Food Transportation Emissions and Estimation Tools

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Selection and Purpose

This subject matter was originally chosen as a Freshman Honors Mentorship Project for the Iowa State University Honors Program. The original intent was to conduct a literature review to compare the sustainability of local and imported food sustainability. During this review, a lack of widely applicable food sustainability modeling systems was noted. To remedy this problem, a set of tools was developed to aid in the analysis of food lifecycle analysis. This program, which was developed by the author of this paper, can use a variety of user inputs to model, analyze, and optimize transportation routes. The program became the subject matter for the study of food transportation emissions factors discussed in this paper. Through the analysis of the included case studies, the validity, breadth, and depth of program applications have been examined.

This study contains both original research and literature review. The tool created in this study is an experimental project created by the author to aid in system modeling. However, many of the case studies include the review and comparison of published works that have been compiled for the overall goal of analyzing multiple factors in food transportation sustainability. These components together comprise the exploration of food transportation system emissions that is detailed in this paper.

Abstract

Food transportation is an increasingly important consideration to total food sustainability in a rapidly globalizing world. To maintain the efficiency of regionalized production, food travels great distances to the consumer’s plate. While this long-distance sourcing is often more sustainable from a production standpoint, the routes from origin to consumer are frequently unoptimized. To reduce emissions due to transportation, many have tried to limit the miles traveled by food items. However, the mode of travel is an equally important factor. Different modes produce vastly different emissions over equivalent distances. To effectively model these routes, a set of transportation emissions estimation tools has been created. This program uses an Excel interface to allow users to input key factors (like cargo mass, origin, and destination) and experiment with different modes and routes of travel to find the optimal transportation system for their application.

This program may be used to analyze or improve the total life cycle analysis of a variety of products. In a case of the comparison of transportation modes, a salmon transportation route from the Faroe Islands (America’s 2nd largest source of imported fresh salmon) to Richmond, VA resulted in a roughly 98% reduction of emissions when shipped via sea rather than flown. In a case of transportation optimization, the reciprocal trade of beef between Costa Rica and the United States was found to result in at least 158,000 kg of CO2 equivalent annually. These cases (and others) show the great need for better route optimization in food transportation systems.
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Introduction

Urbanization and consumer demand for non-local products has made transportation an increasingly vital section of the food economy. While these imports and exports have resulted in regional specialization and increased the dietary options of consumers, the globalization of the food economy has greatly changed the environmental impact of food systems. The current greenhouse gas emission trajectory is estimated to reach over 80 gigatons of CO2 equivalent by 2050 (Mooney, 2015). Comparatively, the widely accepted climate change budget issued by the UN Environment Program would limit carbon emissions to 54 gigatons of CO2eq by 2030 (Mooney, 2015). However, even the 54 gigaton limit will result in climbing world temperatures. To reduce these effects, emissions must be limited from every source, including transportation. According to the EPA, the transportation sector produced 14% of global carbon emissions in 2010 (EPA, 2018). Out of this problem, a new buzz phrase arose – food miles. This term refers to the distance a food item travels from production to consumer, often with a focus on sustainability. Although local sourcing has managed to cut some of the transportation emissions, the trend is mostly practiced at convenience. Many types of food are expensive and difficult to grow and maintain in an unsuitable climate. When transportation is essential for the products that an area relies on – but does not produce – the environmental impact of lengthy travel routes is not always considered or strategized. To remedy this, travel emissions can be modeled to find the best feasible route.

While the focus of transportation optimization is often focused on distance, there are many other factors that affect the sustainability of transportation systems. A truck, train, plane, and ship used to transport the same cargo over the same distance would result in vastly different emissions. Of these, air travel is, the most environmentally costly mode of travel. In the food sector particularly, much of the food that is flown is due to consumer demands for fresh products. Truck travel is the next most costly option for transportation modes. This, however, is a very popular mode of transportation due to the low cost and lack of extra required infrastructure.

In 2015, shipment by HDV (heavy-duty vehicle) accounted for about 66% of total US freight shipment by weight. Rail shipment accounted for about 9.1% of this shipped weight. By 2045, truck shipment is expected to grow in share of freight transportation by about 2% (while rail is expected to shrink by about 1.5%). Water shipment is expected to drop from 3.4% to 2.9% of total domestic shipment, while air freight change is negligible. This trend indicates a general increase in emissions, even if the total food shipped remains the same. This brings an important topic to the table – if shipping routes were altered to allow for more sustainable modes of transportation, could the environmental effects of shipping more food in the future be mitigated?

While there are many other factors that contribute to food sustainability, food sourcing results in an estimate of 9% of the life cycle emissions for food products (EPA, 2018). Depending on the route taken, this proportion can vary from <1% in local produce to about 90% in fresh-floated seafood (Farmery et al., 2015). This variety is what makes the analysis of routes vital to the environmental quality of transportation systems. Changing the origin of the food or the mode of transportation to find a more optimal pathway can play an enormous role in reducing total product emissions.

In response to the environmental issues associated with the food industry, the three tools presented here are intended to model transportation routes. These tools present the opportunity for the user to use various input formats in an Excel workbook interface and receive a CO2eq estimate for a given route. The greenhouse gas emission estimate is calculated for each chosen path of travel based on the mode of travel, mass of cargo, and distance. These modeled routes can be used to examine the sustainability of food sourcing and transportation. Through better analysis and modeling of these systems, engineers and consumers alike can make more environmentally conscious decisions in transportation systems, resulting in an altogether more sustainable society.

