 (AOPL 2011), the average utilization of both crude and petroleum pipelines has increased to approximately 5.5 million t-km/km (6 million ton-miles/mile) of pipeline in 2007, as shown in Figure 52. As regional and seasonal fuel formulations have increased the complexity of fuel distribution logistics (US GAO 2005), pipeline utilization would probably have improved more markedly if fuel regulations had remained constant.

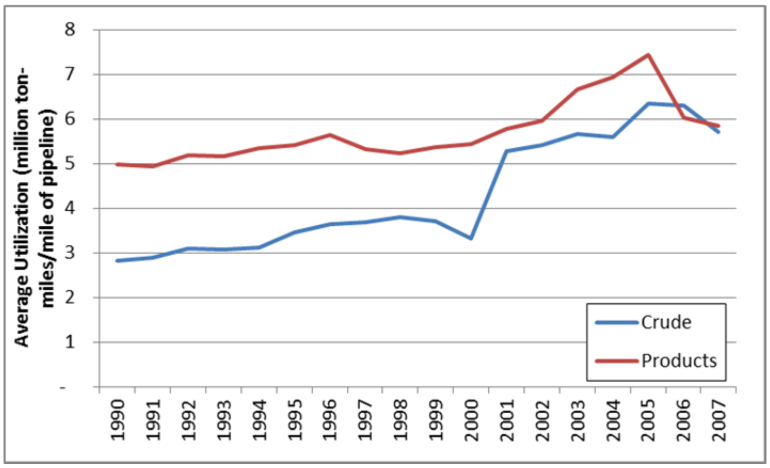

Figure 52. Average Utilization of Petroleum Pipelines (million ton-miles/mile), 1990-2007 (data adapted and reorganized from (AOPL 2011; US DOT BTS 2010)).

The average cost of shipping oil by pipeline was $0.009/t-km in 2004 (US DOT BTS 2010), though this cost is expected to vary drastically by location and pipeline diameter; for example, long distance transport of gasoline has been reported to cost as little as $0.004/t-km (Rabinow 2004).

10.2.1.9.4 OPERATIONAL ENERGY INTENSITY

In 1981, researchers at the Oak Ridge National Laboratory used data from 1978 to estimate the total energy consumption and energy efficiency of petroleum pipelines in the US, after realizing that existing estimates from prior studies varied by a factor of ten (Hooker 1981). Unfortunately, a similarly comprehensive updated study has not been performed since this study was published, and it continues to be cited in documents such as the most recent Transportation Energy Data Book (and studies that cite the Transportation Energy Data Book) to estimate energy consumed by petroleum pipelines. It is important to recognize that the average energy efficiency of pipelines has probably changed over the last few decades, due to the following system changes:

- Retirement and construction of pipelines, resulting in changes to the average and distribution of pipelines by diameter,

- changes in pipeline utilization and fluid velocity, and
- improvements in pumping efficiency (which could be due to improvements in pumps, pipe maintenance, or liquid formulation).

In order to save costs, pipeline operators already invest considerably in energy efficiency. Computer programs (e.g., demand-response software) have improved pipeline and terminal logistics such that energy use per barrel-mile has decreased by 12 percent, and flow improvement additives (e.g., drag-reducing agents, or DRAs) have been claimed to reduce pipeline turbulence, increase throughput, and reduce energy requirements at pump stations, such that energy savings of more than 80% can be obtained (ConocoPhillips 2011). Additionally, some operators may increase pumping activity overnight in order to negotiate cheaper electricity rates with utilities (which could also enable them to purchase "greener" electricity such as wind power).

Although pipelines are the most energy efficient mode of transporting liquid products in most cases, the importance of fluid and pipeline characteristics (e.g., physical properties of the fluid, elevation changes, diameter, velocity and throughput) can lead to drastic differences in specific energy consumed per tonne-km of product shipped. Figure 53 shows that small diameter pipelines can require several times more energy to move a tonne of fluid than would large diameter pipelines (operating at full capacity). Additionally, crude and product pipelines were found to operate on average at 73% and 57% of their estimated design capacity in 1978, which required only 78% and 72% of the energy intensity that would have been necessary to operate at full capacity (181 instead of 233 kJ_e/t-km, and 220 instead of 309 kJ/t-km of primary energy) (Hooker 1981). As with barges and ships, the fluid resistance in pipelines (and therefore pumping power requirements) is extremely sensitive to velocity, so the energy intensity per t-km will vary dramatically with changes in diameter and capacity utilization.

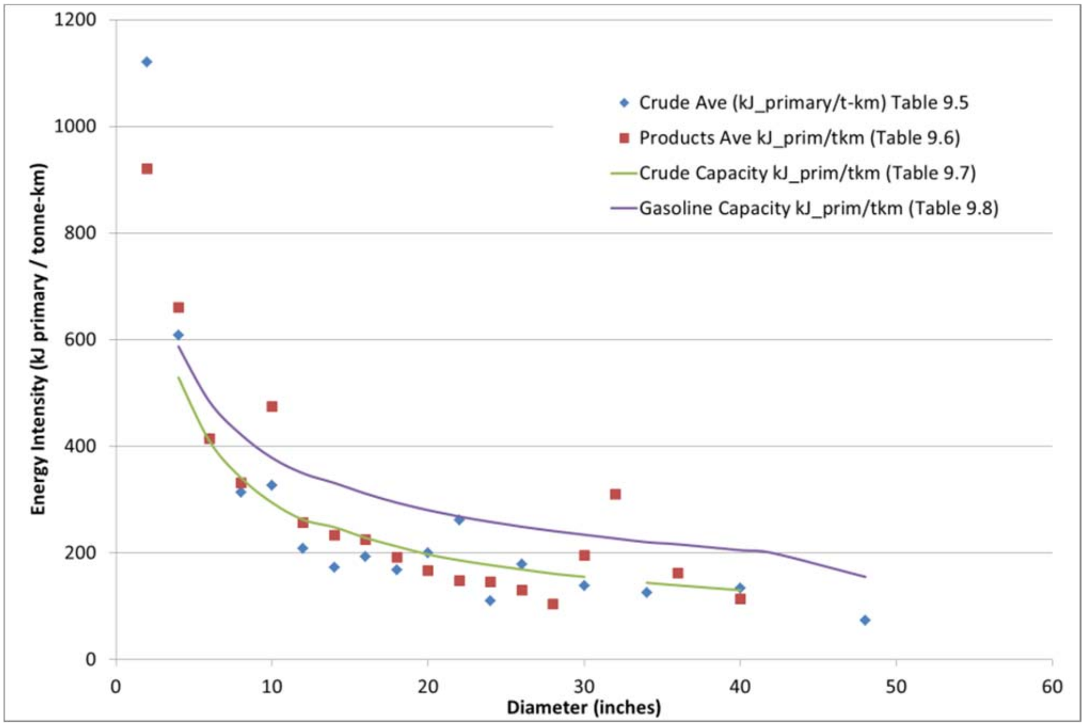

Figure 53. Estimated Primary Energy Intensity of Pipelines Operating at Capacity (lines), and under Average Operating Conditions (points) in 1978 (data adapted from (Hooker 1981)).

Hooker's estimates for primary energy intensity (Figure 53) numbers were back-calculated to units of electrical energy intensity (Figure 54, with data presented in Table 62), by applying his assumption that 1 unit of primary energy was required to produce 0.323 units of electrical energy. This leads to national average electrical energy intensity estimates of 113 kJ_e/t-km, 58 kJ_e/t-km and 71 kJ_e/t-km, to transport crude through gathering lines, crude through trunk lines, and product through trunk lines, respectively. This figure also shows my estimate of the energy intensity for ethanol pipelines, if operating at the same (volumetric) capacity as product (e.g., gasoline) lines. As a result, the pumping energy for ethanol is slightly greater than gasoline, attributed to differences in density and viscosity.

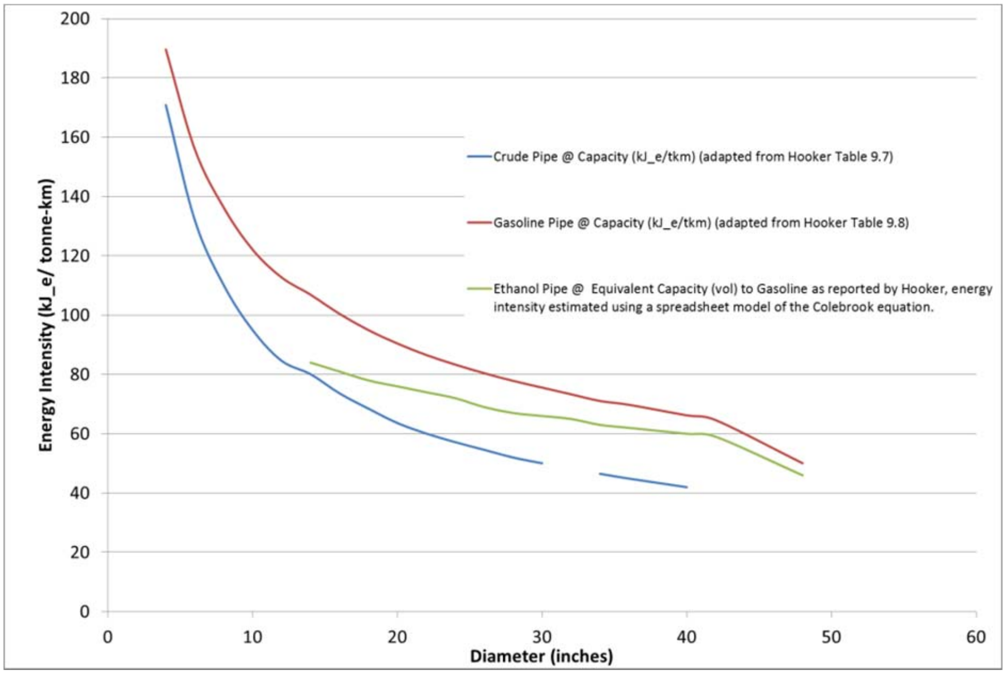

Figure 54. Maximum Pipeline Energy Intensity (kJ_e/t-km) for Crude Oil and Petroleum Products (data[57] adapted from (Hooker 1981)), and Estimated for Ethanol.

Diam (inches)	Crude Capacity Throughput (1000m3/d), (Table 9.7)	Product Capacity Throughput (1000m3/d) (Table 9.8)	Crude Pipe @ Capacity (kJ_e/tkm) (adapted from Hooker Table 9.7)	Gasoline Pipe @ Capacity (kJ_e/tkm) (adapted from Hooker Table 9.8)	Ethanol Pipe @ Equivalent Capacity (vol) to Gasoline as reported by Hooker, energy intensity estimated using a spreadsheet model of the Colebrook equation.
14	11.6	16	80	107	84
16	16.1	22.3	74	100	81
18	21.4	29.8	68	95	78
20	27.6	38.7	64	90	76
22	34.8	48.8	60	87	74
24	42.9	60.4	57	83	72
26	51.4	72.6	55	80	69
28	61.4	87.1	52	78	67
30	72.4	103	50	76	66
32		121		73	65
34	97.7	140	47	71	63
36	112	160	45	70	62
40	144	207	42	66	60
42		233		65	59
48	220	289	38	50	46

Table 62. Maximum Pipeline Capacity Throughput and Energy Intensity for Crude Oil and Petroleum Products (data[58] adapted from (Hooker 1981)), and Estimated for Ethanol.

[57] Supporting data can be found in Table 62.

10.2.1.9.5 TURNOVER

The single ethanol pipeline module (25") was adapted from a single proposed pipeline project, in which an economic lifespan of 40 years was assumed (US DOE 2010). Petroleum pipelines are conservatively assumed to have a 50-year lifespan (though other reports assume 70 years (Ecoinvent 2010)), with an annual asset investment rate of 4% of initial asset value (ignoring asset value depreciation or future discounting), implying a repair or renewal factor of 200% throughout the life of a pipeline. This is reasonably consistent with Rabinow's estimate that non-construction capital investments were typically 177% greater than construction costs (Rabinow 2004), and those derived from Smith's snapshot of 5 representative crude and product pipeline companies (Smith 2009) in which non-construction capital expenses were equivalent to 120% of construction costs for crude pipelines and 181% for product pipelines.

10.2.1.9.5.1 PIPELINE AGE, CONDITION, AND LIFESPAN

Pipelines typically last long enough that the initial construction is a small cost in comparison to life-cycle operating and maintenance costs. In this study, pipelines are assumed to last for 50 years, though 33% of hazardous liquid pipelines operating in 2009 were constructed prior to 1960 (US DOT PHMSA 2011), and the average pipeline age was roughly 40 years old, as can be seen in Figure 56.

Hooker reported 249,000 km of crude and product pipelines in 1978, though other sources cite *Oil & Gas Journal* records (estimated from FERC Form 6 records) which indicate that 275,000 km of pipeline were operating in 1980 (US Census Bureau 2011a), which would imply a negligible change in total pipeline miles over the last three decades, despite roughly 80,000 km of pipelines being constructed during this period, as can be seen in Figure 56.

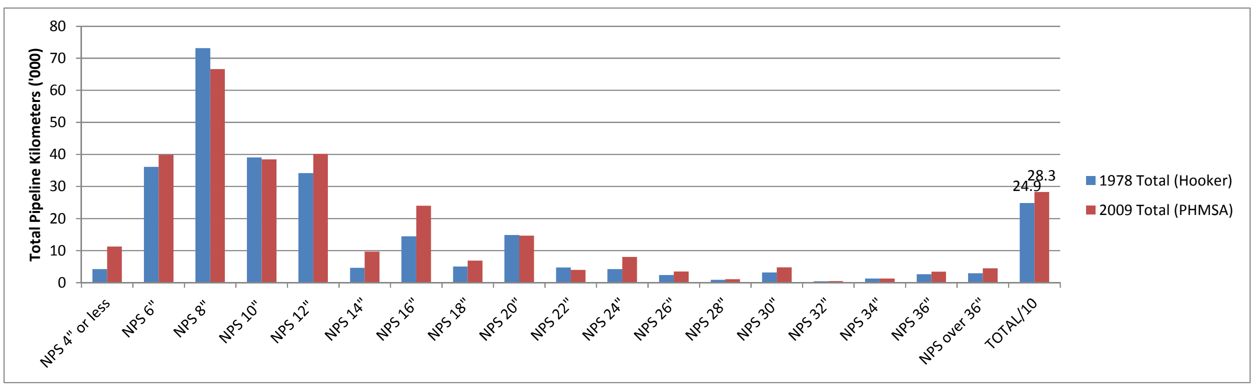

Figure 55. United States Petroleum Pipeline Inventory in 1978 and 2009 (data adapted from (Hooker 1981; US DOT PHMSA 2011)))

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[58] Table provides supporting data for Figure 54.

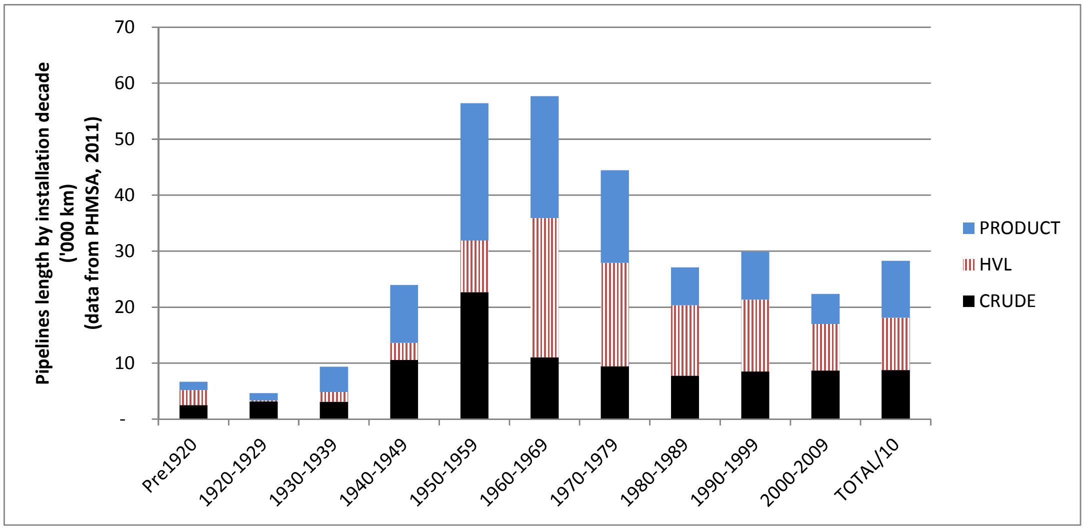


Figure 56. Pipeline Kilometers by Decade of Installation, through 2009 (data[59] adapted from (US DOT PHMSA 2011))

	CRUDE	HVL	PRODUCT
Pre1920	2,550	2,665	1,477
1920-1929	3,168	172	1,306
1930-1939	3,129	1,759	4,480
1940-1949	10,589	3,039	10,363
1950-1959	22,709	9,232	24,470
1960-1969	11,085	24,824	21,758
1970-1979	9,453	18,487	16,524
1980-1989	7,798	12,556	6,765
1990-1999	8,507	12,853	8,563
2000-2009	8,706	8,291	5,411
TOTAL/10	8,769	9,388	10,112

Table 63. Pipeline Kilometers by Decade of Installation, through 2009 (data adapted from (US DOT PHMSA 2011) and presented visually in Figure 56).

[59] Supporting data can be found in Table 63.

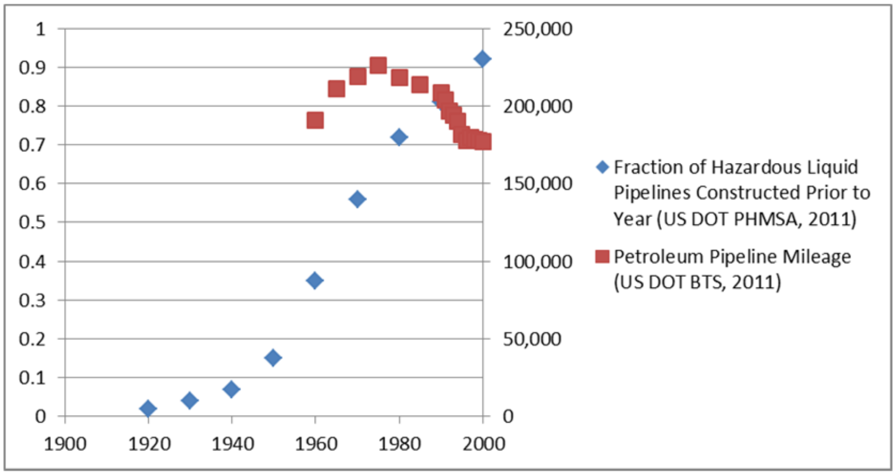


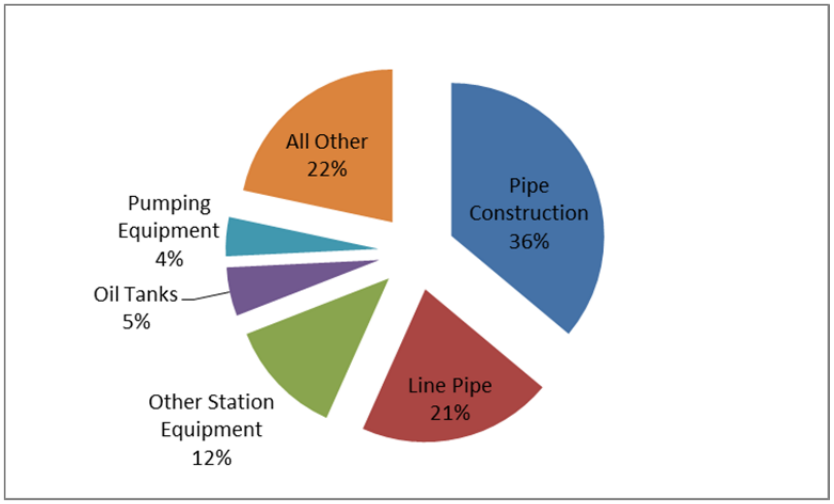
Figure 57. Year of Construction and Total Stock of US Petroleum Pipelines in 2009 (data adapted from (US DOT BTS 2010; US DOT PHMSA 2011))

10.2.1.9.6 ECONOMIC BACKGROUND – PIPELINES

Pipeline construction and maintenance costs were estimated from a summary of pipeline investments, which were challenging to interpret; from 2006-2008, oil pipeline operating revenues averaged $8.6 billion, net income averaged $3.6 billion, but investment in carrier property has been over $30 billion every year since 2005 (Smith 2009). To put these numbers in perspective, the total property (assets) of FERC-regulated oil (trunk) pipelines was $32.6 billion in 2002 (average $135,000/km) and $39 billion in 2008 (average $166,000/km) (US Census Bureau 2011a).

