Assessing On-Road Freight Emissions for Patagonia and Evaluating Low Carbon Fuel Alternatives

J. Choe, K. Fujiwara, J. Hakian, J. Rafter, J. Sultan, D. Wiggam

Bren School of Environmental Science and Management
University of California, Santa Barbara
Santa Barbara, CA 93106-5131

2013 Group Project Final Report

Faculty Advisors:
Roland Geyer, Brandon Kuczenski

As authors of this Group Project report, we are proud to archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

James Choe

Kosuke Fujiwara

Jeremie Hakian

Jeremy Rafter

Jake Sultan

Derek Wiggam

The mission of the Bren School of Environmental Science & Management is to produce professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master's of Environmental Science and Management (MESM) Program. It is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

March 22, 2013

Roland Geyer

ACKNOWLEDGEMENTS

We would like to thank the following people who assisted us by generously sharing their knowledge, time, and energy:

Our advisors, Dr. Roland Geyer (UCSB) and Dr. Brandon Kuczenski (UCSB);

Our external reviewers, Ben Sharpe (ICCT), John Courtis (CARB), Tyson Eckerle (Energy Action Now), Dr. Severin Beucker (Borderstep Institute; Carl von Ossietzky University of Oldenburg) and Eric Wellens (Priority Worldwide)

Patagonia representatives, Elissa Loughman and Jill Dumain

We would also like to thank the faculty and staff at the Bren School of Environmental Science and Management at the University of California, Santa Barbara for their continued support and assistance.

Finally, we are grateful to our friends and family who were extremely supportive throughout this process.

TABLE OF CONTENTS

Notation

AFDC: The Alternative Fuels and Advanced Vehicles Data Center
BC: black carbon
BEV: battery electric vehicle
CAA: Clean Air Act
CARB: California Air Resources Board
CH_4: methane
CI: compression ignition
CIDI: compression ignition direct injection
CNG: compressed natural gas
CO: carbon monoxide
CO_2: carbon dioxide
DOE: US Department of Energy
DOT: US Department of Transportation
EERE: US Department of Energy's Office of Energy Efficiency and Renewable Energy
EIA: US Energy Information Administration
EOL: end-of-life
EPAct: Energy Policy Act
FEAT: Freight Emissions Assessment Tool
FCV: fuel cell vehicle
fuel cycle: fuel life cycle
GHG: greenhouse gas
GREET: The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP: global warming potential
HDV: heavy-duty vehicle
HEV: hybrid electric vehicle
ICE: internal combustion engine
IPCC: Intergovernmental Panel on Climate Change
LCA: life cycle assessment
LCI: life cycle inventory
LCIA: life cycle impact assessment
LCFS: California's Low Carbon Fuel Standard
LDV: light-duty vehicle
LNG: liquefied natural gas
LPG: liquefied petroleum gas
metric ton-km: metric ton-kilometers
mpg: miles per gallon
MPGGE: miles per gasoline gallon equivalent
NG: natural gas
NOx: nitrogen oxide
N_2O: nitrous oxide
PM: particulate matter
ppm: parts per million
RFS2: EPA's Renewable Fuel Standard
SAGD: steam assisted gravity drainage
SCO: synthetic crude oil
SMD: surface mining dilbit
SMR: steam methane reforming
TTW: tank-to-wheel
ULSD: ultra-low sulfur diesel
VMT: vehicle miles traveled
WTT: well-to-tank
WTW: well-to-wheels
ZEV: zero emission vehicle

Abstract

Over the next 25 years, vehicle miles traveled (VMT) by heavy-duty vehicles (HDVs) are projected to increase by over 100 billion. With the transportation sector accounting for nearly one-third of all US energy consumption, VMT by conventional HDVs averaging less than 7 miles per gallon are a growing source of greenhouse gas (GHG) emissions. Accordingly, decoupling GHG emissions from increasing VMT remains a core objective of sustainable transportation practices. Patagonia, an outdoor apparel company, has long been dedicated to promoting environmental stewardship in its own operations and has recently begun to examine its domestic freight distribution network. In this context, the project investigates the life cycle GHG emissions from Patagonia's HDV fuel use, provides actionable recommendations to reduce those emissions, and facilitates the process by which the company identifies alternative fuel options. To meet these objectives, the project also developed the Freight Emissions Assessment Tool (FEAT), a user-friendly logistics tool that evaluates the life cycle GHG emissions from both conventional and alternative fuels (existing and near-term) for Class 8 HDVs. The results indicate that transporting 5.7 million metric ton-km of Patagonia freight within the domestic US generates 534 metric tons of CO_2 equivalents in life cycle emissions, and consumes 42,000 gallons of diesel fuel. While several available fuel systems potentially have lower GHG emissions compared to conventional diesel, modifications in package density represent the most feasible opportunity to reduce Patagonia's domestic freight GHG emissions.

EXECUTIVE SUMMARY

Patagonia, an outdoor apparel company, has long been dedicated to promoting environmental stewardship in its operations and in the greater business landscape. However, because Patagonia does not own or operate its own distribution fleet, the fuel-use GHG emissions associated with moving its products remains poorly understood. In conjunction with requests from non-profits to sign moratoriums on using carbon-intensive fuels, Patagonia proposed the project to evaluate the carbon emissions of their existing distribution network and explore the use of fuel options with lower global warming potential (GWP). The project resulted in the development of the Freight Emissions Assessment Tool (FEAT), a user-friendly logistics tool that quantifies total fuel consumption and GHG emissions from US Class 8 heavy-duty vehicles (HDVs) over the entire fuel life cycle (fuel cycle). In addition, the tool includes a comprehensive inventory of alternative fuels, enabling users to compare emissions from both existing and alternative fuel systems. Using Patagonia's FY 2012 domestic freight data, a baseline GWP emissions assessment was conducted for the company using FEAT, and actionable recommendations were made based on the project findings.

The project was guided by a life cycle assessment (LCA) methodology, comparing GHG emission scenarios through a common functional unit: the movement of freight in metric ton-kilometers. The project scope examined GHG emissions associated with shipments by Class 8 HDVs over the entire Well-to-Wheels (WTW) fuel cycle, which includes both the fuel production and use phases. Patagonia data was limited to the FY 2012 for domestic shipments (excluding Hawaii), collected from ground transportation invoices. Freight data was broken down by Patagonia's four primary distribution legs: inbound shipments from California ports (Long Beach and San Francisco) to the Reno, NV distribution center; and outbound wholesale, retail, and direct-to-customer shipments leaving the distribution center.

The project methodology focused on the development of FEAT, combining existing fuel cycle models and emission factor data into a user-friendly tool (enabling GHG emissions to be calculated from company-specific logistics data). Developing FEAT required three fundamental steps to relate Patagonia's freight transport to a global warming potential (GWP): (1) modeling energy consumption from the defined product system; (2) calculating emission factors for both conventional diesel and alternative fuels as a function metric ton-kilometers; and (3) quantifying total emissions into a single IPCC-characterized GWP value, measured in grams of CO_2e. Steps 1 and 2 leveraged existing LCA models from GaBi (PE International) and GREET (Argonne National Laboratory) and were equilibrated to the project's functional unit (metric ton-km).

Using FEAT, a baseline assessment of Patagonia's contribution to global warming was compared to alternative scenarios by changing several of FEAT's key parameters; these included both fuel-switching and efficiency options. HDV fuel systems considered were conventional petroleum-based fuels (gasoline and diesel), tar sands derived diesel (in-situ and surface mining), biodiesel blends (conventional B20 and soy- and algae-based B100), natural gas (compressed, liquefied, and landfill-

derived), propane gas (LPG), electricity and hybrid-electric, and liquid and gaseous hydrogen. Fuel availability and cost data from the Department of Energy's Alternative Fuels Data Center (AFDC) were also integrated into FEAT. Importantly, the baseline scenario assumed 100% of freight was shipped by conventional diesel HDVs; an average package density, vehicle mix, drive cycle, and truck payload capacity were assumed under all scenarios.

The results quantify a range of GHG emission factors specific to Patagonia freight, broken down into the upstream well-to-tank phase (WTT) and the combustion tank-to-wheel phase (TTW). Based on average Patagonia freight data, the following parameters were adjusted to calculate the emission factors: vehicle utilization rate (0.413), trailer volume (98.9 m^3), product tonnage (10.53 metric tons) and density (106.62 kg/m^3), and maximum truck payload (25.34 metric tons). Several fuel types were found to have lower WTW emission factors compared to the conventional diesel baseline emission factor of 94.69 g CO_2e/metric ton-km; the lowest included LNG from landfill gas (15.90 g CO_2e/metric ton-km), soy-based B100 (23.50 g CO_2e/metric ton-km), and diesel HEV (75.75 g CO_2e/metric ton-km). Both tar sands-based diesels were found to have greater emission factor values relative to conventional diesel at 99.90 g CO_2e/metric ton-km (surface mining) and 115.30 g CO_2e/metric ton-km (in-situ). In several cases, WTT emissions were the only source of emissions (i.e., hydrogen and electricity fuel types).

These emission factors were used to quantify Patagonia's GHG emissions overall and by distribution leg. Over the FY 2012, the movement of 5.7 million metric ton-km of Patagonia freight by HDV emitted 534 metric tons of CO_2e and consumed 42,000 gallons of diesel fuel. The majority of these emissions occurred from wholesale (194.29 metric tons CO_2e) and direct-to-customer shipments (165.03 metric tons CO_2e). Inbound shipments from California ports to the Reno distribution center were also significant (132.62 metric tons CO_2e); the remainder was associated with retail shipments (41.72 metric tons CO_2e).

Further analysis revealed that while total GHG emissions levels can be reduced by utilizing alternative fuel types with lower emission factors (including B20, landfill-derived LNG, and HEV), total fuel consumption and associated GHG output is most sensitive to package density modifications. It was observed that a 20% increase in package density reduces WTW emissions by 70.05 metric tons CO_2e, and a 20% decrease increases WTW emissions by 105.08 metric tons CO_2e. Compared to vehicle switching, changing package density offers a relatively straightforward and effective way to reduce GHG emissions from HDV use.

Based on the project findings, increases in the density of Patagonia's packages above the current average density represent the most feasible opportunity for the company to reduce freight-related GHG emissions. While switching to alternative fuels may also provide emission reductions, these were not evaluated against tradeoffs in other environmental impact categories such as land use change or eutrophication. Furthermore, uncertainties in emission factor data combined with project assumptions limit the confidence of fuel switching options. However, the project provides an important framework from which Patagonia can work to reduce its GWP. The project also identifies important areas of future research that will both increase the accuracy of emission modeling and explore the consequences of large-scale alternative fuel development; these include specific recommendations for Patagonia, as well as broader considerations for the HDV transportation sector.

A disproportionate fraction of US greenhouse gases is emitted by heavy-duty vehicles; by providing Patagonia a baseline assessment of current HDV fuel consumption and GHG emissions, and by identifying alternative fuel options on a life cycle basis, the project empowers the company to develop GHG-reducing strategies in its distribution network. Using FEAT and other informational resources provided by the project, Patagonia may also serve as a catalyst for industry-led environmental change, engaging other companies to assess their freight-related GHG emissions.

PROJECT SIGNIFICANCE

The significance of the project lies in: 1) providing a detailed review of conventional and alternative transportation fuel cycle emissions; 2) developing a user-friendly tool (FEAT) that integrates HDV freight logistics, alternative and conventional fuel data, and well-to-wheel (WTW) emission profiles; and 3) facilitating the process by which Patagonia evaluates existing freight GHG emissions and identifies alternative fuel options on a life cycle basis.

HDVs produce a disproportionate share of GHG emissions. Over 90% of US transportation energy comes from petroleum products (Farrell & Sperling 2007), and approximately one-quarter of all transportation emissions are generated by the movement of freight (US DOT 2011). In the US, trucks over 8,500 lbs currently contribute approximately 370 million metric tons of CO2e annually, about 22% of the total GHG emissions from the transportation sector (Farrell & Sperling 2007). As many companies add to the growing number of vehicle miles traveled (VMT) by shipping their products over greater distances, GHG emissions become increasingly problematic. Importantly, by being mindful of the fuel and technology choices in their distribution networks, companies can have significant control over the magnitude of freight-related GHG emissions. Because a significant fraction of these emissions occur upstream of the fuel combustion phase, it is critically important to consider the global warming potential of freight shipped by Class 8 HDVs over the entire fuel cycle.

In fact, fuel production pathways were of particular concern to Patagonia; the company received pressure from an environmental non-profit to avoid diesel produced from tar sands in the transportation of their products (crude oil produced from tar sands releases higher levels of GHGs relative to conventional sources due to additional energy and material demands). Not owning their own shipping vehicles, Patagonia has limited knowledge of tar sands and other environmental concerns related to distributing their products. In order to make an informed decision regarding the outside pressures they are facing, Patagonia sought to quantitatively evaluate the global warming potential of their current freight distribution network.

While several life cycle assessment (LCA)-based transportation models exist to facilitate this process, many are complicated by licensing issues and technical requirements or cover only specific segments of the transportation network. By integrating primary logistics data, emission models, and standardized LCA methodology, the project has minimized the industry-academic tradeoff and developed a transparent, user-friendly Freight Emissions Assessment Tool (FEAT). Moreover, this project facilitates the process by which Patagonia can identify and evaluate alternative fuels options, provides a baseline GHG emissions assessment of their US distribution network, and makes actionable recommendations for to reduce those emissions.

On a broader scale, the project contributes to the growing body of transportation studies that attempt to decouple GHG emissions from increasing VMT. Considering the partisan nature of climate change policy in the US, the prospect of comprehensive GHG legislation is limited, at least in the near term. This places an even larger role on environmentally conscious and adaptive companies from the private sector to demonstrate the viability of alternative fuel technologies. The intent of this project is to provide companies information that will help them make informed decisions about their logistics operations.

OBJECTIVES

The project was motivated by the following questions:

- What are the GHG emissions associated with Patagonia's domestic HDV use, and what fuel types are currently being used?
- How do life cycle impacts of conventional diesel fuels compare with alternative fuel technologies?
- How can Patagonia assess GHG emissions, and what actions can be taken to reduce these emissions?

To address these questions, the project sets the following objectives:

- Conduct a well-to-wheels fuel cycle assessment of Patagonia's freight GHG emissions
- Construct a transparent, user-friendly logistics tool that includes current and near-term transportation technologies, fuel types, and emission profiles
- Develop recommendations for reducing Patagonia's freight GHG emissions
- Supply Patagonia with relevant information to intelligently respond to concerns about the potential use of specific fuels in their distribution network

BACKGROUND

LCA Standards

Government institutions, academic publications, and industry sources have generated a wealth of life cycle assessment data characterizing the environmental impacts, including greenhouse gas emissions and global warming potential, of fuel types in transportation. Through a carefully conducted LCA, different products can be compared on the basis of a *functional unit*, a reference unit which quantifies the performance of the product system based on categories of interest (ISO 2006). To estimate the inputs and outputs required to deliver the functional unit, a detailed life cycle inventory (LCI) is compiled; this includes the material inputs and outputs, by-products, energy flows, intermediate processes, and wastes/emissions generated in the delivery of the functional unit. Using the LCI, the environmental emissions of the product system are then quantified through a life cycle impact assessment (LCIA). The LCIA results of various products can then be compared based on the common functional unit. Depending on the type of LCA study, the functional unit for transport fuels is generally defined as either a barrel of refined product or as freight in units of metric ton-kilometer (metric ton-km; moving one metric ton over one kilometer) (Farrell & Sperling 2007).

Conventional and Unconventional Fossil Fuels

Compared to gasoline, diesel is more complex and variable in terms of density, volatility, and general composition (MacLean & Lave 2009). Two major benefits that diesel fuel has are high energy density and suitability for use, given that it has the highest thermal efficiency of all currently available petroleum-based fuels. As a result, these two aspects result in fuel economy benefits compared to alternative compression ignition direct injection (CIDI). Some of the important characteristics of diesel fuels are ignition quality (cetane number), density, heat of combustion, volatility, cleanliness, and non-corrosiveness (MacLean & Lave 2009). The cetane number indicates how readily the fuel self-ignites, which is synonymous to an octane rating for gasoline. If a fuel has too low a cetane number, the fuel may not ignite or may ignite poorly, especially on cold days. The viscosity is important when considering fuel injection, starting, and engine performance. The high sulfur content of diesel fuel is also of concern, as well as the acids that form in the atmosphere from the emissions (MacLean & Lave 2009). Removing sulfur from diesel fuel is more energy-intensive and costly than removing it from gasoline due to the fuel's molecular structure. Ultra-low sulfur diesel (ULSD) is a standard for defining fuel with substantially lower sulfur content at 15 ppm. Since 2007, almost all diesel fuel available in the US is ULSD.

While the crude recovery stage includes mostly the process of drilling from conventional oil wells, it also includes unconventional sources like tar sands (also known as oil sands or bitumen), which are argued to be more environmentally damaging than conventional crude oil. To determine the GHG-intensity of tar sands, it is important to characterize the physical nature of bitumen and the extraction processes used. Bitumen is an oily, viscous material that is a naturally occurring byproduct of decomposed organic materials. The term tar sands acknowledge the fact that bitumen is found in combination with clay, sand, and water. Compared to conventional drilling methods, bitumen must be intensively extracted from tar sands due to its extreme physical properties (Farrell & Sperling 2007). There are two different recovery processes utilized to recover bitumen from tar sands: mining and in situ thermal recovery. Depending upon the process, tar sands are transported to refineries as either crude bitumen or upgraded synthetic crude oil (SCO). Bitumen is too viscous to flow through a pipeline, so it is generally blended with a diluent (typically natural gas condensate) or synthetic crude oil (SCO) (Rosenfeld et al. 2009).

Mining is used as a recovery method for bitumen deposits that are within 75 feet of the surface. This process involves large earthmoving equipment to remove overburden and excavate the oil sands, and transportation to a processing facility where they are then “upgraded” (Bergerson & Keith 2006). Upgrading is an offsite process that requires additional energy to convert the bitumen into SCO that can be pipelined to refineries. Approximately 20% of bitumen reserves are recoverable through mining. The remaining majority must be accessed by in-situ techniques. In-situ thermal recovery techniques are used to extract deposits that are too deep to be reached by mining. After vertical and horizontal drilling, steam is injected to reduce bitumen viscosity to a degree that it flows to the surface. In 2010, surface mining accounted for 53% and in-situ for 47% of Alberta’s tar sand production (Government of Alberta 2010)

The additional energy demand, processing, transportation, and infrastructure required for mining and in-situ processing raises the GHG profile of tar sands compared to conventional crude sources. Quantifying the exact magnitude of carbon dioxide (CO_2) emission for oil production from tar sand is considerably variable. However, a meta-analysis of tar sands LCA studies conducted by Keith and Bergeson (2006) reveal a range of GHG estimates (measured in terms of CO_2 equivalents) from the two production types; update values provided by Bergeson et al. (2012) are used later in the project.

Moreover, tar sands emissions go beyond the direct extraction and processing of bitumen. Land-use changes and production impacts on carbon-sequestering peatlands further contribute to GHG intensity. Peat has a high capacity to store carbon and planned tar sands projects would potentially destroy enough peatlands to release 11.4 to 47.3 million metric tons of stored carbon (Marshall & Stecker 2012).