Methodology

Data

The modeling of the transportation emissions requires emissions factors that are specific to common vehicle groupings. The tools use estimates calculated from the Network for Transport Measures (NTM) to rate the emissions for each mode of transportation. To ensure simplicity for the user, the data and figures used are estimates for the most typical travel scenario. The graph in figure 1 shows the emissions ratings (per tonne-kilometer) for each mode of travel (“NTMCalc 4.0,” n.d.). The chart (fig. 2) is the mode decision logic displayed on the initial page of the program.
It must be noted that these are rough estimates and the number of figures used for the mode ratings does not indicate any level of certainty. This data is used only in calculations to give general carbon emission estimates.

The data in figures 1 and 2 was acquired by the NTM from different suitable databases for each mode. The “road” transportation data was collected from the 2010 update of the Handbook of Emissions Factors for Road Transportation (or HBEFA 3.1). This handbook uses the Passenger Car and Heavy-Duty Emission Model, which uses engine mapping to dynamically monitor the emissions exiting the vehicle and compares this data to the actual power of the engine (Hausberger et al., 2009). By collecting data from a multitude of common on-road vehicles of the same hauling capacity, the HBEFA developed a set of values used to estimate the emissions based on vehicle load and distance.

“Rail”-type emissions ratings were collected using similar methodology. The power required to propel a train carrying various cargo weights in common environments was compared with the emissions discharge mapping of the train to gather a multitude of data points. The data was then compiled to form a “typical” emissions rating (using average load percentages and average topographical condition factors) for the three train categories (“NTMCalc 4.0,” n.d.). For the purpose of this program (which is expected to be used for loads that are less than 120 tons), it is most logical to base the type of train used – and the resultant emissions factor – on the mass loaded into an individual rail car. While the NTM was responsible for the organization of the data, the International Union of Railways (or UIC) collected the data (“NTMCalc 4.0,” n.d.).

Data for waterway modes is collected in a less direct method. Since the resistance acting on the vessel has far more variation (from the effects of both load weight and buoyancy), the power simulation techniques used in the ground transportation methods is not as applicable to the calculation of water transportation coefficients. Instead, the International Maritime Organization (IMO) released statistics relating the required energy consumption of the ship to its type and

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Usage range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small cargo train</td>
<td>Cargo mass &lt; 90 t</td>
</tr>
<tr>
<td>Medium cargo train</td>
<td>90 t ≤ Cargo Mass &lt; 110 t</td>
</tr>
<tr>
<td>Large cargo train</td>
<td>110 t ≤ Cargo mass &lt; 120 t</td>
</tr>
<tr>
<td>Regional freight aircraft</td>
<td>Distance travelled ≤ 2300 km</td>
</tr>
<tr>
<td>Continental freight aircraft</td>
<td>2300 km &lt; Distance travelled ≤ 6600 km</td>
</tr>
<tr>
<td>Intercontinental freight aircraft</td>
<td>6600 km ≤ Distance travelled</td>
</tr>
<tr>
<td>Rigid truck</td>
<td>Cargo mass &lt; 7.5 t</td>
</tr>
<tr>
<td>Large rigid truck</td>
<td>7.5 t ≤ Cargo Mass &lt; 20 t</td>
</tr>
<tr>
<td>Truck and trailer</td>
<td>20 t ≤ Cargo Mass &lt; 34 t</td>
</tr>
<tr>
<td>Large truck and trailer</td>
<td>34 t ≤ Cargo Mass &lt; 60 t</td>
</tr>
<tr>
<td>Inland/Coastal cargo ship</td>
<td>Distance travelled ≤ 2000 km</td>
</tr>
<tr>
<td>Regional cargo ship</td>
<td>2000 km &lt; Distance travelled ≤ 4000 km</td>
</tr>
<tr>
<td>Ocean cargo ship</td>
<td>4000 km ≤ Distance travelled</td>
</tr>
</tbody>
</table>
deadweight ("NTMCalc 4.0," n.d.). The related emissions were then calculated from the fuel consumption required to provide that power. For the final rating, a coefficient of resistance was applied to reflect the effects of water drag on the ship (Cooper & Gustafsson, 2004).

The air data collection methods are much more variant than those of the other travel modes. For each general “type” of aircraft, the fuel consumption for a typical load per unit distance is calculated. The fuel consumption (with fuel type assumed to be Jet A-1) is related to a fuel efficiency factor that determines the carbon emissions or this type, much like the ship method ("NTMCalc 4.0," n.d.). The typical load mass used to find the total fuel usage is then taken as two parts—passenger load mass and cargo load mass. Since few planes are solely freight planes, the NTM assumes that the aircrafts used for transportation also carry humans. This dual functionality, the NTM estimates, reduces the total carbon output per unit of flown cargo mass by 30% ("NTMCalc 4.0," n.d.). The aircrafts in the program are grouped by travel distance due to both typical aircraft size and flight pattern at these distances. These figures were collected from the International Civil Aviation Organization and compiled by the NTM. The carbon output per unit cargo mass is, like in all the other modes discussed here, usually reduced by greater total vehicle size. Unlike the other modes, air travel emissions are very dependent on range, as the take-off and landing flight pattern result in added emissions for the total flight. To account for this, a variable emissions factor (related to both distance and unit of cargo mass) and a stagnant emissions factor (variable by only cargo mass for take-off and landing patterns) are combined to form a total emissions factor for each major plane range ("NTMCalc 4.0," n.d.).