Although not correlated directly with fluid throughput, pipeline capital expenses were categorized based on data sources such as the Association of Oil Pipelines (AOPL) and the *Oil & Gas Journal* (OGJ). Unfortunately, both sources aggregate capital expenses from initial construction with renewal and upgrading expenditures.

a)



b)

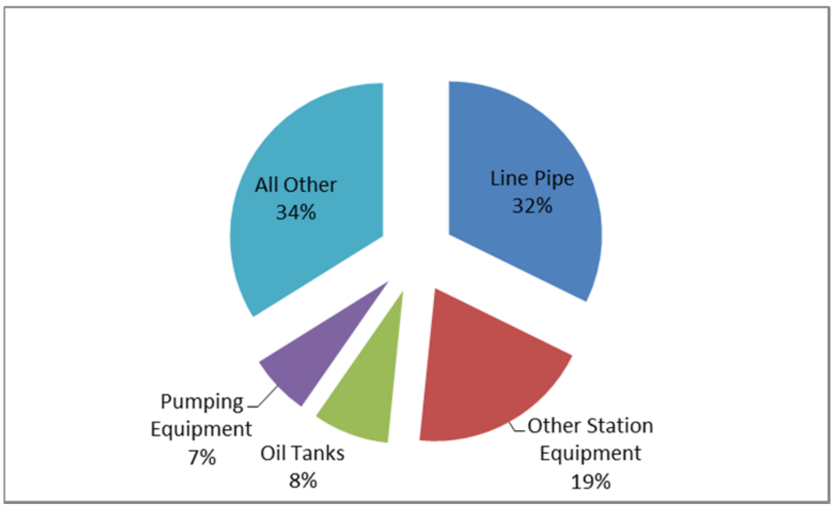


Figure 58. Capital Expenses of Oil Pipelines (data from (Rabinow 2004) citing AOPL), (a) With and (b) Without New Construction.

The expenses associated with constructing and maintaining pipelines is highly variable. Many in the pipeline industry will caution those less familiar with the industry that there are no "rules of thumb" for estimating pipeline construction costs; Figure 59 shows the average costs per constructed pipeline mile by diameter, with error bars indicating high and low costs, for each year throughout the period. As expected, costs do tend to increase with larger diameter pipes, and the often cited "million dollars per mile" rule of thumb is a decent order of magnitude approximation, but the cost variability is enormous. Alternatively, one pipeline expert estimated that pipeline construction requires $40-60 thousand per inch-mile, but may reach as high as one million per mile in residential areas regardless of diameter.

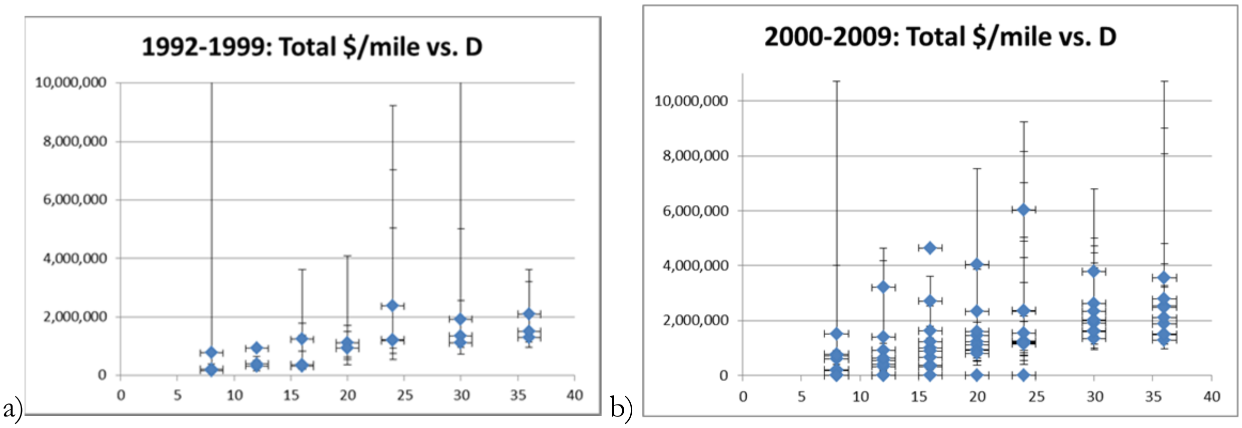


Figure 59. Pipeline Construction Costs[60] for (a) 1992-1999 (data adapted from (True 2001)) and (b) 2000-2009 (data adapted from (Smith 2009)).

Furthermore, the proportion of costs from the four major expense categories also varies tremendously and is not well correlated with pipeline diameter, with labor typically leading with 40-50%, miscellaneous and materials each contributing 15-35%, and right of way costs generally 10% or less. Figure 60 shows the variation and poor correlation between each of these costs and total construction costs, suggesting that a defensible economic analysis can really only be done on a case by case basis.

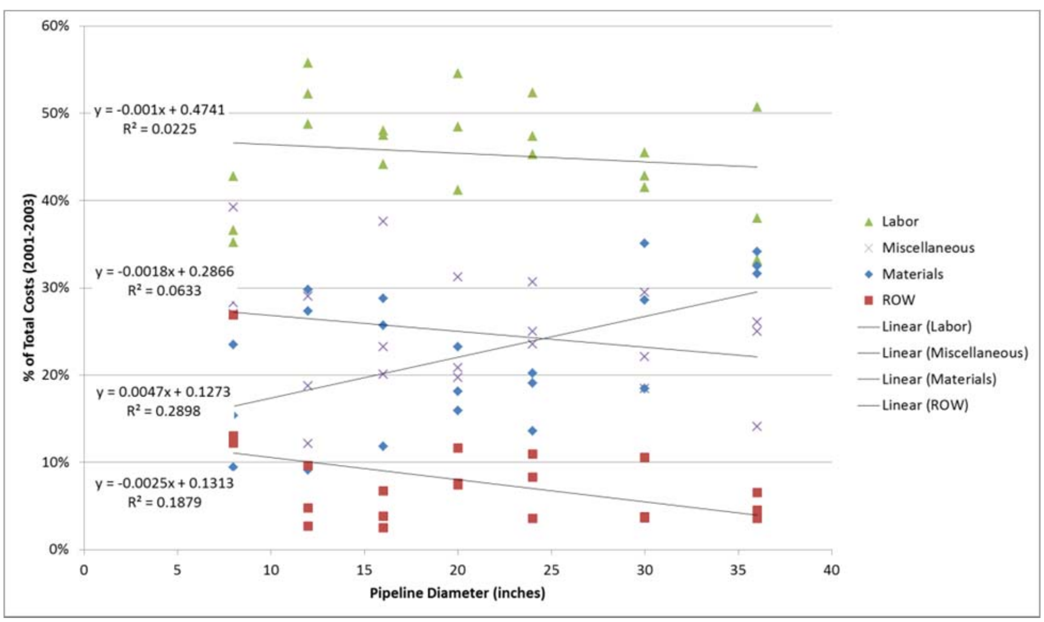


Figure 60. Average Share of Expense Categories in US Pipeline Construction Costs from 2001-2003 (data adapted from (Smith 2009)).

[60] Data were compiled from FERC Form 6 reports, and error bars show low and high values reported for the year, not standard deviation.

Fortunately, absolute material costs do tend to correlate more strongly with diameter than any of the other major expense categories (i.e., labor, right of way, and miscellaneous), as can be seen in Figure 61. This result will be useful for estimating emissions from steel production, which the process-based NACAP report showed is the dominant contributor to emissions from initial construction.

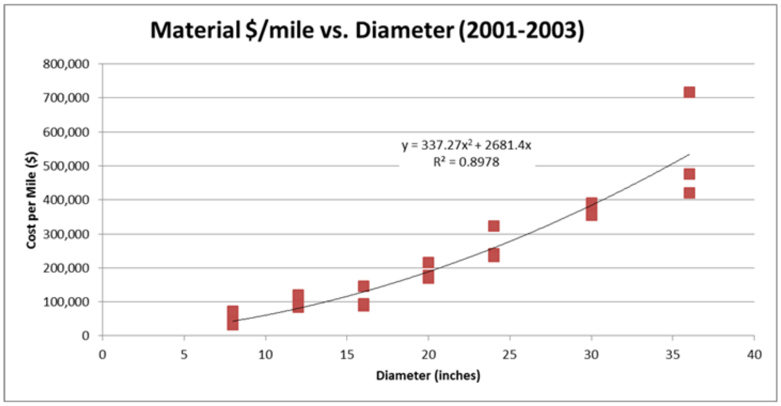
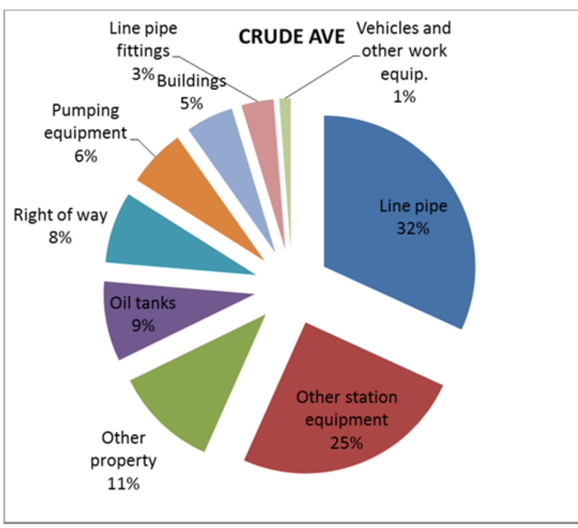


Figure 61. Average Pipeline Material Costs per Mile from 2001-2003 (using data from (Smith 2009))

10.2.1.9.6.1 CAPITAL EXPENSES DATA SOURCES



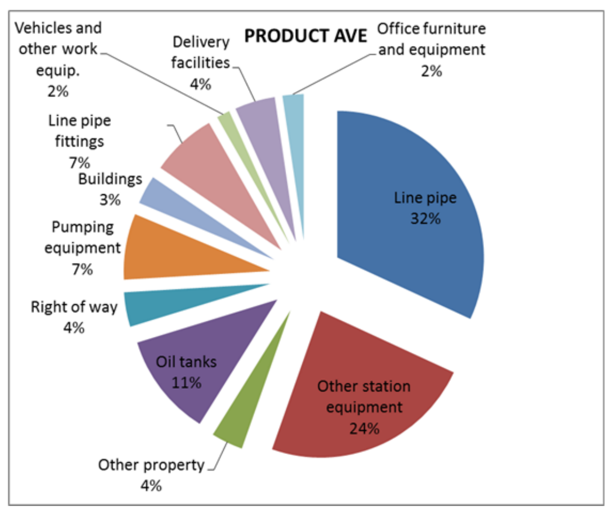
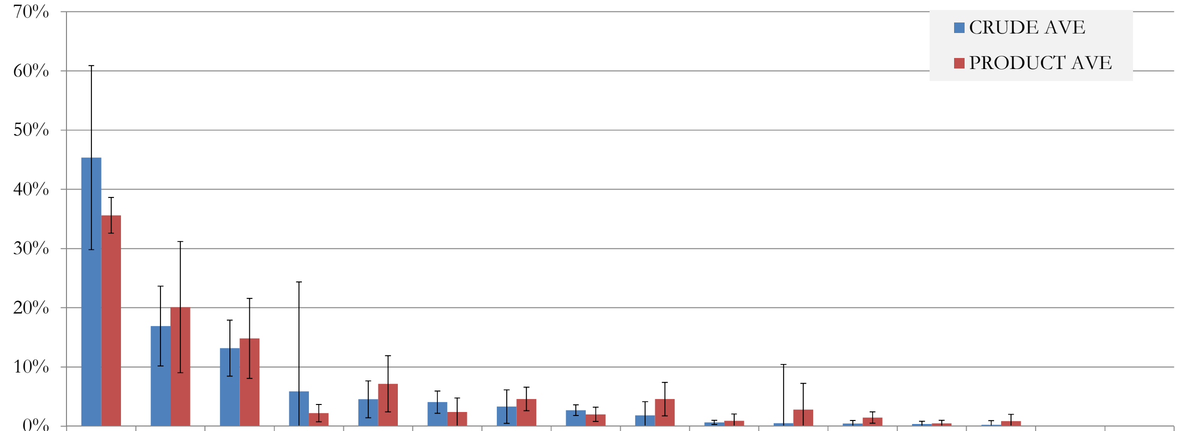


Figure 62. Investments in (a) Crude and (b) Product Pipelines (derived from case studies in (Smith 2009), without construction, truncating expenses less than 1% of the total).



	Pipeline constructi on	Line pipe	Other station equipment	Other property	Oil tanks	Right of way	Pumping equipment	Buildings	Line pipe fittings	Vehicles and other work equip.	Delivery facilities	Office furniture and equipment	Land	Communi cation systems	Boilers	Machine tools and machinery
CRUDE AVE	45.4%	16.9%	13.2%	5.9%	4.6%	4.1%	3.3%	2.7%	1.8%	0.7%	0.5%	0.4%	0.4%	0.2%	0.0%	0.0%
PRODUCT AVE	35.6%	20.1%	14.8%	2.2%	7.2%	2.4%	4.6%	2.0%	4.6%	0.9%	2.8%	1.5%	0.5%	0.9%	0.0%	0.0%

Figure 63. Investments by Five Representative Crude Pipeline and Five Product Pipeline Companies, Totaling $6 Billion[61] in 2008 (data adapted from (Smith 2009)).

The average investment in assets as a fraction of total stock value from 1970-2009 for the entire pipeline industry (natural gas and petroleum) was 6.4%, and has exceeded 8% over the last few years, as can be seen in the Figure 64. Because the total number of pipeline kilometers in the United States has not changed significantly over the last few decades, these investments were interpreted to be steady-state renewal projects, and it was assumed that assets were typically valued at half of what new replacement would cost (so that renewal investments are equivalent to 4%, instead of 8%, of new construction cost).

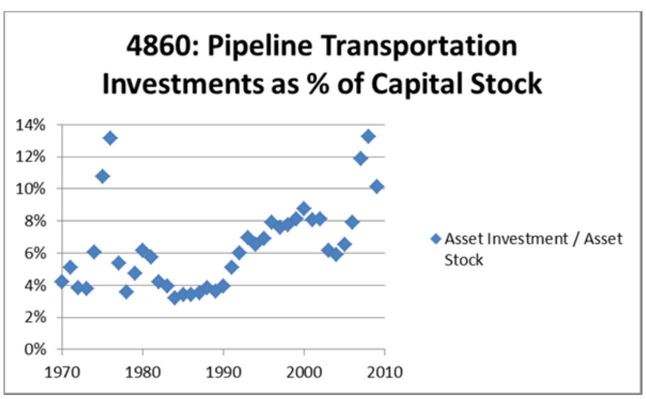


Figure 64. Average Fixed Asset Investment in Proportion to Total Asset Stock Value, 1970-2010 (adapted from (US BEA 2011)).

61 Error bars indicate standard deviation.

10.2.1.9.7 ECONOMIC CHARACTERIZATION – PIPELINE INVESTMENTS

- **Initial Pipeline Construction (2002 dollars):**
  - Total Construction Cost (assumed to be initial asset value) = 49,752*d – 2,504.3 (R^2 = 0.5744) (derived from (Smith 2009) for years 2001-2003). Average asset value is assumed to be 50% of initial construction cost.
    - Crude Average: $501,000/km (estimated by applying equation derived from (Smith 2009) for years 2001-2003 to the 2009 pipeline inventory (US DOT PHMSA 2011)).
      - Average Diameter: 16.2" (by in-km) and 18.3" (by in^2-km)
    - Products (including HVL) Average: $331,000/km (estimated by applying equation derived from (Smith 2009) for years 2001-2003 to the 2009 pipeline inventory (US DOT PHMSA 2011))
      - Average Diameter: 10.7" (by in-km) and 12.4" (by in^2-km)
    - Ethanol (proposed): $1,241,000/km (estimated by applying equation derived from (Smith 2009) for years 2001-2003 to the proposed pipeline as described by the US DOE (US DOE 2010).
      - Diameter (proposed): 25"
  - Total Materials Cost (assumed to be line pipe) = 337.3*d^2 + 2,681*d ($/mile) ($R^2$ = 0.8978) (derived from (Smith 2009) for years 2001-2003)
    - Sector: Iron, steel pipe and tube manufacturing from purchased steel
    - Crude Average: $156,000/km in materials (estimated by applying equation derived from (Smith 2009) for years 2001-2003) to 2009 pipeline inventory (US DOT PHMSA 2011))
    - Products (including HVL) Average: $80,000/km in materials (estimated by applying equation derived from (Smith 2009) for years 2001-2003) to 2009 pipeline inventory (US DOT PHMSA 2011))
    - Ethanol (proposed): $278,000/km in materials (estimated by applying equation derived from (Smith 2009) for years 2001-2003)
  - Right of Way: $70,000/km (average derived from (Smith 2009) for years 2001-2003)
    - Sector: Architectural and engineering services
    - Note: In a review of RS Means estimates for installing natural gas and sewer lines, equipment costs are typically equivalent to 3-8% of material costs, excluding excavation and backfill.
    - Right of Way includes construction of service roads (which is rarely asphalt)

10.2.1.9.7.1 ALTERNATIVE APPROACHES

If BEA statistics were used to categorize fixed asset investments, only 23% would be directed towards pipeline investment, whereas 37% would be directed towards "offices" and more than 20% would be directed towards communications (14%) and software (7%) (US BEA 2011). Because oil pipelines only make up roughly a third of all pipeline revenue, and operating characteristics are quite different for gas in comparison to oil, the average structural and operating material expenses for "pipeline transportation" in the BEA's database are skewed towards natural gas distribution, which is more energy intensive, expensive and requires different equipment than petroleum pipelines (e.g., compressors and refrigeration). For this reason, the fixed asset investment categories shown in Figure 65 were not used in this analysis, in favor of financial data reported from the petroleum industry to the US government.

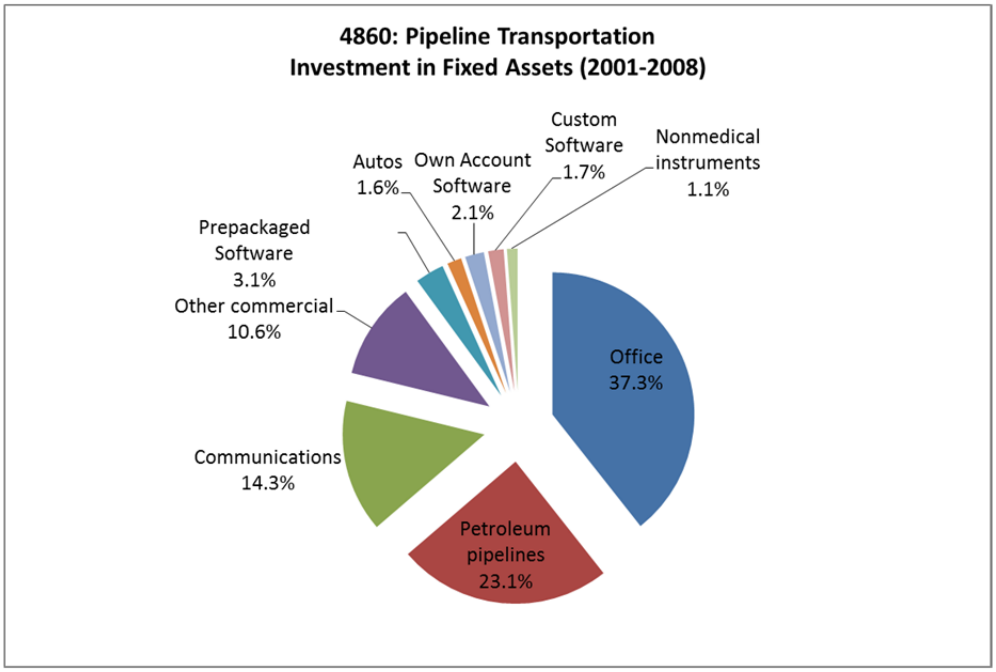


Figure 65. Average Composition of US Investments in Fixed Assets for Pipeline Transportation, 2001-2008 (data adapted from (US BEA 2011)).