Fuel Cycle

Determining the environmental emissions associated with the combustion of fuel alone is both insufficient and misleading (Farrell & Sperling 2007). To quantify the amount of GHG emissions generated from the production and use of various fuels, it is important to include the upstream processes in addition to the combustion process, or the fuel life cycle (*fuel cycle*). The analysis of a fuel cycle is often reported in two distinct phases: 1) the well-to-tank (WTT) phase, which includes resource extraction, feedstock production, fuel production, refining, blending, transportation, and distribution; and 2) the tank-to-wheels (TTW) phase, which includes refueling, consumption, and evaporation (Farrell & Sperling 2007). The complete fuel cycle analysis is also referred to as a WTW analysis. Separation into two phases allows a comparison of fuels independently from vehicle-related assumptions, including efficiency, emissions controls, and fleet turnover rates (Farrell & Sperling 2007).

Although the majority of carbon emissions occur during the combustion phase, crude oil products are commoditized into standard oil products, and as such, there is little difference in carbon emissions from combustion once the crude oil is refined (Charpentier et al. 2009). Moreover, the effects of upstream processes are often diluted when compared to the combustion of the fuel itself. Excluding the combustion processes temporarily from the product system when conducting an impact assessment therefore provides a clearer picture of the carbon intensity for producing comparative fuels. Keeping the system boundary in mind, there is a broad consensus regarding the higher carbon emissions from the refinement of crude oil from tar sands compared to conventional oil production (Charpentier et al. 2009; Gerdes & Scone 2009).

Ultimately, not all LCA models assess emissions equally, even if combustion is included. For instance, the black carbon (BC) component of aerosols has a significant global warming potential (GWP), of which diesel engines are a major source; nevertheless, not all LCAs include BC (Farrell & Sperling 2007). In general, most fuel LCAs consider carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) when quantifying the GWP in order to normalize GHGs emissions to CO_2 equivalents. The GWPs developed by the Intergovernmental Panel on Climate Change (IPCC) "equate gases on the basis of their radiative forcing over a 100-year period" (Farrell & Sperling 2007).

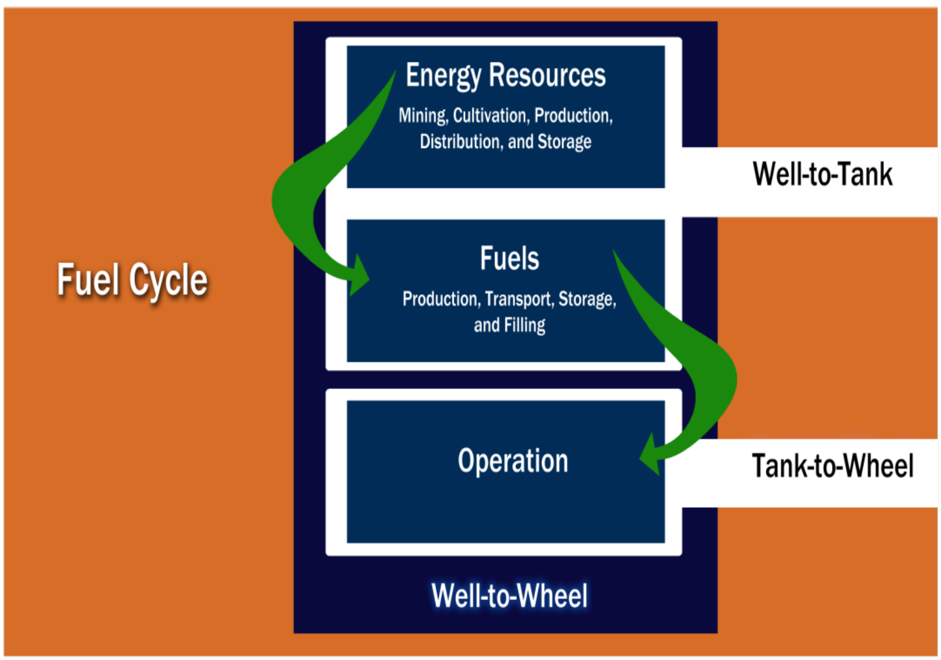


Figure 1. Conceptual representation of a fuel cycle components.

Vehicle Cycle

Fuels vary in their upstream and combustion-phase emissions, and the vehicles they power have similarly variable emissions linked to vehicle production, maintenance, and disposal/recycling. These *vehicle cycle* (or *embodied*) emissions contribute to the total life cycle emissions associated with providing a transportation service. Unfortunately, direct LCA comparisons are difficult due to the limited production of alternative HDVs and, by extension, emission assessments of those vehicles. This is particularly pronounced for vehicle disposal/recycling and maintenance processes, as newer technologies have not been in commission long enough for meaningful comparative studies; bi-fuel vehicles also complicate these comparisons. Currently, HDV powertains are available for biodiesel blends, natural gas, and hydrogen fuel. Electric vehicles and 100% biodiesel (B100) heavy-duty vehicles are in development but in limited production. A more detailed explanation is available in **Appendix 3**.

Alternative Trucks and Fuels

There is agreement that HDVs are a significant and growing source of air pollution in the US. Trucks over 8500 lbs contribute approximately 370 million metric tons of CO_2 annually, or about 22% of the total transportation sector GHG emissions and approximately 7% of the total energy-related GHG emissions for the country (Farrell & Sperling 2007). Furthermore, HDVs in some regions can contribute over 30% of nitrogen oxide (NOx) and over 60% of particulate matter (PM) emissions. Currently, HDVs are almost entirely reliant on petroleum and are responsible for consuming nearly 600 million barrels of petroleum annually in the US (Meyer 2011).

Trucks are categorized into eight classes depending on vehicle weight. Some of these trucks, such as Class 8 HDVs, are responsible for a disproportionately large percentage of annual truck VMT and fuel consumption. For example, the average VMT for all trucks is approximately 13,000 mi/yr, while Class 8 HDVs travel an average of approximately 46,000 mi/yr. This accounts for 30% of total truck VMT and 20% of total truck fuel consumption, despite the fact that only 2.5% of all trucks on US roads are Class 8 HDVs (Davis et al. 2010).

Additionally, the disproportionate consumption of fuel by Class 8 HDVs relative to the other classes is due to low fuel efficiency. The fuel efficiency for Class 8 HDVs averages 5.7-5.9 miles per gallon (mpg) (Davis et al. 2010), although mpg varies by the amount of freight per maximum payload capacity per truck. While the fuel economy of "cars, vans, pickup trucks, and sport utility vehicles increased by an average of 2.1% from 1997 to 2002," the fuel economy based on mpg for Class 8 HDVs decreased 14.8% during that period (Transportation Research Board 2010; Davis et al. 2010). Nevertheless, in terms of energy intensity per metric ton-mile, from 1975 to 2005, the amount of fuel required to move a given amount of freight a given distance was reduced by more than half (Transportation Research Board 2010). Current projections show that domestic shipping metric ton-miles will increase approximately 25% from 2010 to 2035 (US Energy Information Administration 2010).

Freight activity is typically measured in metric ton-kilometers (metric ton-km), which is the product of the mass of freight and the distance it is carried. The total mass of freight depends largely on the types of goods carried and the level of manufacturing activity in a given sector (Kamakate & Schipper 2009). The total distance traveled unit, unlike freight metrics, does not provide information on important characteristics, such as the distance a specific product and each of its components are transported or the value of the freight transported (Kamakate & Schipper 2009).

In the US, almost all HDVs currently use compression ignition (CI) engines that burn ULSD fuel with a sulfur content of 15 parts per million (ppm) or less. Since diesel engines are more efficient and provide more torque than gasoline engines, diesel is utilized by HDVs as their fuel source. While heavy-duty long-haul trucks are essential to US commerce, these vehicles emit PM, NOx, CO_2, and N_2O, in addition to other pollutants at much higher levels than light-duty vehicles (LDVs). They also use significant amounts of fuel and produce substantial emissions while idling.

As a result of climate change, local air pollution, and energy security concerns, many countries, including the US, are seeking to integrate alternative fuels into the national fleet mix. While several alternative fuels may indeed show potential, infrastructure implementation and cost challenges will have to be addressed before any significant market penetration will be observed (Frey et al. 2008).

As mentioned prior, there is an array of potential alternative fuels; however, many of the HDV counterpart technologies are not currently available for purchase. Thus, while some alternative fuels are a topic of interest in academic discourse, they are not necessarily practical for near-term investment. An overview of the alternative fuels associated with the HDV road tractors that are currently available on the market are described below.

Compressed Natural Gas

Natural gas (NG) is commonly sourced from naturally occurring fossil energy; and as with all fossil fuels, it is non-renewable. Alternatively, NG can also be produced from captured landfill gas (GREET 2012).

There are some advantages to NG compared to diesel from an environmental standpoint. It burns cleaner than diesel, although it does contain compounds of sulfur and inert compounds such as nitrogen and CO_2. Nonetheless, because NG has a high octane (110-130), it has potential for use in a high compression engine (MacLean & Lave 2009). Ultimately, NG is composed primarily of CH_4, but also contains small amounts of propane, butane, and pentane, among other hydrocarbon compounds.

Liquefied Natural Gas

The process of liquefaction of NG is to condense it into liquefied natural gas (LNG) by a combination of refrigeration and compression, which consumes approximately 10% of the energy content of the NG (Greene 1996). While liquefaction and storage require expensive equipment, it reduces the volume compared to compressed natural gas (CNG) by a factor of 600, and therefore has been considered a viable alternative fuel option for long-haul applications (MacLean & Lave 2009). Ultimately, technical storage issues such as vapor-boil off from small storage tanks and heat transfer usually require fleet vehicles to return to a central facility each day (MacLean & Lave 2009).

Electric & Hybrid Diesel Electric

While battery electric vehicles (BEV) are marketed to the public as zero emission vehicles (ZEV), as they do not possess any combustion emissions, the source for generating the electricity used to charge the batteries is important to consider. While electricity can be generated by nuclear, wind, hydropower, or solar, and therefore have no associated air emissions during the generation process, the use of coal or wood can result in significant upstream emissions. Thus, the reduction in environmental degradation and emissions are contingent on the source of electricity and ultimately requires infrastructure investments in order to significantly render electricity a "clean fuel" (MacLean & Lave 2009). Furthermore, current batteries have low energy density (thus requiring a large battery mass), are composed of toxic heavy metals, and ultimately result in environmental discharges and undesirable effects from mining and smelting the required metals (MacLean & Lave 2009).

Hybrid electric vehicles (HEV) combine an energy transformation system with one or more energy storage systems (MacLean & Lave 2009). Although the most common HEVs are an IC engine and a battery, other fuels such as diesel could be integrated. There are currently several forms of an HEV: 1) conventional IC engine with a slightly larger battery than a conventional IC vehicle; 2) conventional HEV with much more electricity storage onboard than an IC engine that charges the battery (series hybrid) or charges the battery and provides direct power to the wheels (parallel hybrid); and 3) a vehicle whose batteries are charged from the electrical grid with an IC engine onboard to provide ancillary power and help recharge the battery (MacLean & Lave 2009).

Fuel Cell & Hydrogen

Fuel cell vehicles (FCV) have the potential for zero emissions and high efficiency when fueled with hydrogen. Fuel cells convert energy stored in a fuel directly into electricity without combustion. Furthermore, unlike a battery, where the size limits the supply of chemicals, fuel cells can be continuously filled with fuel to produce electricity indefinitely (i.e., FCVs can be refueled) (MacLean & Lave 2009). The fundamental fuel required for fuel cells is hydrogen, but according to MacLean and Lave (2009) there may be other types of fuel available to power a fuel cell in the future. Current fuel cells convert power by introducing hydrogen at the anode, which splits the hydrogen into ions and free electrons.

A hydrogen economy has been on the agenda for decades as a potentially promising source of fuel (MacLean & Lave 2009). Similar to electricity, hydrogen is an energy carrier and not an energy source, and thus must be generated. The most salient advantage of hydrogen over other alternative fuels is that the oxidation product is water vapor and no CO_2 is produced. While combusting hydrogen in air can result in the formation of NOx, it can be reduced to low levels with proper and advanced engineering. Additionally, hydrogen is non-toxic and non-carcinogenic. Since the onboard storage is limited due to its low energy content per volume, practical usage requires storage as a cryogenic liquid or in a solid-state if possible (MacLean & Lave 2009).

There are three general strategies for hydrogen production and distribution: 1) production at a large centralized facility and then distributed via pipeline or truck to refueling stations; 2) production at a large number of decentralized facilities where it could be delivered to the vehicle; and 3) production by reforming a hydrocarbon fuel (i.e., natural gas, methanol, etc.) onboard a vehicle (MacLean & Lave 2009). There is an array of pathways for hydrogen production. One common pathway is NG reformation and electrolysis (electric current to split water into its constituents) of water using electricity; this process converts NG to synthesis gas and removes CO_2 and carbon monoxide (CO). Since the typical processes for hydrogen production require electricity or steam methane reforming, the upstream emissions for hydrogen production are contingent on which processes are utilized in the product system.

Policy Incentives

Historically, government policies have driven much of the environmental improvements in regards to motor vehicles, beginning over 40 years ago with the Clean Air Act (CAA) of 1970, which first required regulation of mobile sources of pollution. However, over the decades, policymakers have made efforts towards tackling the much more challenging and diffuse issue of climate change by regulating carbon emissions. In 1992, the Energy Policy Act (EPAct) required the Department of Energy (DOE) to establish the Alternative Fuel Transportation Program. Part of this program included establishing and evaluating the Replacement Fuel Goal, which required replacing 30% of national motor fuels with non-petroleum fuels by 2010. However, in 2007, DOE extended the deadline for the goal to 2030. EPAct also created the official list of alternative fuels and established the process by which DOE adds new fuels to the program.

Beyond the federal level, states have also established their own standards. With the CAA amendment in 1990, California was given special authority to regulate its emissions at levels more stringent than the federal standards. Since then, the state has pursued aggressive policies to manage mobile emission sources. In 2007, the state legislature passed Assembly Bill 118 to mitigate transportation-related carbon emissions through a variety of measures, including: creation of the Alternative and Renewable Fuel and Vehicle Technology Fund to stimulate research and efficient improvements; stimulation of research into life cycle impacts of low-carbon fuels; removal of high-polluting vehicles from the roads; and grants to promote alternative fuel technologies.

The majority of government policies at the national and state level focus on LDVs. However, reaching emission reduction targets will require efficiencies to be found in other sectors beyond LDVs; for example, roughly 15% of the GHG emissions in 1990 were related to HDV usage, based on a life cycle perspective (McCollum & Yang 2009). Without broad policies to incentivize modernizing non-LDVs, including HDVs such as Class 8 freight trucks, there has been very limited investment in more efficient technologies. This is especially problematic because HDVs have longer service lives than LDVs; thus, it often takes longer for the benefit of these policies to be realized (McCollum & Yang 2009).

This HDV policy gap is also observed at the state level. For example, California passed a historic law, Assembly Bill 1493, which mandates the California Air Resources Board (CARB) to regulate GHG emissions from vehicles; however, this only applies to passenger cars and pickup trucks. Based on a review by Yang et al, excluding non-LDVs from policies jeopardizes the likelihood of California reaching its ambitious emission reduction goals (2009). Forecasts predicting freight hauling to grow more quickly than passenger travel as the US imports increasing quantities of goods through California ports will only exacerbate the difficulty of achieving emission reduction targets (Farrell & Sperling 2007).

According to research by Kamakaté and Schipper, not only is there a relative increase over passenger travel, but there is also a relative increase in shipping by truck as opposed to by rail or boat. Part of this expansion is due to the flexibility and speed of on-road truck logistics compared to other transportation modes, especially for shipping high-value goods. The researchers noted that policies addressing energy use and emissions should not just focus on fuel costs because they represent only one aspect of logistics and real-world implementation (2009).

Current Policies and Incentives

As previously discussed, there are limited federal policies that guide HDV deployment beyond general limitations set out through pollution regulations. One federal incentive that can be applied to freight hauling trucks is the Improved energy Technology Loan program offered by the DOE. The program guarantees loans for projects that support early adoption of advanced and alternative fuel vehicles.

At the state level, the types and numbers of advanced fuels and vehicles policies vary widely. California offers one of the largest suites of programs; however, even in such an assertive state, the policies open to HDVs are limited. Regional air quality districts administer many of the programs directed towards HDVs:

- Buy-down Incentives for Natural Gas and Propane Vehicles: Through the Alternative and Renewable Fuel and Vehicle Technology Program, applicants can receive assistance in purchasing a NG or propane vehicle, including HDVs
- Goods Movement Emission Reduction Program: A result of Proposition 1B, this program administered by CARB allows local agencies to offer financial incentives to owners of freight hauling equipment to upgrade to advanced technologies
- Carl Moyer Memorial Air Quality Standards Attainment Program: This program provides funding to cover the incremental cost of modernizing equipment, including HDV fleets
- Heavy-Duty Truck Idle Reduction Requirements: This regulation limits the allowable idle time to help reduce emissions
- Heavy-Duty Vehicle Greenhouse Gas Emissions Regulations: Vehicles of a certain size must be equipped with fuel-efficient tires and aerodynamic parts that improve fuel economy
- On-Road Heavy-Duty Diesel Vehicles (In-Use) Regulation: This regulation requires diesel trucks to modify technology to reduce emissions; by 2023, almost all trucks must will have 2010 model year engines or better

In addition to state programs, regional and municipal entities can enforce restrictions that reduce emissions and motivate a shift towards advanced technology vehicles. For example, the ports of Oakland and Long Beach enforce the Clean Trucks programs. These programs incrementally restricted older, higher polluting vehicles operating in those ports until complete bans went into place. The programs also provided assistance during the transitions by offering subsidies for new truck purchases.

Economic Considerations of Alternative Fuel-Use in Heavy-Duty Vehicles

Diesel enjoys many advantages over alternative fuels, mainly due to its cost, efficiency, and established infrastructure. All available heavy-duty, alternative fuel vehicles fall into three classes: diesel-electric, natural gas, and hydrogen fuel cell, each with their own set of economic barriers to implementation (AFDC 2012).

Diesel Electric

Diesel-electric vehicles use a hybrid engine that runs on diesel fuel, but they also use an electric component of the engine that recaptures energy lost during braking and idling. The use of these trucks is becoming increasingly widespread. While only 9,000 diesel-electric trucks were sold globally in 2010, that number is projected to increase to 100,000 by the year 2015, with 300,000 hybrid trucks being sold over that time (Pike Research 2012).

The costs associated with a diesel-electric hybrid truck differ from those of a conventional diesel truck. The initial cost of a hybrid truck is about $100,000, compared to $80,000 to $85,000 for its normal counterpart (East 2012). This represents a 15%-20% price premium that must be recouped over the life of the vehicle. Research has shown that hybrid diesel vehicles are able to offer between a 5% and 50% reduction in fuel costs (Pike Research 2012). For example, diesel-electric trucks used by Coca-Cola are reported to use 30% less fuel than a normal diesel truck (GeorgiaGov 2009).