It must be noted that the emissions factors used in this study are rough estimates and the number of significant figures used for the mode ratings does not indicate any level of certainty. This data is comprised of averages used only in calculations to give general carbon emission estimates. The outputted emissions values in the program are rounded to reflect the range of error found between these factor estimates and the estimates of other references research projects more accurately, but still do not fully reflect on possible error from actual transportation routes and variation in vehicle type.

**Program Logic**

The modeling program is an Excel Macro-Enabled Workbook (*.xlsm) containing several macros and developer controls. The tools run on a series of Visual Basic (VBA) codes. Foundationally, the codes are used to compile three pieces of information—the distance traveled, the mode of travel, and the cargo mass.

The following equation is then used to determine the route’s resulting carbon emissions:

\[ \text{Em} = (\text{dist1} \times \text{mrat1} \times \text{mass1}) + (\text{dist2} \times \text{mrat2} \times \text{mass2}) + \ldots + (\text{distn} \times \text{mratn} \times \text{massn}) \]  

(1)

where

- \( \text{Em} \) = emissions (g CO2eq)
- \( \text{dist} \) = distance (km)
- \( \text{mrat} \) = mode emissions rating ((g CO2eq) / (tonne*km))
- \( \text{mass} \) = cargo mass (tonnes)

The generic setup of the program includes a single module with master equations that are utilized in each tab as well as a tab-specific code for each tool. The master equations are used to call in information from internet resources and contain equations that are used in multiple tools. This results in a system of four unique sets of code (one for each tool) and one code used to integrate the information into a simpler output.

Several of the master equations are needed for locational data. This is usually the first data point calculated in the tools as both distance and mass values are required to select ranges for vehicle types. As the mass and mode of transportation are provided by the user, the distance calculation is the first step in this process. The coordinates of a string address are found using data called in from a Google API (application programming interface). With the input of an address, the program can relay the string of words via an internet connection to the Google Maps API (fig. 3). A set of coordinates for the address is returned.
These values are then used in an equation that helps calculate the distance between two points on the globe. For this function, the latitude and longitude of both locations are inputted and run through a Haversine formula, which calculates the “as the crow flies” distance between the points (fig. 4).

After the distance between points is determined, the three input values – the distance, cargo mass, and mode of transportation – are stored and the most likely mode of transportation is selected based on the usage ranges (the distance traveled or cargo mass) that were entered/selected (fig. 5). For the Plane/Air and Ship/Ferry modes, a distance range determines the rating. For example, if the cargo is traveling 4000 km directly by air, the most likely mode of travel would be by continental freight aircraft. For the Train/Rail and Truck/Road options, the usage range is based on the cargo mass. Similarly, if the user entered a cargo mass of 25 tonnes for a truck route, the most likely mode form would be a truck and trailer.
After the type of vehicle used is determined, a function assigns an emissions rating to the mode of travel and uses this emissions rating to calculate total emissions. This emissions value (in kg CO2eq) is calculated through the multiplication of the mode emissions rating, mass of the cargo, and distance traveled (fig. 6).

The API is also used for error checking in some of the tools to prevent the calculation of distance for truck or rail travel over major bodies of water. For this function, Google Maps treats the two input addresses as a request for road-travel directions between the two points. If road travel is not possible, a geographical barrier (like an ocean) is expected. Figure 7 shows this process. Google’s directions, however, will not provide routes across some national borders (such as that between China and any neighboring country). In this case, the error checking has been overridden with keyed-in edits. For those that receive unwanted or unwarranted error reports, the function is optional. Each tool has a regular function button as well as an override button to opt out of such features.
The tab-specific codes help integrate the master formulas into different scenarios and formats. This allows for the tools to have a resettable structure to clear any edits or entered information. This also enables the mapping of entered locations on the 2nd and 3rd tools. Most of the generic calculations are used in the tab-specific sections to ensure that the cell placement of the inputs and results are accurate.

The third tool also contains unique code to assist in finding potential ports. This function “suggests” ports from the most commonly used ports in the world (the top 100 airports and top 150 ship ports). The porting function integrates the locational codes from the module and some tab-specific port information to find ports that are accessible by road or rail, determined by the error tests provided by the distance Google API (fig. 8). By limiting ports to those that are drivable, the tool more reliably models a likely overseas transportation sequence of ground-overseas-ground travel.

The port-finding capabilities of the third tool also allow for another unique feature – an optimization function. This function helps further suggest low emissions transportation routes given an origin and destination (fig. 9). Due to the great difference between road and rail emissions factors, the ground transportation sections are assumed to be via rail for lowest emissions estimation. While this assumption is not made in the overseas portion, it is extremely likely that this portion of the transportation will be via ship due to the same reasoning.
Tool Overview

Export Estimations

The export estimations tab produces a visualization of the production of food groups by region. The user may select a group from the drop-down list to display dots scaled by the mass of regional exports and the numerical values of the exports. The information may provide insight on likely origins of certain products. The layout of this page is shown in figure 10.

Tool 1

Tool 1 is noted for its simplicity. The user may enter the total distance traveled, the proportion traveled through each mode, and the mass of the load and the tool will return CO2eq estimates (fig. 11). This tool does not allow the user to split the trip into several segments. It also does not allow address inputs or use any distance calculation functions, but still utilizes the “most likely mode of transportation” function for each segment of travel.
Tool 2

Tool 2 is the most versatile portion of the program. This section allows inputs of checkpoint addresses, masses of cargo, and modes of transportation. The distance traveled and carbon emissions are displayed for each section of travel and summed for a total CO2eq estimate. A map is also provided to visualize the route taken. This layout is shown in figure 12. All distances are measured “as the crow flies,” so the map allows the user to see any geographical issues in the route taken. As in the 1st tool, the modes used are product of the “most likely mode” function.