10.2.1.9.8 ECONOMIC CHARACTERIZATION – RENEWAL

- **Investments Excluding Initial Construction (equivalent to 4% of initial construction or asset value per year).** Note: Ethanol pipelines are assumed to have cost ratios similar to products.
    - Line Pipe (and Pipe Fittings)
        - Sector: Iron, steel pipe and tube manufacturing from purchased steel
        - Crude: 35% (derived from data on 5 representative companies reported by (Smith 2009))
        - Products: 39% (derived from data on 5 representative companies reported by (Smith 2009))
        - Rule of thumb: 32% (Rabinow 2004)
    - Pumps, Station, Work and Other Equipment
        - Sector: Pump and pumping equipment manufacturing
        - Crude: 32% (derived from data on 5 representative companies reported by (Smith 2009))

        - Products: 35% (derived from data on 5 representative companies reported by (Smith 2009))
        - Rule of thumb: 26% (Rabinow 2004)
    - Break-out Tanks
        - Sector: Metal tank, heavy gauge, manufacturing
        - Crude: 9% (derived from data on 5 representative companies reported by (Smith 2009))
        - Products: 11% (derived from data on 5 representative companies reported by (Smith 2009))
        - Rule of thumb: 8% (Rabinow 2004)
    - All Other
        - Land Management (other property and right of way)
            - Sector: Architectural and engineering services
            - Crude: 19% (derived from data on 5 representative companies reported by (Smith 2009))
            - Products: 8% (derived from data on 5 representative companies reported by (Smith 2009))
        - Facilities (buildings and delivery facilities)
            - Sector: Other nonresidential structures
            - Crude: 5% (derived from data on 5 representative companies reported by (Smith 2009))
            - Products: 7% (derived from data on 5 representative companies reported by (Smith 2009))
        - Rule of thumb: 34% (Rabinow 2004)

10.2.1.9.9 ECONOMIC CHARACTERIZATION – MAINTENANCE

Although energy consumption makes up a significant 21% portion of operating expenses (discussed in a separate section on energy intensity), a non-trivial 9% of operating expenses are dedicated to supplies and expenses (Rabinow 2004) presented in Figure 66. A similar estimate would be reached by interpreting national average economic data for both oil and gas pipelines (assuming that the ratio of material expenditures to total revenues is similar); intermediate material inputs for the entire pipeline transportation sector were reported as 11% of gross output in 2002 (and around 10% for the following years) (US Census Bureau 2011b). Service and miscellaneous expenses (as presented by Rabinow and BEA statistics) were ignored, so total material expenses were estimated to average $0.001/t-km (assuming that revenue per ton-mile was $0.0133 in 2002 (US DOT BTS 2010)). Categorization of these supplies was influenced by BEA statistics, as shown in Figure 67, ignoring components that would be specific to natural gas pipelines (e.g., refrigeration equipment).

Although structural metal products make up a large portion of intermediate material inputs, this is not believed to entail double counting of investments into pipes, structures, and other infrastructure. According to BEA, private fixed asset investments includes only assets that are "used repeatedly or continuously in the production process—that is, in the production of other goods (including other fixed assets) or of services—for more than 1 year," whereas intermediate inputs are "consume(d) in producing its gross output" (US BEA 2011). The estimated list of intermediate inputs below can be considered "supplies" or "all other," as defined by Rabinow.

Total O&M Material Inputs: $0.001/t-km

Pipe and structural steel component replacement

- Cost: 46% (architectural and structural metal products + other fabricated metal products)
- Sector: Plate work and fabricated structural product manufacturing

Trade

- Cost: 33% (wholesale trade + retail trade + truck transportation)
- Sector: Wholesale Trade

Plastic and rubber products (gaskets, seals, etc.).

- Cost: 8%
- Sector: Plastics packaging materials, film and sheet

Hand tools

- Cost: 6% Cutlery and hand tools
- Sector: Power-driven handtool manufacturing

Paper products

- Cost: 7% (converted paper products + pulp, paper, and paperboard)
- Sector: Paper mills

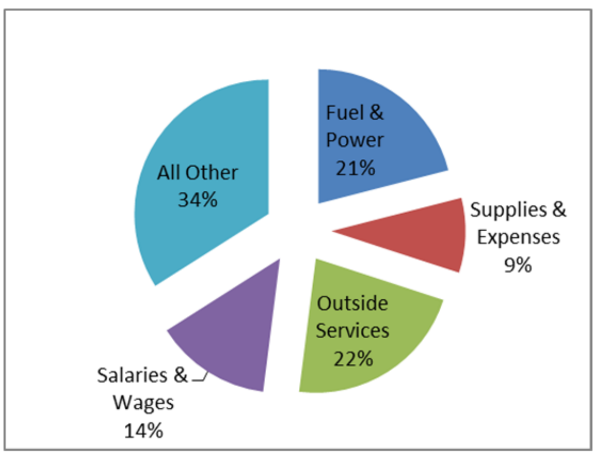


Figure 66. Composition of Operating Expenses for Oil Pipelines (data adapted from (Rabinow 2004), citing AOPL).

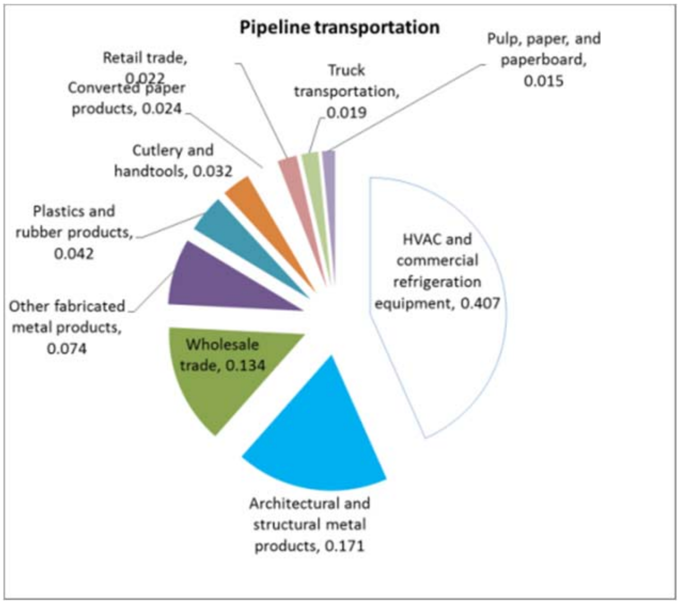


Figure 67. Intermediate Material Inputs for All Pipeline Transportation, 2002 (using data from (US BEA 2011)).

10.2.1.9.10 ALTERNATIVE APPROACHES: PROCESS-BASED ANALYSIS

In order to determine if results from the EIO-LCA-based analysis match up with existing studies or a process-based approach, alternative assessment approaches were reviewed.

10.2.1.9.10.1 NACAP STUDY

The "cradle to gate" greenhouse gas footprint of constructing pipelines was reported for oil and gas pipelines issued by Netherlands-based NACAP (Nazary and Griffioen 2010), which covered the five aspects of pipe manufacturing and installation listed below.

1. ***OVERHEAD***: *Facilities, Flights, Cars*
2. ***EQUIPMENT***: *Earth Moving Equipment, Heavy Lifting Equipment, Pipeline Equipment, Transport Equipment, Other Equipment*
3. ***WELDING CONSUMABLES AND PIPE COATING***: *Coating, Electrodes*
4. ***STEEL PIPE PRODUCTION***: *Blast Furnace, Continuous Casting. Rolling and Pipe Production*
5. ***TRANSPORTATION***: *Pipe Transport, Equipment Transport*

The NACAP analysis showed that the main contributor to total emissions from construction and installation of large pipelines was the production of steel (primarily the blast furnace process),[62] as

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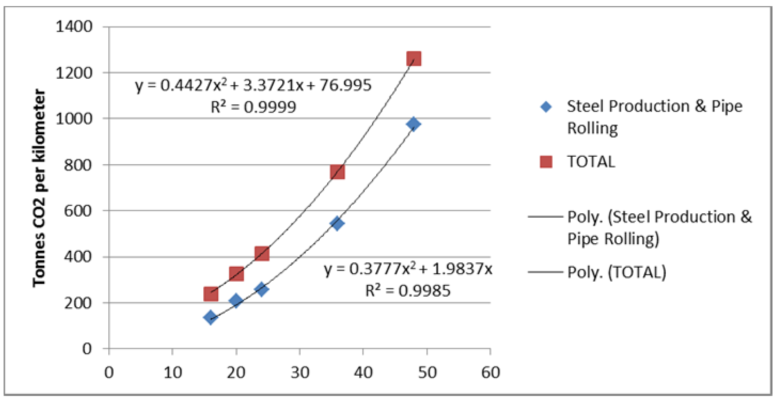
[62] "Steel for pipes is created through the blast furnace route and consists of carbon manganese steel (this steel contains between 1% to 1.8 % manganese in order to increase depth and improve strength and hardness). The reduction of iron ore to hot metal in blast furnace and other reduction processes is almost entirely based on coal products; therefore the steel industry emits large amounts of carbon dioxide" (Nazary and Griffioen 2010).

the total emissions ranged from 1.3-1.8 times the emissions from the steel production alone, assuming an average of 1.55 kg CO_2 per kg of steel (though emissions range from 1.5 in Europe, 1.6 globally, to 1.8 in China) (Nazary and Griffioen 2010). The relationship between emissions for each stage of construction and the diameter of pipe was established through linear regression of the data shown in Figure 68, though overhead expenses were assumed by NACAP to be fixed for each km of pipeline independent of diameter. It is also important to note that NACAP focused on large-diameter pipelines, and steel production dominated emissions, but it is expected that at small diameters, equipment and materials transportation will play a more significant role. Figure 50 shows an inventory of pipelines in the United States, and it can be seen that 73% of US pipeline km have a NPS of 14" or smaller, so NACAP's results are of limited applicability.

a) 

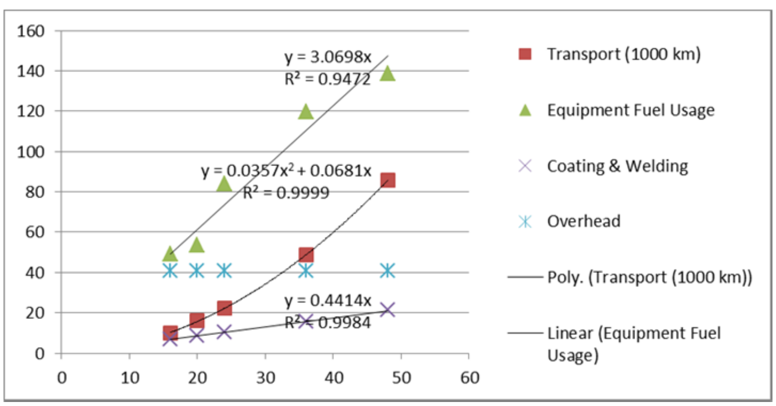
b) 

Figure 68. Embodied Carbon Dioxide Emissions from Petroleum and Gas Pipelines in 2008 from (a) Steel Production and Total Emissions, and (b) All Other Construction Stage Activities (adapted from (Nazary and Griffioen 2010)).

10.2.1.9.10.2 STEEL-CENTRIC PROCESS-BASED ANALYSIS SUMMARY

According to the WorldSteel Association, the global average emission factor for welded pipe steel is 1.3 kg CO_2/kg steel (WorldSteel 2010), which is less than the NACAP study assumed, but higher than would be estimated using the Ecoinvent commercial database (i.e., less than 0.6 kg CO_2-f/kg for several types of steel (Ecoinvent 2010)).

If existing pipelines were all constructed according to the standard thickness prescribed by ANSI Schedule 40 (which may be more or less representative for a given decade) as shown in Figure 69, approximately 31 million tonnes of steel would be dedicated to crude, highly volatile liquids (HVL), and product pipelines as inventoried in (US DOT PHMSA 2011)) (approximately 110 tonnes of steel per km on average), which would translate to approximately 40-55 million tonnes of embodied CO_2 or 150-200 tonnes of CO_2/km if applying the WorldSteel emission factor.

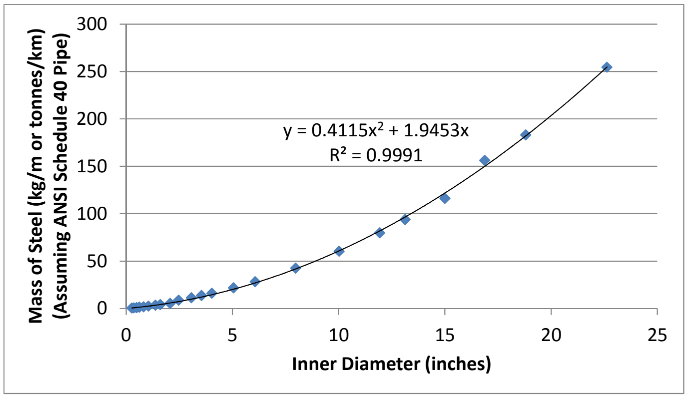


Figure 69. Relationship between Pipeline Diameter and Steel Mass (data adapted from (Engineering Toolbox 2011)).

After steel production, the next most significant contributor to emissions was equipment fuel usage, primarily equipment dedicated to earth moving, according to the NACAP study (Nazary and Griffioen 2010). If one assumed that that all pipelines are buried 2m below ground level, have a 2m flat trench bottom, and are excavated with a 1:1 slope on the sides, approximately 8m^3 of soil would be excavated per meter of pipeline (or 8,000 m^3/km). If applying the emission factor of approximately 0.5 kg CO_2f/ m^3 (Ecoinvent 2010), the estimated excavation emissions would be less than 10% of the equipment fuel demands as estimated by NACAP for most diameter pipelines. In order to remain conservative and relying on a more comprehensive industry report, the NACAP numbers are trusted more than these limited process-based estimates.

10.2.1.9.11 DISCUSSION

If NACAPs numbers were applied to the US average on-shore pipeline, emissions from initial construction would be approximately 300 tonnes of CO_2/km (mostly from steel production), which is just more than half of the life-cycle emissions reported by Ecoinvent for the typical European pipeline. In the Ecoinvent database, two types of pipeline modules are available: offshore and onshore. Both modules were created using emissions data from 1992 for a single (global) company, and the diversity of emissions for pipelines of different diameter is clearly acknowledged in the metadata (Ecoinvent 2010). The life-cycle emissions reported by Ecoinvent (including production, construction and dismantling) for each kilometer was 498 tonnes CO_2-f/km for onshore oil pipelines (with an unspecified lifespan), and 1072 tonnes CO_2-f/km for offshore pipelines with a lifespan of 30 years (Ecoinvent 2010); this estimate was based on materials data from 1980 and environmental data from 2000, and does not provide typical specifications for European pipelines (other than mentioning that the EU has 30,780 km of oil pipelines).

To put these emissions in perspective, the immediate replacement of all steel contained in US pipelines would result in the emissions (40-55 million tonnes of embodied CO_2) of less than 3% of annual CO_2e emissions (1.8 billion tonnes) from petroleum used in the US transportation sector (US EIA 2011b), and total construction emissions (if the NACAP report is representative of United States construction practices) or "life-cycle" emissions reported by Ecoinvent, would likely be 5% or less.

According to my estimates for the initial construction (and life-cycle non-operation stage emissions) of pipelines, the embodied emissions for pipelines would be 175 (550) tonnes per km for product pipelines (50 year lifespan), 330 (1,000) tonnes for crude pipelines (50 year lifespan), and 580 (1,700) tonnes for a hypothetical 25" (ethanol) pipeline (40 year lifespan). These emission factors were expected to be higher than the NACAP and Ecoinvent values, due to the inclusion of maintenance and renewal activities. Similar to trucks and ships, the ratio of life-cycle embodied emissions to payload capacity (estimated from empty pipeline volume) is 7-9.5 for the three pipelines considered (and 5.5-8 times the empty mass of each pipeline). Initial construction alone contributed 1.9-2.6 tonnes CO_2 per tonne of steel, or 2.3-3.1 tonnes CO_2 per tonne of pipe capacity.

Smith, Page, and several other authors cited in this paper warn readers that pipeline costs are extremely variable, cannot be estimated simply by their diameter and length, and often deviate significantly (>10%) from the original project cost estimate. Below is a list of a few potential sources of variability in pipeline construction costs that were ignored in this study and most other generalized life-cycle studies.

- The pipeline manufacturing process, energy source, and shipping distance were assumed to be independent of location and year of activity.
- Depending on the safety requirements at the time, existing pipes may have been manufactured with thicker or thinner steel than I predicted by assuming all pipes were manufactured according to ANSI Schedule 40 standards.
- Laying a pipe over difficult terrain (e.g., with many hills and valleys or rocky terrain) can decrease productivity by more than a factor of two (Page 1977). Along the same token, challenging construction conditions (e.g., remote, offshore, or urban locations, harsh climates, rocky or ecologically sensitive terrain) would lead to larger carbon footprints than would be estimated using average industry data.

10.2.2 Fuel Conversion Facilities

10.2.2.1 PETROLEUM REFINERIES

10.2.2.1.1 PURPOSE/ BACKGROUND

Petroleum refineries convert crude petroleum oil into finished products. The US has almost 150 refineries (141 currently operating), and the capacity of refineries is typically expressed in annual average barrels per calendar day (BPCD). BPCD accounts for necessary turnaround times when refineries are shut down for maintenance, so utilization will be expressed by dividing actual barrels per day (BPD) by BPCD, instead of the maximum daily production rate which is defined as barrels per stream day (BPSD). The US has almost 18 million BPCD in refining capacity.

No new petroleum refineries have been constructed for decades in the United States, but a great deal of capital is still invested into the existing refineries to maintain and improve performance.

10.2.2.1.2 SPECIFICATIONS

The average output of refineries consists of 46% gasoline, and more than 80% of outputs are liquid fuels (US EIA 2011a). Although refineries are diverse in terms of physical configuration, types of crude input handled, and ratio of products produced, the scaling unit employed in this model will be 1,000 BPCD of average US refining capacity.

10.2.2.1.3 OPERATIONAL CONSIDERATIONS

Operating inputs to refineries (e.g., steam, power, and hydrogen) have been studied in detail by researchers at NETL and Argonne National Laboratory (US DOE ANL 2010; US DOE NETL 2008), so this study focused on characterizing capital investments in constructing, renewal and maintenance of US refineries.

10.2.2.1.4 OPERATIONAL ENERGY

Operational (direct and indirect) energy-intensive activities, for inputs such as power, steam, hydrogen and catalyst production, were not included in this analysis.

10.2.2.1.5 TURNOVER

To be consistent with other components considered in this study, an arbitrary lifespan of 50 years was assumed. The US has not built any new refineries recently, and petroleum refining has remained relatively constant over the last decade, so expenses are assumed to occur at a relatively steady-state.

10.2.2.1.6 ECONOMIC BACKGROUND - REFINERIES

According to the 2008 World Energy Outlook issued by the International Energy Agency (IEA), the bulk of oil infrastructure investments from years 2007-2030 are expected to take place in exploration and development (E&D) (80%) and refining (16%) (OECD/IEA 2008), as oil demand is expected to continue increasing over the next few decades. Capital and exploratory expenditures for major worldwide petroleum companies has ranged from \$60-\$300 billion per year from 2001-2008 (US Census Bureau 2011a). Figure 70 shows global refinery investments divided into capital, maintenance, and chemical expenditures; it can be seen that refinery capital investments are comparable to maintenance expenses.