Whether or not it makes financial sense to invest in such vehicles depends highly on their use, as more fuel is conserved in functions where stop-starts are frequent. This technology also benefits from a highly established fuel infrastructure and a historically high national average price of $4.12 per gallon of diesel (Alternative Fuels Data Center 2012).

Natural Gas

CNG is far less energetically dense compared to gasoline and diesel, resulting in limited vehicle range of around 300 miles. Due to their limited range, CNG vehicles are less practical as fleet vehicles compared to LNG alternatives (Whyatt 2010). Nonetheless, CNG trucks can be practical if vehicles travel short distances and return to the same fueling location each day, resulting in their effective use as city buses and municipal waste refuse vehicles. If operated under the correct conditions CNG trucks can be profitable by taking advantage of a somewhat established infrastructure and cheap fuel prices; the national average price for a gallon of gasoline equivalent is $2.08 (Whyatt 2010; Idaho 2005).

For fleet operations, LNG may be the NG fuel of choice. The primary benefit of LNG is the extended operating range of such a vehicle, which can be 500 miles (Whyatt 2010). Since the natural gas is in a liquefied state, it is more energetically dense (although still less than diesel). This makes it more practical for trucking, which is typically done over longer ranges. A truck outfitted to run on LNG is significantly more expensive than its diesel counterpart. While a warrantied diesel truck costs $88,400, an equivalent truck with an LNG powertrain costs $152,000. Including federal and state taxes, this can result in a price premium of $76100, or $47,300 after a $28,800 tax discount. This incremental cost must be made up with fuel cost savings (Whyatt 2010).

Where LNG fuel is available, it is relatively cheap. Although it is slightly more expensive than CNG due to liquefaction costs, it is only about $2.50 per gallon of gasoline equivalent, making it possible to profitably operate an LNG vehicle in areas where conventional fuel prices are inexpensive (Alternative 2012). A significant problem with adopting LNG currently is the lack of available infrastructure; because there are so few LNG vehicles on the road, there are very few available fueling stations (and vice versa). Constructing new LNG stations represents significant capital costs; mechanical systems alone for an LNG station cost from $350,000 to $1,000,000 compared to $50,000 to $150,000 for a conventional station (AFDC 2010). An entire LNG fueling station would cost between $1 million and $4 million (Whyatt 2010).

For lack of infrastructure to no longer be a disincentive, it is estimated that the number of LNG stations must be 20% the number of conventional stations (Yeh 2007). Since there are approximately 170,000 conventional stations and LNG stations cost millions of dollars, this will require an investment in the order of tens of billions of dollars (Whyatt 2010). Until natural gas infrastructure is widespread, LNG fleet implementation is only realistic in situations that require minimal range and are within the vicinity of an operating LNG station.

Hydrogen Fuel Cell / Electric

Hydrogen is an attractive fuel source because of its benign emissions; however, commercialization of hydrogen fuel cell vehicles is very limited, especially in the heavy-duty class. At the HDV level, Vision Motor Corp. produces both current options. One of these vehicles is a terminal tractor used to move cargo around a port, while the other is a Class 8 truck called the Tyrano. The Tyrano boasts 3,300 lb/ft of torque, but it also comes with a $270,000 price tag (Heavy-Duty 2012; Vision 2011).

Although the Tyrano has high upfront costs, it has low fuel and maintenance costs. Similar to natural gas, hydrogen fuel costs between $2.25 and $2.50 per gallon of gas equivalent, which is much cheaper than diesel fuel at $4.12 per gallon. Hydrogen prices are predicted to remain cheap compared to conventional fuel sources. Not only is hydrogen abundant, but also the projected cost of hydrogen delivery dropped by as much as 30 percent between 2005 and 2010, largely because of technical improvements (EERE 2010). Additionally, fuel cell vehicles require far less maintenance than their diesel or natural gas counterparts; operating costs for the Tyrano are 35% less than diesel trucks and 50% less than LNG trucks (EERE 2010).

While hydrogen fuel vehicles are able to save on fuel and maintenance costs, the combination of minimal infrastructure and short driving range significantly limits their current utility. The Tyrano has a single-fill operating range of approximately 200 miles, which is not enough for most long-haul applications (Vision 2011). Also, hydrogen fuel infrastructure suffers from the same competitive disadvantages as natural gas with few hydrogen fuel stations available. This limits the use of the Tyrano to drayage operations, hauling freight from the port of Long Beach to nearby rail yards and other distribution facilities (Vision 2011). Until infrastructure for hydrogen becomes more developed, the Tyrano and other hydrogen fuel cell vehicles will be constricted to short-range shipping.

Existing Tools and Models

GaBi

An abbreviation of Ganzheitliche Bilanz, ("holistic balance" in German), is a life cycle assessment modeling software and database. Created by PE International, GaBi has over 4,500 ready to use LCI profiles based on primary industry data. PE has an annual upgrade, refreshing all contents in GaBi databases to provide current LCI data and impact methodologies. GaBi has current data sets including heavy-duty diesel vehicles, with inputs and outputs that account for diesel, cargo, and combustion emissions. The GaBi data sets used do not consider alternative fuels for HDVs. FEAT accounts for this limitation by consulting additional sources that consider these emissions such as GREET.

GREET

Sponsored by the US Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), Argonne National Laboratory developed the full life cycle model Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET). GREET allows for the calculation of pollutants emitted per mile by vehicle and fuel type. The tool is largely considered the standard for vehicle emissions modeling and is widely used by government agencies for planning and conformity assessment; GREET, and its modified version CA-GREET, serves as the basis for EPA's Renewable Fuel Standard (RFS2) and California's Low Carbon Fuel Standard (LCFS).

VISION

The VISION model was developed to provide estimates of the potential energy demand, oil use, and carbon emission impacts of advanced light and HDV technologies and alternative fuels through the year 2100. Beginning with the 2010 version, hydrogen production pathways have been added. The model has also been expanded to enable simulation of NG-powered medium and single unit heavy-duty trucks and LNG-powered heavy combination trucks (Argonne VISION 2011). Since the goal of the project is to determine feasible, near-term methods to reduce Patagonia's fuel-use GHG emissions, the VISION model is not utilized; however, future use of the project's logistics tool may require integration of Argonne's VISION modeling.

METHODOLOGY

At its core, the project quantifies freight GHG emissions from company-specific logistics data using the Excel-based Freight Emissions Assessment Tool (FEAT); this information is then used in a baseline assessment of Patagonia's contribution to global warming and compared to emissions from alternative fuel scenarios. The project was guided by an LCA framework, an iterative process that defines the system boundary and scope, inventories the flow of GHG emissions generated by the functional unit, and characterizes the emissions into a common impact category (in this case, metric tons of CO_2 equivalent). The results are then interpreted with respect to the data quality, project scope, assumptions and limitations, and parameter sensitivities.

Because Patagonia does not have precise vehicle-use data, the functional unit refers to the movement of freight (in metric ton-km) rather than the movement of vehicles themselves. This is important since emissions are a function of both distance and mass. Moreover, the use of metric ton-km allows calculations to be made in the absence of fleet data and provides a unit with which Patagonia is familiar. Existing LCA models (e.g., PE International's GaBi models) are able to calculate fuel consumption on a freight basis. While this requires assumptions regarding allocation, utilization, and technology mix, these assumptions can be updated as more precise logistics data becomes available. In contrast, emission factor data (including those from GREET) typically describe emissions in terms of vehicle miles traveled or energy consumption (i.e., g CO_2e/mile or CO_2e/BTU), which is primary data unavailable to the project.

Beginning with the project scope, the following sections describe the relevant data collection and modeling operations that underlie FEAT, connecting fuel consumption to a final emission factor used to calculate GHG emissions. Working through these steps helped guide the development of FEAT such that the tool and baseline assessment were developed in conjunction; elements of the baseline were parameterized into the tool, while the outputs of the tool were used as a case study for Patagonia. Exploring alternative fuel options further required the use of FEAT, with the final results and recommendations summarized in this report.

Defining Project Scope

Defining the scope of the project establishes the purpose and intended use of the results; this includes determining WTW emissions for several fuels, identifying opportunities for Patagonia to reduce its global warming potential (GWP) and identifying viable alternative fuels to be integrated into its distribution network via the development of FEAT (see **Appendix 1** for FEAT screenshots). The scope determines which product system will be analyzed, the functional unit, system boundaries, impact categories, data requirements, and limitations. Ultimately, the scope of the project is to determine the fuel cycle GHG emissions associated with the total metric ton-kilometers of domestic Patagonia freight shipped by Class 8 HDVs per distribution leg (excluding Hawaii) during the 2012 fiscal year.

The vehicles within the scope of the project include on-road HDVs available in the near term. The US Department of Energy's Alternative Fuels and Advanced Vehicles Data Center (AFDC) lists alternative fuel types and their applications. This database lists 14 road tractor HDVs that are currently available on the market and are designed to utilize alternative fuels (AFDC 2012). These HDVs utilize the following powertrains: 1) **c**ompressed natural gas (CNG); 2) hybrid diesel-electric; 3) hybrid fuel cell electric, 4) hydrogen; and 5) liquefied natural gas (LNG). Although several other alternative fuel technologies currently do not exist for road tractor HDVs, the fuels themselves are nevertheless included within the scope of the project to assess WTW emissions and viability for future implementation.

Product System

The product systems evaluated in the project are: 1) low-sulfur (LS) diesel; 2) B20 (20% Biodiesel); 3) soy B100 (100% Biodiesel); 4) algae B100 (100% biodiesel); 5) compressed natural gas (CNG); 6) landfill liquid natural gas (LNG); 7) North American liquid natural gas (LNG); 8) liquid petroleum gas (LPG or propane); 9) electricity; and 10) liquid and gaseous hydrogen with refueling steam methane reforming (SMR), central steam methane reforming (SMR), or electrolysis.

Functional Unit

The functional unit for the assessment is defined as one metric ton of Patagonia freight shipped over a distance of one kilometer by Class 8 HDVs.

Impact Category

Many LCA studies cover several categories that include resource use, acidification, toxicity, global warming potential, and other impact categories. The selection of the impact category determines the type of data that will be collected. Since the intended use of the results will be to reduce the GWP of Patagonia's distribution network, the GWP impact category is selected for the project. Moreover, the impacts are quantified for the fuel use only and do not include the emission embodied in the vehicle cycle (i.e., construction, maintenance, and disposal/recycling of HDVs) (see **Appendix 3**).

Data Requirements

In accordance with the goal and scope of the project, and in addition to the utilization of aggregated secondary data included in the unit processes developed by GREET and GaBi software tools, input data required to develop FEAT include: 1) the average package density; 2) the average semi-trailer volume; 3) the average max payload of the truck; 4) the utilization rate; 5) the percent shipped by freeway, rural roads, and urban roads; 6) the fraction of each type of truck technology utilized; 7) the amount of diesel consumed or energy required per metric ton-km for each type of fuel at a given utilization rate; 8) the relative fuel economies for each vehicle type (in miles per gasoline gallon equivalent) at a given utilization rate; 9) the total number of metric ton-km freight for the 2012 fiscal year; and 10) the average marginal cost per unit of fuel consumed in 2012. The output results in FEAT include: 1) WTT metric ton CO_2e; 2) TTW metric ton CO_2e; 3) WTW metric ton CO_2e; 4) amount of each fuel consumed; 5) total fuel cost for each type of fuel consumed; 6) numbers of stations available in the US for each fuel type consumed; and 7) market availability of the technology for each fuel type consumed.

Data Collection

Primary Data Collection

Initial data was needed to examine how Patagonia products move through the domestic portion of their distribution network. Patagonia utilizes three freight forwarders – UPS, FedEx, and Expeditors International – to ship packages within the US. The billing information for Patagonia's 2012 fiscal year (May 2011 through April 2012) from these three companies was used as primary data. Shipping data used in the project is described in terms of the functional unit, metric ton-km; this is opposed to vehicle miles traveled; metric ton-km is a more accurate representation of products being shipped over complex supply chains.

Patagonia freight data was collected for four distribution segments (**Figure 2**): 1) Inbound to the Reno, NV distribution center (Expeditors); 2) Outbound direct-to-customer (UPS); 3) Outbound wholesale (UPS or FedEx); and 4) Outbound to Patagonia retail stores (UPS). The billing information provided the weight and destination of each shipment, making the metric ton-km calculation relatively straightforward. Using this data, total metric ton-kilometers were calculated for each distribution category.

Several assumptions were made during this process, given that the following primary data from UPS was not disclosed to the project team: 1) the percent of alternative fuels currently used for ground freight within the US for distributing Patagonia products; 2) the percent rail utilized for ground freight within the US for distributing Patagonia products; and 3) the absolute, rather than the average, estimated utilization rate for each truck for distributing Patagonia products by ground freight.

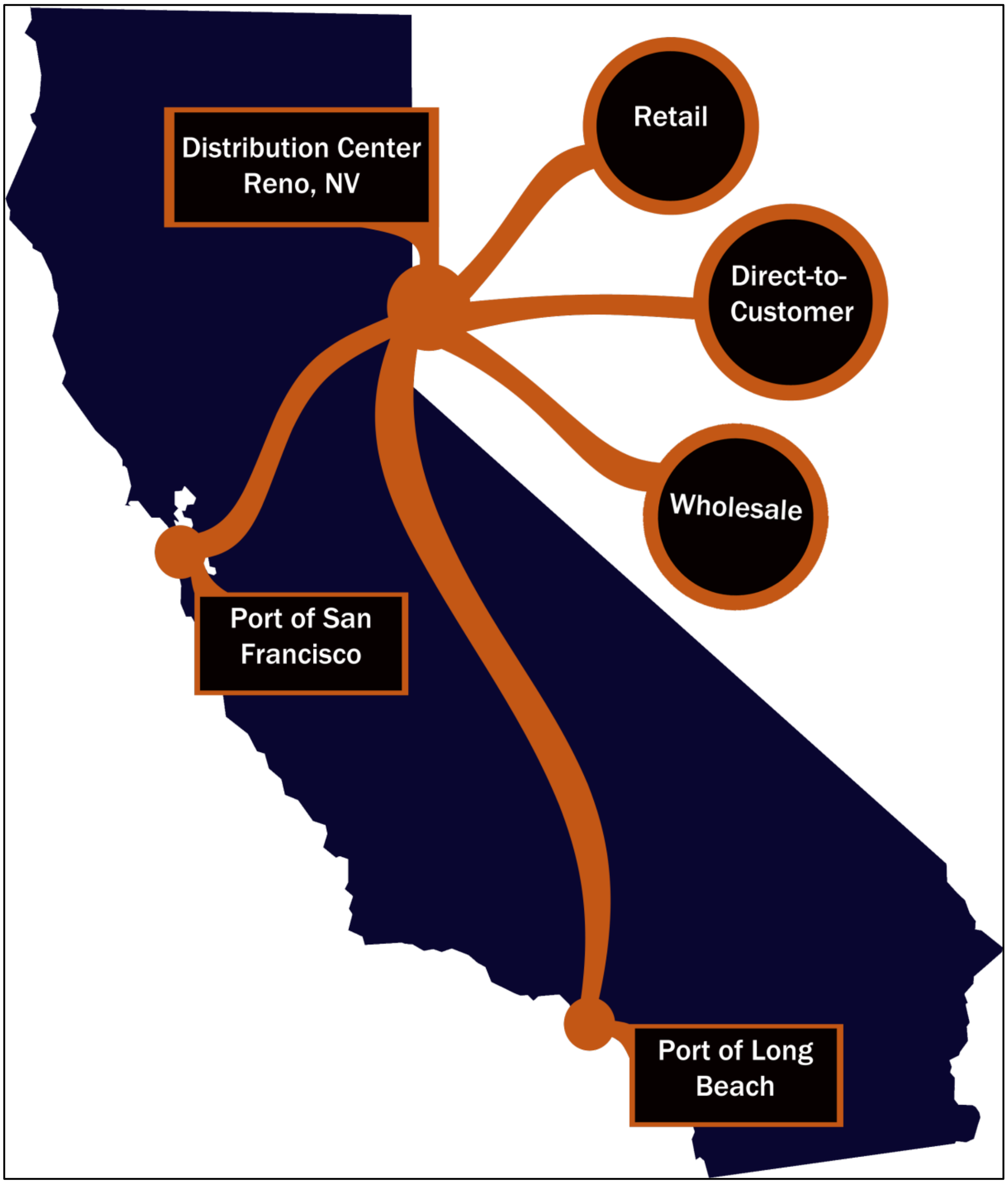


Figure 2. Patagonia's domestic distribution network under study. Cargo shipments arriving at the ports of Long Beach and San Francisco are transported to the Reno Distribution Center; from there, freight is shipped to the rest of the US through 3 primary legs (Retail, Direct-to-Customer, and Wholesale)

To isolate the ground distribution, shipments that were made via UPS Overnight Air and UPS 2nd Day Air were excluded as air shipping was beyond the project scope. To calculate the distance traveled by each package, a fixed distance for each state was determined to facilitate the processing of large amounts of data. To calculate each state's freight miles/kilometers, the distance from the Reno, NV distribution center to the three largest cities in each state was measured using Google Maps. Then, weighted average distances were calculated based on the relative populations of these cities, reflected in **Appendix 2**.

Using these distances, the following freight totals for the 4 separate distribution legs were calculated (**Table 1**, **Figure 3**):

Shipment Category	Freight (metric ton-km)
Inbound	1,414,738
Direct to Customer	1,760,456
Wholesale	2,072,594
Retail	445,002
Total	5,692,790

Table 1: Metric ton-km totals for the corresponding legs of the distribution network.

Trailer Volumes

The project assumed the length of the shipping at 48 feet (14.63 m); at the given trailer length, the container volume is 98.8 cubic meters and the maximum payload is 25.34 metric tons (APL 2013). Federal law requires states to set the maximum length limit for the semitrailer in a truck tractor-semitrailer combination to be at least 48 feet or the grandfathered limit for a particular state; the 48-foot container is set as the allowable length limit in 27 states in the US (US DOT 2011). Data of actual container sizes used for shipping Patagonia products by logistics companies was not disclosed; thus, a best-estimate container size was employed in FEAT.

Due to these requirements, as well as the fact that long-distance trailers often go across states, the project assumed that a 48-foot container is used across the US for long-haul shipping Patagonia product in this tool even though both 48-foot containers and 53-foot containers are commonly used nationwide (Shipping 2013).

Alternative Fuel Availability and Prices

The availability and cost of fuels may determine the feasibility of adopting new technologies to ship products. The Department of Energy's Alternative Fuels Data Center (AFDC) provides quarterly data on the number and locations of alternative fueling stations and the average price of each fuel. The AFDC inventories the public and private stations for biodiesel, CNG, electric, hydrogen, LNG, and LPG alternative fuels. These stations are important to consider because infrastructure for refueling will be needed for alternative fuel vehicles replacements. It is also important to consider what fuel stations are accessible along a company's distribution network in deciding upon what vehicle types to purchase and use. Refer to **Defining Project Scope** regarding the type and availability of trucks that are currently on the market.