Tool 3

The most restrictive and structured section is Tool 3. The formatting is set up to reflect a common pattern of travel for many goods – a route of ground travel from the origin to a major port, where the product is flown or shipped to another major port, from which the product travels by ground to the destination. This tool prompts the user to enter an origin and destination. The modes of travel are then selected, after which the port locations may be selected from a dropdown list.
Figure 13 shows this layout. This requires the use of a function that selects two ports accessible by land, one from the origin and one from the destination. The tool then calculates an estimate of emissions for the route. Like Tool 2, the “most likely mode” and mapping functions are also used. Tool 3 is uniquely useful due to its optimization function. The user may opt to only enter in the cargo mass, origin, and destination. This tool can then suggest the lowest-emission route based on the information given.

Case Studies

Case 1: Importing goods – the effects of varying origins

- The term “food miles” was founded on the premise that differing origins of food items drastically change the emissions related to transportation.
- This is true to an extent -- while other factors also influence the true lifecycle carbon emissions of a product, the distance traveled by an item does impact the transportation emissions.
- The distance traveled by food is largely dependent on global supply chain trends. Regional specification has created popular hubs for certain groups of items.
- For example, about 70% of the fresh apples consumed in Iowa are from out-of-state locations during peak Iowa harvesting season.
- The top two apple-producing states in the US are Washington and New York, respectively, with Washington being the top apple contributor to Iowan grocery stores.
- Case study: What effect does a change in origin of a product (such as Iowan apples) have on the resulting transportation emissions?

Case 2: Modes of travel and relative emissions

- While origin/destination relationships are important to the sustainability of product supply chains, the distance between two points is not an end-all factor.
- The effects of differing modes of transportation is often overlooked and/or underestimated. The emissions that result from equivalent routes (in terms of distance and cargo load) with differing methods of transportation can be enormously different.
• One example of this is distant overseas travel. A long-distance cargo plane results in about 50 times the CO2eq of a long-distance ship over the same distance with an equal cargo load.
• Fish is a product that exemplifies this idea well. The production of fresh and frozen fish is extremely similar, but distribution modes must vary to avoid the spoilage of fresh product.
• Case study: What differences can be observed in the modeling of a single route with differing vehicle types?

Case 3: Brazil to EU beef export model comparison (Direct study comparison)

• A wide variety of modeling methods and calculations can be used to estimate vehicle emissions.
• As there are too many factors to true vehicle efficiency to determine a single accepted estimation procedure, “true” emissions values are difficult to confirm.
• There are two primary practices for these cases. The first uses a vehicle emissions factor per unit distance and mass, while the second compares load capacity and fuel consumption with a fuel efficiency factor.
• This study utilizes the second approach to examine both the fiscal and environmental optimizations of the beef trade path between southern Brazil and northwestern Europe (Soysal et al., 2013).
• Case study: How similar are the emissions estimations calculated through different modeling methods?

Case 4: Efficiency of international trade trends – US beef exchange

• The US is the largest importer, largest producer, and second largest exporter of beef products.
• One of the side effects of this standing in beef trade is reciprocal trade, or trade that is back/forth between the same two nations.
• Reciprocal trade is common and often quite harmless between bordering countries – often the trades are just based on the dynamic of varying locations of production hotspots near the border.
• A less common, but much more impactful, kind of reciprocal trade is between distant countries.
• Of these reciprocal trade patterns, Costa Rican beef exchange was especially notable. Costa Rica imported 27 million pounds of beef from the US in 2016, but also exported 5 million pounds to the US in 2016 (USDA ERS, “Cattle,” 2018).
• Case study: What are the environmental effects of reciprocal trade trends in terms of transportation emissions?

Results

Case 1

In this case, the effects of differing origins (namely Washington, New York, and Iowa) of Iowan apple consumption is modeled using Tool 2. Although Iowa is a key part of historical apple production, the origin of fresh apples at Iowan marketplaces is about 70% out-of-state during peak harvest times and 85% out-of-state in the Iowa apple off-season (Pirog, 1999).

In fall harvest time, one of the top contributors of fresh apples to Iowa is the state of Washington, the top apple-producing state in the country (Pirog, 1999). While the relationship between a top producer and top contributor may seem obvious, there are some exceptions in Iowan apple sources. New York, a much closer state, is comparable in growing conditions and is the second largest contributor to national apple production but is not as commonly seen on Iowan grocery shelves (Cornell University, 2016).

Washington is a northwestern state, so the export of apples to midwestern states is environmentally costly. A shift in Iowa apple sourcing from Washington growers to those of slightly closer states could have a quite substantial impact on systematic transportation emissions. While these states are quite distant, both have excellent apple-growing climates. As both are northern states, they have similar growing seasons and production methods, minimizing extraneous factors in comparisons.

The modeled situation is that of a 10% Iowan market sourcing adjustment from Washington apples to New York apples. Assuming the grocery store stocking mass is proportionate to the average apple consumption per capita in the US (15.3 pounds of fresh apples per year) in the city of Ames with approximately 66,000 people, about 101 thousand pounds (or about 46 tonnes) of Washington apples would be replaced by New York apples in Ames grocery stores over the course of a year (USDA ESMIS, 2012).