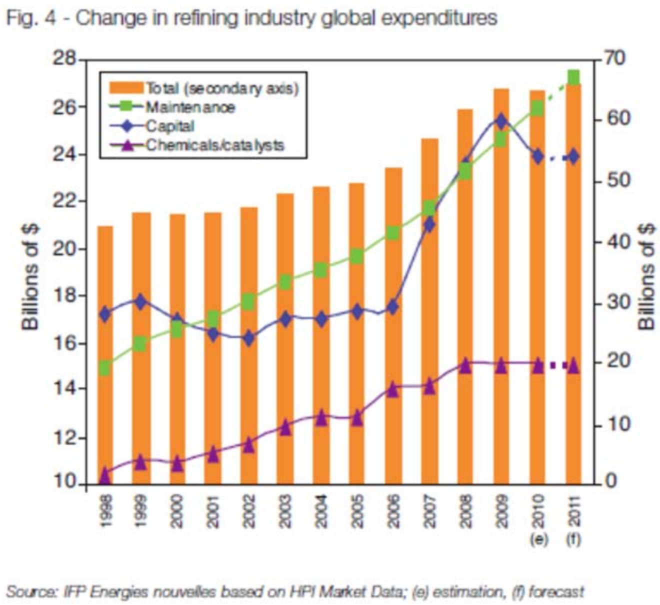


Figure 70. Global Refining Industry Expenditures, 1998-2011 (reproduced from (Silva 2010)).

In the United States, where oil demand has been growing more slowly than the rest of the world, maintenance expenses have been exceeding capital investments. Refining capital projects were estimated at \$2.7 billion in 2006 and \$4.4 billion in 2011, and maintenance projects were estimated at \$5.2 billion in 2006 and \$6.5 billion in 2011, according to the HPI Market Data (Hydrocarbon Processing 2006, 2011). 50% of refining investments, and 40% of maintenance investments, are assumed to be directed towards equipment and materials (as was typical in HPI's reports for global expenditures), and the nature of equipment and material purchases for refinery capital and maintenance projects are assumed to be in similar proportions to those reported for the entire hydrocarbon processing industry, as shown in Figure 71. If allocated to the number of tonnes of oil received by refineries in each year, approximately \$0.61/bbl and \$0.91/bbl was spent on equipment in materials in 2006 and 2011, respectively. The 2006 numbers will be used for the analysis (\$4.20/tonne of throughput).

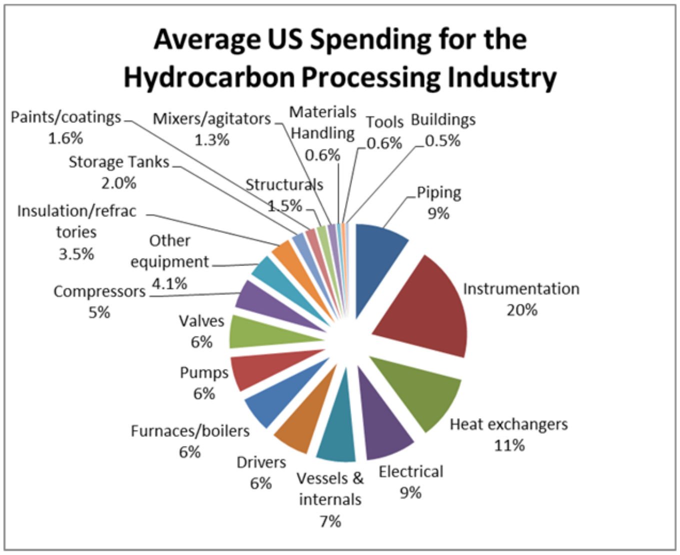


Figure 71. Average US Hydrocarbon Processing Industry (HPI) Spending on Equipment and Materials for the Years 2006 (Total Spending $8.3 Billion) and 2011 (Total Spending $4.8 Billion) (data adapted from (Hydrocarbon Processing 2011)).

10.2.2.1.7 ECONOMIC CHARACTERIZATION – REFINERIES

Refineries are conservatively estimated to cost $25,000/bpd (though other reports, especially in other countries, estimate refineries to cost as low as $9,000/bpd). Using the Chemical Engineering Plant Construction Index (Vatavuk 2002), it was assumed that 50.65% of this conservatively high expense was directed towards equipment and materials (which is also consistent with the numbers reported by HPI), or $12,663/bpd in capacity. Additionally, post-construction capital and maintenance investments for US refineries were estimated at $0.6125/bbl of throughput in 2006 (which could be translated to an annual working capital budget of 1.5% of the initial construction cost, or a lifetime repair factor of 0.77).

Pumps and equipment

- Cost: 29% of total capital and maintenance expenditures (6% drivers, 6% pumps, 6% valves, 5% compressors, 4.1% other equipment, 1.3% mixers/agitators, 0.6% tools)
- Sector: Pump and pumping equipment manufacturing

Piping and heat exchangers

- Cost: 20% of total capital and maintenance expenditures (11% heat exchangers, 9% piping)
- Sector: Iron, steel pipe and tube manufacturing from purchased steel

Instrumentation

- Cost: 20% of total capital and maintenance expenditures
- Sector: Industrial process variable instruments

Vessels, tanks and structural steel

- Cost: 17% of total capital and maintenance expenditures (7% vessels and internals, 6% furnaces/boilers, 2% storage tanks, 1.5% structural, 0.5% buildings)
- Sector: Metal tank, heavy gauge, manufacturing

Electrical equipment

- Cost: 9% of total capital and maintenance expenditures
- Sector: Electricity and signal testing instruments

Insulation, refractories, paints and coatings

- Cost: 5.1% of total capital and maintenance expenditures (3.5% insulation/refractories + 1.6% paints/coatings)
- Sector: Paint and coating manufacturing

10.2.2.1.7.1 ALTERNATIVE APPROACHES

According to BEA's statistics shown in Figure 72, the Petroleum and Coal Products sector (3240) invests an average of 8.75% of capital asset value back into fixed assets each year (as summarized in Figure 73). Within this sector, the "dominant process is petroleum refining that involves the separation of crude petroleum into component products through such techniques as cracking and distillation" (US Census Bureau 2011b), but data and expense categorization for this sector (Figure 73) was not specific enough to petroleum, so data from the Hydrocarbon Processing Industry Market Outlook reports were used instead.

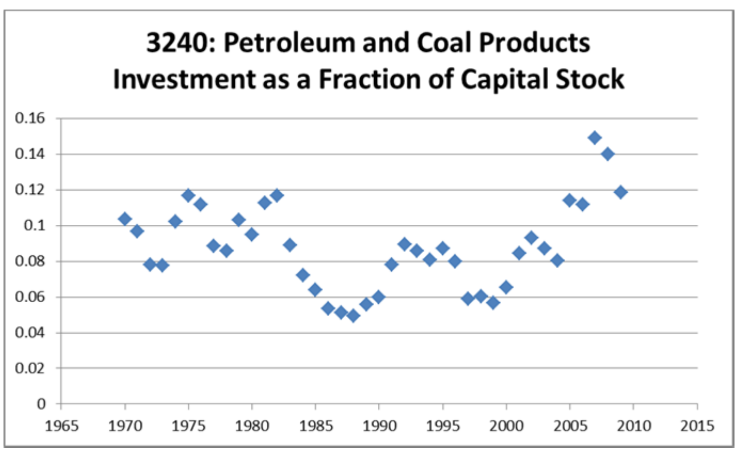


Figure 72. Fixed Asset Investment as a Fraction of Asset Stock Value, 1970-2010 (data adapted from (US BEA 2011)).

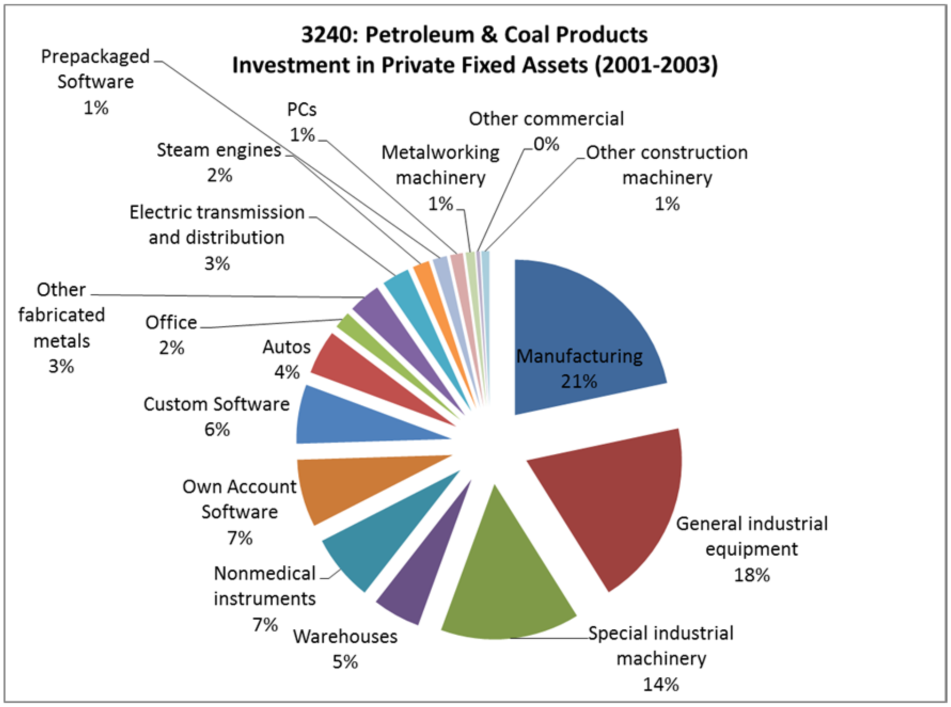


Figure 73. Average Composition of Fixed Asset Investments for the Petroleum and Coal Products Sector, 2001-2003 (adapted from (US BEA 2011))

10.2.2.1.8 DISCUSSION

The Ecoinvent database has a "refinery" infrastructure module that includes use of materials for equipment and land use for refinery chemical processing in Europe, though no data are included for construction, storage facilities and office buildings; embodied refinery emissions were reported as 11.8 kg of CO_2-f for every tonne in annual refining capacity (assumed to last 30 years) (Ecoinvent 2010), which translates to approximately 590 kg per BPCD capacity or 0.4 kg per tonne of crude oil throughput. Recent refinery project press releases suggest that 200-350 kg of steel, 0.8-1.2 cubic yards of concrete, and many other materials are needed for each BPCD in refinery expansion, which would suggest that refinery projects in the United States would have a higher carbon footprint than would be found in the Ecoinvent module. Results from my model (20 tonnes per BPCD of capacity lasting 50 years, which translates to 8.7 kg CO_2 per tonne of crude oil throughput) are more than 20 times greater than Ecoinvent, which is at least partially due to the limited treatment of maintenance and refinery upgrades in the module.

10.2.2.2 2nd GENERATION BIOREFINERIES

10.2.2.2.1 PURPOSE/BACKGROUND

Industrial facilities that convert biomass into a liquid transportation fuel are referred to as "biorefineries" throughout this study. Until now, the dominant types of biorefineries in the world have been sugar-to-ethanol plants (which dominate in Brazil) and corn-to-ethanol plants (which dominate in the United States). Although other conversion technologies exist and do operate (e.g., vegetable oil to biodiesel), these types of technologies are not expected to increase in scale to the extent that ethanol production will.

Over the last several years, many publications have claimed and attempted to quantify the degree to which demand for biofuel production derived from food crops (e.g., sugar cane, corn) increases global food prices, and causes a perverse incentive for biofuel developers to use a) existing (limited) productive agricultural land, or b) clear ecologically sensitive lands (e.g., rainforests). In order to avoid these problems, second generation (or "advanced") biofuel technologies are being explored, with the goal of converting low-input high-productivity lignocellulosic biomass feedstocks into ethanol. (Third generation biofuels will convert such feedstocks into butanol, alkanes, or other molecules that more closely resemble petroleum fuels than ethanol).

10.2.2.2.2 SPECIFICATIONS

The main functional (for easy scaling) was assumed to be 1,000 barrels per calendar day of capacity. In 2011, NREL released a report titled "Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover," which is assumed to contain the most applicable assumptions on costs and equipment for lignocellulosic (Miscanthus) feedstock conversion to ethanol.

10.2.2.2.3 OPERATIONAL CONSIDERATIONS

A yield of 79 gallons (236 kg) of ethanol and 1.8kWh/gal ethanol is expected for every dry US ton of biomass feedstock (Humbird et al. 2011). Assuming Miscanthus bales have an energy density of 19,400 MJ/dry tonne, 0.358 MJ of ethanol and 0.029 MJ of electricity will be produced for every MJ of feedstock entering the facility.

10.2.2.2.4 OPERATIONAL ENERGY

Operational (direct and indirect) energy-intensive activities are not included in this analysis.

10.2.2.2.5 TURNOVER

The plant life for ligno-cellulosic biorefineries is assumed to be 30 years (Humbird et al. 2011), while petroleum refineries were assumed to last for 50 years.

10.2.2.2.6 ECONOMIC CHARACTERIZATION – BIOREFINERIES

The capital investment required for biorefineries was estimated to be \$6.92/annual gallon. Of the total capital cost, \$3.80 (55%) is directed towards installed equipment, which is close to the 50.7% that would be estimated by using the CEPCI. This estimate is higher than most corn-based facilities (approximately \$2/gal (T. West et al. 2009)) but lower than the \$10/gal rule of thumb for ligno-cellulosic biorefineries (which BP has invested into the CP1 plant in Florida). Previous estimates for cellulosic biorefineries estimate \$6/annual gallon of capital costs, with a target of \$4/gallon (Randle 2010).

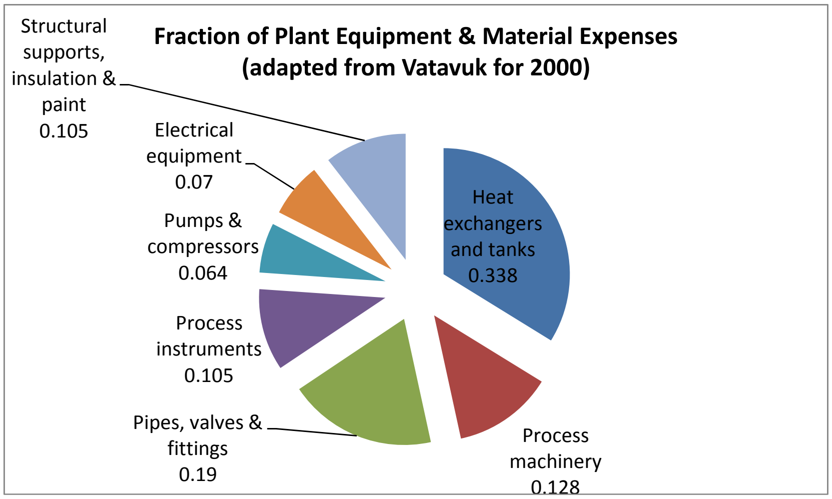


Figure 74. Plant Equipment and Material Expense Categorization in the Year 2000 (adapted from (Vatavuk 2002)).

Equipment expenses were assumed to follow the typical categorization as reported by the CEPCI (Vatavuk 2002). After initial construction is complete, 5% of the fixed capital investment is assumed to be the annual "working capital" (Humbird et al. 2011), which will be referred to as maintenance or upgrading expenses. The proportion of equipment expenses is assumed to remain constant throughout the lifetime of a biorefinery, as is described below.

Heat exchangers and tanks

- Cost: 34% of total capital and maintenance expenditures
- Sector: Metal tank, heavy gauge, manufacturing

Process machinery

- Cost: 12.8% of total capital and maintenance expenditures
- Sector: Other industrial machinery manufacturing

Process machinery

- Cost: 12.8% of total capital and maintenance expenditures
- Sector: Other industrial machinery manufacturing

Pipes, valves and fittings

- Cost: 19% of total capital and maintenance expenditures
- Sector: Iron, steel pipe and tube manufacturing from purchased steel

Process instruments and controls

- Cost: 18% of total capital and maintenance expenditures (10.5% process instruments, 7% electrical equipment)
- Sector: Industrial process variable instruments

Pumps and compressors

- Cost: 6.4% of total capital and maintenance expenditures
- Sector: Pump and pumping equipment manufacturing

Structural supports, insulation and paint

- Cost: 6.4% of total capital and maintenance expenditures
- Sector: Other nonresidential structures

10.2.2.2.7 DISCUSSION

The Ecoinvent database has an "ethanol fermentation plant" infrastructure module, which includes transformation and occupation of land, materials, energy uses, emissions and dismantling for a wheat-based US facility with an annual production capacity of 90,000 tonnes of ethanol and a lifespan of 20 years. Fossil CO_2 emissions were reported as 4,300 tonnes for the unit (48 kg of CO_2 per tonne of annual ethanol production capacity or 2,400 kg CO_2 per BPCD. These results suggest that embodied emission for ethanol production were 4-fold higher than those of petroleum on a capacity basis (e.g., kg CO_2 per BPCD), and 6-fold higher on a throughput-normalized basis (e.g., kg CO_2 per tonne of refined product).

Recent biorefinery project press releases (e.g., Abengoa) suggest that approximately 300-600 kg of steel, 4 cubic yards of concrete, and many other materials are needed for each BPCD in biorefinery construction (approximately double those for petroleum refineries), so the embodied emissions were expected to be at least double those for petroleum refineries.

For comparison, results from my ligno-cellulosic biorefinery module (121 tonnes CO_2 per BPCD, which translates to 98 kg per tonne of ethanol produced) are more than 30 times Ecoinvent's values for a first generation ethanol facility, but it is important to note that second generation facilities will be more expensive and materials-intensive than first generation facilities. Nonetheless, embodied emissions for ethanol production were found in my model to be 6-fold higher than petroleum refining on a capacity basis and 11-fold higher on a throughput basis (also due to a shorter expected lifespan for ethanol facilities), so general comparisons between ethanol and petroleum facilities should be similar whether using results from my model or from Ecoinvent (on a relative basis).

10.2.3 Storage and Dispensing Tanks

Throughout the fuel supply chain, a large fleet of storage facilities supports the inventory and distribution of petroleum fuels in the US. In addition to privately owned storage tanks, the US DOE Office of Petroleum Reserves manages the Strategic Petroleum Reserve (SPR) in addition to a few other fuel storage facilities,[63] which consists of underground salt caverns storing approximately 727 million barrels of crude. The SPR was established after the oil embargo in the 1970s, and was directed by the 2005 Energy Policy Act to begin expanding to enable storage of one billion barrels. Between the government owned SPR and industrial storage facilities, the US is required by the International Energy Agency (IEA) to store 90 days' worth of imported oil (Shackouls et al. 2004). Because the US imports the majority of our crude petroleum, but refines more than 90% of our petroleum products at various locations throughout the country, the US has prioritized storing crude petroleum for security purposes (Shackouls et al. 2004).

The SPR has contained approximately 700 billion barrels of oil since 2004 (but held less than 100 billion barrels prior to 1980); whereas all other large privately owned storage facilities (i.e., those considered in this study) have held roughly one trillion barrels over the same timeframe (US EIA 2010b). Table 64 shows an inventory of 2009 crude petroleum and petroleum products stocks in the United States.

Location	US Volume (million bbl)	US Volume (million gal)
Crude Oil at Tank Farms and in Pipelines	212	8,904
Oil at Refineries	331	13,902
Products in Bulk Terminals (excluding ethanol)	364	15,288
Ethanol in Bulk Terminals	16	672
Products in Pipelines	115.5	4,851
TOTAL	1,038.50	43,617

Table 64. Non-SPR Petroleum Stocks in 2009 (data from (US EIA 2010b)).

10.2.3.1 FLEET INVENTORY

An inventory of aboveground storage tanks (ASTs) in the United States was completed by the American Petroleum Institute (API) in 1989. In 1996, the US EPA prepared a "Liner Study," for which they simplified the results of the API survey into six classes of facilities that house one or more of nine typical (horizontal or vertical) aboveground tanks (US EPA 1996), as shown in Figure 75. In addition to ASTs, underground storage tanks (USTs) are extremely common in the US for fuel storage at commercial and government facilities. Under EPA's most recent count, there are

[63] In addition to the SPR, the DOE owns the 2-million barrel Northeast Home Heating Oil Reserve which was created in 2000 (US DOE OFE 2010). The Department of the Interior and DOE each own parts of the Naval Petroleum and Oil Shale Reserves, though the storage capacity is not known nor considered to be significant for this study.

almost 600,000 USTs at 215,000 facilities (US EPA 2010f), and almost all of these are used for petroleum fuels (US EPA 2010c). Since the EPA's UST program was established in 1984, the number of (reportable) USTs has drastically decreased by almost 1.8 million tanks, due to the decommissioning and remediation of many UST sites (US DOT BTS 2010). A summary of the simplified inventory of ASTs and USTs used in the current study can be found in Table 65 and Table 66.