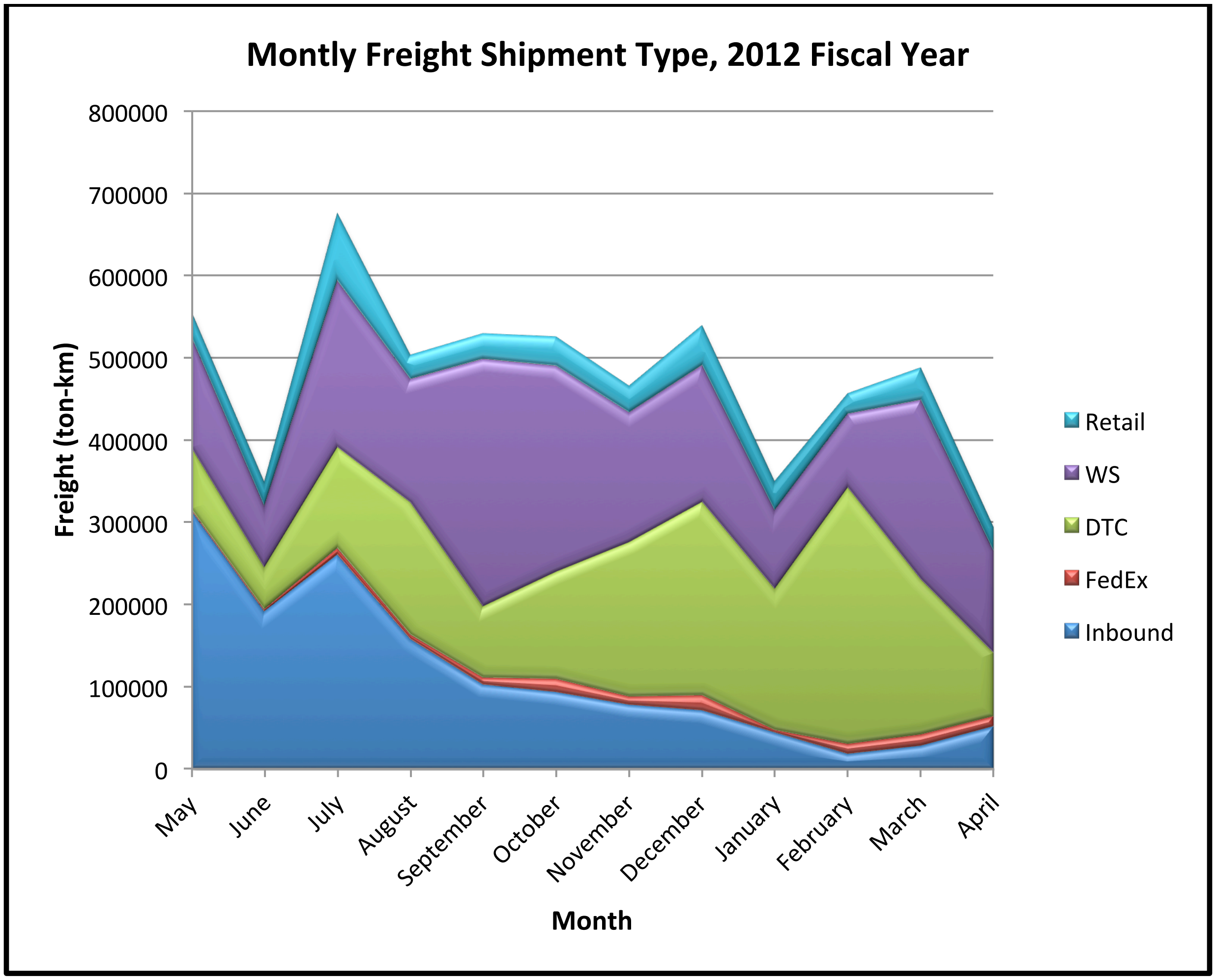


Figure 3: Graphical representation of metric ton-km per month, broken up over the various distribution legs.

GaBi Information and Parameters

To calculate diesel consumption, PE International's GaBi process data set "Truck-trailer used; diesel driven, Euro 0 - 5 mix" (hereafter referred to as GaBi process), which models a diesel combination truck-trailer with a 34- to 40-metric ton gross weight and 27- metric ton payload capacity. This process matches Patagonia freight shipment process in which packaged goods are transported by long-haul heavy-duty trucks. The model includes the following variable parameters: payload, utilization rate, distance, driving cycle type, and vehicle technology mix (i.e. European emission standards 0-5). This dataset models the use phase – the TTW phase – by Class 8 trucks only and does not include truck production, end-of-life treatment of the truck, or the fuel supply chain (e.g. emissions from exploration, refinery, and transportation).

Utilization refers to the fraction of maximum payload being transported by the trucks. Because Patagonia packages have relatively low density, the shipments were limited per truck by a trailer's volume rather than by the payload capacity. For this reason, the utilization rate was based on filling a 48-foot trailer to volume capacity with freight at the average Patagonia package density; this average density was based on the mass and volume of shipments arriving at the Patagonia distribution center (PE International 2011).

$$Utilization = avg\ density\ shipment * \frac{trailer\ volume}{trailer\ payload\ capacity}$$

The GaBi process also includes adjustments for the mix of trucks meeting varying EU regulatory emission standards (*Directive 05/55/EC*), which categorizes new heavy-duty diesel engines into increasingly restrictive emission classes, *Euro 0* through *6*. The model also accounts for three driving cycles: urban, motorway, and rural. These driving cycles are based on the Common Artemis Driving Cycles (CADC) developed by a European research project to reflect real-world driving profiles (Andre 2004). The baseline model currently uses default values for engine emission standards and driving cycles from GaBi.

FEAT Modeling

Determining the total GWP from the product system involves three fundamental steps:

1.

$$\left(\frac{Fuel\ Consumption}{metric\ ton - km}\right) \times (Fuel\ Energy\ Density) = \left(\frac{Energy\ Consumption}{metric\ ton - km}\right)$$

2.

$$\left(\frac{Energy\ Consumption}{Metric\ ton - km}\right) \times \left(\frac{GHG\ Emissions}{Energy\ Consumption}\right) = \left(\frac{GHG\ Emissions}{metric\ ton - km}\right)$$

3.

$$\left(\frac{GHGEmissions}{metrictonkm}\right) \times (Total\ metric\ ton - km) = \boldsymbol{Total\ GWP\ (in\ CO_2 e)}$$

Modeling Energy Consumption

Diesel fuel requirements for freight movement were modeled from the GaBi process (see *GaBi Information and Parameters* under **Data Collection**) for a diesel truck-trailer with a 25.34 metric ton payload capacity. The equation for calculating the amount of diesel required per unit of freight is shown below.

$$Y_{ij} = \frac{\alpha_{ij} + u * (\beta_{ij} - \alpha_{ij})}{p * u}$$

where: *Y* = diesel consumption per unit freight for Euro vehicle type, *i*, and driving cycle, *j*
α = diesel consumed per kilometer for empty vehicle
β = diesel consumed per kilometer for loaded vehicle
p = payload capacity
u = utilization rate

The diesel consumption, *Y*, varies depending on the truck technology type, *i*, and driving cycle profile, *j*. The truck technology types modeled represent different heavy-duty vehicles (labeled Euro 0 through 5) regulated under the European Directive to meet reductions in criteria pollutants; although increased emission control strategies could reduce the energy conversion efficiency (e.g., mile per gallon rate), a large difference in GHG emissions between different Euro class trucks is not expected. The driving cycles were modeled on highway (*mw*), interurban/rural (*ru*), and urban (*ur*) driving profiles.

The payload capacity, *p*, and utilization ratio, *u*, are variable parameters, which were calculated for Patagonia shipments by the aforementioned methodology (see *GaBi Information and Parameters* under **Data Collection**).

Given the six Euro truck types and three driving cycles at a constant payload and utilization rate, 18 different diesel consumption rates (kg/metric ton-km) were calculated. A weighted average based on percentage of each truck Euro type and percentage of trucks driving each of the three vehicle cycles was calculated:

$$Z = \sum_{i \in \{E_0 \ldots E_5\}} \sum_{j \in \{mw, ur, ru\}} c_i d_j Y_{ij}$$

where: *Z* = overall diesel consumption per unit freight
Y = diesel consumption per unit freight for Euro vehicle type, *i*, and driving cycle, *j*
c = Euro vehicle type share
d = vehicle cycle share

Because the Patagonia shipment process was being limited to Class 8 truck transportation, the shipments were modeled to be traveling largely on highway and rural driving cycles. The shares of Euro types in the US was assumed to be the same as those default values provided by the GaBi process.

Summing the diesel consumption values of each type of truck and driving cycle with varying weights provided the overall diesel consumption rate, *Z*, in terms of kg per metric ton-km.

Subsequent to calculating the diesel consumption per unit of freight, the energy required per unit of freight is determined via utilizing the amount of diesel per US gallon and the amount of energy per US gallon of diesel, as shown below.

$$\left(\frac{kg\ diesel}{metric\ ton - km}\right) \times \left(\frac{US\ gallon}{kg\ diesel}\right) \times \left(\frac{BTU}{US\ gallon}\right) = \left(\frac{BTU}{metric\ ton - km}\right)$$

Calculating Emission Factors

The final output of the GaBi process is total fuel consumption (in terms of BTU) per unit of freight (metric ton-km); this output is based on a specific utilization, drive share, and technology mix that most closely aligns with assumed Patagonia Class 8 HDV use.

The literature for existing emission factors are considerably variable; GREET provides the most comprehensive, centralized, and vetted inventory of emission factor data. Further, GREET allows for a range of emission factors to be used based on project scope and data availability (for instance, different process inputs), and can be modified on an *ad hoc* basis. Importantly, emission factor data derived from GREET agrees with the modeled GaBi output and project results (533 metric tons of CO_2e from FEAT versus 542 metric tons of CO_2e from GREET's FLEET model).

GREET also contains a list of relative fuel economies for alternative fuel HDVs that were utilized to calculate conversion efficiency factors. These fuel economies were reported in miles per gasoline gallon equivalent (MPGGE). A GGE equates the energy content of any motor fuel, including alternative fuels, to that of a gallon of gasoline. These factors determine how much energy each vehicle requires to move a given amount of freight relative to conventional diesel HDVs. An efficiency factor over one indicates that more energy is required to move a unit of freight by that alternative fuel vehicle than by a diesel truck. Similarly, a value less than one suggests that less energy is required to move a unit of freight. Moreover, a value of one indicates that the amount of energy required per unit of freight is equivalent to a conventional diesel powertrain.

$$\left(\frac{MPGGE\ diesel}{MPGGE\ alternative}\right) = Y_a$$

where: *Y* = conversion efficiency factor
a = alternative fuel type

Subsequent to calculating several conversion efficiency factors for each fuel type, these factors were then utilized to determine the energy requirement per unit of freight for each HDV.

$$\left(\frac{BTU\ diesel}{metric\ ton - km}\right) \times Y_a = \left(\frac{BTU\ alternative}{metric\ ton - km}\right)$$

The amount of GHG emissions (CO_2e) per BTU for each fuel in GREET were then utilized to calculate the amount of CO_2e per unit of freight for each HDV.

$$\left(\frac{BTU\ alternative}{metric\ ton - km}\right) \times \left(\frac{g\ CO_2e}{BTU}\right) = \left(\frac{g\ CO_2e}{metric\ ton - km}\right) \text{ for alterative fuels}$$

For each fuel type, these values were reported in CO_2e per BTU for WTT and TTW. As such, the emission factors calculated in the previous step were summed, as shown below.

$$GREET\ WTT + TTW\ Emission\ Factors = WTW\ Emission\ Factors\ (in\ g\ CO_2e/BTU)$$

Calculating Total Emissions

$$\left(\frac{GHGEmissions}{metrictonkm}\right) \times (Total\ metric\ ton - km) = \boldsymbol{Total\ GWP\ (in\ CO_2e)}$$

After calculating the final emission factors, the final step was to calculate total emissions. The emissions factors were multiplied by the metric ton-km totals calculated in primary data collection. The result of this equation was total global warming potential in CO2 equivalence. These totals can be seen in the **Results** section.

Cross-referencing Emission Factors

The GREET emission factor reflects a weighted GWP based on the relative contributions of the three primary GHG release from fuel combustion: CO_2, N_2O, and CH_4. The result is a single emission factor characterized to CO_2 equivalents. However, GaBi models each of these GHGs individually based on technology mix and driving cycle. In order to cross-reference the GREET diesel emission factor, an additional emission factor was calculated using the GaBi process (see *GaBi Information and Parameters* under **Data Collection**).

For this process, GaBi calculates emissions for each specific driving cycle and Euro technology mixes combination using the following equation:

$$Emission\ factor\ = \frac{(\alpha\ +\ (\beta - \alpha) *\ utilization)}{(payload\ capacity\ *\ utilization)}$$

Where α is the emission factor for an empty run per kilometer and β is the emission factor for a loaded run per kilometer. The Handbook Emissions Factors for Road Transport (HBEFA 3.1) was used as the data basis for variables in the GaBi model for direct vehicle emissions from trucks in relation to the distance traveled. The variables α and β used to determine average emission values for Euro 0-5 and drive shares were acquired via HBEFA 3.1. The driving cycle and Euro technology mix are weighted based on the model parameters using the same method as in the diesel consumption calculation. Using the default parameters in FEAT, the GaBi process produced the following emission factors for each of the GHGs (Table 2):

GHG	Emission Factor	Unit
CO_2	75.18	grams / metric ton-km
CH_4	0.0003118	grams / metric ton-km
N_20	0.0006315	grams / metric ton-km

Table 2: GaBi GHG emission factors in g / metric ton-km

There are other outputs within the data set but they are not within the scope of this project, which primarily focuses on GHGs. To transform these results into a final CO_2e emission factor, a set of characterization factors was needed. The following IPCC GWP 100 factors were used (Table 3):

GHG	Global Warming Potential
CO_2	1
CH_4	21
N_2O	310

Table 3: IPCC GWP 100 characterization factors

Using these characterization factors resulted in a CO_2e emission factor of 75.38 g/metric ton-km, which is nearly equivalent to the GREET emission factor of 75.75 g/metric ton-km. Given the minimal variation between these two factors, it was determined that sourcing emission factors from GREET is indeed sound.

Tar Sands Emission Factors

To calculate WTT emission factors for tar sands diesel, two major recovery and extraction processes that are currently utilized in Alberta's oil sands were taken from Bergerson et al. (2012). These two process modules, surface mining dilbit (diluted bitumen) pathway (SMD) and steam assisted gravity drainage pathway (SAGD) (*in situ*), are quantified through a life cycle model, Greenhouse gas emissions of current Oil Sands Technologies (GHOST) (Bergerson et al. 2012). The following equation was utilized in developing an emission factor:

$$Emission\ factor = \left(\frac{g\ CO2e}{BTU\ Gasoline}\right)\ x\ W$$

where W is the ratio of WTT GHG emissions for diesel and gasoline taken from GREET, expressed as:

$$W = \left(\frac{\frac{g\ CO_2e}{BTU\ diesel}}{\frac{g\ CO_2e}{BTU\ gasoline}}\right)$$

The emission factor for each pathway is ultimately calculated in metrics of GHG emissions per unit of freight. Furthermore, it is assumed that the TTW emissions of tar sands diesel are identical to the normal consumptive mix of diesel in the model. Therefore, the same TTW emission factor calculated for diesel via the methodology described prior was utilized for both tar sands diesel pathways. Ultimately the TTW and WTT emission factors are summed to calculate each WTW tar sands emission factors.

RESULTS

By utilizing FEAT, the GWP of several fuel WTW emissions were derived; importantly, the following results reflect parameters based on average Patagonia package data: vehicle utilization rate (0.413), tonnage (10.53 metric tons), and max payload (25.34 metric tons). These results ultimately provide a reference from which Patagonia can work to reduce its GWP and identify viable alternative fuels to be integrated into its distribution network.

The first section describes Patagonia's baseline freight emissions. Specifically, this section reports the fuel cycle GHG emissions associated with the total metric ton-kilometers of domestic Patagonia freight shipped by Class 8 HDVs per distribution leg (excluding Hawaii) during the 2012 fiscal year. It is assumed that 100% of the freight is shipped by diesel fuel internal combustion engine trucks. The second section compares Patagonia's baseline to a range of scenarios whereby the use of alternative fuels is explored; sensitivities to specific parameters, including package density, are also reported.

Patagonia Baseline

Emission Factors

Figures 3 and **4** illustrate 1) the emission factors for each fuel type broken into the WTT and TTW components of the fuel cycle and 2) the relative emission factors for each fuel type on a WTW basis. By comparing these two graphs, it is observed that the WTT component of the fuel cycle has a substantial impact on the WTW emission factor as a whole, although the emissions per metric ton-km are primarily from TTW (except for the hydrogen fuel types included within the scope of the project). Furthermore, **Figure 4** shows that LNG derived from landfill gas has the smallest WTW emission factor (15.89 gCO_2e/metric ton-km), with B100 biodiesel derived from soy being the second smallest (23.50 gCO_2e/metric ton-km), and B100 biodiesel derived from algae being the third smallest (46.18 gCO_2e/metric ton-km). It is also observed that liquid hydrogen derived from electrolysis has the largest WTW emission factor (211.82 gCO_2e/metric ton-km), despite having zero WTT emissions per metric ton-km (this is the case for all current hydrogen fuel types), and gaseous hydrogen derived from electrolysis being the second largest (167.77 gCO_2e/metric ton-km), and liquid hydrogen derived from refueling station SMR being the third largest (120.33 gCO_2e/metric ton-km) (**Table 4**).