The modeling route used for the Washington emissions estimation is shown in figure 14. The first portion of the route is travel via semi-truck from Yacoma, WA (the county seat of the top apple-producing county in the state) to Pasco, WA (the location of a major railway station) (USDA ESMIS 2012). Next, a typical rail route was estimated by adding “checkpoints” in Boise, ID and Cheyenne, WY. The mode of travel then switches back to semi-truck from Omaha (another major railway stop) to Ames, IA.
The modeling route for New York emissions estimation is shown in figure 15. This route is very similar in road/rail proportions to maintain consistency in distance modeling. The origin of the apples is estimated as Rochester, NY. This is also the county seat of a top-producing county (Cornell University, 2016). The cargo is then carried via semi to Buffalo, NY, where it is loaded onto rail-travel. A “checkpoint” in Cleveland, OH is used to better estimate the path taken by the area railway. The cargo is then switched back to semi travel in Cedar Rapids after which it is carried to the destination, Ames, IA.

Figure 15. Modeled route from New York

Using Tool 2, the carbon emissions of both routes were modeled. The maps (without arrows) were shown to visualize the route and check for inconsistencies with common travel methods. In both modeling scenarios, the cargo load was estimated as 460 tonnes and adjusted to 46 tonnes post-modeling. This was done to better predict the type of mode used in each travel “leg,” as it is likely that the shipments would be made with a large mass of other products (which would change the mass range used to choose the vehicle emissions rating). It should also be noted that the total distance traveled in the New York route was about 1400 km while the Washington route was about 2400 km. The resulting adjusted emissions for the Washington and New York scenarios were 2400 and 1500 kg CO2eq/year respectively, showing that the distance of travel really is an impactful factor in similar scenarios.

Case 2

While distance is the most commonly cited source of emissions disparities, the method by which the goods are transported is potentially more important for route optimization. In the case of American fish consumption, this is a very applicable and easily modeled problem. Overseas fresh fish imports are extremely common and require very inefficient travel routes due to high spoilage risk. While frozen, canned, and otherwise processed fish products may be transported via ocean travel, it is necessary to transport fresh varieties by air, resulting in far greater vehicle emissions factors.

Americans ate about 2.3 pounds of salmon per capita in 2014 (749 million pounds total) (Kantor, 2016). About 80% of this salmon was imported, with nearly 40% of salmon imports being fresh (USDA ERS, “Aquaculture,” 2018). About 8.4% of American fresh salmon imports come from the Faroe Islands, the 2nd largest source of fresh imported salmon. Chosen for ease of modeling, the city of Richmond, VA has a population of about 220,000. Assuming average annual salmon consumption and import proportion in this area, about 13,600 pounds (or 6.2 tonnes) of fresh salmon is imported to the city from the Faroe Islands annually (USDA ERS, “Aquaculture,” 2018).

Using Tool 2, this is a simple route to model (fig. 16). The intention of this case study is to demonstrate the effect of differing vehicles on total transportation emissions. For the sake of minimizing extraneous factors, two very similar routes have been selected – a “fresh salmon” route and a “frozen salmon” route. The Port of Virginia in Norfolk, VA is one of the top 5 North American ship ports and a common checkpoint for international imports (McCabe, 2017). Similarly, the Richmond, VA airport is the largest airport in the state and handles about 140 million pounds of cargo annually (Richmond International Airport, n.d.).
Figure 16. Potential salmon shipping routes through a combination of ship and road travel (shown in (a) and (b), respectively) and through strictly plane travel (c)

These locations lead to two natural freight routes between the origin (the Faroe Islands) and the destination (Richmond, VA). The likely ship cargo route, used for frozen, canned, or processed salmon, would result in ship freight from the Faroe Islands to Norfolk, where a truck would likely continue the cargo route to Richmond. In the case of air travel, commonly used for fresh salmon, a plane would carry the salmon from the Faroe Islands to Richmond, where it could be distributed.

When these routes, along with a cargo mass of 6.2 tonnes, are plugged into Tool 2, extremely different emissions values are obtained. In the case of fresh fish transport, the most direct route results in a flight of about 5400 km from the Vágar airport of the Faroe Islands to the Richmond airport. This flight results in about 29,000 kg CO2eq. The frozen fish transportation is a 5500 km route which results in about 560 kg CO2eq. The factor of a continental aircraft (the most likely type for this air distance) is 70 times greater than the factor for an ocean watercraft at this distance, leading to this disparity.

Case 3

Differences in reporting and calculations often create a gap in information that is prone to biased exploitation. In order to find a consensus on issues such as the environmental impacts of a product line, it is of great importance to cross-reference and compare the data and methodology of a variety of research projects. A study published by the Operations Research and Logistics Group of Wageningen University examined 18 studies modeling different kinds of transportation emissions to find the distinctions that separate such projects (Soysal et al., 2013). In doing so, they designed a singular-situation modeling program to compare the fiscal and environmental impacts of supply chain changes in Brazilian beef trade.

While the financial and infrastructural research included in this project is compelling and impactful to the overarching emissions problem, the interest of this project is focused on the comparison of emissions modeling tools. In the research of the Wageningen group, the window of focus was much narrower, bringing higher precision in likely vehicle choices and exact transportation routes. This led to the use of singular averaged fuel efficiency factors (in liters per km), estimated for typical road/ocean conditions, truck/ship sizes, and fuel types. This factor is scaled with the load capacity of the truck or ship. Then, the product of the factor, the distance traveled, and a fuel-emissions conversion factor is used to assume the volume of CO2eq expelled during travel on a per-vehicle basis.