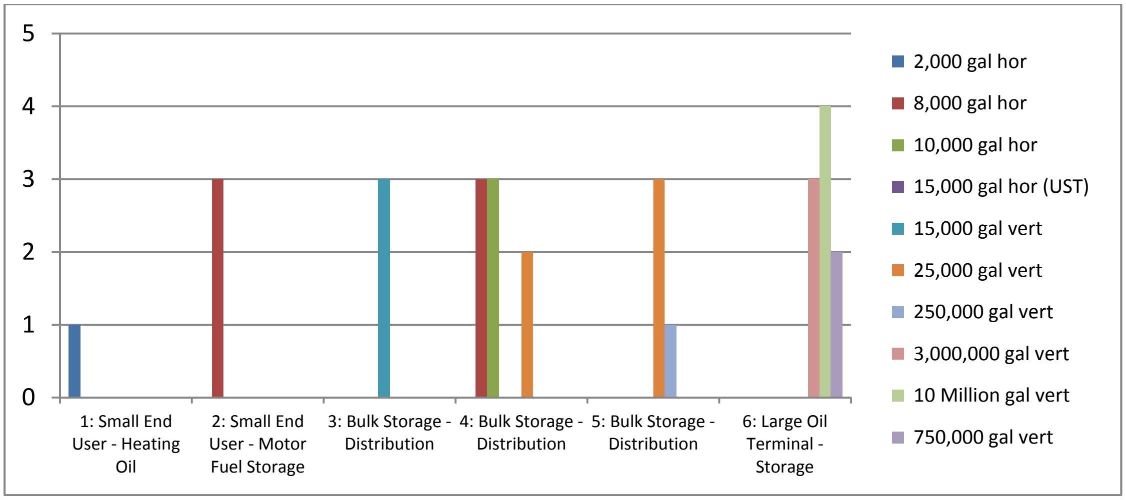


Figure 75. Number of Characteristic Aboveground Storage Tanks within the EPA's Six Model Fuel Storage Facilities (data from (US EPA 1996)).

AST Facility Type	Model Facility Description (dedicated to oil and products)	Facility Capacity (gal)	Number of Facilities	Gallons Capacity in this Category	Total Tanks in this Category
1	Small End User - Heating Oil	2,000	201,427	402,854,000	201,427
2	Small End User - Motor Fuel Storage	24,000	49,296	1,183,104,000	147,888
3	Bulk Storage - Distribution	45,000	97,277	4,377,465,000	291,831
4	Bulk Storage - Distribution	104,000	55,623	5,784,792,000	444,984
5	Bulk Storage - Distribution	325,000	13,663	4,440,475,000	54,652
6	Large Oil Term - Storage	50,500,000	3,927	198,313,500,000	35,343
	TOTAL		421,213	214,502,190,000	1,176,125

Table 65. United States Aboveground Storage Tank (AST) Inventory (adapted from (US EPA 1996)).

UST Facility Type	Model Facility Description (assuming all USTs are dedicated to fuel)	Facility Capacity (gal)	Number of Facilities	Gallons Capacity in this Category	Total Tanks in this Category
A	Service Station	45,000	156,383	7,037,235,000	469,149
B	Other UST Facility (Government, Military, Commercial)	32,802	58,617	1,922,760,000	128,184
	TOTAL		215,000	8,959,995,000	597,333

Table 66. United States Underground Storage Tank (UST) Inventory (adapted from (US EPA 1986) and (US EPA 2010c)).

10.2.3.2 OPERATIONAL CONSIDERATIONS

The amount of current storage tank capacity is difficult to estimate, as there is not a direct relationship between oil stocks nor oil throughput and volumetric storage capacity. Even the most comprehensive online terminal tank directory (TankTerminals.com 2011) only captures a fraction of in-service petroleum storage tanks. Storage tanks serve as a financial and security buffer for supply fluctuations, and are critical for efficiently receiving and distributing oil through the supply chain (which became challenging in 2011 at the Cushing terminal, for example). For these reasons, the outdated, but thorough, inventories performed by API and EPA surveys were assumed to be relevant and informative to this study.

In 1996, the ratio of petroleum products supplied to petroleum stocks was 7.1 (estimated using data from EIA), though this ratio went from a low of 4.7 in 1981 to a high of 7.8 in 2004. The volume of non-SPR stocks has remained remarkably constant (averaging 42 billion gallons) since 1981, so the amount and characteristics of storage tanks are assumed to have remained similar. In reality, the amount of storage capacity has likely increased due to the increased output and consumption of petroleum products, decreased flexibility of supply due to higher utilization (typically over 90%) of existing refineries, and increased regional and seasonal variability in fuel formulation regulations.

Assuming non-pipeline non-SPR stocks are held among the 3,000+ facilities that fit the EPA Liner Study description of *Large Oil Terminals* (which is twice the IRS's inventory of motor fuel terminals), and that the number of storage tanks has not changed significantly in 14 years, 39 billion gallons of fuel are held at facilities capable of storing almost 200 billion gallons (or 66% of annual throughput of crude oil consumed in the US in 2009). As a result, it is believed that just less than 20% of the nation's bulk fuel storage capacity is occupied on average throughout the year.

In existing reports that estimate the infrastructure needs for ethanol (e.g., (Reynolds 2002a)), the storage tank needs were estimated by assuming each tank is filled and emptied 24-36 times per year. In a conversation with a transportation area director in Brazil, two general rules of thumb were mentioned: chemical terminal tanks "rotate" 6 to 12 times per year, and commodities tanks "rotate" from 10 to 24 times per year (though many tanks exist with lower utilization values). Tank utilization assumptions were considered in estimating the divergent paths of petroleum products through blending and dispensing tanks, as summarized in Table 67. Because I assumed most tanks are used in parallel (when they may actually be in series), Table 67 may underestimate the actual number of fill-empty cycles for many tanks.

	Crude Petroleum		**Petroleum Products**		**Miscanthus-based Ethanol**	
	Fraction Handled by this Tank Model	*Average Number of Annual Fill-Empty Cycles*	*Fraction Handled by this Tank Model*	*Average Number of Annual Fill-Empty Cycles*	*Fraction Handled by this Tank Model*	*Average Number of Annual Fill-Empty Cycles*
E85 (Dispensing) UST					1	10
Small (Dispensing) AST			0.13	6		
Retail (Dispensing) UST			0.37	6		
Commercial (Dispensing) AST			0.23	6		
Mid-Size (Blending) AST			0.27	6	1	6
Large (Storage) AST	1	1.6	1	2.6	1	2.6

Table 67. Assumed Utilization of Various Tank Configurations for Fuel Products (i.e., default values used in modeling efforts).

10.2.3.3 OPERATIONAL ENERGY AND MASS LOSSES

Operational energy consumption and emissions result from fuel delivery vehicle emissions from idling and/or powering pumps. Although electricity is used to power pumps that are used to fill delivery vehicles, my calculations showed that this energy requirement is negligible in comparison to energy used by the actual vehicles, and even lighting fuel service stations (though no estimate was made for fuel terminal lighting requirements).

Additionally, fuel losses (mainly fugitive emissions) were estimated using conservatively high values described in Appendix H of (US DOE NETL 2008), and all lost fuel was assumed to eventually oxidize to CO_2. Similar evaporative losses were reported specifically for ethanol (Table 3.3-7) and petroleum (Table 3.1-20) of (US EPA 2010d), and never exceeded $1/1{,}000^{th}$ of the products handled. As the same module for storage tanks was used for petroleum products and ethanol, one (albeit insignificant) shortcoming in this approach is that ethanol–gasoline blends tend to have similar evaporative losses, and that losses also oxidized to fossil CO_2 (though CO_2 from biomass-based ethanol should not be considered a greenhouse gas). In reality, ethanol evaporative losses will be greater than conventional gasoline at low-level blends, and would probably be lower than conventional gasoline for high-level blends (due to differences in volatility).

10.2.3.4 LARGE ABOVEGROUND STORAGE TANKS (ASTs)

10.2.3.4.1 PURPOSE/ BACKGROUND

Large ASTs are assumed to be used for the following purposes:

- Storing 100% of crude petroleum prior to refining.
- Storing 100% of refined petroleum product immediately after refining.
- Storing 100% of ethanol immediately after conversion.

10.2.3.4.2 SPECIFICATIONS

Large storage tanks are assumed to be 3-10 million gallons (US EPA 1996), or even larger.

Unit (for scaling): Million gallons of storage capacity

10.2.3.4.3 OPERATIONAL CONSIDERATIONS

Large ASTs are assumed to rotate 6 times per year, and have a fuel loss factor of 0.0009 for products and 0.0028 for crude (adapted from (US DOE NETL 2008)), which accounts for all losses from the transportation stage preceding the tank.

10.2.3.4.4 OPERATIONAL ENERGY

As fuel delivery vehicles idle and transfer fuel to storage tanks, approximately 0.01% as much fuel as is delivered is assumed to be combusted by the delivery vehicle, or approximately 4,330 kJ/tonne of fuel.

10.2.3.4.5 TURNOVER

All fuel tanks and associated equipment are assumed to last for 25 years.

10.2.3.4.6 ECONOMIC CHARACTERIZATION

Storage Tank

- Cost: $0.24/gallon in 2000 (adapted for tanks larger than one million gallons (Reynolds 2002a))
- Sector: Metal tank, heavy gauge, manufacturing

Pipes, valves and fittings

- Cost: 5% of initial tank cost
- Sector: Iron, steel pipe and tube manufacturing from purchased steel

Controls, level and leak detection sensors

- Cost: 5% of initial tank cost
- Sector: Relay and industrial control manufacturing

Plastic liner

- Cost: 5% of initial tank cost (though higher estimates would be found on (US EPA 1996))
- Sector: Plastics packaging materials, film and sheet

Tank supports, stairs, offices

- Cost: 5% of initial tank cost
- Sector: Other nonresidential structures

Concrete foundation

- Cost: 3% of initial tank cost
    - Note: At $6/CF (adapted from (State of Michigan 2003)), and assuming a 12-inch foundation for most tanks, concrete material was estimated to cost approximately 3% of steel cost for large tanks.
- Sector: Ready-mix concrete manufacturing

10.2.3.5 MID-SIZE ASTs

10.2.3.5.1 PURPOSE/ BACKGROUND

Mid-size ASTs are assumed to be used for the following purposes:

- Handling 27% of refined products (e.g., gasoline for blending) after first being transported from product storage tanks at a refinery.
- Handling 100% of ethanol (e.g., for blending with gasoline) after first being transported from storage tanks at a biorefinery.

10.2.3.5.2 SPECIFICATIONS

The universe of ASTs considered "mid-size" includes all 250,000 and 750,000 gallon ASTs listed in (US EPA 1996). For the purposes of this report, ethanol tanks (assumed to be 20 mbbl or 840,000 gallons by (Reynolds 2002a)) are assumed to have a similar footprint as the 750,000 gallon tanks. Ethanol tanks are conservatively assumed to be built new, implying that petroleum demand will remain constant, consisting primarily of a steel tank, small foundation, and a pump. However, converting an existing petroleum tank is far cheaper (~80% cheaper than large storage tanks (Reynolds 2002a). The mass of steel used is assumed to be 0.59 tonnes per 1,000 gallons of storage capacity.

Unit for scaling: 1 million gallons

10.2.3.5.3 OPERATIONAL CONSIDERATIONS

Mid-size ASTs are assumed to rotate 6 times per year, and have a fuel loss factor of 0.0006 (adapted from (US DOE NETL 2008)).

10.2.3.5.4 OPERATIONAL ENERGY

As fuel delivery vehicles idle and transfer fuel to storage tanks, approximately 0.01% as much fuel as is delivered is assumed to be combusted by the delivery vehicle, or approximately 4,330 kJ/tonne of fuel. It should also be noted that the frequency of deliveries to (and therefore emissions at) storage facilities has likely been reduced over time, due to improvements in tank monitoring and logistics tools that enable "just-in-time" fuel delivery (Glass et al. 2011), in comparison to higher frequency of deliveries that would have resulted from "keep it full" type programs popular in the past.

10.2.3.5.5 TURNOVER

All fuel tanks and associated equipment are assumed to last for 25 years.

10.2.3.5.6 ECONOMIC CHARACTERIZATION

Storage Tank

- Cost: $0.33/gallon in 1998 (volume-weighted average using cost estimates from (Loh et al. 2002) and US tank inventory estimate from (US EPA 1996))
- Sector: Metal tank, heavy gauge, manufacturing

All other supplemental material and equipment costs were estimated using the same scaling factors as large ASTs.

10.2.3.5.7 DISCUSSION

A common concern with ethanol is that many new product terminals will require new tanks, rail spurs, blending equipment, and other retrofits. In a conservative case, a terminal may need to invest $355,000 in rail spurs and $300,000 in blending equipment, and a typical terminal (as analyzed by Reynolds) might hold 250,000 barrels (approximately 10 million gallons), so these costs end up being less than the 5% conservative estimate used in constructing petroleum product tanks. However, converting currently existing tankage was estimated to cost only 20% of the cost of installing new tanks, which would include floating internal covers, piping changes, etc. (Reynolds 2002a).

10.2.3.6 RETAIL STATION STORAGE TANKS OVERVIEW (USTs and ASTs)

10.2.3.6.1 PURPOSE/ BACKGROUND

Retail or Service Station USTs and ASTs are assumed to be used for the following purposes:

- Handling 60% of refined products (primarily gasoline and diesel).
- Handling 100% of ethanol that has been blended with gasoline.

Underground storage tanks are the most common tanks used for dispensing liquid fuels to the end user, in particular motor fuels sold at service stations and fleet fueling locations, though some stations (e.g., in areas with high water tables) will use Aboveground Storage Tanks (ASTs).

In the United States, the number of gasoline retail stations has declined quite steadily from 190,000 in 1996 to 159,000 in 2010 (Reid 2010; US DOE AFDC 2010a); this decline is presumably due to higher costs from new regulations on tank protection. Since the 1984 inception of the UST program (which banned unprotected tanks and pipes), 1.75 million USTs have been closed, and just over 80% of the roughly 500,000 leak sites have also been cleaned up (US EPA 2010c).

When this model was created, the United States had approximately 162,350 service stations nationwide (US DOE AFDC 2010a) which typically have three USTs for petroleum fuels (US EPA 1986), though 6,000 of these retail stations are assumed to have 3 ASTs and no USTs (in order to conserve the number of tanks as presented in the EPA Liner Study). By the end of 2010, approximately 2,500 stations in the United States sold E85 (E85 Vehicles 2011). All UST-containing facilities were simplified by assuming the capacity of each tank is 25,000 gallons, and after accounting for retail stations, the remaining 58,617 facilities are assumed to contain 2.2 USTs each (which is consistent with (US EPA 1986)). A summary of the simplified inventory of USTs can be found in Table 66.

10.2.3.6.2 SPECIFICATIONS

The universe of ASTs captured in this analysis includes all 10,000 and 25,000 vertical ASTs listed in (US EPA 1996). The universe of USTs captured in this analysis includes all USTs listed by the EPA, with the assumption that the average UST has a storage capacity of 25,000.

Retail station tanks will be equipped with a pump and dispenser to move and measure fuel sold to customers, as well as a (lighted) canopy to minimize the extent to which rainfall washes spilled fuel into storm drains. A typical service station has 3 storage tanks and 4 fuel dispenser stations (12 nozzles) was also assumed to have pumps and metering equipment for 12 nozzles (Horvath 2000).

Storage tanks are assumed to be steel, glass-reinforced plastic is now commonly used in conjunction with steel. Since 2000, most tanks are GRP-Steel-GRP, and tanks have also been increasing in size, such that most new USTs installed can hold 30,000 gallons according to one industry representative. The mass of steel used is assumed to be 0.39 tonnes per 1,000 gallons of storage capacity for USTs, and 0.25 tonnes for ASTs.

10.2.3.6.3 OPERATIONAL CONSIDERATIONS

In a recent survey, most retail stations sold between 0.5-3.0 million gallons of fuel each year, and had between 2-16 fueling positions per site (Reid 2010); on average retail stations sell 1.6 million gallons and have 6.8 fueling positions, for an average of 240,000 gallons sold per year per fueling position.

It is important to also note variability in the activity level at retail stations due to seasonal changes and brand loyalty. Some stations may sell 25,000 gallons (approximately one tank's worth) over the winter, and sell 180,000 gallons in the summer – and nearly 75% of fuel transactions are driven by brand loyalty (Warren 2005). Another source estimated that the typical retail station in PADD I sells 744,000 gallons per year of gasoline, and that a station selling E85 could expect to sell up to 180,000 gallons of E85 per year (Reynolds 2002a). However, another source mentioned that E85 tanks may sell as few as 45,000 gallons per year in a conservative case, and more than 100,000 gallons per year in a modest growth case (Tyner et al. 2010); E85 USTs are assumed to have a volume of only 4,000 gallons, which would imply just over 11 rotation cycles per year.

The rule of thumb used for this study (6 fill-empty cycles per year) implies 150,000 gallons are sold annually from each gasoline or diesel tank. E85 tanks, however, are assumed to only sell 80,000 gallons per year, implying 20 cycles per year. Additionally, retail tanks are assumed to have a fuel loss fraction of 0.0009 (adapted from (US DOE NETL 2008)), almost all of which results from gasoline losses because gasoline is much more volatile than diesel and kerosene.

10.2.3.6.4 OPERATIONAL ENERGY

When fuel is delivered to retail stations by truck, trucks are assumed to turn off due to flammable vapors safety concerns, and USTs are typically gravity fed from the tank of a truck (without needing an auxiliary power supply). Assuming that dispensing gasoline into vehicles requires 0.00125 kWh per gallon of gasoline or diesel dispensed (US DOE NETL 2008), and that gasoline's density is 2.8 kg/gallon, this translates to 1,600 kJ/tonne dispensed, which is relatively negligible.

Exterior lighting typically requires 25-30 kW of power for convenience stores that dispense fuel, making up 25-40% of the total electric bill (Ward 2006). Although many of the operating expenses for convenience stores should be allocated to food, beverage, tobacco and shelf item sales, exterior lighting is assumed to be dedicated to fueling stations (under the canopy). The average retail station has 6.8 fueling positions (Reid 2010), so it is estimated that each position has 4 kW of dedicated exterior lighting, which operates just over 10 hours per day.[64] If put into the perspective of storage capacity units for each dispenser, this translates to 40 kWh/day per 39,000 gallons in capacity or 1 kWh/day (1,314 MJ/yr) per 1,000 gallons of capacity. However, this intensity could vary enormously, as one case study on a *7-eleven* with 4 fill-up locations showed 66% reduction in energy expenses, after starting with 0.247 kWh/day (325 MJ/yr) per 1,000 gallons (assuming the station had 3x25,000 gallon tanks). If tanks undergo 6 fill-empty cycles per year, the energy intensity per unit of fuel would be 18,000-73,000 kJ/tonne dispensed, based on the low and high scenarios presented.

As lighting efficiency has undergone drastic improvements over the last few years, a low estimate of 300 MJ/year per 1,000 gallons of storage capacity was used in my analysis for the three types of retail station tanks. Fuel dispensing energy was therefore considered negligible in comparison to lighting energy (which is highly variable), so fuel dispensing has been cut out of this module. Electricity for retail stations is assumed to come from United States average baseload electricity.

10.2.3.6.5 TURNOVER

All retail fuel tanks and associated equipment are assumed to last for 25 years.

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[64] If 40 kWh/d costs $4/day or $5k/year (at roughly 10c/kWh), lighting electricity will cost approximately $0.02 per gallon (assuming an average of 240,000 gallons sold per year per position), which seems reasonable when considering gross margins average $0.12/gallon. For gasoline wholesalers, the average gross margin was $0.12, and net margin $0.08; for retailers, the gross margin was also $0.12, but net margin only $0.06, on a per-gallon basis in 2010 (Reid 2010).