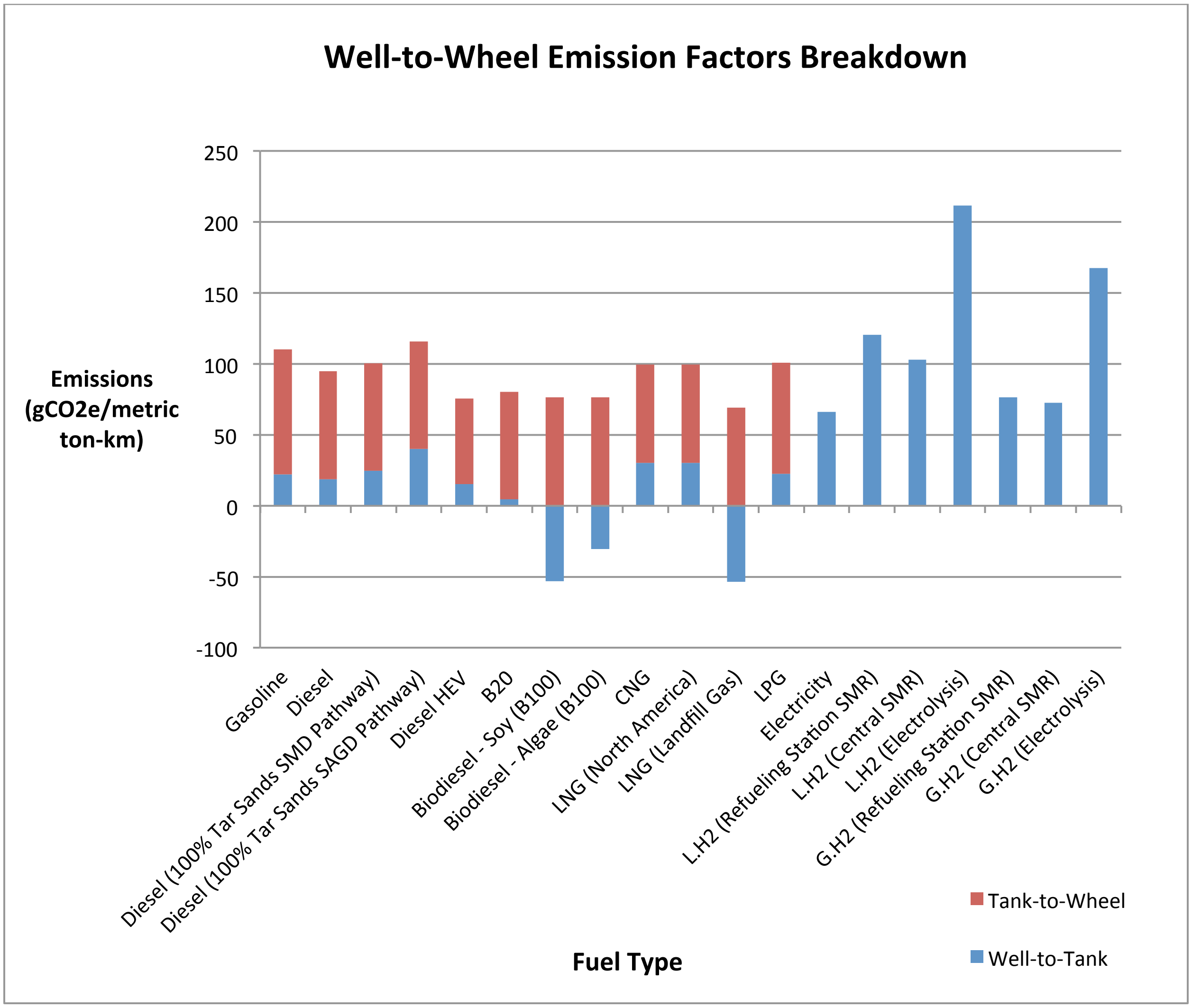


Figure 4: Calculated WTW emission factors showing the relative contributions of upstream (WTT) and use (TTW) emissions at a utilization rate of 0.413, a payload of 10.53, and a max payload of 25.34 metric tons.

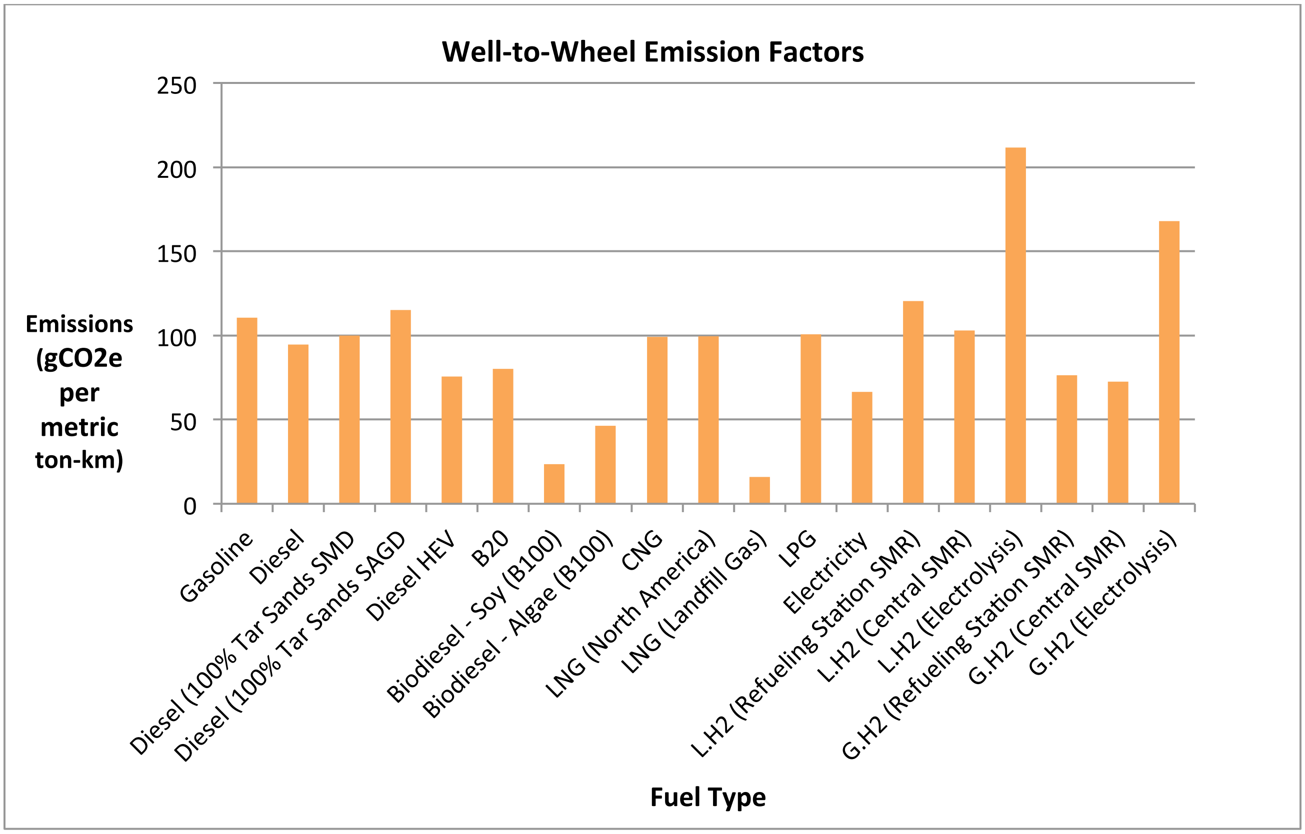


Figure 5: Total calculated WTW emission factors at a utilization rate of 0.413, a payload of 10.53, and a max payload of 25.34 metric tons.

Fuel Type	Emission Factor (in *g CO_2e/metric ton-km*)
Gasoline	110.4
Diesel	94.69
Diesel (100% Tar Sands SMD Pathway)	99.91
Diesel (100% Tar Sands SAGD Pathway)	115.3
Diesel HEV	75.75
B20	80.12
Biodiesel - Soy (B100)	23.50
Biodiesel - Algae (B100)	46.18
CNG	99.35
LNG (North America)	99.62
LNG (Landfill Gas)	15.90
LPG	100.8
Electricity	66.39
L.H2 (Refueling Station SMR)	120.33
L.H2 (Central SMR)	102.8
L.H2 (Electrolysis)	211.8
G.H2 (Refueling Station SMR)	76.52
G.H2 (Central SMR)	72.63
G.H2 (Electrolysis)	167.8

Table 4: Well-to-Wheel emission factors in gCO_2e / metric ton-km

Fuel Cycle GHG Emissions

Figure 6 and **Table 5** illustrate the WTW fuel emissions broken down by distribution leg; **Figure 7** compares WTW emissions for current diesel mix to two tar sands extraction pathways. The table presented above shows the actual emission values in metric tons of CO_2e per distribution leg. The wholesale leg of Patagonia's distribution network was shown to have the largest relative emissions associated with the total metric tons of Patagonia product packages shipped by Class 8 HDVs (194.29 metric tons CO_2e). Moreover, the direct-to-customer leg had the second highest relative emissions (165.03 metric tons CO_2e), with the inbound leg being the third highest (132.62 metric tons CO_2e), and the retail leg being the lowest (41.72 metric tons CO_2e). Furthermore, it is observed that the retail leg has an order of magnitude fewer emissions than all the other distribution legs, which are all of the same order of magnitude. Ultimately, fuel cycle emissions associated with the total metric tons of Patagonia product packages, shipped by Class 8 HDVs, over the sum of the average kilometers driven per freight leg in the domestic US during the 2012 fiscal year is observed to be 533.66 metric tons CO_2e. Trucks over 3,855 kg in the US contribute approximately 370 million metric tons of CO_2e annually, or about 22% of the total transportation sector GHG emissions (Farrell & Sperling 2007). Only 0.0001442% of those GHG emissions were contributed by Patagonia's freight WTW emissions in the domestic US during the 2012 fiscal year.

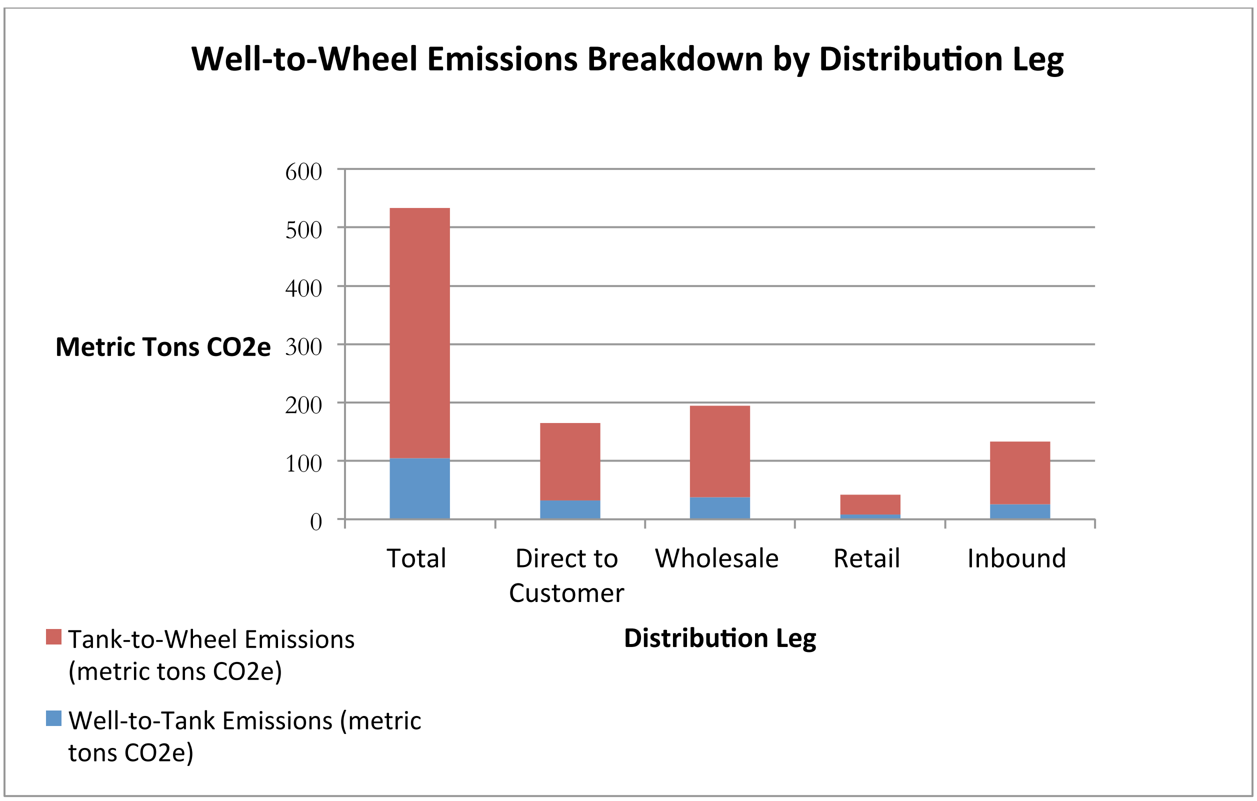


Figure 6: Breakdown of Patagonia freight GHG emissions by distribution leg at a utilization rate of 0.413, a payload of 10.53, and a max payload of 25.34 metric tons.

Distribution Leg	Well-to-Tank Emissions (metric tons CO_2e)	Tank-to-Wheel Emissions (metric tons CO_2e)	Well-to-Wheel Emissions (metric tons CO_2e)
Total	104.5	429.1	533.7
Direct to Customer	32.33	132.7	165.0
Wholesale	38.06	156.2	194.3
Retail	8.172	33.54	41.72
Inbound	25.98	106.6	132.6

Table 5: Breakdown of Patagonia freight GHG emissions by distribution leg at a utilization rate of 0.413, a payload of 10.53, and a max payload of 25.34 metric tons.

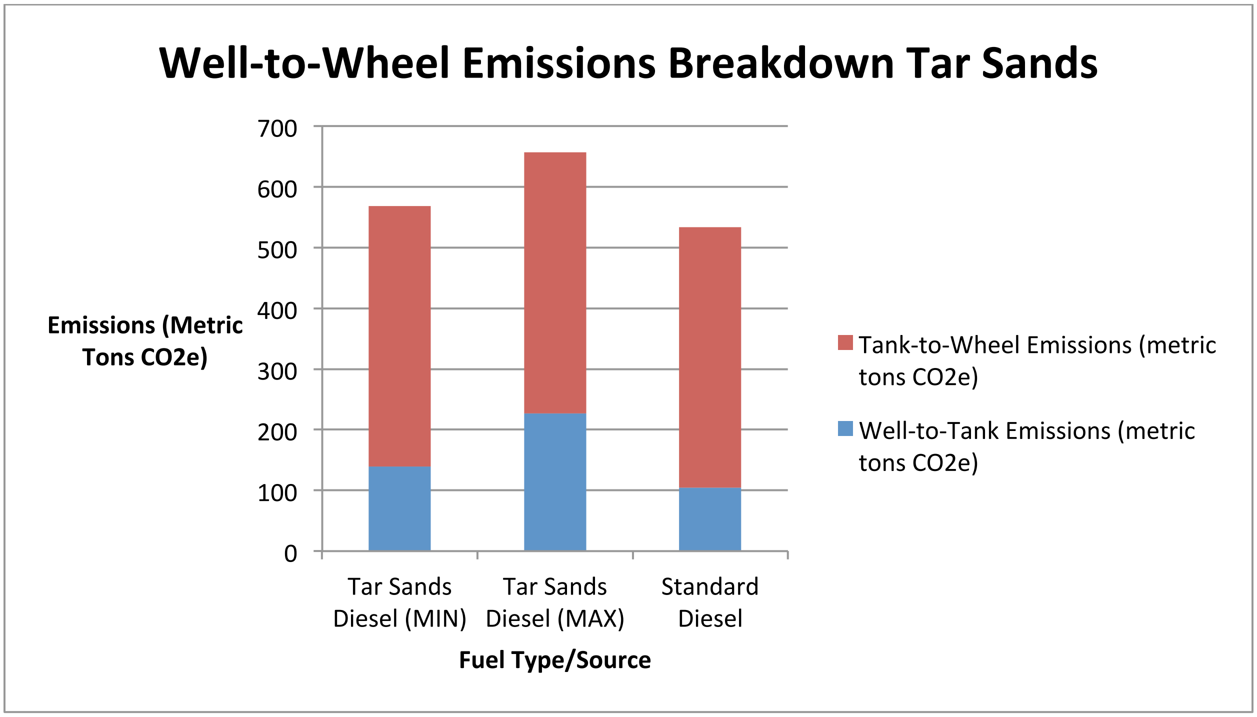


Figure 7: Well-to-Wheel emissions in metric tons CO_2e. These values represent 100% of the total domestic Patagonia freight shipped during 2012 FY for each pathway. Therefore, these values represent the potential range of life cycle baseline emissions associated with diesel use by Class 8 trucks in the model, and the corresponding sensitivity of each emission factor pathway. Tar Sand Diesel (MIN) represents SMD pathway and Tar Sand Diesel (MAX) represents SAGD pathway, described in subsection *Tar Sand Emission Factors* under **FEAT Modeling** section. Well-to-Wheel emissions for SMD pathway (569 metric tons CO_2e) and SAGD pathway (656 metric tons CO_2e) correspond to a 34% and 117% increase in upstream emissions relative to the standard diesel consumptive mix in the model, respectively.

Scenario Testing and Sensitivity Analysis

After establishing the baseline, implementation of alternative fuels was considered. In considering implementation scenarios, only those fuels that had both lower emissions than diesel, and available truck technologies, were examined. The three fuels that fit these criteria are B20, Diesel HEV, and LNG (landfill gas).

Having identified the alternative vehicles to analyze, the project considered scenarios in which diesel trucks were replaced by the different alternative fuel vehicles, from 0% replacement of diesel trucks to 100% replacement. As seen in **Figure 8**, LNG trucks using natural gas from landfills showed the largest decrease in emissions from replacement, while diesel HEV and B20 fuels show more modest improvements.

While these scenarios suggest that Patagonia's freight emission concerns could be eliminated with the use of LNG trucks, there was the concern of whether these alternative fuel technologies were feasible for Patagonia given that they do not own their own fleet and contract with third-party shipping companies.

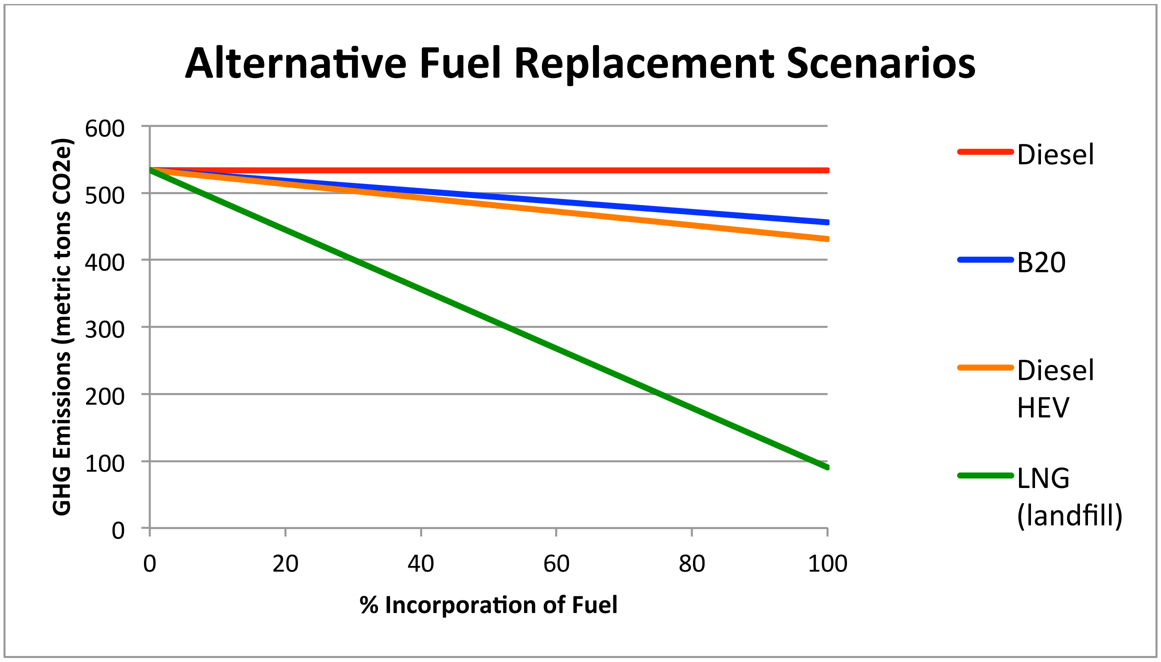


Figure 8: Alternative fuel replacement scenarios at utilization rate 0.413

Sensitivity Analysis

In order to observe how sensitive each of the input parameters utilized for the project were, a sensitivity analysis was performed. Each of the parameters listed in the table below were reduced and increased by 20% of the original value, and the resulting change in WTW emissions was observed so that a variation factor could be calculated. Furthermore, in conducting a sensitivity analysis for technology mix parameter inputs, each type was consecutively phased out and substituted by the newest truck technology. Essentially, the newest trucks replace the fraction of oldest trucks, and each time the next fraction of oldest technology mixes are substituted until the entire fleet is composed solely of the most recent diesel ICE technology.