The route chosen in this study considered the beef exports from a small region – Nova Andradina. The beef produced in this region is likely to be shipped out of Porto de Paranaguá or Porto de Santos and unloaded at either Rotterdam or Hamburg. The exported masses in this scenario are 124 tonnes through Porto de Paranaguá and 676 through Porto de Santos (Soysal et al., 2013). The study assumes equal consumption by both end ports (Rotterdam and Hamburg).

To model a comparable case, the total system was split into four separate routes. First through Port de Santos to Rotterdam, then through Port de Santos to Hamburg, then through Porto de Paranaguá to Rotterdam, and finally through Porto de Paranaguá to Hamburg, all scaled per the masses and proportions described above (fig. 17). The emissions for these routes were 54,000 kg CO2eq, 55,000 kg CO2eq, 9100 kg CO2eq, and 10,000 kg CO2eq, respectively. This led to a total of about 128,000 kg CO2eq.

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The results of this model are very in-line with the estimates from the Wageningen group. The group reported a “lowest cost” emissions value of 127,917 kg CO2eq and a “lowest emissions” value of 113,633 kg CO2eq (Soysal et al., 2013). As the vehicle emissions estimations used for this study are from on-road averages, it is expected that the modeled values would be nearest to the lowest cost scenario, which includes 100% used vehicles and no changes in infrastructure from the current transportation situation (Soysal et al., 2013).

Case 4

Beef supply and demand is of nearly matching quantities in the United States, so it is surprising that international beef trade is a common occurrence. The US imported 3.0 billion pounds, exported 2.6 billion pounds, produced 25.3 billion pounds, and consumed 25.7 billion pounds of beef carcass weight in 2016 (USDA ERS, “Cattle,” 2018). Intuitively, one may think that the international exchange of 650% more beef than required by the production deficit may be the result of trade with the most accessible nations (i.e. bordering countries), but USDA data shows otherwise.

Over half of imports (about 1.8 billion pounds) and over two-thirds of exports (also about 1.8 billion pounds) of processed beef are from/to countries that do not border the US. From this, around 16 million pounds are purely reciprocal trades between non-bordering countries (USDA ERS, “Cattle,” 2018). Of these reciprocal trade patterns, Costa Rican beef exchange was especially notable. Costa Rica imported 27 million pounds of beef from the US in 2016, but also exported 5 million pounds to the US in 2016 (USDA ERS, “Cattle,” 2018). While it is not entirely clear why this practice is so common for beef products, the environmental impact of such trades is significant.

The case of Costa Rica was chosen for both the demonstration of severity and ease of modeling. As it is a relatively small country, there are two major ports, Puerto Limón on the Atlantic side and Puerto Caldera on the Pacific side. Using Tool 2, both the import and export scenarios of reciprocal trade were modeled. The 5 million pounds (or about 2269 tonnes) of imported beef was estimated as having come from the two major Costa Rican ports. In this model, a baseline estimation of emissions was used to avoid overestimation. Because of this, the model assumes all product is transported via Ship/Ferry travel and only includes port-to-port transportation emissions. These routes are shown in figure 18. Although geographically impossible, the “as the crow flies” distance between the closest ship ports was also used. The US ports were selected on account of their proportion of total US - Costa Rican import values (compiled from USA Trade Census data), so this modeling situation assumes that beef trade follows the same trading trends as total product trade. As shown below, the model only accounted for 81.5% of the imports, as the top-eight ports only represented 81.5% of total trade (World Port Source, 2016). Through summing the exports of these eight trade routes, the estimated emissions value for this portion of the case is 88,000 kg CO2eq. If it was assumed that this case was representative of 100% of the reciprocal imports, the estimate for total reciprocal import emissions would total about 88,000 kg CO2eq.
The emissions value for the exports to Costa Rica were calculated in the same way. These routes are illustrated in figure 19. To maintain as much consistency as possible, the top 9 ports were used to represent 81.7% of total reciprocal exports (World Port Source, 2016). The lowest possible emissions modeling methods were used for this model as well. Through the estimation of the export routes shown below, about 70,800 kg CO2eq result from the modeled 81.7% of US - Costa Rican reciprocal beef exports. Extrapolated to include 100% of reciprocal beef exports, this would total about 70,800 kg CO2eq.

As this data is derived from the lowest possible estimation, there are several other factors to be considered in this type of trade. First, geographical barriers are very important to non-air travel. The routes modeled here result in lower distances than true routes, as ships in a true transportation scenario would have to avoid the land through which the modeled routes pass. Another large consideration is that a significant portion of transportation emissions are the result of land travel. Transportation from producer to processor and from processor to port require much less direct routing and use either truck or train travel – both of which have larger emissions factors than ship travel. Lastly, this is also a low assumption because it is assuming all beef product is transported via ship. Some products may use air travel, resulting in far greater emissions.

In total, the reciprocal trade trends of the US and Costa Rica result in an estimated emissions value of at least 158,000 kg CO2eq per year. When all the effects of this reciprocal trade are summed, the actual impact of these trends are much larger than this model shows. While economic and political incentives often drive this sort of needless, non-bordering trade, observing the true environmental impacts of current practices reveals a great need for more sustainable trade tactics.