10.2.3.6.6 ECONOMIC CHARACTERIZATION – RETAIL USTs (E85 – 4,000 gallons)

Since gasoline stations rarely have a spare tank, the number of tanks available for conversion to ethanol blends is limited. On the extreme ends, some estimate that tank retrofitting can cost as little as $10,000, while a new UST and pump system for E85 can cost $100,000-200,000 (B. D. Yacobucci and R. D. Schnepf 2007). Commonly reported estimates for the cost of installing a new UST (e.g., for ethanol) typically range from $50,000-$70,000 on average, and EPA estimated that costs reach $122,000 if new dispensing equipment must also be installed (Moriarty et al. 2009). Table 68 shows an itemized list of expenses for installing an E85 tank "from scratch," which was used to guide this analysis.

E85 pump	$19,000
4,000 gal underground storage tank	$11,000
Ballast tank	$500
Piping	$1,200
Other materials	$7,000
Monitoring equipment	$2,000
Signage	$1,000
Permits	$1,500
Labor	$50,000
Paving	$4,500
Electrical	$10,000
Fire suppression	$5,000
Miscellaneous/contingency	$11,270
Total	**$123,970**

Table 68. E85 Installation Costs (data from Gulf Oil LP, cited by (Protec Fuel 2010)).

In addition to tank and dispenser installation costs, the costs of fitting new vehicles with the modification required to operate with higher ethanol blends was also factored into the capital burden of building a successful E85 storage and dispensing tank. Manufacturers must invest a premium in engine parts to distinguish a FFV from a conventional vehicle (though they are partially subsidized to do so by earning credits towards CAFE requirements for every FFV produced, regardless of the FFV's fuel efficiency). This additional expense in equipment is assumed to create a slightly higher environmental burden associated with manufacturing a FFV over a conventional vehicle.

Tank purchase

- Cost: $11,500 ($11,000 UST, $500 ballast) in 2010 (adapted from (Protec Fuel 2010))
- Sector: Metal tank, heavy gauge, manufacturing

Fuel pump and dispenser

- Cost: $19,000 in 2010 (Protec Fuel 2010)
- Sector: Industrial process variable instruments

Electrical and monitoring equipment

- Cost: $12,000 ($2,000 monitoring equipment, $10,000 electrical equipment) (adapted from (Protec Fuel 2010))
- Sector: Relay and industrial control manufacturing

Paving materials

- Cost: $1,500 (assuming asphalt is one third of the $4,500 pavement cost) in 2010 (adapted from (Protec Fuel 2010)
- Sector: Asphalt paving mixture and block manufacturing

Fire suppression, signage, piping, and other materials

- Cost: $4,733 (assuming metal is the dominant material in these components, and that the cost of materials is on average one third of final costs: $5,000, $1,000, $1,200, and $7,000 respectively) in 2010 (adapted from (Protec Fuel 2010)
- Sector: Other fabricated metal manufacturing

Flex-fuel vehicle (FFV) modification

- Cost: $18.33 per tonne of throughput (not storage capacity), or $8.18/gal UST capacity ($33,000 for this 4,000 tank), assuming a tank life of 25 years while operating at 10 fill-empty cycles per year.
    - $100-$200 in 2009 (Anderson and Sallee 2009) beyond the standard cost of manufacturing a vehicle; $200 was used in this analysis. An optimistic case was used, assuming that every FFV is on average consuming 1 gallon of E85 per day for 10 years (11 tonnes of throughput), which is enough to travel 6,500 miles per year (65,000 lifetime miles) in a vehicle rated at 25 mpgge. For reference, the EPA projects that FFVs will utilize E85 40% of the time according to (Tyner et al. 2010).
- Sector: Motor vehicle parts manufacturing

10.2.3.6.7 ECONOMIC CHARACTERIZATION – RETAIL USTs (Petroleum Products – 25,000 gallons)

Below are the typical costs of installing various components of retail fuel tanks and dispensers for petroleum products, such as gasoline and diesel. Although the typical fuel tank is assumed to hold 25,000 gallons, most costs are expressed in terms of per gallon of tank holding capacity, to enable easier scaling.

Tank purchase

- Cost: $0.57/gallon of holding capacity in 2011(estimated from (Matches 2003))
- Sector: Metal tank, heavy gauge, manufacturing

Fuel pump and dispenser

- Cost: $1.01/gallon of holding capacity in 2011(assuming $19,000 per dispenser (Protec Fuel 2010), 1.3 dispensers per tank, and 25,000 gallons per tank)
- Sector: Industrial process variable instruments

Electrical and monitoring equipment

- See UST (E85)
- Note: One report estimated that a $4,000 leak detection system is installed per UST in 2003 (State of Michigan 2003)

Paving materials

- Cost: $3,000 in 2010 (assuming double the asphalt is needed for initial station construction for a 25,000 gallon tank than a 4,000 gallon tank, as estimated by (Protec Fuel 2010))
- Sector: Asphalt paving mixture and block manufacturing

Canopy manufacturing, fire suppression, signage, piping and other materials

- Cost: $0.40/gallon
  - Fire suppression, signage, piping and other materials
    - See UST (E85) section
  - Canopy: $0.27/gallon of holding capacity in 2011 (adapted from conversation with a tank installer from Constellation, assuming a canopy serves 3x25,000 gallon USTs).
    - TFC Canopies are estimated to be mostly steel, cost $20/ft^2, with the cost consisting 50% of structural components, 25% of the deck and gutters (also steel), and 25% facia (aluminum composite).
- Sector: Other fabricated metal manufacturing

10.2.3.6.8 ECONOMIC CHARACTERIZATION – RETAIL ASTs (Petroleum Products – 25,000 gallons)

Use: Fleet fueling stations, or retail stations in a location instead of a UST.

Unit: 1,000 gallons

Typical size: 15,000-25,000

Tank purchase

- Cost: $1.85/gallon of holding capacity in 2000 (estimated from (Matches 2003))
- Sector: Metal tank, heavy gauge, manufacturing

Tank liner

- Cost: $0.20/gallon of holding capacity in 1996 (adapted from (US EPA 1996)
- Sector: Plastics packaging materials, film and sheet

Pump and dispenser

- Cost: $1.01/gallon in 2010 (assuming $20,000 (NACS 2011b) per dispenser, 4 dispensers for a 3-tank station)
- Sector: Industrial process variable instruments

Electrical and monitoring equipment

- See UST section

Canopy manufacturing, fire suppression, signage, piping, and other materials

- Cost: $0.41/gallon
    - Fire suppression, signage, other materials, piping (5,000+1,000+7,000+1,200, respectively) (Protec Fuel 2010)
    - Canopy: $0.27/gallon of holding capacity in 2011(adapted from conversation with a tank installer from Constellation, assuming a canopy serves 3x25,000 gallon USTs).
        - TFC Canopies are estimated to be mostly steel, cost $20/ft^2$, with the cost consisting 50% of structural components, 25% of the deck and gutters (also steel), and 25% fascia (aluminum composite).
- Sector: Other fabricated metal manufacturing
    - Note: This sector has a carbon and water footprint of 839 tonnes CO_2e and 43 thousand liters per $MM, which is in between the 945 and 39 for "Metal tank, heavy gauge, manufacturing" and the 2030 and 56 for "Steel pipe and tube manufacturing from purchased steel."

Concrete foundation

- Cost: 10% of initial tank cost (higher proportion than larger tanks, as some of the concrete is assumed to be used for the driving pad, whereas asphalt was assumed for the UST-containing stations)
- Sector: Ready-mix concrete manufacturing

10.2.3.7 SMALL ASTs

10.2.3.7.1 PURPOSE/ BACKGROUND

Small aboveground storage tanks may be installed at commercial and industrial facilities (e.g., for back-up generators), and consist primarily of a steel tank, small foundation, and a pump. Only 13% of refined products (e.g., home heating oil, diesel for generators) are assumed to be delivered to end-users through a small AST.

10.2.3.7.2 SPECIFICATIONS

Small ASTs consist primarily of a steel tank, small foundation and holding structure, and a pump. The average tank wall thickness was taken to be 0.1875 inches. All ASTs that fell in the 2,000, 8,000 and 10,000 gallon slots estimated by EPA were grouped in this category. The mass of steel used is assumed to be 0.59 tonnes per 1,000 gallons of storage capacity.

10.2.3.7.3 OPERATIONAL CONSIDERATIONS

Small ASTs are assumed to undergo 6 fill-empty cycles (or rotations) per year. Additionally, small tanks are assumed to have a fuel loss fraction of 0.00003 (adapted from (US DOE NETL 2008)), which conservatively assumes kerosene-like emissions from all small tanks. Kerosene losses are expected to be less than 10% of the losses for gasoline, but several times higher than the emissions that would be expected from diesel from (US DOE NETL 2008). However, diesel and fuel oil are expected to be the dominant fuels distributed to small residential and business tanks and would result in even fewer emissions.

10.2.3.7.4 OPERATIONAL ENERGY

As fuel delivery vehicles idle and transfer fuel to storage tanks, approximately 0.01% as much fuel as is delivered is assumed to be combusted by the delivery vehicle, or approximately 4,330 kJ/tonne of fuel.

10.2.3.7.5 TURNOVER

All fuel tanks and associated equipment are assumed to last for 25 years.

10.2.3.7.6 ECONOMIC CHARACTERIZATION

Tank purchase

- Cost: $0.65/gallon of holding capacity (volume-weighted average using cost estimates from (Matches 2003) and US tank inventory estimate from (US EPA 1996))
- Sector: Metal tank, heavy gauge, manufacturing

Tank plastic liner

- Cost: $0.40/gallon in 1996 (adapted from (US EPA 1996))

- Sector: Plastics packaging materials, film and sheet

Pump and piping

- Cost: 10% of tank cost
- Sector: Industrial process variable instruments

Tank supporting structure, fire suppression system, etc.

- Cost: 27% of initial tank cost
- Sector: Other fabricated metal manufacturing

10.2.3.8 ALTERNATIVE APPROACH – PROCESS BASED

In order to estimate the materials requirements and the embodied carbon emission associated with the manufacturing and construction of various sizes of fuel storage tanks, the mass of steel was estimated by regressing data from existing manufacturer websites (see Equation 8 and Equation 9, $R^2 > 0.99$), and estimated quantities of excavated soil, volume of concrete, controls and pumping equipment, and liners were estimated from existing literature (e.g., EPA) or from best guesses after several conversations with industry employees. As construction and manufacturing practices vary by location, time of installation, etc., emission factors created for storage tanks are considered to be rough approximations.

$$M = Mass\ of\ Steel\ (tonnes)$$

$$V = Tank\ Volume\ (m^3)$$

$$V \leq 30{,}000\ gallons\ (113\ m^3):\ M = -0.0005V^2 + 0.1133V$$

Equation 8. Relationship between Tank Volume and Mass of Steel (regressed using tables from (Greer Tank and Welding Inc. 2010)).

$$V > 30{,}000\ gallons\ (113\ m^3):\ M = -8^{-8}V^2 + 0.0215V$$

Equation 9. Relationship between Tank Volume and Mass of Steel (regressed using tables from (Fisher Tank Company 2006)).

In the Ecoinvent database, only two modules exist for storage of petroleum or other chemicals. One module is for small 3,000 L heating oil storage tanks, which is of minor relevance to this study. The other "infrastructure module includes 4 tanks with storage capacity of 4,000 m^3 each," with a total storage capacity of 16,000 m^3, and was generated using estimates "from literature and from pictures and maps of 3 sites for fuel storage" with a 50-year lifespan. According to the authors, "[t]his infrastructure module has a high uncertainty and should only be seen as an approximation of the infrastructure for regional storage of liquid chemical, (and is) based on weak data valid for Switzerland." Included processes are "[m]aterial for construction, transport of material to construction site, no energy use for construction included, dismantling and disposal processes, no contamination assumed for disposal, land use included."

Emission factors from my hybrid EIO (H-EIO), process-based modeling efforts (for construction only), and Ecoinvent module values were normalized by volumetric storage capacity and presented in Figure 76.

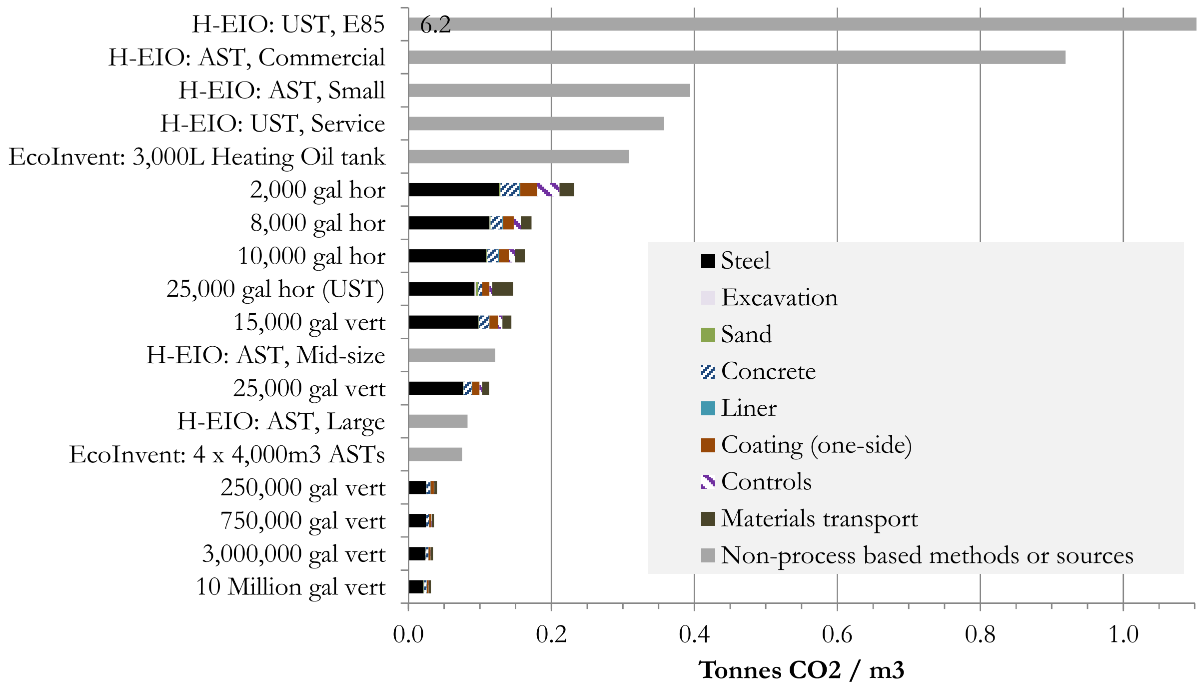

Figure 76. Volume-normalized Embodied Fossil CO_2 Emissions[65] of Fuel Storage Tank Construction.

10.2.3.9 GENERAL DISCUSSION

As can be seen in Figure 76, my process-based approach yielded volume-normalized emission factors that were approximately half of the values generated by Ecoinvent modules or by my hybrid EIO-LCA for most tank sizes considered. Results generated by hybrid EIO-LCA approach were slightly higher than those of Ecoinvent for the large storage tanks and small household-level oil tanks considered. Regardless of the data source considered, if emissions are normalized by tonne of product handled, the embodied emissions from tank manufacturing and installation are nearly negligible for products stored and dispensed from any well utilized tank.

[65] The majority of bars were generated from process-based analysis, using material-specific emission factors from EcoInvent. For comparison, gray bars indicate the value that would be taken from the two EcoInvent modules for storage tanks, and values that were obtained using hybrid economic input-output LCA (indicated by "H-EIO") as described for the current study.

10.2.4 Agricultural Equipment

Unlike petroleum, where the feedstock is typically a liquid material that can be shipped by any mode (typically pipelines), the starting feedstock for the production of ethanol is solid biomass. This biomass (corn, grasses, etc.) is expected to be grown in dedicated agricultural areas. In order to make a fair comparison with the petroleum feedstock (crude) and product (gasoline, diesel, etc.) supply chain, it is important to capture the storage and distribution activities that occur in moving biomass feedstock from the soil to the biorefinery. For this activity, the following characterized activities are assumed to be unique to biofuels (in this study, ethanol).

As mentioned in the methodology, the boundary of analysis for Miscanthus-based ethanol starts after the grass has completed growing in the fall. Several types of equipment are used on the farm to harvest, bale, transport (in the field), stack, store, and load the bales onto flatbed trucks at the farm gate. The majority of assumptions about equipment choice, purchase cost, and operation were taken from the Biofeed Model (Shastri et al. 2010, 2011), which was created for conditions found in Illinois (though general lessons from this case study are expected to apply in other regions). As with the rest of the analysis, costs were converted to 2002 dollars using an inflation rate of 3%, though the actual farm machinery price index fluctuated between 2% and 8% from 2000-2008 ((Turhollow et al. 2009) citing USDA/NASS).

Average maintenance expenses were estimated using tables published by the American Society of Agricultural and Biological Engineers (ASABE 2011)), with the following caveat.

> *Repair and maintenance costs are highly variable and unpredictable as to time of occurrence. Surveys of accumulated repair and maintenance costs related to accumulated use do show consistent trends; however, a standard deviation equal to the mean is a typical variation in these data. Values listed are for machines used under typical field conditions and speeds. These data provide estimates of the average cost for all machines of a given type. The estimate is intended to be within 25% of the actual cost of maintaining most machines in good working order. Some machines may require considerably more or less repair than this estimate. A more complete description of the intended purpose and procedure for use of the data is given in ASAE EP496.*
> Section 6.2 of (ASABE 2011)

10.2.4.1 MOWER 65 hp (attached to tractor)

10.2.4.1.1 PURPOSE/ BACKGROUND

Mowers are used for chopping Miscanthus grass, after in-field senescence drying. Mowers function as an attachment to a tractor.

10.2.4.1.2 SPECIFICATIONS

A typical mower can handle 44.2 tonnes per hour, and has an equipment life of 1,500 hours. In contrast, a typical 200 hp tractor is assumed to have an equipment life of 12,000 hours (ASABE 2011). A single mower-tractor system is assumed to weigh 5 tonnes (similar to the weight of a 200 hp mower (Deere & Company 2011)).

10.2.4.1.3 OPERATIONAL CONSIDERATIONS

Approximately 5% of the dry mass handled by mowers will be lost (Shastri et al. 2010).

10.2.4.1.4 OPERATIONAL ENERGY

A (diesel-powered) mower-tractor assembly is modeled to consume 34,100 kJ/tonne of biomass handled, based on the assumption that mowers require 41.4 liters of diesel per hour (Shastri et al. 2010).

10.2.4.1.5 TURNOVER

Assuming an average equipment life of 2,000 hours, a mower will handle 88,400 tonnes of biomass over the course of one lifespan.

10.2.4.1.6 ECONOMIC CHARACTERIZATION – MANUFACTURING

Mower (65 hp) Manufacturing

- Cost: $17,000 in 2009 (Shastri et al. 2010))
- Sector: Farm machinery and equipment manufacturing

Tractor (225 hp) Manufacturing (only 17% of a tractor lifespan is consumed in one mower lifespan)

- Cost: $98,787 in 2009
- Sector: Farm machinery and equipment manufacturing

10.2.4.1.7 ECONOMIC CHARACTERIZATION – MAINTENANCE

Mower (65 hp) Maintenance

- 150% of initial purchase price (adapted from repair factors for similar equipment (ASABE 2011))
- Sector: Commercial machinery repair and maintenance

Tractor (225 hp) Maintenance

- 100% of initial purchase price (adapted from repair factors for similar equipment (ASABE 2011))
- Sector: Commercial machinery repair and maintenance

10.2.4.2 BALER 120 hp (attached to tractor)

10.2.4.2.1 PURPOSE/ BACKGROUND

Balers are used for converting mowed Miscanthus grass into (round) bales, and function as an attachment to a tractor.

10.2.4.2.2 SPECIFICATIONS

A typical baler can handle 13.2 tonnes per hour, and has an equipment life of 1,500 hours. In contrast, a typical tractor is assumed to have an equipment life of 12,000 hours (ASABE 2011). A single baler is assumed to weigh 5 tonnes (similar to the weight of a 200 hp mower (Deere & Company 2011))

10.2.4.2.3 OPERATIONAL CONSIDERATIONS

Approximately 5% of the dry mass handled by balers will be lost (Shastri et al. 2010).

10.2.4.2.4 OPERATIONAL ENERGY

A (diesel-powered) baler-tractor assembly is modeled to consume 137,000 kJ/tonne of biomass handled, based on the assumption that balers require 49.74 liters of diesel per hour (Shastri et al. 2010).