Parameter	*Value*	*WTW Emissions Variation Factor*
Package Density (kg/m3)		
Current	106.619	-
Min	85.2952	1.192459325
Max	127.9428	0.8717
Average Trailer Volume (m3)		
Current	98.80	-
Min	88.92	1.1925
Max	118.56	0.8717
Max Payload (metric tons)		
Current	25.859	-
Min	20.6872	1.05754
Max	31.0308	0.9616
MW Drive Share (MW,R,U)		
Current	0.7, 0.23, 0.07	-
Min	0.56, 0.337, 0.103	1.0156
Max	0.84, 0.123, 0.037	0.9844
All MW	1, 0, 0	0.9667
R Drive Share (MW, R, U)		
Current	0.7, 0.23, 0.07	-
Min	0.7344, 0.184, 0.0816	1.0031
Max	0.6516, 0.276, 0.0724	1.0023
All R	0, 1, 0	0.9959

U Drive Share (MW, R, U)		
Current	0.7, 0.23, 0.07	
Min	0.634, 0.310, 0.056	0.9970
Max	0.615, 0.301, 0.084	1.0074
All U	0, 0, 1	1.3460
Technology Mix		
Current	0.007, 0.004, 0.046, 0.348, 0.083, 0.512	-
Eliminate Euro 0	0, 0.004, 0.046, 0.348, 0.083, 0.519	0.9988
Eliminate Euro 0,1	0, 0, 0.046, 0.348, 0.083, 0.523	0.9986
Eliminate Euro 0,1,2	0, 0, 0, 0.348, 0.083, 0.569	0.9979
Eliminate Euro 0,1,2,3	0, 0, 0, 0, 0.083, 0.917	0.9823
Eliminate Euro 0,1,2,3,4	0, 0, 0, 0, 0, 1	0.9793

Table 6: Sensitivity of all major parameters included in the model

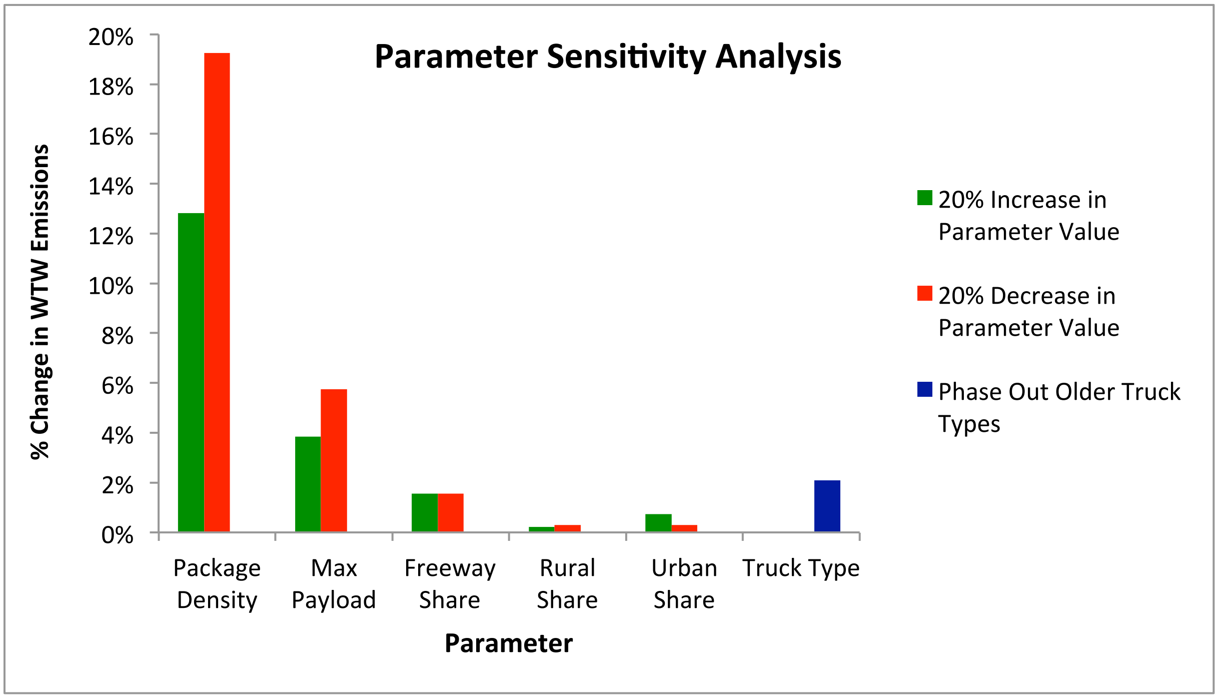


Figure 9: Sensitivity of all major parameters included in the model

As shown in **Table 6** and **Figure 9** above, reducing and increasing each of the current parameter input values by 20%, the alteration in package density and trailer volume inputs resulted in the largest variation in WTW emissions. By reducing the package density by 20%, the WTW emissions increase by 19.25%. Similarly, by increasing the package density by 20%, WTW emissions decrease by 12.83%. The WTW emissions as a function of package density are discussed in the next subsection *Package Density*. Since the payload value is package density multiplied by the trailer volume, which is one of the direct variables utilized in calculating both TTW emission factors and energy required per metric ton-km, both parameters possess equivalent sensitivity in the model. While a long-haul distribution network solely composed of urban use is entirely unrealistic, it is interesting to note that by altering the drive share to 100% urban use, WTW emissions increase by 34.60%. On the other hand, if drive share is altered to 100% motorway, WTW emissions only decrease by 3.33%.

Package Density

As one of the objectives of the project is to develop recommendations for reducing Patagonia's GHG emissions, the project considered WTW emissions as a function of package density, since the package density parameter is observed to be the most sensitive. Moreover, while trailer volume is observed to have the equivalent sensitivity, increasing semi-trailer volume is likely less feasible for Patagonia to implement than the increase in package density to reduce its GWP; this is discussed further in **Interpretation** and **Recommendation**.

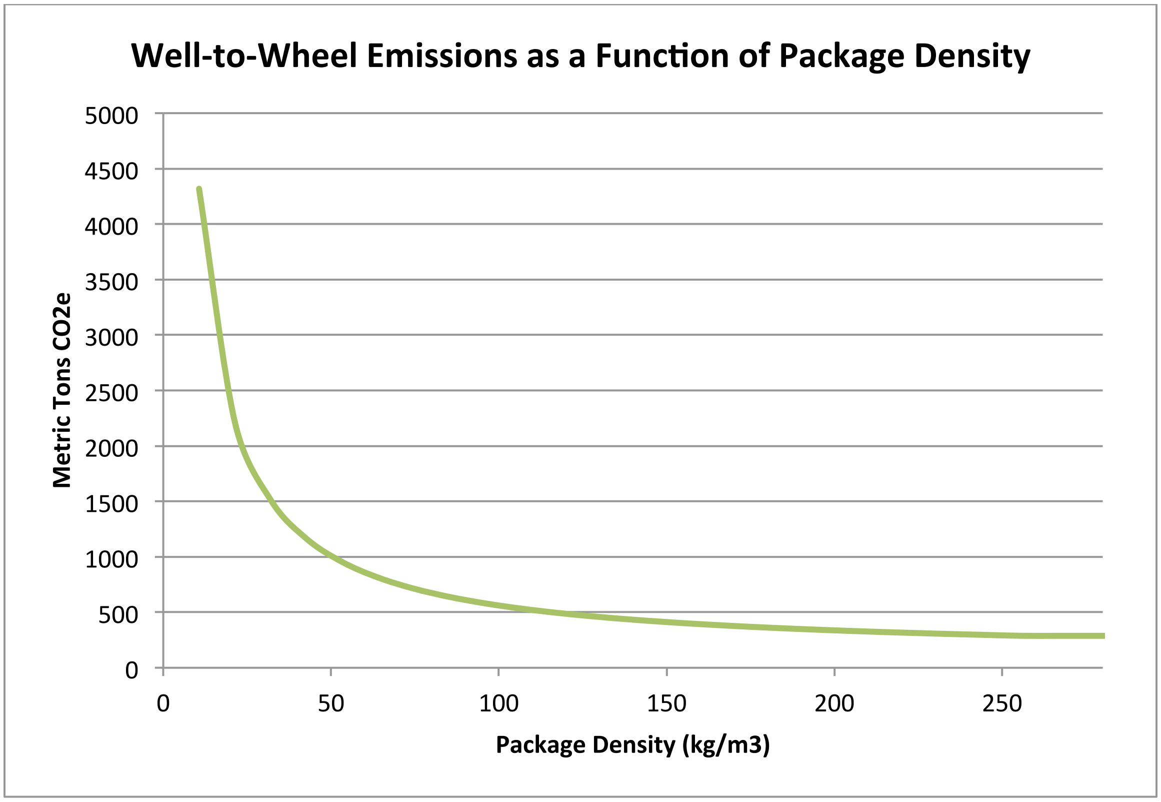


Figure 10: Metric tons of CO_2e emissions as a function of package density at utilization rate 0.413

The above graph (**Figure 10**) illustrates the WTW emissions as a function of package density at a utilization rate of 0.413, a payload of 10.53, and a max payload of 25.34 metric tons. The project assumed a current average package density of 106.62 kg/m^3, which results in total WTW emissions of 533.66 metric tons of CO_2e. As the package density increases, the potential reduction in WTW emissions decreases. Furthermore, as the package density increases and approaches 256.48 kg/m^3, the potential reduction in WTW emissions reaches a maximum of 288.08 metric tons CO_2e. Therefore, increasing the package density beyond 256.48 kg/m^3 causes no marginal decrease in WTW emissions. Since it is difficult to observe how significant of a reduction in WTW emissions results from increasing or decreasing the package density by 20%, the graph (**Figure11**) is displayed below.

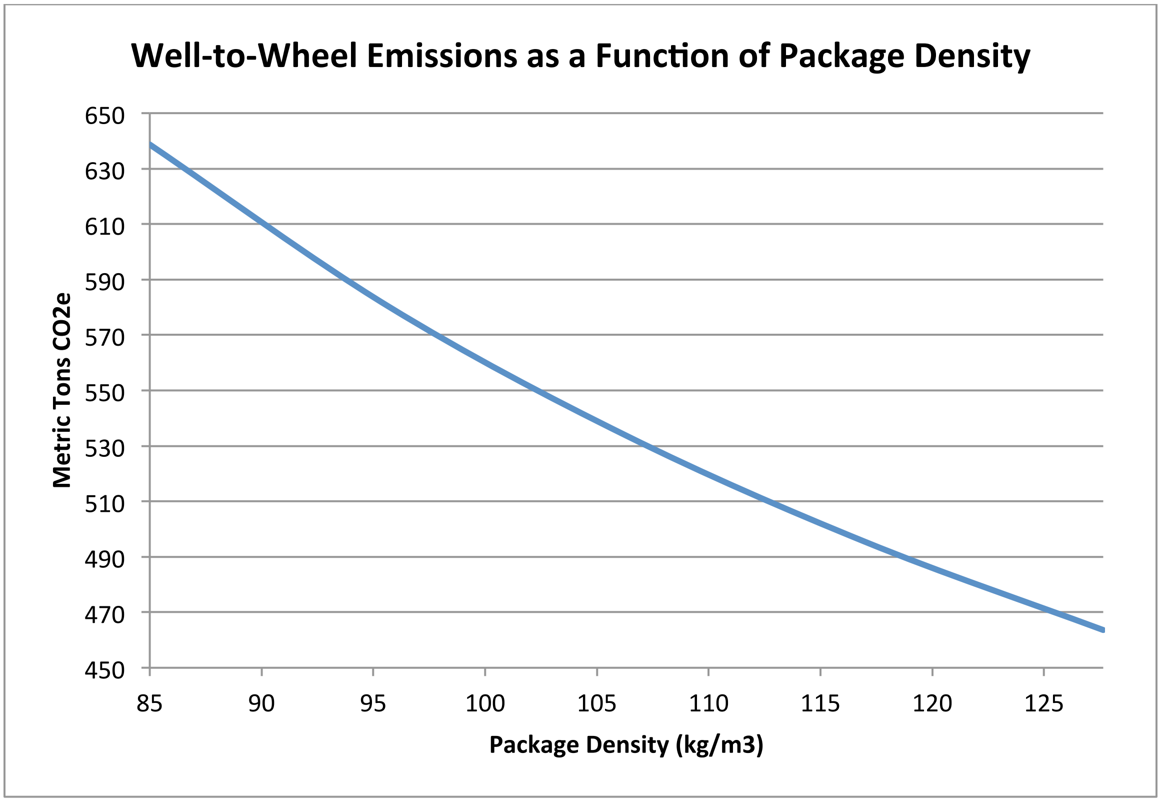


Figure 11: Metric tons of CO2e emissions as a function of package density at utilization rate 0.413

In **Figure 11**, it is clear how substantial an impact the change in package density has on WTW emissions. It is observed that a 20% increase in package density reduces WTW emissions by 70.05 metric tons CO_2e, and a 20% decrease increases WTW emissions by 105.08 metric tons CO_2e.

INTERPRETATION

The true value provided by FEAT lies in its illustrative potential and in establishing a more comprehensive framework to account for GHG emissions. As such, the results are interpreted as relative values; their robustness in absolute terms is limited by the range of uncertainty in emissions data and by project assumptions. For instance, emission factors taken from GREET and fuel consumption coefficients from GaBi were derived from distinct methodologies and independent studies; future research is needed to clarify the range of uncertainty in these values. By clarifying the project assumptions, uncertain parameter values in FEAT can be updated as more reliable data becomes available.

The project was initially motivated by concerns over the use of unconventional fuels in Patagonia's distribution network – specifically the use of oil sands. Based on the findings of the project, not only is the avoidance of oil sands difficult, but there are non-fuel switching options available that more effectively reduce GHG emissions. The only true way to avoid tar sands is to reduce diesel fuel consumption altogether, as the US consumptive mix is difficult to determine; moreover, this does little to prevent other freight operators from using oil sands that Patagonia would presumably avoids. From Patagonia's perspective, the ultimate objective is not to avoid tar sands per se, but to reduce the absolute levels of GHG emissions.

The fuel cycle data combined with the freight emission calculations in FEAT provide Patagonia an important source of leverage when considering transportation fuel options. By synthesizing emission factor data, LCA methodology, and primary logistics data into an industry friendly tool, FEAT can help businesses address the growing demand for sustainable freight practices. Moreover, packaging above Patagonia's optimum density may further assist emission reduction by compensative for less dense packages loaded onto the same truck; thus, payload could be met even with a fraction of sub-optimal package densities. However, Patagonia will have to do an analysis of product packaging limitations and the costs associated with increasing density to determine whether achieving or exceeding optimum density would be feasible.

Assumptions and Limitations

The results are interpreted in light of specific assumptions and limitations in the project; these limitations were largely determined by the scope of the project, data availability, and modeling decisions, as well as Patagonia's interests. Arguably the greatest limitation is the lack of a more complete environmental impact assessment – choosing between different impact categories often involves significant tradeoffs in environmental emissions. Contributions to global warming may be reduced, but the project does not address changes in other emissions categories such as eutrophication, smog formation, or resource use. Rebound effects, infrastructure changes, and non-fuel switching options (e.g., improved fuel economy, optimized trucking routes, and behavioral changes) are also not considered by the project.

The project is also limited by considering only the emissions from Class 8 vehicles, and not from the vehicle production (embodied emission of the vehicle cycle were excluded from the scope; a preliminary assessment is available in **Appendix 3**). However, other modes of transport (e.g., rail or plane), as well as non-Class 8 trucks, are all used in combination to deliver Patagonia products. While the emissions from fossil fuels are largely from HDV use, emissions from alternative transportation systems are not insignificant. Furthermore, it was assumed that the freight forwarders were using 100% diesel to ship Patagonia goods in FY 2012; according to their annual sustainability report, UPS indicates that roughly 1% of their global on-road vehicles (not necessarily Class 8) are alternative fuel vehicles. Lastly, the project also relied on aggregated and/or average data sets; FEAT assumes all trucks are full at all times with "average" package types. This may underestimate total freight emissions if all Class 8 trucks are not full at all times; it also ignores package heterogeneity on different trucks.

The emissions from seasonal and annual variation are also limited. Variable seasonal shipments may make maximizing logistics efficiency during peak and low sales periods difficult. And long-term, Patagonia continues to experience a growing market share and increased sales, which will certainly affect future emissions from their distribution network. Patagonia's continued growth further underscores the value of being able to explore alternative fuel options to meet growing demand.

Despite these limitations, the project provides an important basis for comparison of alternative fuel systems and represents an important starting point in motivating changes in the transportation sector. By making the assumptions transparent, important parameters for future research are identified and recommendations can be made within the context of our system boundary. By using FEAT with this transparently defined scope, Patagonia is better positioned to explore GHG-reducing options from a life cycle approach.

Optimum Density

As the project results indicate, an important relationship emerged from the analysis between package density, payload, and trailer volume. Ideally, every truck would be fully loaded by weight (i.e., pulling the maximum payload) at all times; this translates to a utilization rate of one so that all of the vehicle's towing capacity is put towards the movement of freight. Whenever volume limits the amount of freight per truck, the extra package space displaces otherwise usable payload capacity that could be used to transport additional freight mass. However, as is the case for Patagonia, the density of their "average" package is below the payload limit, meaning that it is volume and not mass that limits the freight capacity; the trailer is "cubed out" with Patagonia packages before the maximum payload is reached. To simplify calculations in the model, all trucks were assumed to be completely filled with average Patagonia packages for the entire trip. Again, this assumption likely under-calculates Patagonia's total emissions, since it is unreasonable to assume all trucks are filled at all times with average Patagonia packages of 106.62 kg/m^3. However, it does provide a useful reference from which to evaluate logistical decisions and underscores the impact of truck utilization rates.

A key finding is that emission reductions are maximized at a specific point, beyond which increasing density no longer reduces WTW emissions. This threshold value represents a utilization rate of one, and increasing packages beyond this density no longer adds to the metric ton-km requirement since the trucks are filled to capacity (in terms of weight, not volume). Importantly, the optimum density is a function of maximum payload and trailer volume; dividing the trailer volume by the maximum payload represents the "breakeven" point between the volume/weight tradeoff, such that the trailer volume and payload are simultaneously maximized.

This has important implications for both Patagonia and their freight forwarders. Patagonia, not operating their own fleet, has more control over the density of their packages than the types of vehicles moving their packages. Fortunately, as the sensitivity analysis results indicate, this is the area of greatest GHG reduction potential; changes in technology mix, driving cycle, or even fuel choice are all unable to reduce emissions as much as package density. In other words, of the parameters included in this model, emissions are most sensitive to package density. At a package density of 106.62 kg/m^3, trailer volume of 98.8 m^3, and assumed payload of 25.34 metric tons, the density of an average Patagonia product is approximately 50% of the optimum density of 256.48 kg/m^3.