**Discussion**

**Other Emissions Factors**

Food trade trends depend heavily on a variety of factors. Spoilage, taste, consumer preference, political influences, regional climates, and economic incentives all determine the traveled route of food items before reaching the consumer’s plate. While these tools have the capability of modeling the primary steps of transportation in the life cycle of food products, the total lifecycle of these goods have a variety of sustainability factors that are not supported by this modeling system. The
first, and possibly most obvious, source of emissions from food products is the actual agricultural production and processing stage. This is indirectly related to food transportation but is categorically separate from the issues of the transportation sector. Another source of emissions—possibly the most underrated—is the portion of the transportation chain that takes the food from its point of sale to the door of the consumer. Last-step LDV transportation emissions are not accurately modeled through these tools but are an important part of the total supply chain and are estimated to result in about double the emissions of products direct-delivered via HDV (Wygonik & Goodchild, 2012).

The biggest drive for international product transportation is regional specialization. It is far more efficient for an area to excel at the production of one item and engage in foreign trade that it is for an area to self-sustain. Environmentally, this concept is still applicable. While locally sourced items may cut transportation emissions, often these emissions act as a sort of “red herring” in the grand scheme of sustainability. The life cycle analysis (LCA) of food products contain so much more than what happens after the food is produced. In the case of sourcing problems, one key factor is the environment of the consumer area. Crop growth requires much more use of resources and subsequently creates a much larger carbon footprint in an unsuitable environment. A study on tomato growth published by the French National Institute for Agricultural Research exemplified this well. When comparing the environmental impact of locally grown tomatoes in Austria with imported Spanish tomatoes, transportation was found to be relatively unimportant in the comparison of total emissions. Overall, the LCA of conventional, multi-tunnel greenhouse tomatoes in Spain resulted in about half the CO2eq emissions of the Austrian-grown conventional, greenhouse tomatoes (Theurl et al., 2013). While the transportation was the largest source of emissions in the lifecycle of the Spanish tomatoes, the Austrian greenhouse’s heating requirement resulted in about double the emissions—greatly overshadowing any advantage that the locally-grown tomatoes had in the transportation sector (Theurl et al., 2013).

This production regionalization, however, creates problems when the transportation of fresh food is demanded. A Ghent University study observing food perceptions in Europe found that fresh fish products are thought to be significantly healthier than frozen varieties in every country studied (Vanhonacker et al., 2013). While there isn’t scientific support behind this idea, the perception is still a driving factor in the fish market. This is often at the expense of supply chain sustainability, as never-frozen fish requires quick (and environmentally costly) transportation methods. In cases like these, air travel is common, which greatly increases the emissions resulting from the route. One example of this is described in a study over the carbon emissions of Australian seafood exports. Australia transports about 10% of total seafood exports via air travel (Farmery et al., 2015). Most of this seafood is flown due to risk of spoilage for fresh fillets. In the case of salmon, the transportation of frozen fillets to the US via sea expends about 0.7 kg CO2eq per kg. The air travel required for fresh fillets, on the other hand, expends 18.3 kg CO2eq per kg fish for the same route, which is about 9 times the total carbon emissions for farming and processing combined (Farmery et al., 2015). Even if the demand for freshness is maintained, there are alternatives to 100% air travel. By altering routes to introduce air-sea combination routes (where the food is only flown part way), the food could still reach its destination without spoiling while greatly reducing the emissions of the route (Sims et al., 2014).

Even in the cases of foods that do not require overseas travel, the modes of transportation contain variances that are hidden upon first observation. In the trucking and heavy-duty vehicle (HDV) section, replacement by rail travel would greatly cut emissions. The International Energy Agency predicts that a 35% replacement of HDV freight by rail freight would cut global freight emissions by 16% (Sims et al., 2014). However, updating to rail travel is not a simple process. The railroads of urbanized areas are inflexible and difficult to expand, hindering the growth of the rail sector. The European Commission has a set goal of using only water or rail vehicles in all freight travel over 300 km (Sims et al., 2014). While this would be an effective way to cut transportation emissions over time, the immediate fiscal and environmental cost of infrastructure production and installation would be great. It is estimated that the European rail system would have to double to accommodate this change, requiring a lot of resource allotment to a network that is slow and costly to replace and improve.

Technology evolution, however, is not such a slow process in most other modes. HDV travel is the most easily and consistently improved mode of travel. Due to the shorter lifecycle of road vehicles, replacement is high. This means that outdated vehicles are not as common on road routes as on the routes of other modes. It is much more difficult and costly to replace airplanes, ships, and trains, so HDVs are a more popular target for technological improvement. While trains and ships are still a more sustainable transportation method currently, trucks may begin to close the gap with the focus of vehicle emissions advancements and regulations.

These technological advancements are often the product of a forced hand or heavy outside incentive. Inciting change is not an easy process and requires a great deal of coaxing when the fiscal benefits are hidden or nonexistent. Often, governmental regulation is one of the only ways to push for development of freight vehicles. The immediate investment of such improvements is daunting to customers of the products, hindering the demand for more sustainable choices. Fiscal and governmental pulls have a clear history of polarizing perceptions of certain subjects—including sustainability and green initiatives. Without creating some sort of demand for greener products in the market, change is controversial and slow.

Applications

The intended use of this project is to provide engineers, designers, and planners with a program to model transportation
routes. Greater insight in product routing can help supply-chain engineers pluck the “low-hanging fruit” of simple sourcing inefficiencies to greatly decrease greenhouse gas emissions in the transportation sector. As exemplified in the case studies discussed above, these tools can help provide some guidance and insight on a wide variety of cases and questions. If used properly, this program could provide a simple and quick way to model many routes of travel to find the most sustainable (and feasible) method of product sourcing.