10.2.4.2.5 TURNOVER

Assuming an average equipment life of 1,500 hours, a baler will handle 19,800 tonnes of biomass over the course of one (baler) lifespan.

10.2.4.2.6 ECONOMIC CHARACTERIZATION – MANUFACTURING

Baler Manufacturing

- Cost: $175,900 in 2009 (Shastri et al. 2010)
- Sector: Farm machinery and equipment manufacturing

Tractor (300 hp) Manufacturing (only 13% of a tractor lifespan is consumed in one baler lifespan)

- Cost: $184,500 in 2009 (estimated by applying the tractor:baler interest cost ratio in 2009 (Shastri et al. 2010))
- Sector: Farm machinery and equipment manufacturing

10.2.4.2.7 ECONOMIC CHARACTERIZATION – MAINTENANCE

Baler Maintenance

- Cost: 90% of initial purchase price (adapted from repair factors for similar equipment (ASABE 2011))
- Sector: Commercial machinery repair and maintenance

Tractor (300 hp) Maintenance

- 100% of initial purchase price (adapted from repair factors for similar equipment (ASABE 2011))

- Sector: Commercial machinery repair and maintenance

10.2.4.3 STINGER (FIELD BALE TRANSPORTER) 350 hp

10.2.4.3.1 PURPOSE/ BACKGROUND

Stingers are used for transporting bales in the field to the storage pad on at the edge of the farm.

10.2.4.3.2 SPECIFICATIONS

Stingers can handle 260 tonnes of biomass per hour (Shastri et al. 2010), with an equipment life of 5,000 hours (over 10 years or so). While not used in the analysis, stingers are expected to weigh approximately 2 tonnes (the listed weight for a John Deere bale carrier (Deere & Company 2011)).

10.2.4.3.3 OPERATIONAL CONSIDERATIONS

Only 0.5% of the dry mass of bales is expected to be lost while bales are being handled by a stinger (Shastri et al. 2010).

10.2.4.3.4 OPERATIONAL ENERGY

A diesel-powered stinger is modeled to consume 8,100 kJ/tonne of biomass handled, based on the assumption that stingers require 57.95 liters of diesel per hour (Shastri et al. 2010).

10.2.4.3.5 TURNOVER

A stinger is assumed to operate for 5,000 hours (over 10 years or so), and will handle 1.3 million tonnes of Miscanthus biomass over the course of its lifespan.

10.2.4.3.6 ECONOMIC CHARACTERIZATION – MANUFACTURING

Stinger Manufacturing

- Cost: $133,186 in 2009 (Shastri et al. 2010))
- Sector: Farm machinery and equipment manufacturing

10.2.4.3.7 ECONOMIC CHARACTERIZATION – MAINTENANCE

Stinger Maintenance

- Cost: 90% of initial purchase price (inferred after reviewing repair factors for other equipment (ASABE 2011))
- Sector: Commercial machinery repair and maintenance

10.2.4.4 TELESCOPIC BALE LOADER 120 hp

10.2.4.4.1 PURPOSE/ BACKGROUND

Bale loaders are used to move bales from the storage pad to flatbed trucks.

10.2.4.4.2 SPECIFICATIONS

Bale loaders are assumed capable of handling 124 tonnes of dry Miscanthus per hour (Shastri et al. 2010).

While not considered in emissions estimation, a typical loader is assumed to weigh approximately 3 tonnes (inferred from reviewing specifications for skid steer loaders (Deere & Company 2011)).

10.2.4.4.3 OPERATIONAL CONSIDERATIONS

Bale loaders may lose up to 5% of the dry mass of the biomass in handling (Shastri et al. 2010).

10.2.4.4.4 OPERATIONAL ENERGY

A diesel-powered telescopic bale loader/unloader is modeled to consume 5,870 kJ/tonne of biomass handled, based on the assumption that bale loaders require 19.86 liters of diesel per hour (Shastri et al. 2010). Note: if a telescopic bale stacker was chosen for this task, approximately 50% more biomass could be handled per unit of diesel input, so this piece of equipment was chosen as a conservative estimate.

10.2.4.4.5 TURNOVER

Bale loaders are assumed to operate for 5,000 hours, handling 620,000 tonnes of material over one lifespan.

10.2.4.4.6 ECONOMIC CHARACTERIZATION – MANUFACTURING

Telescopic Bale Loader Manufacturing

- Cost: $66,511 in 2009 (Shastri et al. 2010))
- Sector: Farm machinery and equipment manufacturing

10.2.4.4.7 ECONOMIC CHARACTERIZATION – MAINTENANCE

Telescopic Bale Loader Maintenance

- Cost: 90% of initial purchase price (inferred after reviewing repair factors for other equipment (ASABE 2011))
- Sector: Commercial machinery repair and maintenance

10.2.4.5 FARM STORAGE PAD

10.2.4.5.1 PURPOSE/ BACKGROUND

Storage pads are designed for holding bales of Miscanthus until being picked up and delivered to a biorefinery. Bales are stored on the farm so that (very capital-intensive) biorefineries, and the associated fleet of feedstock-collecting trucks, can operate almost continuously near maximum capacity year-round, and can purchase feedstock when needed. Essentially, it is cheaper to store feedstock at the farm than to increase storage of feedstock or final product at the biorefinery.

10.2.4.5.2 SPECIFICATIONS

Bales are assumed to stack 2.5m high with a dry weight density of 160 kg/m^3, resulting in an average throughput of 0.40 dry tonnes of Miscanthus/m^2/year.

10.2.4.5.3 OPERATIONAL CONSIDERATIONS

Bales are assumed to lose on average 15% of dry mass content while in storage under a tarp over an asphalt pad; for comparison, bales stored on gravel pads would be expected to lose up to 25% of dry mass (Shastri et al. 2010). Because the harvest season is assumed to be 4 months, half of the asphalt pad can be used twice each year, resulting in an average lifespan throughput of 6 tonnes per m^2).

10.2.4.5.4 TURNOVER

Asphalt is assumed to require replacing or repaving every 10 years. Hay tarps are assumed to require replacing every 5 years.

10.2.4.5.5 ECONOMIC CHARACTERIZATION

Asphalt Pad

- Cost: \$6.13/m^2 in 2010 (assuming asphalt materials constitute 20% of the total construction costs of \$30.64/m^2, as reported by (Shastri et al. 2010))
- Sector: Asphalt paving mixture and block manufacturing

Hay Tarp

- 2 hay tarps per asphalt pad life
- Cost: \$\$2.36/m^2 in 2007 (adapted from (Turhollow et al. 2009), by removing labor costs)
- Sector: Plastics packaging materials, film and sheet

10.2.4.6 GENERAL DISCUSSION

Few published studies were found to estimate the life-cycle emissions of agricultural equipment. The Ecoinvent commercial database groups a few types of agricultural equipment as “tractors,” based on a typical 3-tonne tractor with a useful life of 7,000 hours, and a “repair factor” of 0.74; this database estimates that 5.7 kg of CO_2-f are emitted over the production, maintenance, repair and disposal of each kg of tractor (Ecoinvent 2010). For comparison, the embodied emissions per tonne of equipment that I estimated (albeit crudely) using the hybrid EIO-LCA approach were 10-20 times equipment mass; emissions using this method were expected to be several times greater than Ecoinvent values.

As another point of comparison, the GREET model includes the equipment listed in Table 69 for the corn stover scenario, resulting in 11 kg/dry ton/year of embodied CO_2 (more than half of which is from steel production). The embodied emissions estimated using the hybrid EIO-LCA approach for the Miscanthus scenario were approximately 10 times higher than GREET's values, at approximately 9 kg CO_2-e/dry ton of Miscanthus handled.

	Machinery Weight (ton/farm)	**Weight Share of Steel in Equipment**	**Steel Weight (ton/farm)**	**Tire Weight (ton/farm)**	**Total Accumulated Repair**	**Lifetime (Year)**
Mower/Conditioner	3.4	82.1%	2.8	0.6	92.6%	10.0
Wheel Rake	0.5	82.1%	0.4	0.1	76.0%	10.0
Baler	3.3	82.1%	2.7	0.6	60.7%	10.0
Bale Wagon	4.8	82.1%	3.9	0.9	76.0%	10.0
Telescopic Handlers	5.0	82.1%	4.1	0.9	60.7%	12.0
Small Tractor 95 hp	5.9	82.1%	4.9	1.1	89.1%	15.0
Large Tractor 190 hp	9.8	82.1%	8.1	1.8	89.1%	15.0

Table 69. List of Agricultural Equipment Defined in the GREET Corn Stover Scenario (US DOE ANL 2010).

10.2.5 Passenger Vehicles

10.2.5.1 PURPOSE/ BACKGROUND

Motor fuel must be retrieved by operators of motor vehicles, so this errand is included in the analysis of the energy and emissions costs of distributing transportation fuels. Approximately 40% of petroleum products are delivered to their final destination by freight delivery mode, and 60% is dispensed through private or commercially active service stations from a UST (37%) or AST (23%), as described in the previous section.

The current US fleet of motor vehicles is capable of operating with 10% ethanol blended into gasoline (E10), and an increasing number of flex-fuel vehicles (FFVs) are being manufactured with the capability of operating with blends as high as 85% ethanol (E85).

Whether or not retail stations start selling mid-level ethanol blends (i.e., greater than E10), it will become necessary for a significant percent of the US vehicle fleet to be capable of operating with, and frequently purchasing, higher level blends such as E85. The premium expense of manufacturing flex-fuel vehicles was allocated to the E85 storage and dispensing system, whereas this module covers only the refueling errands of vehicle operators

10.2.5.2 SPECIFICATIONS

A typical vehicle is assumed to weigh 2 tonnes, with a fuel tank that holds 15 gallons. At 2.95 and 2.80 kg/gal (E85 and gasoline), fuel tanks are assumed to hold a maximum of just over 40 kg of fuel. A typical refueling errand is assumed to include the purchase of 10 gallons of fuel.

10.2.5.3 OPERATIONAL CONSIDERATIONS

In this analysis, it is simply assumed that E85 and conventional gasoline will combust with equivalent efficiency on an energy-basis. However, it may be possible for ethanol–gasoline blends to produce greater working energy output (per unit energy of input) than conventional gasoline in modified engines (Szklo et al. 2007), and E85 was found in a limited study to combust up to 3.5% more efficiently than conventional gasoline in FFVs (Schulz et al. 2011). Another (less controlled) study found that E85 had 26.5% worse mileage (per gallon) than standard gasoline, which is the expected result if the standard gasoline control contained 10% ethanol and the E85 fuel actually contained a full 85% ethanol (neither of which is likely to be completely accurate), and first law combustion efficiency is constant (Edmunds and Reed 2007).

When operating with E85, FFVs will need to refuel their gasoline tank more frequently than if they were operating on conventional gasoline, due to the lower volumetric energy density of ethanol. Although consumers are highly heterogeneous, it's been estimated that 6.2% of flexible non-work trips (with an average trip distance of approximately 15km) are dedicated to purchasing gas (McGuckin et al. 2010). Without more detailed national statistics, vehicle drivers are assumed to dedicate 1 mile of every 300 miles to visiting a retail stations and returning to their originally scheduled driving route. FFV drivers are assumed to dedicate one mile in every 213 miles to this errand, due to the lower volumetric energy density of E85 in comparison to gasoline. Because retail stations selling E85 are much less common than retail stations selling gasoline, it is also likely that FFV operators that purchase E85 drive a further distance to refuel their vehicle on average, in comparison to the average vehicle operator. This assumption seems reasonable, as 79% of consumers list brand or price as the most important factor when deciding where to buy gasoline, whereas only 19% listed the location of the station (NACS 2011a).

Results from a survey conducted by the National Association of Convenience Stores (NACS), as shown in Figure 77, was used to determine the range of likely errand distances. The questions used in this survey (listed below) pertain to whether consumers would take a given action if they know gasoline is $0.03 per gallon cheaper at a facility 10 minutes away.

Q1: Take a left hand turn across a busy street?

Q2: Drive 10 minutes out of your way?

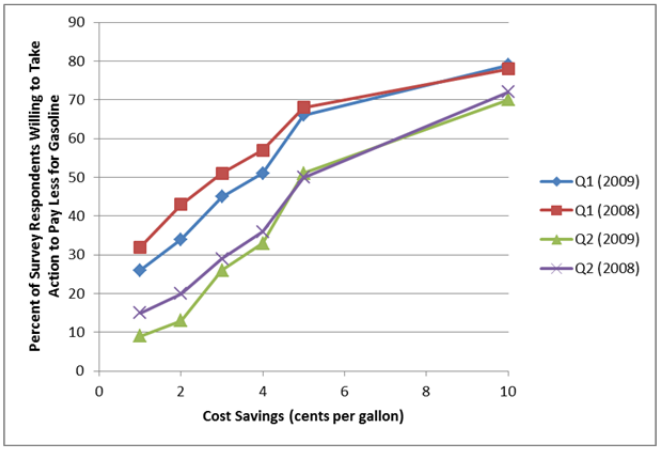

Figure 77. Consumer Refueling Errand Survey Results (data from (NACS 2011a)).

10.2.5.4 OPERATIONAL ENERGY INTENSITY

Vehicle refueling: 270,000 kJ/t-km

- The round-trip energy intensity of a vehicle errand to fill up the gas tank was made with the following assumptions:
  - Fuel economy of 20 mpgge (126 MJ/km) in the vicinity of the service station.
  - Payload of 10 gallons (28 kg, or 0.028 tonnes)

10.2.5.5 TURNOVER

Vehicles are assumed to operate for 10 years, driving an average of 20,000 miles per year (i.e., 200,000 miles before scrapping). Assuming a typical fuel efficiency of 30 mpgge, conventional vehicles are assumed to use 19 tonnes of gasoline in a lifetime. Assuming the same number of kilometers driven per vehicle life, the average FFV is expected to consume 11 tonnes of E85 fuel over one lifespan (in addition to approximately 11 tonnes of gasoline).

The turnover of conventional vehicles is irrelevant to this study, as there is no unique manufacturing burden (for enabling fuel distribution) attributed to conventional vehicles. In contrast, the turnover of (and assumed E85-utilization of) FFVs is considered in the construction and manufacturing burden of E85 underground storage tanks (not this section), as FFVs must be manufactured specifically to enable consumption of higher ethanol–gasoline blends.

10.2.5.6 DISCUSSION

To model refueling errands is challenging due to the high degree of consumer variability and statistical uncertainty. Nonetheless, results are likely within an order of magnitude, and demonstrate that this stage deserves more attention in analysis of fuel supply chains. Although personal vehicles are not designed to efficiently haul fuel from remote service stations, vehicles are only 1/10,000 as energy efficient as large ocean tankers, 1/1,000 as energy efficient as rail and barge, and less than 1/100 as energy efficient as delivery trucks. As a result, improvements to consumer refueling behavior will likely have an impact comparable to most improvements to fuel distribution infrastructure and logistics (though more difficult to measure).

10.3 National Optimization Model Description

10.3.1 Definitions of Modeling Variables

- State-specific ethanol production (ENPRP, Thousand Barrels), ethanol consumption (ENTCB, Billion BTU), and motor gasoline consumption (MGTCB, Billion BTU) statistics were downloaded from the State Energy Data System (US EIA 2011d).
    a. Note: motor gasoline includes ethanol, whereas a separate variable (MMTCB) captures motor gasoline excluding ethanol (equivalent to MGTCB – ENTCB).
- Fuel consumption and production volumes were converted to Billion BTUs, using the following values from SEDS (US EIA 2011d).
    a. The energy content of motor gasoline was reported to be 5.253 MM-BTU/bbl through 1993; this is assumed to still be the approximate energy content of gasoline leaving refineries, prior to blending with oxygenates.
    b. The energy content of ethanol was reported to be 3.563 MM-BTU/bbl.
- The following variables were created for each state for each year from 2000 until 2009:
    a. Ethanol Consumption
        i. Eth_Cons_Total_BB-BTU = ENCTCB
    b. Ethanol Production
        i. Eth_Prod_BB-BTU = ENPRP * 3.563
    c. Gasoline Consumption
        i. Gas_Cons_Total_BB-BTU = MGTCB
    d. Maximum Potential Ethanol Consumption
        i. E10_MaxEth_BB-BTU = 0.070 * MGTCB
            1. Note: The 10% volumetric blend wall is equivalent to a 7% energetic blend wall for ethanol.
    e. Ethanol Exported (net)
        i. E_Export_Actual = Eth_Prod_BB-BTU - Eth_Cons_Total_BB-BTU
    f. Ethanol Consumed In State of Production (net estimate)
        i. E_InStCons =
        ii. If Eth_Prod_BB-BTU > 0:
            1. Yes → If E_Export_Actual > 0
                a. Yes → Eth_Prod_BB-BTU – E_Export_Actual
                b. No → Eth_Prod_BB-BTU
            2. No → 0
    g. Minimum "Necessary" Ethanol Export Volume (to prevent a state from exceeding the E10 blend wall)
        i. E10_NecExport =

   ii. If Eth_Prod_BB-BTU > E10_MaxEth_BB-BTU
      1. Yes → Eth_Prod_BB-BTU - E10_MaxEth_BB-BTU
      2. No → 0

h. Ethanol "Unnecessarily" Exported from Net Producer States, defined as exported ethanol that could have potentially been consumed within the state of production without exceeding the E10 blend wall.
   i. E10_UnnecExport =
   ii. If E_Export_Actual > E10_NecExport
      1. Yes → E_Export_Actual - E10_NecExport
      2. No → 0

10.3.2 State-to-State Distances

		1	2	3	4	5	6	7	8	9	10	11	12
		AL	AZ	AR	CA	CO	CT	DE	FL	GA	ID	IL	IN
1	AL	100	2,527	684	3,545	2,112	1,746	1,397	703	375	3,257	952	861
2	AZ	2,527	100	1,926	1,142	989	3,816	3,577	3,147	2,862	1,526	2,323	2,562
3	AR	684	1,926	100	2,914	1,491	2,097	1,758	1,372	979	2,683	766	900
4	CA	3,545	1,142	2,914	100	1,832	4,760	4,545	4,176	3,881	1,359	3,270	3,530
5	CO	2,112	989	1,491	1,832	100	3,016	2,777	2,800	2,407	1,239	1,502	1,761
6	CT	1,746	3,816	2,097	4,760	3,016	100	433	1,868	1,546	3,905	1,534	1,279
7	DE	1,397	3,577	1,758	4,545	2,777	433	100	1,485	1,195	3,733	1,295	1,040
8	FL	703	3,147	1,372	4,176	2,800	1,868	1,485	100	514	3,944	1,595	1,463
9	GA	375	2,862	979	3,881	2,407	1,546	1,195	514	100	3,507	1,110	979
10	ID	3,257	1,526	2,683	1,359	1,239	3,905	3,733	3,944	3,507	100	2,518	2,757
11	IL	952	2,323	766	3,270	1,502	1,534	1,295	1,595	1,110	2,518	100	268
12	IN	861	2,562	900	3,530	1,761	1,279	1,040	1,463	979	2,757	268	100
13	IA	1,402	2,155	911	2,902	1,229	1,891	1,720	2,076	1,592	2,029	528	749
14	KS	1,452	1,463	849	2,451	690	2,398	2,158	2,140	1,747	1,864	900	1,144
15	KY	616	2,678	792	3,666	1,918	1,322	1,034	1,160	675	3,012	548	308
16	LA	672	2,061	493	3,090	1,761	2,352	2,003	1,141	1,007	2,981	1,215	1,292
17	ME	2,312	4,349	2,663	5,223	3,529	569	999	2,435	2,112	4,367	2,027	1,803
18	MD	1,263	3,442	1,624	4,411	2,642	484	152	1,384	1,063	3,602	1,160	905
19	MA	1,862	3,932	2,213	4,837	3,132	119	549	1,985	1,662	3,982	1,642	1,396
20	MI	1,305	2,944	1,372	3,749	2,106	1,274	1,103	1,853	1,369	2,800	625	485
21	MN	1,866	2,530	1,432	3,068	1,575	2,207	2,035	2,525	2,041	1,927	947	1,089
22	MS	340	2,235	462	3,264	1,935	1,980	1,631	961	675	3,087	908	951
23	MO	960	1,973	483	2,961	1,230	1,872	1,633	1,647	1,230	2,335	394	618
24	MT	2,966	1,838	2,392	1,913	1,243	3,425	3,254	3,653	3,212	726	2,148	2,307
25	NE	1,770	1,637	1,196	2,327	697	2,454	2,280	2,457	2,020	1,503	1,026	1,254
26	NV	3,294	1,055	2,670	663	1,235	4,162	3,949	3,981	3,588	756	2,674	2,933
27	NH	2,026	4,029	2,343	4,903	3,209	297	727	2,162	1,840	4,047	1,707	1,483
28	NJ	1,501	3,600	1,862	4,569	2,801	248	188	1,623	1,301	3,739	1,318	1,064
29	NM	1,989	616	1,388	1,641	611	3,278	3,038	2,612	2,328	1,646	1,785	2,024
30	NY	1,736	3,616	1,929	4,489	2,796	335	509	1,915	1,571	3,634	1,294	1,070
31	NC	832	3,250	1,336	4,238	2,586	1,002	644	915	588	3,672	1,183	923
32	ND	2,373	2,263	1,825	2,622	1,336	2,721	2,550	3,033	2,548	1,481	1,455	1,603
33	OH	1,022	2,870	1,177	3,838	2,070	979	757	1,522	1,039	3,015	578	329
34	OK	1,198	1,420	526	2,408	986	2,425	2,186	1,885	1,492	2,200	989	1,172
35	OR	3,756	1,770	3,182	1,106	1,720	4,462	4,284	4,443	4,006	650	3,017	3,257
36	PA	1,383	3,334	1,626	4,273	2,534	502	344	1,593	1,226	3,418	1,052	798
37	RI	1,847	3,918	2,198	4,865	3,118	113	534	1,970	1,648	4,009	1,636	1,381
38	SC	632	3,089	1,176	4,077	2,549	1,252	877	681	331	3,648	1,212	962
39	SD	2,084	1,947	1,510	2,480	1,007	2,580	2,409	2,772	2,317	1,476	1,261	1,462
40	TN	371	2,525	611	3,513	1,913	1,501	1,152	988	504	3,012	615	496
41	TX	1,303	1,372	841	2,425	1,215	2,906	2,568	1,923	1,638	2,414	1,510	1,692
42	UT	2,795	788	2,171	1,178	736	3,688	3,449	3,482	3,089	756	2,174	2,434
43	VT	1,983	3,963	2,277	4,837	3,143	311	712	2,140	1,810	3,981	1,641	1,417
44	VA	1,020	3,298	1,384	4,286	2,523	778	429	1,155	795	3,568	1,078	819
45	WA	3,855	2,155	3,281	1,554	1,939	4,378	4,206	4,542	4,101	868	3,048	3,260
46	WV	991	3,074	1,240	4,062	2,290	860	572	1,260	877	3,316	826	572
47	WI	1,494	2,658	1,308	3,285	1,726	1,749	1,577	2,136	1,652	2,297	573	686
48	WY	2,492	1,487	1,918	1,741	696	3,140	2,968	3,180	2,742	765	1,753	1,992

Table 70. 48x48 US State-to-State Road Distance Matrix (1 of 4).