For UPS and other freight forwarders, if the volume constraints of their packages are anticipated, these companies may work to expand their trailer capacities to allow for the added mass that would otherwise be left to another truck. The project recognizes that packages may not be so easily homogenized and that the logistical realities of freight movement require less-than-full trucks; however, avoiding the volume constraints of freight shipments is a feasible and effective step in reducing overall emissions. Ultimately, freight forwarders should strive to get as close to the maximum payload as possible.

RECOMMENDATIONS

The first section provides actionable recommendations that Patagonia can take to explore and potentially reduce their freight GHG emissions. The latter section provides broader recommendations for future research.

Recommendations to Patagonia

Recognizing the assumptions and limitations of the project, the following recommendations provide a starting point for Patagonia to develop GHG-reducing strategies from their domestic Class 8 distribution network:

1. **Increase package density**
   As noted above, the optimum package density from a GHG emissions perspective is 256.48 kg/m^3, given the assumed trailer volume and truck payload. Because the trailer is limited by volume at a current product density of 106.62 kg/m^3, Patagonia should attempt to increase the density of their shipped products whenever possible to decrease emissions. This could take place at either the Reno, NV distribution center, or farther upstream in the distribution process.

2. **Solicit logistic specific data from their distribution network**
   To more precisely model fuel-use GHG emissions, Patagonia should seek to better understand the following questions:
   - What percentage of freight is moved by train, plane, and truck type?
   - How much are alternative fuels already integrated into the distribution network?
   - What are the absolute distances the packages travel (i.e., what are the transportation nodes and trucking routes)?
   - How full are trucks, on average (average utilization rate)?
   - What is the average Patagonia package density?

3. **Work with freight forwarders from the port (Expeditor's International) to utilize alternative fuels on the inbound distribution leg in California**
   This section of the network, mostly in California, has the greatest potential for alternative fuel-use given the availability of existing alternative fuel infrastructure and supportive California policies and incentives. Moreover, this portion of the distribution network is less complex then the outgoing legs and can be more easily evaluated for potential improvements; it also deals exclusively with Patagonia freight.

4. **Consider the use of alternative fuels that potentially have lower life cycle GHG emissions throughout the distribution network**
   Using new, life cycle-based knowledge of which fuels are least impactful with regards to GHG emissions, Patagonia should engage UPS and other freight forwarders to consider the use of fuel types, which have lower WTW emission profiles. Given existing emission factor

data, they should initially investigate the potential use of biodiesel and hybrid-electric fuel types. Natural gas systems from landfill sources should also be considered, assuming supply is not otherwise constrained. Importantly, these alternatives should be evaluated against potential tradeoffs associated with fuel switching.

Future Research

To more accurately model freight emissions and to increase opportunities for GHG reduction, the following have been identified as important future areas of research:

1 **Investigate additional non-fuel switching options (in addition to density changes)**

Fuel switching and package density modifications are one of several strategies with the potential to reduce Patagonia's GWP. Increased powertrain efficiency/fuel economy, use of auxiliary power units, vehicle dematerialization, and reduced drag (wind-resistance) are additional options to reduce GHG emissions.

2 **Perform a consequential Analysis**

The project is attributional in approach; modeling environmental impacts in a static state that do not fully evaluate the consequences of logistical changes. For instance, switching to alternative fuels on a larger scale would require significant changes to infrastructure, alternative vehicle development, and supply chain processes (e.g., making packages more dense). While it is easy to compare fuel options in FEAT, each alternative involves additional factors that are not considered in the project.

3 **Refine emission factor uncertainty**

The project results assume a single emission factor value, when in fact a range of values exists in the literature. Uncertainty in these values, particularly fuels with emission factors similar to conventional diesel, should be more thoroughly evaluated.

4 **Quantify tar sands consumptive mix**

The extent to which tar sands are already present in the diesel consumptive mix remains poorly quantified; accordingly, potential GHG "savings" from avoiding tar sands-based fuel is equally difficult to determine. Reducing tar sands consumption requires a more complete understanding of the WTT pathway over temporal and geographic scopes.

5 **Include the Vehicle Cycle**

A more complete impact assessment would address the vehicle cycle, as the production, use, and disposal of alternative vehicles differ from those of conventional vehicles. A preliminary assessment indicates that the vehicle cycle may account for approximately 15% of the fuel cycle GHG emissions (**Appendix 3**), reflecting an important tradeoff between alternative fuel use and associated vehicle cycle.

REFERENCES

Alternative Fuels and Advanced Vehicles Data Center (2010). Clean Cities Alternative Fuel Price Report. [ONLINE] Available at: http://www.afdc.energy.gov/afdc/pdfs/afpr_apr_12.pdf

Alternative Fuels and Advanced Vehicles Data Center (2012). *Heavy-Duty Vehicle and Engine Search*. [ONLINE] Available at: http://www.afdc.energy.gov/afdc/vehicles/search/heavy/#filter%5Burl%5D=&filter%5Bparams%5D=vehicles%255Bmanufacturer_id%255D%3D%26vehicles%255Bfuel_id%255D%3D%26vehicles%255Bapplication_id%255D%3D8

Alt Fuel Prices.com (2012). *Alternative Fuel Prices and Fill Stations for the Entire US*. [ONLINE] Available at: http://www.altfuelprices.com/

APL Limited (2013). *Equipment Specifications - Standard Containers*. [ONLINE] Available at: http://www.apl.com/equipment/html/equipment_specs_standard.html

Argonne National Laboratory. Transportation Technology R&D Center (2011). *GREET Model.* [ONLINE] Available at: http://greet.es.anl.gov/main

Argonne National Laboratory. Transportation Technology R&D Center (2011). *The VISION Model.* [ONLINE] Available at: http://www.transportation.anl.gov/modeling_simulation/VISION/index.html

Bergerson J.A, Kofoworola O., Charpentier A.D., Sleep S., and MacLean M.L. Life Cycle Greenhouse Gas Emissions of Current Oil Sands Technologies: Surface Mining and In Situ Applications. ACS Publications. Environ. Sci. Technol. (46) 7865-7874. 2012

Fleets & Fuels Show Time (2011). *Vision's Hydrogen Tyrano for Ports*. [ONLINE] Available at: http://showtimesdaily.com/fleetsfuels/visions-hydrogen-tyrano-for-ports

GeorgiaGov (2009). *Coca-Cola Enterprises Launches Largest Hybrid Electric Delivery Trucks in North America*. [ONLINE] Available at: http://gov.georgia.gov/00/press/detail/0,2668,78006749_129886711_130691375,%2000.html

Government of Alberta (2011). *About Oil Sands: Facts and Statistics*. [ONLINE] Available at: http://www.energy.alberta.ca/OilSands/791.asp

HBEFA (2010). Handbook Emission Factors for Road Transport. *INFRAS International Inc.* [ONLINE] Available at: http://www.hbefa.net/e/index.html

Idaho National Laboratory (2005). *Natural Gas Technologies Low-Cost Refueling Station*. [ONLINE] Available at: http://www.inl.gov/lng/projects/refuelingstation.shtml

International Organization for Standardization (2006). *Life cycle assessment; Requirements and guidelines.* 1st ed. : ISO 14044.

National Research Council (2010). *Technologies and Approaches to Reducing the Fuel Consumption of*

Medium- and Heavy-Duty Vehicles. [ONLINE] Available at: http://www.nap.edu/openbook.php?record_id=12845&page=R1

PE International (2010). *GaBi Software*, *Process data set: Truck-trailer; diesel driven, Euro 0 - 5 mix, cargo; technology mix; 34 - 40t gross weight / 27t payload capacity (en)*. [ONLINE] Available at: http://gabi-dataset-documentation.gabi-software.com/xml_data/processes/4e47891c-25ca-4263-8ebd-e1b462c0f4b8_05.00.000.xml

PE International (2012). *GaBi Software, GaBi Database & Modelling Principles 2012.* [ONLINE] Available at: http://www.pe-international.com/fileadmin/gabi/documentation5/GaBiModellingPrinciples.pdf

Pike Research (2012). *300,000 Hybrid Trucks and Buses to be on the Road by 2015*. [ONLINE] Available at: http://www.pikeresearch.com/newsroom/300000-hybrid-trucks-and-buses-to-be-on-the-road-by-2015

US Department of Energy (2012). *About the EPAct Transportation Regulatory Activities.* [ONLINE] Available at: http://www1.eere.energy.gov/vehiclesandfuels/epact/about.html

US Department of Energy (2012). *Heavy-Duty Vehicle and Engine Search.* [ONLINE] Available at: http://www.afdc.energy.gov/afdc/vehicles/search/heavy/

US Department of Energy (2011). *Key Federal Legislation.* [ONLINE] Available at: http://www.afdc.energy.gov/afdc/laws/key_legislation

US Department of Energy (2011). *2010 Fuel Cell Technologies Market Report.* [ONLINE] Available at: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/2010_market_report.pdf

U.S. Department of Transportation (2011), Federal Highway Administration, *Federal Size Regulations for Commercial Motor Vehicles.* [ONLINE] Available at: http://ops.fhwa.dot.gov/freight/publications/size_regs_final_rpt/

US Energy Information Administration (2012). *Output growth for energy-intensive industries remains slow*. [ONLINE] Available at: http://www.eia.gov/forecasts/aeo/sector_transportation_all.cfm

US Energy Information Administration (2010). *Annual Energy Outlook 2010 with Projections to 2035.* [ONLINE] Available at: http://infousa.state.gov/economy/technology/docs/0383.pdf

US Energy Information Administration (2011). *Canada Energy Data, Statistics, and Analysis.* [ONLINE] Available at: http://www.eia.gov/emeu/cabs/Canada/pdf.pdf

US Energy Information Administration (2012). *How dependent are we on foreign oil?.* [ONLINE] Available at: http://www.eia.gov/energy_in_brief/foreign_oil_dependence.cfm

US Energy Information Administration (2012). *US Imports by Country of Origin.* [ONLINE] Available at: http://www.eia.gov/dnav/pet/pet_move_impcus_a2_nus_ep00_im0_mbblpd_a.htm

US Energy Information Administration (2012). *What are the major sources and users of energy in the United States?.* [ONLINE] Available at:

http://www.eia.gov/energy_in_brief/major_energy_sources_and_users.cfm

André Michel. (2004). *The ARTEMIS European driving cycles for measuring car pollutant emissions*. Science of The Total Environment, Volumes 334–335, Pages 73-84, ISSN 0048-9697, 10.1016/j.scitotenv.2004.04.070.

Bergerson Joule A. and Keith David (2006). *Life Cycle Assessment of Oil Sands Technologies.* Institute for Sustainable Energy, Environment and Economy. Paper No.11 of the Alberta Energy Futures Project, pp.1-24. [ONLINE] Available at: http://www.ucalgary.ca/files/iseee/ABEnergyFutures-11.pdf

Burnham, M, Wang, M., and Wu, Y. (2006). *Development and Applications of GREET 2.7-Transportation Vehicle-Cycle Model*. [ONLINE] Available at: http://www.transportation.anl.gov/pdfs/TA/378.PDF

Charpentier Alex D., Bergerson Joule A. and MacLean Heather A. (2009). *Understanding the Canadian oil sands industry's greenhouse gas emissions*. IOP Science. 4 (014005), pp.1-11. [ONLINE] Available at: http://iopscience.iop.org/1748-9326/4/1/014005

Davis Stacy C, Diegel Susan W. and Boundy Robert G. (2010). *Transportation Energy Data Book: Edition 29.* Oak Ridge National Laboratory: Roltek, Inc. [ONLINE] Available at: http://info.ornl.gov/sites/publications/files/pub24318.pdf

East JD (2012). *2012 Kentworth T370 For Sale in Indiana*. [ONLINE] Available at: http://news.palmertrucks.com/blog/kenworth-t370

Farrell Alexander E. and Sperling Daniel (2007). *A Low-Carbon Fuel Standard for California, Part 1: Technical Analysis.* [ONLINE] Available at: http://www.energy.ca.gov/low_carbon_fuel_standard/UC_LCFS_study_Part_1-FINAL.pdf

Farrell Alexander E. and Sperling Daniel (2007). *A Low-Carbon Fuel Standard for California, Part 2: Policy Analysis.* [ONLINE] Available at: http://www.energy.ca.gov/low_carbon_fuel_standard/UC_LCFS_study_Part_2-FINAL.pdf

Frey H.Christopher, Rouphail Nagui M. and Zhai Haibo (2008). *Link-Based Emission Factors forHeavy-Duty Diesel Trucks Based on Real-World Data.* Trans. Res. Rec. J. Trans. Res. Board **2008**, 2058, 23-32. [ONLINE] Available at: http://www4.ncsu.edu/~frey/conf_pr/Frey_Rouphail_Zhai_2008_TRB_Paper.pdf

Gerdes Kristin J. and Skone Timothy J. (2009). *An Evaluation of the Extraction, Transport and Refining of Imported Crude Oils and the Impact on Life Cycle Greenhouse Gas Emissions.* National Energy Technology Laboratory. [ONLINE] Available at: http://www.netl.doe.gov/energy-analyses/pubs/PetrRefGHGEmiss_ImportSourceSpecific1.pdf

Kamakaté Fatumata and Schipper Lee (2009). *Trends in truck freight energy use and carbon emissions in selected OECD countries from 1973 to 2005.* Energy Policy, Volume 37. Pages 3743-3751, ISSN 0301-4215, 10.1016/j.enpol.2009.07.029. [ONLINE] Available at: http://www.sciencedirect.com/science/article/pii/S0301421509005217

Kuczenski Brandon. "LCA Overview.' University of California, Santa Barbara, Bren Hall 1414 Lecture. Santa Barbara, CA. 5 April 2012.

MacLean Heather L. and Lave Lester B. (2003). *Evaluating automobile fuel/propulsion system technologies.* Progress in Energy and Combustion Science. 29, pp.1-69. [ONLINE] Available at: http://engineering.dartmouth.edu/~cushman/courses/engs171/EvalAutoFuel.pdf

Marshall Christa, Stecker Tiffany and ClimateWire (2012). *Oil Sands' CO2 Emissions Could be Higher Than Thought.* [ONLINE] Available at: http://www.scientificamerican.com/article.cfm?id=oil-sands-co2-emissions-higher-than-thought

McCollum David L. and Yang Christopher (2009). *Achieving deep reductions in US transport greenhouse gas emissions: Scenario analysis and policy implications*, Energy Policy, Volume 37, Issue 12, December 2009, Pages 5580-5596, ISSN 0301-4215, 10.1016/j.enpol.2009.08.038. [ONLINE] Available at: http://www.sciencedirect.com/science/article/pii/S0301421509006089

McDonnell Tim (2011). *There's No Hiding From Tar Sands Oil.* [ONLINE] Available at: http://www.motherjones.com/environment/2011/12/theres-no-hiding-tar-sands-oil

Rosenfeld Jeff, Pont Jennifer, Law Karen, Hirshfeld Dave and Kolb Jeffrey (2009). *Comparison of North American and Imported Crude Oil Lifecycle GHG Emissions*. TIAX LLC & MathPro Inc. Final Report. [ONLINE] Available at: http://www.assembly.ab.ca/lao/library/egovdocs/2009/aleri/173913.pdf

Shipping containers 24 (2013), *Shipping Container Dimensions & Sizes*. *Shipping Containers 24 Intermodal Sea Shipping Containers.* [ONLINE] Available at: http://www.shippingcontainers24.com/dimensions/

Whyatt GA (2010). *Issues Affecting Adoption of Natural Gas Fuel in Light- and Heavy-Duty Vehicles.* Pacific West National Laboratory. [ONLINE] Available at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19745.pdf

Yang Christopher, McCollum David L., McCarthy Ryan and Leighty Wayne (2009). *Meeting an 80% reduction in greenhouse gas emissions from transportation by 2050: A case study in California*. Transportation Research Part D: Transport and Environment, Volume 14, Issue 3, Pages 147-156, ISSN 1361-9209, 10.1016/j.trd.2008.11.010. [ONLINE] Available at: http://www.sciencedirect.com/science/article/pii/S1361920908001491

Yeh Sonia (2007). *An Empirical Analysis on the Adoption of Alternative Fuel Vehicles: The Case of Natural Gas Vehicles.* UC Davis: Institue of Transportation Studies. [ONLINE] Available at: http://ideas.repec.org/a/eee/enepol/v35y2007i11p5865-5875.html

APPENDICES

APPENDIX 1: FREIGHT EMISSIONS ASSESSMENT TOOL (FEAT)

FEAT

Freight Emissions Assessment Tool

v1.0 February 2013

BREN SCHOOL OF ENVIRONMENTAL SCIENCE & MANAGEMENT

UNIVERSITY OF CALIFORNIA, SANTA BARBARA

patagonia

Developed for the Bren School Master's Group Project:
Assessing On-Road Freight Emissions for Patagonia and Evaluating Low Carbon Fuel Alternatives

Authored and developed by:
Jeremie Hakian, Jeremy Rafter, James Choe, Jacob Sultan, Derek Wiggam, Kosuke Fujiwara

Client:
Patagonia (Elissa Loughman, Jill Dumain)

Advisors:
Dr. Roland Geyer (UCSB), Dr. Brandon Kuczenski (UCSB)

Acknowledgements:
Ben Sharpe (ICCT), John Courtis (CARB), Tyson Eckerle (Energy Action Now), Dr. Severin Beucker (Borderstep Institute; Carl von Ossietzky University of Oldenburg), Eric Wellens (Priority Worldwide)

Disclaimer and use:
This product includes software developed by the UChicago Argonne, LLC as Operator of Argonne National Laboratory under Contract No. DE-AC02-06CH11357 with the Department of Energy (DOE).

This product includes unit process data developed by PE INTERNATIONAL GmbH; LBP-GaBi, University of Stuttgart: GaBi Software System, Leinfelden-Echterdingen / Germany, 2009.

This software tool was developed for educational purposes only. The Bren School Master's Group Project, "Assessing On-Road Freight Emissions for Patagonia and Evaluating Low Carbon Fuel Alternatives," developed the Freight Emissions Assessment Tool (FEAT) to facilitate the process in determining the well-to-wheel (WTW) emissions of several fuels, identifying opportunities for Patagonia to reduce its global warming potential (GWP), and identifying viable alternative fuels to be potenitally integrated into its distribution network.