Uncertainty

All estimates provided by the program contain a great deal of uncertainty. The program is intended to model transportation routes for emissions comparisons, so the numbers and figures given are rough calculations, not measured values. The emissions ratings for the modes of travel are averages of the most typical travel characteristics (more about this can be found in the discussion of data acquisition and at the Network for Transport Measures). The distances are all calculated “as the crow flies,” so the actual transportation paths may add distance (and excess emissions) due to indirect routing.

Uncertainties may also arise from user error. Although Tools 2 and 3 are programmed to prevent Train/Rail and Truck/Road travel across oceans, the code will not always prevent unlikely or impossible routes. There are also no features in place to prevent Ship/Ferry travel across land (to allow for possible river routes). The maps on the tools are provided to help visualize any errors that may occur due to the geography of the regions.

The override buttons available in the tools may be used to troubleshoot when the error-checking boundaries prevent likely or necessary travel. These extraneous functions run the program with lowered error-checking, allowing for more travel routes. It is recommended, however, to utilize the mapping functions to determine whether there is a possible routing error before overriding.

Future developments

As discussed in the section of extraneous emissions factors, transportation is a multifaceted issue. There is an abundance of functions and considerations that could be added to create a more useful and comprehensive program.

First, the porting options in the third tool are not expansive enough to make the optimization function effective in low-population areas. The top world freight ports are often nor food-focused and do not include many of the potential food ports in Central/South America which are large contributors to global agriculture. Expanding the selectable and suggested options in Tool 3 would help make more informed decisions about real food transportation routes.

Second, the store-to-home step of transportation is a very important part of emissions modeling. This variable in food supply is one of the most impactful and most easily altered parts of the total lifecycle emissions scheme. Providing a way to model and compare mass delivery systems with personal consumer vehicle use could provide a great deal of insight on an unclear emissions source. This would require the addition of LDVs to the list of modes.

Another key feature that could possibly be integrated into future reiterations of the set of tools are time constraint functions. Perishability is a key consideration in fresh foods and a time estimation function added to the second and third tools would help the user consider the possibility of routes from a spoilage perspective. The added emissions factors of refrigerated trucks would also aid in modeling transportation of perishables. Reflecting those factors in the tools would create a simpler way to measure the feasibility as well as a more accurate measure of emissions.

Conclusion

Transportation sustainability is a multifaceted problem. Economic, political, and regional (such as specialization and climate) factors all play important roles in how countries import and export goods. Nearly all foods, regardless of origin, are now quite easily accessible, often resulting in less-than-optimal transportation practices. The set of tools described in this study help examine these issues more closely, giving insight into variations in transportation practices that could reduce carbon footprints.

These tools have a variety of functions and purposes, but all have very common categories of inputs/outputs. In each, the user must either give locational or distance data, which is interpreted as a distance between points. The cargo mass is also an essential factor to the emissions results. Lastly, the user usually needs to give a mode of transportation order, which is used (along with the distance and mass) to determine the specific emissions factor used on the route. This distance, mass, and factor are multiplied to yield an emissions product in kg CO2eq. These tools use an Excel file format to maintain simplicity and provide an easily understood form of emissions modeling for those that wish to find an estimate of currently practiced transportation routes.

The case studies provided here exemplify the variety of uses for these tools. Estimating the LCA of various products and finding inefficiencies in current practices are two of the most prominent possible uses. As shown in Cases 2 and 3, there are many factors that directly impact transportation emissions. Although distance (or “food miles”) can contribute greatly to the total emissions, the modes by which these distances are traveled leave an equally large footprint. A change in origin of Iowa apples from the state of Washington to the state of New York resulted in a reduction of carbon emissions that was roughly
proportionate to the change in route distance (about 37%). However, the modeled salmon transportation route from the Faroe Islands (America’s 2nd largest source of imported fresh salmon) to Richmond, VA resulted in a roughly 98% reduction of emissions when shipped via sea rather than flown, even though the flown route was slightly shorter in distance. The validity of these tools has been strengthened through comparison a similar, single case study. This study, involving an emissions estimation for Brazilian beef transportation by Wageningen University, used an estimation method that compiled methods from 18 other transportation emissions projects. The comparison of the use of these tools with their final estimation resulted in a 1-11% disparity in results, depending on the method used by the Wageningen University group. This helped confirm that the emissions factors used in these tools are very close to the methods and factors used in other literature. In Case 4, transportation optimization was observed. The purely reciprocal trade pattern of beef between Costa Rica and the United States was analyzed and found to result in at least 158,000 kg of excess CO2 equivalent annually.

Although these tools do help model one portion of the LCA of a food product, users must be advised that transportation itself is not an end-all part of food sustainability. Many other factors play into both the transportation sector as well as the other parts of a product lifecycle. The last part of transportation, store-to-consumer, is not covered by this modeling program, which may lead to the misinterpretation of true emissions. Where and how food is produced both directly impact total emissions and indirectly affect transportation. Foods produced in a nearby unnatural environment requiring heat input are likely to result in more emissions from production alone than the emissions from the total lifecycle of a product from a distant natural environment. Infrastructure and the construction of vehicles also play a role in total transportation lifecycle emissions. Although train and ships still result in less emissions, trucks are easier to replace with new technologies, speeding up the potential for improvements.

Transportation emission reductions would be one of the many ways that the world could resist the rise of global carbon emissions. The food sector, driven by the globalization of the food economy, has created a rising environmental cost of food transportation. The tools outlined in this report provides a variety of methods for users to analyze and model these transportation systems. While there are many considerable factors in the total lifecycle sustainability of an item, modeling feasible food transportation routes is clearly a step towards lessening the burden of food transportation emissions.
References