		13	14	15	16	17	18	19	20	21	22	23	24
		IA	KS	KY	LA	ME	MD	MA	MI	MN	MS	MO	MT
1	AL	1,402	1,452	616	672	2,312	1,263	1,862	1,305	1,866	340	960	2,966
2	AZ	2,155	1,463	2,678	2,061	4,349	3,442	3,932	2,944	2,530	2,235	1,973	1,838
3	AR	911	849	792	493	2,663	1,624	2,213	1,372	1,432	462	483	2,392
4	CA	2,902	2,451	3,666	3,090	5,223	4,411	4,837	3,749	3,068	3,264	2,961	1,913
5	CO	1,229	690	1,918	1,761	3,529	2,642	3,132	2,106	1,575	1,935	1,230	1,243
6	CT	1,891	2,398	1,322	2,352	569	484	119	1,274	2,207	1,980	1,872	3,425
7	DE	1,720	2,158	1,034	2,003	999	152	549	1,103	2,035	1,631	1,633	3,254
8	FL	2,076	2,140	1,160	1,141	2,435	1,384	1,985	1,853	2,525	961	1,647	3,653
9	GA	1,592	1,747	675	1,007	2,112	1,063	1,662	1,369	2,041	675	1,230	3,212
10	ID	2,029	1,864	3,012	2,981	4,367	3,602	3,982	2,800	1,927	3,087	2,335	726
11	IL	528	900	548	1,215	2,027	1,160	1,642	625	947	908	394	2,148
12	IN	749	1,144	308	1,292	1,803	905	1,396	485	1,089	951	618	2,307
13	IA	100	722	1,048	1,404	2,354	1,589	1,969	908	521	1,279	512	1,653
14	KS	722	100	1,290	1,195	2,927	2,024	2,514	1,520	1,101	1,282	576	1,653
15	KY	1,048	1,290	100	1,131	1,889	899	1,439	735	1,393	752	757	2,611
16	LA	1,404	1,195	1,131	100	2,918	1,869	2,468	1,764	1,924	380	976	2,819
17	ME	2,354	2,927	1,889	2,918	100	1,051	459	1,737	2,669	2,547	2,405	3,888
18	MD	1,589	2,024	899	1,869	1,051	100	601	972	1,904	1,497	1,498	3,123
19	MA	1,969	2,514	1,439	2,468	459	601	100	1,352	2,284	2,097	1,988	3,503
20	MI	908	1,520	735	1,764	1,737	972	1,352	100	973	1,422	1,015	2,191
21	MN	521	1,101	1,393	1,924	2,669	1,904	2,284	973	100	1,754	1,016	1,263
22	MS	1,279	1,282	752	380	2,547	1,497	2,097	1,422	1,754	100	790	2,796
23	MO	512	576	757	976	2,405	1,498	1,988	1,015	1,016	790	100	2,044
24	MT	1,653	1,653	2,611	2,819	3,888	3,123	3,503	2,191	1,263	2,796	2,044	100
25	NE	596	435	1,525	1,614	2,917	2,146	2,531	1,473	906	1,600	848	1,223
26	NV	2,304	1,900	3,141	2,897	4,625	3,814	4,239	3,151	2,453	3,071	2,453	1,298
27	NH	2,034	2,607	1,581	2,632	365	779	186	1,417	2,349	2,260	2,085	3,568
28	NJ	1,726	2,182	1,093	2,107	815	239	365	1,109	2,041	1,735	1,656	3,259
29	NM	1,617	924	2,139	1,526	3,811	2,904	3,394	2,405	2,008	1,700	1,434	1,789
30	NY	1,621	2,194	1,172	2,285	755	532	368	1,004	1,936	1,905	1,671	3,155
31	NC	1,664	1,958	720	1,468	1,569	518	1,119	1,153	2,007	1,118	1,425	3,226
32	ND	1,023	1,178	1,907	2,318	3,184	2,419	2,799	1,487	559	2,230	1,478	813
33	OH	1,002	1,451	417	1,533	1,496	622	1,090	450	1,325	1,153	926	2,543
34	OK	904	403	1,263	815	2,958	2,051	2,542	1,605	1,374	978	618	2,028
35	OR	2,586	2,344	3,511	3,424	4,925	4,149	4,539	3,389	2,521	3,586	2,834	1,281
36	PA	1,405	1,916	852	1,978	1,063	284	613	788	1,720	1,598	1,390	2,939
37	RI	1,996	2,499	1,424	2,453	498	586	85	1,379	2,311	2,082	1,973	3,530
38	SC	1,702	1,922	697	1,277	1,818	768	1,368	1,283	2,047	926	1,380	3,265
39	SD	758	804	1,766	1,961	3,043	2,278	2,658	1,382	635	1,914	1,163	966
40	TN	1,097	1,286	252	912	2,068	1,018	1,617	940	1,546	532	735	2,716
41	TX	1,445	895	1,602	821	3,472	2,434	3,023	2,125	1,925	1,011	1,138	2,301
42	UT	1,860	1,401	2,642	2,398	4,180	3,314	3,795	2,727	2,067	2,571	1,954	1,067
43	VT	1,968	2,541	1,519	2,589	420	756	258	1,351	2,283	2,217	2,019	3,502
44	VA	1,560	1,896	698	1,629	1,344	294	894	1,022	1,898	1,257	1,363	3,117
45	WA	2,542	2,533	3,563	3,644	4,840	4,075	4,455	3,144	2,243	3,685	2,933	979
46	WV	1,308	1,663	465	1,591	1,427	438	977	778	1,637	1,211	1,130	2,855
47	WI	518	1,224	990	1,763	2,211	1,446	1,826	505	470	1,452	873	1,688
48	WY	1,264	1,112	2,247	2,278	3,603	2,837	3,217	2,067	1,376	2,322	1,570	617

Table 71. 48x48 US State-to-State Road Distance Matrix (2 of 4).

		25	26	27	28	29	30	31	32	33	34	35	36
		NE	NV	NH	NJ	NM	NY	NC	ND	OH	OK	OR	PA
1	AL	1,770	3,294	2,026	1,501	1,989	1,736	832	2,373	1,022	1,198	3,756	1,383
2	AZ	1,637	1,055	4,029	3,600	616	3,616	3,250	2,263	2,870	1,420	1,770	3,334
3	AR	1,196	2,670	2,343	1,862	1,388	1,929	1,336	1,825	1,177	526	3,182	1,626
4	CA	2,327	663	4,903	4,569	1,641	4,489	4,238	2,622	3,838	2,408	1,106	4,273
5	CO	697	1,235	3,209	2,801	611	2,796	2,586	1,336	2,070	986	1,720	2,534
6	CT	2,454	4,162	297	248	3,278	335	1,002	2,721	979	2,425	4,462	502
7	DE	2,280	3,949	727	188	3,038	509	644	2,550	757	2,186	4,284	344
8	FL	2,457	3,981	2,162	1,623	2,612	1,915	915	3,033	1,522	1,885	4,443	1,593
9	GA	2,020	3,588	1,840	1,301	2,328	1,571	588	2,548	1,039	1,492	4,006	1,226
10	ID	1,503	756	4,047	3,739	1,646	3,634	3,672	1,481	3,015	2,200	650	3,418
11	IL	1,026	2,674	1,707	1,318	1,785	1,294	1,183	1,455	578	989	3,017	1,052
12	IN	1,254	2,933	1,483	1,064	2,024	1,070	923	1,603	329	1,172	3,257	798
13	IA	596	2,304	2,034	1,726	1,617	1,621	1,664	1,023	1,002	904	2,586	1,405
14	KS	435	1,900	2,607	2,182	924	2,194	1,958	1,178	1,451	403	2,344	1,916
15	KY	1,525	3,141	1,581	1,093	2,139	1,172	720	1,907	417	1,263	3,511	852
16	LA	1,614	2,897	2,632	2,107	1,526	2,285	1,468	2,318	1,533	815	3,424	1,978
17	ME	2,917	4,625	365	815	3,811	755	1,569	3,184	1,496	2,958	4,925	1,063
18	MD	2,146	3,814	779	239	2,904	532	518	2,419	622	2,051	4,149	284
19	MA	2,531	4,239	186	365	3,394	368	1,119	2,799	1,090	2,542	4,539	613
20	MI	1,473	3,151	1,417	1,109	2,405	1,004	1,153	1,487	450	1,605	3,389	788
21	MN	906	2,453	2,349	2,041	2,008	1,936	2,007	559	1,325	1,374	2,521	1,720
22	MS	1,600	3,071	2,260	1,735	1,700	1,905	1,118	2,230	1,153	978	3,586	1,598
23	MO	848	2,453	2,085	1,656	1,434	1,671	1,425	1,478	926	618	2,834	1,390
24	MT	1,223	1,298	3,568	3,259	1,789	3,155	3,226	813	2,543	2,028	1,281	2,939
25	NE	100	1,729	2,596	2,288	1,197	2,183	2,169	780	1,554	823	2,039	1,967
26	NV	1,729	100	4,305	3,972	1,485	3,891	3,809	2,007	3,242	2,165	768	3,675
27	NH	2,596	4,305	100	542	3,491	434	1,297	2,864	1,176	2,638	4,605	742
28	NJ	2,288	3,972	542	100	3,062	378	758	2,555	770	2,210	4,296	332
29	NM	1,197	1,485	3,491	3,062	100	3,077	2,712	1,880	2,331	882	2,055	2,796
30	NY	2,183	3,891	434	378	3,077	100	1,049	2,450	763	2,225	4,191	374
31	NC	2,169	3,809	1,297	758	2,712	1,049	100	2,522	734	1,850	4,172	716
32	ND	780	2,007	2,864	2,555	1,880	2,450	2,522	100	1,839	1,531	2,076	2,235
33	OH	1,554	3,242	1,176	770	2,331	763	734	1,839	100	1,479	3,565	493
34	OK	823	2,165	2,638	2,210	882	2,225	1,850	1,531	1,479	100	2,680	1,944
35	OR	2,039	768	4,605	4,296	2,055	4,191	4,172	2,076	3,565	2,680	100	3,975
36	PA	1,967	3,675	742	332	2,796	374	716	2,235	493	1,944	3,975	100
37	RI	2,558	4,267	261	350	3,379	418	1,104	2,826	1,082	2,527	4,567	605
38	SC	2,161	3,772	1,546	1,007	2,551	1,287	283	2,561	864	1,689	4,147	942
39	SD	406	1,882	2,723	2,415	1,516	2,310	2,381	374	1,698	1,170	2,055	2,094
40	TN	1,525	3,136	1,781	1,256	1,986	1,413	731	2,053	661	1,124	3,511	1,098
41	TX	1,209	2,271	3,152	2,672	859	2,739	2,099	1,952	1,987	553	2,823	2,436
42	UT	1,286	581	3,860	3,473	1,013	3,447	3,310	1,698	2,742	1,665	1,165	3,207
43	VT	2,530	4,239	149	528	3,425	367	1,274	2,798	1,110	2,572	4,539	684
44	VA	2,065	3,726	1,072	533	2,760	803	279	2,413	625	1,898	4,068	472
45	WA	2,113	1,224	4,520	4,212	2,275	4,107	4,178	1,792	3,496	2,874	576	3,891
46	WV	1,813	3,480	1,122	632	2,535	766	466	2,151	344	1,676	3,816	401
47	WI	1,069	2,687	1,891	1,583	2,119	1,478	1,605	984	923	1,406	2,892	1,262
48	WY	738	1,143	3,283	2,974	1,243	2,869	2,907	1,001	2,250	1,488	1,322	2,653

Table 72. 48x48 US State-to-State Road Distance Matrix (3 of 4).

		37	38	39	40	41	42	43	44	45	46	47	48
		RI	SC	SD	TN	TX	UT	VT	VA	WA	WV	WI	WY
1	AL	1,847	632	2,084	371	1,303	2,795	1,983	1,020	3,855	991	1,494	2,492
2	AZ	3,918	3,089	1,947	2,525	1,372	788	3,963	3,298	2,155	3,074	2,658	1,487
3	AR	2,198	1,176	1,510	611	841	2,171	2,277	1,384	3,281	1,240	1,308	1,918
4	CA	4,865	4,077	2,480	3,513	2,425	1,178	4,837	4,286	1,554	4,062	3,285	1,741
5	CO	3,118	2,549	1,007	1,913	1,215	736	3,143	2,523	1,939	2,290	1,726	696
6	CT	113	1,252	2,580	1,501	2,906	3,688	311	778	4,378	860	1,749	3,140
7	DE	534	877	2,409	1,152	2,568	3,449	712	429	4,206	572	1,577	2,968
8	FL	1,970	681	2,772	988	1,923	3,482	2,140	1,155	4,542	1,260	2,136	3,180
9	GA	1,648	331	2,317	504	1,638	3,089	1,810	795	4,101	877	1,652	2,742
10	ID	4,009	3,648	1,476	3,012	2,414	756	3,981	3,568	868	3,316	2,297	765
11	IL	1,636	1,212	1,261	615	1,510	2,174	1,641	1,078	3,048	826	573	1,753
12	IN	1,381	962	1,462	496	1,692	2,434	1,417	819	3,260	572	686	1,992
13	IA	1,996	1,702	758	1,097	1,445	1,860	1,968	1,560	2,542	1,308	518	1,264
14	KS	2,499	1,922	804	1,286	895	1,401	2,541	1,896	2,533	1,663	1,224	1,112
15	KY	1,424	697	1,766	252	1,602	2,642	1,519	698	3,563	465	990	2,247
16	LA	2,453	1,277	1,961	912	821	2,398	2,589	1,629	3,644	1,591	1,763	2,278
17	ME	498	1,818	3,043	2,068	3,472	4,180	420	1,344	4,840	1,427	2,211	3,603
18	MD	586	768	2,278	1,018	2,434	3,314	756	294	4,075	438	1,446	2,837
19	MA	85	1,368	2,658	1,617	3,023	3,795	258	894	4,455	977	1,826	3,217
20	MI	1,379	1,283	1,382	940	2,125	2,727	1,351	1,022	3,144	778	505	2,067
21	MN	2,311	2,047	635	1,546	1,925	2,067	2,283	1,898	2,243	1,637	470	1,376
22	MS	2,082	926	1,914	532	1,011	2,571	2,217	1,257	3,685	1,211	1,452	2,322
23	MO	1,973	1,380	1,163	735	1,138	1,954	2,019	1,363	2,933	1,130	873	1,570
24	MT	3,530	3,265	966	2,716	2,301	1,067	3,502	3,117	979	2,855	1,688	617
25	NE	2,558	2,161	406	1,525	1,209	1,286	2,530	2,065	2,113	1,813	1,069	738
26	NV	4,267	3,772	1,882	3,136	2,271	581	4,239	3,726	1,224	3,480	2,687	1,143
27	NH	261	1,546	2,723	1,781	3,152	3,860	149	1,072	4,520	1,122	1,891	3,283
28	NJ	350	1,007	2,415	1,256	2,672	3,473	528	533	4,212	632	1,583	2,974
29	NM	3,379	2,551	1,516	1,986	859	1,013	3,425	2,760	2,275	2,535	2,119	1,243
30	NY	418	1,287	2,310	1,413	2,739	3,447	367	803	4,107	766	1,478	2,869
31	NC	1,104	283	2,381	731	2,099	3,310	1,274	279	4,178	466	1,605	2,907
32	ND	2,826	2,561	374	2,053	1,952	1,698	2,798	2,413	1,792	2,151	984	1,001
33	OH	1,082	864	1,698	661	1,987	2,742	1,110	625	3,496	344	923	2,250
34	OK	2,527	1,689	1,170	1,124	553	1,665	2,572	1,898	2,874	1,676	1,406	1,488
35	OR	4,567	4,147	2,055	3,511	2,823	1,165	4,539	4,068	576	3,816	2,892	1,322
36	PA	605	942	2,094	1,098	2,436	3,207	684	472	3,891	401	1,262	2,653
37	RI	100	1,354	2,685	1,603	3,008	3,790	336	879	4,482	962	1,853	3,245
38	SC	1,354	100	2,420	664	1,908	3,273	1,523	511	4,218	603	1,645	2,883
39	SD	2,685	2,420	100	1,822	1,578	1,458	2,657	2,272	1,855	2,011	892	765
40	TN	1,603	664	1,822	100	1,421	2,637	1,738	778	3,606	711	1,157	2,247
41	TX	3,008	1,908	1,578	1,421	100	1,781	3,086	2,194	3,042	2,049	1,947	1,754
42	UT	3,790	3,273	1,458	2,637	1,781	100	3,794	3,226	1,384	2,981	2,263	719
43	VT	336	1,523	2,657	1,738	3,086	3,794	100	1,042	4,454	1,076	1,825	3,217
44	VA	879	511	2,272	778	2,194	3,226	1,042	100	4,069	308	1,496	2,803
45	WA	4,482	4,218	1,855	3,606	3,042	1,384	4,454	4,069	100	3,808	2,641	1,421
46	WV	962	603	2,011	711	2,049	2,981	1,076	308	3,808	100	1,235	2,551
47	WI	1,853	1,645	892	1,157	1,947	2,263	1,825	1,496	2,641	1,235	100	1,603
48	WY	3,245	2,883	765	2,247	1,754	719	3,217	2,803	1,421	2,551	1,603	100

Table 73. 48x48 US State-to-State Road Distance Matrix (4 of 4).