FEAT homepage

Freight Emissions Assessment Tool

INPUTS

(black boxes are for user inputs; assumes truck fully loaded with average package)

Product Characteristics		
Average Package Weight (kg)	106.6189952	
Average Package Volume (m3)	1	
Truck Characteristics		
Average Trailer Volume (m3)	98.8	
Average Max Payload of Truck (metric tons)	25.34	
Payload Check		
Average Package Density (kg/m3)	106.6189952	
Allowable # packages@ input density	98.8	
Package Volume Limited?	YES	
Tonnage of full trailer (metric tons)	10.53395673	
# packages on when volume limited	98.8	
# packages when weight limited	237.6687189	
Breakeven density (kg/m3)[a]	256.4777328	
What was the Total Freight Shipped? (metric ton-km)	5692790.163	
Percent Shipped by Gasoline Truck	0.0000%	
Percent Shipped by Diesel Truck	100.0000%	
Percent Shipped by Diesel Truck (100% Tar Sands Surface Mining Dilbit (SMD) Pathway)	0.0000%	
Percent Shipped by Diesel Truck (100% Tar Sands Steam Assisted Gravity Drainage (SAGD) Pathway)	0.0000%	
Percent Shipped by Diesel HEV Truck	0.0000%	
Percent Shipped by B20 Truck	0.0000%	
Percent Shipped by B100 Soy	0.0000%	
Percent Shipped by B100 Algae	0.0000%	
Percent Shipped by Compressed Natural Gas Truck	0.0000%	
Percent Shipped by Liquefied Natural Gas (North America) Truck	0.0000%	
Percent Shipped by Liquefied Natural Gas (Landfill Gas) Truck	0.0000%	
Percent Shipped by Liquid Propane Gas Truck	0.0000%	
Percent Shipped by Electric Truck	0.0000%	
Percent Shipped by Liquid Hydrogen Fuel Cell (Refueling Station SMR) Truck	0.0000%	
Percent Shipped by Liquid Hydrogen Fuel Cell (Central SMR) Truck	0.0000%	
Percent Shipped by Liquid Hydrogen Fuel Cell (Electrolysis) Truck	0.0000%	
Percent Shipped by Gaseous Hydrogen Fuel Cell (Refueling Station SMR) Truck	0.0000%	
Percent Shipped by Gaseous Hydrogen Fuel Cell (Central SMR) Truck	0.0000%	
Percent Shipped by Gaseous Hydrogen Fuel Cell (Electrolysis) Truck	0.0000%	
Percent Total (***should equal 100%***)	100.0000%	OK
% of Freight Shipped on Freeway (if unknown, input 70%)	70.00%	
% of Freight Shipped on Rural Roads (if unknown, input 23%)	23.00%	
% of Freight Shipped on Urban Roads (if unknown, input 7%)	7.00%	
Percent Total (***should equal 100%***)	100.0000%	OK

[a]Optimum package density @ trailer volume

FEAT inputs and fuel types

RESULTS

Fuel Type	Well-to-Tank Emissions (metric tons CO2e)	Tank-to-Wheel Emissions (metric tons CO2e)	Well-to-Wheel Emissions (metric tons CO2e)
Gasoline	0.0000000	0.0000000	0.0000000
Diesel	104.5372959	429.1272454	533.6645413
Diesel (100% Tar Sands SMD Pathway)	0.0000000	0.0000000	0.0000000
Diesel (100% Tar Sands SAGD Pathway)	0.0000000	0.0000000	0.0000000
Diesel HEV	0.0000000	0.0000000	0.0000000
B20	0.0000000	0.0000000	0.0000000
Biodiesel - Soy (B100)	0.0000000	0.0000000	0.0000000
Biodiesel - Algae (B100)	0.0000000	0.0000000	0.0000000
CNG	0.0000000	0.0000000	0.0000000
LNG (North America)	0.0000000	0.0000000	0.0000000
LNG (Landfill Gas)	0.0000000	0.0000000	0.0000000
LPG	0.0000000	0.0000000	0.0000000
Electricity	0.0000000	0.0000000	0.0000000
L.H2 (Refueling Station SMR)	0.0000000	0.0000000	0.0000000
L.H2 (Central SMR)	0.0000000	0.0000000	0.0000000
L.H2 (Electrolysis)	0.0000000	0.0000000	0.0000000
G.H2 (Refueling Station SMR)	0.0000000	0.0000000	0.0000000
G.H2 (Central SMR)	0.0000000	0.0000000	0.0000000
G.H2 (Electrolysis)	0.0000000	0.0000000	0.0000000
Total Emissions	104.5372959	429.1272454	**533.6645413**

Fuel Type	Fuel Consumption (Units Specified)	Fuel Cost ($US 2012)	Number of Stations in US	Tractor Currently Available? (Y/N)[a]	Fuel Economy (miles/ GGE)[b]
Total Diesel Consumption; Diesel HEV Included (gallons)	41926.2416	$ 157,223.41	-	Y	8.01
Total B20 Consumption (gallons)	0	$ -	696	N	8.01
Total Biodiesel - Soy (B100) (gallon)	0	$ -	696	N	8.01
Total Biodiesel - Algae (B100) (gallon)	0	$ -	696	N	8.01
Total CNG Consumption (cubic ft)	0	$ -	1190	Y	6.67
Total LNG (North America) Consumption (gallons)	0	$ -	66	Y	6.67
Total LNG (Landfill Gas) Consumption (gallons)	0	$ -	66	Y	6.67
Total LPG Consumption (gallons)	0	$ -	2776	N	6.67
Total Electricity Consumption (kWh)	0	$ -	15192	N	22.69
Total L.H2 (Refueling Station SMR) Consumption (gallons)	0	$ -	58	Y	13.35
Total L.H2 (Central SMR) Consumption (gallons)	0	$ -	58	Y	13.35
Total L.H2 (Electrolysis) Consumption (gallons)	0	$ -	58	Y	13.35
Total G.H2 (Refueling Station SMR) Consumption (cubic ft)	0	$ -	58	Y	13.35
Total G.H2 (Central SMR) Consumption (cubic ft)	0	$ -	58	Y	13.35
Total G.H2 (Electrolysis) Consumption (cubic ft)	0	$ -	58	Y	13.35
		Total Fuel Cost ($US 2012)			
		$ 157,223.41			

[a]Source: http://www.afdc.energy.gov/vehicles/search/heavy/

[b]At Utilization rate = 0.415704685

Total emissions and fuel consumption

APPENDIX 2: PRIMARY PATAGONIA DATA

State	Weighted Average Distance (miles)
Alabama	2296
Alaska	2487
Arizona	781
Arkansas	1855
California	496
Colorado	1078
Connecticut	2771
Delaware	2659
Florida	2832
Georgia	2444
Idaho	421
Illinois	1915
Indiana	1867
Iowa	1664
Kansas	1579
Kentucky	2128
Louisiana	2079
Maine	3056
Maryland	2599
Massachusetts	2895
Michigan	2168
Minnesota	1926
Mississippi	2110
Missouri	1707

Montana	926
Nebraska	1442
Nevada	366
New Hampshire	2933
New Jersey	2687
New Mexico	1042
New York	2682
North Carolina	2597
North Dakota	1443
Ohio	2210
Oklahoma	1631
Oregon	511
Pennsylvania	2614
Rhode Island	2899
South Carolina	2658
South Dakota	1431
Tennessee	2118
Texas	1806
Utah	533
Vermont	2808
Virginia	2767
Washington	723
West Virginia	2325
Wisconsin	1949
Wyoming	939

Table 2-1: Weighted Average Distance for each State, used for direct to consumer and wholesale calculations

Distribution Legs

Patagonia shipments fall into one of four categories: 1) Inbound to the Reno, NV distribution center (Expeditors); 2) Outbound direct-to-customer (UPS) 3) Outbound wholesale (UPS or FedEx); and 4) Outbound to Patagonia retail stores (UPS). To calculate metric ton-km for each shipment, information on the weight of each package was required, in addition to how far it traveled. Each shipment contained a listed weight and a destination, making the metric ton-km calculation relatively straightforward. Using all of this information, the total metric ton-km for each distribution category was calculated.

Shipment Category	**Freight (metric ton-km)**
Inbound	1,414,738
Direct to Customer	1,760,456
Wholesale	1,960,788
Retail	445,002

Table 2-2: Metric ton-km totals for each distribution category.

For each of the three outbound categories, Patagonia had additional information about which state or retail store the shipment went to. This allowed a state-by-state, or store-by-store, breakdown of freight contributions to the total for each category. When looking at these graphs it is important to remember that states or stores farther from Reno, NV have a larger contribution to the metric ton-km totals due to the longer shipping distances to these locations.

Due to difficulties associated with collecting primary data from Patagonia's freight forwarders, such as UPS, and acquiring unambiguous emissions factors, the project was required to accommodate more assumptions and expert opinions into the model: 1) difficulty finding unambiguous, standardized emission factors for several HDV types, and 2) the lack of primary data detailing the exact movement of Patagonia's products throughout the distribution systems.

Regarding the first challenge, vehicles vary in their relative emissions depending upon the age of the vehicle, driving cycle, environmental conditions, and utilization rate among several other factors. For the second challenge, the trailer sizes associated with alternative HDV technologies, the extent to which rail and other non-HDV freight are used within the domestic US, and accurate logistics utilized by Patagonia freight forwarders such as UPS and FedEx have not been determined. Accordingly, the process of compiling and organizing all available data on these issues is ongoing, and all assumptions are being clarified where needed.

APPENDIX 3: VEHICLE CYCLE

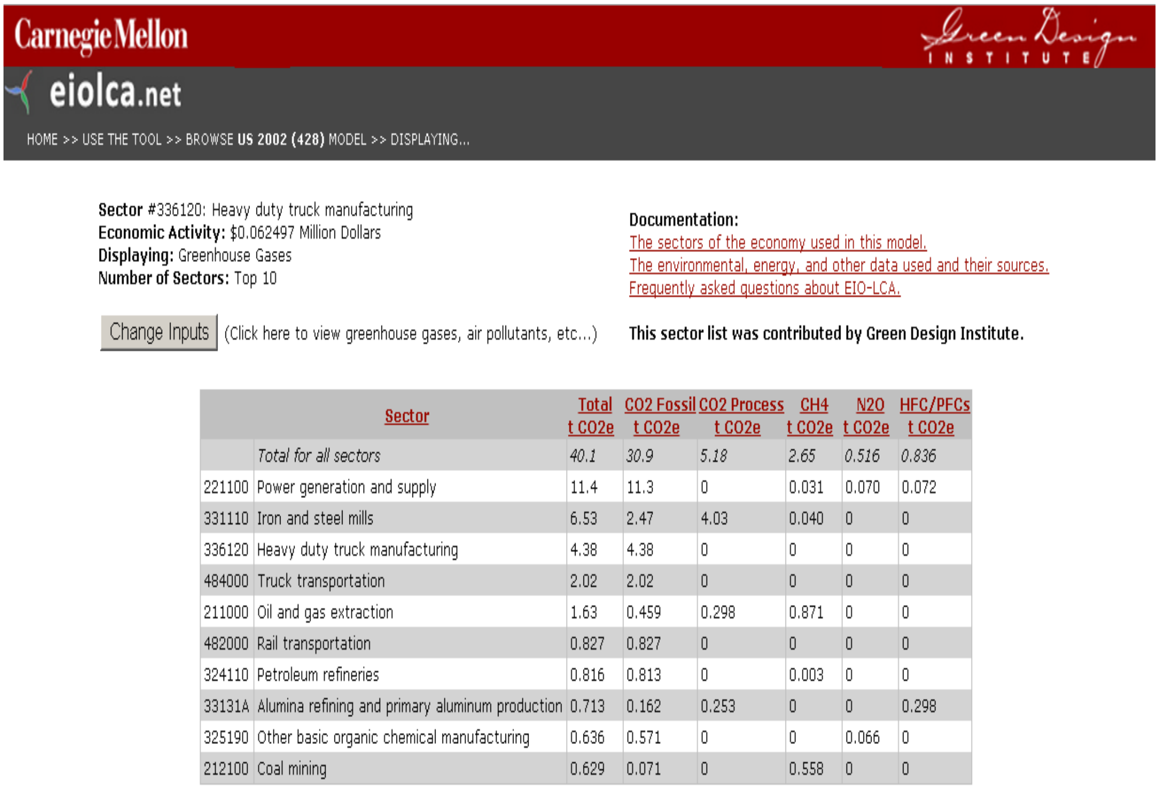
In addition to fuel production and use data, GREET also models the impacts from vehicle production, use, and disposal. These vehicle cycle emissions are conducted for three vehicle types and five drive-train technologies: a mid-size passenger car, a mid-size SUV, and a full-size pick-up truck, each with an internal combustion engine (ICEV), a hybrid electric engine (HEV), a plug-in HEV, a battery electric vehicle (BEV), and a fuel cell vehicle (FCV). (Source: *Updated Vehicle Specifications in the GREET Vehicle-Cycle Model, Andrew Burnham Center for Transportation Research Argonne National Laboratory, July 2012*).

From the GREET vehicle cycle data, some rudimentary comparisons can be made based on the different vehicle drivetrains and the total GHG emissions over the vehicle lifetime. Normalizing each vehicle type to the ICEV reference (**Table 3-1**), vehicle cycle emissions were then generated for each alternative vehicle type.

Powertrain	ICEV	HEV	EV	FCV
Grams CO2e/Pick-Up Truck	7,620,231	8,086,717	10,133,971	10,053,620
Normalized to ICEV	1	1.061	1.330	1.319

Table 3-1. Vehicle cycle GHG emissions (battery, assembly/disposal/recycling, components, and fluids) taken from GREET 2 and normalized to an internal combustion engine (ICEV)

To scale these emissions to the larger HDV class, an economic input-output table of GHG values derived from Carnegie-Mellon's EIO calculator was used; production of a single $80,000 consumer-price truck in 2012 USD (from Section G in **Background**) is estimated to emit nearly 40,000 kg of CO_2e (a screen shot is shown in **Figure 3-1**). Multiplying by the normalized ICEV weights, the additional GHG burden associated with each alternative vehicle type was then calculated (**Table 3-2**). These values were referenced against values from Pistoia (2010), who estimated GHG emission from a passenger ICEV cycle at about 58,000 kg CO_2e (a value in the same order of magnitude as the Carnegie-Mellon calculator). The range of values, however, indicates the need for standardized vehicle cycle research.



Carnegie Mellon

Green Design Institute

eiolca.net

HOME >> USE THE TOOL >> BROWSE **US 2002 (428)** MODEL >> DISPLAYING...

Sector #336120: Heavy duty truck manufacturing
Economic Activity: $0.062497 Million Dollars
Displaying: Greenhouse Gases
Number of Sectors: Top 10

Change Inputs (Click here to view greenhouse gases, air pollutants, etc...)

Documentation:
The sectors of the economy used in this model.
The environmental, energy, and other data used and their sources.
Frequently asked questions about EIO-LCA.

This sector list was contributed by Green Design Institute.

	Sector	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
	Total for all sectors	*40.1*	*30.9*	*5.18*	*2.65*	*0.516*	*0.836*
221100	Power generation and supply	11.4	11.3	0	0.031	0.070	0.072
331110	Iron and steel mills	6.53	2.47	4.03	0.040	0	0
336120	Heavy duty truck manufacturing	4.38	4.38	0	0	0	0
484000	Truck transportation	2.02	2.02	0	0	0	0
211000	Oil and gas extraction	1.63	0.459	0.298	0.871	0	0
482000	Rail transportation	0.827	0.827	0	0	0	0
324110	Petroleum refineries	0.816	0.813	0	0.003	0	0
33131A	Alumina refining and primary aluminum production	0.713	0.162	0.253	0	0	0.298
325190	Other basic organic chemical manufacturing	0.636	0.571	0	0	0.066	0
212100	Coal mining	0.629	0.071	0	0.558	0	0

Figure 3-1. Screenshot of the Carnegie-Mellon Input/Output model output for the construction of an $80,000 HDV (in 2012 USD).

	ICEV	HEV	EV	FCV
GHG for $80K vehicle (metric ton CO_2e)	40.1	42.55	53.33	52.91
Added GHG Burden (metric ton CO_2e)	0	2.455	13.23	12.81

Table 3-2. Calculated GHG burden from alternative vehicle drive trains.

Knowing the GHG emissions of each vehicle, the final step was to calculate the number of actual trucks required to move a given amount of freight. Specific to Patagonia, the number of trucks needed to transport 5.7 million metric ton-km of freight had to be determined. Assuming that each truck is fully loaded at an average Patagonia tonnage of 10.5 metric tons and that 5.7 million metric tons are transported per year, a single fully loaded truck would travel 336,000 miles per year (total Patagonia freight divided by tonnage per truck). Allocating over the total number of HDV lifetime miles yields the required number of trucks. Based on the project calculations, a total of 1.2 trucks are required to transport Patagonia products. Note that this refers to an allocated truck (for emission assessment calculations) and not the actual number of trucks being used. These equations are summarized below:

1)

$$\frac{Package\ density \times Trailer\ volume}{Annual\ ton - km} = Annual\ VMT$$

2)

$$Lifetime\ of\ a\ HDV \times\ Annual\ VMT\ of\ a\ HDV = Total\ mileage\ of\ a\ HDV\ within\ its\ lifetime$$

3)

$$\frac{Total\ mileage\ of\ a\ HDV\ within\ its\ lifetime}{Annual\ VMT} = Number\ of\ trucks\ needed\ a\ year$$

With the total number of trucks known, the payback period was then calculated. Payback refers to the fact that while the use phase of alternative trucks may have lower GHG emissions, the production of alternative trucks are initially more burdensome and must be offset during the use phase. In general terms, the payback period (or a "breakeven" amount of total freight) occurs when:

$$(Total\ Freight)x\left(EF_{df}\right) + (\#\ trucks)x\ \left(\frac{GHG\ Emissions}{Diesel\ Truck}\right) = (Total\ Freight)x\left(EF_{af}\right) + (\#trucks)x\left(\frac{GHG\ Emissions}{Altnerative\ Truck}\right)$$

Rearranging for Total Freight, the equation simplifies to:

$$Total\ Freight = \frac{(\#\ trucks) \times (GHG_{alt\ truck} - GHG_{diesel\ truck})}{EF_{df} - EF_{af}}$$

Using the above equation, the vehicle payback time results are shown in **Table 3-3**:

	HEV	**EV**	**FCV**
Payback Freight (metric ton-km)	155,783	561,678	697,624

Table 3-3. The total amount of breakeven freight that must be shipped by the chosen alternative vehicle. Below these values, the benefits of lower fuel cycle emissions are outweighed by the added GHG emissions of the vehicle cycle.

As a first order estimate, vehicle cycle emissions are in fact significant, ranging from 9-15% of fuel cycle emissions (**Table 3-4**). These values agree with existing literature that indicates the vehicle cycle GHG emissions are approximately 10% of fuel cycle emissions. According to a vehicle cycle LCA (using a 900 kg vehicle) study by Castro et al. (2003), the fuel cycle accounts for roughly 90% of the vehicle lifecycle GHG emissions. Importantly, these values depend on the average vehicle lifetime and miles traveled, and may also change as end-of-life (EOL) design and recycling rates increase to offset production burdens. Future versions of FEAT may attempt to capture these embodied emissions as more data becomes available. Moreover, LCA studies should additionally consider the infrastructure requirements to sustain alternative fuel propulsion systems; these include expanding hydrogen reformulation technologies, battery charging stations, alternative fueling stations, and other technology requirements to deliver the alternative fuels. Clearly, the impacts from alternative vehicle use (particularly HDVs) warrant continued investigation.

	ICEV	HEV	EV	FCV
GHG from 1.2 trucks (metric ton CO_2e)	48.19	51.14	64.09	63.58
Fuel Cycle GHG emissions	533.7	431.2	377.9	413.5
% of Fuel Cycle	9.031	11.86	16.96	15.38

Table 3-4. First order approximation of the significance of vehicle cycle GHG emissions relative to fuel cycle.